EVALUATING THE IMPACT OF DIFFERENT ATRIA CONFIGURATIONS ON THE ENERGY PERFORMANCE OF BUILDINGS IN DIFFERENT CLIMATES

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ABSTRACT

EVALUATING THE IMPACT OF DIFFERENT ATRIA CONFIGURATIONS ON THE ENERGY PERFORMANCE OF BUILDINGS IN DIFFERENT CLIMATES

Farhoudi, Meysam

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Generally, the impact of the building sector on the world energy consumption and environmental protection is considerable; in fact, the building sector holds the half of the world total energy consumption share. Nowadays, energy efficiency phenomena as the result of several challenges that the world is encountering has become an important issue. Meanwhile, the atrium as a tool to improve the energy performance of a building can be utilized to address the high energy consumption of the conventional buildings.

This study aimed to examine the impacts of different physical properties of an atrium on the energy performance of the atrium buildings in different climates. To be more specific, this research intended to understand the impacts of atrium orientation, aspect ratio and the atrium building height on the heating, cooling and lighting loads of the atrium buildings in different climatic conditions.

To examine the effect of each variable on the energy performance of the building several digital models of atrium buildings were prepared and their energy performance were simulated by DesignBuilder software. Each of the atrium buildings were set with different variables to monitor the effects of a single variable or the combination of the variables on the energy performance of the buildings. According to this research, in few examined climates the height of the atrium building has the most effect on its energy performance. Though the effect of the atrium aspect ratio on the building energy performance is almost considerable, the atrium orientation does not contribute to it significantly. To further clarify the conclusions, atrium buildings with square shape atria have better energy performance than those with rectangular shaped atria, regardless of the atrium orientation.

Keywords: Atrium building, Energy simulation, Energy performance, Physical Properties

ÖZ

FARKLI ATRİUMLAR BİÇİMLERİNİN FARKLI İKLİMLERDE BINALARIN ENERJİ PERFORMANSINA ETKİSİNİN DEĞERLENDİRİLMESİ

Farhoudi, Meysam
Yüksek Lisans, Yapı Bilimi, Mimarlık Bölümü
Tez Danışmanı: Prof. Dr. Soofia Tahira Elias Ozkan
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Genellikle, bina sektörünün etkisi dünyadaki enerji masrafında ve çevresel koruma açısından etkisi önemlidir; aslında, bina sektörü dünyadaki tüm enerjinin yarısını tuketmektedir. Günümüzde, dünyanın karşılaştığı çeşitli zorluklar nedeniyle enerji verimliliği olayları önemli bir konu haline gelmiştir. Bu arada, atriyumlar binanın enerji performansını gelişleten bir araç olarak, kanvensiyonel binalardada fazla enerji masrafı meselesini hal etmek içinde kullanıla bilirler.

Bu çalışma Çeşitli iklimlerde bulunan atriyumlu binalarda atriyumun farklı fiziksel özelliklerinin binanın enerji performansı üzerinde olan etkisinin incelenmesi amaçlandırmaktadı. Daha spesifik olmak gerekirse, bu araştırma farklı iklim koşullarında atriyumlu yapılarda atriyum oryantasyonu, boy oranı ve binaların yüksekliğinin, binanın ıstma, soğutma ve aydınlatma yüklerinin üzerinde bulunan etkilerini anlamak niyetinde.

Her değişkenin binanın enerji performansı üzerinde olan etkisini incelemek için, atrium binaların çeşitli dijital modelleri hazırlanıp ve modellerin enerjı performansları DesignBuilder yazılım tarafından simüle edilmiştir. Her bir değişkenin ya değişkenler kombinasyonun binanın enerji performansı üzerinde olan etkisini izlemek için her bir atriyum binası farklı değişkenler ile tanımlanmıştır.

Bu araştırmaya göre, incelenen Birkaç iklimde atrium binanın yüksekliği binanın enerji performansı açısından en fazla etkiye sahiptir. Atriumun boy oranı bina enerji performansında dikkate değer etkisi olmasına karşın, atrium oryantasyonu önemli ölçüde katkıda bulunmamaktadır. sonuçu daha açıklamak gerekirse, atriyum binalarda atriyum oryantasyon faktörünü göz önünde almaksızın, kare şekilinde olan atriyumlar dikdörtgen atriyumlara göre daha iyi enerji performansına sahiptir.

Anahtar Kelimeler: Atriyum bina, Enerji simülasyonu, enerji performansı, Fiziksel Özellikler

To My Family

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I owe my deepest gratitude to my supervisor Prof. Dr. Soofia Tahira Ozkan for her great guidance, encouragement and endless support at all times with patience, understanding and sincerity. It has been a pleasure and honor to work with her.

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LIST OF ABBREVIATIONS

SYMBOL	DEFINITION
3D	3 Dimension
ADF	Average Daylight Factor
B.C	Before Christ
BTU	British Thermal Unit
CGY	Calgary
EPBD	Energy Performance of Buildings Directive
E-W	East-West
GHR	Global Horizontal Radiance
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IEO	International Energy Outlook
IPCC	Intergovernmental Panel on Climate Change
MTOE	Million Tonnes of Oil Equivalent
N-S	North-South
PHX	Phoenix
PRS	Paris
RH	Relative Humidity
SHGC	Solar Heat Gain Coefficient
SGP	Singapore

UNEP	United Nations Environment Program
U.S.	United States
USA	United States of America
US DOE	United States Department of Education

CHAPTER 1

INTRODUCTION

This study concerns atrium buildings in terms of energy performance by focusing on the effects of different physical properties of an atrium building on the energy performance of the whole building. In this chapter, the argument, objectives of the study, and a short summary of procedure are presented. The chapter concludes with a disposition of the following chapters.

1.1 Argument

Buildings are responsible for almost 40% of global primary energy use and they are the largest contributors to the global Greenhouse gas emission with a share of one-third of the total global emission (United Nations Environment Programme). On the other hand, according to Wigginton and Harris (2002), energy efficiency phenomena which is one of the challenging issues of the era, has become a necessity rather than a desire as the result of economical, developmental and environmental issues that the world is facing.

Saxon (1986) believes that the idea of the atrium has a background as old as two millenia. It could play the role of a focal courtyard, grand entrance space or sheltered semi-public area. Bendar, (1986) gives a contemporary definition for an atrium as a centroidal, interior, daylit space, which organizes the building. The author introduces several generic atrium forms; however, the closed atrium is the subject of this research.

According to the Bendar, (1986), the inherent energy saving potential of atrium buildings is the main reason for their resurgence in 1967. Meanwhile, Goulding, Lewis, and Steemers, (1994) state that considering an atrium in a building does not necessarily increase the energy efficiency; in fact, it may actually decrease it. On the other hand, according to Voeltzel , Carrie, and Guarracino (2001), the inappropriate design of highly glazed buildings may lead to a significant energy waste and discomfort. However, Saxon (1986) believes that designing an atrium building while considering energy efficiency principles in mind can lead to a better energy performance in comparison to the conventional buildings.

Nevertheless, designing an atrium that improves the energy performance of the building is a challenging task. Understanding the effect of different physical properties of an atrium on the energy performance of the parent building can lead to designing more energy efficient atrium buildings. Whereas, there is not a comperehensive knowledge regarding this subject to help the designers and reserachers to bring forth atrium designs which also aid the energy performance of the atrium building.

This study intends to address the problem regarding the energy efficiency of atrium buildings by defining the effects of different physical configurations of an atrium on the energy performance of the whole building under different climatic conditions. This research will help to have better understanding of potential of an atrium in increasing the energy performance of an atrium building.

1.2 Aim and Objectives

The first aim of this study is to understand the types of atria that were used and are being used both historically and in modern era, through a thorough literature review. The second and the most important aim is to investigate the effects of the design variables of an atrium building under different climatic conditions. The variables are the height of the atrium building; the aspect ratio of the atrium; the atrium orientation and the climatic condition. The amount of consumed energy for heating, cooling and lighting is the indicator for the contribution of the atrium to the buildings energy performance.

1.3 Procedure

The study begins with a literature review, mentioning the importance of energy efficiency and energy performance in buildings, followed by historical background of atrium buildings and their potential in reducing the energy consumption of buildings. Subsequently, different atrium building models with various physical properties are created and simulated under different climatic conditions. Finally, the recorded results are gathered and compared to reveal the effect of each physical property on the energy performance of the atrium buildings.

1.4 Disposition

The report is composed of five chapters.

First chapter introduces the subject of study including its argument, aim and objectives with procedure of study and its disposition.

Second chapter presents literature review, which includes importance of energy performance, historical background of atrium buildings and potential energy efficiency of atrium buildings.

Third chapter presents the method of the study.

Fourth chapter evaluates results of simulations and includes discussion.

Fifth, the final, chapter presents the conclusion derived from literature and result evaluation.

CHAPTER 2

LITERATURE REVIEW

2.1 Energy Performance in Buildings

Wigginton and Harris, (2002) believe that Industrial Revolution led to an increase in energy consumption by societies due to the discovery of the significant benefits of the electrical power. The author also states that the side effects of the expanding use of energy were neglected for a considerable time. The energy crisis of 1973 and the publication of The Limits to Growth, a report by the Club of Rome in 1972 can be considered as two milestones in the history of energy that draw the world's attention toward the total dependency of the developed countries on the availability and the price of the energy.

According to Braham and Willis (2013), during fuel crisis energy frequently becomes the primary concern in architectural design as it became in the late 1940s, 1970s, and the end of the twentieth century. The authors also mention the discussion during 1960s brought up by Reyner Banham regarding the importance of energy in buildings during both energy abundance, and the periods of fuel scarcity or high prices. In this regard, Wigginton and Harris (2002) declare that since the early twentieth century, the potential of design of the buildings in reducing their energy consumption had been realized, and significantly developed by the 1930s.

According to Braham and Willis (2013), by the energy crisis in the 1970s, a new generation of admirers of passive design emerged who advocated the environmental control of the buildings with only structural elements. Wigginton and Harris (2002) state that now it is commonly accepted that the buildings are responsible for almost half of the delivered energy consumption within the majority of the developed countries. Thereby, energy performance of buildings can play a significant and vital role in increasing the total energy efficiency and reducing the overall energy consumption throughout the world.

To provide cohesive and consistent information regarding the energy performance of the buildings we need to have an unambiguous definition of energy performance itself. According to Zgajewski (2015), energy performance of buildings is defined by the Energy Performance of Buildings Directive (EPBD) as, “The amount of energy actually consumed or estimated to meet the different needs associated with a standardized use of the building, which may include, inter alia, heating, hot water heating, cooling, ventilation and lighting” (p. 7).

2.1.1 Importance of Energy Performance in Buildings

According to the United Nations Environment Programme (UNEP), buildings are responsible for 40% of global primary energy use and they are the largest contributors to the global Greenhouse gas emission, with a share as large as one-third of the total global emission. On the other hand, according to the U.S. Department of Energy (U.S. DoE) (2012) in the year 2010, building sector with 41% holds the largest share of the primary energy consumption among all three sectors in the U.S. The industry sector with 30% and transportation sector with 29% of the U.S. total primary energy consumption hold the second and third places, respectively (Figure 2.1). The primary energy consumption is defined by the International Energy Agency, (2012) as, “the direct use of energy at the source, or supplying users with crude energy which has not been subjected to any conversion or transformation process” (p. 43).

According to the U.S. Energy Information Administration (2013) in the year 2011, 524 quadrillion BTU was the marketed energy consumption throughout the world, of which, 382 quadrillion BTU was the total delivered energy consumption. Four sectors, commercial, industrial, residential and transportation, are the consumers sector. In the same year, the building sector (residential and commercial sectors) was responsible for 21% of delivered-energy consumption, whereas, the industrial sector dominates the delivered energy consumption by 52% of the total share (Figure 2.2). U.S. Energy Information Administration (2004) defines the Site Energy Consumption as "The BTU value of energy at the point it enters the home, building, or establishment; sometimes referred to as delivered energy".

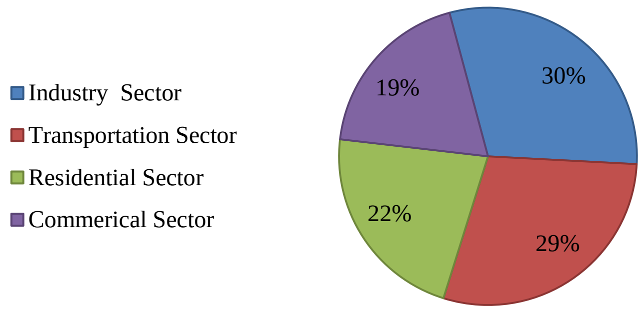


Figure 2.1: Primary Energy Consumption by different Sectors in 2010
Source: U.S. Department of Energy (2012)

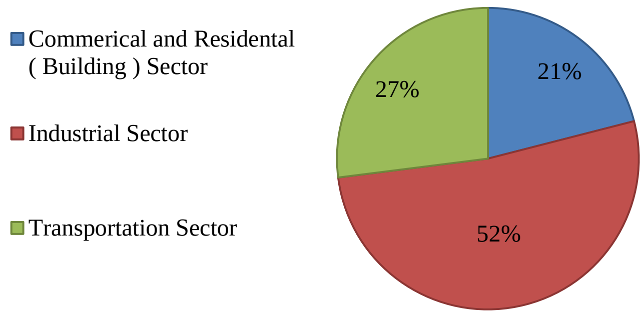


Figure 2.2: World Delivered Energy Consumption by Different Sectors in 2011
Source: U.S. Department of Energy (2012)

Space heating with 37% of the total delivered energy consumption is the predominant energy use in building sector. Water heating by far is the second delivered energy use with 12% of the total share. Thereby, space heating, water heating, space cooling, and lighting account for about 70% of total delivered energy consumption in 2010, in the U.S (Figure 2.3) (U.S. Department of Energy, 2012).

According to Sustainable Energy Authority of Ireland, the primary energy supply gives a better understanding of the effects that individual sector has on energy consumption and CO_2 emission. Hence, statistics regarding primary energy consumption for different end-uses of the building sector would help to better comprehend the situation.

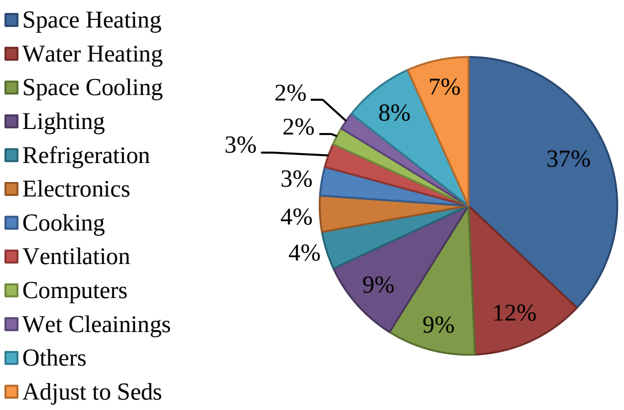


Figure 2.3: U.S Primary Energy Consumption by End-use 2010
Source: U.S. Department of Energy (2012)

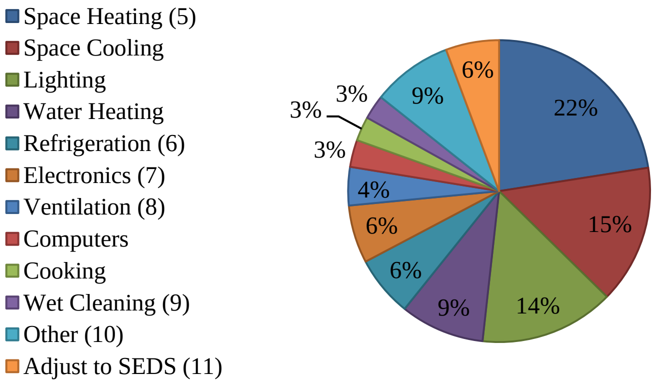


Figure 2.4: U.S Delivered Energy Consumption by End-use 2010
Source: U.S. Department of Energy (2012)

According to U.S. DoE (2012) space heating with 22.5% has the highest share of total primary energy consumption in the U.S. building sector in 2010. Space cooling and lighting with 14.8% and 14.4% of the total primary energy consumption are the second and third end-uses, respectively (Figure 2.4). Meanwhile, according to the U.S Energy Information Administration (2013), the IEO2013 reference case, total world delivered energy demand of the building sector will increase by an average annual growth rate of 1.6 percent per year from 2010 to 2040. It is equal to 50 quadrillion BTU increase from 81 quadrillion BTU in 2010 to nearly 131 quadrillions BTU in 2040.

According to European Commission, Directorate-General for Energy and Transport (2007), the highest cost-effective saving potential in the European Union is available in the residential and commercial building sectors, mainly as a result of its large share of total energy consumption. According to this report, the estimated energy saving potential for 2020 is around 91 MTOE for residential and 63 MTOE for commercial buildings (Table 2.1).

Table 2.1: Saving Potential of Each Sector in the European Union for 2020
Source: (European Commission, Directorate-General for Energy and Transport, 2007)

Sector	Energy Consumption (2005) MTOE	Energy Consumption 2020 (business-as-usual) (MTOE)	Energy Saving Potential 2020 (MTOE)	Energy Saving Potential 2020 (%)
Household (residential)	280	338	91	27
Commercial Buildings (tertiary)	157	211	63	30
Transport	332	405	105	26
Manufacturing Industry	297	382	95	25

2.1.2 Availability and Cost of the Energy

According to Mongillo (2011) currently, petroleum is the number one energy source throughout the world. U.S Energy Information Administration (2013) estimates that liquid fuels, natural gas and coal will still provide more than three-quarter of the total global energy consumption in 2040. It is also estimated that the liquid fuels consumption will decrease in building and electric power generation sections throughout the world, while it will increase in industrial and transportation sectors. The decline in liquid fuels consumption in commercial, residential and power sector is the outcome of rising world oil prices, which provides motivation to switch from liquid fuels to alternative fuels where possible.

Yergin (2011) believes that from the very first day of the establishment of the modern oil industry, in 1859, the world has experienced several peak oil warnings. Peak oil is defined as the fear that the world is running out of oil; it describes the world, which is almost at its maximum output, and the major decline would start soon or maybe has already begun. As illustrated in Figure 2.5, U.S Energy Information Administration estimates a significant rise in world energy consumption by the year 2040.

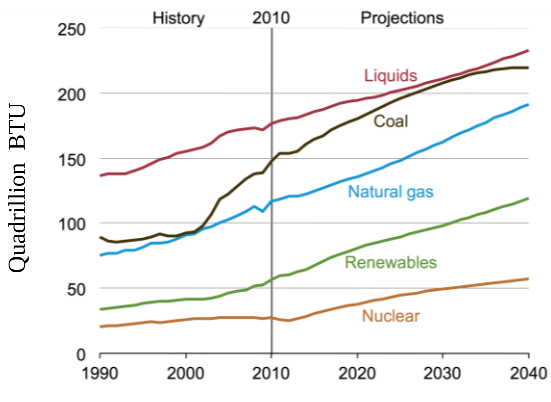


Figure 2.5: Estimated World Energy Consumption by Fuel Type
Source: U.S Energy Information Administration (2013)

According to Wigginton and Harris, (2002) though the burgeoning use of energy and its subsequent impacts was ignored for a long time, finally the humanity’s thirst for energy consumption came to the light in 1972 by the Club of Rome’s report, “The

Limits of Growth". The author also declare that the 1973 and 1974 energy embargo applied by some oil-producing countries, as one of the several "peak oils" in history, increased the concerns regarding the security and the price of the resources.

According to Yergin (2011), the fifth and the last of the peak oil series started by the twenty-first century. Growing oil consumption of China and other emerging economies, and significant increase observed in oil demand outlook, predictably caused the anxiety regarding the adequate future supplies. However, this time the climatic concerns timely paired with the ongoing oil peak, providing enough motivation to distant from carbon-based fuels.

Yergin (2011) adds on, at the time being, how much oil we have and for how long it would be sufficient is the question, which challenges the mind. However, according to an analysis, clearly the world is not running out of oil. According to the author, since the beginning of oil industry in 1859, the world has produced about 1 trillion barrels. Whereas, at the time it is estimated that there are minimum 5 trillion barrels of petroleum resources, of which 1.4 trillion barrels can economically and technically account as the probable reserve.

On the other hand, according to International Energy Agency (2012) the price of the energy is a determinative variable in energy consumption trend. As Illustrated in Figure 2.6, the author considers three different IEA crude oil price scenarios to estimate the oil price until 2030, which in two of the scenarios the rise in the oil price is evident.

According to International Energy Agency (2012), the government support, falling costs of the technology, CO_2 pricing in some regions and expectation for the rise in fossil fuel price, help to increase the share of renewable resources as the primary energy. As stated by U.S Energy Information Administration (2013), in IEO2013 reference case, renewable energy will be the fastest growing source of electricity generation. Total electricity generation from renewable resources estimated to increase by 2.8 percent annually, and the share of the renewable energy of world electricity generation to grow from 21 percent in 2010 to 25 percent in 2040.

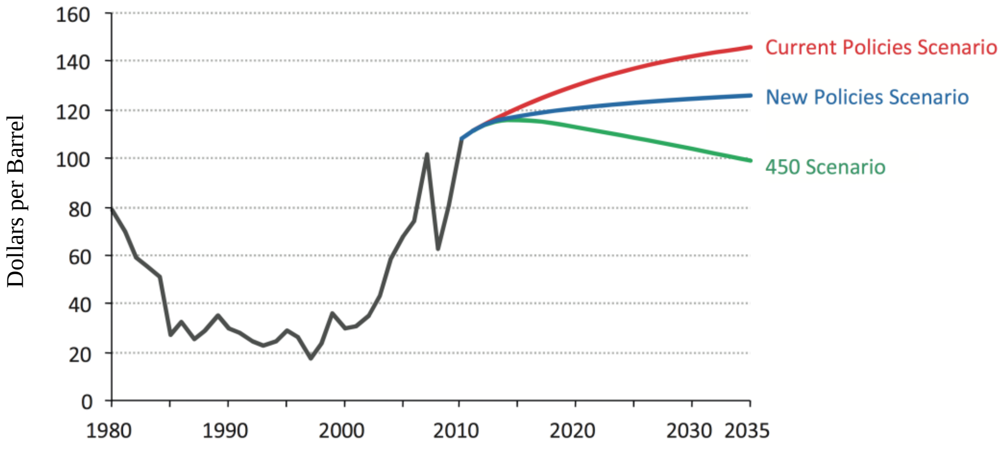


Figure 2.6: Average Estimated IEA Crude Oil Price in Three Scenarios
Source: International Energy Agency (2012)

2.1.3 Environmental Considerations

Weisman (2007) in his book "The World Without Us" brings several questions regarding the human being and his effects on the face of the planet earth. We, human beings ask ourselves whether we unconsciously poisoned or destroyed the planet, and ourselves included. We abused the soil and water in such harsh severity that there is less of each now. We directly or indirectly caused the extinction of thousands of species, which probably would not get back to nature ever. The author continues by asking the question that if one day our earth degenerates to a very sick planet, at what point would things have gone so far, we, the so-called intelligent beings, would not be among the survivors? However, the truth is, nobody knows the answer. Maybe our stubbornness pushes us to deny the possibility that it has already become degenerated.

Wigginton and Harris (2002) believe that effects of buildings on the environment have been known for a long time; dating from Vitruvius's book to William Morris's concern about the significant rate of urbanization, industrialization and its harm to the environment in the late nineteenth. According to Cullers (2015), for the first time in the 1880s the scientific concern of human impact on the climate expressed; however, it did not draw the attention of the public seriously till 1980s. Wigginton and Harris (2002) state, the possible potential in buildings for efficiency in energy consumption and introducing new energy strategies, such as; taking advantage of solar power, became obvious in the twenty century and evolved by the 1930s. By the 1960s and 1970s, ecological effects of the buildings were widely discussed that was the beginning of ecological design, as we know it today.

