Increasing efficiency of Atriums in Hot Arid zones

في مناطق المناخ الحار والجاف زيادة الكفاءة في المنور

By

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Abstract

This research evaluates the efficiency of Atrium in hot, arid regions and analyzes the reduction of energy consumption that could be achieved in buildings by application of optimal variables. A virtual model of a shopping mall in Dubai, United Arab Emirates is created in IES-VE software using the existing parameters. The variables that impact the energy consumption such as Roof profile, Roof ventilation, Number of floors, Light to solar gain ratio (LSG), Insulation value (U) of envelope are analyzed by changing one variable at a time. Efficiency is analyzed in terms of energy consumption, cooling load, dehumidification load, lights energy and carbon emission to obtain optimal values. These values are applied to optimal model and simulated. An analysis of simulation results of base case and optimal cases demonstrate that an energy reduction of about 20% could be achieved in this research. Sensors placed inside building and U value of roof are noted to be the most effective variables reducing the energy consumption by 8.5 and 7.5% respectively, while Glazing profile, U value of external wall and number of floors reduce energy consumption by around 3.5%. Roof ventilation and LSG ratio of external glazing have minimal impact of around 1.5 and 0.66% respectively, while LSG ratio of internal glazing does not have any impact. The results demonstrate that the summation of percentage reduction in energy consumption when variables are applied individually need not be equal to the reduction achieved when all optimal values are applied together due to effect of one variable over other. As the height of building increases, the reduction in cooling load is offset by the increased lighting load. It also demonstrates that when all optimal values are applied together, the percentage reduction achieved is 20% irrespective of the number of floors. Designers by applying these optimal values in their design of Atriums can achieve an energy consumption 181 kWh/m^2 in their buildings. Thus this research establishes Optimal standards in Atrium design in Hot Arid climates.

Key words : Atrium, Energy performance, Cooling load, Light energy, Roof profile, Roof ventilation, Number of floors, LSG ratio, U value, IES-VE

ملخص

تقيم هذه الدراسة البحثية كفاءة المنور أو الأتريوم (Atrium) في المناطق الحارة والجافة وتقوم بتحليل إنخفاض الإستهلاك للطاقة الذي من الممكن تحقيقه في البنايات بواسطة تطبيق المتغيرات المثلى. تم محاكاة نموذج مركز تسوق في دبي بإستعمال التطبيق IES-VE *وقمنا بإستعمال العوامل المحددة الموجودة ذات التأثير في إستهلاك الطاقة، مثل مقطع السطح، تهويه السطح، عدد الطوابق، نسبة الوفرمن الضوء العادي إلى ضوء الشمس* (LSG)، قيمة العزل (U) لغلاف المبنى، وقد تم تحليل كافة هذه العوامل منفردة بتغيير عامل واحد فقط كل مرة. وفد تم تحليل الكفاءة بالنسبة لإستهلاك الطاقة، حمولة التبريد، حمولة مقاوم الرطوبة، طاقة الضوء، وإنبعاثات الكربون للحصول على أفضل القيم، وتم تطبيق هذه القيم على النموذج التجريبي وفحصها .

تبين تحاليل النتائج المستقاة من المقارنة بين الحالات المثلى والحالات المبدئية بأن تخفيض طاقة بقيمة 20% ممكن تحقيقه في هذه التجربة. سجلت المجسات التي وضعت داخل البناية وقيمة العزل في السطح (U value) أفضل النتائج بتخفيض إستهلاك الطاقة بنسبة 8.5% و7.5% على التوالي. بينما المقطع الطبقي، وقيمة العزل للجدار الخارجي وعدد الطوابق تخفض إستهلاك الطاقة بحوالي 3.5% أما تهوية السطح ونسبة الوفر بين الضوء العادي والشمسي (LSG ratio) للمقطع الطبقي فقد كان لها أثر محدود بنسبة 1.5% و 0.66% فقط على التوالي، بينما نسبة الوفر بين الضوء العادي والشمسي (LSG ratio) للمقطع الطبقي الداخلي كانت معدومة الأثر.أظهرت النتائج أن مجموع نسب التوفير في إستهلاك الطاقة عندما يتم تطبيق المتغيرات بشكل منفرد ليس بالضرورة مساوية لقيمة التخفيض عندما يتم تطبيق كافة المتغيرات مجتمعة وذلك بسبب التأثير لكل متغير على الآخر. وأيضا بينت الدراسة أنه عندما يتم تطبيق كل المتغيرات مع بعض فإن نسبة التخفيض تكون 20% بغض النظر عن عدد الطوابق. وكلما زاد الإرتفاع في البناية فإن التخفيض الناتج في حمولة التبريد يستهلك بالمقابل من الزيادة الناتجة من حمولة الإضاءة . وعليه فإن تطبيق القيم المثلى من قبل المصممين في تصميم المناور ممكن أن يحقق تخفيض في إستهلاك الطاقة بقيمة 181 كيلوواط/ متر مربع في أبنيتهم. ولهذا فإن هذا البحث يوصي بإستخدام المقاييس المثلى في تصميم المناور في المناخ الحار والجاف.

كلمات رئيسية: منور، أداء الطاقة، حمولة التبريد، طاقة الإضاءة، مقطع السقف، تهوية السقف، عدد الطوابق، نسبة الضوء العادي للشمسي (*LSG*)، قيمة العزل (*U value*) ، تطبيق ال *IES-VE*.

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Table of Contents Page

List of Figures

Page

List of Tables **Page**

Chapter 1

Introduction

Chapter 1 : Introduction

Sustainability is defined as a necessity of our generation to utilize the resource base in such a way that the average life quality that we ensure for ourselves can possibly be shared by future generations also (Asheim 1994). Ensuring that the planet earth's resources are not depleted is our responsibility. Two of the major factors that impact the sustainability of this planet earth are namely, energy consumption and CO2 emissions.

The current world population by mid of 2014 is 7,24,37,84,121 (7 billion) and by year 2050 it will reach 9,55,09,44,891 (9.5 billion) according to the data published by the United Nations, Department of Economic and Social Affairs, Population Division (2014). Figure 1.1 shows that the expected rate of growth of world population in 70 years, i.e. from the year 1970 to 2050 will be more than 2.5 times. The energy consumption has risen mainly due to the tremendous population growth rate, in addition to the better standards of living of the people. According to World Energy Outlook report published by IEA, the global energy demand grows for all forms of energy and it increases by one-third from 2011 to 2035.

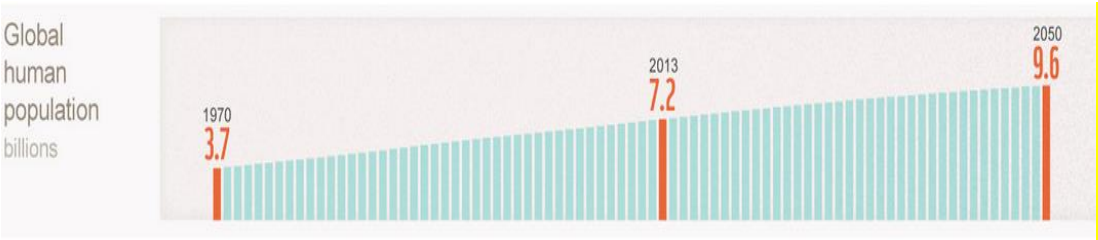


Figure 1.1 : Global human population in billions (WWF 2013)

Living planet report 2013 warns that at the present rate, CO2 emission is likely to reach 80 gigatonnes in 2050 from 14.9 gigatonnes in 1970 which is more than 5 times in 70 years (Figure 1.2).

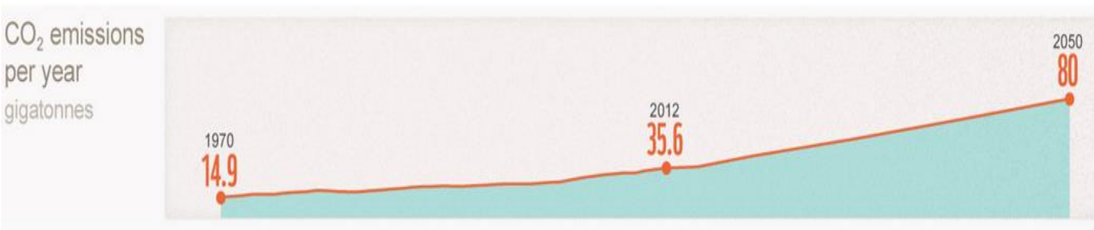


Figure 1.2 : CO_2 emission prediction in gigatonnes (WWF 2013)

Although efforts are taken to meet the energy demand by other sources of energy such as renewables and nuclear, restraining the energy consumption and lowering CO_2 emission become a vital task for a sustainable environment.

1.1 Significance of building sector in Sustainability

Energy efficient buildings with low energy consumption and low carbon dioxide emission are key to sustainability. Organization for Economic Co-operation and Development, OECD (2013) states that building sector is the largest consumer of energy in the world and consumes over one third of total world's energy. It can be seen from Figure 1.3, that building sector with total energy consumption of 35% are the major consumers of energy among other sectors.

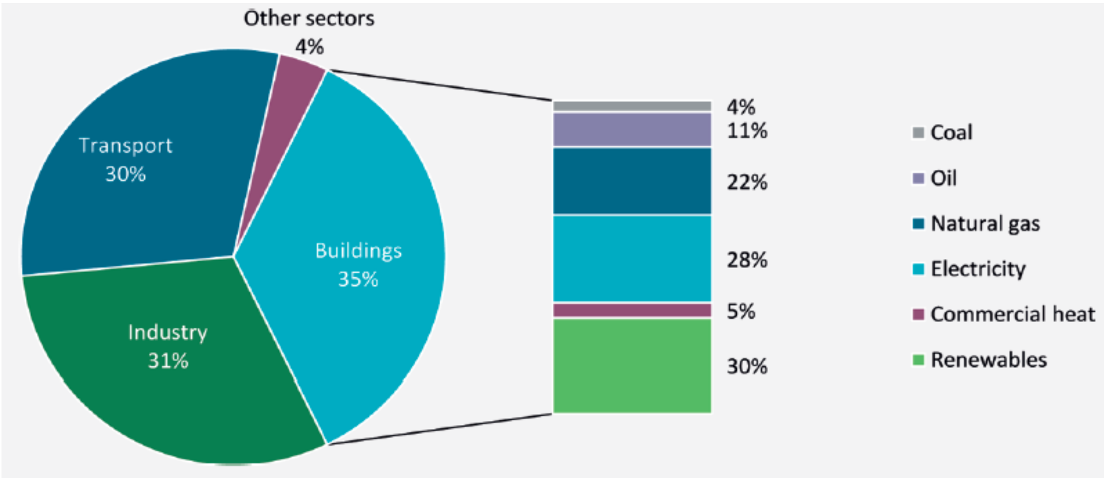


Figure 1.3 : Energy consumption by sector and building energy mix in 2010 (IEA 2013)

Buildings are also an equally significant source of carbon dioxide (CO_2) emissions. According to USGBC (2007) data, the level of CO_2 emission from commercial and residential buildings alone accounted for 39% of total CO_2 emissions of US and amounted to 2226 mil. metric tonnes in the year 2006. The use of electricity for heating, cooling, lighting, appliances contributes to this CO_2 emission from buildings.

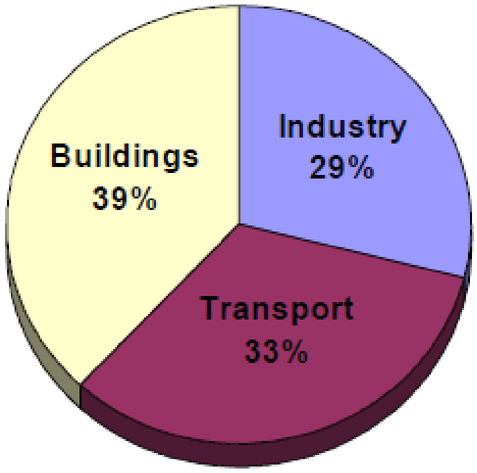


Figure 1.4 : CO_2 emissions of major sectors from fossil fuel in 2006 (USGBC 2007)

Attaining substantial drop in energy and CO_2 emissions in the building sector plays a major contribution to world sustainability. Constructing buildings which are energy efficient and with low CO_2 emissions is a challenge for architects and engineers.

1.2 Building sector and Sustainability in Dubai

Among the GCC countries, UAE takes the second place next to Saudi Arabia in terms of number of projects planned or underway (Figure 1.5). UAE is one of the fastest growing countries in the world and its construction sector is booming and back after the recession, looking forward to host the prestigious World Expo 2020. The forthcoming Expo 2020 is one of the largest event held once in 5 years and a prestigious event participated by the global community sharing innovations and issues of international significance like life quality, economy and sustainability. This expo will run for 6 months from October 2020 to April 2021 and will be the first one to be held in the Middle East, North Africa, and South Asia region projected to attract 25 million visitors (Milne 2014). According to MEED data, the infrastructure needs for this expo will boost construction industry. The basic infrastructure for the expo at the 4,380,000 square meter site at Jebel Ali Dubai World Central (DWC) will cost US $ 2-4 Billion. The secondary infrastructure spend will be more than US $ 8 B.

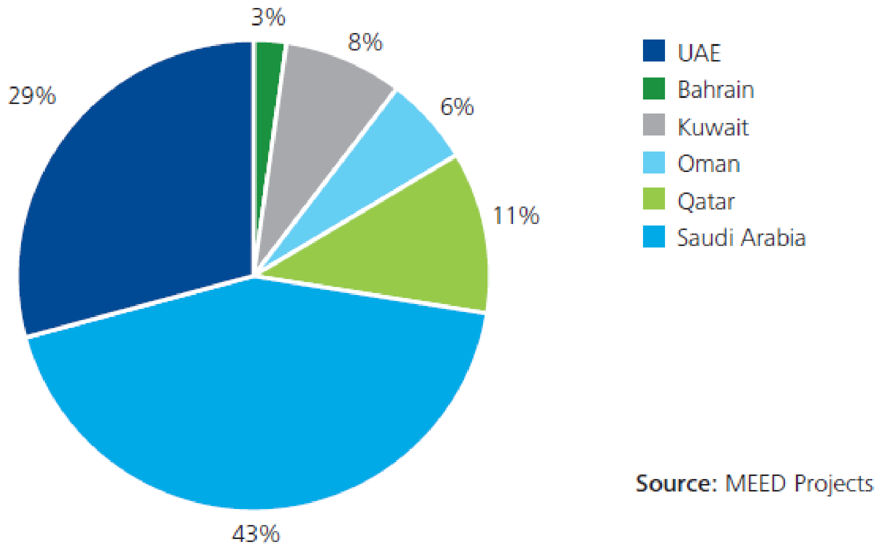


Figure 1.5 : GCC Projects planned or underway as on febraury 2013 (Deloitte 2014)

Middle East Economic Digest (MEED 2014) estimates the total value of projects planned or underway in UAE at US $ 727 B as on April 8, 2014 which is more than 9% of the value , a year ago. According to Dubai chamber base data, the construction sector outlook is on the upward trend and in year 2021 (Fig 1.6) and its contribution to UAE GDP will be 11.5%.

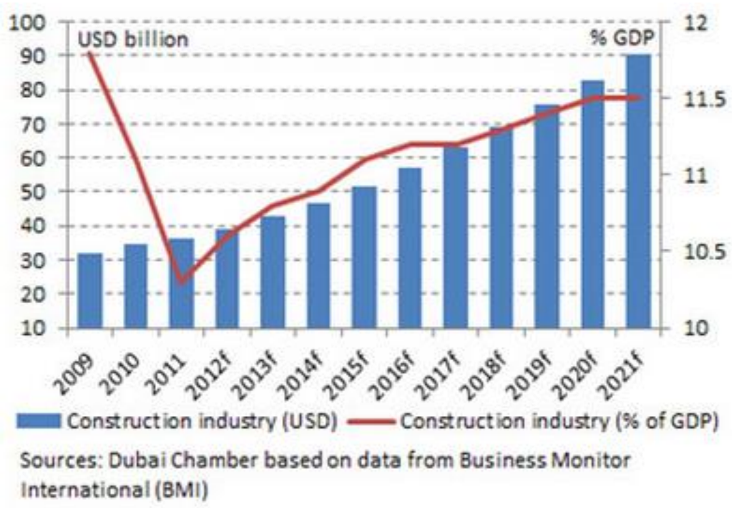


Figure 1.6: Construction Sector outlook in United Arab Emirates

(DCCI 2012)

Figure 1.7 shows the sector wise spend as on April 2014 by the construction industry. It can be seen that the mixed use has the maximum spend of 36% followed closely by 33% of commercial sector. United Arab Emirates outlook 2014-15 report published by Samba Financial Group SFC in June 2014 shows that the retail sector contributes 1.2% to the country's GDP growth which is quiet significant compared to other sectors (Figure 1.8).

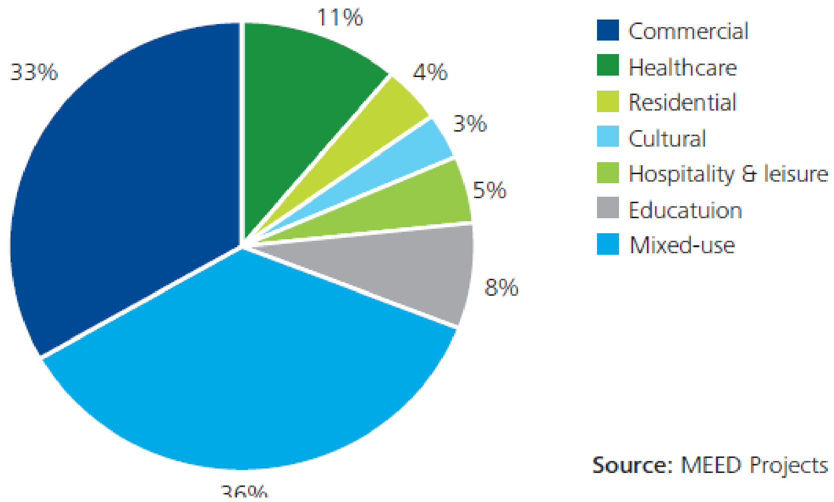


Figure 1.7 : Construction spend per sector as on April 2014 (Deloitte 2014)

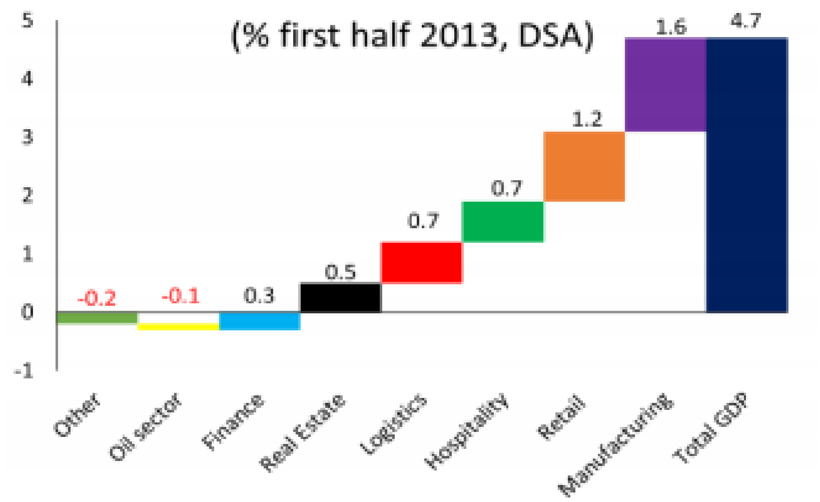


Figure 1.8 : Breakup of sector wise contribution to GDP growth in Dubai (SFG 2014)

The growth of the retail sector is supported by numerous factors such as population growth, growing wealth of residents, tourist inflow etc. According to data provided by Jones Lang LaSalle (JLL 2013), an estimated 2.16 million sqm of retail space is available in Dubai as of 2013 and a further 347000 sqm is due by 2015. The number of shopping malls are under construction or in design stage.

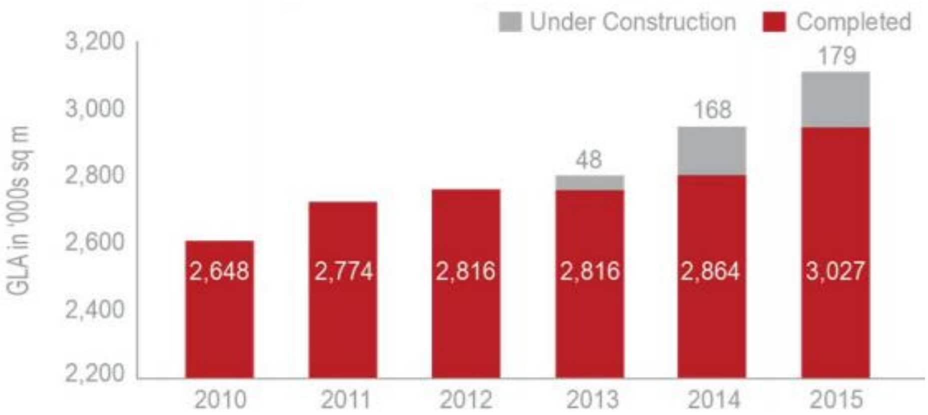


Figure 1.9 : Growth of retail sector in area 2010-2015 (JLL 2013)

By year 2020, to cater to these growing number of shopping malls and other developments and the 25 million visitors expected for Dubai Expo 2020, the electric consumption is likely to reach 9.6 gigawatt. That is almost a 50% jump from 2012. To meet this huge demand, Dubai needs to produce more electricity and reduce its consumption. Dubai Electricity and Water Authority (DEWA) has taken up expansion schemes of value AED 20 B (US$ 5.5B) to increase its power generation capacity. Further Dubai plans to diversify its energy source by 2030 (Figure 1.10) with nuclear energy 12%, clean coal 12%, renewable energy 5% and gas 71%.

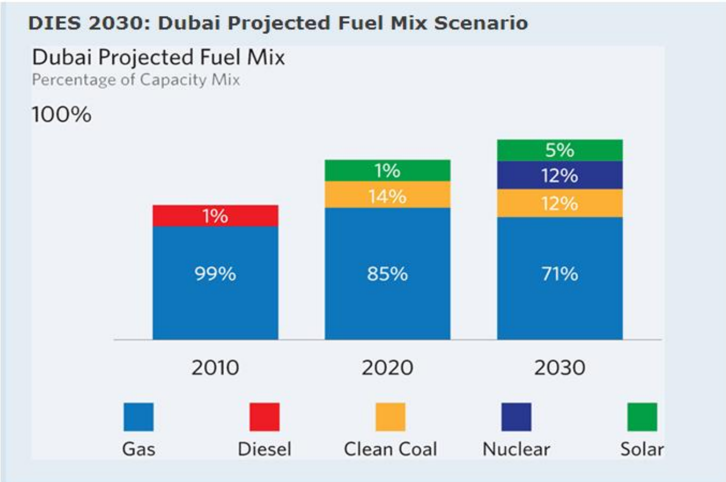


Figure 1.10 : Dubai projected fuel scenario (DSCE 2013)

In spite of all these ambitious plans, Dubai needs to cut down its energy consumption to meet the challenge of growing energy demand. The growing number of shopping malls in UAE consume a lot of energy for their lighting and cooling. If the energy consumption of these malls could be reduced by proper planning in their design, it will be a significant contribution to sustainability in the country.

1.3 Atriums and Sustainability

Atrium is an enclosed glass roofed area in the center of a building and used as an architectural feature in a number of commercial, institutional buildings around the world. It connects the interior to the open outdoor environment but at the same time provides protection from the harsh extreme climate of the exterior. It not only provides an informal social meeting place but also brings in sunlight, warmth, thus bringing cheer to the people inside an enclosure. The oxford dictionary describes Atrium, a Latin word as an open-roofed entrance hall or central court in an ancient Roman house. It was open to sky and had a shallow pool to catch rain water. (dictionary.com nd). Hence the atrium has had its origin from an entrance hall with an open to sky roof and has now developed into enclosed glazed area. An atrium should be constructed not only for spatial and visual reasons but also the energy and environmental aspect has to be considered.

Nowadays, a number of hotels, shopping malls, office and institutional buildings are built with an atrium in the center. The architects incorporate atrium in their design for various reasons. It could be purely for aesthetic reasons or for spatial function where it serves as a sociable meeting place or for environmental reasons where it connects the interior to the outdoor or for energy considerations bringing in sunlight thus reducing lighting energy consumption. A properly designed atrium can increase the building's efficiency.

It should be remembered that when the atrium brings in free sunlight, it also brings in thermal heat along with it. While more daylight decreases energy consumption in lighting, it increases or decreases the indoor air temperature, thus increasing the cooling load or heating load of the building respective to the climate zone it is located. A properly designed atrium can increase the daylight performance by reducing the need for artificial lighting and increase the thermal performance by reducing the cooling/heating load. Balancing the daylight performance and the thermal performance increases the efficiency of the atrium. But if not properly designed then the natural light coming inside Atrium will not be utilized efficiently and it will increase the cooling load in tropical climates or increase the heating load in cold climates. But if designed efficiently, they will not only be an aesthetic feature in buildings but also one of the main sustainable feature.

1.4 Research Motivation

Most of the new buildings constructed, be it public, recreational, educational or even residential, whether high rise or low rise try to have an atrium as one of its key architectural features. If this feature – Atrium, is designed properly it can increase the building's efficiency. Efficiency meaning the thermal performance and the daylight performance of the building.

Dubai being one of the best shopping destinations of the world, this research focusses on shopping malls in the city of Dubai. An overview of buildings in UAE, established that almost all the shopping malls had an atrium as one of their design feature. As discussed in the previous section, if designed properly they will not only be an aesthetic feature in shopping malls, but also become one of the main sustainable feature reducing the total energy consumption to a great extent. If all the upcoming malls are designed to incorporate an efficient Atrium with some basic standards, the saving on the total energy consumption in UAE will be significant.

Hence a research to examine the basic standards to be adopted in the construction of atrium in malls, increasing the building's efficiency becomes necessary. Having some basic standards will motivate the designers and builders to easily incorporate this feature in their designs in an efficient way, while they will also be aware of the percentage reduction in energy they are contributing to with their design. The study should examine the parameters that influences the atrium's performance and arrive at optimal values for each parameter. The natural day light coming inside the building through the Atrium will not only open the enclosed space of the building to nature but should efficiently reduce energy consumption with lesser artificial lighting and it should also avoid un-necessary heat gain. Motivated by the above factors, a real life scenario of an existing atrium in Dubai is taken up and it is critically examined to find out the amount of energy that could be saved by an appropriate atrium design.

1.5 Research Aims and objectives

The aim of this research is to investigate on the factors affecting the efficiency of the atrium and to find optimal values for the different variables. The question developed for further research is**,** what are the factors that increase the efficiency of atrium, efficiency meaning optimization of daylight penetration and thermal performance in terms of energy consumption. The question is applied to a real life case, an atrium in Dubai, United Arab Emirates. This research tries to set some standards for atrium design that would help the designers in their design of atriums in hot arid climatic zone.

The objective of this research project is as follows:

- To identify the factors / variables that influences the daylight penetration and affects the thermal performance of the building.
- To study an existing shopping mall and examine its present performance in terms of total energy, cooling, dehumidification and lighting load.
- To apply different parameters for each variable and investigate on the effect of these factors/variables on atrium efficiency.
- To identify the optimum value for each variable that can be incorporated for an efficient atrium design and to investigate the amount of reduction in total energy consumption if these optimal values are applied together.
- To identify the most important variable the designer has to look into, to achieve efficiency.
- To facilitate the designers and builders by providing optimal parameters for each variable and set some basic standards in the design of Atriums in hot arid climatic zones.

An efficient atrium in a shopping mall building saves on the total energy consumption of the building and plays a significant role in the total savings on the energy consumption of United Arab Emirates. Thus this research aims to contribute to the sustainability of this region.

1.6 Dissertation structure

This Dissertation is organized into Six chapters. Chapter 1 introduces the significance of the building sector in sustainability and the sustainability scenario in the building sector in Dubai. It overviews how Atriums contribute to sustainability. Further, it also discusses on the research motivation and establishes research aims and objectives.

In Chapter 2, a literature review is conducted with previously published papers and resources on Atrium mainly, to study the history of Atrium, to study the characteristics of Atrium and to study the variables tested by other researchers impacting the efficiency of Atrium.

Chapter 3 deals with research methodology in which methodology used previously to conduct similar studies are noted and a methodology is selected and justified. Further, a research plan is developed, bearing in mind the practicality of conducting the research. Also the resource requirements for the research is identified and the software to be used for this analysis is validated. The variables to be tested in this study is also established from the previously conducted literature review.

Chapter 4 focuses on base case model wherein an existing shopping mall in Dubai is selected. This chapter explains the construction of virtual base case model with materials and working profile as on site and simulation of this model and the models with altered variable. Each variable case by case is analyzed to reason the change in building's performance and establish optimal parameters for each. This chapter also explains how the final energy consumption is calculated by the used software tool. This helps to reason the energy performance changes of the building.

Chapter 5 discusses the optimal case modeling and data analysis. It compares the simulation results of optimal case and base case. Energy performance of the building is analyzed and the percentage reduction in energy that could be achieved by applying together all optimal values is reviewed.

Chapter 6 concludes the research by highlighting the main findings. Recommendations for an optimal Atrium in hot arid zone is provided based on the findings and also recommendations for future study on Atriums is suggested in this chapter.

Chapter 2

Literature Review

Chapter 2 : Literature Review

In order to develop the research question further and to find out the methodology suitable to arrive at a solution, a literature review was conducted.

The literature review is done with 4 objectives;

1. to study the history of Atrium,
2. to study the characteristics of Atrium,
3. to study the variables impacting efficiency of Atrium from previously researched papers,
4. to study the methodology used for research in the various published papers.

The previous published research papers on Atrium were searched for, from the online journal resources available through the British university library and from internet resources. The search was done with the key word 'Atrium' combined with subsidiary words such as 'Daylighting', 'Thermal performance' 'Ventilation', and 'Simulation' etc. The search was limited to peer reviewed journals. Mainly the papers were from scientific journals such as Building and environment, Energy & Buildings, Lighting Research & Technology, Energy and environment, Environment International, International Journal of Energy Research, International Journal of Low Carbon Technologies, and Solar Energy. Numerous papers nearly 75 in number were extracted, studied, their abstracts reviewed and the papers were shortlisted for review.

Published books, handbooks were also reviewed for useful information. Atrium Buildings, Design and Development by Saxon,R published in 1983, cited by 110 authors as on 15 october 2014, Design Principles of Atrium Buildings for the Tropics by Ahmad.M.H, SLL lighting handbook were some of the reviewed books.

Literature review on history, characteristics and efficiency of atrium will be done in this chapter and the review on methodologies used by various authors will be done in chapter 3. Following are the observations from the literature review.

on Chronological and Topical basis :

The oldest published peer reviewed paper on Atrium which could be obtained from this search is in the year 1984 by Navvab M. and Selkowitz S presented in the ninth national passive solar conference at Ohio, US. The research is supported by the U.S

Department of Energy. This paper 'Day lighting data for Atrium design' focuses on the atrium characteristics such as geometry, orientation, interior surface treatments and glazing systems and how they can influence the admittance and distribution of sunlight and solar gain.

At present, 3 decades after the first published paper, numerous papers on the topic Atrium have been researched and published. The first decade from year 1984 to 1993, very less number of papers (only 2 from this search) were published which mainly dealt with the topic of day lighting. In the second decade 1994 to 2003, the number of papers increased considerably (17 from this search) and they mainly dealt with the topic of day lighting as well as simulation techniques. There was even 1 paper published in 1998 which is a review of papers published on prediction methods for atria illuminance. The third decade 2004 to 2014 saw a maximum number of papers, (54 from this search) dealing with day lighting, ventilation, simulation techniques and thermal performance. 5 review papers (from this search) were published in this decade dealing with daylighting (2), ventilation (1), simulation techniques (2).The above observation is from the results of this search only. This shows that the awareness on sustainability has increased tremendously and atrium as a means to implement sustainability in a building and reduce energy consumption has increased with the designers and clients and hence, research interest on this topic has grown tremendously.

on the basis of region :

The collected papers were also analyzed on the basis of the region from where the research were conducted. It is observed that mainly the researches were done in UK, Canada, China, US, Malaysia, Italy, Sweden and Korea. Australia, Brazil, Singapore, Slovenia, and the Middle eastern countries such as Dubai, Jordan, Saudi Arabia, Qatar, Turkey had a very minor contribution of papers. It is observed that very few researches were conducted in the Middle eastern region or we can say, hot arid climates. In the Asian region, there are a few researches conducted in the hot humid climate of Malaysia. Mostly the researches are done in the cold climates with overcast sky conditions not with clear sky, hence proving the need for research to be conducted in the hot arid climate of the Middle east with clear sky conditions.

Following sections discusses the results of the literature review conducted.

2.1 History of Atrium

Atrium is a generic building form which has evolved over centuries. Saxon in his book Atrium Buildings, Design and Development published in 1983, states that atrium is a 2000 year old idea. This ancient roman Atrium has developed into an enclosed glazed area in the modern times. Atrium is a latin word with first known use in 1557 (Merriam-Webster).