According to Wigginton and Harris (2002), greenhouse effect and the subsequent impact of climate change are the main worldwide environmental problems which human beings are encountering from the onset of the twenty-first century. In 1988, the Greenhouse effect was officially accepted by Intergovernmental Panel on Climate Change (IPCC) as a problem for the planet earth. Cullers (2015) explains that the Greenhouse effect is a natural phenomenon in which specific atmospheric gases resist against the solar radiation escaping into space. Wigginton and Harris (2002) add that this layer of the gases is permeable to the incoming short-wave radiation, whereas, it blocks the long-wave ones leaving the atmosphere. As the result, the radiation is trapped inside the atmosphere, heating the surface of the earth.

Cullers (2015) believes that the Greenhouse effect is a part of the nature to help the planet to maintain its essential temperature; however, a range of human activities intensifies the process and causes the global warming. There is a belief that rapid global warming could result in catastrophic effects, such as, mass extinction, loss of ecosystems rises in ocean level and increase in pollution (Cullers, 2015).

Cullers (2015) mentions that the issue regarding the credibility of the accusation, which considers human activities partly responsible for global warming, is widely debated. However, as stated by Wigginton and Harris (2002), there are concerns about the damage being inflicted on fragile ecosystems by increasing the development and resource extraction, and the depletion of the ozone layer, which allows harmful ultraviolet radiation to penetrate the lower atmosphere. In addition, the author states, there has been an overall diminution in air quality, perceptibly in urban areas. Albeit, it is generally accepted that buildings inflict a considerable burden on the environment and they have the obvious potential to prevent major and possible environmental degradation.

On the other hand, considering the energy efficiency of the buildings is becoming one of the main principles during the design process. As it is clear, minimizing the energy consumption not only contributes to the environmental protection, but it also reduces the energy expenses; meanwhile, the potential of atria in moderating the energy consumption can help to achieve this goal. In this regard, Saxon (1986) reiterates that designing an atrium building with the energy issues in mind would result in considerable energy efficiency in comparison to the conventional buildings.

2.2 Atria and Atrium Buildings

In this part, overall history of the atrium, its definition and architectural functions have been discussed. Moreover, an investigation into the possible energy efficiency that atrium building with different physical properties can offer has been conducted.

2.2.1 Historical Background of the Atrium

According to Saxon (1986), the atrium is not a new idea; in fact, it has an old history as long as 2000 years. Atrium could function as a focal courtyard, grand entrance space or sheltered semi-public area. Middle-eastern and Mediterranean architecture are its cradle, where it has been developed through the centuries within the limits of masonry and timber technology. The author states that, as the result of the industrial revolution, the western world utilized iron and glass technology to create different spaces such as covered court, arcade, galleria, winter garden and atrium, as we know them today (Saxon, 1986).

In the following part, more detailed information regarding the courtyard as the primary shape and ancestor of the modern atrium, and its development through the ages will be given. This part is divided into four subsections as four epochs, starting with describing the origin of the atrium and concluding with the atrium development in the contemporary period.

2.2.1.1 First Epoch: Courtyard, the Ancestor

According to Bendar (1986), as the result of urban settlement, the Courtyard concept, which is the evolved format of nomadic encampments brought into the individual dwelling creating the atrium house form. Early cities in comparison to nonurban locations were more potential sites to utilize the true atrium plan as a prevalent house form. The author believes that conditions created by urbanism, such as limited exposure to the communal space, the lack of privacy and the limited land area along with the intention to control the climatic conditions justifies the atrium plan as a rational design. Rapoport (1969) has a cultural perspective toward the courtyard houses and believes that there is a cultural explanation behind the essence of the courtyard houses. The author states that this type of house used to belong to the societies, which are populous and hierarchical allowing a person to have some privacy, while not leaving the folds of the family. Rooms surrounding the courtyard create separate zones, and courtyard itself works as a communal space.

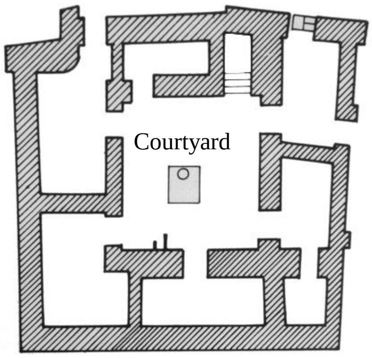


Figure 2.7: Plan of a Courtyard House at Ur, Mesopotamia
Source: Bendar (1986)

According to Bendar (1986), the oldest example of the courtyard house, which dates from third millennium B.C., was found during an archeological exploration at Ur on the Euphrates River in Mesopotamia. The role of the courtyard in organizing the whole spaces is evident in the floor plan as shown in Figure 2.7 above.

According to Bendar (1986) the Greek took the next step toward the courtyard house; between the fifth and sixth centuries B.C. they expanded and developed the concept.

Subsequently, dating from the third century B.C. the classical concept of the atrium in the houses of Rome is clearly evident. However, Romans have probably borrowed the idea of the atrium from Etruscans, who utilized the idea during the sixth and fifth centuries B.C. On the other hand, Pollio (1914) believes that the atrium has a Tuscan origin. The common word that he used to refer to the closed court is Cavaediu.

Bendar (1989) believes that the combination of Greek peristyle and Tuscan atrium in the same plan forms the main body of the completely developed Roman house with a Roman atrium. The Roman atrium is the primary space in the plan, which is surrounded by rooms as the secondary spaces (Figure 2.8). The spaces have direct visual and physical access to the atrium to benefit from the fresh air and light flowing through the opening of the atrium. According to the author, it is noteworthy that during the succeeding period of architectural history until the eleventh-century, space in front of the entrance to the Christian basilica, was also called the atrium. One good example is the church of San Ambrogio located in Milan (Figure 2.9).

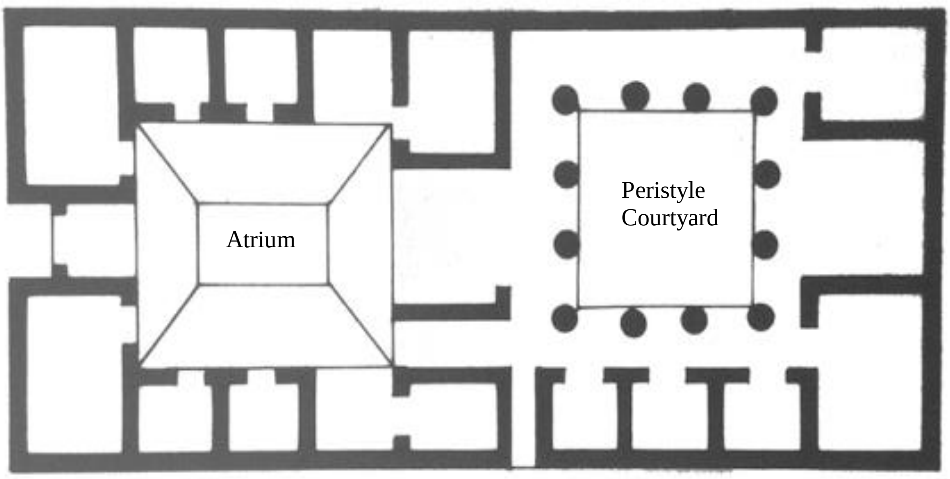


Figure 2.8: Roman House Plan at Herculaneum
Source: Bendar (1986)

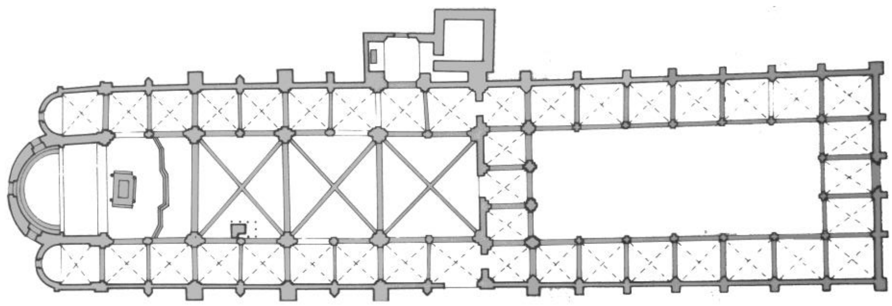


Figure 2.9: Plan of Basilica Atrium, San Amborgio, Milan
Source: Bendar (1986)

2.2.1.2 Second Epoch: Developing in Europe

According to Saxon (1986), as a result of the industrial revolution, the western world inclined to utilize iron and glass technology to create various spaces, such as covered court, arcade, galleria or winter garden. Bendar (1986) states that during the years before 1800 though the cast and wrought iron were available but they were not commonly used. Development of glass manufacturing, besides the invention of Henry Bessemer in 1855 of a new method for producing larger and stronger steel components, provided the opportunity for the development of a wholly new architecture. The author believes that the climax of the development, both in terms of sophistication and scale was the Crystal Palace, located in Hyde Park, London, and designed by Joseph Paxton in 1851 (Figure 2.10). It was one of its kind in terms of scale; completely transparent and constructed with the mesh of structural iron. It was completely prefabricated and could be disassembled and transported to a different site; as was done in 1852.

Simultaneously with the growth of the all-glass-and-iron building, there was an effort to combine the idea with the conventional masonry buildings. This effort emerged in the shape of two new spaces: arcade, and the atrium (Bendar, 1986). Geist (1983), defines the arcade as "a glass covered passage way which connects two busy streets and is lined on both sides with shops (P. 3)". According to Bendar (1986) it developed in the nineteenth century as the answer to the demand of the society for the public space, which is protected from traffic and harsh weather conditions, to help the growing business of luxury merchandise. Probably the most famous of the arcades is Galleria Vittorio Emanuele II in Milan.

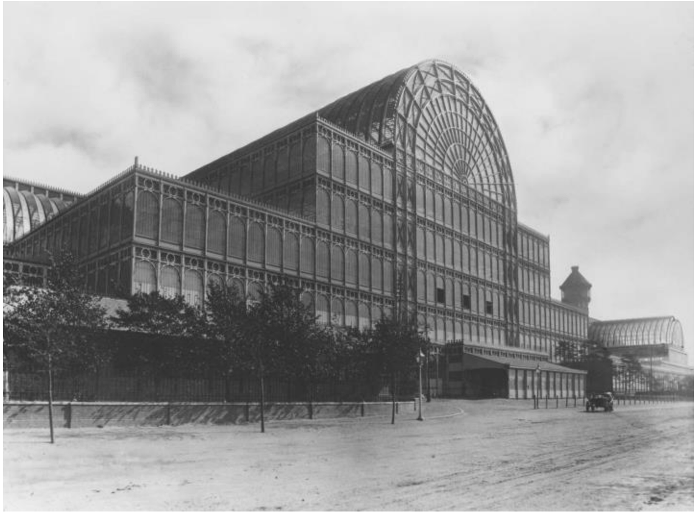


Figure 2.10: Crystal Palace Designed by Joseph Paxton
Source: http://www.britannica.com/topic/Crystal-Palace-building-London

Bendar (1986) believes that the development of arcade is directly connected to that of the atrium. Though both share several similarities, the arcade is only for commercial spaces, whereas atrium covers lot more functional applications. As a result, the new spatial type, the atrium was born when Sir Charles Barry designed the first known atrium in the Reform Club, London (1837-1841). He used Pallazzo Farnese as a pattern for the design form and modeling plan and covered the court with steel and glass structure as the next historical step toward an atrium building. Subsequently, for the first time the court merges with the interior of the building, protecting the interior from the weather, yet, not eliminating the natural light of open courtyard (Figure 2.11).

According to Bendar (1986) the first half of the nineteenth century in England and France can be considered as the first epoch when, the atrium started to develop and to be utilized as a spatial type. However, in Europe by the second half of the nineteenth century the atrium building started to lose its popularity. Bendar (1986) states that the main reason was the poor resistance of the atria, which were mostly constructed by glass and steel, against the fire hazards. There were many iron and glass buildings destroyed as the result of the drawback.

Figure 2.11: Reform Club Designed by Sir Charles Barry
Source: http://www.ifacs.co.uk/portfolio-post/reform-club/#

2.2.1.3 Third Epoch: Development in USA

According to Bendar (1989) the new epoch for the atrium begins in the United States by the turn of the nineteenth century. In this period, most of the buildings were based on their European predecessors, which, designers had read about or visited previously. During this period, the buildings were mostly masonry; iron, steel and glass were being used only for the atrium part of the building, probably, as the design strategy toward safer atrium buildings against fire hazard. The author states that the most of the atria at the period were orthogonal in plan with several floors. Within many of the buildings, the glazed roof was designed at the intermediate level in the light court rather than at the top of the building so that the atrium and light court occupied same plan position. These atria were equal in function to their European models. They were geographically spread all over the country, but in the south and southwest, perhaps because of more favorable climate, hardly any were to be found.

According to Saxon (1986) and Bendar (1986), few architects have contributed to the atrium development during its third epoch, and Frank Lloyd Wright, who designed the Larkin Building at Buffalo, New York in 1903, was one of them (Figure 2.12). In this project, the selected site for the construction had limited outlook and pollution problem, caused by a nearby coal yard. Saxon (1986) states that the architect designed a single volume building with four floors, which are sky-lit. The ground floor was a workplace overlooked by levels of offices, inspiring the sense of cohesiveness. Besides, he fed the atrium space with filtered air to protect the occupants from the pollution of the site.

Figure 2.13: Atrium of Larkin Building
Source:
https://www.pinterest.com/pin/51791464436523594/

Figure 2.12: Atrium of Bradbury Building
Source:
http://arquiscopio.com/archivo/2013/02/16/edificio-bradbury-de-los-

According to Bendar (1986), another atrium building, which has frequently been used as the pattern for later atrium designs, is the Bradbury Building in Los Angeles, designed by George Wyman in 1893 (Figure 2.13). This building has the best design among the buildings of its kind. As stated by the author, it has Victorian street architecture character lined by brick facades. The 14.3m x 36.3m atrium functions as the interior lobby surrounded by five levels of offices. The clear-glass skylight allows the natural light of the day inside. The building had the low-energy design scheme; the pivoted windows just under the skylight help in balancing the natural lighting and natural ventilation.

According to Saxon (1986), following World War I the third epoch of the atrium came to an uncertain close. Bendar (1986) states, the late nineteenth century and early twentieth century was the epoch when the atrium buildings injected the great exuberance and architectural spirit in a wide variety of the buildings. Though the certain reason for the decreasing presence of the atrium in this era is not clearly known, but as in Europe, the fire hazard can be considered as a significant obstacle to its existing in the United states. On the other hand, the International Style had an influence on architecture and the new plan typology, as the postwar economy had.

2.2.1.4 Fourth Epoch: Revival of the New Atrium

Saxon (1994) states that though, the advent of modern architecture in the twentieth century with its contradictive characteristics affected the atrium concept prevalence, however it could not eliminate it completely. The atrium concept got back to life again in the late 1960s mainly in North America. The author believes that though, certain technical developments such as the safe elevator, resulted in the significant rise of the skyscrapers, there is no such particular reason for the resurgence of the atrium building in North America. However, according to Bendar (1986), there are multiple reasons, which assisted the atrium building to revive; such as marketing economic, energy consciousness, technological advancement, programmatic needs and architectural invention are few of the factors to mention.

According to Saxon (1986), the Architectural Review called the atrium “An idea whose time has come”. It is the sentence that The Architectural Review used to comment on the Regency Hyatt Hotel Atrium in Atlanta, Georgia designed by John Portman in 1967. The concept fulfills many of the expectations, expecting the enjoyment of the old cities while expressing the excitement of the future urban area. As stated by Bendar (1986), John Portman’s intention as one of the advocates of atrium concept was to design a new type of hotel while trying to avoid the typical dark corridors and dismal lobbies of central-city hotels. Saxon (1986) believes that though Portman did not invent the atrium, but he did a good job in resurrecting it. According to Portman and Barnett (1976) Portman later described the intention regarding the design of the Regency Hyatt Hotel in Atlanta as follows:

"I wanted to explode the hotel; to open it up; to create the grandeur of space, almost a resort in the center of the city. The whole idea was to open the everything up; take the hotel from its closed, tight position and explode it; take the elevators and literally pull them out of the walls and let them become an experience within themselves, let them becoming giant kinetic sculpture (p. 33)" (Figures 2.14 and 2.15).

Figure 2.15: Atrium of Regency Hyatt Hotel in Atlanta
Source: Bendar (1986)

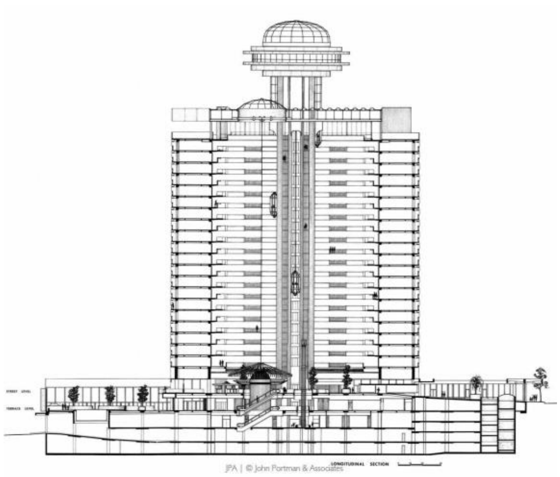


Figure 2.14: Section Drawing of Regency Hyatt Hotel in Atlanta
Source: https://wdanielanderson.wordpress.com/2014/06/08/polaris-atlantas-favorite-ufo-to-return-tuesday/

As a summary, Bendar (1986) restates that, the origin of the atrium concept lies in the Greece and the Roman houses built in years before Christ. By the first half of the nineteenth century the concept developed as we know it today. Later on, the new advancements in glass and steel production technology assisted the atrium development significantly. The next period of the development happens mostly in

North America in the second half of the nineteenth century and the beginning of the twentieth century. The author believes that the Fourth and last epoch of the atrium development started in the 1960s and still continues to the time of the book's compilation at 1986. For sure, the atrium is the essential and interesting aspect of the present architecture, which justifies the allocation of time and resources to study and analyze it.

2.2.2 Defining the Atrium

Bendar (1986) believes that the atrium, by present-day definitions would be considered a cloister in ancient times. According to Fleming, Honour, and Pevsner, (1960), the cloister is defined as, "a quadrangle surrounded by roofed or vaulted passages connecting the monastic church with the domestic parts of the monastery. (p. 64)" On the other hand, Bendar (1986) believes that from our understanding of the nature of the Roman atrium, it seems incorrect to refer to this ecclesiastical forecourt as an atrium rather than cloister. According to Moosavi, Mahyuddin, Ghafar, and Ismail (2014), atrium is a Latin word referring to "a main room or central court with hearth, which caused the room walls to be covered with black soot through time, giving it its name (atrium) in a typical ancient Roman house (p. 2)". Moreover, the definition given by Stein and Urdang (1967) describes the new atrium as "a high interior usually having a glass roof and surrounded by several floors of galleries or the like" (P. 23).

The contemporary definition given by Bendar (1986) defines the atrium as "a centroidal, interior, daylit space, which organizes the building" (P. 63). The word centroidal is a key component of the definition. Putting the space in the center of the plan spontaneously provides the opportunity to spatially organize the building. By saying centroidal, it does not have to be necessarily centered geometrically; as long as the space has the connection with the majority of the building, the goal is achieved. The author also believes that the atrium should be an interior space; a space closed and protected from the weather; otherwise, it should be called the courtyard. Allowing the natural light into space is another important characteristic of an atrium. However, when a space possesses all the characteristics of an atrium but spatially connects different buildings together, it should be called a Plaza atrium (Bendar, 1986).

Meanwhile, there is a confusion regarding the definition of an atrium since there is no accurate and consistent definition available (Bendar, 1986). The definition developed by Bendar (1986), concerning the atrium in its contemporary form, and the term Roman atrium used to refer to the ancient form is the terminology that has also been used throughout this research.

2.2.3 Why Atrium?

Saxon (1986) states that the atrium at the first sight looks like a luxury space that could be found only in the frame of expensive developments. Though, given that it first has been utilized in luxury hotels emphasizes on the image, however, its several advantages made it applicable for wide range of buildings. International Energy Agency (1995) suggests several basic reasons to include an atrium within a building design; creating a dramatic entry or central space, increasing the amenity for building users, providing more perimeter space, and facilitating circulation are a few of them.

According to Hillier and Leaman (1972), the expectations from designing, implementing and overall architecture of a building can be classified into four categories. Cultural, economic, shelter and accommodation functions are the four of the criteria, which an architect should try to address each of them in the best fashion possible. However, the capability and quality of an atrium building is an issue, which is sought to be answered within the given frame.

2.2.3.1 Cultural Function

Saxon (1986) believes that architecture is for introducing ourselves and making statements about our culture by affecting the senses; it is pleasant for both mind and senses; it can gather the people at the center of the building in a way, which is forgotten in recent architecture. It motivates the people to move, watch and enjoy the social life; as Portman and Barnett (1976) declare that the movement is pleasing to eyes, movement of people, objects, water and even the sound of movement could be significant (Figure 2.17). As for instance, if not impossible, it would be difficult to find a person who does not like the log fire and its dancing flames; this is an absolute and inherent evidence for the obsession of people for kinetics.

Figure 2.17: People Interacting with Architectural Elements in an Atrium Space, Regency Hyatt Hotel in San Francisco
Source: Portman and Barnett (1976)

Figure 2.16: The Atrium Spaces Enhances the Socializing Among the People. Regency Hyatt Hotel in San Francisco
Source: Portman and Barnett (1976)

The atrium buildings are not retreats from the city; they serve it by restoring its character. The plaza, usually an unpleasing desert can be part of a resurrection; it can be made more welcoming space. In fact, the atrium building resembles more popular and welcoming city rather puritanical architecture (Figure 2.16) (Saxon, 1986). The author states that in future, by telecommunication advances there would be less absolute need to visit the offices or shopping places. However, we would visit the town to enjoy ourselves. The atrium building also resembles a culture with more introspection and much closer to the eastern thoughts. It provides great pleasure in contrast to visually insensitive interiors and formless exteriors of spaces of today.

2.2.3.2 Economic Function

Bendar (1989) believes, the predominant perception regarding the atrium is an exciting while expensive space. The amount of usually non-functional space allocated for the atrium, and the complexity of the skylight would easily keep the developers away from the atrium concept. However, frequently by a closer examination of the atrium buildings, they seem more economical. The author states, though the atrium space mostly is a non-functional space, thanks to the interesting image that it contributes to the building, increases the profitability. The skylight may be expensive to build, but it allows the natural light in, reducing the energy costs. In comparison to the tower form, though the towers occupy less land area, they also have higher structural façade and elevator expenses.

For analyzing the economic function of the atrium buildings, Bendar (1986) subdivides the issue into four branches. Profitability, construction cost, operating cost and financing. Since it is assumed that there are little or no special considerations regarding financing an atrium building, only the first three of issues will be discussed. However, it is noteworthy that one of the few issues involved with financing the atrium is its potential to provide shorter construction period.

In describing the profitability of the atrium buildings Saxon (1986) states that most of them look much expensive in comparison to the conventional form of buildings. The author also believes that extra attraction and earning power are the main secrets of their success. Atrium hotels are more pleasing to people; while offices and shops around atrium are always let out at a premium rent since the atrium is an outstanding space.

Saxon (1986) compared the construction cost of two competing alternatives, the atrium buildings, and the high-rise buildings (Table 2.2). The construction cost of four-story atrium design and twelve-story high-rise design both as an office building with the identical program area on a site with 3:1 floor to area ratio is compared. The results provided by Saxon (1986) show that the high-rise alternative could cost 11.4 % more while delivering 90% as much usable area. The atrium buildings superiority lies in serving larger floor space in one core. Besides, low-rise buildings need fewer toilets and elevators. On the other hand, Bendar (1986) believes, the capital cost of an atrium building is not essentially higher than conventional buildings with the same floor area. Atrium buildings mostly are more expensive as the result of higher construction quality, finishes, and furnishings. The factors causing the difference in construction costs of a high-rise building and an atrium building are mentioned in Table 2 In this Table, construction and finishes are evaluated equally.

Table 2.2: Comparison between Construction Cost of an Atrium Building and a High-rise Building
Source: Bendar (1986)

Factor	**Comparison between High-rise and Atrium concepts**
Foundations	The tower has less foundation area, but more heavily loaded bases
Frame and upper floors	The suspended floor area of tower is higher and frame must resist more wind forces
Roof	The atrium solution has more roof, and the roof has higher unit cost than that of the tower
Stairs	The atrium has more stair-shafts, but only two-thirds of the stair-flights
External walls	The atrium form has a better surface to floor-area ratio
Service	Services. The atrium building will have higher servicing cost, even if equal energy performance is sought. The fire-defense systems account for an extra, whilst the system is on a par for this so climate-control example, even though the atrium is serviced standards.
Landscape	The internal landscaped area of the atrium solution is less than the external area in the tower form. Specification will differ, but costs are likely to favor the atrium in this Case
Preliminaries	The contractor's costs rise with the number of stories built. Equipment and time needed increase, and energy costs of construction are higher in tall buildings
Elevator	The tower scheme needed for 4 elevator versus 2 in atrium building
Contractor	A tower takes longer to build with more expensive equipment

Operating cost is the third factor affecting the economy of the design. Bendar (1986) states that, mostly over the life of a building, the maintenance cost is significantly higher than construction cost. The main potential of an atrium building for reducing the operation cost is its energy performance. Mostly, the atrium buildings in comparison to conventional buildings have a higher potential to harness the passive energies. However, the atrium buildings would have some extra operating costs; for example, windows, walls, and skylight need to be cleaned often by specialized equipment and personnel. In case, there is interior landscape, watering, cleaning, and overall maintenance would be required; also, a higher level of security would be needed (Bendar, 1986).

2.2.3.3 Shelter Function

The atrium provides a public space for all seasons and weathers to people come together and socialize. In fact, shelter function is the main criterion of the architecture, which is central to the atrium buildings (Saxon, 1986). The author states that the atrium allows the light in, while protecting the occupants from rain, wind, solar gain and extreme temperatures. The shelter function of the atrium is more noticeable when it is not pushed to complete comfort condition and while, acting as a transition and buffer space between inside and outside.

Goulding *et al.* (1994) believes that the atria are great in linking the streets. However, the modern tendency to design secure buildings, and the city planning that rarely gives the priority for public amenity, exclude the advantageous use of atria in many cities. In spite of that, several exceptions in North America can be found where the extreme climates force the arcades to join along with the streets, providing the protected spaces.

2.2.3.4 Accommodation Function

Saxon (1986) declares that mostly the need for accommodation is the key instinct toward a building process. In atrium buildings, frequently the surrounding space of an atrium is the directly required space, whereas the atrium itself is a premium space, though they both interact. The author believes that, aside to functioning as a central lobby and a circulation space, the atrium can also function as a premium space. Its floor can be a restaurant, performance space, lounge, and expedition or market area. The view and accessibility provide sense of cohesiveness and connection between ground floor and other stories.

Moreover, according to Goulding *et al.* (1994), using an atrium in different parts of a building would help to improve vertical and horizontal communication in it. As for instance, in Landzentral bank, various banking functions used to be carried out in separated offices; while, in the new building staff constantly meet each other in the atrium as a linking space. In the same way, four glass lifts and the exposed walkways, which connect the sides of the atrium at each floor level in the Wiggins Teap headquarter, encourage people to interact.

2.2.3.5 General Advantages and Disadvantages

There is a predominant perception that integrating an atrium or sunspace with a building would result in an absolute reduction in energy consumption of the building. Whereas, atria do not always reduce the energy consumption, and may even increase it (Landsberg, Misuriello, and Moreno, 1986). Moreover, atrium buildings provide larger and more efficient floor areas than their rivals that are tower buildings. They offer a shallow space for perimeter offices; whereas, a low-rise building or a tower create deep spaces (Saxon, 1989)

Goulding *et al.* (1994) offer series of advantages and disadvantages to a typical atrium building as mentioned below. There are eight advantages as introduced by the authors.

- Providing a semi-outdoor space while protecting the building from the cold and wet weather
- Evolution of open court to the protected and daylit space which can be used for different functions

- The potentiality of the atrium to be used as storage of warm extract air or as a preheater for ventilation air.
- Reducing the heat loss from the surface of the building in winter.
- Reducing the costs of the maintenance for the façade exposed to the outdoor conditions.
- Providing day light, which reduces the number of hours that artificial lighting is required during the office hours.
- Providing wide and interesting interior gardens.
- The provision of links, both within one building and between streets

On the other hand, Goulding *et al.* (1994) list the disadvantages of an atrium building as follows:

- Enhancing the risk of fire and smoke
- High chance of overheating
- The cost of glazing
- Potentiality of atrium to provide cross contamination in hospitals and spread of smell in shopping malls
- Poor day-lighting of rooms adjacent to atrium resulted by roof structures
- The provision of ventilation to spaces which would otherwise be open to ambient conditions

2.2.4 The Generic Atrium Forms

Different sources suggest different taxonomy for atrium buildings. Saxon (1986) categorizes the atrium buildings in two groups, simple atria and complex atria that each have several subcategories introducing possible formation of atrium buildings. However, one of the well-known classifications is introduced by International Energy Agency (1995), which puts different atrium buildings in five categories; core atrium, integrated atrium, linear atrium, attached atrium, and envelope atrium.

Bendar (1986) categorizes the atrium building into five different generic forms in an effort to systematically analyze their architecture. Regarding the adequacy of each type of the atrium for different building designs Saxon (1986) states that the pure forms of the atrium buildings such as linear atrium can be considered for both small buildings and complex developments. However, the complex forms of atrium buildings are mostly appropriate for large-scale and complex developments. The five different atria types categorized by Bendar (1986) are presented in the following sections.

2.2.4.1 Closed Atrium

According to Bendar (1986), closed atrium is the most prevalent type of the atrium that can be any shape in plan, rectangular, circular or triangle (Figures 2.18 and 2.19). In this subtype, occupied zones surround the atrium in all directions putting it in the middle of the building. Besides, in this type of the atrium the roof skylight and roof clerestory is the only source of daylight and view.

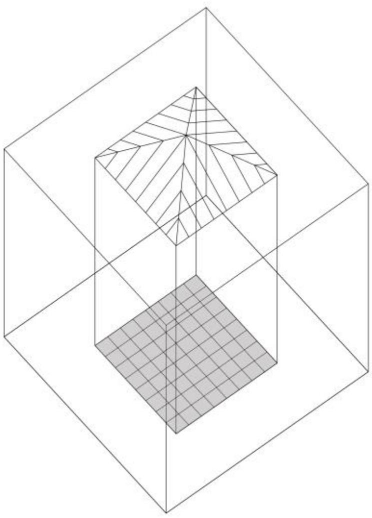


Figure 2.19: A Closed Atrium
Source: Bendar (1986)

Figure 2.18: A Sample of a Closed Atrium, Atlanta Apparel Market
Source: http://www.examiner.com/article/atlanta-s-apparel-market-debuts-spring-2010-fashions

2.2.4.2 Open-Sided Atrium

Bendar (1986) states that open-sided atrium building, is a subtype that one, two or three sides of it are partly or completely glazed, whereas the roof may or may not be. Regarding the glazed sides, careful designs should be considered for harnessing the solar radiation, daylight and view (Figures 2.20 and 2.21).

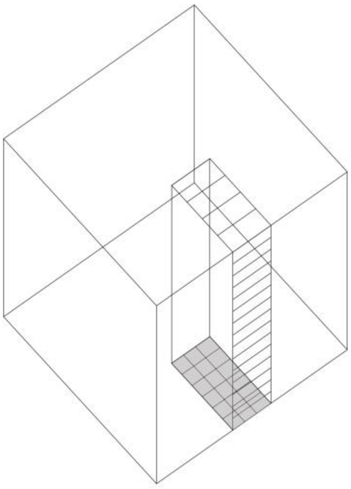


Figure 2.21: A Open-Sided Atrium
Source: Bendar (1986)

Figure 2.20: An example of an Open-Sided Atrium, Ford Foundation Building
Source: http://tclf.org/albums/ford-foundation-atrium

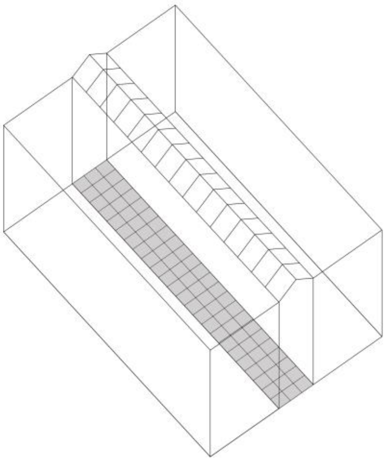


Figure 2.23: A Linear Atrium
Source: Bendar (1986)

Figure 2.22: An Example of a Linear Atrium, University of Rochester, Wilson Commons Building
Source:
http://www.himberassociates.com/educat

2.2.4.3 Linear Atrium

According to Bendar (1986), in linear atria occupied zones face each other on opposite sides and circulation connections across; usually an elongated rectangle in the plan; whose ends may be glazed or capped with building elements. In linear atria, a roof clerestory and the skylight are the major source of daylight (Figures 2.22 and 2.23).

2.2.4.4 Multiple Lateral Atrium

Bendar (1986) refers to an atrium building with several atriums within its boundary as a multiple lateral atrium. In this type, each atrium of the building composes a complete subtle of its own, which spatially organizes a part of the building. The prevalent type is two atria with a circulation element in between (Figures 2.24 and 2.25).

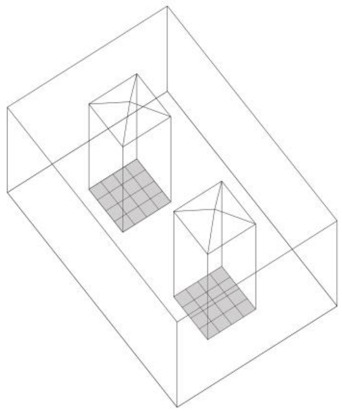


Figure 2.25: A Multiple Lateral Atrium
Source: Bendar (1986)

Figure 2.24: Example of a Multiple Lateral Atrium, Intelsat headquarters
Source: https://en.wikipedia.org/wiki/Intelsat_headquarters#/media/File:Intelsat_headquarters_aerial_colorized.png

2.2.4.5 Partial Atrium

Bendar (1986) describes the partial atrium as any atrium that spatially organizes a part of a building. It can be tower base with an atrium or vertically stacked form with several atria in high-rise building, each connecting only a set number of floors (Figures 2.26 and 2.27).

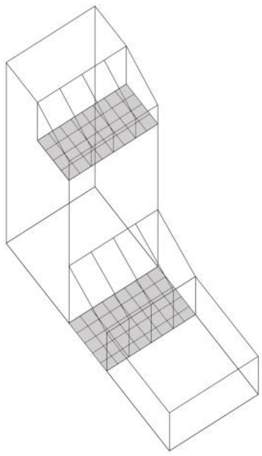


Figure 2.26: A Partial Atrium
Source: Bendar (1986)

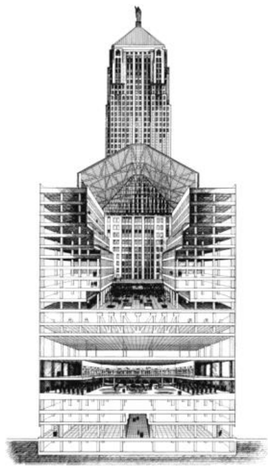


Figure 2.27: An Example of a Partial Atrium in Chicago Board of Trade Addition building
Source: http://effettobeaubourg.tumblr.com/page/38

2.2.5 Energy Efficiency Potentials Suggested by Atrium Buildings

Though, International Energy Agency (1995) believes that the energy conservation rarely has been the primary reason to consider an atrium within a building; however according to Bendar (1986) the inherent energy saving potential of atrium buildings can be considered the major reason for the resurgence of the atrium buildings in 1967. On the other hand, according to Saxon (1986) designing an atrium building with the energy issues in mind would result in considerable energy efficiency in comparison to the conventional buildings. In this regard Voeltzel *et al* (2001) declare that the inappropriate design of highly glazed buildings would lead to a significant energy waste and discomfort. Goulding *et al.* (1994) are against the general perception, that considering an atrium within a building would automatically reduce the energy consumption of the building; the authors believe that the atria do not always reduce the energy consumption and may actually increase it (Figure 2.28).

According to Bendar (1986), the energy efficiency potentials offered by the atrium buildings can be categorized into three sectors, efficiency in cooling, heating, and lighting. The author declares that an atrium building, which is designed for energy efficiency should utilize the passive energy flows as much as possible. The building can benefit from natural ventilation as a passive cooling strategy while utilizing the natural lighting provided by skylight or glazed wall to mitigate the use of purchased energy for lighting. On the other hand, the controlled natural lighting can contribute to the energy efficiency of atrium buildings by heating the interior space at the same time.

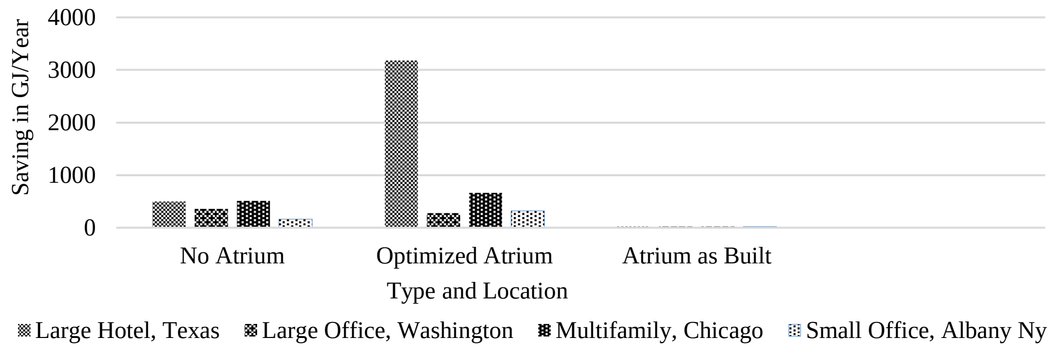


Figure 2.28: Energy Performance of Commercial Buildings with and Without Atria
Source: Landsberg *et al.* (1986)

2.2.5.1 Energy Efficiency Potentials Suggested for Cooling

Givoni (1994) differs the bioclimatic architectural design and context of passive cooling. The author believes that the bioclimatic design strategies such as proper shading would reduce the difference between indoor and outdoor temperature to the minimum; however, lowering the indoor temperature than outdoor temperature requires a cooling energy, which in passive cooling systems is obtained from renewable natural resources. The author introduces several natural heat sinks for passive cooling systems, such as ambient air, the upper atmosphere, water, and the undersurface soil; while each of these heat sinks can be utilized in various ways resulting different passive cooling systems.

Apart from controlling the solar heat gain, Bendar (1986) brings forward three passive cooling techniques adequate to be implemented in atrium buildings; use of thermal mass also known as nocturnal ventilative cooling, radiative cooling, and natural ventilation also known as convective cooling, are the suggested techniques by the author. Moreover, AIA Research Cooperation (1979) declares that the evaporation cooling technique is also applicable in atrium buildings by using fountain courts or atrium pools, particularly in hot and dry climates. According to Bendar (1986), none of the mentioned techniques, single-handedly or in integrated form can be relied on as the complete cooling system for a large-scale atrium building; however, they can significantly reduce the cooling need, hence assisting the mechanical air-conditioning systems.

2.2.5.1.1 Natural Ventilation

According to Etheridge (2012), the concept of natural ventilation is not new; in fact, mechanical ventilation is the one with a short life of around 150 years. Clearly, natural ventilation offers a set of advantages and disadvantages as any other cooling technique of buildings. Bendar (1986) believes that the convection cooling or natural ventilation is the most beneficial passive cooling technique, which can be designed and applied to the atrium buildings.

According to Wood and Salib (2013), the pressure difference created across the envelope of a building can induce natural ventilation within the interior of the building. The pressure could be generated either by the wind or temperature differences or the combination of both. Hence, the natural ventilation can be categorized into the wind-induced and the buoyancy-induced ventilation.

As stated by Wood and Salib (2013), buoyancy-induced ventilation, also known as the chimney effect or stack effect occurs as the result of pressure differences between indoor and outdoor air. The authors believe that in this type of natural ventilation the pressure difference is due to the height difference between the air inlet and outlet, and variation in air temperature and moisture causing the difference in air density (Figure 2.30). According to Moosavi *et al.* (2014), the stack effect occurs when the indoor temperature is higher than of outdoor. Three factors are required to provide natural ventilation; low-level inlet opening, a higher-level outlet opening and heat source creating the temperature difference between indoor and outdoor environment.

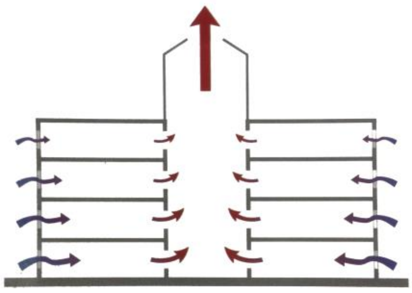


Figure 2.29: Buoyancy-Induced Ventilation in an Atrium Building
Source: Wood and Salib (2013)

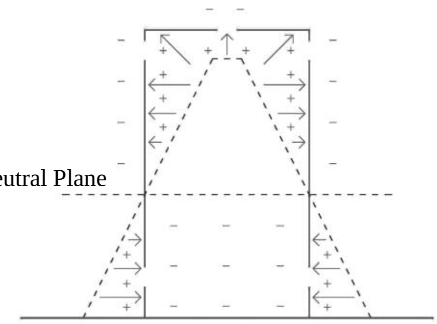


Figure 2.30: Pressure Difference Generated by Temperature Difference of Indoor and Outdoor Environment
Source: Wood and Salib (2013)

According to Wood and Salib (2013), In buoyancy-induced ventilation the heated air inside has lower density than the air outside of the building; causing the higher outdoor air pressure and flow of air into the building from lower inlet and the air exhaust from higher outlet; as long as the inside and outside air pressure are balanced. Moosavi *et al*. (2014) declares that the significant higher outdoor temperature than indoor temperature could result in reverse stack effect, where high-pressure air enters from higher opening and discharges from the lower one. The authors also introduce the neutral plane or neutral pressure level as a certain height of the building that the outdoors pressure and indoor pressure get equal (Figure 2.29).

The other factor capable of creating the pressure difference across the envelope of a building is the wind. Wood and Salib (2013) state that the wind-induced ventilation occurs when the pressure difference drives the wind into the envelope from the windward side of the building as the result of positive pressure, and sucks out the air from the leeward side of the building as the effect of negative pressure (Figure 2.31). Moosavi *et al.* (2014) state that the wind-induced ventilation is particularly effective in areas with high wind speed; whereas the effectiveness of the wind is also dependent upon the surrounding conditions. For example, in a dense area with several high-rise buildings the wind would not have the effect as expected.

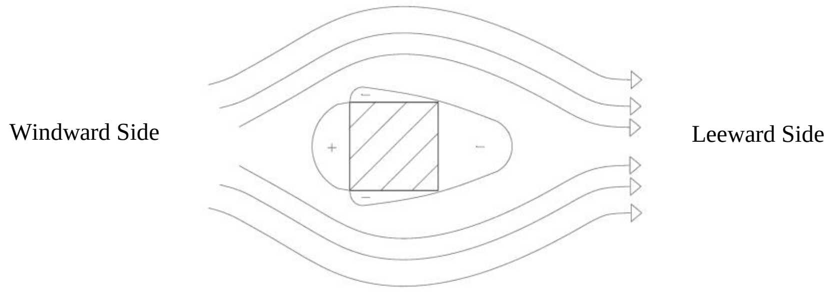


Figure 2.31: Buoyancy-Induced Ventilation in an Atrium Building
Source: Wood and Salib (2013)

Etheridge (2012) discusses the sustainable building environment that natural ventilation can provide; in mechanically ventilated buildings; as artificial ventilation can constitute 25% of the total electrical energy consumption while it can be replaced by natural ventilation to reduce the energy consumption. Moosavi *et al.* (2014). believe, thought the natural ventilation is an enormous contribution toward energy efficiency of a building; however, the healthy and productive condition that it provides cannot be neglected. Moreover, Etheridge (2012) believes, usually the building occupants have the desire to have control over their environment, and they do not like to feel confined and isolated from the external environment; which can be addressed by natural ventilation systems. Meanwhile, according to Loftness, Hartkopf, and Gurtekin (2003) the employees who works in buildings which are only equipped with natural ventilation or its combination with mechanical ventilation, presents annually 3% to 18% higher productivity. In another word, if we consider the annual salary of each employee about 45000 USD this would bring about 3900 USD per employee as the result of the increase in productivity.

Moosavi *et al.* (2014) believe, that overall there are few drawbacks regarding natural ventilation in buildings. In fact, natural ventilation and its applicability is highly dependent on the climate of the location, where the building would be constructed. As for instance, monsoon in tropical areas or sand storm in hot and dry climates can create problems in the efficient function of the natural ventilation in a building. Furthermore, Etheridge (2012) believes that it may be more difficult to refine the design errors in naturally ventilated buildings, which in turn can justify the idea of mixed-mode systems.

Regarding comparison between the wind-induced and buoyancy-induced ventilation Lomas (2007) believes that the buoyancy-induced ventilation system provides an opportunity for better control of airflow than the wind-induced ventilation system. Also, it offers more reliable performance prediction through design level. On the other hand, according to Gan (2010), since in designing a naturally ventilated atrium building the buoyancy force is not strong enough, it requires the integration of wind-induced force and buoyancy-induced forces simultaneously. This is more critical for the regions with low indoor and outdoor temperature difference.

Different aspects of atrium openings; such as number, position, size and location and their effects on natural buoyancy-induced ventilation of the atrium buildings have been significantly researched. Among all of the variables, the size of the openings has more considerable effect. In general, to reach strong and well-distributed airflow in a building the size proportion of inlet and outlet openings has a significant role (Moosavi *et al.* 2014). As for instance, according to Holford and Hunt (2003), in temperate climate and within a buoyancy-induced ventilated atrium, providing a medium size upper opening and sufficiently small size lower opening will result in a better airflow within the story. Moreover, as stated by Moosavi *et al.* (2014), increasing the number of openings increases the airflow within the atrium, at the same time decreasing the airflow and the temperature lost in all heights of the building. The authors also believe that to achieve equal ventilation flow rate in different heights, different opening area should be provided for different stories. Higher the story is the less buoyancy-induced ventilation occurs, requiring the larger effective openings area.

Hussain and Oosthuizen (2013) have conducted a research examining the effect of solar energy on buoyancy-induced natural ventilation in atrium buildings with or without solar stack along with various geometric configurations. A three-story atrium building was modeled and simulated as a part of the Concordia University campus site, using CFD numerical simulation, in six different configurations, as shown in Figure 2.32. The results show that by increasing the glazing area from 80 to 154 m^2 in the building without a solar stack (cases 1 and 2) the temperature increases about 1.1 degree centigrade. Whereas, by adding the solar stack to the building and also increasing the glazing area from 118 to 286 m^2 (cases 5 and 6) the temperature decreases on average by about 2 degrees centigrade.

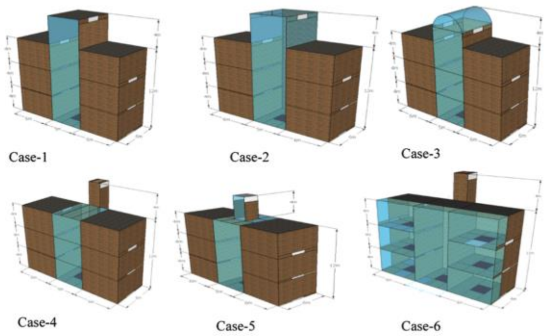


Figure 2.32: Six Different configuration of an Atrium Building
Source: Hussain and Oosthuizen (2013)

Regarding the effect of the atrium geometry on the natural ventilation Shafiei Fini and Moosavi (2016) also carried out a research work to examine the atrium inner wall angularity on the natural ventilation and thermal performance of atrium buildings. According to the authors, converging tilted walls in a tall atrium space only enhances thermal comfort for stories that are located lower than neutral pressure level and deteriorates thermal comfort for upper stories; and no advantage was observed for diverging walls in atrium. According to the authors, the Results indicate that a combination of vertical and tilted wall yield the best performance whenever the tilted walls are used for lower stories and vertical walls are used for upper stories (Figure 2.33).