The original word 'Atrium' should not be confused with the word 'Courtyard'. Though they serve the same function of bringing light and ventilation inside a building and act as social gathering place, the atrium is a large room with a roof opening at its center while courtyard is open to sky space around which the building is constructed (Fig 2.1). Both Atrium and courtyard have rooms arranged around it. The plan of the ancient roman house shows that they had an atrium near the entrance and a courtyard called 'Peristylum' at the rear of the house. (Fig 2.2)

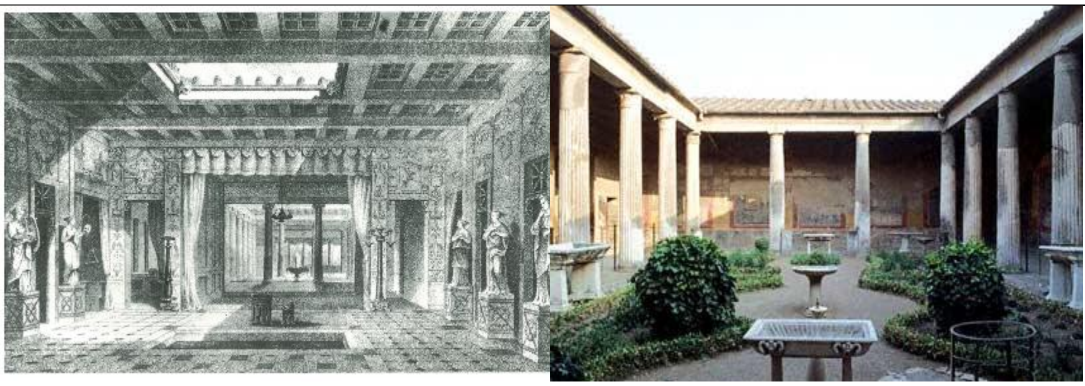


Figure 2.1 : Interior view of the rich Roman house, Domus.

a) Atrium of a roman house – a central hall with roof opening at the entrance (Saxon 1983)

b) Peristylum at the house of Vetti, Pompei - an open courtyard within the house (BBC 2011)

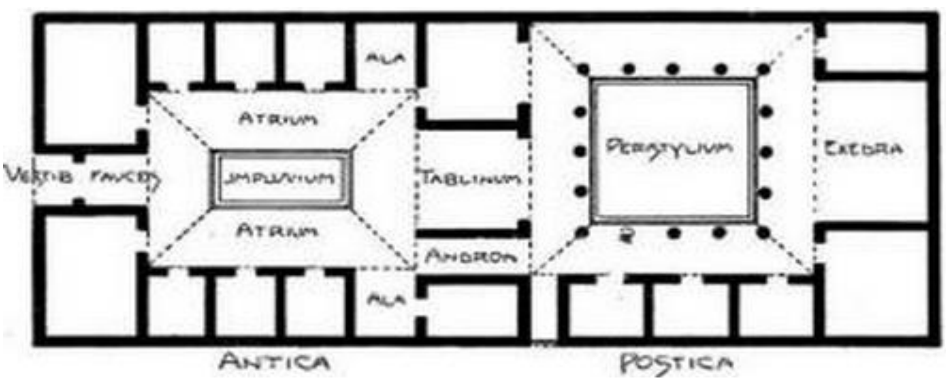
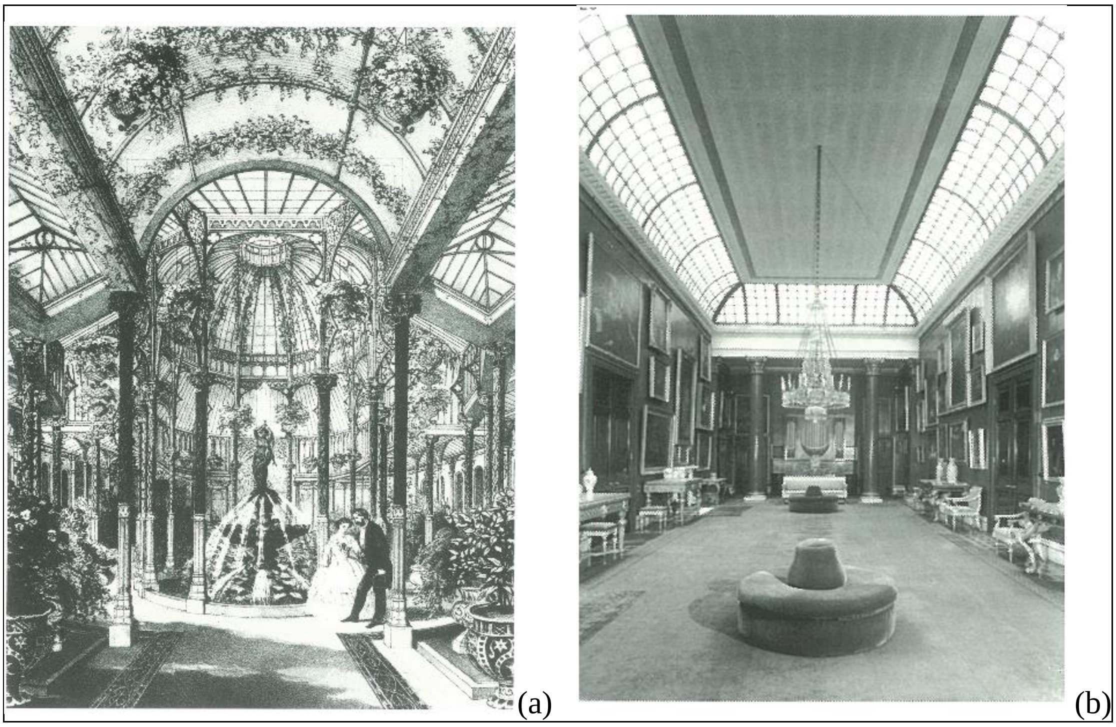


Figure 2.2: Plan of a house - Domus in pompei, Ancient Rome (History on the net 2014)

Origin: The origin of atrium is of the 2nd century AD roman times. It is a central hall at the entrance of the rich roman house 'Domus'. The center of its roof was open to sky and had a shallow pool called an 'Impluvium' to catch rainwater. It served as an imposing entrance area with arrival focus or a focal court around which rooms were arranged with circulation focus and they acted as a semi-public area where people gathered (History on the net 2014).

Over the centuries, within the restrictions of materials available at that period mainly masonry and timber, it developed into a central concept in Mediterranean and Middle eastern architecture. Later during industrial revolution glass and iron technology was added to this and the simple atrium developed into covered courts, arcades, galleria and winter gardens (Saxon 1983).

19th century : In early 19th century green houses were constructed which utilized the solar heat coming inside the building but not passing out easily to achieve temperature change inside. Central heating allowed these glass houses to work all year round and people began include this in conventional buildings as conservatories (Fig 2.3a).



(a) (b)

Figure 2.3 : 19th century buildings in England with skylight (Saxon 1983)

a) A conservatory built in 1855 b) John Nash's Attingham park,Shropshire,1806

These glass house buildings had a distinct influence on atrium concept. Architects merged this glass and iron technology with conventional courtyards to create well lit interiors. In1806, John Nash constructed one of the first modern atrium at Attingham park, Shropshire to lit an interior of a picture gallery (Fig 2.3b). Glass roofed cortile (courtyard) at Reform club, London built by Sir Charles Barry in 1837 (Fig 2.4) is considered one of the first true atria. (Saxon 1983)

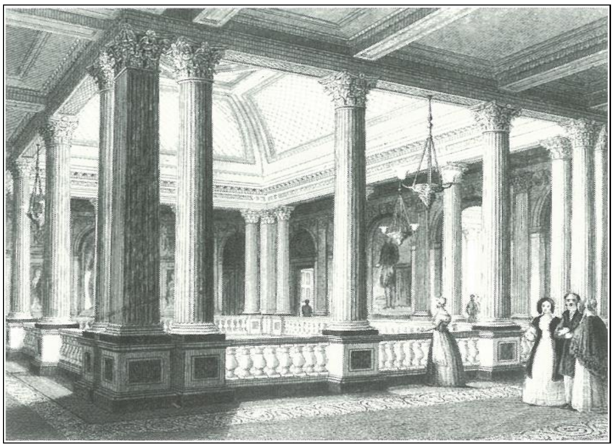


Figure 2.4 : Sir Charles Barry’s Reform club, London, 1837 (Saxon 1983)

The galleria at Milan by Mengoni 1867 (Fig 2.5) is an arcade with shops on ground floor and offices on the above 3 floors emerged as an intriguing design for shopping arcades worldwide.

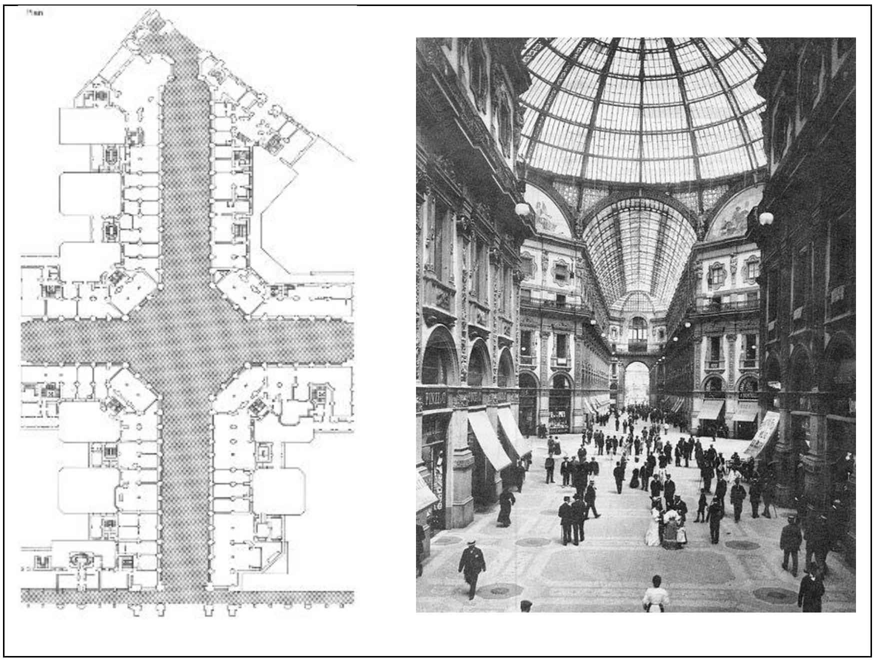


Figure 2.5 : Plan and view of The Galleria, Milan, 1867 (Saxon 1983)

20th century: In the early 20th century, the interest of atriums waned and was revived again in the 1960's. John Portman's Regency Hyatt Hotel in atlanta, Georgia (Fig 2.6) built in 1967 was recognized instantly and had a great influence on the future design of atriums.

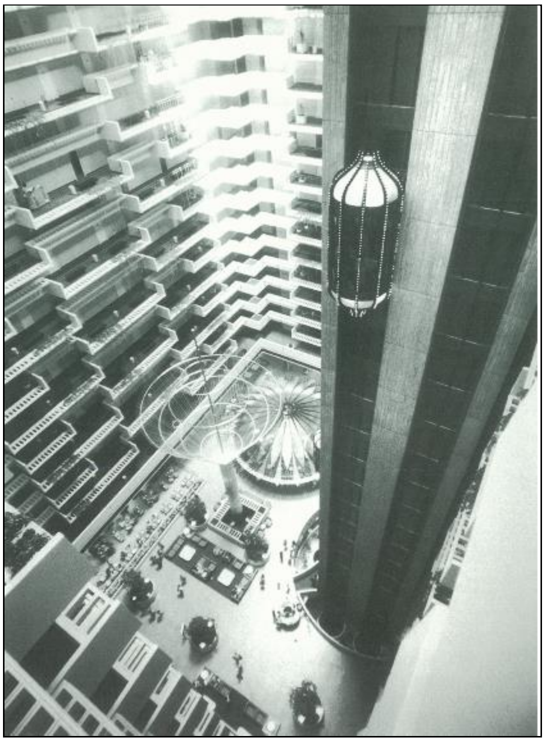


Figure 2.6 : 20th century - Hotel Regency Hyatt, Atlanta, Georgia, 1967 (Saxon 1983)

In 1980's the atrium design developed in its richness with technological advances and the mainstream commercial developments around the world started adapting atrium and galleria in their design.

21st century: Atrium is a popular design feature now because of its social and economic values and technical feasibility. With the awareness of energy savings and passive design among the architects and builders, the future of retail atrium is bright and will be improved both in technicality and in style.

An analysis of shopping malls in Dubai shows that almost all of them include atrium as a feature. Below in Figure 2.7 A-F is shown, pictures of interior of some of the popular malls in Dubai.

[A] Mall of the Emirates

[B] Burjuman Center

[C] Mercato Mall

Figure 2.7 [A-C] : Interior photos of popular shopping malls in Dubai

[D] Dubai Festival City Mall

[E] Wafi Mall

[F] Dubai Mall

Figure 2.7 [D-F] : Interior photos of popular shopping malls in Dubai

It can be seen that these malls have utilized atrium either for aesthetic reasons to open the interior to nature or to increase their corporate retail image or for sustainability factors to bring in sunlight and reduce energy consumption during day time. Whether these atriums are effective in reducing the energy consumption is a matter to be analyzed.

2.2 Characteristics of Atrium

2.2.1 Form and Function

Saxon (1983) in his book classifies the simple generic forms of atrium. These forms are defined by the number of sides, the atrium abuts the building namely, one sided, two sided, three sided, four sided or enclosed and linear atriums as can be seen in Figure 2.8 below.

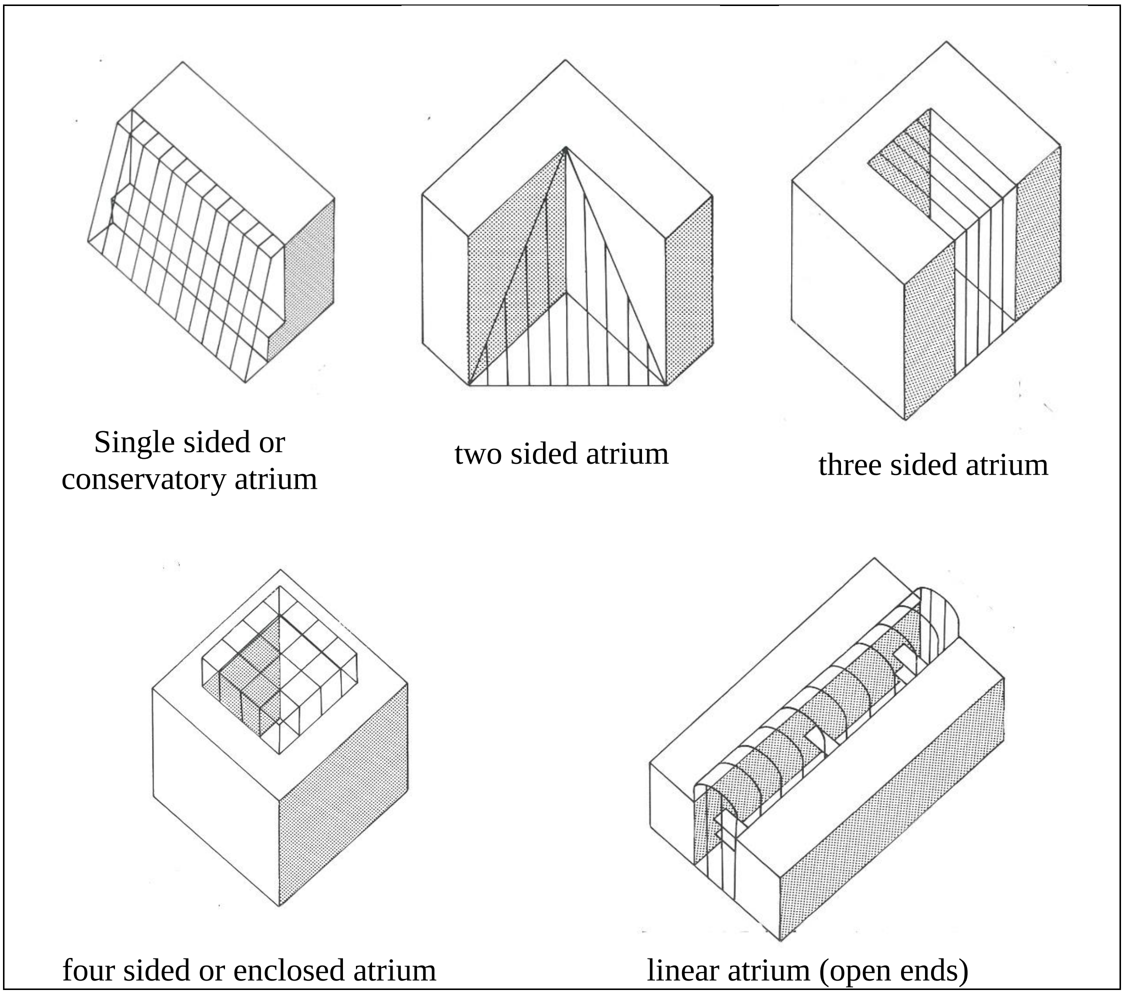


Figure 2.8 : Simple generic forms of Atrium (Saxon 1983)

These simple forms are suitable for a small building as well as large complexes. The most common form is the four sided or enclosed atrium which is found in deep plan buildings to allow daylight into the core of the building.

The Roman atrium served as an arrival space at the entrance where people could meet before entering the other rooms. It served as a place where the wealth and status of the rich romans could be displayed. It provided natural light and ventilation for the rooms, since mostly the outer wall of the house had no openings. Today, the glazed atriums with technological advances serves greater purposes and has become a popular feature of passive design in buildings. Ahmad & Rasdi (2000) in their book, Design Principles of Atrium Buildings for the Tropics gives some interesting reasons for the development and function of atriums in shopping malls.

Social aspects:

- Atrium is a focal point of a building and it defines the space organization and circulation.
- It adds a corporate retail image for a shopping mall without which it will be considered ordinary.
- Retail spaces has a perceived need for special interior design and atriums uplifts the interior ambience and becomes a marketing strategy.
- Atrium space opens nature to the closed interior space, thus uplifting the moods of the people inside, but at the same time it protects them from the harsh weather outside.
- It is a private space for the building users where they can connect with nature without being observed by outsiders.
- It acts as an entertaining and a connective space.

Economical aspects :

- It brings in natural sunlight, thus reducing the need for artificial lighting during day time and helps in reducing energy consumption, thus reducing the utility bill. If the amount of sunlight entering the building is optimized, then the cooling / heating load of the building could be reduced, thus again reducing the utility bill. Hung & Chow (2001) state that a well designed atrium will require only about one half to two thirds of that required for other buildings.

- However if the atrium is not designed properly, there will be an additional cost for cooling the large volume of atria which has a direct solar heat gain.
- Doiron, Shilling & Sirmans (1992) state that the market value or the rental value of buildings with atriums, tends to be higher and it attracts major retailers.

Saxon (1983) illustrates with an example in his book, Atrium Buildings, Design and Development that the atrium as a daylighting device can be used to cut down the utility bill of the buildings. In 1978, Bullocks departmental stores in Oakridge mall, San Jose, CA (Fig 2.9) has used atrium as a day lighting device par excellence and saves $18000 per annum as of the year 1983. A fabric made with Teflon coated glass fiber which is 16% translucent as one layer and 7% translucent as 2 layers and roofs the 18000 sqft central court. This limited translucence allows adequate light level to the courtyard and the adjoining spaces and also resists heat gain and reflects the artificial light efficiently at night.

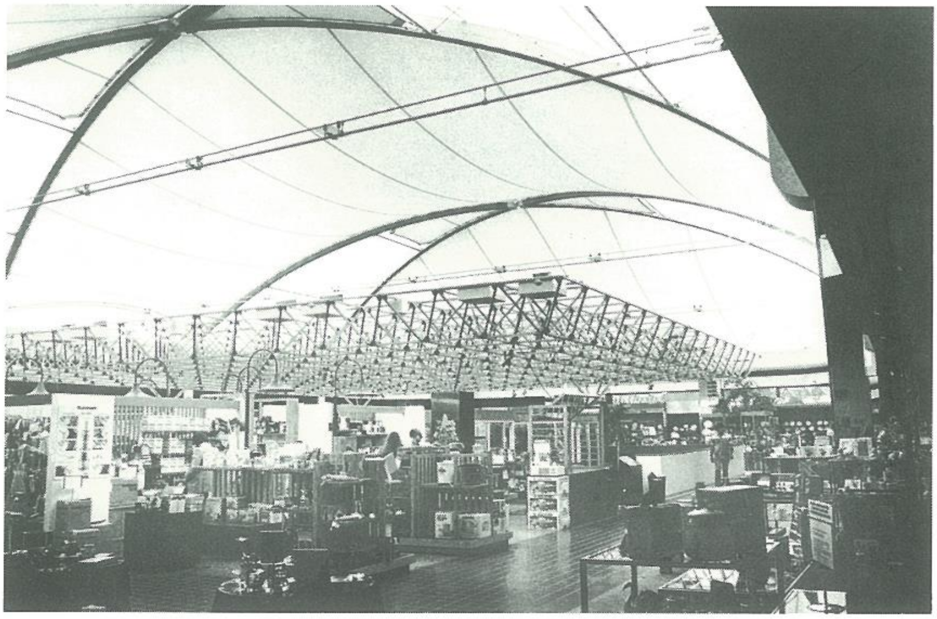


Figure 2.9 : Atrium as a daylighting device in 1978 in Oakridge mall,CA (Saxon 1983)

In a study conducted by PG&E in 1999, it is seen that an atrium can be used for social and economical aspects. 108 stores, twothirds with skylights and one third without skylights, operated by large chain retailers were selected and their retail sales performance compared. Except for the skylights the store were alike in their interior design, merchandise, management and advertising all handled by their head quarters. Variables that had significantly effected the sales performance was statistically analyzed by regression analysis. The variable found to be significant by the researchers were skylighting, number of hours the store was open, the population in that area, average income of that population and the number of years since the store had been remodelled. Out of these 5 factors, the largest impact was by skylighting which boosts the sales by 40%. To explain, if \$20/m2 is the average sales of a non daylit store then the sales was expected to increase to \$26-30/m2 if skylight was added. The researchers concluded with statistical analysis that this is a 99.9% certainty. The study concludes that skyighting offers a huge competitive advantage to retail outlets by attracting customers and boosting sales performance (Ahmad & Rasdi 2000).

Environmental aspects:.

- Atrium is a key component of a sustainable, environmental approach to architectural design. A controlled lighting of atrium is a source of natural light for deep plan buildings in addition to other environmental benefits in terms of solar gain (useful in cold climates), reduced energy losses and natural ventilation. (Sharples & Lash 2007)
- The reduction in day lighting, cooling load and energy consumption, leads to less fuel usage and less CO_2 emission thus contributing to a sustainable environment.

2.2.2 Atrium responsive to the local climate

Further, in their book Ahmad & Rasdi (2000) warns that some designers have an idea that the use of atrium in a building spontaneously leads to energy efficiency. The atrium design can be successful only if it is responsive to the local climate. In the cooler climates, the atrium is designed to bring in more sunlight into the building and trap heat inside and reduce its heating load. But in the tropical regions the designers should be careful in bringing the optimum amount of sunlight inside, so that the building does not get overheated, which will then require additional mechanical cooling to achieve a comfortable temperature inside (Fig 2.10). A wrongly designed atrium can lead to higher energy consumption and therefore will fail to meet the basic environmental purpose of the atrium (Ahmad & Rasdi 2000).

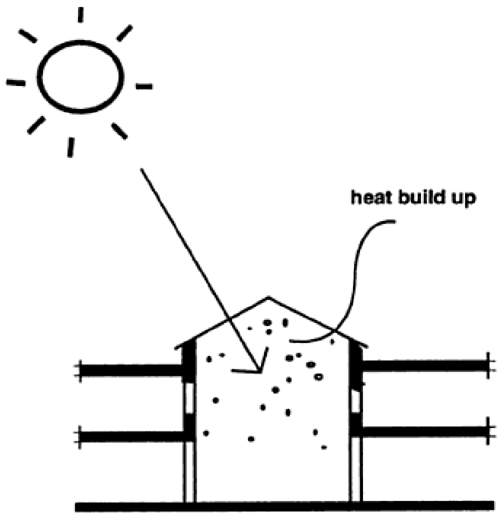


Figure 2.10 : Atrium to bring in optimum sunlight to avoid heat build up inside (Ahmad & Rasdi 2000)

The sunlight penetrating into the glazed courtyard of the atrium provides daylight but at the same time it allows direct solar heat gain and traps the heat inside. In a tropical region with high external air temperature, the atrium temperature can rise to undesirable levels as shown in Figure 2.11. So measures should be taken to minimize solar heat gain and maximize heat losses. Many passive techniques such as control of solar heat gain, optimum daylight from sunlight to reduce heat load from electric lighting, use of thermal mass etc could be applied

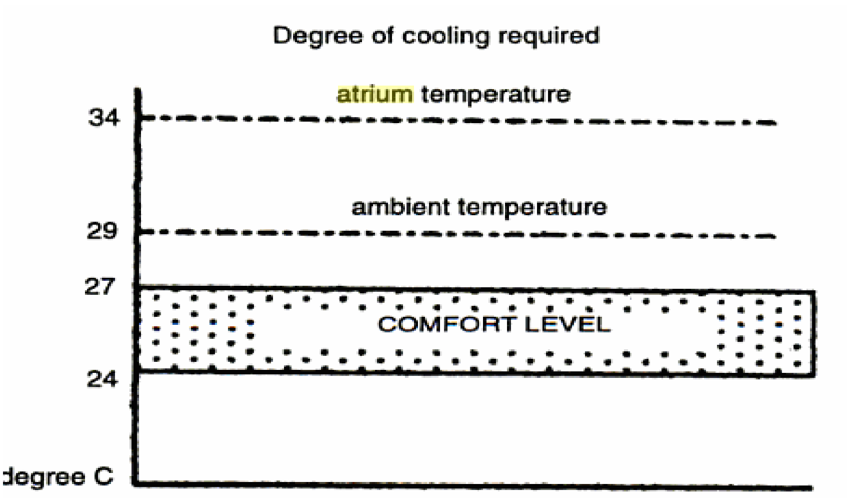


Figure 2.11 : Degree of cooling required in warm humid condition

(Ahmad & Rasdi 2000)

Pan et al. (2010) also points out that in tropical climate, extreme solar radiation passing through the glazed atrium can worsen interior thermal climate. Baharvand et al. (2013), note that in hot climates over heating reduces the thermal comfort and becomes a major problem.

Application of western principles of atrium design without any adaptation to the local context of climate and high irradiance levels in countries such as Malaysia and Middle east will lead to more energy consumption. Unlike the atriums of the temperate climate, in the tropical countries the atrium should function as a cooling device (Fig 2.12).

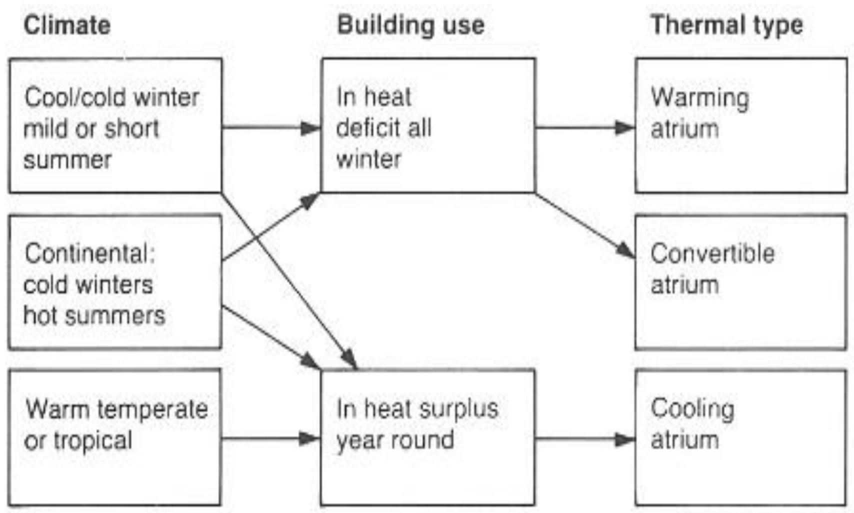


Figure 2.12 : Thermal type selection of Atrium (Saxon 1983)

The basic character of a cooling atrium should be the reverse of warming atrium. The cooling atrium should protect against hot outside air, high temperature, high humidity and strong sunlight. Direct sun should be avoided and glazing should be polar oriented. In humid climates where cultures allow thermal comfort achieved by cross ventilation, the atrium can induce cross ventilation by stack effect, wind scoop and solar chimney. Bur most are built with complete air conditioning. (Saxon 1983)

From the literature surveys, it could be noted that daylight penetration and thermal performance are 2 important aspects that should be taken care of in atrium design.

2.2.3 Day light performance:

Daylighting is bringing in natural sunlight into the buildings using skylights and windows (EERE 2013). The day light available in different regions will vary during different time of year and day as can be seen in Figure 2.13. (SLL Lighting Handbook 2009)

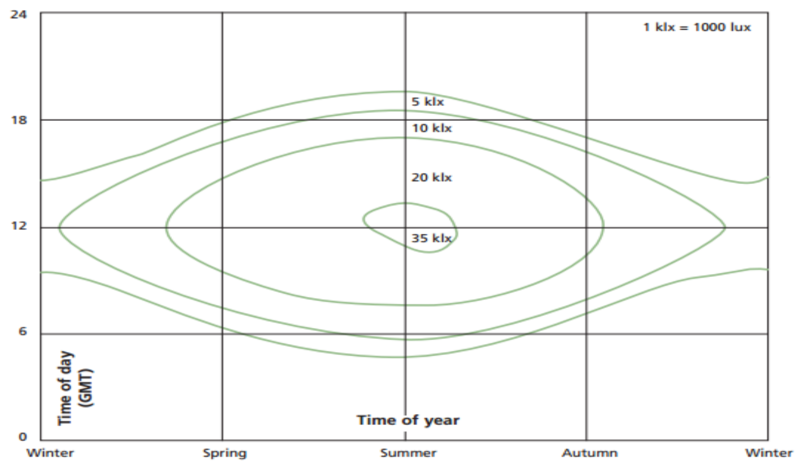


Figure 2.13 : A typical daylight chart (SLL Lighting Handbook 2009)

The measure of natural daylight in a space is expressed as daylight factor (DF) in percentage (SLL Lighting Handbook 2009). 3 components make up the daylight factor, DF (Fig 2.14). They are the (i) SC sky component - direct component from sky, (ii) ERC externally reflected component - reflected light by buildings, trees, ground etc, and (iii) IRC, internally reflected component - reflected internally in room surface.

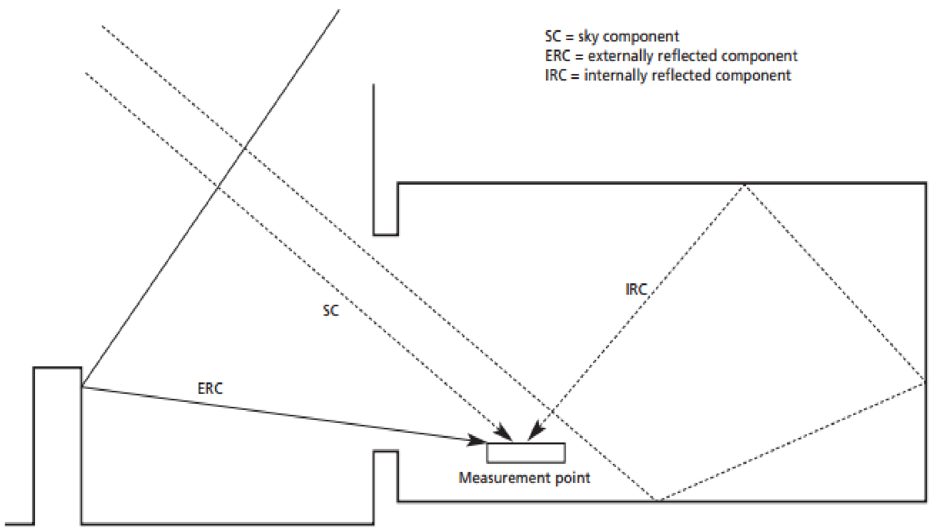


Figure 2.14 : Daylight factor components (SLL Lighting Handbook 2009)

$DF = SC + ERC + IRC$ ……………………………………………………….……..[2.1]

Wherein, SC is sky component, ERC is externally reflected component, IRC is internally reflected component.

Day light factor is also a ratio of internal illuminance at a given point to the external illuminance. It is schematically illustrated in Figure 2.15.

$DF = (E_{in} / E_{ext}) \times 100$ ………………………………………………………..[2.2]

Wherein, Ein : Interior illuminance at a fixed point on the work plane and Eext : Exterior illuminance under an CIE overcast sky.(SLL Lighting Handbook 2009)

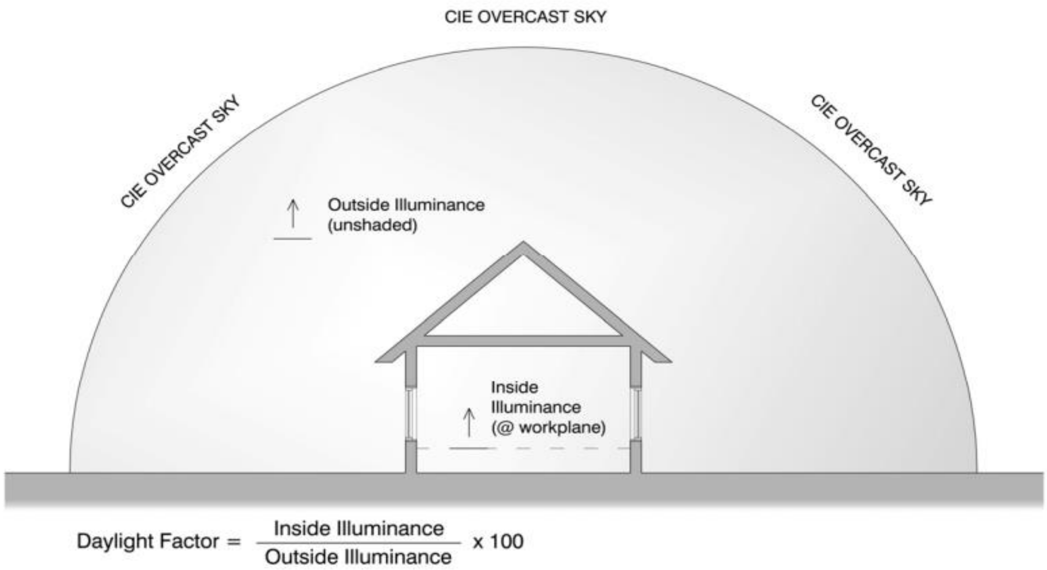


Figure 2.15 : Daylight factor (Otis and Reinhart 2009)

DF 2% means daylight at an interior point is 2% of outdoor light available. So if outside light available is 10000 lux, then interior day light will be 200 lux. (Robertson 2003).

The amount of daylight obtainable within a building will be determined by geometry and location of windows and roof lights. In UK, windows facing south will have higher values than those facing north. Corrections for window orientation can be applied by multiplying the daylight factor by a weighting factor to give the orientation-weighted daylight factor. The weighting factors for north, east, south and west-facing windows are 0.77, 1.04, 1.20 and 1.00 respectively (SLL Lighting Handbook 2009)

Illuminance is the luminous flux or the quantity of light falling on a surface per unit area (lumens / sq m) and measured in lux (Figure 2.16)

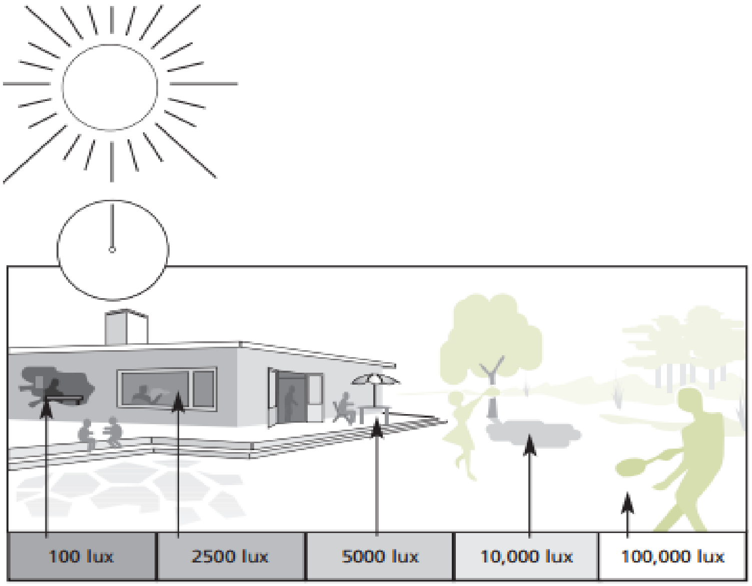


Figure 2.16 : Typical illuminances on different surfaces under the noonday sun in temperate climates. (SLL Lighting Handbook 2009)

Exterior illuminance (E_{ext}) varies with different latitudes. For a particular latitude, we can determine the recommended Lux levels from Autodesk's Ecotect software. (Fig 2.17).

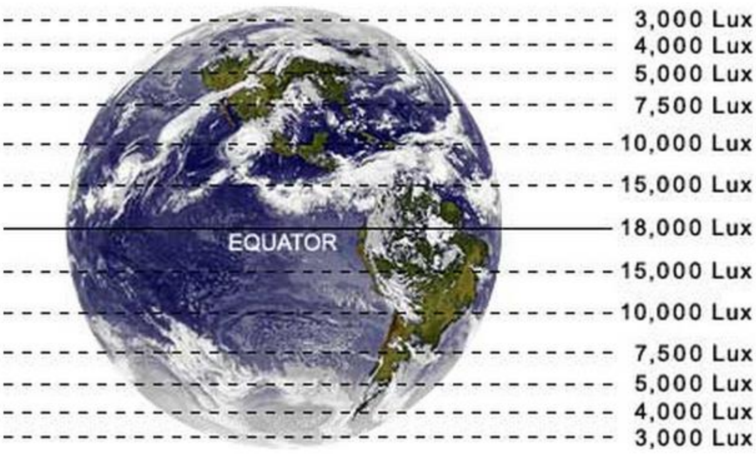


Figure 2.17 : Exterior illuminance at varying latitudes (Luo 2009)

The exterior illuminance of different cities can be calculated using design sky illuminator available online at http://wiki.naturalfrequency.com/files/wiki/daylight/design-sky.swf. The Figure 2.18 below show the design sky illuminance of Dubai and London which lie on latitude 25.27 below and 51.51 respectively. It varies from 9100 to 6500 Lux.

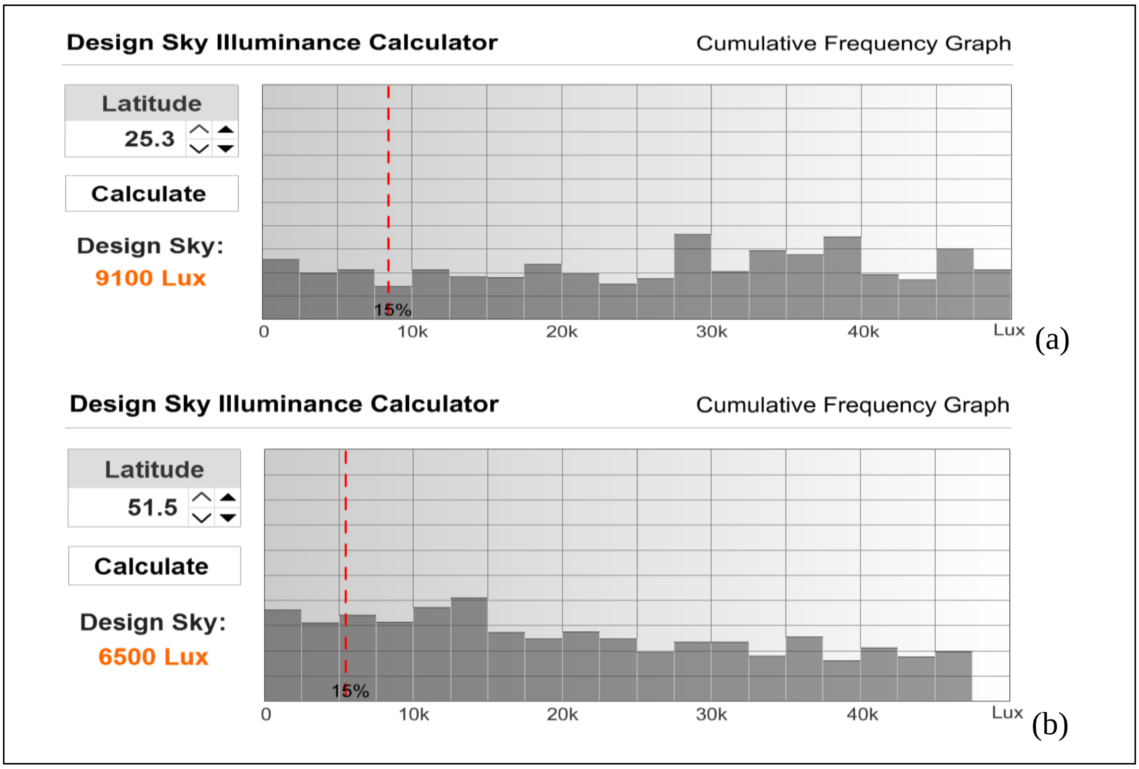


Figure 2.18 : Design sky illuminance a) Dubai, b) London (natural frequency.com)

CIBSE-2002-Code for Lighting recommend the daylight factor and illuminance level for different types of workspaces. Under an standard CIE overcast sky, if average daylight factor of a room is not less than 5%., then the room is strongly daylit and does not need electric lighting during daytime. If below 2%, then the room is average daylit and needs electrical lighting most of the time. It if is between 2-5%, then it is predominantly daylit but supplementary lighting is necessary.

The above method of generalizing the room lighting condition with day light factor is not very accurate. The internal illuminance calculated with same DF under sunny sky and overcast sky will be much different, since external illuminance of sunny sky is much brighter than that of an overcast sky. Kensek & Suk (2011) state that daylight factor must be calculated under CIE overcast sky condition only. In an overcast sky direct light is not taken into account. So this DF mentioned in the above paragraph is most useful only in places with overcast sky as their primary condition such as London but even there a more nuanced calculation might be more appropriate. So the light performance of a room has to be assessed with interior illuminance (Lux) and daylight uniformity rather than Daylight factor.

CIBSE (2002) recommends the level of Interior illuminance (E_{in}) at a fixed point on the work plane which is measured in Lux for different categories of workspaces (Table 2.1) and also for different types tasks (Table 2.2).

Table 2.1: Recommended illuminance level for varying workspaces (CIBSE 2002)

Retail Premises:

Area	Illuminance (lux)	Limiting Glare rating	Minimum colour rendering (R_a)
Sales area	300	22	80
Till area	500	19	80
Wrapper table	500	19	80

Residential :

Area	Illuminance (lux)	Limiting Glare rating	Minimum colour rendering (R_a)
Lounge	100 - 300	19	80
Kitchens	150 - 300	-	80
Bathrooms	150	-	80
Toilets	100	-	80

Theatres, Concert halls :

Area	Illuminance (lux)	Limiting Glare rating	Minimum colour rendering (R_a)
Practice rooms, dressing rooms	300	22	80
Foyers	200	-	-
Auditoria	100	-	-

Offices :

Area	Illuminance (lux)	Limiting Glare rating	Minimum colour rendering (R_a)
Filing, copying etc.	300	19	80
Writing, typing, reading, data processing	500	19	80
Technical drawing	750	16	80
CAD work stations	500	19	80
Conference and meeting rooms	500	19	80
Reception desk	300	22	80
Archives	200	25	80

Hotels and Restaurants :

Area	Illuminance (lux)	Limiting Glare rating	Minimum colour rendering (R_a)
Kitchen	500	22	80
Restaurant, dining room, function room.	-	-	80
Self service restaurant	200	22	80
Conference rooms	500	19	80

Table 2.2 : Recommended illuminance level for varying tasks. (CIBSE 2002)

Illuminance (lux)	Activity	Area
100	Casual seeing	Corridors, changing rooms, stores
150	Some perception of detail	Loading bays, switch rooms, plant rooms
200	Continuously occupied	Foyers, entrance halls, dining rooms
300	Visual tasks moderately easy	Libraries, sports halls, lecture theatres.
500	Visual tasks moderately difficult	General offices, kitchens, laboratories, retail shops.
750	Visual tasks difficult	Drawing offices, meat inspection, chain stores.
1000	Visual tasks very difficult	General inspection, electronic assembly, paintwork, supermarkets.
1500	Visual tasks extremely difficult	Fine work and inspection, precision assembly.
2000	Visual tasks exceptionally difficult	Assembly of minute items, finished fabric inspection.

CIBSE gives recommendations for retail lighting. The retail lighting will include general lighting, accent lighting and display lighting. The illuminance level will be in the range of 500to1000 lux depending on shop profile ranging from budget to exclusive. For budget shops the lighting illuminance could be 250-500 lux while exclusive shops can have general lighting level can be lower at 100-200 lux to highlight the accent lighting. Regardless of the illuminance level, the general lighting should have an illuminance uniformity (min or average) of at least 0.7. (SLL Lighting Handbook 2009)

As explained in the beginning of this section daylight factor is not a very accurate parameter to evaluate good lighting condition. Some of the parameters to assess the daylight performance are building's internal illuminance (Lux level), lighting uniformity ratio.

A good lighting design should achieve uniform distribution of light throughout the room. In deeply planned buildings DF tends to higher near the windows and moderate to poor at the core. Sky lighting can solve this problem by bringing in daylight into the core of the building. As seen from this discussion, an interior illuminance level of 500 Lux is recommended for a shopping mall. The main purpose of Atrium is to bring in natural day light and hence artificial lighting could be used only when illuminance level goes below this recommended level. Sensors could be placed inside the mall to cut off artificial lights when the daylight illuminance level goes beyond 500 Lux. Day light performance will be measured in this research by the amount of light energy required for artificial lighting. Variables such as number of floors, roof profile will have an impact on the amount of natural light coming inside an atrium.

2.2.4 Thermal performance

Thermal performance of a building determines its thermal efficiency. The thermal performance of a building is its performance with respect to the energy transfer between building and its surroundings. Heat transfer is by conduction, convection, radiation and evaporation (Fig 2.19). This energy transfer or heat flow will be determined by building properties such as glazing area, profile and material, surface reflectance, thermal mass, insulation, internal heat source such as number of people, equipment, lighting inside, and ventilation and also the ambient environment such as humidity, air velocity, air temperature outside and solar radiation.

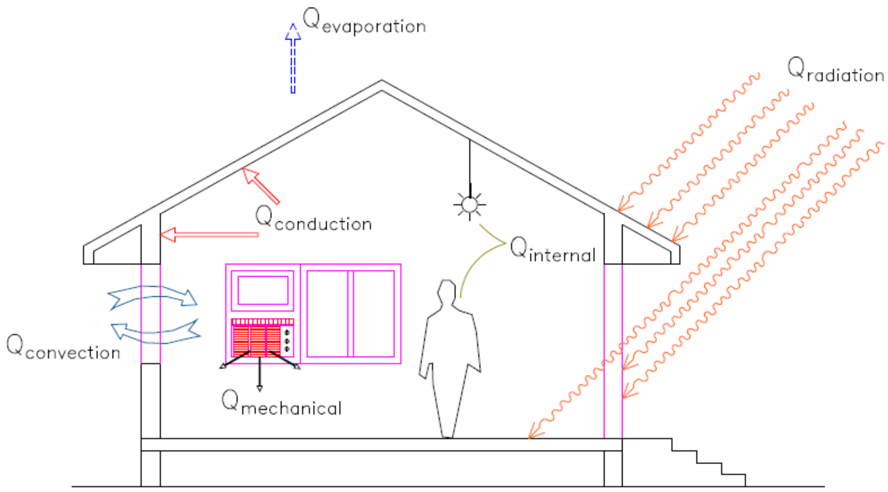


Figure 2.19 : Heat transfer between building and external environment (MNRE 2006)

Estimating the thermal performance with different alternatives for materials and design will help architects and builders to choose justifiable materials and design. It is necessary to calculate the thermal performance of a building to create energy efficient buildings.

For a non air conditioned building, its temperature variation over time is calculated and the number of uncomfortable period is determined. For a conditioned building, heating and cooling load is calculated and appropriate HVAC equipment sizing is done. (MNRE 2006). Some of the other parameters that could be to assessed thermal performance are building's annual energy consumption, indoor temperature, Solar heat gain and external conduction gain.

2.3 Key variables altering the efficiency of atrium

From the literature survey, it is clear that the efficiency of atrium and its adjoining spaces depends on balancing day lighting and thermal performance. Allowing sufficient daylight penetration into the atrium well without increasing the thermal load on the building increases the efficacy of the atrium. The various authors in their peer reviewed journals have analyzed the variables which will alter the efficiency of atrium. It is noted that the daylight performance of an atrium will depend on various factors such as well geometry, orientation, glazing profile, material, surface reflectance and sky condition. Thermal performance of the atrium is determined by wall thickness, thermal mass, insulation type, ventilation, internal heat source such as number of people, equipment, lighting inside, and also the ambient environment such as humidity, air velocity, air temperature outside and solar radiation in addition to the above mentioned variables.

In the following sections, the key variables altering the efficiency of atrium based on the literatures reviewed are discussed.

2.3.1 Roof profile

The roof profile is critical in an atrium when daylighting performance and thermal comfort and economy are concerned and many researches have been done with this variable. Yunus et al. (n.d) observed in their studies (Fig 2.20) that the flat roof has the highest daylight illumination for both skies condition over pitched, pyramidal and sawtooth profiles. They also observed that for all roof profiles under overcast sky, center of atrium received the most illumination and center edge position 75% and corner received the lowest 50% illumination.

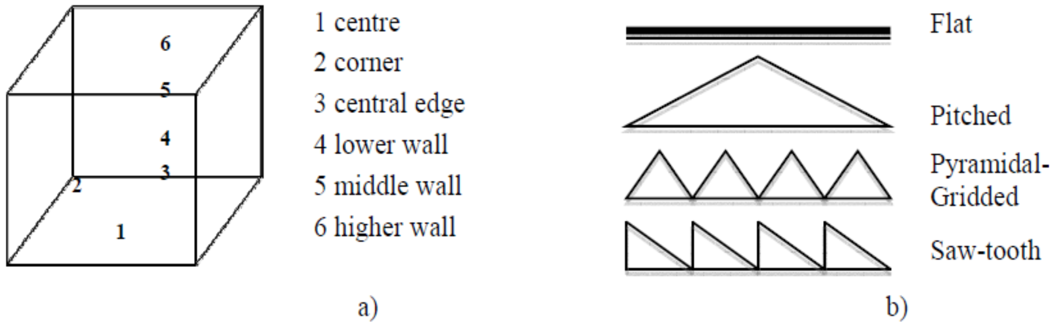


Figure 2.20 : (a) location of sensor for illuminance measurement (b) Roof profiles (Yunus et al. n.d)

The research by Navvab & Selkowitz (1984) is still one of the most inclusive studies on the roof structures with varying glazing. (14 options) under different sky conditions. From the results shown in Figure 2.21, it can be seen that Pyramids, vaults, A-frames allow more interior illumination than sawtooth and monitor roofs (Figure 2.22).

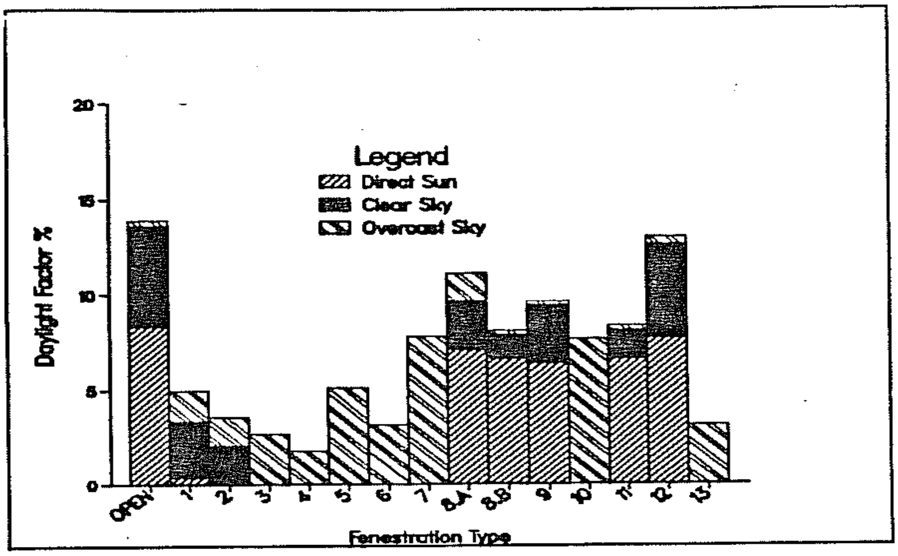


Figure 2.21 : Respective daylight factors for roof profiles (Navvab & Selkowitz 1984)

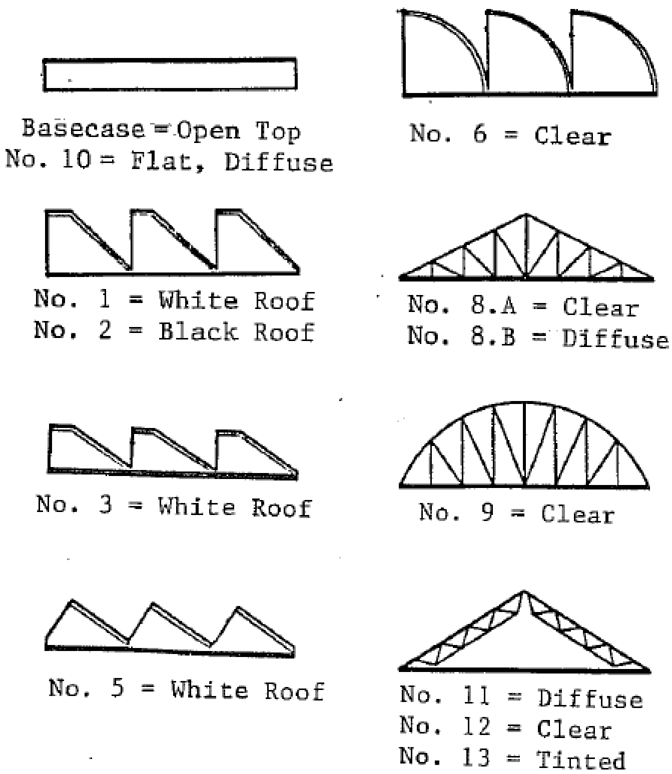


Figure 2.22 : Roof profile options (Navvab & Selkowitz 1984)

Laouadi, Atif. & Galasiu (2002) inferred from their studies that Pyramidal or pitched skylights while compared to flat skylights increased solar heat gain by upto 25% in summer while compared to flat skylights for enclosed and linear atriums and for three sided atrium it was 10%. This is because they collected more solar radiation at low sun altitudes than flat skylights. Depending on the U-value and SHGC ratio of glazing, the impact of skylight shape on annual cooling and heating energy may vary.

Researchers have also inferred that a sidelit model is better than a top lit model in terms of air temperature and ventilation impacts in the tropical climates of Malaysia. Abdullah & Wang (2012) concluded that the sidelit delivered better thermal and energy performance. Baharvand et al. (2013) agreed that the sidelit model is better with lower temperature 30^{o}C than toplit atrium 36.82^{O}C-39^{O}C and toplit model has high air velocity at outlet and inlet while there is effective air distribution around corridors in side lit model.

Abdullah & Wang (2012) revealed that in the hot humid climates of South Asia, an atrium with full natural ventilation is not viable and it resulted in higher temperature than that of outside air and much above the indoor comfortable temperature.

2.3.2 Glazing

The illumination level is influenced by the transmittance of glazing. Lowering the transmittance by using diffused or tinted glazing instead of clear glazing lowers the lighting inside. Navvab & Selkowitz (1984)

Laouadi et al. (2002) have agreed in their research that solar heat gain ratio for a clear glass is much higher than other glazing types (Figure 2.23). Low SHGC values result in lower solar heat gains and thus low cooling loads. As compared with base case, double gray or triple clear low e-glazing reduced cooling peak load ratio by 30-39%, double clear low-e by 17-20% and triple clear glazing by 10-13% because of their reducing SHGC values. High U value leads to more heat loss from building and thus resulted in high heating loads. They also inferred that U value of glazing was more important than SHGC values in terms of heating peak load. As compared with base case, double gray glazing (SHGCR = 0:63 and UR = 1:03) increased heating peak load by 6% and double clear glazing 3%. And triple clear glazing decreased heating peak load by 29% double clear low-e by 36% and triple clear low e-glazing (SHGCR = 0:63 and UR = 0:36) by 58%. Annual total energy reduced with the UR and SHGCR. The double gray glazing reduced the annual total energy by 23-35%, and the triple clear low-e glazing by 40%. They analyzed the impact of glazing on enclosed, three sided and linear atriums in Canada. Solar heat gain ratio, peak cooling and heating loads, annual heating, cooling and total energy were calculated to evaluate the performance.

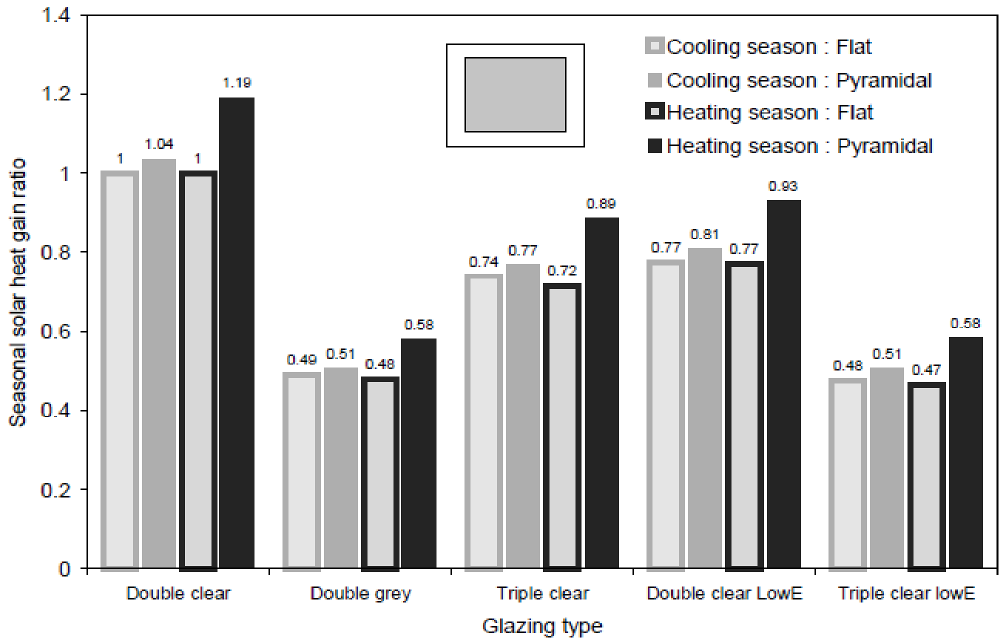


Figure 2.23 : Solar heat gain for various glazing systems (Laouadi et al. 2002)

The glazing industry uses some parameters such as VT, SHGC, LSG, U-value for accurate comparison of glazing.

LSG ratio = VT/SHGC…………………………………………………….……..[2.3]

VT or T vis is the visible transmittance, ie the percentage of visible light transmitted through glazing. When Tv is of high value (0.7 to 0.9), it delivers lots of natural light inside and good vision, but can also become a source of unwanted glare. When Tv is less than 0.4, it can become dark and gloomy on cloudy days. (EDR 2000).

SHGC is the Solar heat gain coefficient, ie. ratio of total solar heat ratio of total transmitted solar heat through a glazing to the incident solar heat. And ranges between 0 for solid wall and 1 for non glazed opening.

It is a very useful index which compares light and visibility of a glazing system to its solar gain. Typical T vis and SHGC valus for glazing systems are given by ASHRAE (Table 2.3)

Table 2.3 : Light transmission /SHGC in percentage given by ASHRAE (PWGS 2002)

Glazing Light Transmission/Solar Heat Gain Coefficient (in percent)					
Glazing System (6mm glass)	Clear	Blue/Green	Spectrally Selective	Grey	Reflective
Single	89/81	75/62	71/51	43/56	20/29
Double	78/70	67/50	59/39	40/44	18/21
Double, hard low-e + argon	73/65	62/45	55/34	37/39	17/20
Double, soft low-e, + argon	70/37	59/29	53/27	35/24	16/15
Triple	70/61	59/42	53/34	34/40	17/19
Triple, hard low-e + argon	64/56	55/38	52/31	32/36	15/17
Triple, soft low-e, + argon	55/31	52/29	50/27	30/26	14/13

As illustrated in Figure 2.24 by McCluney (n.d), LSG ratio > 1 means the glass provides more light than heat. Where heat is a concern, SHGC of low value is used. Reflective coatings are not preferred for day lighting.

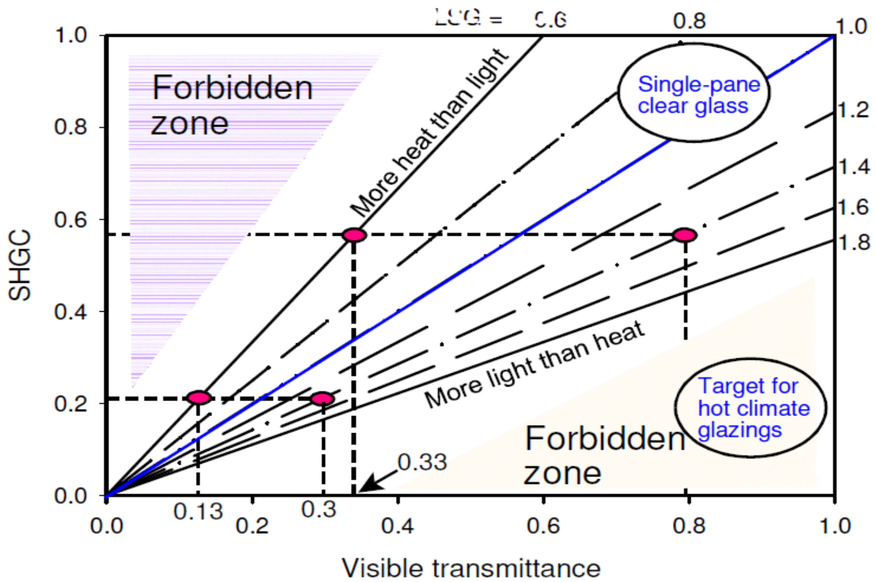


Figure 2.24 : VT AND SHGC relationships for glazings (McCluney n.d).

U value = measure of heat transfer thro a glazing per degree temperature difference across windows measured in W/m2K.

Table 2.4 : Typical U value for Glazing system given by ASHRAE (PWGS 2002).

Glazing System	Center-of Glass U-value (W/(m^2K))	Total Window U-value (W/(m^2K))	
		Typical Frame	High-Performance Frame
Single	5.91	6.30	5.90
Double	2.73	3.51	3.03
Double, hard low-e + argon	1.70	2.63	2.19
Double, soft low-e + argon	1.42	2.39	1.94
Triple	1.76	2.63	2.22
Triple, hard low-e + argon	1.25	2.19	1.79
Triple, soft low-e + argon	0.80	1.79	1.40

2.3.3 Number of floors

Day light penetration reduces sharply as it travels from the top to the ground floor. (Su et al. 2010). They inferred from their study that DF of top floors can be improved by 30–50% and for lower floors G,F,S, it could be improved by100% when reflectance value of surface (mirror finish =0.95, matt white finish =0.80 diffuse reflectance) is increased (Fig 2.25). Figure 2.26 are the rendered images for various floors under CIE overcast sky from their study.

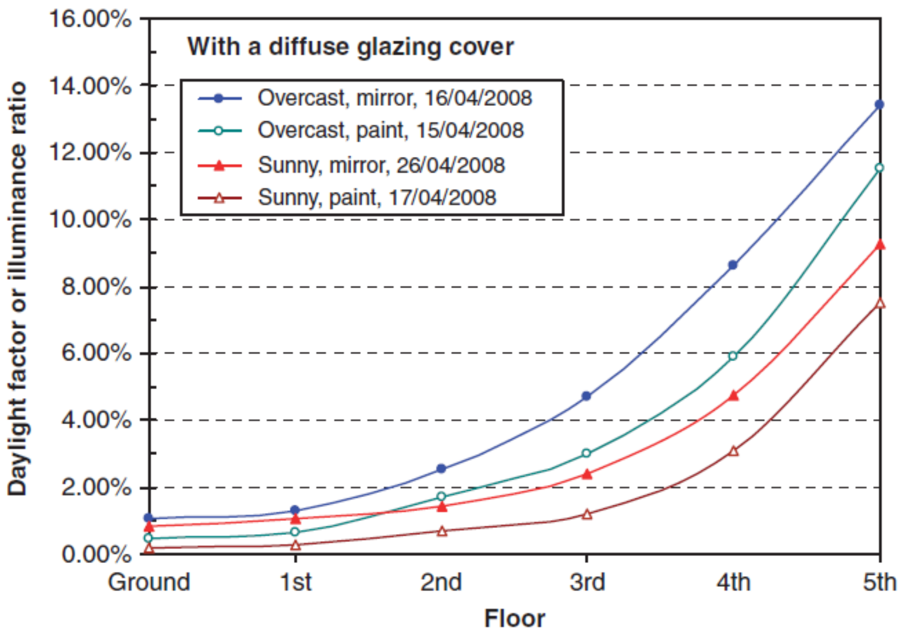


Figure 2.25 : Illuminance ratios at different floors(Su et al. 2010).

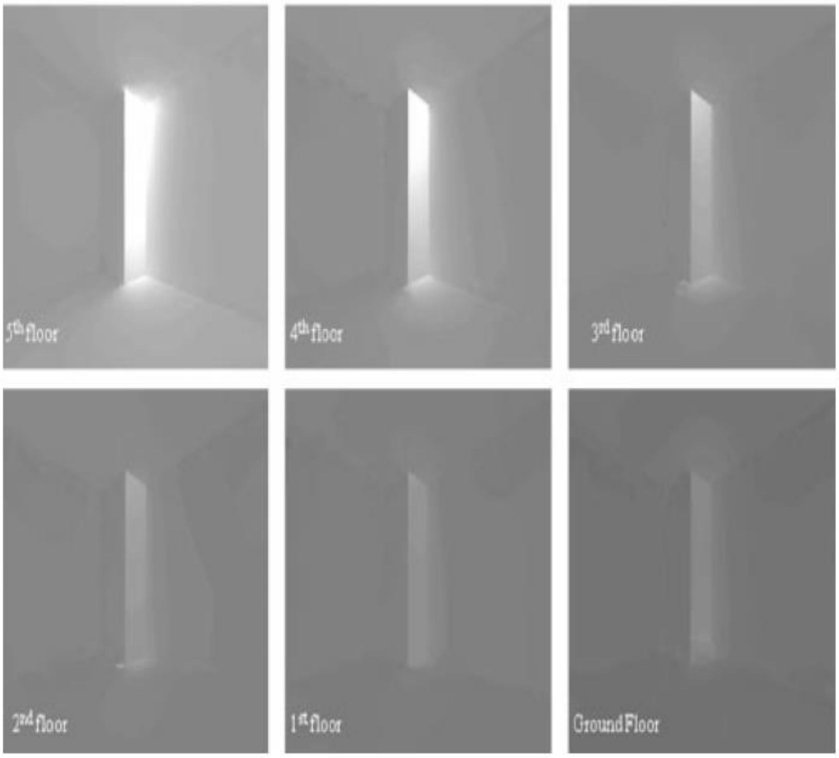


Figure 2.26 : Computer rendered images at different floors (Su et al. 2010).

This is confirmed in the study by Sharples & Lash (2004) in Figure 2.27 and also by Aldawoud (2013) in Figure 2.28 that the daylight factor decreases towards the lower floors.