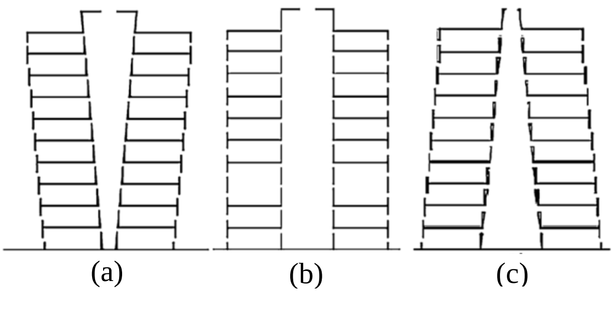


Figure 2.33: Different case studies of atrium geometries: case (a) diverge wall; (b) vertical wall; (c) converge wall
Source: Shafiei Fini and Moosavi (2016)

The research work carried out by Moosavi, Mahyuddin, and Ghafar (2015) focuses on efficiency of three different passive and hybrid cooling strategies that are thermal stack flue, cross ventilation and water wall. According to this research the cross ventilation has a considerable effect in improving the atrium indoor thermal conditions and enhancing the performance of other strategies. In fact, the atrium has the highest performance with the implementation of full cross ventilation via all inlet openings at the atrium lobby, together with the semi stacking flue outlet openings and water wall during the working time with high inlet to outlet opening area ratio (>15). However, the effect of stack flue is more on the reduction of the humidity.

Laouadi, Atif, and Galasiu (2002) examine the cooling peak load ratio of a closed atrium with different fenestration glazing type and 100% flat skylight. According to this research, cooling peak load ratio of the atrium decreases by the decrease in SHGC (Solar Heat Gain Coefficient) of the glazing. As compared to the base case design, the double gray or triple clear low-e glazing reduced the cooling peak load ratio by about 30% to 39%, and double clear Low-E glazing, clear triple glazing, decrease the cooling peak load ratio by 17to 20% and 10 to 13%, respectively.

2.2.5.1.2 Nocturnal Ventilative Cooling

According to Givoni (1994), use of thermal mass for the cooling purpose, is a passive cooling techniques that can also be utilized in atrium buildings for nocturnal ventilative cooling. In this technique, the building thermal mass absorbs the internal and penetrated heat during the daytime and loses it as the result of ventilation during the night. For better performance of the technique, thermal insulation is installed at the exterior surface of the thermal mass. Although, the mechanical and natural ventilation of the buildings should be stopped during the day both can be used during the night interactively or solely. On the other hand, according to Bendar (1986) this concept best works in climates where the night temperature falls below the 20-degree centigrade and the diurnal temperature swing is 8.3 to 11.1 degrees Centigrade.

2.2.5.1.3 Radiative Cooling

Any surface that faces and sees the sky loses the heat by the emission of long wave radiation to the atmosphere. Though, the radiant heat loss does not stop during day or night; however, the balance between gaining to losing the heat is only negative during the night. In essence, during the daytime the heat gained by solar radiation exceeds the heat loss during the same period; the complete opposite happens during the night time (Givoni, 1994). According to Bendar (1986) in enclosed atrium buildings, the unobstructed roofs get the best radiative cooling, whereas, the floors can only achieve the indirect radiative cooling. Furthermore, as it is clear, an atrium building with low section aspect ratio would be benefit more from radiative cooling during the night.

The research work carried out by Wang, et al. (2014) focuses on developing a weather responsive internal shading system for atrium spaces in tropical climates. According to this research, the sun shading is very effective in reducing inner surface temperatures in the space and consequently reducing radiant heat gain into the atrium space. Moreover, the authors state that high-level shading, with blinds fixed close to the glazed roof are generally (Figure 2.35) less effective in the provision of thermal and lighting conditions of the atrium, than the low-level shading, where blinds are fixed 3 to 5 m below the glazed roof (Figure 2.34) to form a ventilated void. In fact, in summer this configuration would reduce two third of the solar heat gain in the atrium space.

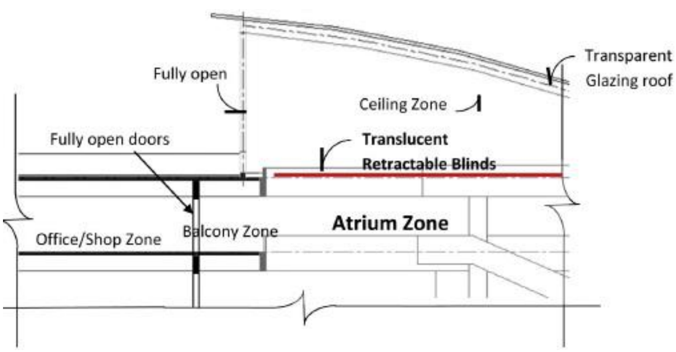


Figure 2.34: Detailed cross-section showing the low-level shading screening option
Source: Wang, et al. (2014)

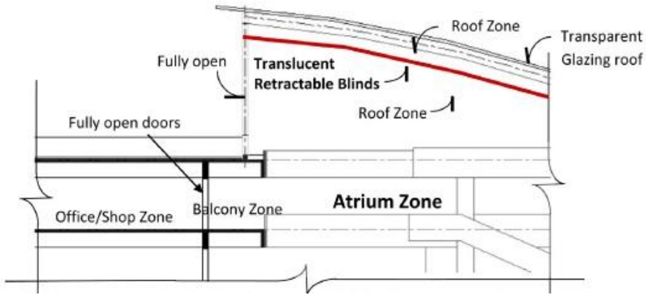


Figure 2.35: Detailed cross-section showing the high-level shading screening option
Source: Wang, et al. (2014)

2.2.5.2 Energy Efficiency Potentials for Heating

Bendar (1989) declares that in most commercial, institutional and office atrium buildings due to the significant heat generated by occupants, office machines and artificial lighting, heating is not a significant concern in comparison to lighting and cooling function of the atrium buildings (Figure 2.36). The author believes that heating increases in importance in the other building types with atrium such as hotels, residences, or in buildings in cold climates. Saxon (1986) declares that warming atria are more interesting to the countries in North Europe, where there is the winter with different severity, cool cloudy autumns and short erratic summers; where the heating might be needed for nine months of the year. In this regard, Bendar (1986) states that an atrium can enhance the heating function of an atrium building when needed by the means of passive solar heating, by increasing the efficiency of mechanical systems and operation and conservation of building heat.

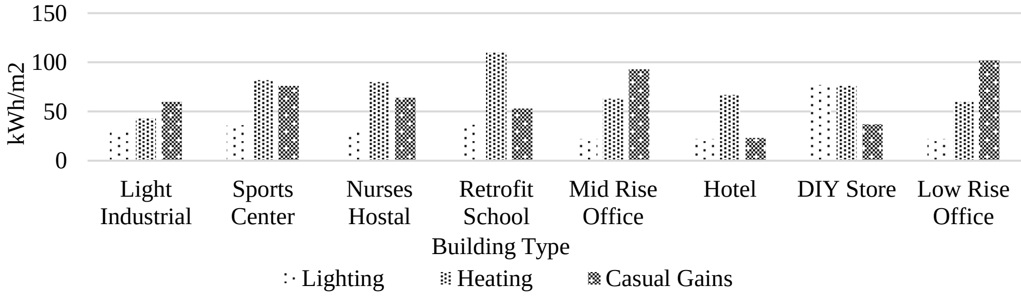


Figure 2.36: Breakdown of None-domestic Energy Use in Atrium Buildings
Source: Goulding *et al* (1994)

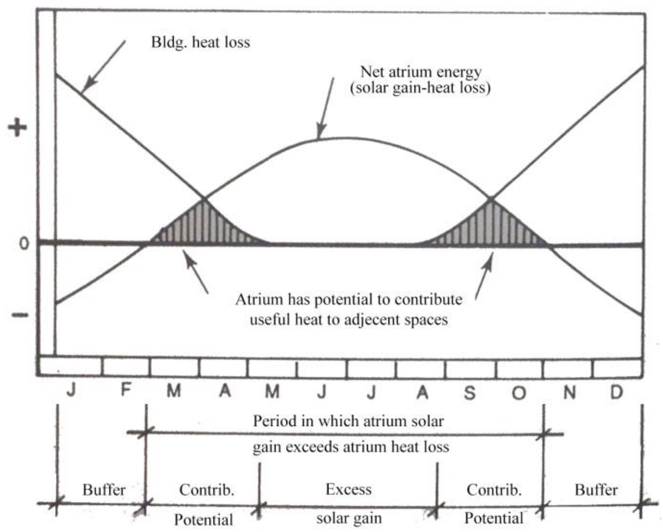


Figure 2.37: Potential Thermal Behavior of a Warming Atrium in Different Months of a Year
Source: International Energy Agency (1995)

International Energy Agency (1995) has studied several atrium buildings which in terms of energy performance mostly they fall into two groups. atrium that works as a buffer zone for surrounding spaces to reduce their heat loss, and the second type of atrium which contributes to total building heat requirements by acting as a buffer zone in coldest part of the year and provide the heats for surrounding spaces during the milder parts with the aid of solar heat (Figure 2.37).

According to Saxon (1986), in warming buffer atrium, which is designed to allow the warm winter sun in, the indoor temperature will be at least 5 degrees Centigrade warmer than ambient air; unless, in long cloudy days that will be 1 or 2 degree Centigrade warmer than outdoor temperature in daytime, which is mostly due to the effect of heat gained from the parent building. Goulding *et al.* (1994) believe that the temperature increase is dependent on three factors. First, the ratio of the external glazing area of the atrium to the wall area of the parent building which is protected by the atrium. Second, the thermal transmittance of separating wall; usually this will be dominated by the amount of glazing on this wall. Third, the orientation and inclination of the glazing of the atrium sun space. For the best passive solar gain, Bendar (1986) suggests south facing glazing façade for the atrium buildings in the North hemisphere.

The skylights do not contribute to the passive solar heating of the atrium because of the low angle of winter sun. Slop glazing is also beneficial as long as the tilt angle is not lower than the latitude in degrees.

Bendar (1989) believes that the most effective passive solar atrium in terms of solar heating is a sun space within an isolated solar gain system. In this method, the solar heat is collected in mass storage that is separated from the living space. The challenging step is the controlling and distribution of the stored heat, either naturally or mechanically aided, to the occupied zone. According to the author, though this atrium mode is the most efficient system in terms of solar heating, few large-scale buildings have utilized it because of a large amount of air occupied by this system as a solar collector. Bendar (1989) declares that by utilizing the sunspace as the living space, the atrium will function as the direct-gain system. In the case, the sun will warm the atrium first, and then the excessive heat would be stored in the mass storage elements.

Bendar (1986) suggests a more economic strategy for use of an atrium as a tool to augment the mechanical system. This strategy includes, using the atrium as a return air plenum; the air used to heat the occupied zones can be returned to the atrium space to heat it. Fresh air can be introduced into the atrium space for preheating by solar heat and naturally stratified at the high portion of the atrium space, providing the simple collection of the heated air inside the atrium. According to the author, eventually, the air would be recycled through the heating system. Utilizing this strategy for the atrium offers a great financial gain by reducing the cost of return duct system.

Conserving the heat within the building is the final consideration for an atrium building suggested by Bendar (1986). The exterior envelope of the atrium is highly important since usually it has a high percent of glazing. The insulated glazing is proposed to mitigate the heat loss through convection from atrium glazing. In fact, as stated by Goulding *et al.* (1994) the glazing would be beneficial for warming atrium if the solar gain over 24 hours dominates the added thermal loss through the glazing. Bendar (1986) suggests, glazing with low emissivity but high-transmittance for better energy efficiency. Furthermore, the radiative energy loss through the skylight in winter nights should be obstructed; Saxon (1986) suggests using night-shutters made of fabric or folding sheet metals. According to Saxon (1986) the nature of the wall separating the occupied zoned from the atrium is dependent on the level of conditioning which is provisioned for the atrium. If the atrium is fully conditioned it is possible to eliminate the wall totally, however, if it is not, the wall is needed to act as the exterior boundary in terms of insulation and infiltration.

Regarding the physical properties of an atrium, International Energy Agency (1995) states that the glazing type of the skylight has a great importance if the atrium is heated near to the comfort zone. As for instance, in a parametric study carried out by IEA (1995) on a certain atrium building, by reducing the U-value of the skylight glazing from 2.1 unit to 1.0 unit while keeping the solar gain constant, the atrium heating energy requirements drops by approximately 50%, while the change in the U-value reduces 5% of total building heating energy requirements. Moreover, Laouadi *et al.* (2014) have examined the effect of several characteristics of an atrium on their energy performance. According to the research, in enclosed atria the solar heat gain ratio in cooling and heating seasons in comparison to base case design with double clear glazing increases with the solar transmittance ratio (Figure 2.38).

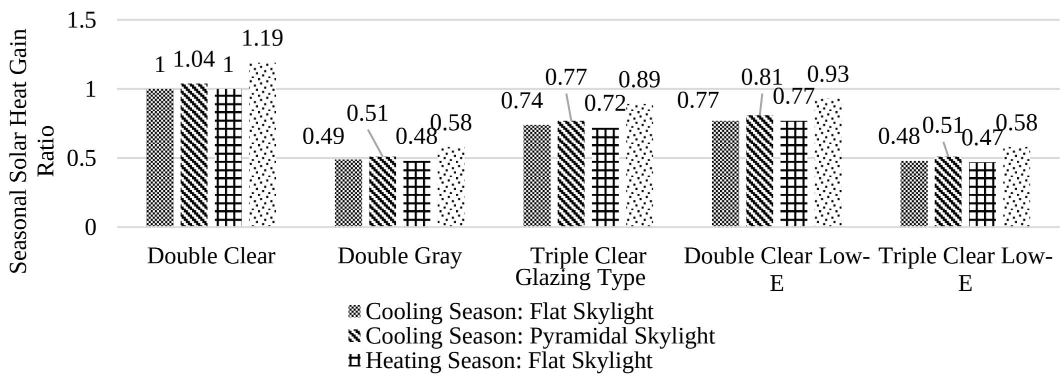


Figure 2.38: Effect of Different Fenestration Glazing Type On Seasonal Solar Heat Gain Ratio of Enclosed Atria with 100% Glazed Roof
Source: Laouadi *et al.* (2014)

Laouadi *et al.* (2014) also examined the effect of fenestration glazing type on heating peak load ratios of the enclosed atria. According to this research the heating peak load of an atrium with flat 100% glazed skylight and with the atrium space closed to the adjacent spaces, decreases by the U-value of the glazing. In comparison to the base case, with double gray glazing, the heating peak load ratio increases by up to 6%, whereas, triple clear glazing, double clear low-e glazing and triple clear low-e glazing, decreased the heating peak load ratio by 29%, 36% and 58% respectively (Figure 2.39). Obviously, this is due to the fact that a high U-value results in significant heat loss and higher heating load. On the other hand, according to the author, the simulation on the atrium building to assess the effect of increasing the thermal mass in the atrium façade, in all climates, reveals that by replacing the wood frame construction with concrete blocks results in very small reduction in heating energy requirements, typically less than 1%, in atrium or adjacent spaces in all climates.

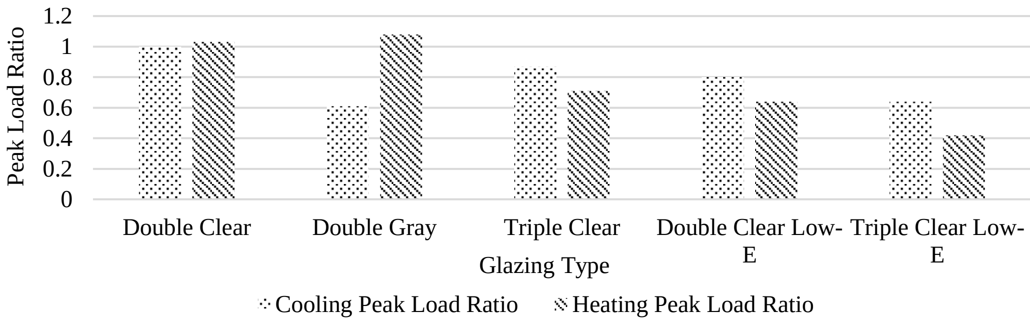


Figure 2.39: Effect of Fenestration Glazing Types on Cooling and Heating Peak Load Ratios of Closed Atrium Spaces with at Skylights and 100% Glazed Roof and Walls
Source: Laouadi *et al.* (2014)

According to the research conducted by Laouadi *et al.* (2014), the pitched or pyramid shape skylight increases the solar heat gain slightly by about 6% in comparison to the flat shaped skylight during the cooling season. Whereas, the pyramid or pitched shaped skylight contributes to the passive heating of the building by 25% more than the flat shaped skylight during the heating season; it could be the result of a higher capability of the pyramid and pitched shaped skylight to collect and transmit more radiation at lower sun altitudes than the flat skylight.

The research work carried out by Aldawoud, (2013) focuses on the effect of atrium shape on the building total energy consumption (Heating and Cooling). The results of this study indicate that the atrium geometry is an important factor to consider from a design and an energy efficiency perspective. In all climatic regions, the effect of the atrium geometry has been found to be more evident in the elongated atrium shapes and this is due to the size of the skylight exposed to environmental conditions. In other words the total energy consumption of the narrow, elongated atrium or the rectangular atrium with high ratio of length to width is significantly greater than the square shaped atrium.

2.2.5.3 Energy Efficiency Potentials for Lighting

Goulding *et al.* (1994) believe, atria make a significant contribution to energy saving of the atrium buildings by partially replacing the artificial lighting with the natural one, which reduces both lighting and cooling load of the building. Regarding the effect of artificial lighting on cooling load Bendar (1986) states that each unit of energy consumed for artificial lighting requires an additional one-half unit of energy for air conditioning to offset the heat generated by the lights. According to Goulding *et al.* (1994) also, the buffer zone created by an atrium space provides the possibility to consider larger glazing on atrium facades, to admit more natural light without sacrificing the heating performance of the building.

Bendar (1986) introduces three main design issues that are important to consider while planning the natural lighting system for an atrium building. Daylight source is the first concern: hence, how and where the daylight is brought into the atrium is the overall extent of this scope. The second issue is about light box, which discusses techniques and overall modality that the natural light can be distributed within the atrium. The last and most challenging issue is illumination, focusing on how the daylight could be utilized within the occupied spaces.

Saxon (1986) considers the climate as the most important factor affecting the way that light can be admitted into the atrium; Bendar (1986), also adds local contextual circumstance, besides the sky condition, as a factor affecting the choice between overhead glazing or side glazing as the source of the natural light. The author believes that some form of the overhead source is optimal choice both in terms of quantity and control of light (Figure 2.40 and Table 2.3). A side-glazing wall is an option as the light source that usually is considered to capture the long-distance view or visually connect the outer space to indoor space. Moreover, this form of the light source does not work efficiently under a cloudy sky; its efficiency as a source of light, is also affected by neighboring and obstructions under the sunny sky condition.

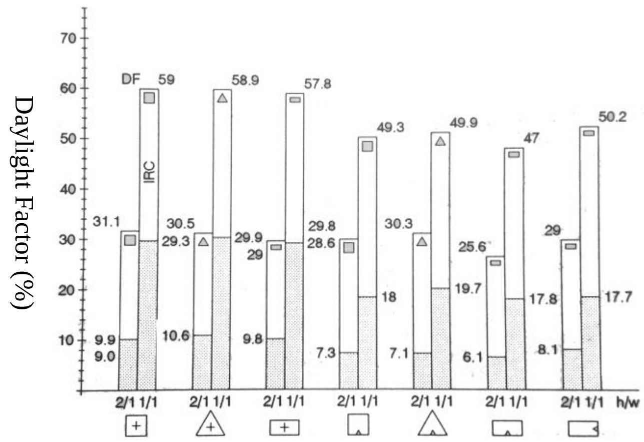
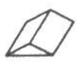
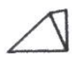


Figure 2.40: Percentage of Light Reaching to the Floor from Different Geometrical Shapes and Sectional Proportion of the Atria for a Given Area of Glazing
Source: Goulding *et al.* (1994)

Table 2.3: Percentage reduction of light admitting area by different roof constructions
Source: Goulding *et al.* (1994)

	Quadrangular Floor Area				**Rectangular Floor Area**			**Triangular Floor Area**
Shape								
Vertical Supporting Structure	6.8	7.7	8.8	8.8	7.5	8.0		8.0
Vertical + Horizontal Supporting Structure	10.5	11.0	11.7	11.4	11.7	10.5	10.5	11.6

Saxon (1986) suggests different design patterns for the atrium skylight in various climates. The author considers the overcast sky as the prevalent situation in the Britain and the rest of Northern Europe. In this situation, the optimal atrium, regarding natural lighting, is a top-lit atrium with clear glazing and no obstruction, to admit the natural light as much as possible (Figure 2.41, 42 and 43). However, in sunny weather the diffusion of light into the rooms at the shaded part of the atrium needs to be provided. On the other hand, for the climates with predominant overcast skies Goulding *et al.* (1994) propose minimizing the area taken up by the primary or secondary structural elements as much as possible to provide wider glazing on the skylight for a better natural lighting of the building.

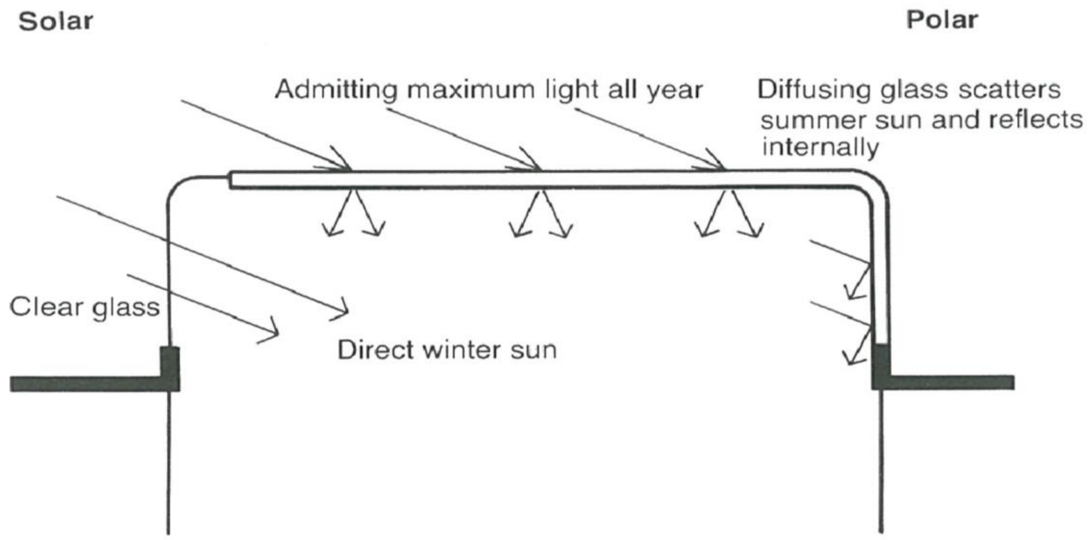


Figure 2.41: A Type of Skylight Suggested for the Locations with Mostly Overcast Sky
Source: Saxon, Atrium buildings: Development and design (1986)

When the sky becomes clear the main challenge in naturally lighting an atrium starts. Though direct sunlight is acceptable during the winter as a passive heating source, it is truly challenging to keep the sun out during the summer (Bendar, 1986). According to Saxon (1986), because of high contrast that the sunlight creates, it is difficult to achieve successful natural lighting by means of direct light. In this situation, the sunlight either should be converted to diffused light or should be totally filtered out by the aid of proper shading design.