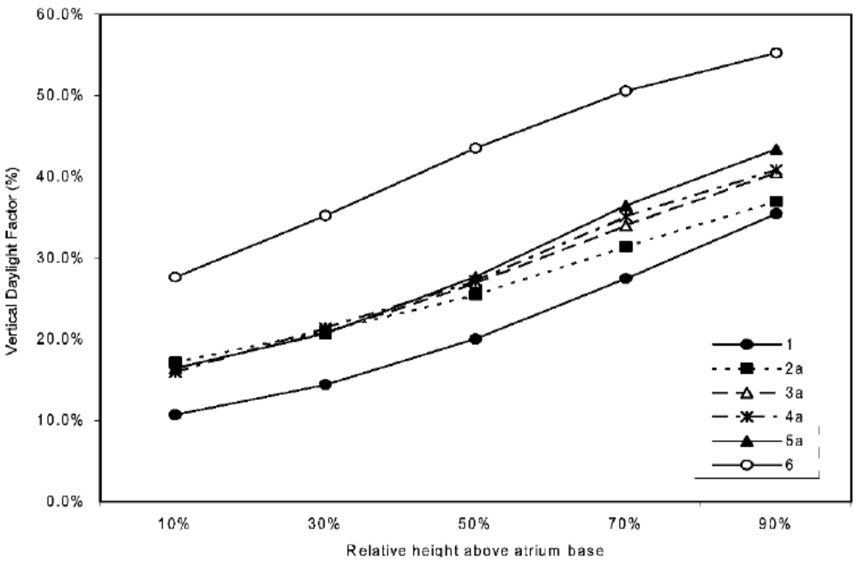


Figure 2.27 : Vertical daylight factor Vs height (Sharples & Lash 2004)

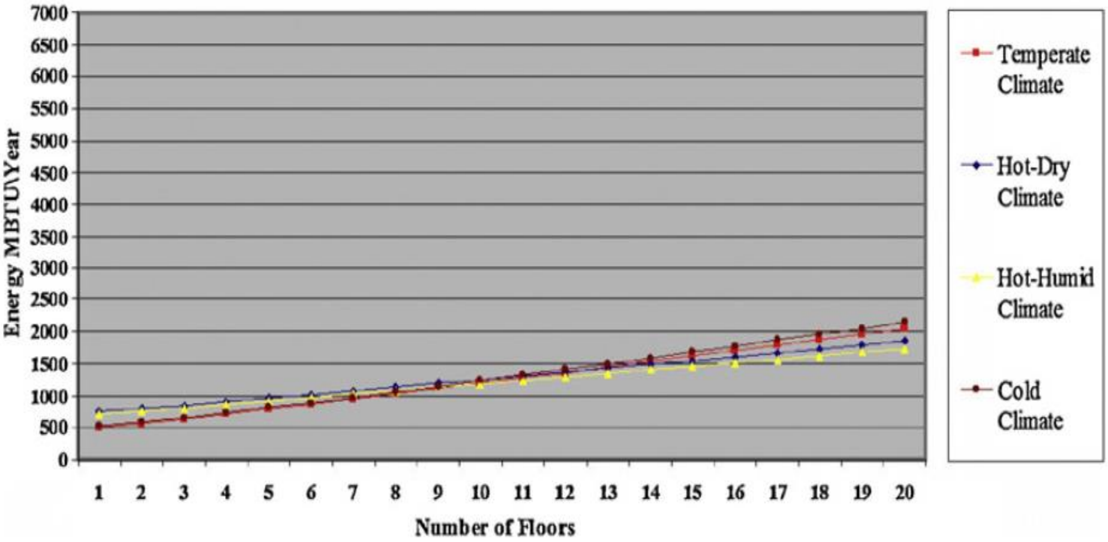


Figure 2.28 : Total energy consumption using double clear glass vs no of floors in 4 climates (Aldawoud 2013)

2.3.4 Geometry

From the literature surveys it is seen that various papers mention 3 geometric parameters namely, plane aspect ratio (PAR), section aspect ratio (SAR) and well index (WI) to define a proper design geometry and this is being described even in 1983 in the book published by Saxon.

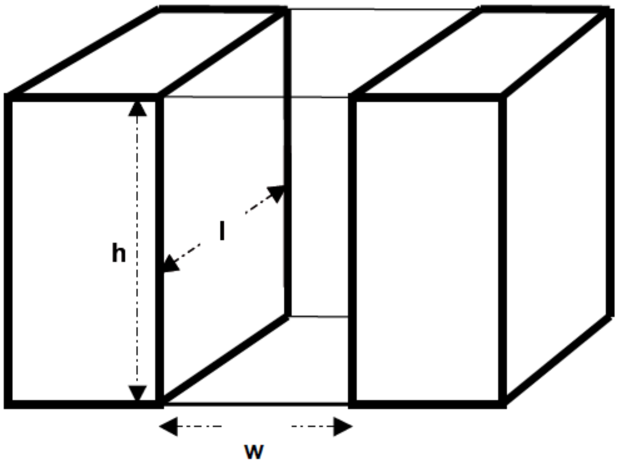
Plane aspect ratio PAR = W/L ………………………………………...…..[2.4]

Section aspect ratio SAR= H/L …………………………………… …..….[2.5]

Well index WI = H(W+L) / 2WL ………………………………..…..……[2.6]

Where, W, L, H = width, length and height of atrium respectively.

Sharples & Lash (2007) in his review of the last 15 years paper in 2007 explains the main terms used to describe an atrium and its characteristics such as PAR, SAR, WI, DF, surface reflectance. PAR is width to length ratio, SAR is height to width ratio and WI relate to the vertical surface area to the horizontal surface area. (Fig 2.29)



$$PAR = \frac{w}{l}$$

$$SAR = \frac{h}{w}$$

$$WI = \frac{h \times (l + w)}{2 \times l \times w}$$

$$WI = \frac{SAR \times (PAR + 1)}{2}$$

Figure 2.29 : Geometry of atrium well (Sharples & Lash 2007)

Less WI or SAR value means a shallow atrium and less PAR means linear atria. PAR between 0.9 and 1 define a square atria while 0.4 to 0.9 are rectangular atria and below 0.4 are linear atria. It should be noted that different combinations of PAR and SAR could be used to give the same WI. For example, WI of 2 can be achieved with a PAR of 1 and an SAR of 2 or also with PAR of 1/3 and SAR 3 (Sharples &Lash 2007).

Du & Sharples (2012) noted that when PAR decreases (narrower) illuminance level on walls especially lower wall improve in comparison to square atrium of same width.

Yi (2009) studies the effect of atrium geometry on day light performance under overcast sky conditions in August. It is a case study of 2 existing atriums (linear and enclosed) in Hongkong. They concluded that for enclosed atrium, the DF and SAR or WI have linear correlation while for the linear atrium DF and PAR have a linear relationship. For a comfortable DF, WI = 1.5 for enclosed atrium and PAR = 0.5 for the linear atrium is the recommended geometric factor.

It was concluded from the research by Aldawoud (2013), a linear atrium (model 4) with more L:W aspect ratio had a much higher energy consumption than a square shaped one (model 1) in all climatic conditions (Fig 2.30). As a low rised building, it is more energy efficient in cold and temperate climates and as a high rise building it is more efficient in hot dry and hot humid climates for all glazing types.

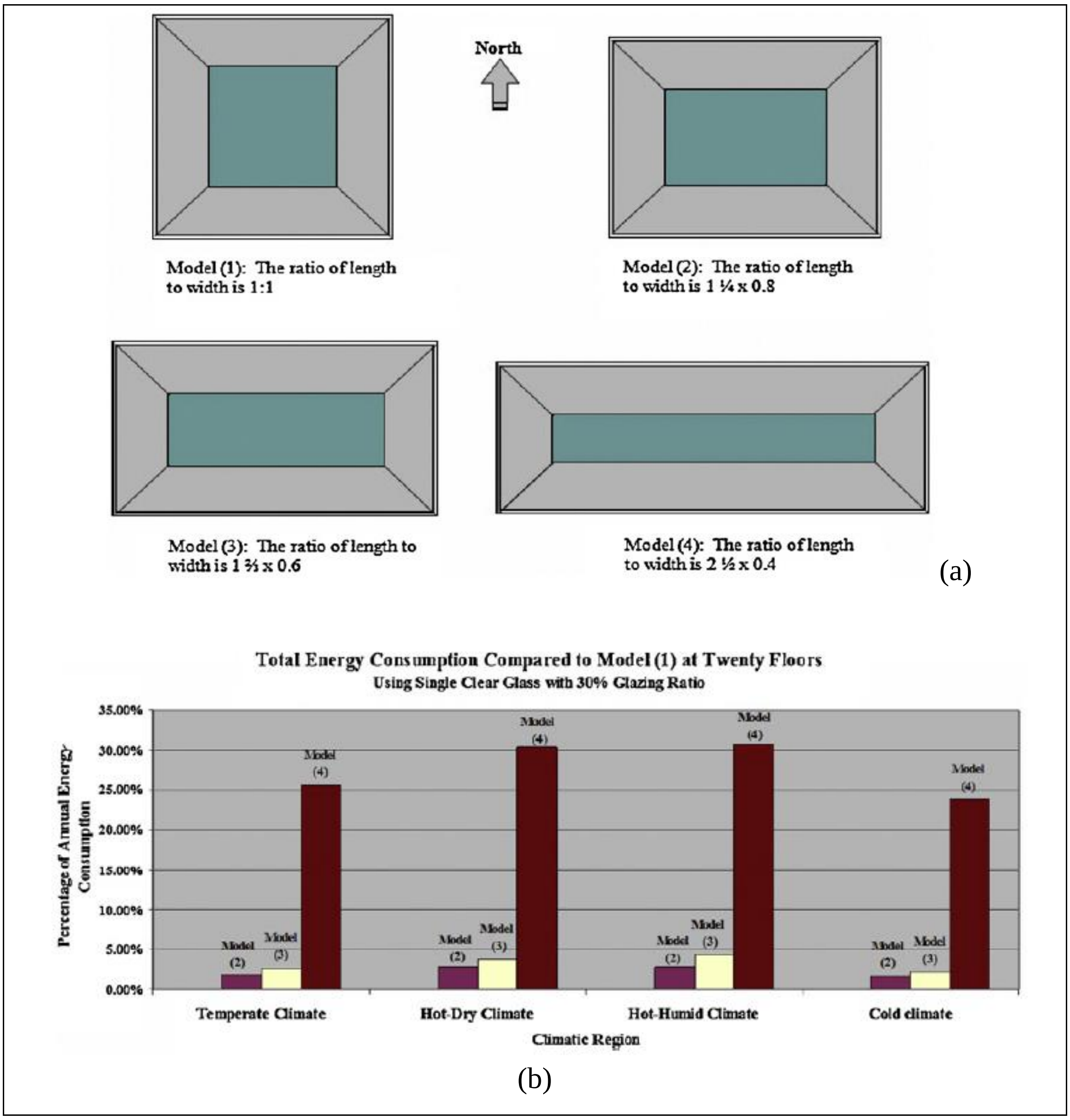


Figure 2.30 : (a) 4 models each with 20 floors ht and varying L:W ratio and (b) simulation results showing their energy consumption for 4 climates (Aldawoud 2013)

2.3.5 Surface Reflectance

Surface reflectance of a material is defined as the percentage of light that is reflected back from a surface. Since an atrium is made up of many surfaces, so an area weighted reflectance is considered which is calculated by multiplying reflectance value of each material with its area and then dividing the value by total area. (Sharples & Lash 2007).

Even though, the amount of daylight entering the atrium is determined mainly by the glazing's transmittance, the distribution of daylight in the atrium and its adjoining spaces is determined by the surface reflectance properties. Specifically in a deep atrium, surface reflectance values play a major role in the provision of adequate daylight levels. (Samant & Medjdoub 2006).

This is confirmed in the study by Navvab and Selkowitz in 1984 where he recorded a drop in illuminance on a vertical surface with lowering reflectivity (high 0.86 ; modest 0.5 ; low 0.015).

Another study under 2 different sky conditions - overcast and sunny sky by Su et al. (2010), also confirms that increasing the reflectance value of surface (mirror finish =0.95 ; matt white finish =0.80) increases the DF. It is 100% improvement for lower floors G,F,S and 30–50% for the top floors.

Sharples & Lash (2004) also agree with the above in their study that the entirely white model had more DF value than the entirely black model. Further they note that, reflectance distribution's effect on the lower portion of atrium well had little effect on vertical DF and IRC values but higher up the well it large differences were observed by in their study. It was found that the When the upper half of atrium model was painted white (high reflectance value) it recorded the highest DF and IRC value. The results show that as the when top half black and bottom half white is interchanged with top white and bottom black, the daylight factor behavior varies.

Table 2.5 : Reflectance values used by Sharples & Lash (Sharples & Lash 2004)

Model No.	Atrium Configuration	Area-weighted average reflectance R
1	All surfaces painted black	R = 0.02
2a	1/2 black at the top	R = 0.29
2b	1/2 white at the top	R = 0.29
3a	1/4 black on top	R = 0.29
3b	1/4 white on top	R = 0.29
4a	1/6 black on top	R = 0.29
4b	1/6 white on top	R = 0.29
5a	1/8 black on top	R = 0.29
5b	1/8 white on top	R = 0.29
6	All walls painted white	R = 0.57

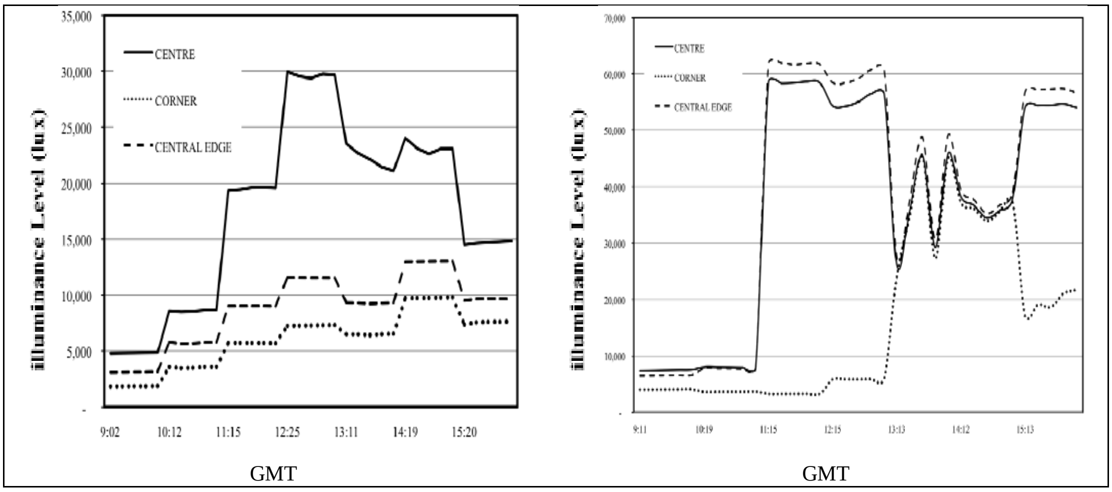
Du & Sharples (2012) again confirm that daylight level on the wall of atrium increases proportionately as reflectance value of surface increase. Further it was insubstantial at higher floors. Difference between DF of long and short sides in a rectangular atrium could be reduced by increasing the reflectance value. They researched on the geometry and surface reflectance value on vertical DF on a rectangular atrium under CIE standard overcast sky. Illuminating Engineering Society of North America, IESNA recommends the surface reflectances as in Table 2.6 for optimal daylighting.

Table 2.6 : Surface reflectance recommended by IESNA (PWGS 2002)

Surface	Reflectance (%)
ceiling	80
wall	50-70
floor	20-40
furniture	25-45

2.3.6 Sky condition

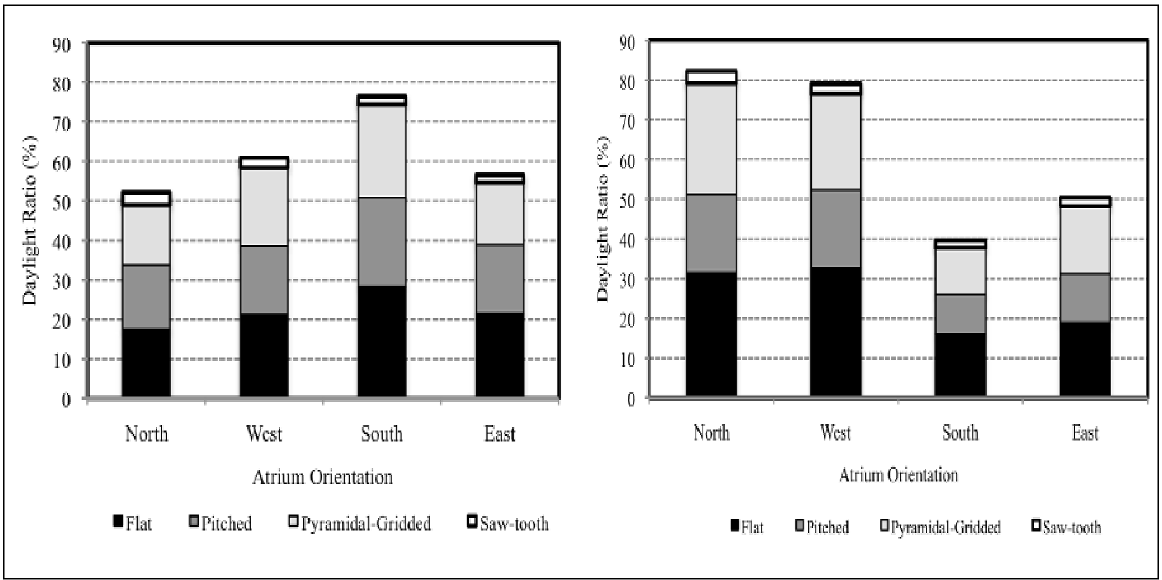
Sky condition and orientation has a great impact on the day light level inside atrium. Illuminance level inside an atrium for a sunny sky is much higher than that of overcast sky (Fig 2.31). (Yunus et al. n.d, Su et al. 2010, Navvab & Selkowitz 1984). The light well performance on 2 different sky conditions - overcast and sunny sky with 2 different surface finishes - matt white paint and mirror-finish was studied by Su et al. (2010).



a) b)

Figure 2.31 : Illuminance level under real sky conditions for flat roof (Yunus et al. nd)
a) overcast day b) sunny day

On an overcast day, the illuminance level is more constant than on a sunny day. Under overcast sky condition, south and west facing skylights were exposed to the highest DF. In contrast, under sunny day, north and west facing skylights received the highest DF ratio for the 4 roof profiles tested as seen in Figure 2.32 (Yunus et al. nd). They also noted that north and west facing atrium surface has to be taken care of under overcast skies since the illuminance decreased considerably.



a) b)

Figure 2.32 : Daylight ratio vs orientation for 4 roof profiles (Yunus et al. nd)
a) overcast day b) sunny day

Navvab & Selkowitz (1984) observed that not only that horizontal illuminance is greater for a clear sky but it also depends on the solar altitude (Figure 2.33)

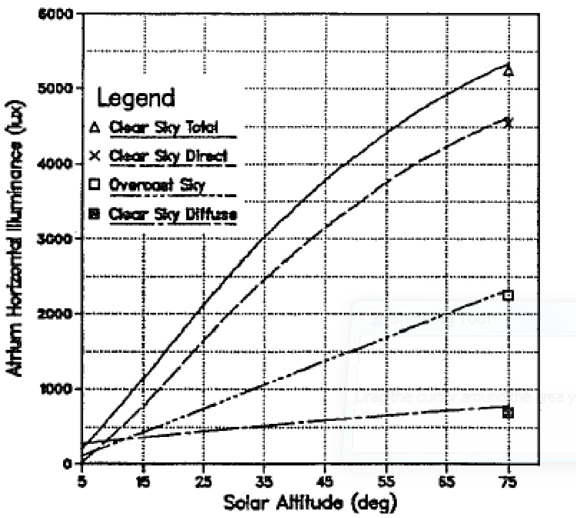


Figure 2.33 : Illuminace Vs solar altitude for clear and overcast sky
(Navvab & Selkowitz 1984)

Kensek & Suk (2011) analyzes 2 sky conditions CIE sunny sky (less than 30%clouds) and CIE overcast sky (100%clouds) and states that performance of a building varies under different sky conditions. So the real sky condition of the place has to be used while assessing the building's performance.

2.3.7 Summary

It was noted in the literature study that the researchers have done their studies with a few selected parameters. Atif (1992) had chosen height (2 values), length (2 dimensions), reflectance value of wall (3values), solid wall to total wall ratio (2 values) as the variables to be tested. They were tested by keeping one value as a variable and the others constant. This was repeated for all the variables. Al-Masri & Abu Hijleh (2012) had chosen the number of floors, type of glazing, wall thickness and insulation type and insulation thickness as the variables to be tested. Aldawoud (2013) had selected height, glazing type (4 types), geometry of atrium (4 dimensions) and climate zones (4 climate zones) as the variables to be tested.

Based on the study of published papers, it is clear that testing all parameters with different variables will go beyond the scope of one research paper. It is essential to finalize the scope of this research by deciding on the parameters to be tested in this research.

It is also noted that no significant research is done in an atrium located in a hot arid place like Dubai, although there are a few papers conducted in hot humid climate of Malaysia.

Chapter 3

Research methodology

Chapter 3 : Research methodology

From the previous papers studied, it was noted that the authors have used various methods, namely, Physical scale model, Field measurement, Computer modeling and simulation. Below the details of how each methodology can be applied to the research is discussed.

3.1 Physical scale model

Samant & Medjdoub (2006) have used physical scale model study for their research. Six Physical models constructed to a scale of 1:100 . The wall surface inside for each model was painted in black or white or in bands of black and white representing 6 values of reflectance of the paint finish used in the wall. For white surface, 2 coats of white matt of reflectance value 0.85 was used. For black surface, a specialist primer base coat and topcoat of velvet finish of low reflectance value of 0.02 was used. The model was placed inside an artificial sky created in a mirror lined box wherein the luminance distribution of the CIE overcast sky was reproduced. Illuminance measurements were taken with a calibrated lux meter with photopic and cosine correction. Measurements re taken at predetermined points – center of well, corner of well and mid edge position of well. The measurements were repeated 4 times for each point and average value was recorded. The obtained results were analyzed to identify the impact of reflectance value on the illumination level.

Another paper by Atif et al. (1992) also uses physical scale model study for their research. Here a physical model created in the scale of half inch to one foot and kept inside a sky simulator at Texas A&M university. Beams, columns, floor finish were also recreated in the model. Illumination measured with Illumination Data Acquisition System (lDAS) which consists of a computer, Serial Analog Module (SAM), and eight sensors. The illumination measurements were taken 110 times, each time altering a variable. The sky simulator was set for clear sky and measurements were taken. Then it was repeated with sky simulator set for completely overcast sky (CIE) . This paper analyzes the effect of reflectance value of walls and shape of atrium roof on day light factor.

Du & Sharples (2012) use physical scale model in their study to investigate the impact of well geometry and surface reflectance on daylight factors. Three scale models were created and tested under artificial sky simulator replicating the luminance distribution of CIE standard overcast sky. The illumination measurements were taken with Minolta LS-110 luminance meter. But the models had variable wall reflectances 0.02 (black), 0.44 (grey) and 0.85 (white).

Yunus et al. (n.d) used physical scale model (Fig 3.1) equipped with six newly calibrated illuminance sensors attached to independent data logger (data Taker DT80) for all internal measurements. A data logger, connected to a portable computer, recorded the illumination level of each sensor using a computer program called DeLogger5. Extech Illuminance Meter (HD450) with built-in memory was also used. EKO Lux meter (ML020O) for outdoor illuminance monitoring under real sky conditions.

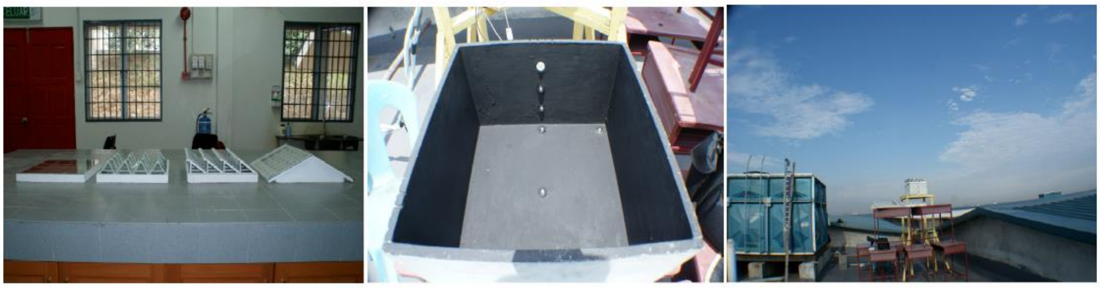


Figure 3.1 : Physical scale model experiment (Yunus et al. n.d)

From the above literature studies, it is clear that the physical scale model approach requires specific calibrated instruments such as Illumination Data Acquisition System (lDAS) or calibrated lux meter or Minolta LS-110 luminance meter or Extech Illuminance Meter or EKO Lux meter for measuring illumination and sky simulators to replicate the sky conditions and data logger etc. It also requires materials for constructing the model and paint finishes of known reflectance values. Further it requires manpower to construct the model and to conduct the research which will be a laborious process.

3.2 Field measurement

Yi (2009) studies the effect of atrium geometry on day light performance. Field measurements taken under overcast sky conditions in August. The illuminance was measured at fixed points and corresponding day light factor calculated by dividing internal illuminance by the external illuminance. The variables in this study are the height and length of atrium well. The measurement instruments used were Hagner Lux meters, Model E2-X, (2nos) which is a precise instrument for measuring illuminance over a range of 0.01–200 000 lux, both in the field as well as in the laboratory. The experiments were carried out in 2 atriums (linear and enclosed) in Hongkong.

Laouadi et al. (1998) used field measurement in their study of an pyramidal sky lit atrium in Ottawa, Canada. It was taken at 2 times of the year, one in June (summer) and one in December (winter). Indoor temperature was recorded with three thermocouple trees hung from an I beam in the atrium and outdoor temperature with shielded thermocouple. Indoor solar radiation measured with five radiometers hung in the I beam and outdoor solar radiation measured from a weather station fixed on the roof top. It also recorded the RH value, wind speed and wind direction. This paper compares the field measurement study to the simulation study.

Field measurement approach is followed by Abdullah et al. (2009) also in his study of an atrium of a guesthouse located in China representing hot, humid climate. Measurement is done for 10 consecutive days representing both clear sky as well as overcast sky. Variables such as thermal comfort indices PPD, PMV were measured with portable B&K Thermal Comfort Meter Type 1212. Wet bulb and dry bulb thermocouples were used to measure temperatures both indoor and outdoor and the thermocouples were connected to a data logger which recorded the temperature every 20 minutes. There were thermocouples placed at 9 points inside building and at one point outside the building. Thermo point Infrared System was used to calculate average internal surface temperatures of the floors, walls, ceilings and roof glazing on each floor and thermal Radiometer was used for measuring radiation intensity of the internal surfaces exposed to solar radiation. The recorded data represents the indoor conditions of atrium. Tests were repeated internal blinds and with water spray on the glazed atrium roof's external surface. This paper studies the effect of two low cost measures - internal solar blinds and external water spray on the indoor thermal environment of atrium.

Field measurements require specialized instruments to record accurate measurements. This can be seen in the above 3 studies which adapts field measurement approach. The researchers have used a number of instruments such as Hagner Lux meters, Model

E2X, portable B&K Thermal Comfort Meter Type 1212, thermocouples, data logger, thermo point Infrared System, thermal Radiometer etc.

3.3 Computer Modeling and Simulation

Many researchers have used Simulation research. According to Groat & wang (2002), simulation research involves controlled replications of the real world context for the purpose of studying dynamic interaction within that setting. Yi (2009) uses ECOTECT and RADIANCE simulation to assess the relationship between daylighting performance and geometric parameters. Simulation done with variable geometries. Ecotect program was used as an operating platform and model created since Ecotect has a convenient drawing and parameter setting platform. Then the model is opened in Radiance and illuminance calculated. 800 mm above the floor is considered as the working plane and the analysis grids are placed at this level. The illumination level and Daylight factor are calculated in the simulation program.

Du & Sharples (2012) created virtual models in CAD tool and transferred into Radiance for simulations. Radiance was used to assess the impact of geometry and reflectance value variations on vertical daylight factor on the virtual model rectangular atrium. It was tested under CIE standard overcast sky condition and at different vertical planes. Illumination level at different SAR, PAR, WI levels are tested. Results analyzed with regression analysis. Aldawoud (2013) tested the influence of atrium geometry on thermal performance with DOE-2.1E software program. 4 virtual models of varying L:W ratios created. 4 varying glazing types, 3 varying glazing ratios, 2 varying heights were tested, each under 4 different climatic zones. Energy consumption for different combinations of the variables were recorded and analyzed.

Al-Masri & Abu-Hijleh (2012) analyze the thermal performance of a courtyard against thermal, solar shading and daylight parameters for variables such as type of glazing, thickness of wall, insulation material and height using (IES-VE) an integrated building performance analysis platform. The authors have chosen this software for its analysis options, accuracy. Then a comparative study is done for conventional and courtyard model for optimal energy consumption.

Other simulation programs such as ESP-r program by (Laouadi et al. 1998), Energy Plus by (Pan et al, 2010) are also used by other researchers. From the literature review done, it was noted that authors deciding to do research with computer modeling and simulation have gone in for different softwares depending on the availability, knowledge to use the software, capability of the software.

3.4 Selection and Justification of an appropriate method

Literature review identified the different methodologies used by other researchers for investigating a similar topic. Justification for choosing a methodology over others is discussed in this section. Physical scale model approach requires specific calibrated instruments such as Illumination Data Acquisition System (lDAS) or calibrated lux meter or Minolta LS-110 luminance meter for measuring illumination and Sky simulators to replicate the sky conditions. It also requires materials for constructing the model and paint finishes of known reflectance values. Acquiring these instruments will be difficult. Further it requires budget and manpower to construct the model and to conduct the research. The whole process seems to be time consuming and more laborious.

On the other hand, field measurements also require specialized instruments to record accurate measurements. The researchers have used a number of instruments such as Hagner Lux meters, Model E2-X, portable B&K Thermal Comfort Meter Type 1212, thermocouples, data logger, thermo point Infrared System, thermal Radiometer etc. Further it requires repeated site visits and permission from the building management to conduct field measurements during the course of their working hours.

While field measurement approach and the physical scale model approach requires a lot of resources such as instruments, time, human resource in addition to permission from authorities, Simulation research creates a virtual world wherein real life parameters can be recreated virtually and its effect on the environment studied by varying these parameters. Even the materials for wall, floor, roof, glazing etc could be integrated into the virtual model by applying parameters for that material. The variables could be easily altered in a simulation and it is less time consuming and cost effective. By calculating the energy consumption and daylight factor with variables such as geometry, orientation and materials, the optimal parameters for an efficient atrium could be identified easily. However, the limitation with this method is the technical expertise needed to work with the software. But this limitation can be overcome by attending training workshops and online tutorials.

Based on the above discussions, computer simulation is identified as the best feasible methodology to investigate on this research question. It was noted that in the published papers, software chosen for researching with simulation methodology by the authors varied. For simulating the daylighting and building energy performance DOE-2.1E software program was used by (Aldawoud 2013) & (Pedrini et al. 2002), ESP-r program by (Laouadi et al. 1998), EnergyPlus by (Pan et al. 2010) . ECOTECT and Radiance by (Samant & Medjdoub 2006) & Yi (2009), IES-VE program by (Al-Masri & Abu-Hijleh 2012) and RADIANCE program by (Du & Sharples 2012).

The availability of the simulation software and professional training needed to use the program will be the criteria for choosing the particular program. Since IES-VE (Integrated Environmental Solutions- Virtual Environment) fulfills the above criteria, it is chosen for the proposed research. It is user friendly and internationally accepted as one of the leading simulation tools and used commercially worldwide. It consists of a group of integrated analysis tools, which can investigate the energy performance of a building (U.S. DOE 2011).

3.5 Research Plan

Based on the literature review a research plan is developed for this research. The methodology found most appropriate to tackle the question is decided and details worked out, bearing in mind the practicality of conducting the research. The research plan involves the following steps.

1. An existing atrium in Dubai will be selected as a base case and the existing parameters for the different variables are studied with existing drawings and site measurements. The availability of drawings and assistance from the building management will be the criteria for choosing the atrium. The actual materials used at site will be observed and noted.

2. In the next step, the various parameters / variables that influence or increase the daylight performance and thermal performance of the building are identified from the literature review and the variables to be tested are established. From the literature survey done for this research, Glazing profile, Number of floors, LSG ratio of the glazing system and Sky condition are identified as factors that influence the amount of daylight coming inside an atrium and impact the energy consumption of the atrium. Further, U value of envelope and Roof ventilation are also taken as factors that influences the thermal performance of atrium. These variables are taken for further research. The test matrix shown in Table 3.1 indicates the variables that would be tested and the range of values tested for each variable. The existing values as on site is taken as the base case value.

Table 3.1 : Test Matrix of tested variables

Variable	Roof ventilation (% openable area)*	Glazing profile	Number of floors	LSG ratio of glazing **		U value of envelope *** (W/m^{2}K)	
				External	Internal	Wall	Roof
Values	Closed #	vault glazed #	2 #	0.95	0.48 #	0.3074	0.1839
	10%	Flat glazed	4	1.24 #	0.95	0.5603	0.2908
	20%	Closed roof	8	1.34	0.96	0.5771	0.2951
	30%	North light L20		1.35	1.13	0.8120	0.5294
	40%	North light L40		1.55		1.0115	0.6101
	50%	North light L40SL				2.3969 #	1.5647 #
	60%	North light D					
	80%	North light & flat combined					
	100%						

Footnotes :

The existing values as on site and is taken as the base case value.

* refers to Roof openable area of atrium glazing for ventilation in percentage. It is connected to a sensor and opens automatically when outdoor climatic conditions are favorable. i.e. , outdoor temperature falls below 22^{o}C and relative air humidity is less than 90%. Roof ventilation variable is tested with varying percentages of roof opening area.