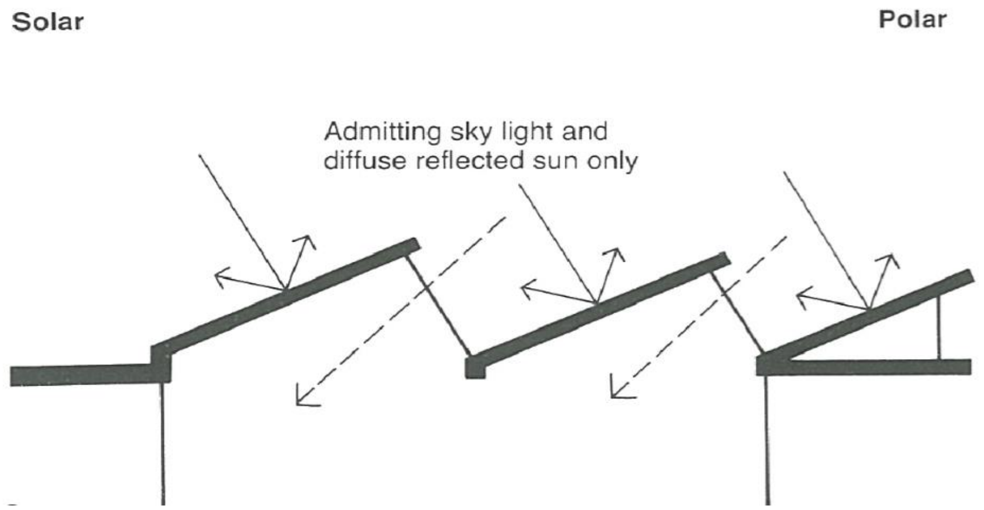


Figure 2.42: A Type of Skylight Suggested for the Locations, Where Solar Heating Is Not Required
Source: Saxon, Atrium buildings: Development and design (1986)

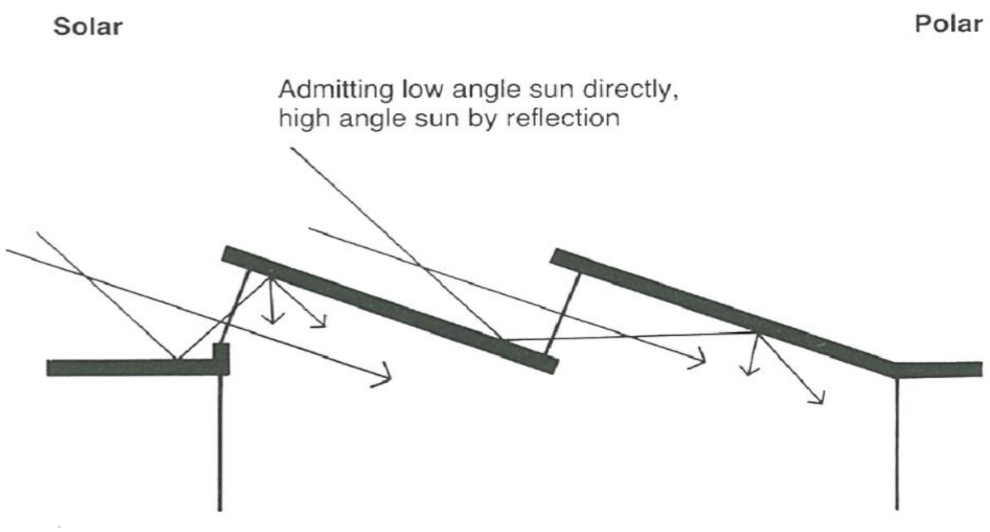


Figure 2.43: A Type of Skylight Suggested for the Locations, Where Solar Heating Is Required
Source: Saxon, Atrium buildings: Development and design (1986)

Bendar (1986) proposes the trihedron skylight with delicate aluminum sunscreens as used in National Gallery of Art East Building as an example of a proper design pattern for adequate natural lighting of an atrium in sunny climates (Figure 2.44). Moreover, Saxon (1986) suggests the saw-tooth shape skylight in two different orientations, South to North and North to South, to allow diffuse light and low angle winter sun, while rejecting the hot summer light.

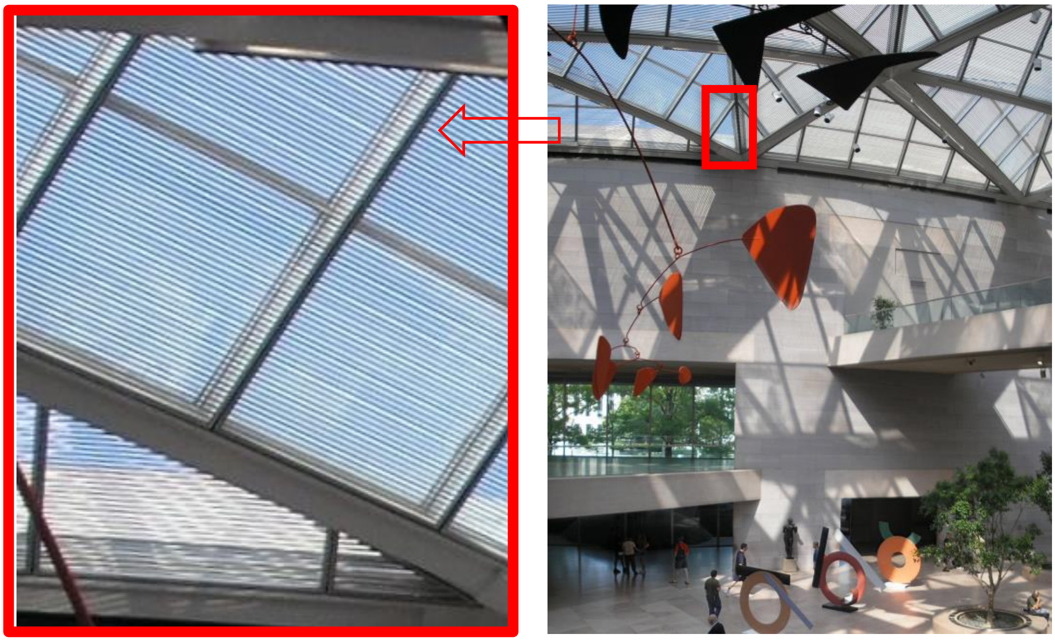


Figure 2.44: The Trihedron Skylight with Delicate Aluminum Sunscreens, National Gallery of Art East Building, Washington DC
Source:
https://upload.wikimedia.org/wikipedia/commons/2/2f/National_Gallery_of_Art_DC_2007i.jpg

The atrium as a light box distributing the natural light is the next concern. Section aspect ratio, the sectional scheme, and the atrium surfaces are three main factors affecting the performance of an atrium as a light box (Bendar, 1986). Saxon (1986) states, the atrium section proportion, is the factor that directly affects the amount of natural light reaching to the floor of the atrium and its surrounding spaces. There is no optimal proportion for the atrium section since there are several other design factors involved in the overall performance of atrium in terms of natural lighting. However, it is clear that a lower atrium section proportion i.e. a lower height to the width ratio would make it easier to naturally illuminate the atrium floor.

Bendar (1986) believes, the scheme of the atrium section also can significantly contribute to the daylight distribution. One example of the sectional scheme for an atrium is Step-shape section, each floor extending forward more than the upper floor providing a view of the atrium skylight. According to Saxon (1986) step-shape section gives each floor a window jutting into the light without shading the floor below. If little useful reflection is provided by the walls of the atrium, this type of section would be useful. However, it only increases the brightness at the front of the rooms, though utilizing the light shelves would enhance the lighting performance. Moreover, step-shape section reduces the atrium floor level area, while increasing the depth of the occupied zone, making it harder to be naturally lit.

Saxon (1986) considers the reflectivity of the atrium walls as an important factor affecting the performance of natural lighting in an atrium building. In fact, for the lower stories, the light source is the reflective surface of the opposite wall. If the opposite wall is highly glazed, less light will bounce off toward lower levels, reducing the natural light available there. The light should be drawn off for each story to the extent necessary. Bendar (1986) suggests light-colored, opaque, smooth, and reflective surfaces for the atrium façade to enhance the natural lighting performance of the atrium. Meanwhile, the author believes that dense planning, heavily foliated trees and brick pavers absorb the light and reduce the lighting performance.

Saxon (1986) proposes a technique to control the light admitted by the atrium walls. The author recommends various glazing to opaque surface ratios for different floors, considering the smaller glazing area for higher floors with abundant available natural light, while increasing the glazing area from top floors to down progressively to admit as much light as possible (Figure 2.45 and 2.46). The concept is also possible to be implemented by utilizing the different glazing types with various reflectiveness for each floor without changing the glazing area. IEA (1995) mentions the Dragvoll building in Trondheim, Norway, as an example where, for providing balanced natural light in adjacent three stories of the atrium, 40%, 70% and 90% glazing to opaque surface ratio for third, second and first stories, respectively, has been considered.

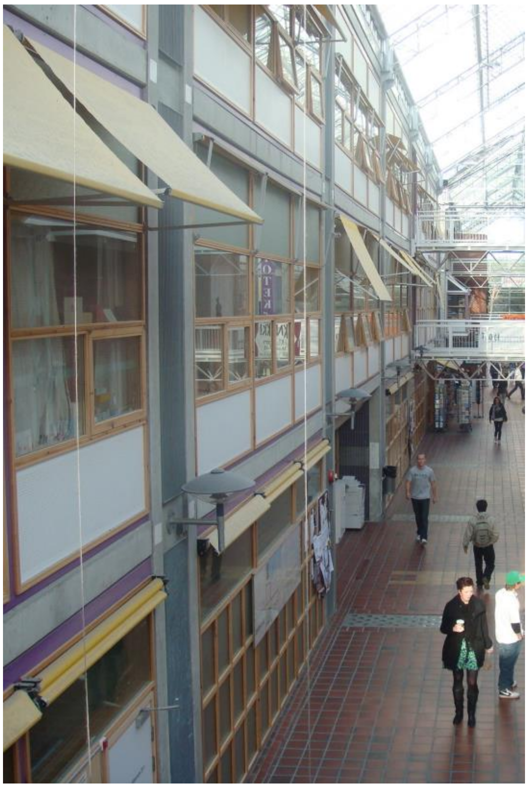


Figure 2.46: Different Glazing Area for Different Floors to Control the Natural Lighting, Trondheim, Norwegian University of Science and Technology, Campus
Source: https://soraj.files.wordpress.com/2008/10/dsc

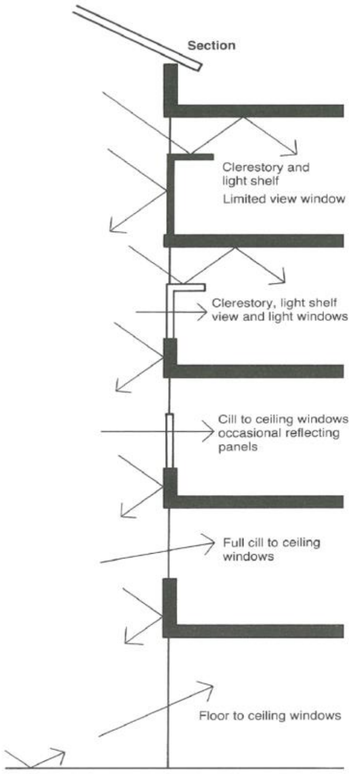


Figure 2.45: Different Glazing Area for Different Floors to Control the Natural Lighting
Source: Saxon, Atrium buildings: Development and design (1986)

According to Bendar (1986) the most challenging step in designing an atrium building for natural lighting is the illumination of occupied zones around the atrium. Saxon (1986) believes, reaching the adequate amount of light four or five meters from the window with conventional floor height, regardless of window brightness is hard to achieve. On the other hand, too much light from the window causes the glare and gloom effect. The author states, most of the light entering from the window should be directed upward to bounce off the ceiling, penetrating into the depth of the floor. The idea of the light shelf is being revived for external and atrium use. Light shelve is a horizontal or inclined baffle in the window installed above the eye level and as far below as possible from ceiling level, helping the natural light to travel deeper in the story (Figure 2.47).

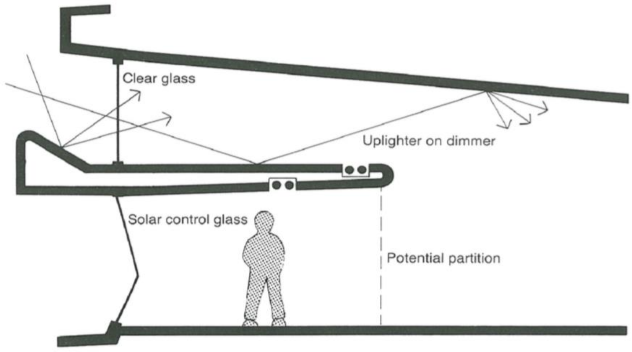


Figure 2.47: Light Shelf Function
Source: Saxon, Atrium buildings: Development and design (1986)

The research work carried out by Ghasemi, Noroozi, Kazemzadeh and Roshan (2015) focuses on the impact of the atrium width and clerestory height on the amount of average daylight factor (ADF) in atrium building adjacent spaces. In this research the only source of natural light into the building are the clerestory windows and no skylight is considered. According to the authors, by increasing the atrium width, the amounts of sky view angle at the top floor decreases sharply (Figure 2.48). Therefore, the ADF in the adjoining spaces of top floor reduces. Variation of ADF in the ground floor is almost contrary in comparison to the top floor. According to this research, the minimum level of ADF in ground floor occurs when the width of the atrium is the lowest. Furthermore, the authors state that the minimum acceptable ratio of clerestory height to atrium height for providing the sufficient level of ADF in the atrium adjacent spaces is 3 to 8.

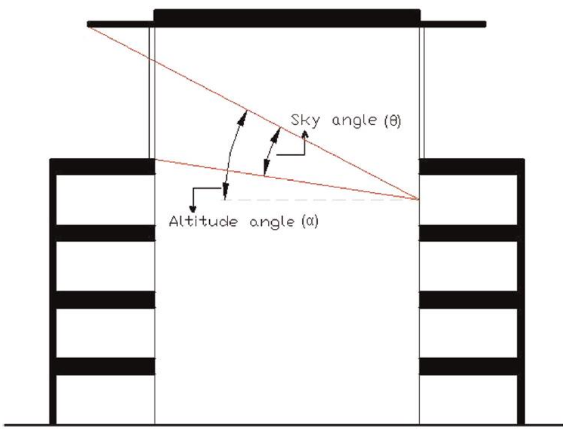


Figure 2.48: Sky View Angle of Adjoining Spaces from Clerestory Windows
Source: Ghasemi, Noroozi, Kazemzadeh, & Roshan (2015)

Borong, Yingxin, Yao, and Huanga, (2015) in the research that they have carried out have examined several properties of an atrium building with double atria. The authors have utilized a simulation software to record the lighting consumption trends of first and sixth floor of a 10-floors atrium building. According to the authors, spacing, shape, position and area distribution of atria, have little influence on the daylighting effect. However, in the experiment that they have prepared the rectangular atria present better performance than square atria in terms of providing natural light.

CHAPTER 3

MATERIAL AND METHODOLOGY

In this Chapter, material and the method of the study is presented. Descriptions and selection criteria of the subject matter are given under the material section. The methodology and operational procedure that is used to assess the material is described under the methodology section.

3.1 Material

The aim of this research was to examine the effects of determined physical properties of an atrium building on its energy performance in different climates. In this research, the impact of height (number of floors) of an atrium building, the orientation, and the aspect ratio of a rectangular shaped closed atrium on the energy performance of the atrium building in four different climates were examined.

As the first variable, three different heights for atrium building were considered to be examined, atrium buildings with 5, 10 and 20 floors height. Considering 3.5 meter as the height of a single floor, we will have buildings with 17.5, 35 and 70 meter height, respectively (Figure 3.1).

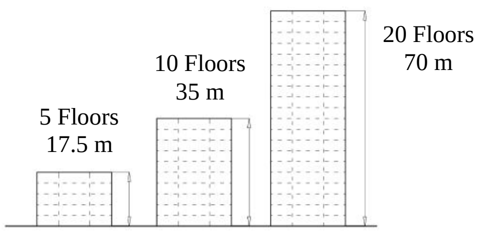


Figure 49: Three Different Heights for an Atrium Building as Alternatives for The First Variable

As the second variable, four different aspect ratios for atrium were considered. In the first aspect ratio, the ratio of the width to the length of the atrium was 1:1, in the second one the aspect ratio was 1:2, in the third one it was 1:3 and in the fourth one the ratio of the length to the width of the atrium was 1:4 (Figure 3.2).

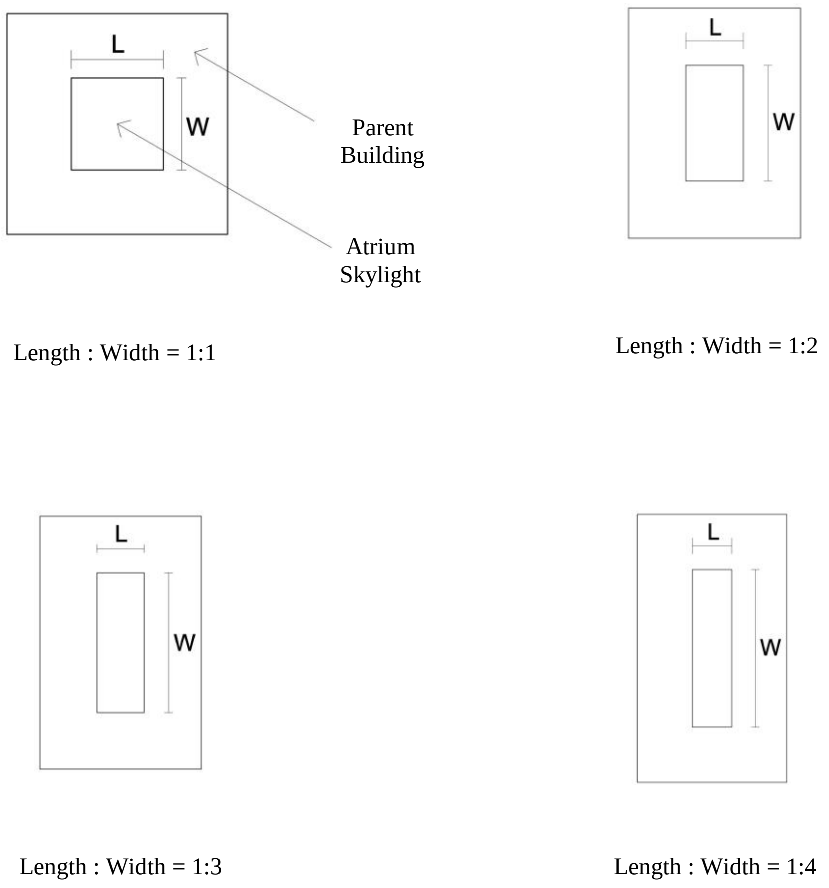


Figure 50: Four Different Aspect Ratios of an Atrium as The Alternatives for The Second Variable

Different orientations of atrium were included in the research as the third variable. Two different orientations were considered; one was parallel to the North - South axis and the second one was parallel to the East - West axis (Figure 3.3). Obviously, an atrium with 1:1 aspect ratio is symmetric in both X and Y directions, thus no orientation can be considered for this atrium.

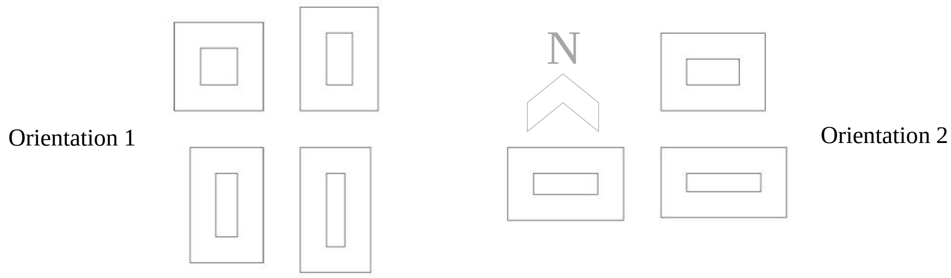


Figure 51: Two Orientations of Atria with Different Aspect Ratios

The Köppen climate classification was utilized as a system that categorizes different climatic conditions in which the atrium buildings with different configurations were to be examined. The climate subtypes, were chosen from the main four climate typologies of the Köppen system, which are, Tropical, Arid, Temperate and Cold (Continental). The fifth climate typology of the Köppen system, which is Polar type, has not been included in this research, since polar areas are not noticeably inhabited. Among the subdivisions of four chosen climate typologies the ones, which represent the more severe climatic conditions, were selected. The availability of the climate data of each climate subtype was another selection factor. The Calgary city in Alberta, Canada representing the Cold Continental climate type (Dfb), the Paris in France representing the Temperate climate type (Cfb), Singapore, representing the Tropical climate type (Af), and Phoenix located in Arizona, United States, representing the Arid (Bwh) climate type, were the chosen locations. Climate data for the mentioned locations were gathered from Calgary, Charles de Gaulle, Changi and Deer Valley International Airports' weather stations for the cities Calgary, Paris, Singapore and Phoenix, respectively.

Figures 52 to 55 are prepared to facilitate the comparison between different attributes of the climates, which are introduced earlier. Figure 3.4 compare the average weekly dry-bulb temperature of the four climates throughout a year. According to this Figure and in average, Calgary has the lowest average dry-bulb temperature (4°C) throughout a year. Whereas, the highest dry-bulb temperature belongs to Singapore with a steady and average dry-bulb temperature of 27.5 °C through a year; however, in few weeks of the summer the average weekly dry-bulb temperature of the phoenix exceeds of the

Singapore. It is noteworthy that the Phoenix has the average dry-bulb temperature of 22.8 °C through a year. Furthermore, as expected the average dry-bulb temperature of the Paris in a year (11.2°C), as a city with a temperate climate, seats somewhere between the Singapore and Calgary.

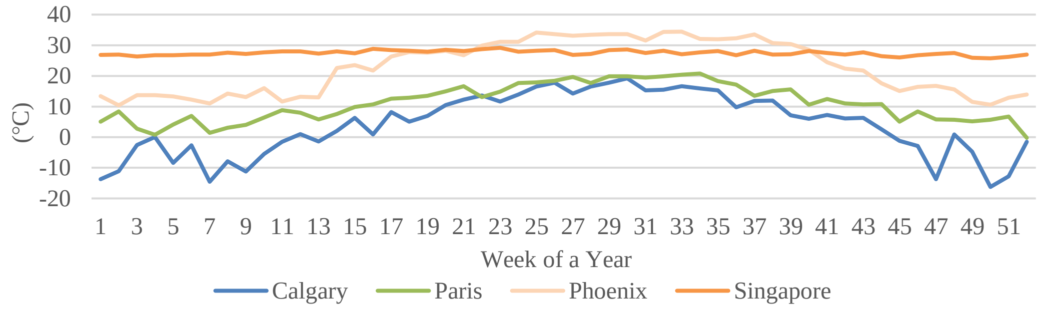


Figure 52: Average Weekly Dry-Bulb Temperature in the Four Climates
Source: DesignBuilder database

The Figure 3.5 demonstrates the average weekly Relative Humidity (RH) of four climates in a whole year, which were selected for this study. According to this Figure, the lowest average RH through a year belongs to phoenix with an RH of 32%. However, as expected the Singapore as a land surrounded by water and with an average Relative Humidity of 83% throughout a year has the highest value. The Paris and Calgary with an average RH of 76% and 60% through a year, respectively, fall between Singapore and Phoenix.

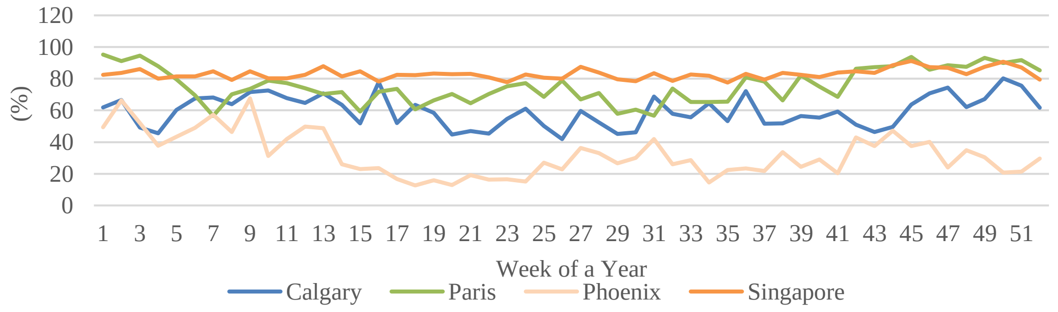


Figure 53: Average Weekly Relative Humidity in the Four Climates
Source: DesignBuilder database

The wind speed of the four climates as one of the main factors introducing the climatic characteristics of a region are demonstrated in Figure 3.6. According to Figure 3.6, the wind speed in all four climates fluctuates considerably throughout a year. Singapore has the lowest average wind speed through a year with an average wind speed of 2.18 m/s, and Calgary with an average wind speed of 4.36 m/s through a year has the highest value among the four climates. Moreover, Phoenix has an average wind speed of 2.89 m/s through a year. Meanwhile, Paris among three other climatic conditions has the most annual fluctuation in wind speed and it has an average wind speed of 4 m/s throughout a year.

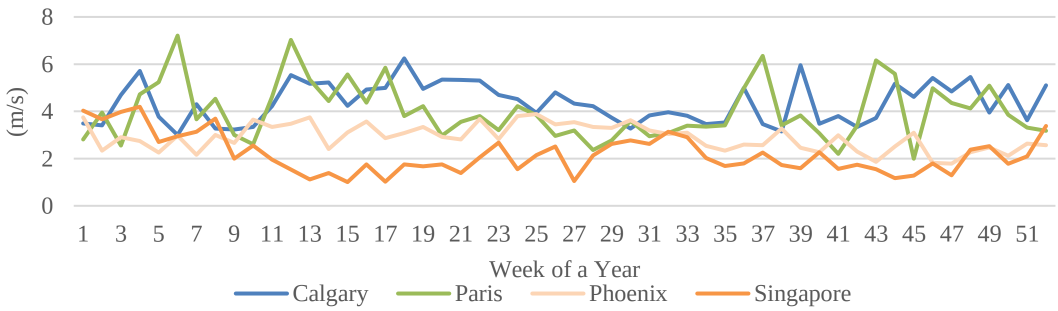


Figure 54: Average Weekly Wind Speed in the Four Climates
Source: DesignBuilder database

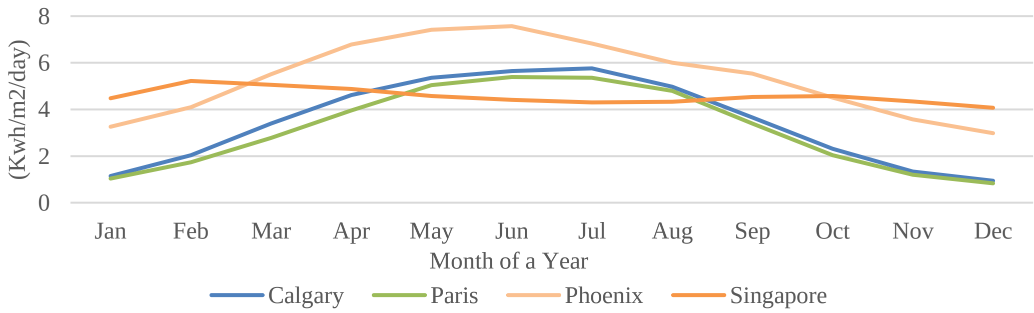


Figure 55: Average monthly Global Horizontal Radiation in the four climates
Source: NASA (2016)

The Global Horizontal Radiation (GHR) of the four climates as a factor considerably affecting the thermal comfort and energy consumption of buildings are also compared.

According to Figure 3.7, the highest average daily GHR belongs to Phoenix with 5.33 kwh/m^2/day. Singapore has the average daily GHR of 4.55 kwh/m^2/day. Moreover, Paris and Calgary with a small difference have the average daily GHR of 3.12 and 3.43 kwh/m^2/day, respectively.

There are some other attributes of the four selected climates that their comparison can help to understand their similarities and differences more clearly. However, this information is provided in Appendix A that include comparison of Dew-bulb temperature and atmospheric pressure of the four climates.

The construction materials and different occupancy settings of the atrium buildings are also important in this research. In fact, the atrium buildings with different physical configurations, which were examined in this research, had the same properties and settings related to building activity, occupancy, environmental control, construction materials, interior lighting, and HVAC systems, which are all the suggested properties and settings by DesignBuilder for an office building.

Activity template for all atrium buildings was considered as generic office area with an occupancy of 0.111 person/m^2. Also the occupancy schedule was considered as presented in Table 3.1. Occupants clothing was considered to be 1 for winter and 0.5 for summer. Regarding the construction materials, 10 cm cast concrete with 2.929 W/m^{2}k of U-value was utilized as construction material of ground floor, roof and intermediate floors. Moreover, interior partitions were consisted of two layers of gypsum plasterboard with the depth of 2.5 cm each on outer and inner surfaces, and with 10 cm air gap in between which creates a total U-value of 1.639 W/m^{2}K.

Table 3.1: Occupancy Schedule of the Atrium Buildings

	Until: 07:00	Until: 08:00	Until: 09:00	Until: 12:00	Until: 14:00	Until: 17:00	Until: 18:00	Until: 19:00	Until: 24:00
Week Days Occupancy	0	0.25	0.5	1	0.75	1	0.5	0.25	0
Weekends Occupancy	0	0	0	0	0	0	0	0	0

The only fenestration on the atrium buildings, which lets the natural light in, was the atrium skylight. The skylight glazing was double-glazing with 6 mm of clear glazing on each side and 13 mm of air in between; the total U-value for the skylight glazing was 2.708 W/m^{2}K. The surrounding walls of the atrium were completely transparent. The glazing type was as same as the glazing system for the skylight, which had the U-value of 2.708 W/m^{2}K.

Moreover, the interior lighting was considered to provide 400 lux for occupied spaces with 5 W/m^2/100 lux normalized power density. No lighting system was considered for the atrium spaces and only the parent buildings were artificially lighted. Suspended general lighting with radiant fraction and visible fraction of 0.42 and 0.18, respectively were considered for all atrium buildings. The lighting control system was set as linear. In this system overhead lights dim continuously and linearly from maximum electric power, maximum light output to minimum electric power, minimum light output as the daylight illuminance increases.

A fan coil unit (4-Pipe) system was the HVAC system for cooling and heating in atrium buildings. The energy source for heating system was natural gas and for cooling system was electricity from grid. The mechanical ventilation with the rate of 10 l/s/person was also included in the simulations. Moreover, all of the zones except the atrium space were set to be conditioned. The heating and cooling set points were 22 and 24 degree centigrade. Heating and cooling set back were also considered. The cooling set back was 28 degree centigrade and the heating setback was 12 degree centigrade. Although, in this research the natural ventilation was not considered the airtightness with 0.7 air change per hour was include for the atrium buildings.

For simulating the energy performance of the atrium buildings, DesignBuilder simulation software was utilized. This software is a comprehensive user interface for the EnergyPlus dynamic thermal simulation engine. For conducting this research, the version 4.6.0.015 of the DesignBuilder was used.

3.2 Methodology

As described in the previous section, there were four variables, which were examined in this research, the height of the atrium building, the aspect ratio, and the orientation of the atrium, and the climate in which the building is located. For examining the effect of a single variable individually or in combination with any of three others on the energy performance of the atrium buildings, 3D models with different combinations of variables were prepared and their energy performance were simulated by means of the simulation software DesignBuilder. By considering the number of variables and suggested alternatives for each variable, and by doing a simple calculation it becomes clear that 84 models and simulations in total were needed to cover all the combinations of the variables. The total steps of the research methodology are presented in Figure 3.8 in a shape of a flowchart.

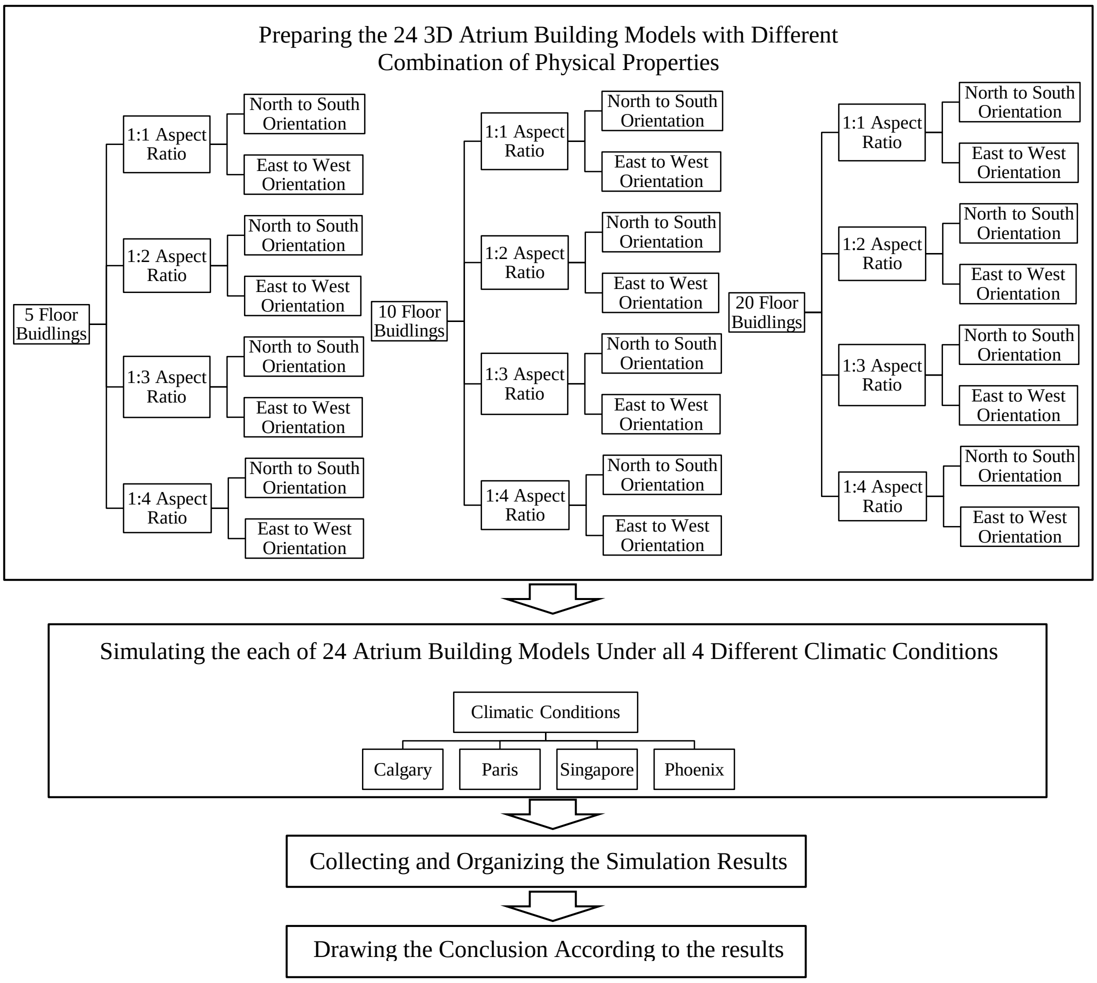
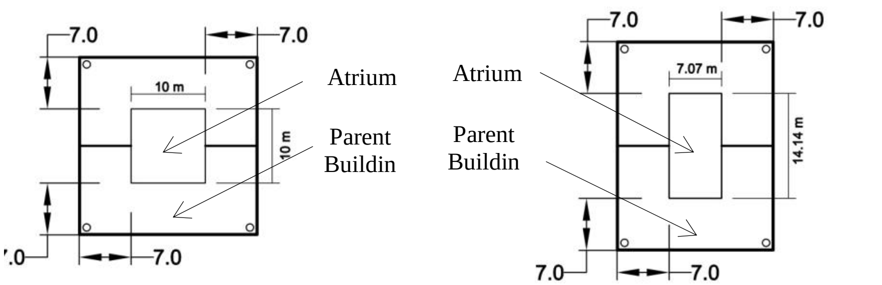


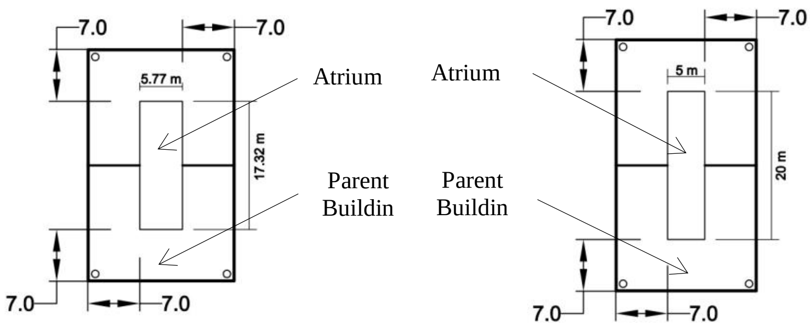
Figure 56: The Steps of the Research Methodology

Basically, the prepared atrium building models for this research were atrium buildings in which a rectangular shape atrium with 100 m^2 area is put into the center of a parent building. Parent buildings are occupied spaces, which have a depth of 7 meter around the atrium (Figure 3.8). The 7 meter depth was chosen, generally because it is the distance from the natural light source where adequate amount of light can reach in an interior space. Four different aspect ratios were considered for the atrium. The first aspect ratio was 1:1, where the length and width were both 10 m long. The second aspect ratio was 1:2 where the length and width were 14.14 m and 7.07 m long, respectively. As the third aspect ratios, the length is 17.32 m and the width is 5.77 m long, which represents 1:3 aspect ratio. Finally, the fourth aspect ratio is 1:4 in which the length and width were 20 m and 5 m long, respectively. As described earlier the height of an atrium building also was considered as one of the variables.



Atrium Aspect Ratio 10/10 = 1
Atrium Area 100 m^2
Total Building Area 576 m^2

Atrium Aspect Ratio 1014.14/ 7.07 = 2
Atrium Area 100 m^{2a}
Total Building Area 593 m^2



Atrium Aspect Ratio 17.32/ 5.77 = 3
Atrium Area 100 m^2
Total Building Area 619.3 m^2

Atrium Aspect Ratio 20/ 5= 4
Atrium Area 100 m^2
Total Building Area 646 m^2

Figure 57: Plan Drawings of Atrium Buildings with Four Different Atrium Aspect Ratios

It is noteworthy that in all of the configurations, the atrium walls were orthogonal which means the skylight and the atrium footprint, always share the same aspect ratio. Moreover, in order to focus on the aspect ratio of the atrium and its effect on the energy performance of the building the area of the atrium skylight was kept constant in all models (100 m^2); regardless of the aspect ratio of the atrium. In addition, no framing structure for atrium glazing surfaces was considered to eliminate the effect of change in length of framing on the results as the aspect ratio of the atrium changes.

Also, to cancel the effect of the different shape of the parent buildings on the energy performance of the models, all exterior surfaces of the atrium buildings, including ground floor, exterior walls and roof were set to be adiabatic (but not the skylight glazing). However, by default DesignBuilder software automatically changes the construction materials of walls to Gypsum plasterboards-as same as the ones utilized in interior partitions-by setting them as adiabatic.

Since, the aim of this research is to measure the effect of different variables specifically on the heating, cooling and lighting loads of the atrium buildings, and to avoid the complexity in analyzing the results, any other type of energy consumptions, such as energy consumption for computers, office equipment, domestic hot water and catering in all models were eliminated.

The energy consumption for interior lighting as one of the main three energy loads was examined in this research. DesignBuilder software provides an opportunity to measure the natural light available in a space by means of light sensors whose position can be set manually by the software user. In all atrium building models, to measure the amount of available natural light in the parent building, four light sensors were provided in each floor. Unfortunately, the DesignBuilder software in maximum allows for two light sensors in each zone; thereby to put the four light sensors in a single floor, each floor had to be divided into two smaller zones. The light sensors are located in four corners of parent buildings with 1 meter distance from exterior surface of the walls and 0.8 m off the floor (Figure 3.9)

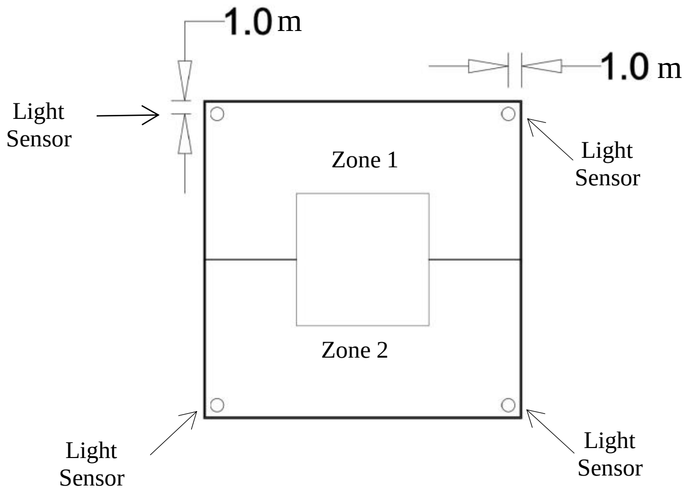


Figure 58: Position of the Light Sensors in the Parent Buildings

Finally, all 84 models with different combinations of four variables, were simulated with DesignBuilder simulation software and the results were collected and compared to see the effect of variables on the interior lighting, cooling and heating loads throughout a complete year.

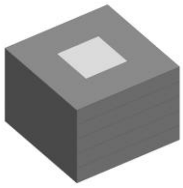
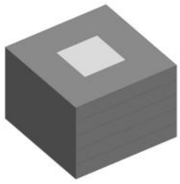
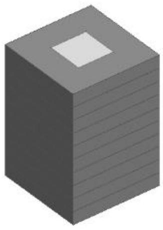
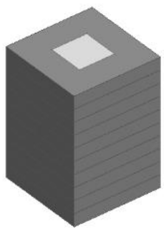
CHAPTER 4

RESULTS AND DISCUSSION

To simplify the presentation of the results, the atrium building models are named according to the different alternatives of the variables. To refer to different climate types, the abbreviated forms of the cities' name are used: i.e. (CGY), (PRS), (SGP) and (PHX), are terms, which represent the climatic conditions of Calgary, Paris, Singapore and Phoenix, respectively. The letter (F) represents the number of floors; 5F, 10F and 20F identify atrium buildings with 5 floors, 10 floors and 20 floors. As the third variable, the aspect ratios of the atria are also presented in short forms. R1, R2, R3 and R4 are referring to atria with aspect ratios of 1:1, 1:2, 1:3 and 1:4, respectively. The last variable is the orientation of the atrium. The term (NS) represent the atria, which are oriented along with North-South axis and the term (EW) refers to the atria that are parallel to the East-West axis. As an example, the atrium building SGP-10F-R4-NS tells us that the building is a 10 floor high atrium building which is simulated under Singapore climatic condition and it has an atrium with 1:4 aspect ratio that is oriented parallel to North-South axis. It is noteworthy that, since the atria with 1:1 aspect ratio are symmetric in both X and Y axis, the terms representing their orientations are omitted from their name.

Prior to presenting the numerical results it is good to mention that, since the area of atrium buildings with various atrium aspect ratios and number of floors are different from each other, in this research, the simulation results regarding the energy consumption of the atrium building models are presented per square meter of conditioned building area.

Table 4.1: Atrium Buildings with Minimum and Maximum Energy Consumptions in The Four Climates

The City	**Maximum Energy Consumption**	**Minimum Energy Consumption**
Calgary	CGY-F20-R4-NS 146.21 kWh/m^2/year 	CGY-5F-R1 139.58 kWh/m^2/year 
Paris	PRS-F20-R4-NS 108.44 kWh/m^2/year 	PRS-5F-R1 103.11 kWh/m^2/year 
Phoenix	PHX-F20-R4-NS 112.98 kWh/m^2/year 	PHX-10F-R1 106.11 kWh/m^2/year 
Singapore	SGP-F20-R4-NS 286.95 kWh/m^2/year 	SGP-10F-R1 281.26 kWh/m^2/year 

As illustrated in Table 4.1, under Calgary climatic condition the highest energy consumption belongs to atrium building CGY-F20-R4-NS with 146.21 kWh/m^2/year, and the atrium building CGY-5F-R1 with 139.58 kWh/m^2/year have the lowest energy consumption. Under the Paris climatic condition, the 108.44 kWh/m^2/year is the highest energy consumption recorded among all atrium buildings in this climate, which belongs to building PRS-F20-R4-NS and the atrium building PRS-5F-R1 with 103.11 kWh/m^2/year has the lowest energy consumption. Meanwhile, under phoenix climatic condition the atrium building PHX-F20-R4-NS with 112.98 kWh/m^2/year has the highest energy consumption, and the atrium building PHX-10F-R1 with 106.11 kWh/m^2/year shows the least energy consumption among other atrium buildings in this climate. In Singapore climatic condition, the highest energy consumption belongs to the atrium building SGP-F20-R4-NS with 286.95 kWh/m^2/year. The atrium building SGP-10F-R1 with 281.26 kWh/m^2/year has the lowest energy consumption among atrium buildings simulated in this climatic condition.

Figures 58, 59, 60and 61 are prepared to present the effect of the height of an atrium building on the energy performance of the building. In these charts, along the horizontal axis the names of the atrium buildings are provided and the vertical axis indicate the energy consumption per building conditioned area per year of the atrium building models.

According to the Figure , under Calgary climatic condition and in all atrium buildings with all combination of variables, by increasing the height of the atrium building, total energy consumption per conditioned building area per year increases. To be more detailed, on average when compared to 5 floor atrium buildings, 10 floor ones consume 1.34% more energy per conditioned building area per year; while 20 floor atrium buildings consume 2.97% more than 10 floor ones. As it is clear in the Figure 4.1, the dominant energy consumption in all atrium buildings in Calgary climate is heating; and cooling consumes the least energy. In fact, on average, the 10 floor atrium buildings present 1.60% less energy consumption for heating per building conditioned area than 5 floor ones. Meanwhile, 20 floor atrium buildings consume 2.47% less energy for heating in comparison to 10 floor ones. On the other hand, according to the Figure 4.1 the cooling load under Calgary climatic condition does not present a linear trend. On average, in this climate 10 floor atrium buildings consume 25.86% less energy per building conditioned area for cooling than 5 floor ones, Whereas, 20 floor atrium buildings consume 17.35% more energy per building conditioned area in comparison to 10 floor ones. Regarding the interior lighting loads, on average 20 floor atrium buildings in comparison to 10 floor ones consume 15.97% more energy per conditioned building area and the 10 floor atrium buildings consume 12.15% more energy for interior lighting per building conditioned area in comparison to 5 floor ones.