** refers to LSG ratio = LT/SHGC , which is ratio of visible transmittance of light (LT) to solar heat gain co-efficient (SHGC). It measures efficiency of different glass types in transmitting daylight while blocking heat gain (DOE n.d). From the literature review it is seen that, if LSG value is less (i.e., < 1) then the glass transmits more heat than light. LSG ratio of external glazing (atrium roof and external windows) and internal glazing is tested separately.

*** refers to U value which is defined as the rate at which thermal energy is conducted through unit area, per kelvin temperature difference between its two sides and its unit is W / m^2K (SEAI 2014). It measures the efficiency of a material in terms of its heat transmittance and could be varied either by altering the thickness or the material type. From the literature review it is seen that, low U value indicates that the material is a good insulator. U value of external wall and roof is tested separately.

From the data available online in weatherspark, it can be seen that the Sky condition of Dubai is mostly clear with average cloud cover ranges from 0% (clear) to 25% (mostly clear). The cloudiest day is January 14 and clearest is June 1. Since the sky condition of Dubai is mostly clear as seen in the climatic data, the variables will be tested under standard CIE Clear sky condition.

3. Construction of virtual model in the software : A virtual model will be created with the real dimensions and existing parameters at site and the details of actual materials given as the input data. The weather data file (EPW) for United Arab Emirates will be loaded. The IES simulation program will be run to calculate the performance of the building in terms of the energy consumption, Carbon emission, Cooling sensible load, Dehumidification latent load and lights energy. This is the base case.

4. Next step involves altering one variable at a time, keeping all other variables constant as shown in the test matrix, simulating the model in IES software to find the thermal and daylight performance and the findings are recorded for each case.

5. In this data analysis stage, the results are analyzed with to find the best parameter/value for each variable which gives the most efficient energy consumption and the reason for increase or decrease in its performance.

6. The next step involves modelling the optimal case where the best parameter for each variable is applied to the IES model and simulating the model and recording its performance.

7. In this final research analysis stage, thermal and daylight performance for the base case which is the as-in-site case is compared to the optimal case which has the best parameter for each variable. The reduction in energy consumption, cooling load, dehumidification load, carbon emission and light energy that could be achieved by applying the optimal case is studied and optimal values for variables to be applied in design of Atriums is established.

3.6 Resource Requirement

Any research plan can develop into a successful research, only when there are appropriate resources and good management of the resources within a stipulated time. The following are identified as the requirements for this research.

- Computer with IES-VE software package
- EPW file for United Arab Emirates
- Drawings and details of the selected atrium in Dubai
- Permission from building management to take measurements and photographs.
- This simulation research does not need much human resources. Initially an additional person's help may be necessary to carry out the field measurements and photographs. However, it needs expertise to use the software. Training via online tutorials or otherwise to familiarize with the simulation program will be necessary.

3.6.1 IES-VE software validation

From the literature review, IES<Virtual Environment > by Integrated Environmental Solutions is chosen as the software to be used for this research. It is an integrated building performance analysis package software which is explicitly designed for sustainable analysis. The package contains several modules namely, ModelIT, SunCast, ApacheSim, FlucsDL, Radiance, FlusPro, LightPro, MacroFlo, MicroFlo, Apache HVAC and Vista within.

ModelIT is a model building module which creates 3D virtual model. Solar analysis is done with SunCast module. Simulations to assess the building's performance is done using ApacheSim module. Lighting analysis is done using FlucsDL, Radiance, FlusPro or LightPro modules. Ventilation analysis is done with MacroFlo or MicroFlo modules. Apache HVAC module is used for HVAC system modelling and advanced energy simulations. Finally Vista module is used for results analysis and to create necessary data and graphs.

Any simulation tool will not give precise results. But through comparison of similar simulation tools, IES<VE> has been evaluated as one of the best simulation tools and validated by many researchers. Leng et al. (2012) in their study conducted in Malaysia compare it with field measurements and concluded that it is a valid software for thermal simulation with least discrepancy percentage of results ranging from 0 to 15%. Nikpour et al. (2013) in their study of an office room in Malaysia concluded validity of the IES tool comparing it with field measurements with a difference of not more than 10% to field results.

Yassin, Hamza & Zaffagnini (n.d). in their study of a residential building in Egypt conclude that IES<VE> is a reliable tool with an acceptable percentage difference of 6% in results between simulation and field measurement and could be used for building performance calculations in hot arid climate. Almhafdy et al. (2013) in their study of courtyard design in Malaysia infer that the difference between field measurements and simulation is about 6% and well within an acceptable accuracy margin. Thus the use of IES<VE> as simulation tool to be used for this research is validated.

3.6.2 Climatic data

Dubai is one of the seven emirates comprising United Arab Emirates and is located on the south eastern coast of Arabian Gulf (Fig 3.2). It lies on latitude 25.25^{o} N and longitude 55.33^{o} E and at a time zone of + 4.00 hours GMT. It is a tropical desert and has a hot arid climate. Summer is extremely hot and dry and winter is extremely cold. From the data charts given below, following could be analyzed.

Figure 3.2: Location map of Dubai (RTWU 2010)

July and August are the hottest months with mean high temperature reaching 44.2° C and January and February are the coldest months with mean low temperature reaching 19.5°C. Figure 3.3 shows that the minimum temperature reaches 5^{O}c for few days in winter (IES-VE). Wind & weather statistics of Dubai Airport reveals that the wind strength varies from 5-20 knots. Strong winds can bring in lots of sand and dust and turn into a sand storm. Figure 3.4 shows that the Prevailing wind direction is North West.

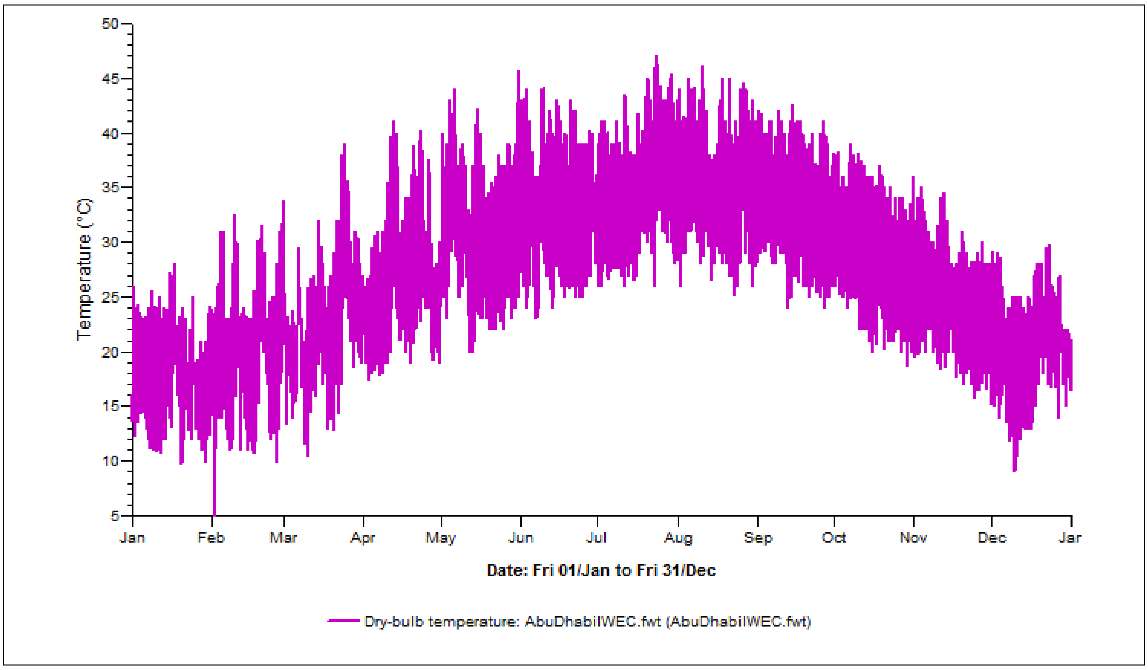


Figure 3.3 : Dry bulb temperature (IES-VE)

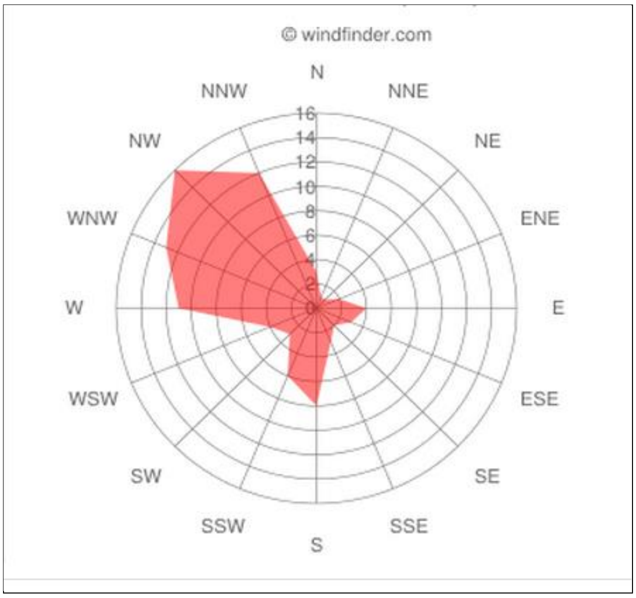


Figure 3.4 : Wind data (Wind & weather statistics Dubai Airport)

Table 3.2 shows that the Precipitation value is too low and average monthly value is only 7 mm. The coastal regions have a high humidity with dew and fog at night, and early morning but, the inland is very dry most of the year. Average relative humidity minimum value is 36% and it is minimum during months of April to October. Average relative humidity maximum value is 81% and it is maximum during months of September to march and also June (World climate). IES weather data shows that outside relative air humidity is above 90% for 546 hours.

Table 3.2 : Mean Humidity and Precipitation value for 12 months
(World climate 2010)

0615	**Precipitation Mean Monthly Value**	mm	11.3	35.7	22.4	7.6	0.7	0.0	0	0	0.0	0	1.8	14.3	7.82
1101	**Relative Humidity Mean Value**	%	65.0	65.0	63.0	55.0	53.0	58.0	56.0	57.0	60.0	60.0	61.0	64.0	59.75
1109	**Relative Humidity Mean Daily Maximum Value**	%	83.0	85.0	84.0	79.0	76.0	82.0	79.0	78.0	84.0	84.0	82.0	84.0	81.67
1110	**Relative Humidity Mean Daily Minimum Value**	%	44.0	43.0	40.0	32.0	29.0	32.0	32.0	34.0	31.0	34.0	38.0	44.0	36.08

Sun chart demonstrates the position of the sun at any time of the day and year and in Figure 3.5, it shows the sun path during the Solstice days- June 21 and December 21 and during Equinox days – March 21 and September 21. Daylight chart in Figure 3.6 shows that throughout the year there is good daylight in Dubai.

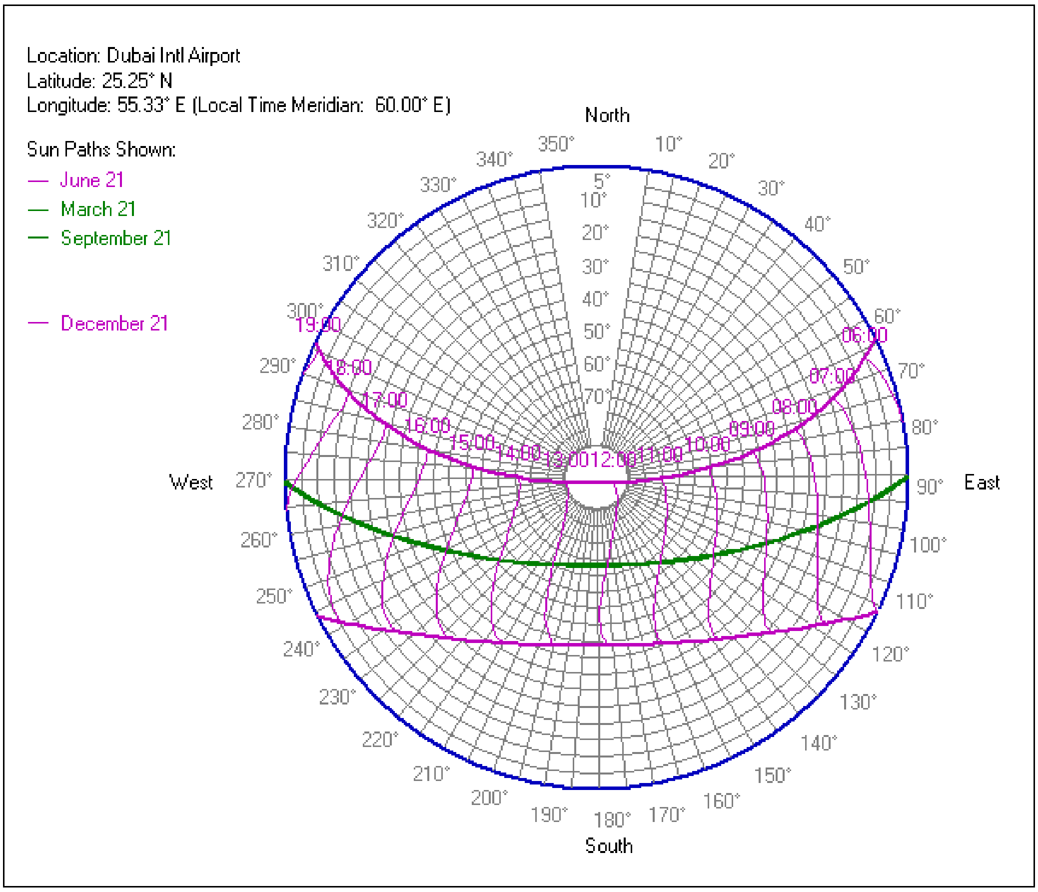


Fig 3.5 : Sun Chart (IES - VE)

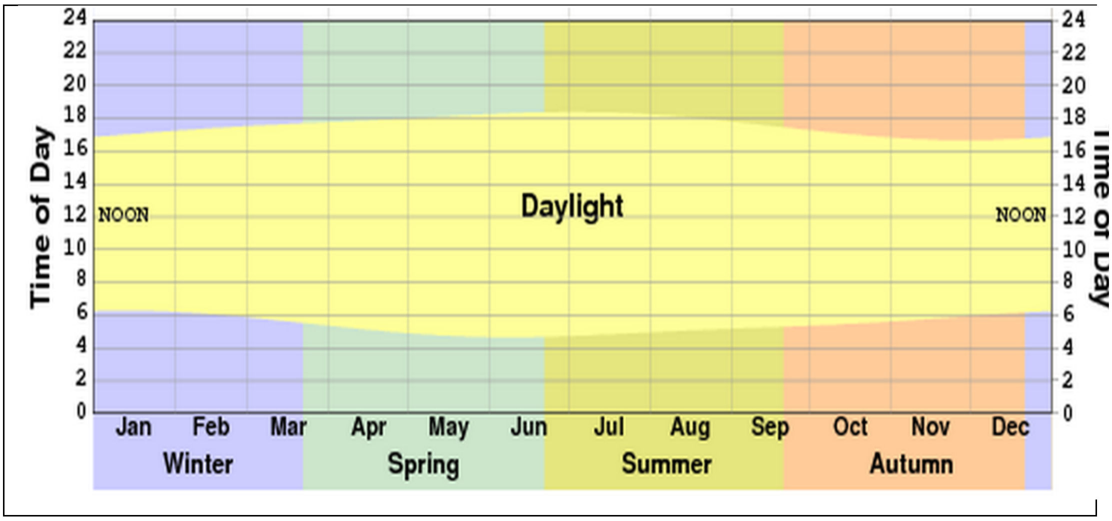


Fig 3.6 : Day light Chart (World climate 2010)

Sky condition of Dubai is mostly clear as can be seen from the data available online in weatherspark (Fig 3.7) and the average cloud cover ranges from 0% (clear) to 25% (mostly clear). The cloud cover is maximum during March and minimum during June and the cloudiest day is January 14 and clearest is June 1. Since the sky condition of Dubai is mostly clear, the variables will be tested under standard CIE Clear sky condition.

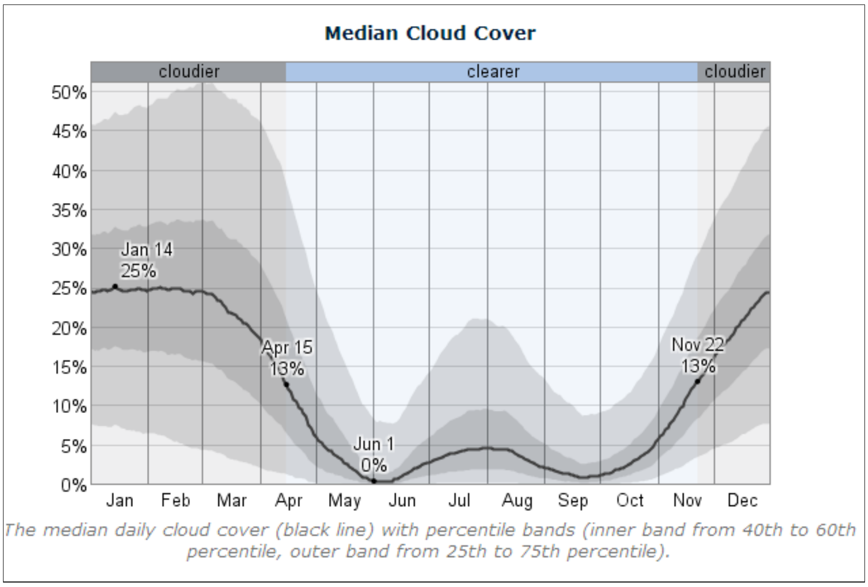


Figure 3.7 : Annual cloud cover graph (weatherspark)

From the above climatic data analysis of Dubai, it is seen that the high outdoor air temperature and mostly clear cloud cover increases the solar exposure of buildings and this direct solar radiation impacts buildings and increases heat gain, thus increasing the energy consumption of buildings. Avoiding this heat gain and thus reducing the cooling load while utilizing the daylight to reduce artificial lighting will be the main consideration to be taken care of while designing buildings in hot arid climate.

Chapter 4

Computer Modeling, Simulation and Results Analysis

4.1 Base case computer modeling and Simulation

Times Square Mall located in Sheik Zayed road with easy access from Dubai and Abudhabi is selected for analysis for this study. This G+1 mall constructed in June 2007 has a built-up floor area of 35413.45 m^2 and a total volume of 202604.30 m^3. This mall is a community and family oriented center and has an unique shopping ambience with an atrium of size 30 m x 26 m in the center of the building with glazed skylight covering an area of 780 m^2. This atrium not only provides light inside but acts as a social gathering place around which a lot of activities for kids, art workshops, handicraft exhibition cum sale, food and craft markets are planned on weekends and holidays. A food court planned around the atrium on one side on the first floor serves an inter-continental cuisine offering. It also has entertainment centers such as Chillout ice lounge and Adventure zone which attract a lot of families. There are brand outlets for electronics, toys, sports, music, car accessories etc and also lots of other shops. In short, this is one of the most popular family oriented mall which focusses on its atrium area and hence it is selected for this study.

Initially, site visits were made to take photographs and to note down the materials. The working profile of the mall and the drawings were obtained from time square center mall management. Figures 4.1 and 4.2 illustrate the section and floor plan drawings. The building is divided into 16 zones totally and using the model builder ModelIT in IES VE software, the model was virtually built. Ground floor is divided into 10 zones namely, Zone Atrium, entrance lobby, area adjoining atrium, zone 8 – the kiosks in the adjoining area, zone 4,5,6 and 7 – the 4 showroom areas around adjoining area, zone corridor, and zone 9- the back side store/office area. First floor is divided into 6 zones namely, adjoining area, zone 1,2,3 – the showroom area around adjoining area and 2 corridor zones on left and right. The schematic drawing showing the zones is illustrated in Figure 4.3. The weather data for Dubai was incorporated using the weather data base manager and the building model was rotated to 140^o to replicate the orientation of the existing Times square mall. Next using the construction data base in the Building template manager, a material template (Fig 4.4) for the existing materials used in site was created. Figure 4.5 shows the images of Times Square mall from virtual model in IES-VE and as on site photographs.

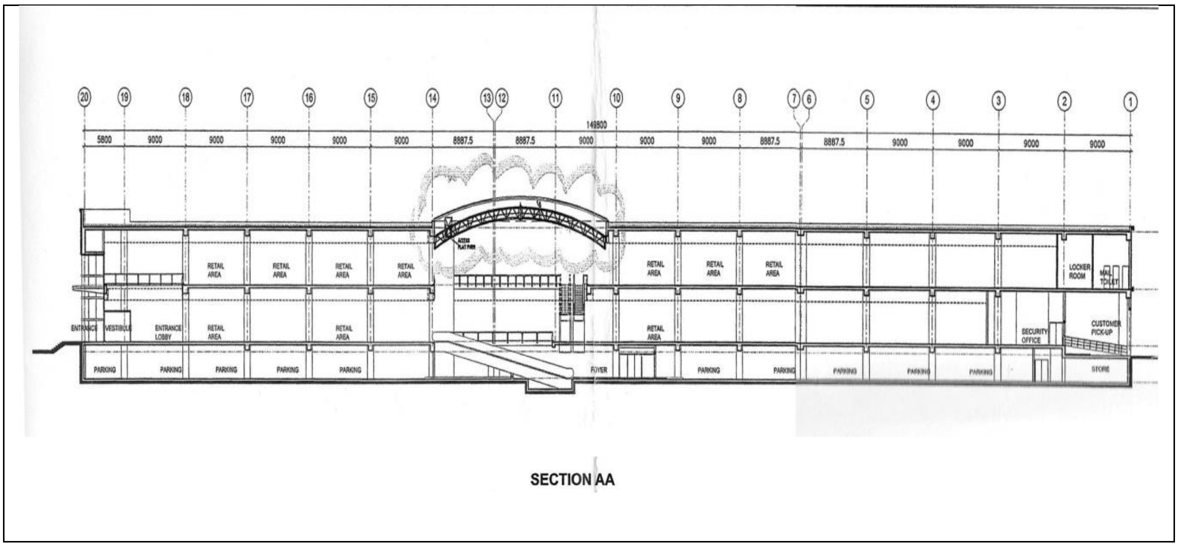


Figure 4.1 : Section detail of Times Square Mall Dubai

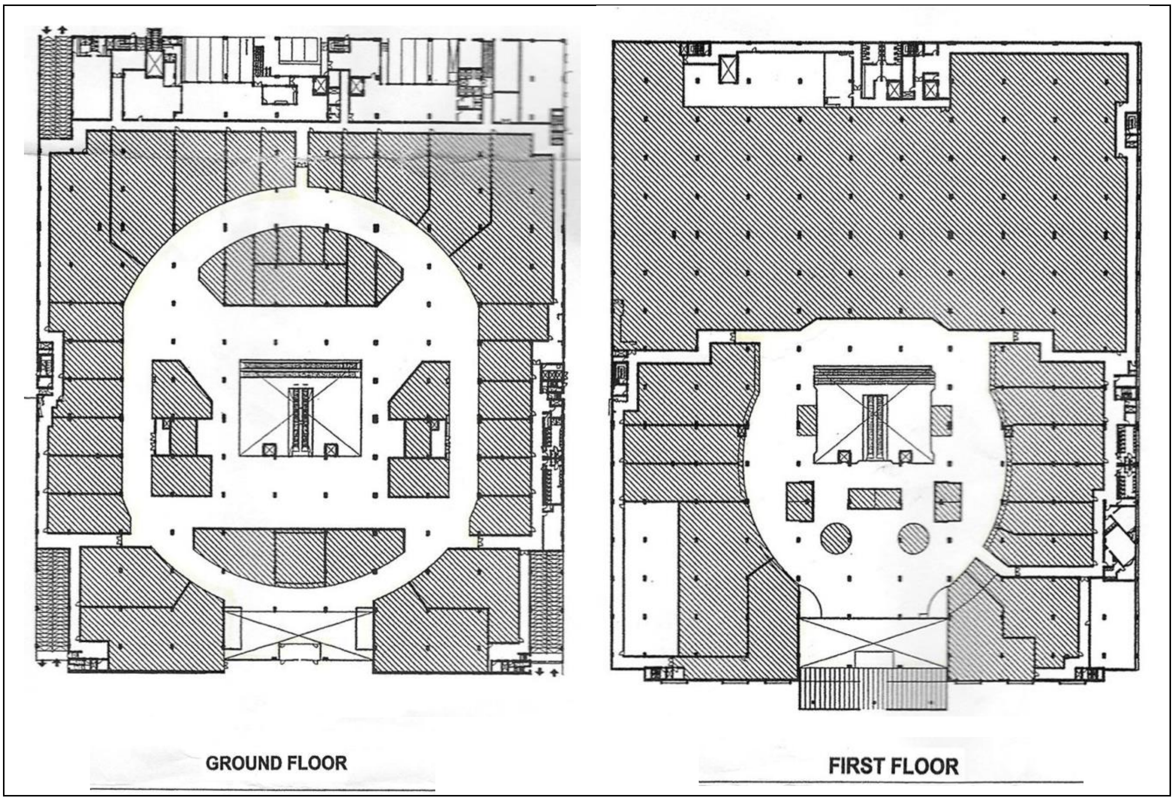


Figure 4.2 : Floor Plan of Times Square Mall Dubai

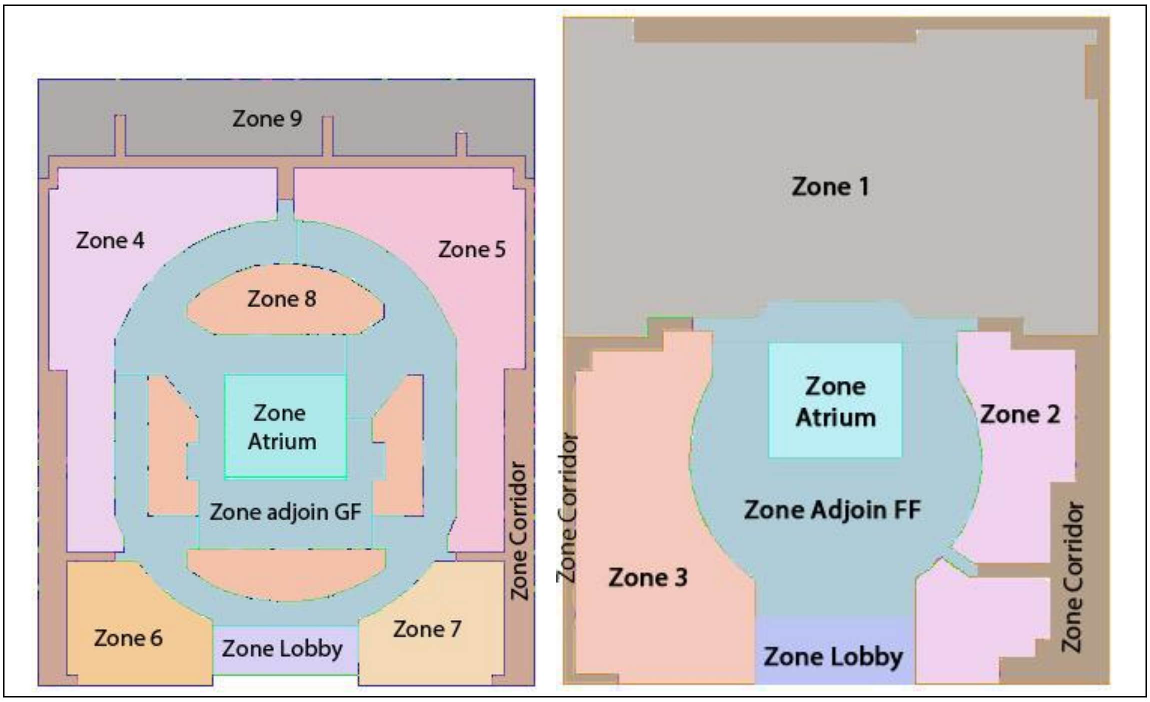
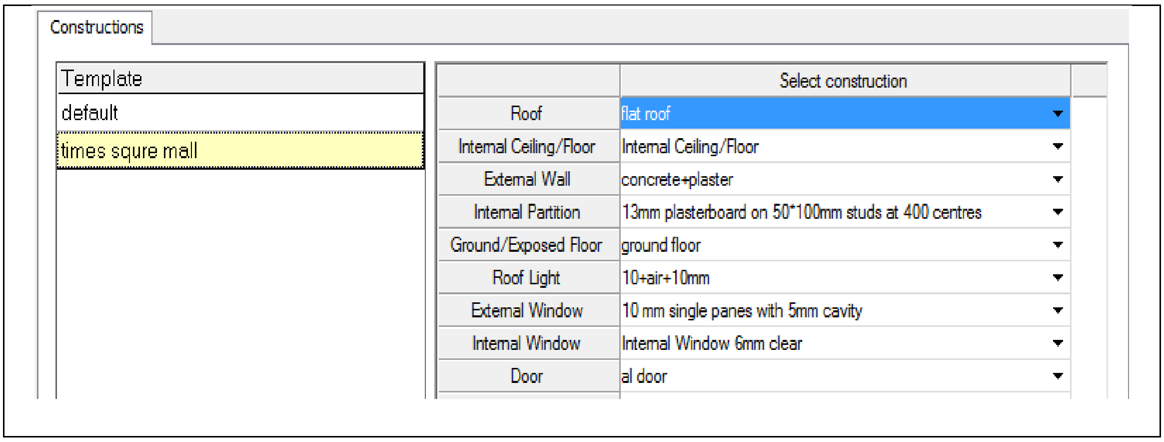


Figure 4.3 : Schematic drawing of Floor plans showing the Zones


Constructions

Template
default
times squre mall

	Select construction
Roof	flat roof
Internal Ceiling/Floor	Internal Ceiling/Floor
External Wall	concrete+plaster
Internal Partition	13mm plasterboard on 50*100mm studs at 400 centres
Ground/Exposed Floor	ground floor
Roof Light	10+air+10mm
External Window	10 mm single panes with 5mm cavity
Internal Window	Internal Window 6mm clear
Door	al door

Figure 4.4 : Construction template for Base case (IES-VE Acdb)

Times square center mall timings are 10 am to 10pm on week days and 10 am to 12 pm on weekends. Hence different profiles for week days and week ends were created for air conditioning, lights, people and dimmer in APpro as described below. Normally in the malls across UAE, the air-conditioner is not switched off after the mall timings, since the materials inside showrooms will be affected by a drastic change in temperature and there may be people working on maintenance in the night time. Hence the after working hours profile is given as 50% for air-conditioner (Fig 4.6) and 25% for lights (Fig 4.7). People profile (Fig 4.8) is given as 0.1% of the mall working time profile which accounts for the few people in maintenance works and for security after the mall working times.