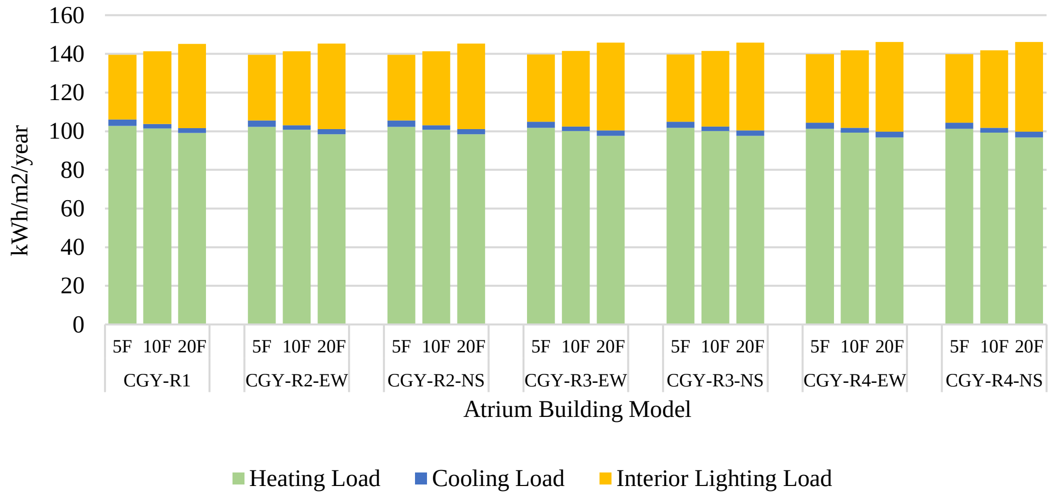


Figure 59: Energy Consumption of Models with Three Different Number of Floors Under Calgary Climatic Condition

As presented in Figure 4.2, the highest energy consumption among all atrium buildings simulated under Paris climatic condition belongs to the 20 floor ones. On average and in comparison to 5 floor atrium buildings, 10 floor ones consume 0.85% more energy per building conditioned area per year. Whereas, 20 floor atrium buildings on average present 3.31% more energy consumption per building conditioned area than 10 floor ones. Furthermore, under Paris climatic condition, the dominant energy load of the atrium buildings is the heating load and the next higher energy consumption with small difference is the lighting load. In fact, on average, 10 floor atrium buildings in comparison to 5 floor ones consume 1.68% less energy per building conditioned area for heating. Meanwhile, the 20 floor atrium buildings on average consume 1.47% less energy per building conditioned area for heating than 10 floor ones. Regarding the cooling load, the 10 floor atrium buildings consume 14.05% more energy per building conditioned area than 5 floor models, whereas, the 20 floor models consume 3.24% less energy than 10 floor ones. Regarding the lighting loads, it needs to be mentioned that as in all atrium buildings under all climatic conditions, in this climate also by increasing the number of floors the energy consumption for interior lighting increases.

To be more specific, 10 floor atrium buildings consume 6.81% more energy per building conditioned area for interior lighting than 5 floor ones and 20 floor atrium buildings consume 7.62% more energy per building conditioned area than 10 floor ones.

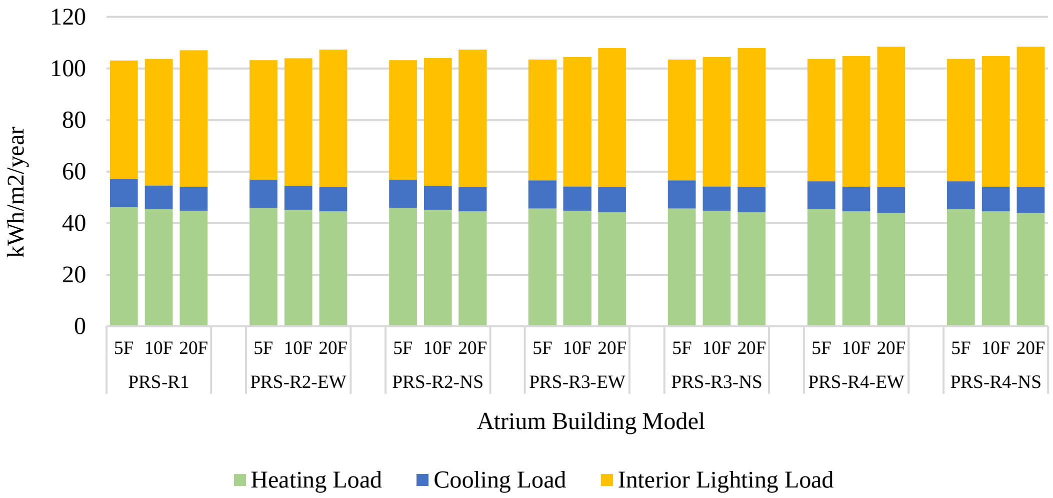


Figure 60: Energy Consumption of Models with Three Different Number of Floors Under Paris Climatic Condition

In Phoenix climatic condition and in most cases 5 floor and 20 floor atrium buildings have roughly equal total energy consumption per building conditioned area; and the 10 floor atrium buildings have the least energy consumption. As anticipated, under this climatic condition the cooling load is the main contributor to the atrium buildings' total energy consumption and the lighting loads come next (Figure 4.3). In fact, 10 floor atrium buildings have 3.57% less total energy consumption per building conditioned area in comparison to 5 floor ones, whereas the 20 floor atrium buildings consume 3.91% more energy per building conditioned area than 10 floor ones. Regarding the heating load, on average the 10 floor atrium buildings consume 4.68% more energy per building conditioned area than 5 floor ones. While, the 20 floor atrium buildings consume 8.05% less energy per building conditioned area than 10 floor ones. However, under this climate and in case of cooling load by increasing the number of floors the energy performance increases. In fact, on average 10 floor atrium buildings consume 9.56% less energy per building conditioned area than 5 floor ones, and 20 floor atrium buildings consume 1.84% less energy per building conditioned area for cooling in comparison to 10 floor ones. Regarding the interior lighting loads, 10 floor atrium buildings on average consume 14.8% more energy per building conditioned area than 5 floor ones, and 20 floor atrium buildings consume 23.63% more energy per building conditioned area than 10 floor atrium buildings.

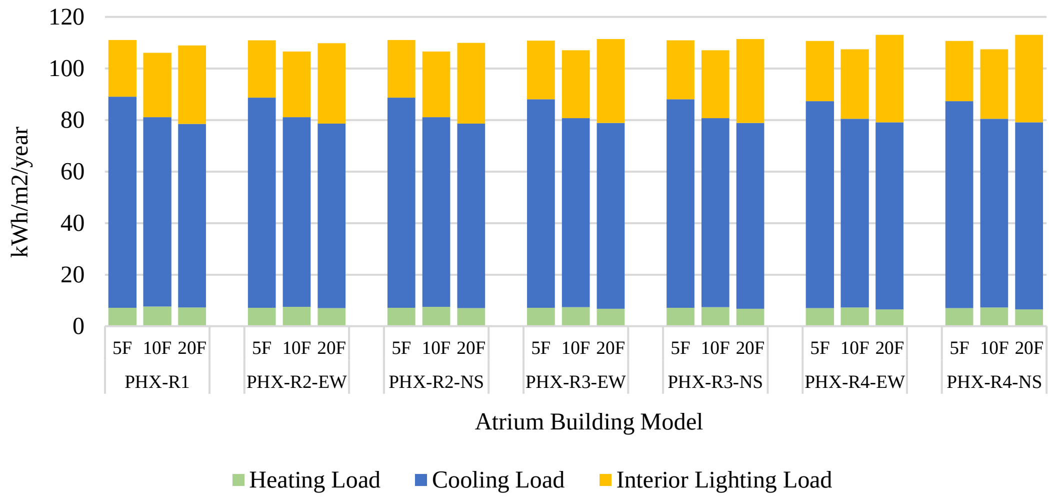


Figure 61: Energy Consumption of Models with Three Different Number of Floors Under Phoenix Climatic Condition

However, the atrium buildings simulated under Singapore climatic condition indicate different trends in energy loads. In this climate, the difference in total energy consumption per building conditioned area among atrium buildings with different combination of variables is small. On average and in comparison to 5 floor atrium buildings, 10 floor ones consume 1.06% less energy per building conditioned area, and 20 floor atrium buildings in comparison to 10 floor ones consume 0.97% less energy per building conditioned area. As expected, under Singapore climatic condition, we do not have any heating load; however, the cooling load is significant. To be more clear, the 10 floor atrium buildings consume 3.35% less energy per building conditioned area for cooling in comparison to the 5 floor ones; and 20 floor atrium buildings consume 0.93% less energy per building conditioned area than 10 floor atrium buildings. Regarding the interior lighting, on average the 10 floor atrium buildings consume 12.34% more energy than 5 floor ones, whereas 20 floor atrium buildings consume 10.56% more energy in comparison to 10 floor ones (Figure 4.4).

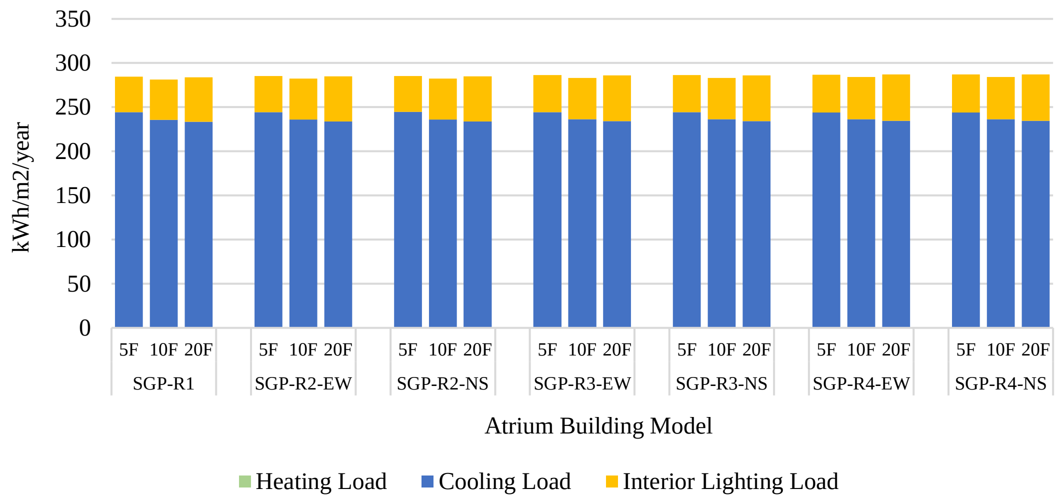


Figure 62: Energy Consumption of Models with Three Different Number of Floors Under Singapore Climatic Condition

Under Calgary and Paris climatic conditions, the main reason for increase in total energy consumption by increasing the height of the atrium buildings (number of floors) is decreasing the natural light intensity and subsequent increase in interior lighting load. However, under Phoenix and Singapore climatic conditions and mostly in 10 floor atrium buildings, the reduction in natural light intensity and solar gain per square meter of the buildings, results in the reduction of cooling loads, which compensate for the increase in the interior lighting loads.

The cooling and heating loads of the simulated atrium buildings mainly is depended on solar gain and internal gains (generated heat by interior lighting). In atrium buildings simulated under Calgary and Paris climates, the predominant factor is the internal gain. The decrease in the heating loads of the atrium buildings in these climates can be ascribed to the increase in the internal gains, which is the result of reduction in natural light intensity by increasing the height of the atrium building, and subsequent increase in the demand for interior lighting.

As mentioned earlier, the increase in number of floors decreases the available natural light per square meter of the building and increases the interior lighting and internal heat gain in turn. On the other hand, solar gain is one of the main factors affecting the cooling load, which decreases per square meter of the atrium buildings by increase in the number of floors. Under Calgary and Paris climates by going from 5 floor atrium buildings to 10 floor ones the increase in internal gains is higher than decrease in solar gain per square meter of the building, thus the cooling load decreases. However, by going from 10 floor to 20 floor atrium buildings, decrease in solar gain per square meter of the building is higher than increase in the interior gain, which results in a lower cooling load in comparison to 10 floor atrium buildings. However, In Phoenix and Singapore the solar gain has more effecting role in cooling load. In other word, in these climates by increasing the height of the atrium buildings the decrease in solar gain is higher than increase in internal gain.

Two other physical properties of an atrium building which were examined in this research are atrium aspect ratio and its orientation. Tables 6, 7 and 8 are prepared to facilitate the comparison of energy performance of different atrium buildings with different configuration and physical properties. Tables 6, 7 and 8 include atrium buildings with 5, 10 and 20 floors, respectively. Each Table organize the atrium buildings in horizontal rows according to 4 climates in which their energy performance was simulated. The energy consumption loads, including Interior Lighting, Heating, Cooling and total energy consumption loads are given separately in four different columns within these Tables.

Each cell of the Tables 6, 7 and 8 under the four main columns include a graph. Each graph presents the energy performance of seven different atrium buildings related to the type of the energy consumption mentioned on the heading of the column. In these graphs, the vertical axis presents the energy consumption in kWh/m2/year, and the horizontal axis orders the seven different atrium buildings. Among these seven atrium buildings, the middle one has an atrium with 1:1 aspect ratio. The atrium buildings on the right side have the atria with East to West orientation and the atrium buildings on the left side have the atria with North to South orientation. By moving from middle atrium building to the ones on right or left side on horizontal axis, the aspect ratio of the atria increases. In other words, the middle atrium has the aspect ratio of 1:1, the first atrium building on the right or the left side has 1:2 aspect ratio, the second ones has 1:3 aspect ratio and the fourth ones has 1:4 aspect ratio (Figure 4.5).

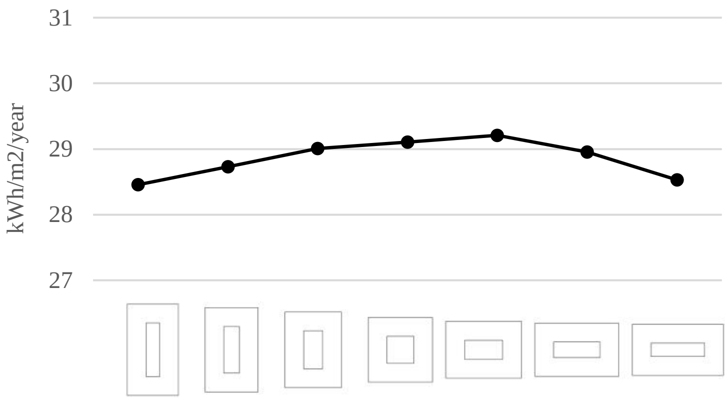


Figure 63: An Example of a Complete Form of a Graph from Tables 6, 7 And 8

According to the results obtained from this research work, the orientation of the atrium does not affect the total energy consumption or any of three main energy loads considerably. It is mainly due to the symmetric shape of the atrium buildings and equal occupancy and schedule type in all 4 sides of the buildings which make the atrium buildings indifferent toward changes in orientation of a roof opening (horizontal opening) like an atrium.

According to Tables 6, 7 and 8 in all climates and building heights, Interior lighting load increases by increase in atrium aspect ratio in both orientations. In other words, the atrium buildings with 1:4 aspect ratio atrium have the most interior lighting load and ones with 1:1 aspect ratio have the least energy consumption for interior lighting. The reason is mainly the decrease in sky view angle. In fact, by increasing the aspect ratio of the atrium the sky view angle decreases considerably, which is the main reason of reduction in natural light and increase in interior lighting load.

The cooling load trend is not similar in all atrium buildings with different heights. In 5 floor atrium buildings and under all climates the cooling load decreases by increase in the atrium aspect ratio. However, in all climates the cooling load of the atrium buildings with 10 and 20 floors increases by increase in the atrium aspect ratio. Except the cooling load of 10 floor atrium buildings under phoenix climatic condition, that by increasing the atrium aspect ratio the cooling load slightly decreases. In fact, in 5 floor atrium buildings the solar gain is the determinative factor for cooling load, thereby by increasing the aspect ratio of the atria the solar gain reduces and the cooling load decreases in return. However, in 10 and 20 floor atrium buildings the main affecting factor on the cooling load is heat generated by interior lightings. On the other hand, by increasing the aspect ratio of the atrium the lighting load and subsequently generated heat by interior lighting increases. At the end, this chain of reaction results in an increase in cooling load.

As expected, the atrium buildings simulated under Singapore climatic condition have no heating loads. However, in all atrium buildings with different heights and in three other climates by increasing the atrium aspect ratio the heating load decreases. The decrease in heating load is chiefly related to the increase in interior lighting load by increasing the atrium aspect ratio. Generated heat by interior lightings partially compensate the heating energy required to provide comfortable space in the building and thereby decreases the heating load.

According to the Table 6, 7 and 8, in all atrium buildings and under all climatic conditions and in both orientations by increasing the aspect ratio of the atrium the total energy consumption increases. In fact, the atrium buildings with 1:1 aspect ratio have the least total energy consumption. Except in 5 floor atrium buildings simulated under Phoenix climate that by increasing the atrium aspect ratio in both orientations the total energy consumption slightly decreases. It is mostly due to the fact that in 5 floor atrium buildings the solar gain has more effect on heating and cooling load than in10 or 20 floor atrium buildings. On the other hand, phoenix climate has relatively higher Global Horizontal Irradiance (GHI) than other three climates. Thereby, in 5 floor atrium buildings and under Phoenix climate, increasing the aspect ratio of the atrium results in a more decrease in cooling load than increase in lighting load which leads to a slight decrease in total energy consumption by increase in atrium aspect ratio. However, as described earlier, the general reason of increase in total energy consumption of atrium buildings is related to increase in interior lighting load. In other words, by increasing the atrium aspect ratio the sky view angle decreases, thereby the natural light available in the building reduces and interior lighting load increases which is the main contributor to the total energy consumption.

Table 4.2: 5 Floors Atrium Buildings Behavior toward Different Aspect Ratio and Orientation

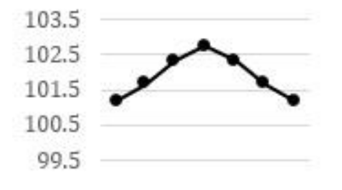
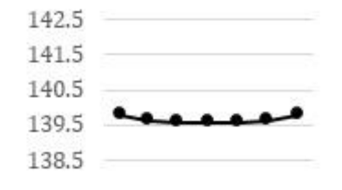
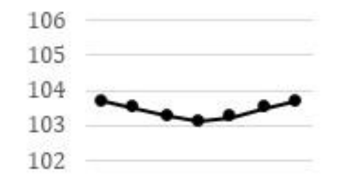
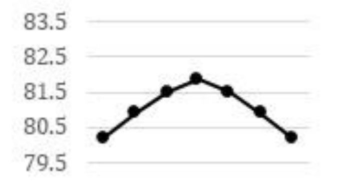
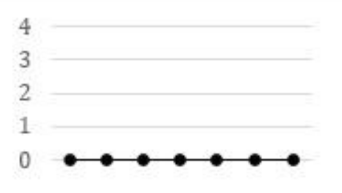
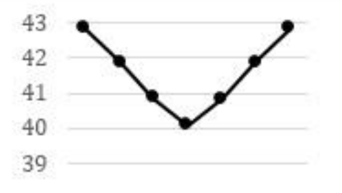
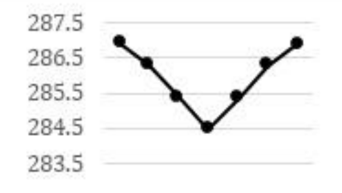
Number of Floors	Climate	Heating Load	Cooling Load	Interior Lighting Load	Total Energy Consumption Load
5	CGY				
	PRS				
	PHX				
	SGP				

Table 4.3: Floors Atrium Buildings Behavior toward Different Aspect Ratio and Orientation

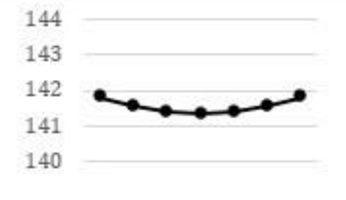
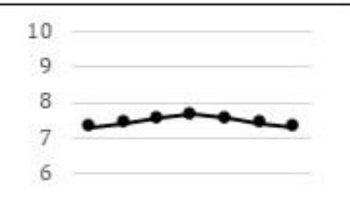
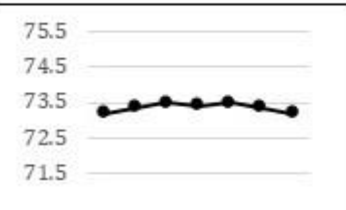
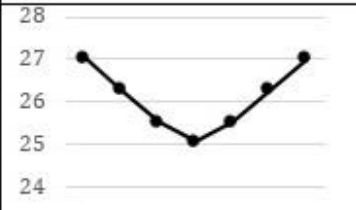
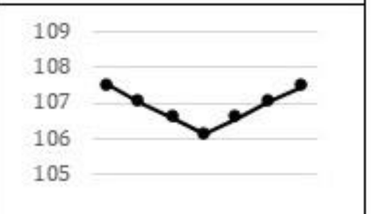
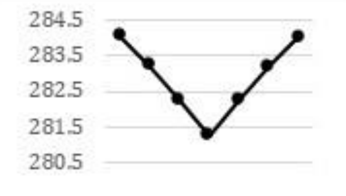
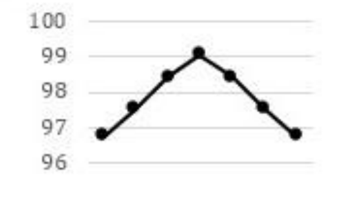
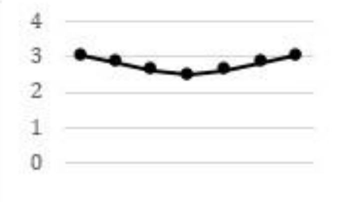
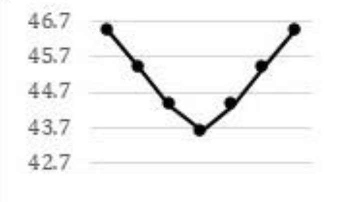
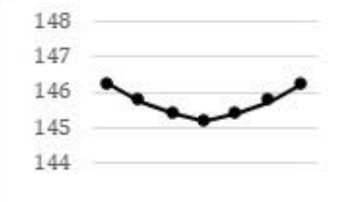
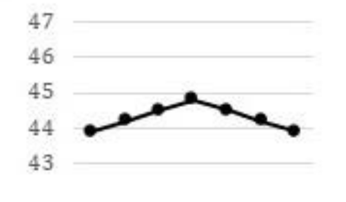
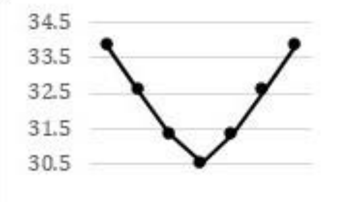
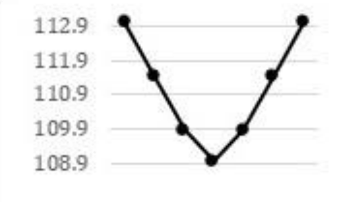
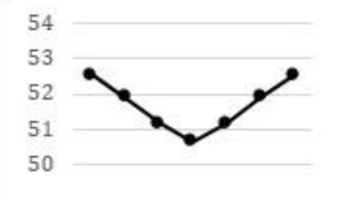
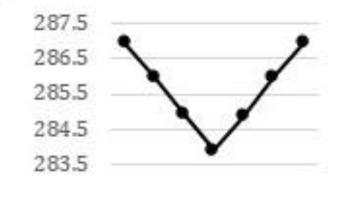
Number of Floors	Climate	Heating Load	Cooling Load	Interior Lighting Load	Total Energy Consumption Load
10	CGY				
	PRS				
	PHX				
	SGP				

Table 4.4: 20 Floors Atrium Buildings Behavior toward Different Aspect Ratio and Orientation

Number of Floors	Climate	Heating Load	Cooling Load	Interior Lighting Load	Total Energy Consumption Load
20	CGY				
	PRS				
	PHX				
	SGP				

CHAPTER 5

CONCLUSION

Atrium buildings with different physical properties can have various effects on the energy performance of the whole building. In the same way, the physical properties studied in this reseach, that include atrium building height, atrium aspect ratio and atrium orientation, generally contribute to the energy performance of the building in all four studied climates.

Basically, among three variables related to the physical properties of an atrium that are studied in this research, the height of an atrium building has the most considerable effect on the energy performance of the building. However, the increase in the height of the atrium building, depended on the climate in which the building is located, may increase or decrease the total energy consumption.

According to this research the orientation of the atrium does not affect the energy performance of an atrium building considerably. In other words, the energy performance of two identical atrium buildings oriented along North- South and East-West axes are almost equal.

As the third variable related to the physical properties of an atrium building, the aspect ratio of an atrium has noticeable effect on the total energy consumption. According to this research, in all studied climates the atrium buildings with 1:1 aspect ratio have the highest and atrium buildings with 1:4 aspect ratio have the lowest energy performance.

Generally, as expected in all four climates the interior lighting load of an atrium building increases by increase in the number of floors of the building. Furthermore, by increasing the aspect ratio of the atrium the interior lighting loads increases. However, as mentioned earlier the orientation of the atrium does not affect the interior lighting load noticeably.