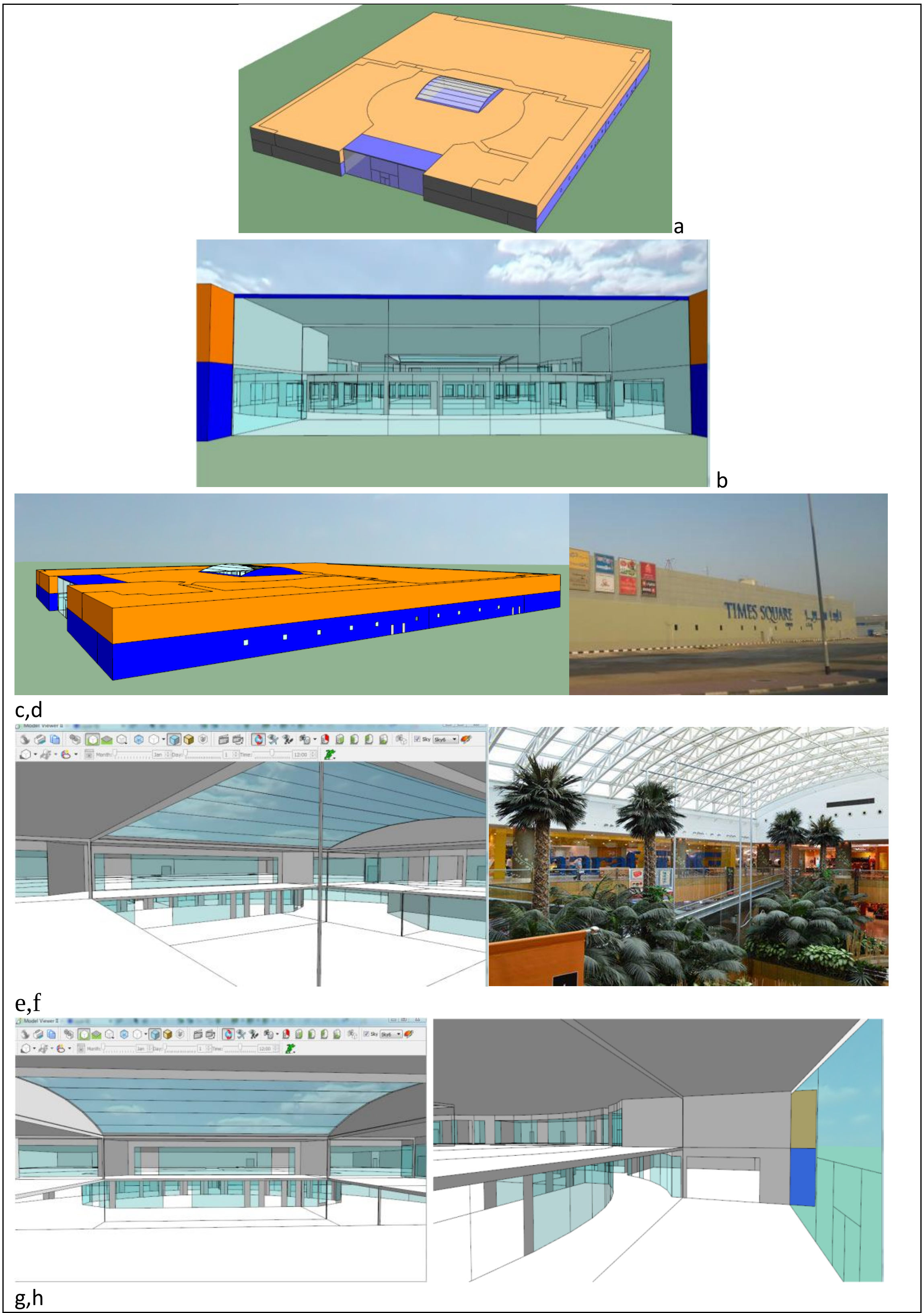


Figure 4.5 : Images of Times Square Mall,Dubai from virtual model in IES-VE and as on site photograghs

a) birds eye view of Times square mall –virtual model ; b) view from entrance;
c,d) view from South West side; e,f) view of atrium from first floor ;
g) view of atrium facing sharaf DG showroom; h) interior view from entrance lobby

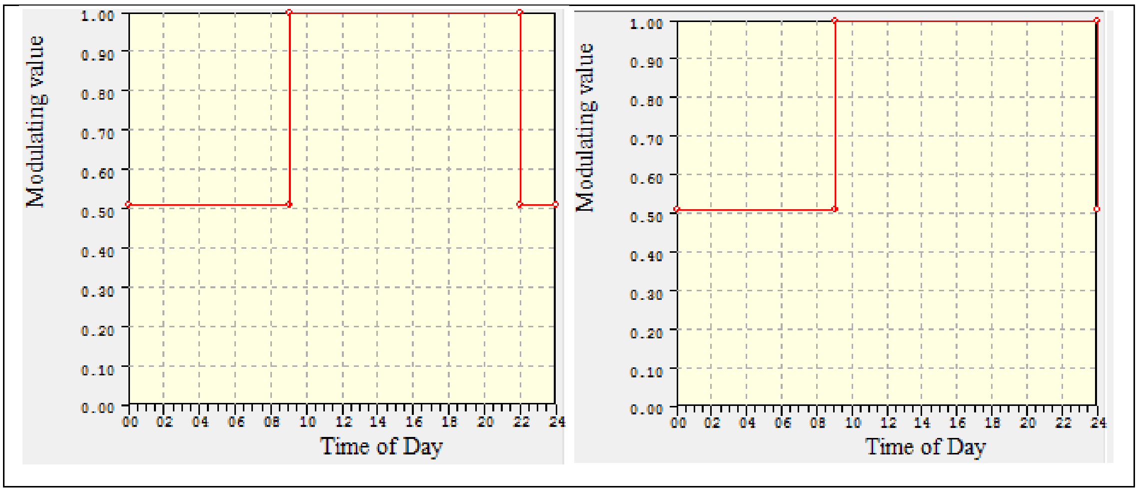


Figure 4.6 : Weekday and weekend profile for airconditioning (IES-VE APpro)

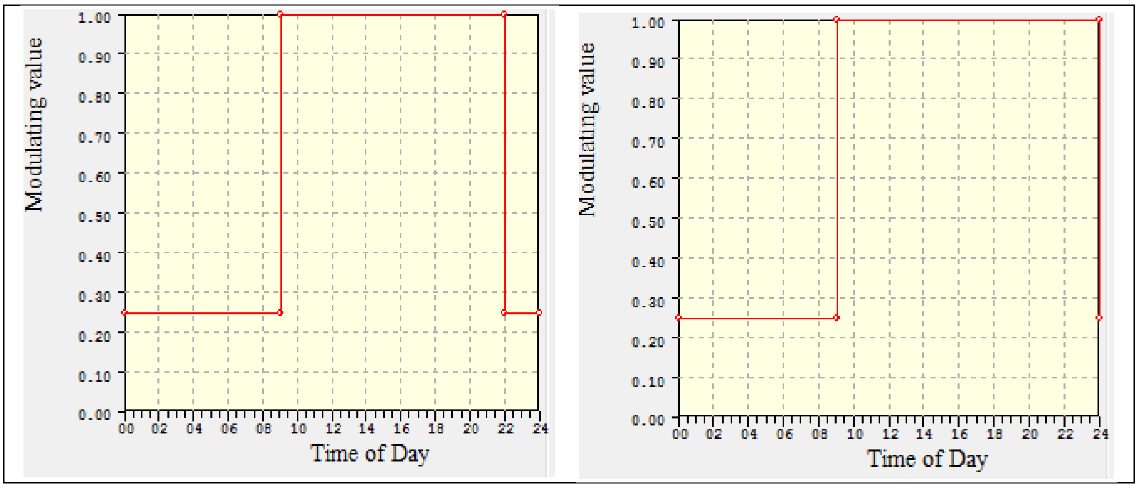


Figure 4.7 : Weekday and weekend profile for lights (IES-VE APpro)

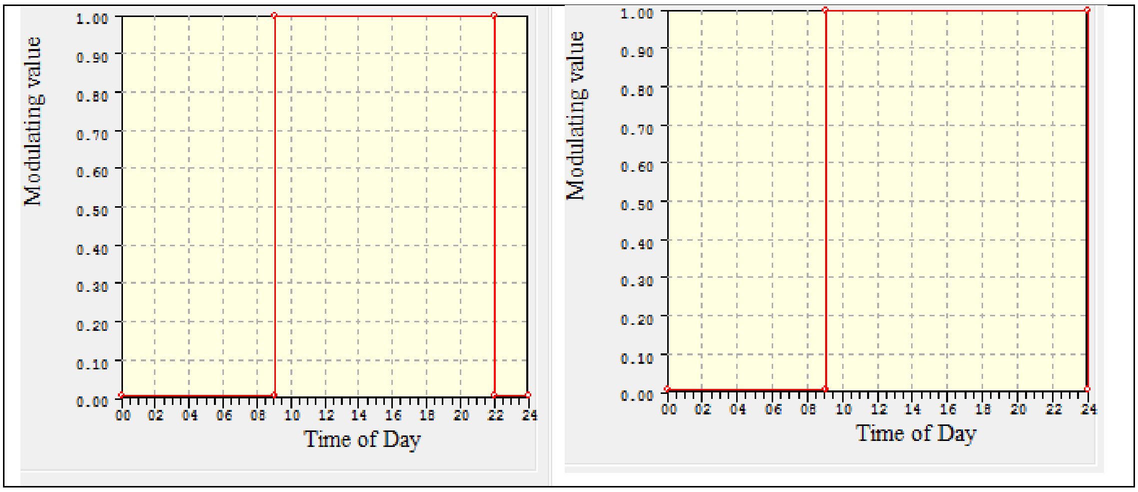


Figure 4.8 : Weekday and weekend profile for people (IES-VE APpro)

A thermal template for the base case was created in the Building template manager using all these above profiles. The other factors taken into consideration while creating this thermal template are humidity, internal gain and air infiltration. Humidity percentage is controlled at 30 to 70% since humidity outside this range will lead to thermal discomfort. Airchange per hour (ACH) for infiltration is by default 0.25 ach in IES software and this is maintained as it is. For the internal gain, two factors – lights and people are considered. From the ASHRAE standards the heat gain in a conditioned mall for people is taken as maximum sensible gain of 75W/m^2 and maximum latent gain of 55W/m^2 with an occupancy density of 10 m^2 /person in a mall and heat gain from lights is 15W/m2 (ASHRAE 2007). Appendix A shows the ASHRAE standards. This Thermal and Material template was incorporated into the model using Apache. Thermal analysis for this base case is done in ApacheSim.

Any research on atrium is not effective without sensors since the main purpose of atrium is to bring in sunlight and reduce the lighting energy. If there are no sensors installed lighting energy will not change and the study will not be complete. Hence for this study, the lights are controlled by installing sensors in the atrium and adjoining spaces in the building model that controls the light when the illumination by daylight reaches 500 lux. Using IES-VE Radiance module, Sensors are placed in the atrium and the adjoining spaces in the GF and FF (Table 4.1). Thermal analysis is done again for this basecase with sensor using the radiance link in ApacheSim. Simulation results obtained in IES-Vista showing the monthly breakup of energy consumption, cooling load, dehumidification load, carbon emission and lights energy for the 2 cases is shown in Appendix C.

Table 4.1 : Sensor settings (IES-VE Radiance)

Room	Sensor ID	Position	Direction	On/Off
[ZN000001] zone 8 gf	ZN000001:1	-104.867, -48.000, 5.228	0.00, 0.00, -1.00	ON
[ZN000015] Zone adjoin gf	ZN000015:1	-104.775, -100.000, 5.228	0.00, 0.00, -1.00	ON
[ZN000000] Zone Atrium	ZN000000:1	-104.500, -79.384, 10.675	0.00, 0.00, -1.00	ON
[ZN000006] Zone adjoin ff	ZN000006:1	-102.000, -98.000, 10.675	0.00, 0.00, -1.00	ON
[ZN000007] Zone lobby	ZN000007:1	-104.500, -134.724, 10.675	0.00, 0.00, -1.00	ON

4.2 Energy Calculations in IES-VE

Before getting into the data analysis stage, it is necessary to understand how the final energy consumption is calculated by the IES-VE Vista module. Hence a study of breakup of total energy consumption as given in IES VE Vista Tutorial, version 8 is undertaken and it reveals that the total energy consumption is the sum of system energy, lights energy and equipment energy. The detailed breakup is illustrated in Figure 4.9. It can be seen that Cooling plant sensible load is sum of internal gain, external conduction gain, solar gain, internal conduction gain and infiltration gain. The sum of cooling plant sensible load and dehumidification latent load is the total load on chillers which when divided by the cooling delivery efficiency of the system (i.e., 1.08) gives the Chiller load. When that is divided by Chiller seasonal efficiency (i.e., 2.5) gives the chiller energy. The sum of chiller energy and fan/pump energy gives the system energy. This system energy together with light and equipment energy gives the total energy consumption of the building. Annexure B illustrates how the total energy consumption is arrived for one of the cases tested namely, flat glazed roof beginning from the summation of cooling plant sensible load up to total energy consumption.

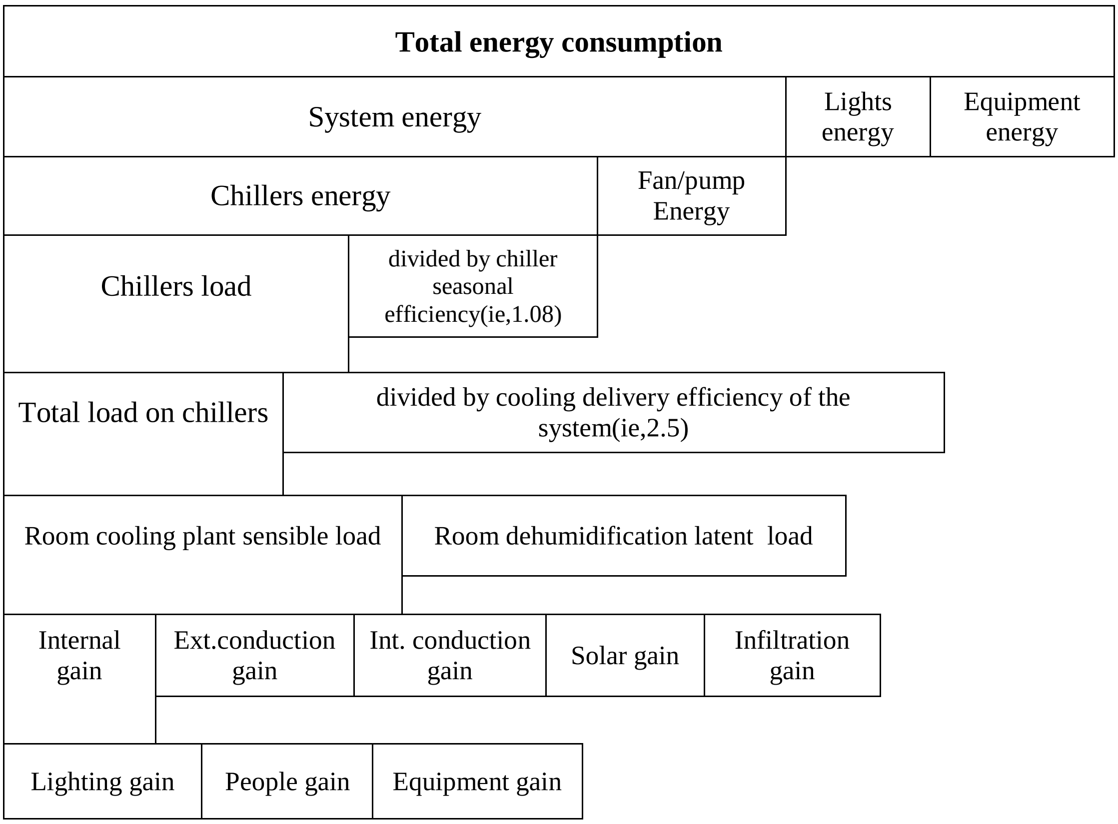


Figure 4.9 : Breakup of total energy consumption (IES n.d)

From the study of energy calculations in IES, the following point are noted to be kept in mind during the data analysis stage of this research.

- The overall performance of Atrium should be judged by total energy consumption.
- It can be noted that the total energy consumption is always a lesser value than the cooling load (Table 4.2), since the sum of cooling and dehumidification load is converted into chiller load by dividing it by cooling delivery efficiency of the system (ie.,2.5) and this chiller load is divided by chiller seasonal efficiency (ie.,1.08) to get the chiller energy and then system energy.
- In some cases we find that the cooling load is lesser, but when added with light energy, the final energy consumption will become high and vice versa. This is due to the fact that the total energy consumption is summation of system energy, light energy and equipment energy. In some case due to lesser light penetration, the cooling load and hence system energy is less, but light energy required becomes higher. Finally when they are added up, the total energy consumption becomes high. (eg. variable – number of floors). Hence there is always a balance between light energy and system energy.
- It can also be noted from simulation results, that the percentage reduction of energy consumption (MWh) and Carbon emission (kgCo2) is always the same (Table 4.2). This is due to the fact that carbon emission is deduced from the energy consumption value in IES. An analysis of simulation results shows that a conversion factor of 519 is used to convert energy consumption in MWh to carbon emission in kgCo2 (Table 4.2). i.e., IES calculates that 1 MWh of energy consumed will produce carbon emission of 519 kgCo2.

Table 4.2 : Carbon emission deduced from energy consumption

Number of floors	**2**	**4**	**8**
Total energy consumption (MWh)	7406.8	14036.37	27354.65
Multiplied by conversion factor	519		
Carbon emission (kgCO2)	3844127	7284877	14197053

- Thermal performance will be highlighted by the analysis of cooling load and dehumidification load. If further analysis of sensible cooling load is necessary, then the Internal gain, External conduction gain, Solar gain, Infiltration gain, Internal conduction gain are studied and if further analysis of latent dehumidification load is necessary, Infiltration gain, MacroFlo gain are studied.

- Daylight performance will be highlighted by the analysis of Light energy required.
- Hence in this research, in data analysis stage the thermal performance is rated based on the room cooling plant load (MWh), room dehumidification plant load (MWh) and daylight performance is rated base on light energy consumption (MWh). Finally, overall performance of the building based on Yearly energy consumption (MWh). Total carbon emission (kgCo2) performance percentage will be same as that of energy consumption.

4.3 Data analysis of the base case

Simulation results obtained in IES-Vista showing the monthly breakup of energy consumption, cooling load, dehumidification load, carbon emission and lights energy for the 2 cases is shown in Appendix C. Table 4.3 summarizes the simulation results with and without sensors.

Table 4.3 : Comparison of base case with and without sensor

Options	Yearly energy consumption (MWh)	cooling plant load (MWh)	dehumid. Plant load (MWh)	Total Light energy (MWh)	Total carbon emission (kgCo2)
Base case with no sensor	8092.3 (228.5 kWh/m^2)	8326.46	1500.42	3178.84	4199894
Base case with sensor	7406.8 (209.2kWh/m^2 (-8.47%)	7880.16 (-5.36 %)	1500.48 (0%)	2716.48 (-14.55%)	3844127 (-8.47 %)

The results show that installing a dimming sensor in atrium and adjoining areas which will control the lights when room illumination level by daylighting goes above 500 Lux, reduces energy consumption and carbon emission by 8.47%, cooling load by 5.36%, lights energy by 14.55% and there is no change in dehumidification plant load.

The dehumidification plant load remains the same at 1500MWh annually since the fresh air coming in through HVAC system and infiltration is not altered in both cases (Appendix C).

Figure 4.10 compares the light energy for the mall building with and without sensor. It can be seen that when no sensors are used, the light energy required is constant in summer and winter. But when sensors are active, the light energy required drops considerably (-14.55%) reducing the total energy consumption (Table 4.3). The sensors cut off the lights when illumination level reaches 500 Lux, thus reducing the lights energy required. It can also be noted that the light gain varies in summer and winter depending on the sunrise and sun set times. The cooling plant load is reduced by 5.36 % when there is sensor . This is due to the reduction in lighting gain since the sensors cut off the lights when illumination level reaches 500 Lux. Appendix C shows breakup details of cooling load for base case with and without sensor from IES-Vista.

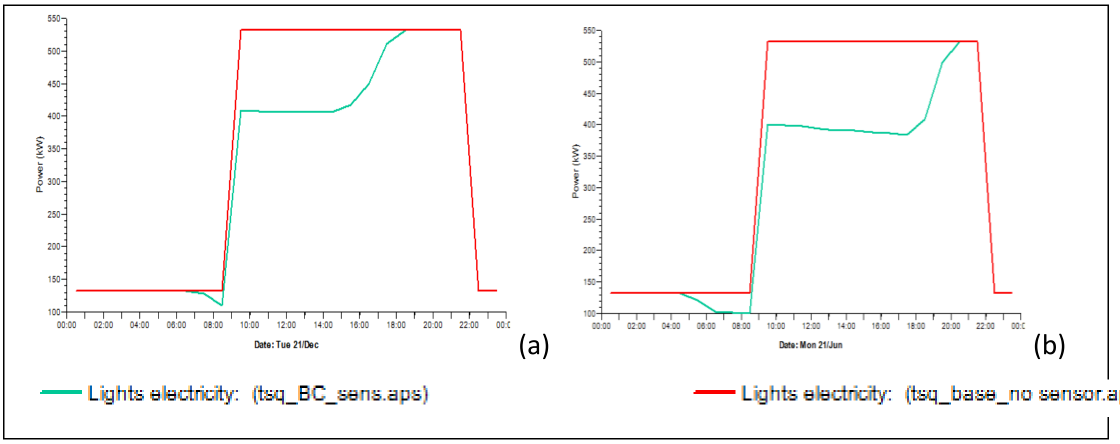


Figure 4.10 : Light energy comparison with and without sensor
(a) in winter and (b) in summer (IES-VE Vista)

It can be observed in Fig 4.11 that the cooling plant load is much higher in summer compared to that of winter since the dry bulb temperature is high in summer. The maximum cooling load on June 21 and Dec 21 are 1980 kw and 814 kw and maximum dry bulb temperature 42^{0}C and 22^{0}C respectively. Further observation shows that the cooling plant load almost takes the profile of dry bulb temperature.

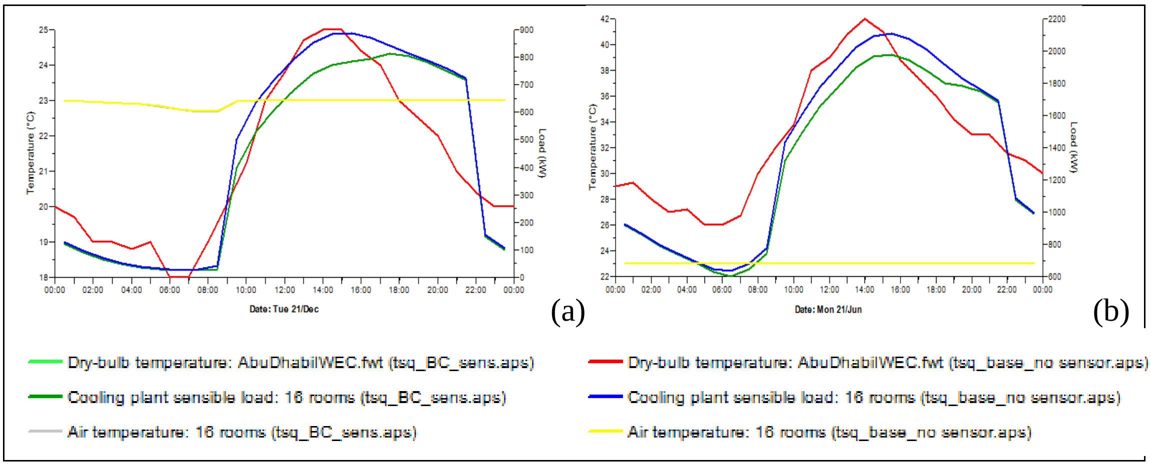


Figure 4.11 : Cooling plant sensible load, Dry bulb temperature, Air temperature (a) in winter and (b) in summer (IES-VE Vista)

The total energy consumption drops down to 8.47% mainly due to reduction in lights energy consumption, when sensors are placed inside the building. Hence, sensors play a vital role and any research on atrium is not effective without sensors. For e.g., when number of floors increase or when the roof profile is changed the light transmitted inside the building through the atrium varies, lighting energy needed may become less or more depending on each case and only if sensor is placed inside the building it will control the artificial light needed, thus impacting the total energy consumption. If there is no sensor, the effect of light transmitted inside will not be taken into consideration and thus the study will not be complete. Hence for testing all other variables, the model with sensors will be taken as the base case.

4.4 Simulation of model with altered variables

From the literature review, the various parameters/ variables that influence or increase the thermal performance and the daylight performance and of the building are identified and the variables to be tested are established. The literature survey identified Glazing profile, Number of floors, LSG ratio of the glazing system and Sky condition as factors that influence the amount of daylight coming inside an atrium and impact the energy consumption of the atrium. Further, U value of envelope and Roof ventilation are also taken as factors that influences the thermal performance of atrium. These variables are taken for further research. The test matrix shown in Table 3.1 in the previous chapter summarizes all variables and their values to be tested. Selection of the range of values for each variable is explained in the following sections.

In the following sections, the base model is modified by altering the variables one at a time while keeping all other values constant and the results are analyzed to find the optimal values for each variable.

4.4.1 Variable – Roof ventilation

When the outside dry bulb temperature goes below 22ºC and the outside air humidity is less than 90%, it is a comfortable thermal environment inside the mall that does not need mechanical ventilation and hence, roof ventilation could be provided by a openable roof in the atrium space. Therefore ventilation analysis is done in IES-VE MacroFlo and Apache to find the amount of thermal load that could be reduced if the openable roof functions under comfortable climatic conditions outside – i.e., outside dry bulb temperature < 22ºC and outside air humidity < 90 %. Analysis done in IES-VE Vista, (Fig 4.12) shows that the outside air temperature drops below 22ºC for 2275 hours out of 8760 hours (25.9%) and the outside relative air humidity is above 90% for 546 hours.

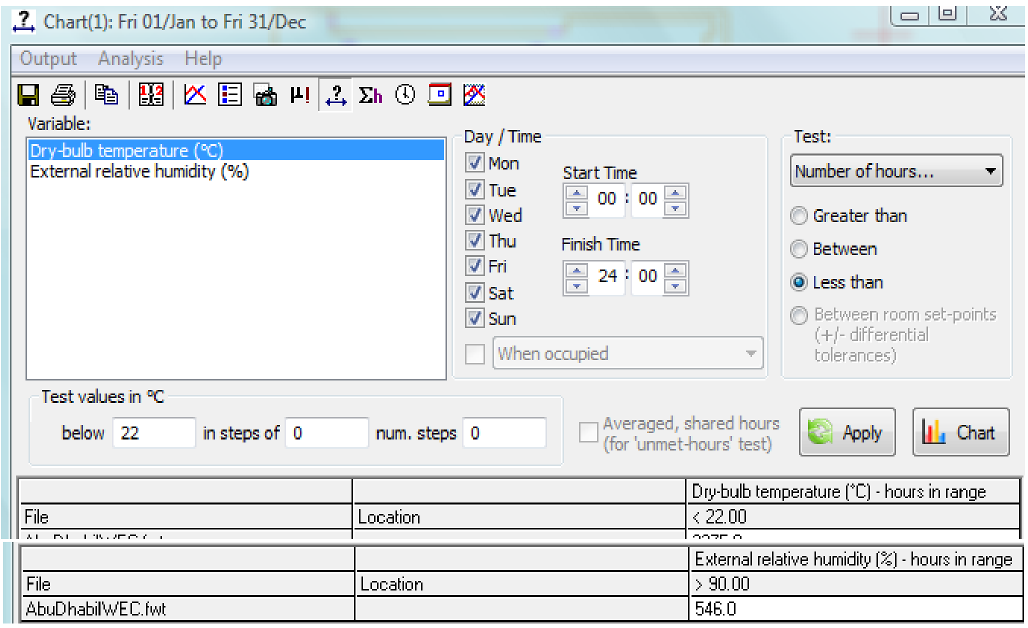


Figure 4.12 : Chart for number of hours when drybulb temperature <22ºC and External humidity >90º (IES-VE Vista)

A Vent opening profile with required condition was created in APpro (Fig 4.13). Atrium roof opens automatically when outside dry bulb temperature drops below 22ºC and external humidity is below 90%. But if any one of the above conditions is not met, then the roof remains closed.

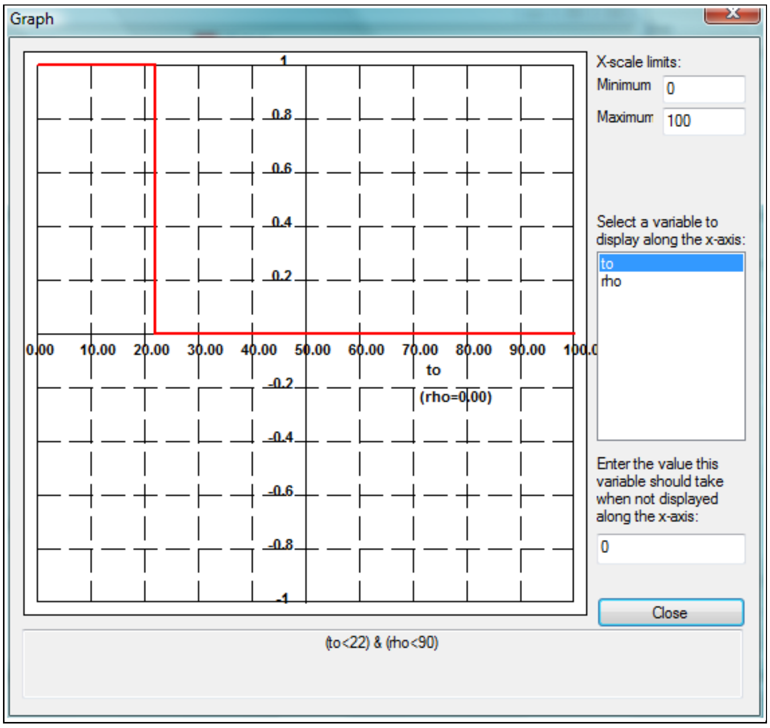


Figure 4.13 : Vent opening profile (IES-VE APpro)

In MacroFlo opening data base manager, 8 varying opening types were created with 10, 20, 30, 40, 50, 60, 80 and 100 percentage openable area respectively as shown in Figure 4.14. Base case is the case at site which is 0% open. Assigning these roof openings to the Atrium roof light, one at a time with all other variables constant, simulation for thermal analysis was done in ApacheSim with MacroFlo link to find the best value for openable area.

Ref. ID	Description	Exposure Type	Opening	Openable Area %	Equivalent Orifice Area (% of Gross)	Crack Flow Co-efficient (l/(s·m·Pa^0.6))	Crack Length (% of Opening Perimeter)	Opening Threshold (°C)	
XTRN0000	External window opening	05. semi-exposed wall	Custom / sharp edge ori...	0.000	0.000	0.15	0.000	0.00	on c
XTRN0001	Roof opening 10	02. exposed roof <10deg	Custom / sharp edge ori...	10.000	10.000	0.15	0.000	22.00	Roof
XTRN0002	Roof opening 20	02. exposed roof <10deg	Custom / sharp edge ori...	20.000	20.000	0.15	0.000	22.00	Roof
XTRN0003	Roof opening 30	02. exposed roof <10deg	Custom / sharp edge ori...	30.000	30.000	0.15	0.000	22.00	Roof
XTRN0004	Roof opening 40	02. exposed roof <10deg	Custom / sharp edge ori...	40.000	40.000	0.15	0.000	22.00	Roof
XTRN0005	Roof opening 50	02. exposed roof <10deg	Custom / sharp edge ori...	50.000	50.000	0.15	0.000	22.00	Roof
XTRN0006	Roof opening 60	02. exposed roof <10deg	Custom / sharp edge ori...	60.000	60.000	0.15	0.000	22.00	Roof
XTRN0007	Roof opening 80	02. exposed roof <10deg	Custom / sharp edge ori...	80.000	80.000	0.15	0.000	22.00	Roof
XTRN0008	Roof opening 100	02. exposed roof <10deg	Custom / sharp edge ori...	100.000	100.000	0.15	0.000	22.00	Roof

Figure 4.14 : Variable values for 8 openable roof lights and base case for roof ventilation analysis (IES-VE MacroFlo)

Simulation results obtained in IES-Vista showing the monthly breakup of energy consumption, cooling load, dehumidification load and lights energy for all 9 cases is shown in Appendix D. The results are summarized in Table 4.4.

Table 4.4 : Comparison of results in ApacheSim for roof ventilation analysis

Options (Openable area %)	Yearly energy consumption (MWh)	Room cooling plant load (MWh) [Sensitive load]	Room dehumidification plant load (MWh) [Latent load]	Light energy (MWh)
Base case - 0% (closed)	7406.80	7880.16	1500.48	2716.48
V1 – 10%	7348.34 (- 0.79%)	7764.47 (-1.47%)	1499.22 (-0.08%)	2716.48
V2 – 20%	7323.58 (-1.12%)	7703.66 (-2.24%)	1510.46 (+0.67%)	2716.48
V3 – 30%	7312.66 (-1.27%)	7663.94 (-2.74%)	1528.31 (+1.86%)	2716.48
V4 – 40%	7310.22 (- 1.30%)	7635.90 (-3.10%)	1551.41 (+3.40%)	2716.48
V5 – 50%	7313.49 (-1.26%)	7614.83 (-3.37%)	1578.95 (+5.23%)	2716.48
V6 – 60%	7320.39 (-1.17%)	7598.33 (-3.58%)	1609.18 (+7.24%)	2716.48
V7 – 80%	7341.36 (-0.88%)	7573.93 (-3.89%)	1675.40 (+11.66%)	2716.48
V8 – 100%	7368.04 (- 0.52%)	7556.49 (-4.12%)	1746.07 (+16.37%)	2716.48

Results Analysis:

The results obtained from simulation of 9 cases of openable roof area including the base case is analyzed for thermal and daylight performance. Following observations were made from the results.

- The total lights energy required for the building remains constant for all cases since the amount of light coming inside atrium is not changed. Hence the variable –roof ventilation does not have any effect on the daylight performance. [Table 4.4]
- The total energy consumption of the building is minimum when area of roof openable is 40%, and it increases thereafter. [Table 4.4, Fig 4.15]
- This is due to dehumidification plant load which keeps increasing as openable area increases though the cooling plant load decreases.[Table 4.4, Fig 4.16 & 4.17]. The cooling plant load of the building is a sensitive load and the dehumidification plant load is a latent load. As the openable area increases bringing more cool and humid air in winter, the latent load increases due to humidity of air while the cool

air decreases the sensible cooling load. So the cooling plant load keeps decreasing while dehumidification plant load keeps increasing and at 40% openable area, they reach a point where the energy consumption starts to increase. Monthly break-up of MacroFlo ventilation latent gain for all cases is shown in Appendix D.