The effect of increaseing the height of the atrium building (number of floors) on the heating and cooling load is greately depended on the climate in which the building is located. In cold and temperate climates increasing the height of the atrium building decreases the heating load. However, in these climates the cooling load dose not have a linear trend. In hot and tropical climates the cooling load decreases by increase in atrium aspect ratio; in other words the narrower atria induce a lower cooling load. However, the heating load in the hot climate does not have a linear behaviour. Furthermore, in all climates increase in the atrium building aspect ration decreases the heating load. However, the effect of atrium aspect ratio on the cooling load is greately depended on the height of the atrium building.

The impact of the height of the atrium building is highly related to the climate that the building is located in. In cold and temperate climates, mainly because of the lower lighting load, the lower atrium buildings have higher energy performance, however, in hot and tropical climates the total energy consumption varies by the height of the building as described in results section. The atrium aspect ratio also affects the total energy consumption considerbly. Genrally, by increasing the atrium building aspect ratio the energy consumption increases.

Throughout the research process several challenges were encountered; the main challenge was the limitations imposed by DesignBuilder software for the number of light sensors in a single zone. The atrium building models basicaly consist of several floors and by default each floor is considered a single zone. In DesignBuilder software, each zone can have maximum two light sensors which is not enough for one whole floor. Thereby, each floor had to be divided in a number of zones to provide the possibility to set more than two light sensors in each. Meanwhile, the evaluation version of DesignBuilder software has a further limitation of maximum 50 zones in one simulation that needed to be considered also.

Since, there are lots of factors affecting the energy performance of an atrium building, and each of them can behave differently within different combination of factors, it is recommended to include the ones which can affect each other concurrently to come up with more realistic results. For instance natural ventilation and stack effect which are not examined in this research are potentials of atrium buildings that can be studied in more details in combination with other factors.

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APPENDIX A

CLIMATIC DETAILS OF THE FOUR EXAMINED CITIES

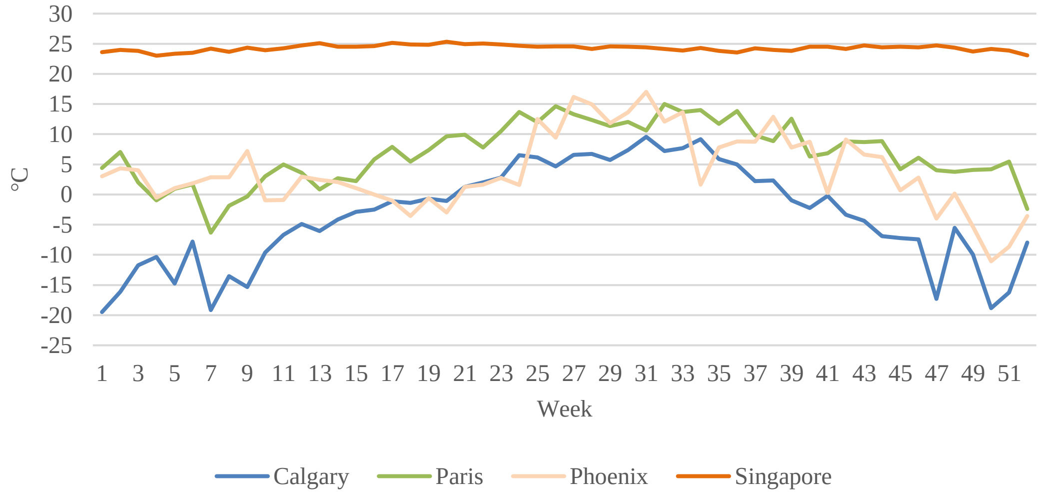

Figure 64: Average Weekly outside Dew-Point Temperature in the Four Climates
Source: DesignBuilder database

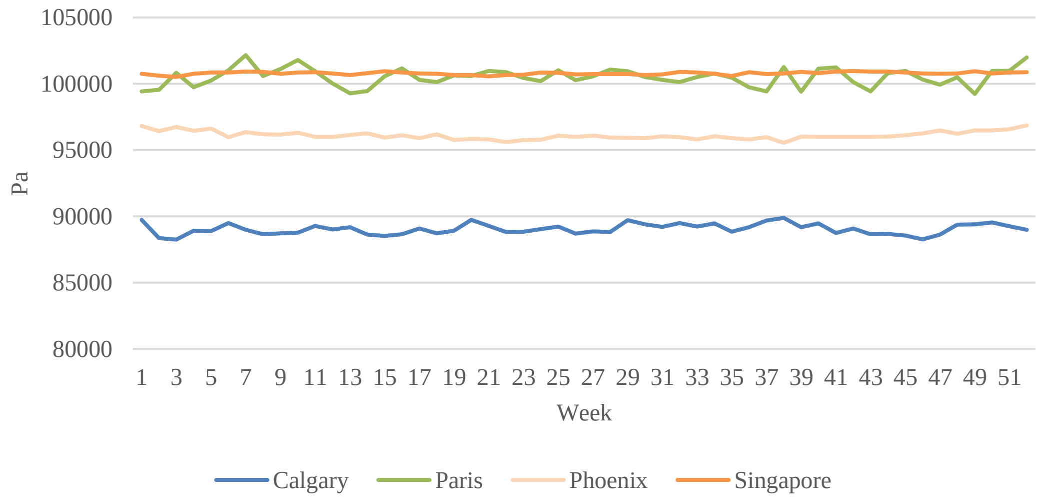

Figure 65: Average Weekly Atmospheric Pressure in the Four Climates
Source: DesignBuilder database

APPENDIX B

SIMULATION SETTINGS

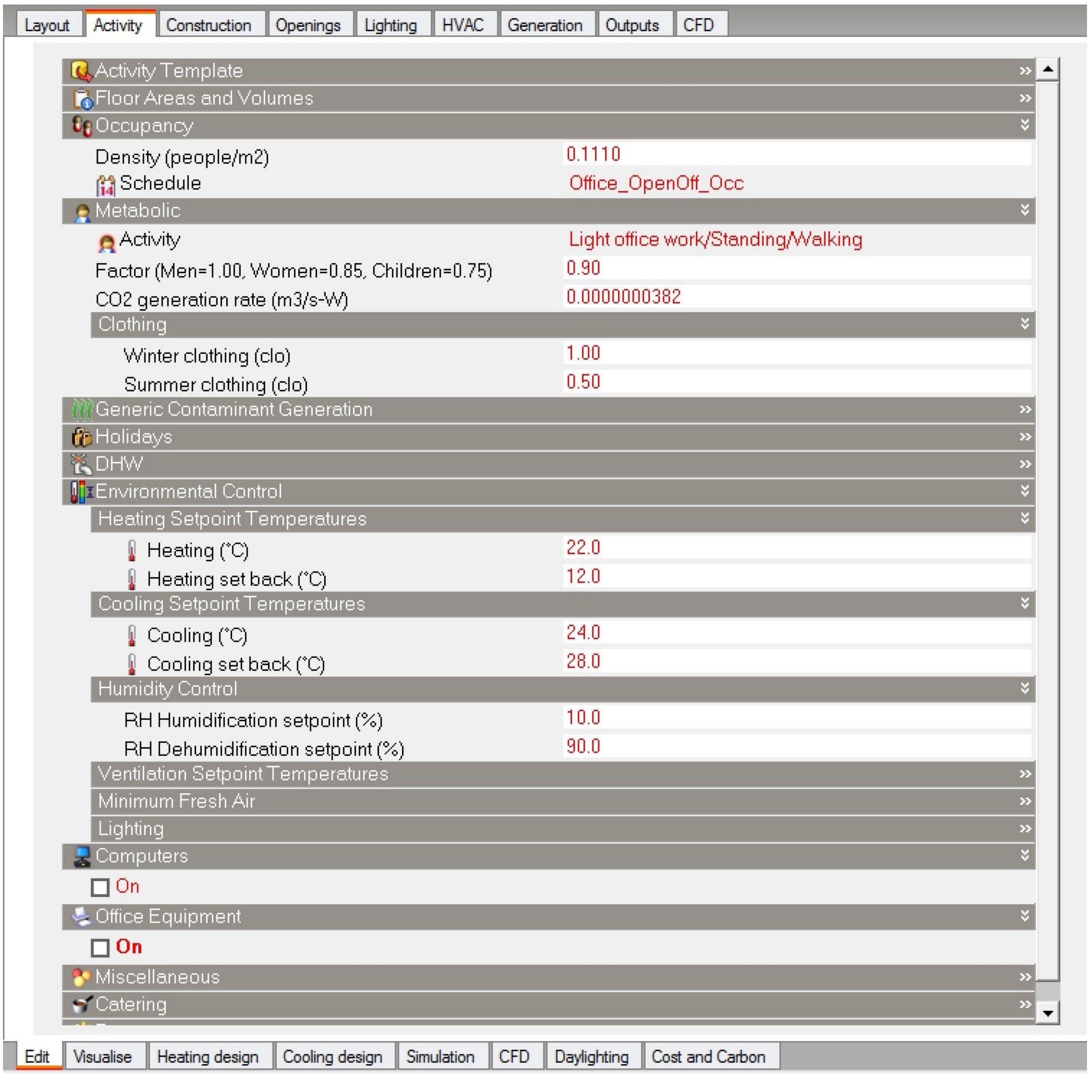

Figure 66: Occupancy and Environmental Control Settings of the Simulations

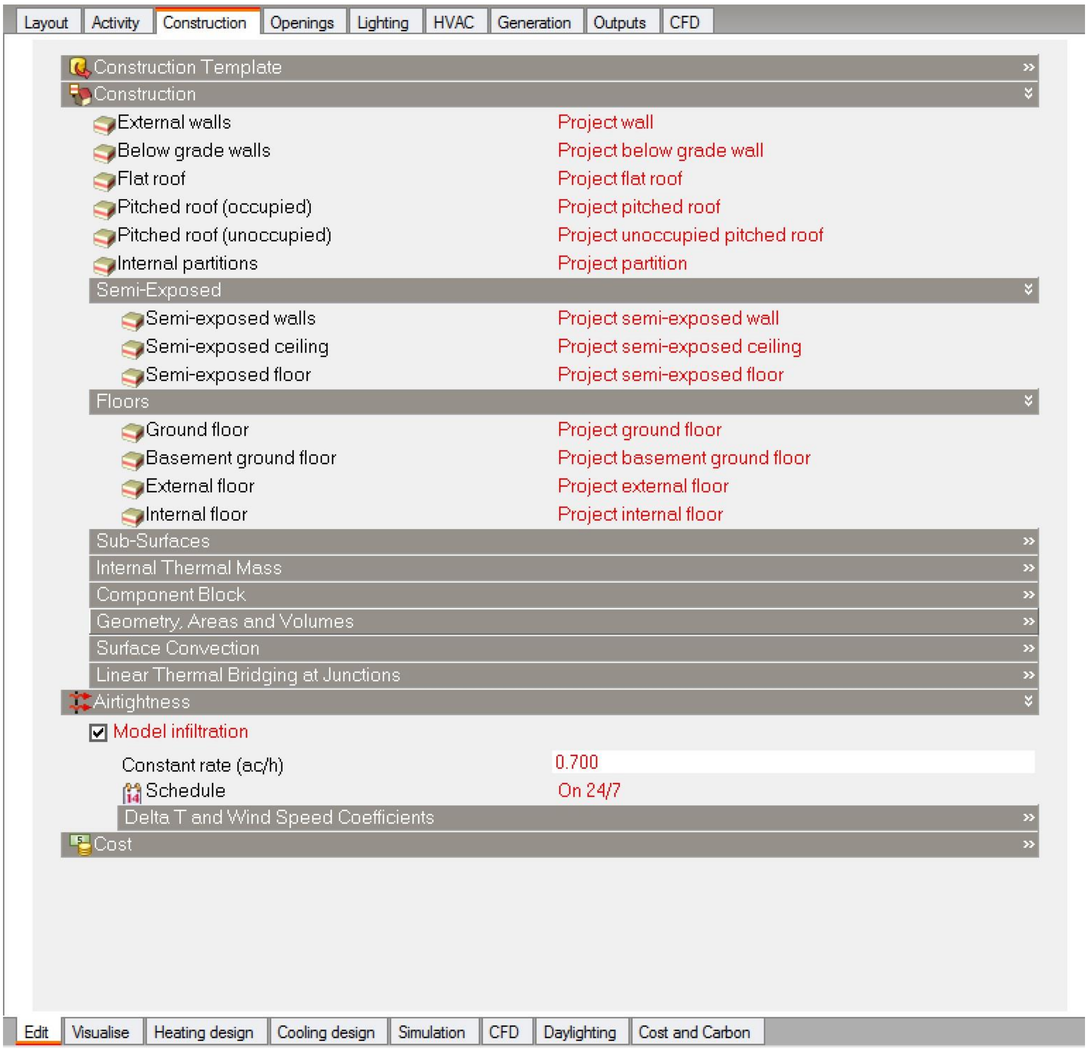

Figure 67: Construction Materials of the Atrium Buildings during the Simulations

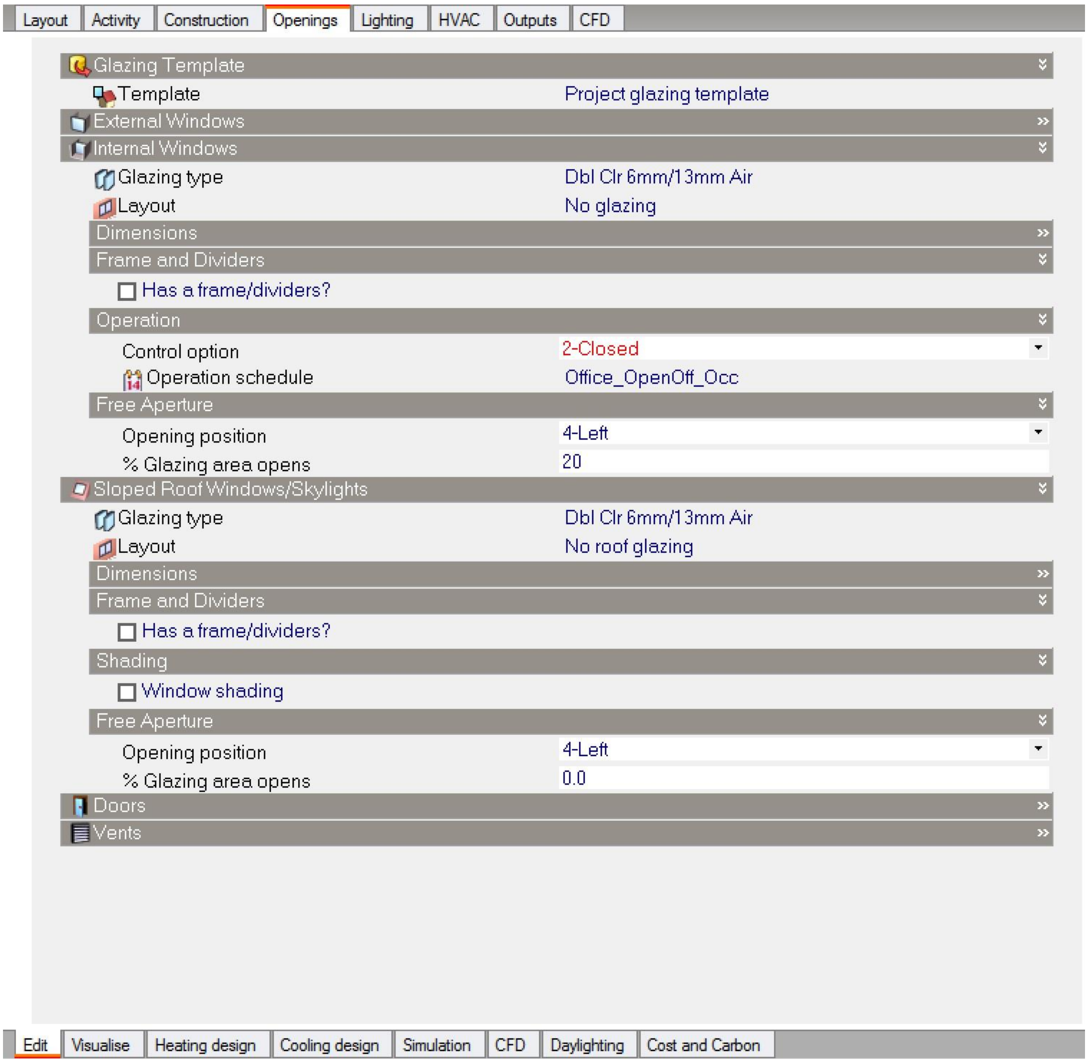

Figure 68: Materials and Settings Related to the Openings of Atrium Buildings During the Simulations

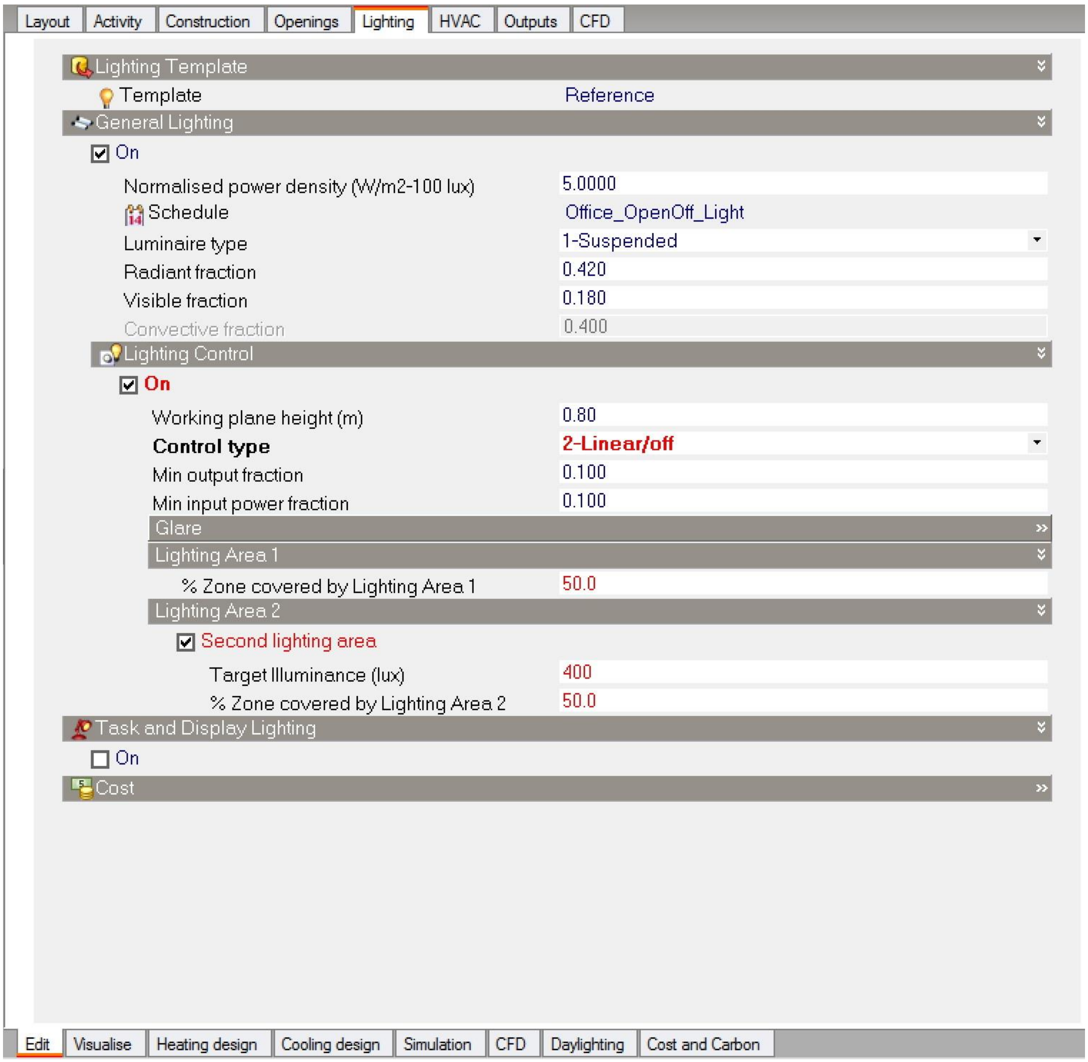

Figure 69: Lighting Settings of the Parent Buildings during the Simulations

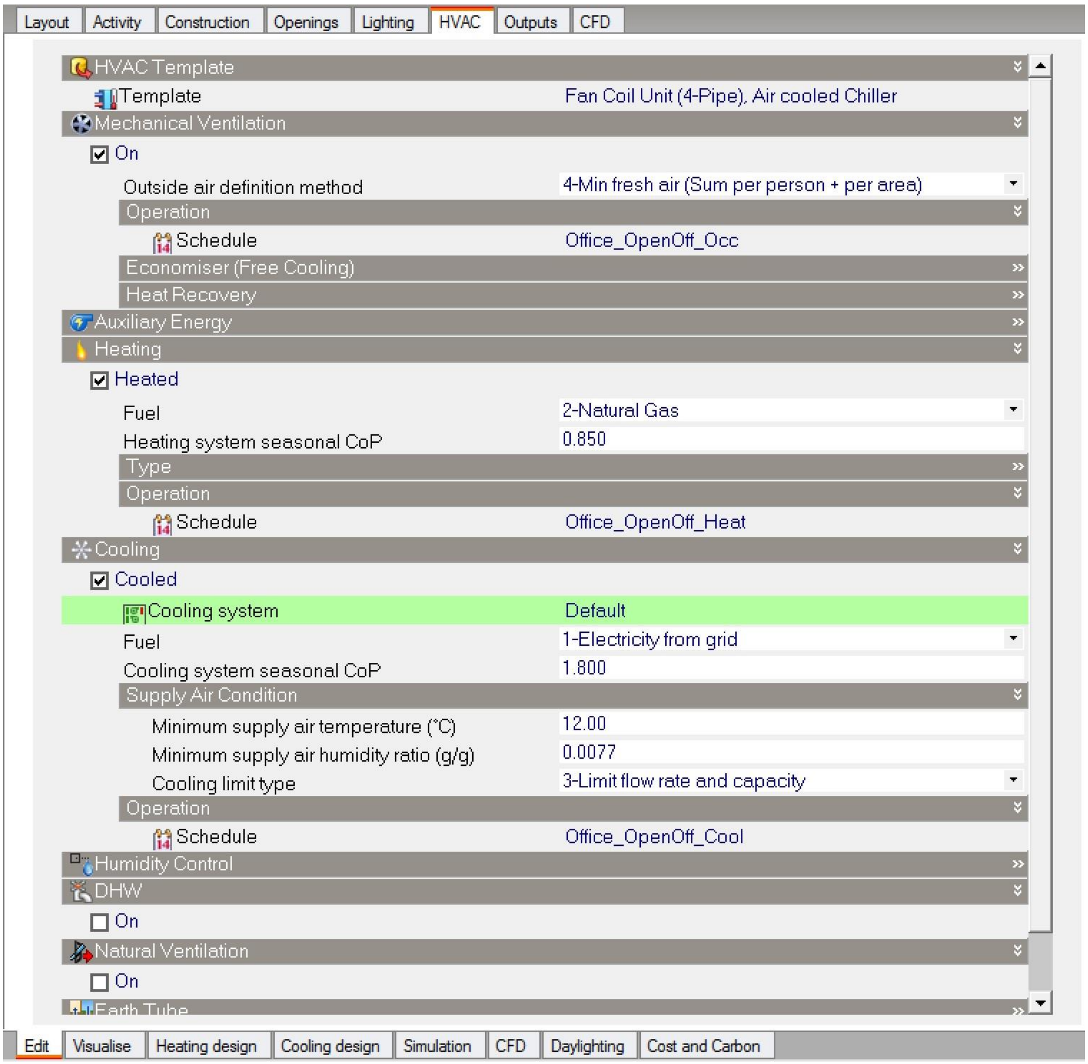

Figure 70: HVAC Systems' Settings of the Atrium Buildings during the Simulations