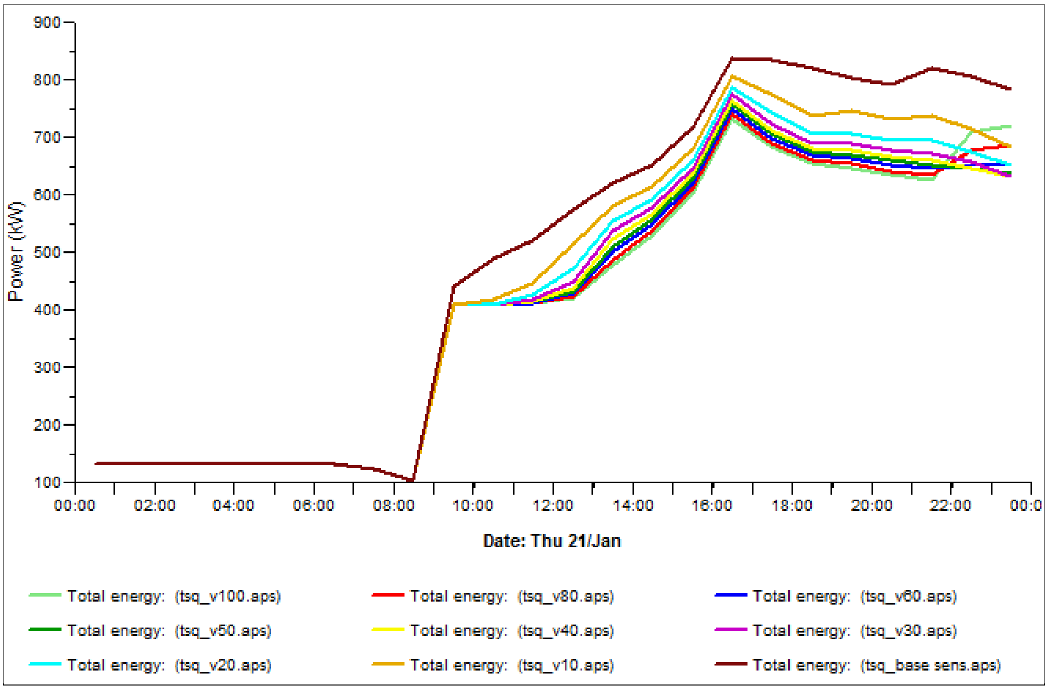


Figure 4.15: Total energy consumption increasing after 40% openable area (IES-VE Vista)

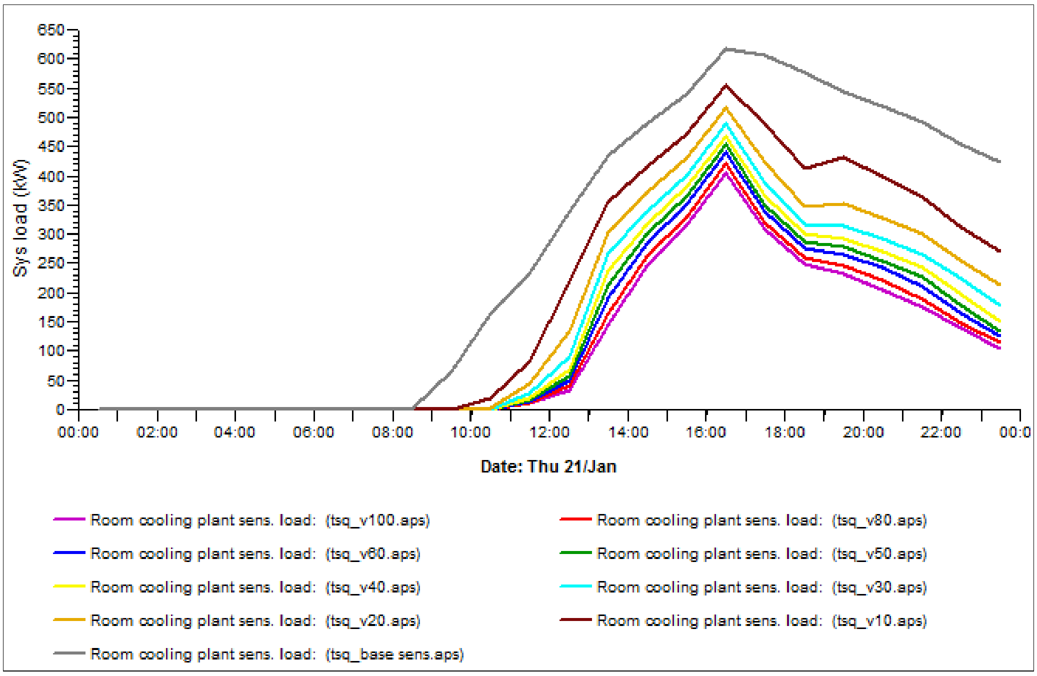


Fig 4.16 : Cooling plant load decreasing when openable area increases (IES-VE Vista)

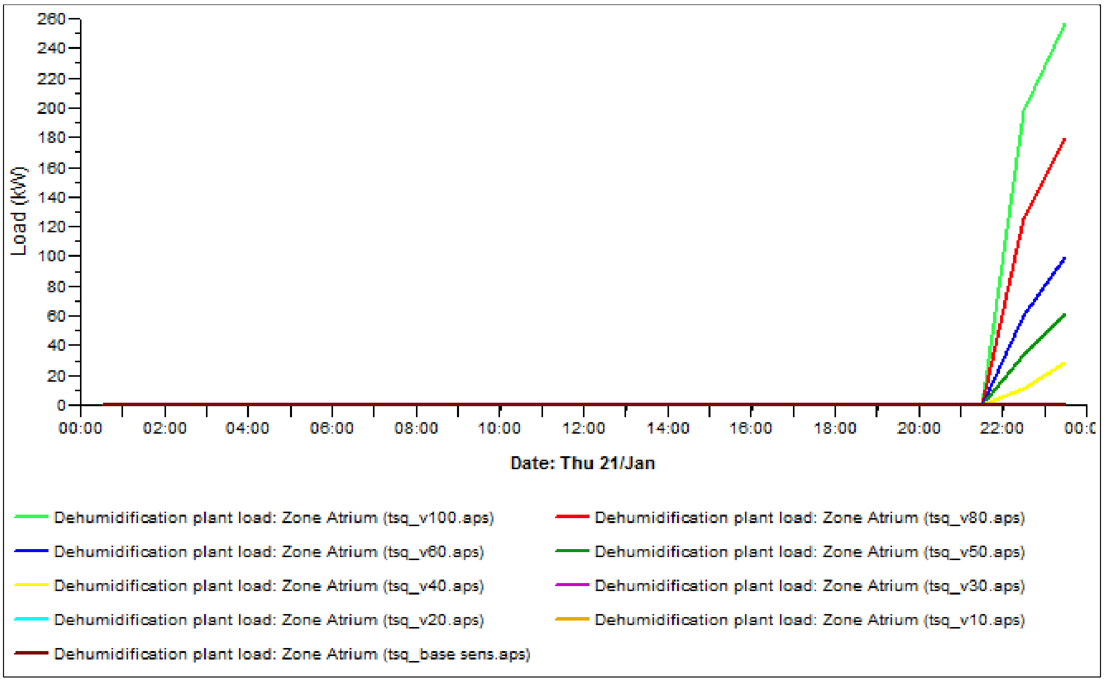
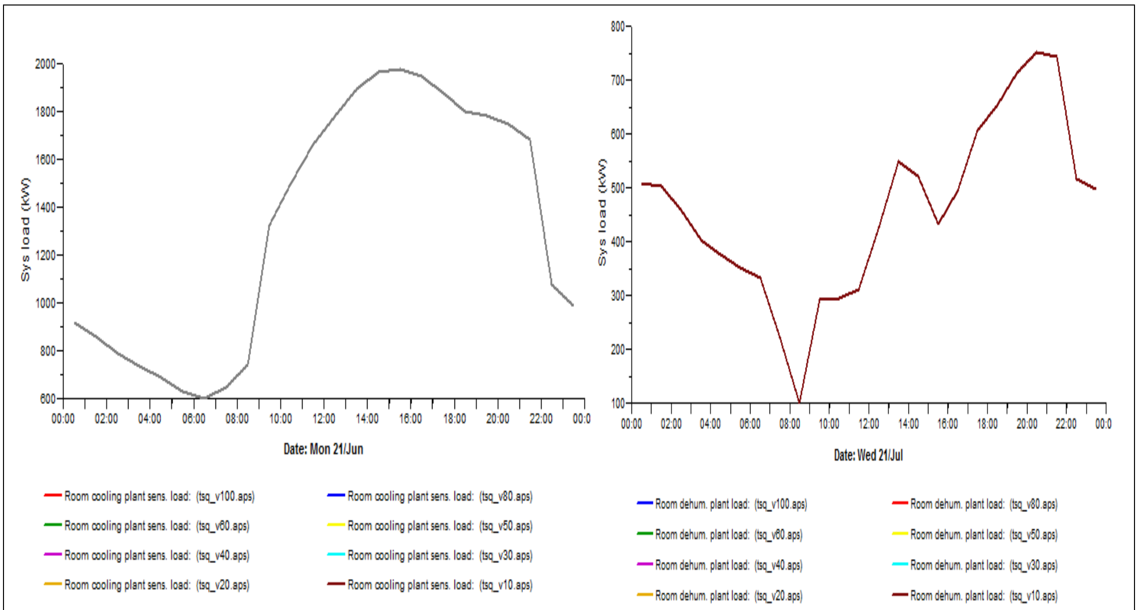


Figure 4.17: Dehumidification plant load for various vent opening area (IES-VE Vista)

- Further it can be seen that during summer months there is no change in energy consumption. The reason is that during summer months the vent opening does not open since the outdoor air condition does not satisfy the requirements for the vent to open. (Dry bulb temperature < 22^{O}C and humidity < 90%) [Fig 4.18 & 4.19]. It can be seen from Table 4.5, that the summer months records no variation in latent and sensible load since the roof does not open due to unsatisfactory outdoor climatic conditions.



(a) (b)

Figure 4.18 : Total Cooling plant load (a) and dehumidification plant load (b) in summer with no variation (IES-VE Vista)

Table 4.5 : Space conditioning Latent load and Sensible load for base case, 40and 100% openable area showing no variation in summer

	Space conditioning LATENT LOAD-(MWh)			Space conditioning SENSIBLE LOAD- (MWh)		
	tsq_v100	tsq_v40	tsq_base	tsq_v100	tsq_v40	tsq_base
Jan 01-31	52.87	20.59	21.55	135.53	154.95	224.45
Feb 01-28	51.98	24.06	21.33	221.22	238.55	289.92
Mar 01-31	121.59	82.74	69.92	379.12	392.30	431.47
Apr 01-30	88.92	67.37	58.51	605.97	611.00	621.34
May01-31	109.23	108.17	107.68	857.57	857.87	858.35
Jun 01-30	180.73	180.73	180.73	934.29	934.29	934.29
Jul 01-31	256.90	256.90	256.90	1043.58	1043.58	1043.58
Aug 01-31	244.89	244.89	244.89	1053.77	1053.77	1053.77
Sep 01-30	256.97	256.97	256.97	912.77	912.77	912.77
Oct 01-31	152.13	145.54	141.90	725.00	726.05	727.97
Nov 01-30	150.14	120.94	105.55	469.21	474.09	484.89
Dec 01-31	79.72	42.53	34.55	218.45	236.67	297.37
Sum total	1746.07	1551.41	1500.48	7556.49	7635.90	7880.16

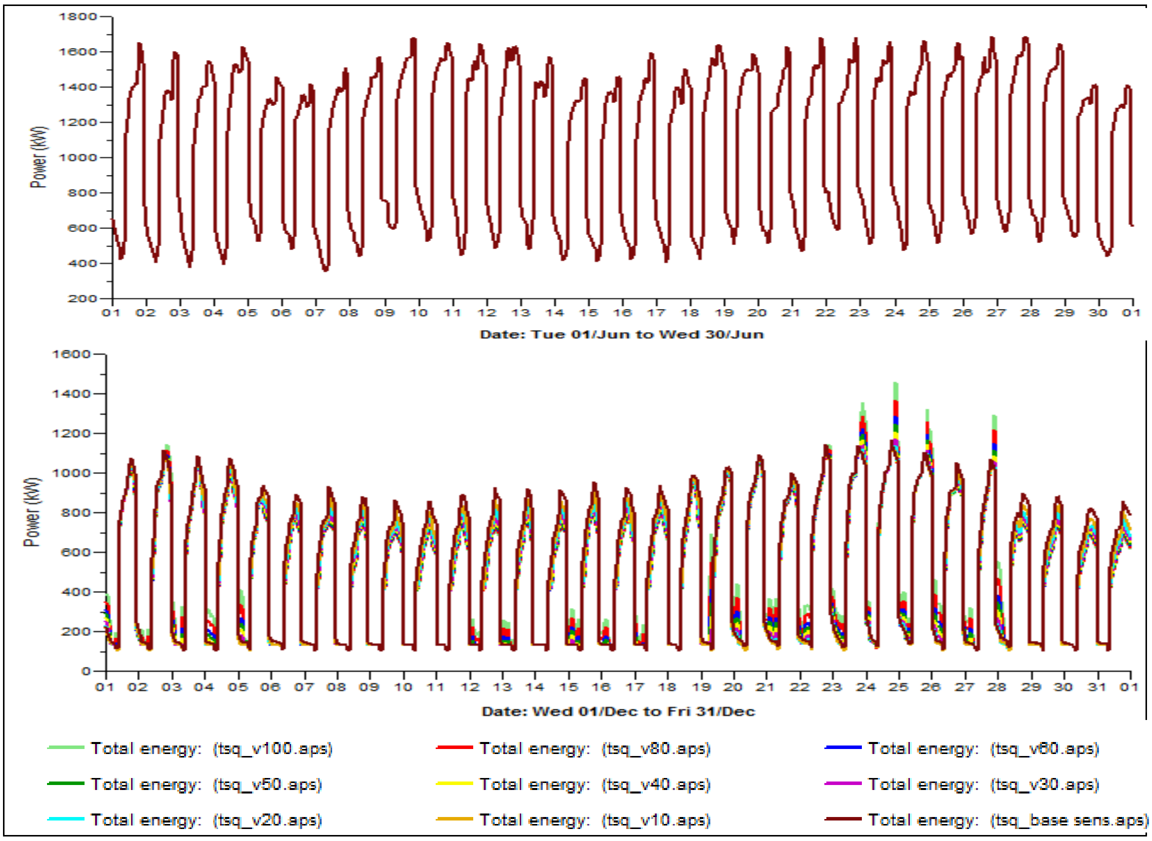


Figure 4.19 : Energy consumption during typical summer (no variation) and winter month (with variation) (IES-VE Vista)

From this analysis it is seen that 40% openable area reduces total energy consumption best by 1.30% (Table 4.4). Further study is done to analyze if having a dynamic opening, ie, variable openable area for different months instead of having 40% openable area for all months will be more efficient. From figure 4.20, it can be seen that having 50% operable area for month of January and Febraury, 30% for march, 20% for April, 10% for October, November and 40% for December will maximize the energy savings. Table 4.6 shows the total energy consumption for each month for the various openable areas tested and the last column R gives the reduction in energy consumption by having a dynamic openable area while compared to a constant 40% openable area. The minimum value and constant values are marked green and grey respectively. It can be seen that the total difference in energy consumption by having a dynamic openable areas and a constant 40% operable area will be only 6.88 MWh (0.09% of total energy).

Table 4.6 : Total energy consumption for 12 months for various openable areas and reduction in MWh compared to 40% opening by having a dynamic opening

	Total energy (MWh)									R
	tsqv10	tsqv80	tsqv60	tsqv50	tsqv40	tsqv30	tsqv20	tsqv10	tsq_base	
Jan	331.16	326.87	324.20	323.93	324.73	327.25	332.05	340.78	359.96	0.80
Feb	346.59	343.09	340.89	340.60	341.09	342.85	346.38	352.57	365.33	0.49
Mar	482.48	476.96	472.45	470.73	469.64	469.40	470.60	474.10	482.82	0.24
Apr	571.97	568.80	565.96	564.74	563.71	562.97	562.62	562.93	564.45	1.09
May	709.34	709.19	709.06	709.01	708.96	708.92	708.91	708.91	708.95	0.05
Jun	772.95	772.95	772.95	772.95	772.95	772.95	772.95	772.95	772.95	
Jul	875.80	875.80	875.80	875.80	875.80	875.80	875.80	875.80	875.80	
Aug	875.25	875.25	875.25	875.25	875.25	875.25	875.25	875.25	875.25	
Sep	806.87	806.87	806.87	806.87	806.87	806.87	806.87	806.87	806.87	
Oct	672.24	671.25	670.32	669.88	669.48	669.11	668.81	668.61	668.61	0.87
Nov	537.07	532.79	528.67	526.72	524.91	523.31	522.09	521.57	522.62	3.34
Dec	386.31	381.54	377.98	377.01	376.83	377.97	381.25	387.97	403.19	0
Sum total	7368.04	7341.36	7320.39	7313.49	7310.22	7312.66	7323.58	7348.34	7406.80	**6.88**

(R = Reduction in energy consumption with dynamic opening as compared to 40% opening area)

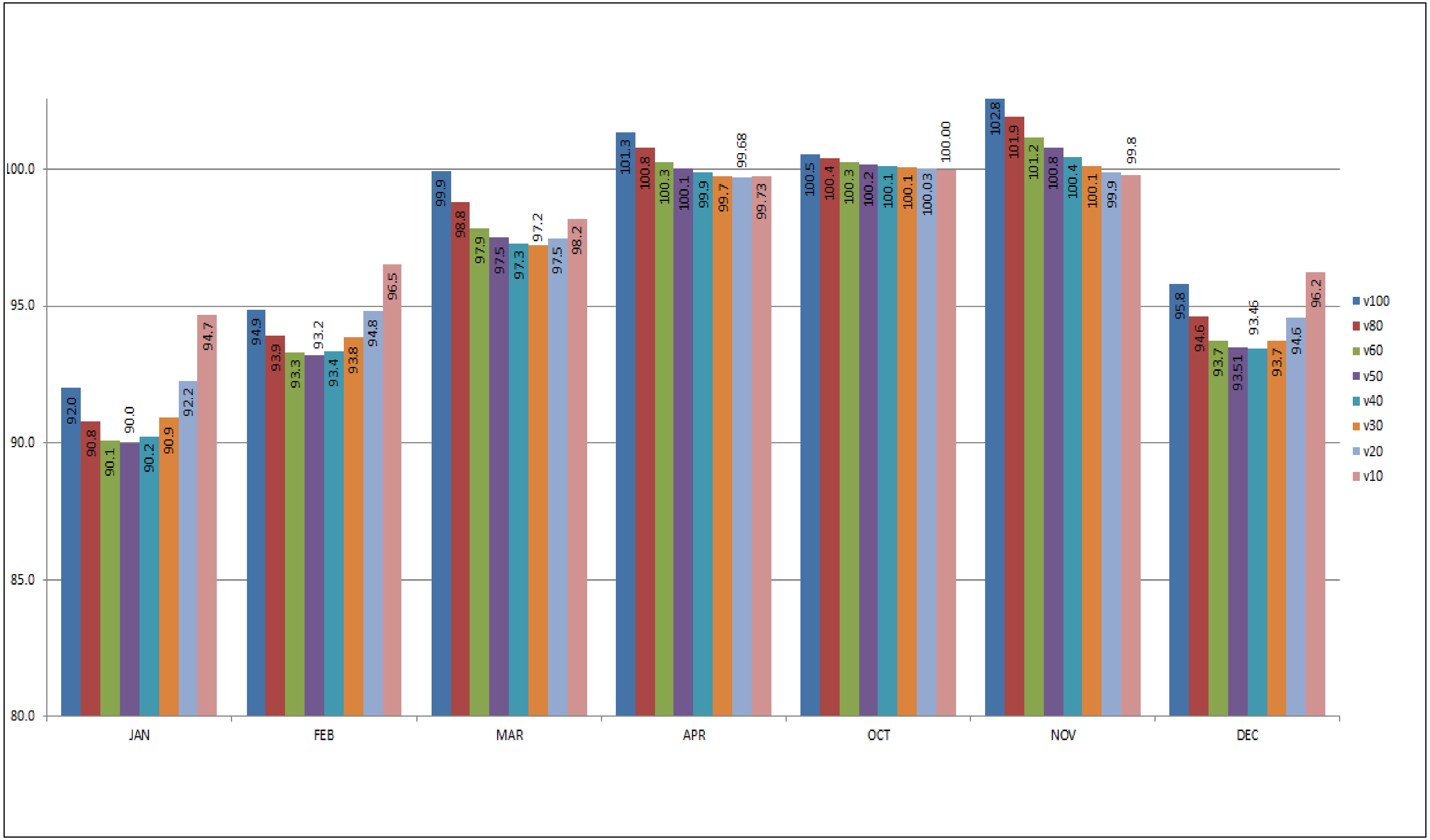


Fig 4.20 : Energy consumption % reduction for various openable areas for each month

This result is validated by creating a dynamic profile with the best openable area for each month as mentioned above in IES-VE MacroFlo data base manager and simulating the model in ApacheSim and recording the energy consumption. The results are recorded in Table 4.7 which compares the energy consumption in MWh for the base case, dynamic operable area and 40% operable area.

Table 4.7 : Results comparison from simulation of model in IES-VE

Month	Dynamic openable area		40% openable area	Base case
	openable area %	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)
Jan	50	323.926	324.729	359.961
Feb	50	340.598	341.094	365.331
March	30	469.403	469.642	482.817
April	20	562.622	563.714	564.453
May	40	708.909	708.959	708.950
June	40	772.950	772.950	772.951
July	40	875.799	875.799	875.798
August	40	875.250	875.250	875.250
Sept	40	806.871	806.871	806.872
Oct	10	668.615	669.475	668.614
Nov	10	521.573	524.906	522.617
Dec	40	376.826	376.827	403.188
Sum total		**7303.341**	**7310.215**	7406.800
Reduction		**-1.397%**	**-1.304%**	Basecase
Savings from dynamic operable area compared to 40% operable area = **6.874Mwh** (.09%)				

From Table 4.7, it can be seen that during the summer months when there is maximum energy consumption, the roof openings remain closed due to unsatisfactory external climatic conditions and hence the difference between the 40% openable area and dynamic openable area is only 0.09 % ie, is 6.874 MWh. Considering that the DEWA electricity tariff for that slab is 38 fils per kWh, the total reduction in cost will be only 2612.00 AED annually, which is a negligible amount compared to the total cost. Further, automated controls for dynamic opening will increase the building cost. Considering all these factors, 40% openable area which reduces energy consumption by 1.30% can be taken as the optimum value for roof ventilation openable area. This value will be the recommended value for roof openable area to enhance the thermal performance.

4.4.2 Variable – Number of floors

The existing Times Square Mall is G +1 floor. The thermal performance and daylight performance of the mall is tested by adding additional floors. The number of floors tested are 2, 4 and 8. The existing 2 storey mall has varying plan for its ground and first floor. In the model builder ModelIT in IES VE software, the G+1 model was made into a high rise building of 4 and 8 floors by copying the first floor and adding it as additional floors (Fig 4.21). Then sensors were placed in the atrium and the adjoining spaces of each floor using IES-VE Radiance module.

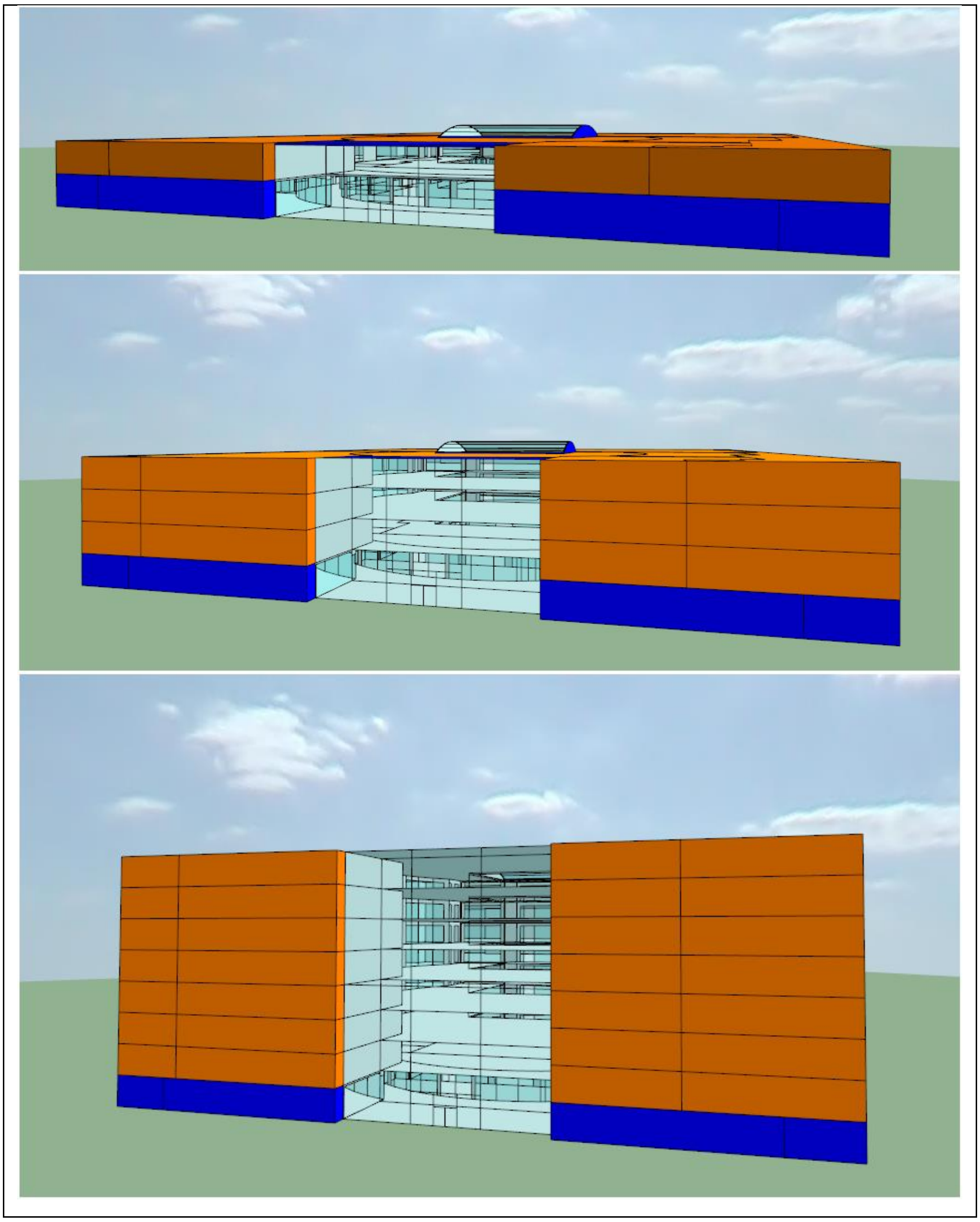


Fig 4.21 : Three cases tested for variable – no. of floors (IES-VE)

Thermal analysis is done with the radiance link in ApacheSim and the Simulation results obtained in IES-Vista showing the monthly breakup of energy consumption, cooling load, dehumidification load, lights energy and carbon emission for all 3 cases is shown in Appendix E. The results are summarized in Table 4.8.

Table 4.8 : Thermal performance comparison for 2,4,8 floors (IES-VE Vista)

	No. of floors	**2**	**4**	**8**
	Area m2	35413.45	69536.14	137781.52
Total Area	Total energy consumption (MWh)	7406.8	14036.37	27354.65
	Cooling plant load (MWh)	7880.16	13699.04	25339.03
	Dehumidification plant load (MWh)	1500.48	2972.25	5918.63
	Carbon emission (kgCO2)	3844127	7284877	14197053
	Lights Energy (MWh)	2716.48	5700.71	11725.83
PER m^2	Energy consumption (kWh/m^2)	209.15	201.86 (-3.49%)	198.54 (-5.07%)
	Cooling plant load (kWh/m^2)	222.5	197.01 (-11.46%)	183.91 (-17.3%)
	Dehumidification plant load (kWh/m^2)	42.37	42.7 (+0.87%)	42.96 (+1.39%)
	Carbon emission (kgCO2 / m^2)	108.55	104.76 (- 3.49%)	103.04 (-5.08%)
	Lights Energy (kWh/m^2)	76.71	81.98 (+6.87%)	85.11 (+10.95%)

Results Analysis:

The results obtained from simulation of the 3 cases of variable – number of floors is analyzed for thermal and daylight performance. Following observations were made from the results.

- The results show that as the number of floors increase to 4 and 8 floors, cooling load is reduced by 11.5% and 17% respectively. But dehumidification plant load increases very slightly to 1.4% and the lights energy increases by 7% and 11% for 4 and 8 floors. However, the overall thermal performance is increased in terms of energy consumption and carbon emission. They reduce by 3.5% and 5% respectively (Table 4.8).

As explained in section 4.2, energy consumption is summation of system energy, light energy and equipment energy. The cooling load is sum of light gain, external conduction gain, solar gain and infiltration gain. The reason for this increase in efficiency as number of floors increase is further studied by analyzing the break up of cooling load.

- In terms of light gain, the overall energy required for lights increases from the base case by 6.87% and 10.95% in 4 and 8 floor building respectively.(Table 4.8). As the height of building increases the daylight reaching ground floor decreases and hence ground floor rooms will need more lights leading to higher light gain. Fig 4.22 shows the increases in light gain in the atrium zone in summer and winter when number of floors increase.

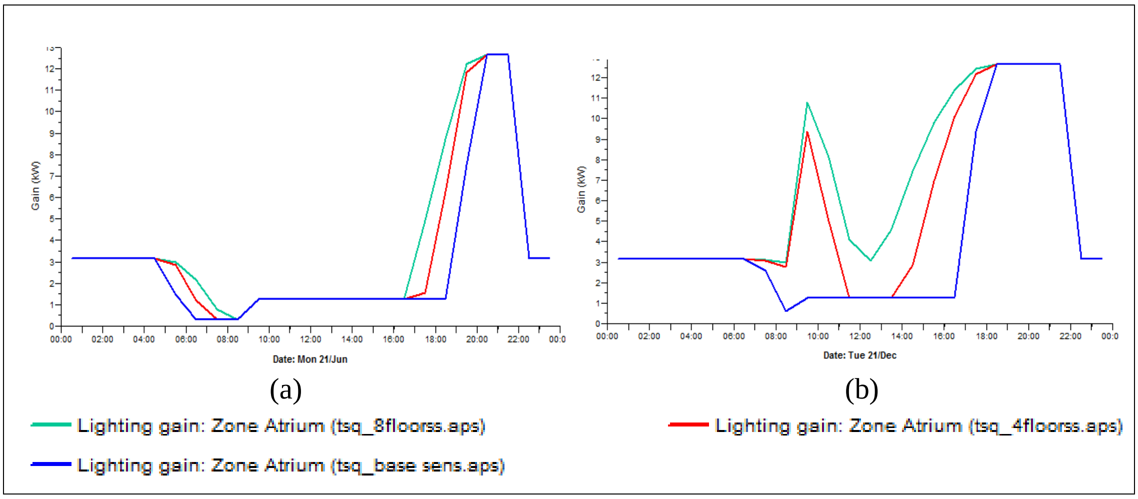


Fig 4.22 : Light gain in Atrium zone for 2,4,8 floors – (a) in summer and (b) in winter (IES-VE Vista)

- In terms of external conduction gain, only ground, top floor and external walls will receive the gain. Hence per square meter, this external conduction gain becomes very less when number of floors increase. This will decrease cooling load to a large extent. It reduces by 31.25 % and 41.44 % in 4 and 8 floor building respectively. (Table 4.9). Fig 4.23 shows that the topmost floor receives the highest external conduction gain due to roof being exposed to direct sunlight. For the floors in between, the amount of external conduction gain does not show variation.

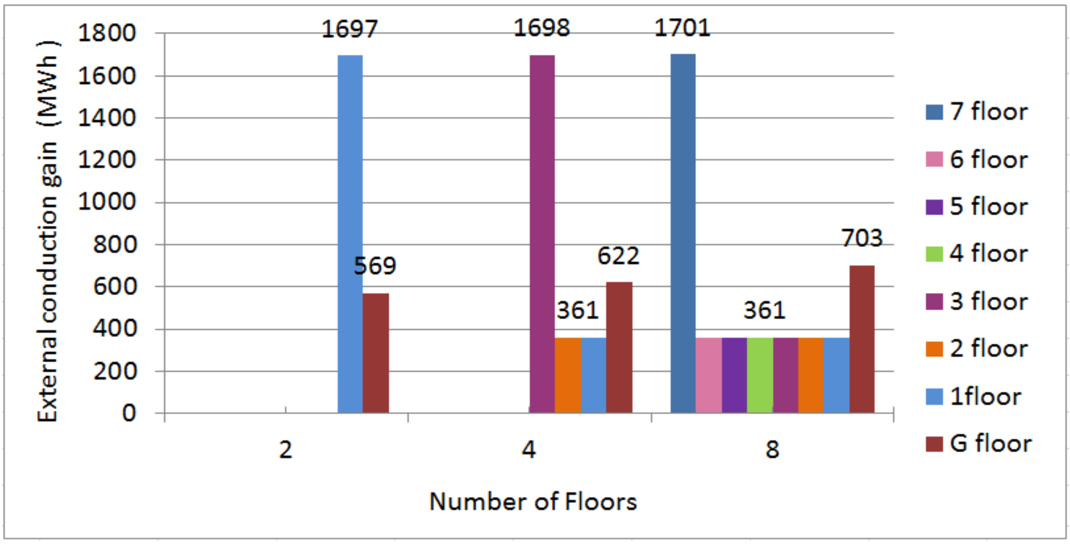


Fig 4.23 : External conduction gain in each floor of 2,4 and 8 floor building

Table 4.9 : External conduction gain comparison in 2,4 and 8 floor building

Floors	**2**	**4**	**8**
Area m^2	35413.45	69536.14	137781.52
7 floor			1701.113
6 floor			360.535
5 floor			360.720
4 floor			360.711
3 floor		1698.363	360.705
2 floor		360.485	360.710
1 floor	1696.726	360.713	360.761
G floor	569.357	622.167	703.041
TOTAL (in MWh)	2266.0832	3041.7275	4568.2966
per m^2	**0.064**	**0.044**	**0.033**
Percentage reduction per m^2	**Basecase**	**-31.25 %**	**-48.44 %**

- In terms of solar gain, the decrease in solar gain will be 42.30% and 65.38% for 4 and 8 floor building respectively (Table 4.10). In a 8 floor building, the top floors receives more direct sunlight penetration while the lower floors will receive much less sunlight. Thus the solar gain will be more on the top floors than the GF rooms in a multistory building (Fig 4.24). It can also be noted that the solar gain in GF which has the atrium floor will receive less solar gain as the number of floors increase since the sunlight reaching the floor reduces (Fig 4.25) Overall, a 8 floor building will receive less solar gain per floor area than a 2 floor building and hence less cooling load.

Table 4.10: Solar gain comparison in 2,4 and 8 floor building

Floors	**G+1**	**G+3**	**G+7**
Area m2	35413.45	69536.14	137781.52
7 floor			111.728
6 floor			113.325
5 floor			100.478
4 floor			85.778
3 floor		128.720	77.285
2 floor		134.449	67.244
1floor	149.227	114.837	58.428
G floor	757.566	658.910	651.827
TOTAL in Mwh	906.794	1036.917	1266.092
per m^2	**0.026**	**0.015**	**0.009**
percentage reduction per m^2	**base case**	**-42.30%**	**-65.38%**

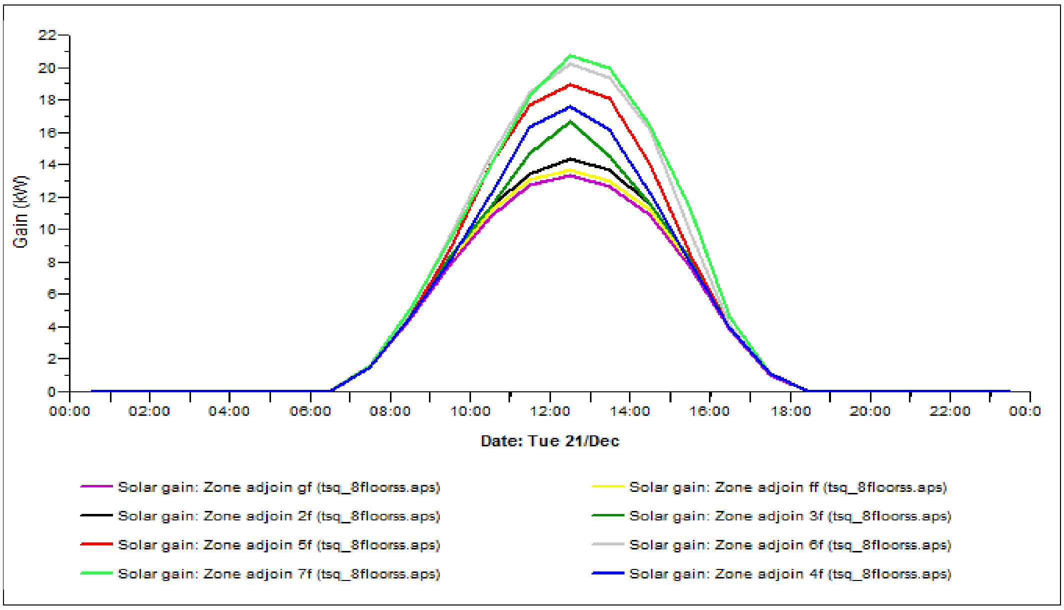


Fig 4.24 : Solar gain in adjoining area for each floor in the floor building showing a decrease in the lower floors (IES-VE Vista)

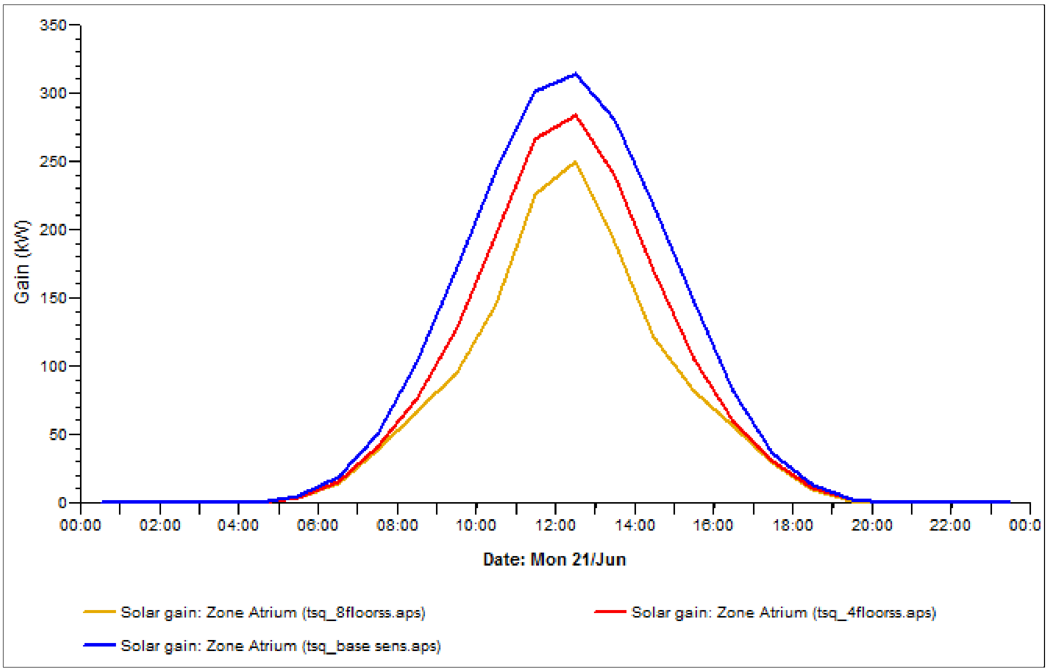


Fig 4.25 : Solar gain in atrium zone in 2,4,8 floor building showing decrease as number of floors increase. (IES-VE Vista)

The infiltration gain is constant at .018 kWh/m2 as seen from Appendix E. As seen above, although the light gain increases in a high rise building, the solar gain and external conduction gain decreases significantly, thereby reducing the total energy consumption. The overall energy consumption can be reduced by 5% in a 8 floor building and 3.5% in a 4 floor building. (Table 4.8). Hence a building with more number of floors gives a better thermal performance.

Hence from this analysis, it is seen that a building with more number of floors gives a better performance when only the variable - number of floors is changed. But it should be remembered that most of the malls found in UAE are usually built with a wide floor plan and are not more than 2 to 4 floors. Next, the malls being built on the main commercial and residential areas will get approval only for lesser number of floors. This will depend on the location of the mall. Hence if municipality approval is available and if the client advices, then more number of floors can be added. However, for optimal case analysis, the optimal values of all other valuables will be applied to all 3 cases of variable- number of floors, i.e., 2,4 and 8 floor building and analyzed to study its impact on building's performance when all optimal values are applied together.

4.4.3 Variable – Roof Profile

The existing Times Square Mall has vault roof of size 30m x 26m which covers 100% of atrium zone. The model is analyzed by changing the roof profile to find the best profile that can improve its overall performance. Various options were tried out by changing the roof profile in IESVE ModelIT software and the tested roof profiles are shown in Figure 4.26. North light with 20% and 40% of original vault glazing area is tried out (case 3,4). Also North light with slope at back (case 5), diagonal side glazing (case 6) and diagonal side glazing combined with flat glazing (case 7) is tried out. Table 4.11 lists the character of each profile.

Table 4.11: Options for roof profile for the analysis

Options	Roof Profile	Ht (m)	Facing side	Glazing area
Base case	Vault roof	2.75	Top	As on site, 100% glazing in atrium area
Case 1	Flat glazed roof	-	Top	100% glazing in atrium area
Case 2	Closed roof	-	-	No glazing on roof
Case 3	North light L20	2.75	NE,SE	L shaped & 20% glazing area
Case 4	North light L40	6.2	NE,SE	L shaped & 40% glazing area
Case 5	North light L40SL	6.2	NE,SE	Same as case 4, but with slope at back
Case 6	North light D	6.2	N	Diagonal & 30% glazing area
Case 7	North light & flat combined	6.2	N andTop	Same as case 6 but combined with flat glazing (55% glazing area)

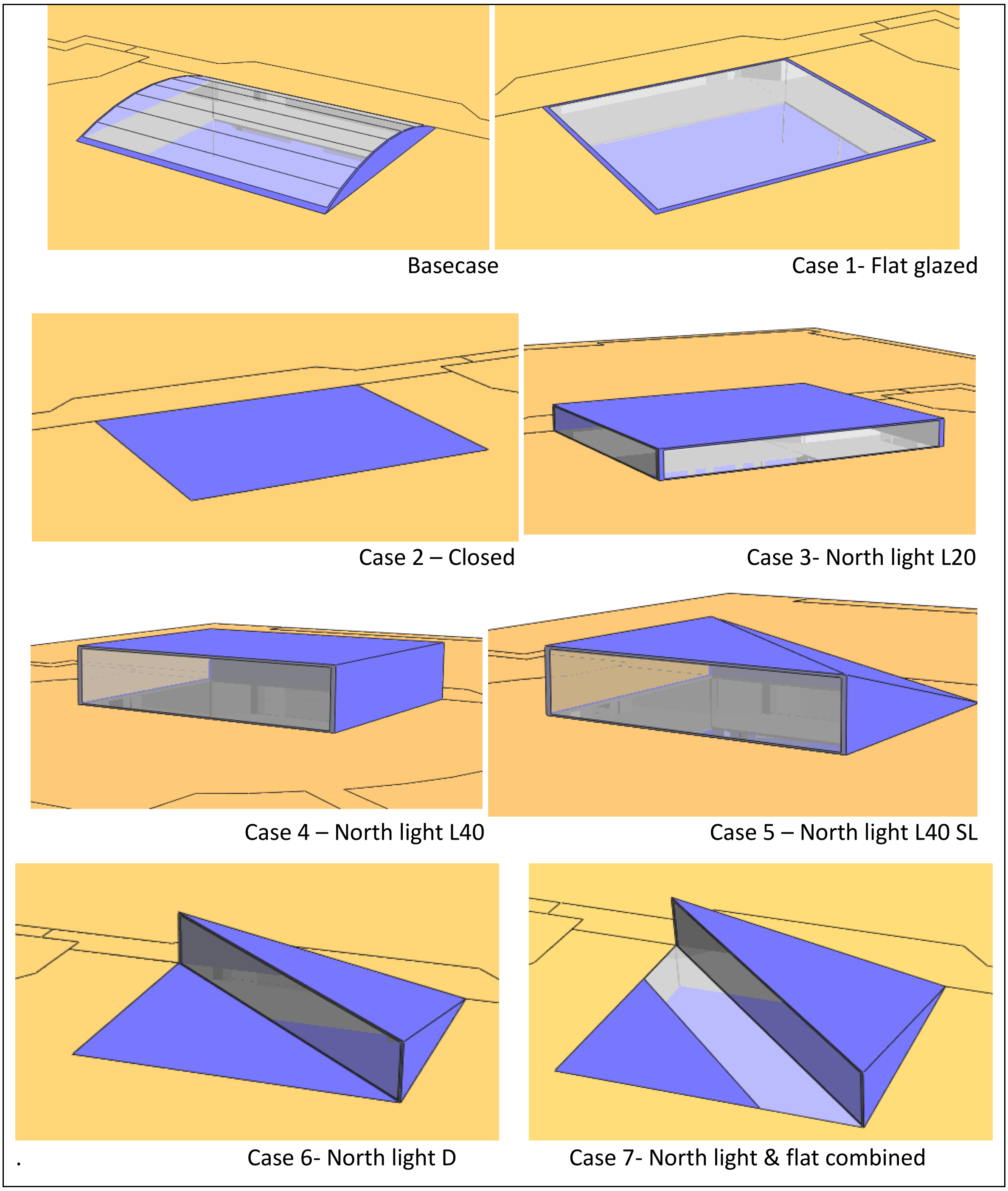


Figure 4.26 : Roof profile configurations for analysis

Simulation results obtained in IES-Vista showing the monthly breakup of energy consumption, cooling load, dehumidification load lights energy and carbon emission for all 8 roof profiles is shown in Appendix F. The results are summarized in Table 4.12.

Table 4.12 : Thermal performance comparison for the 8 roof profiles (IES-VE Vista)

OPTIONS	Total energy consumption (MWh)	Room cooling plant load (MWh)	Room dehumid. plant load (MWh)	Lights energy (MWh)	Annual Carbon emission (kgCo2)
Vault	7406.8	7880.2	1500.5	2716.5	3844127
Flat glazed	7489.1 (+1.1%)	7925.0 (+0.57%)	1493.9	2779.7 (+2.3%)	3886860 (+1.1%)
Closed	7684.9 (+3.75%)	7582.9 (-3.8%)	1493.9	3146.5 (+15.8%)	3988445 (+3.75%)
North light L20	7675.4 (+3.63%)	7628.6 (-3.2%)	1502.1	3110.0 (+14.5%)	3983507 (+3.63%)
North light L40	7667.9 (+3.53%)	7687.9 (-2.4%)	1512.8	3067.5 (+12.9%)	3979618 (+3.53%)
North light L40SL	7653.8 (+3.33%)	7663.7 (-2.8%)	1509.5	3067.2 (+12.9%)	3972328 (+3.33%)
North light D	7728.3 (+4.34%)	7674.6 (-2.6%)	1500.1	3140.9 (+15.6%)	4010988 (+4.34%)
North light & flat combined	7484.6 (+1.05%)	7596.7 (-3.6%)	1500.2	2936.2 (+8.1%)	3884522 (+1.05%)

Results Analysis:

The results obtained from simulation of 8 roof profiles for the variable – roof ventilation is analyzed for thermal and daylight performance. Following observations were made from the results.

It shows that the total energy consumption is lowest with vault roof followed by North light and flat combined roof and then flat glazed roof and it is highest in the other North light cases and closed case. But it could also be noted that although the cooling plant load is lowest for closed roof and North light cases, the final energy consumption becomes higher. Similarly, even though, the cooling plant load is higher for flat glazed roof profiles and vault roof, their final energy consumption is lowest. Hence, further analysis of results is done to find the reason for this.

As discussed in section 4.2, total energy is sum of system energy and lights energy. Hence energy break up of roof profiles is taken fron IES Vista. Table 4.13 summarizes the breakup of total energy consumption for all 8 cases of roof profiles tested.

Table 4.13 : Breakup of total energy consumption for 8 roof profiles (IES-Vista)

	Lighting gain (MWh)	People gain (MWh)	Solar gain (MWh)	External cond gain (MWh)	Internal cond gain (MWh)	Infiltration gain (MWh)		cooling sens. (MWh)		Dehumid load (MWh)		Cooling + dehum plant load (MWh)	cooling delivery effciency	chiller load	chiller season efficiency	Chillers energy (MWh)		Ap Sys heat rej fans/ pumps energy		System energy		Total lights energy (MWh)		Total energy (MWh)
VAULT GLAZED	2716.5	1353.5	906.8	2266.1	0.0	637.4		7880.2		1500.5		9380.6		8685.8		3474.3		1216.0		4690.3		2716.5		7406.8
FLAT GLAZED	2779.7	1351.1	907.2	2254.6	0.0	632.5		7925.0		1493.9		9418.9		8721.2		3488.5		1221.0		4709.5		2779.7		7489.1
CLOSED	3146.5	1351.1	115.8	2336.5	0.0	632.9		7582.9		1493.9		9076.7		8404.4		3361.8		1176.6		4538.4		3146.5		7684.9
NL20	3110.0	1351.1	158.5	2368.5	0.0	640.5	=	7628.6	+	1502.1	=	9130.7	/1.08	8454.3	/ 2.5	3381.7	+	1183.6	=	4565.3	+	3110.0	=	7675.4
NL40	3067.5	1351.1	212.0	2407.1	0.0	650.1		7687.9		1512.8		9200.7		8519.2		3407.7		1192.7		4600.3		3067.5		7667.9
NL 40L SLB (6.2)	3067.2	1351.1	211.9	2386.4	0.0	647.2		7663.7		1509.5		9173.3		8493.8		3397.5		1189.1		4586.6		3067.2		7653.8
NL 30HALFCUT(6.2	3140.9	1351.1	164.6	2379.1	0.0	638.9		7674.6		1500.1		9174.7		8495.1		3398.1		1189.3		4587.4		3140.9		7728.3
NL30 + FLAT	2936.2	1351.1	301.2	2369.0	0.0	639.2		7596.7		1500.2		9096.9		8423.1		3369.2		1179.2		4548.5		2936.2		7484.6

As mentioned earlier it can be seen that the cooling plant load and hence system energy is lowest for closed roof profile and also for North light roof profiles (Fig 4.27). But light energy required for these cases is much higher since roof glazing area is null for closed roof case and only 20-40% of original vault glazing area in north light cases and hence natural light penetrating into the building is reduced significantly which necessitates the need for artificial lighting throughout which in turn increases light energy consumption. (Fig 4.28). So finally when system energy and light energy is added up, the total energy consumption goes much higher for closed roof (+3.75%) and north light cases (+3.33 to 4.34%).

Similarly, because of more natural light coming into the building in case of flat glazed and vault roof profiles, the building gets heated up soon and thus the cooling load and system energy is much higher (Fig 4.27). But the sensors in the building will cut off the lights when daylight illumination reaches 500 Lux and hence lighting load will be much lesser in these 2 cases (Fig 4.28). Hence when system energy and lights energy are added up for final energy consumption it becomes much lower for vault roof (lowest) and flat glazed roof (+1.1%) (Fig 4.29).

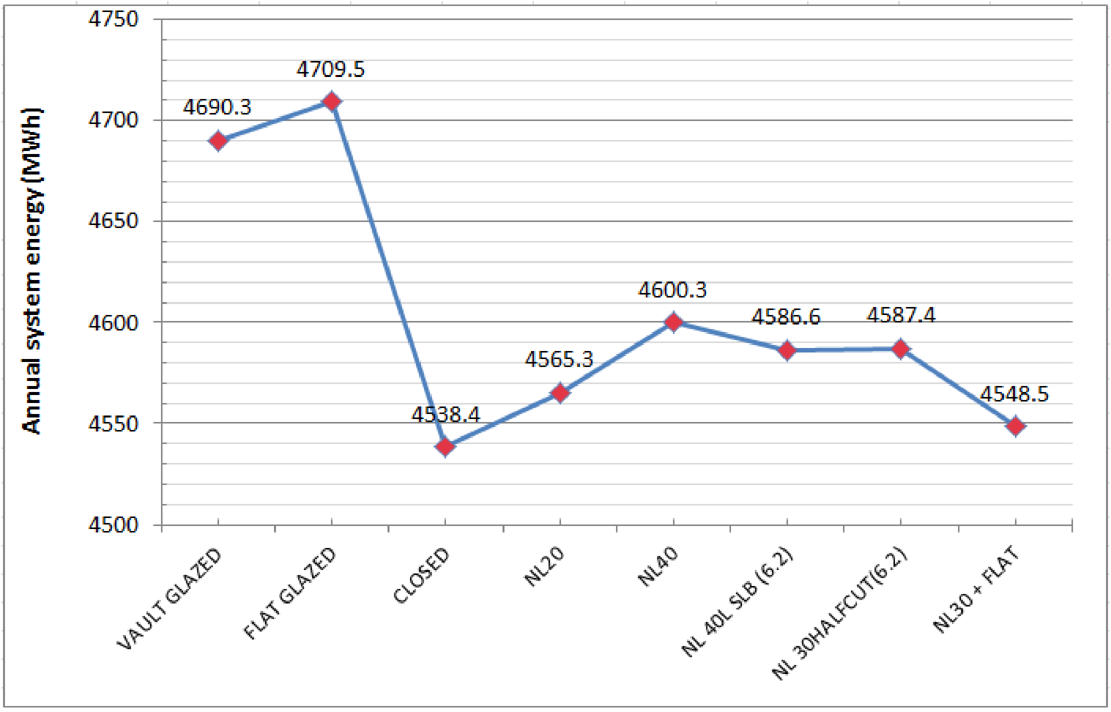


Figure 4.27 : System energy graph for various roof profiles

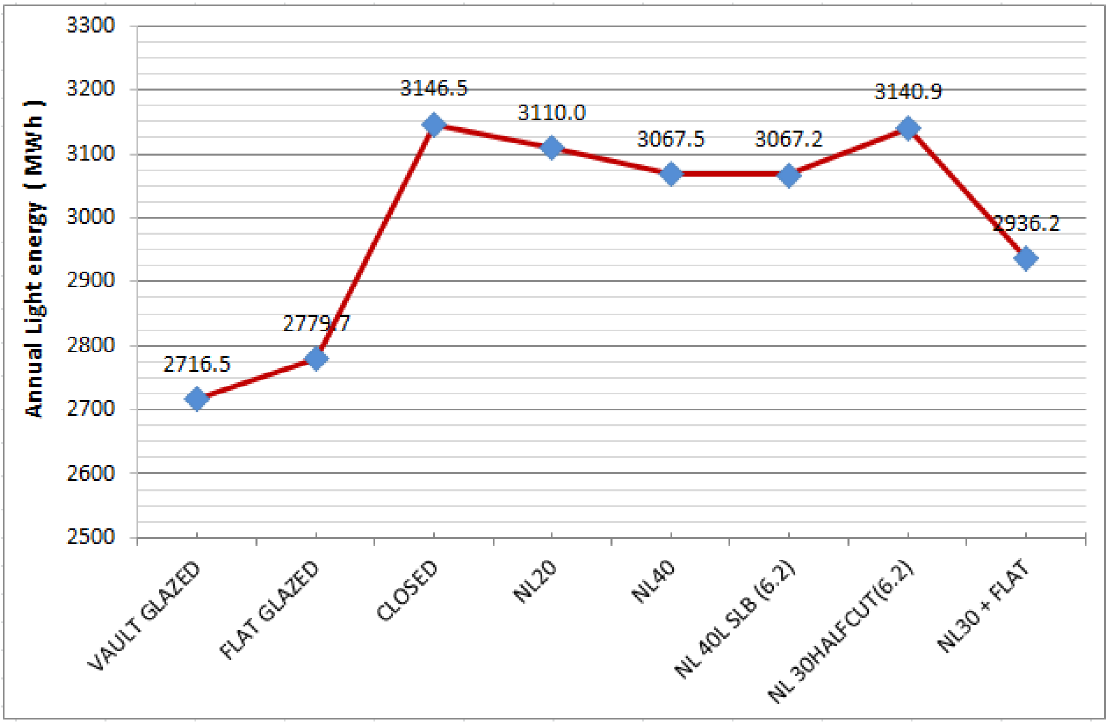


Figure 4.28 : Total lights energy graph for various roof profiles

In case of by north light & flat combined roof, lighting gain is reduced by the small flat glazed area which allows more natural light into the building and since this flat glazed portion lies in the shade area of north light, the solar gain also is greatly reduced compared to the flat glazed roof. (Table 4.13). So when system energy and lights energy gets added up for total energy consumption, the performance of this roof is better than the other north light roofs.

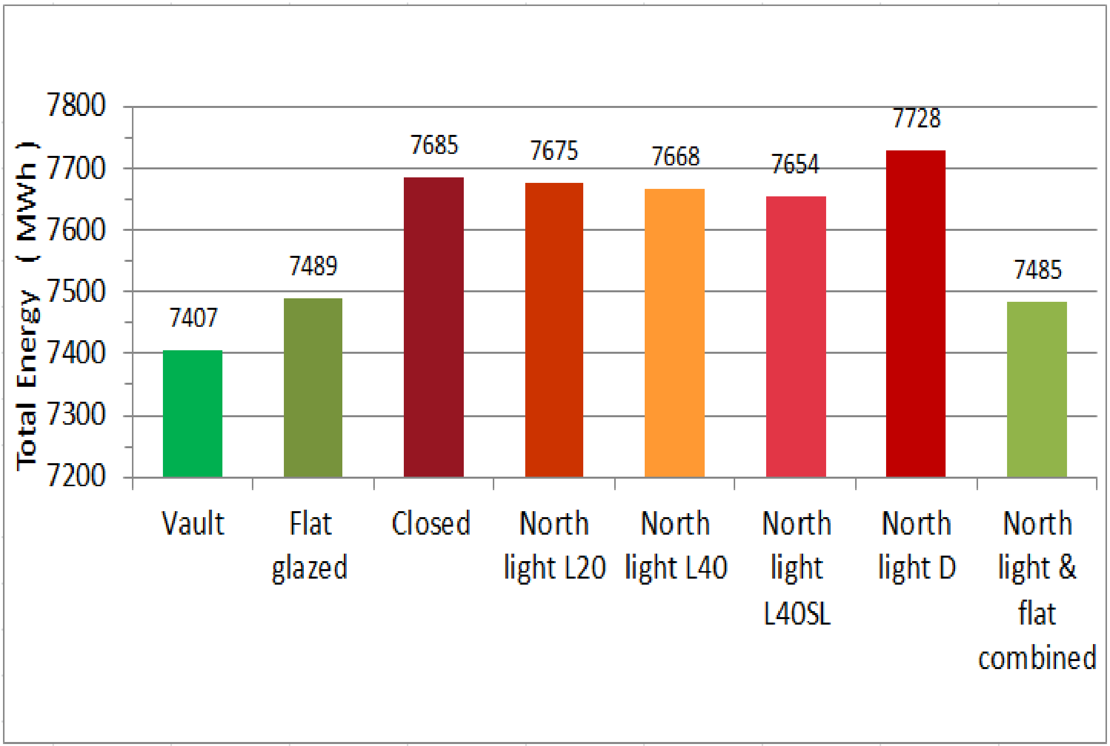


Fig 4.29: Total energy consumption comparison for the 8 roof profiles (IES-VE Vista)

However, the overall energy consumption is much lesser in vault roof followed closely by north light & flat combined roof (+1.05%) and flat glazed roof (+1.1%) as seen in Fig 4.29. Closed roof and north light roofs increase the energy consumption by +3.3% to 4.3%. From the above analysis it is clear that vault roof gives the best performance among all the 8 cases tested. Since Times square center mall already has vault roof, the roof profile will not be changed for the optimal case.

4.4.4 Variable – LSG Ratio of glazing

For an atrium located in a hot dry climate, blocking of solar heat gain without blocking the visible transmittance is very important. So the LSG ratio of glazing is taken as the parameter to assess the efficiency of glazing. As seen in the literature review, LSG ratio is a very useful index which compares visibility of a glazing system to its solar gain. LSG = VT/SHGC where VT or Tvis is the visible transmittance of light and SHGC is the solar heat gain co-efficient. (DOE nd)

In this research, to study the effect of glazing system on the mall building's efficiency, the thermal performance is assessed by altering the LSG value of the glazing system. In the construction database of Building template manager, glazing is classified into 3 categories - Internal window, External window and Roof light. For any building the exterior glazing properties need not be the same as that of interior glazing since the amount of daylight and heat gain from sun exposure will be different for both. Hence for this analysis, internal glazing and external glazing (external window and Roof light) is analyzed separately. It can be seen from Table 4.14, that the LSG value of glazing used in external openings (External window and Roof light) are similar while for the internal window, a lower glazing value will be sufficient.

The LSG value of various glazing materials are calculated from the VT and SHGC values given in the construction data base of IES-VE ApacheSim. Fig 4.30 illustrates the values as shown in construction data base in ApacheSim for a sample of glazing material – 6 mm clear glazing. LSG value of the existing glazing used at site is taken as the base case value. Few glazing materials are chosen from the data base, so that they represent LSG values over and below the base case value. Table 4.14 shows the 3 categories of glazing system shown in Apache construction database manager and LSG values of the materials chosen for the study. Case by case, each glazing material is applied to the model keeping all other variables constant (glazing profile, number of floors, U value of insulation, ventilation of roof opening) and thermal simulation is done in ApacheSim. While testing internal windows, only the LSG value of that category is changed while that of external window and roof light is kept as base case value. Simulation results obtained in IES-Vista showing the monthly breakup of energy consumption, cooling load, dehumidification load lights energy and carbon emission for all 7 tested cases is shown in Appendix G. The results are summarized in Table 4.15.

Table 4.14 : Glazing material chosen for analysis and their properties (IES-VE)

Options	VT	SHGC	LSG value	Glazing material
EXTERNAL WINDOW				
Base case	0.77	0.6214	1.24	Clear double 10mm
Case 1	0.77	0.8116	0.949	Clear single 6mm
Case 2	0.76	0.5657	1.344	Low e double 10mm
Case 3		0.5650	1.345	Low e triple 6mm
Case 4	0.76	0.4891	1.554	Low e triple 10mm
ROOF LIGHT				
Base case	0.76	0.6338	1.119	Clear double 10mm
Case 1	0.77	0.8114	0.945	Clear single 6mm
Case 2	0.76	0.5690	1.336	Low e double 10mm
Case 3		0.5676	1.339	Low e triple 6mm
Case 4	0.76	0.4925	1.543	Low e triple 10mm
Options	**VT**	**SHGC**	**LSG value**	**Glazing material**
INTERNAL WINDOW				
Base case	0.41	0.855	0.48	Clear single 6mm
Case 5	0.77	0.8150	0.945	Clear single 10mm
Case 6		0.80	0.963	Low e 6mm
Case 7	0.76	0.6727	1.130	Low e double 6mm

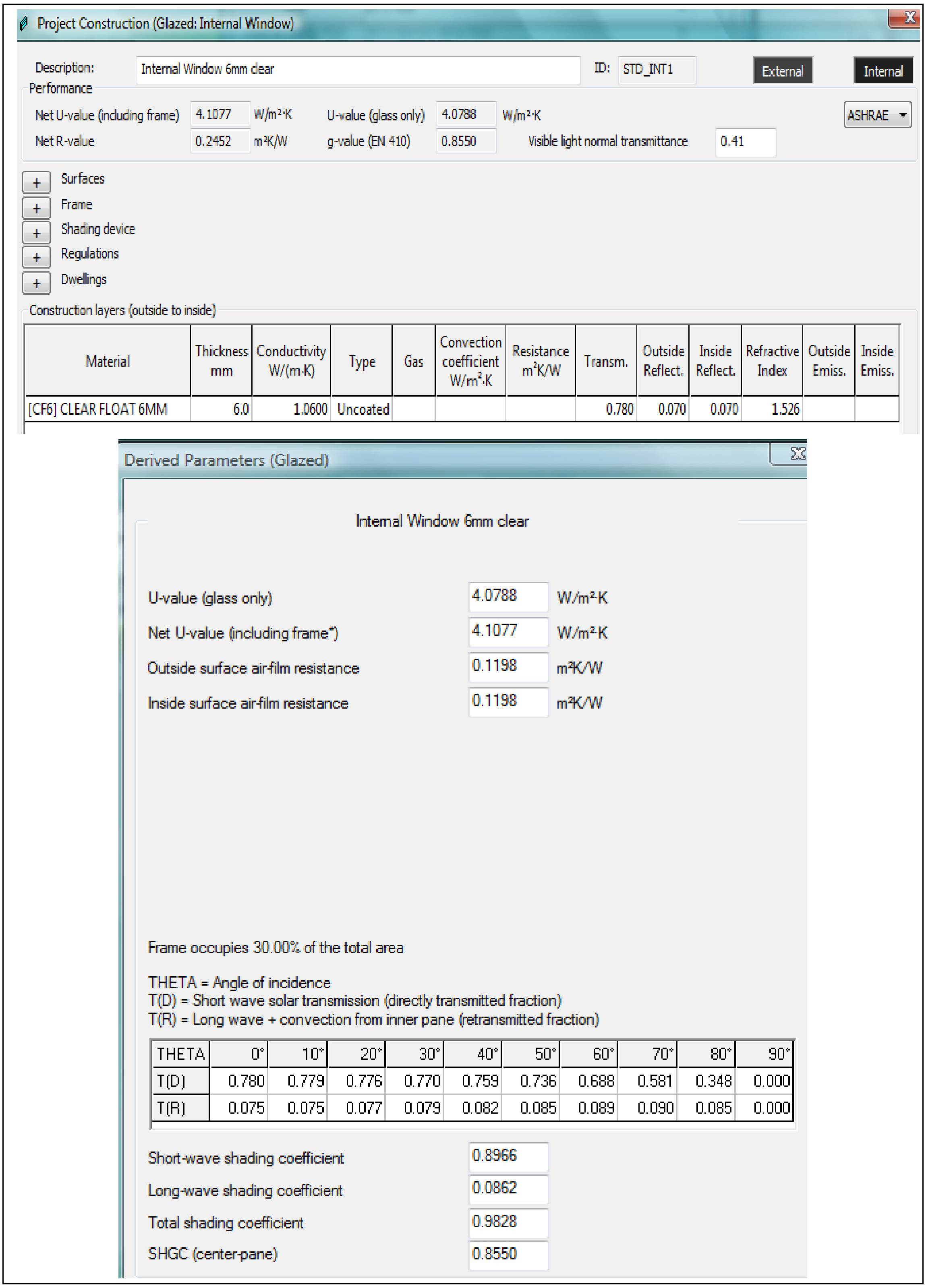


Fig 4.30: Glazing material properties (base case) from construction data base manager (IES-VE Apcdb)

Table 4.15 : Comparison of cases for LSG ratio analysis in ApacheSim

Options	LSG ratio	Yearly energy consumption (MWh)	Room cooling plant load (MWh)	Room dehum. plant load (MWh)	Lights energy (MWh)	Total Carbon emission (kgC02)
External Openings : (External window and Roof skylight)						
Base case	1.24	7406.80	7880.16	1500.48	2716.48	3844127
Case 1	0.949	7549.94 (+1.93%)	8164.81 (+3.61%)	1502.11 (+0.11%)	2716.48	3918419 (+1.93 %)
Case 2	1.344	7358.97 (- 0.66%)	7784.57 (-1.21%)	1500.41 (-0.00%)	2716.48	3819306 (-0.66 %)
Case 3	1.345	7356.34 (-0.68%)	7779.43 (-1.28%)	1500.28 (-0.01%)	2716.48	3817938 (-0.68 %)
Case 4	1.554	7309.11 (-1.32 %)	7684.92 (-2.48%)	1500.34 (-0.01%)	2716.48	3793426 (-1.32 %)
Internal Openings : (Internal window)						
Base case	0.48	7406.80	7880.16	1500.48	2716.48	3844127
Case 5	0.945	7407.02 (+.00 %)	7880.60 (+.01%)	1500.48 (+.00%)	2716.48	3844242 (+.00 %)
Case 6	0.963	7407.00 (+.00 %)	7880.55 (+.01 %)	1500.48 (+.00%)	2716.48	3844249 (+.00 %)
Case 7	1.130	7407.18 (+.01%)	7880.90 (+.01 %)	1500.49 (-0.00%)	2716.48	3844325 (+.01 %)

Results Analysis:

The results obtained from simulation of 4 cases of external openings and 3 cases of internal openings for the variable – LSG ratio is analyzed for thermal and daylight performance. Following observations were made from the results.

- For the external wall, glazing material with high LSG ratio gives good thermal performance (Table 4.15, Fig 4.31). Figure 4.32 shows that as the LSG value of glazing decreases, the solar gain increases heating up the interior and thus increasing the energy consumption.
- But for internal wall LSG ratio does not make much difference in thermal performance. For eg, LSG value of 0.48, 0.945 and 1.13 for the internal openings gives the same thermal performance.(Table 4.15, Fig 4.33)
- It is also noted that different glazing materials can give the same performance if their LSG value is same. For eg, case 2&3 and also case 5&6 are different

materials but with same LSG ratio, but their thermal performance in terms of energy consumption, cooling load and carbon emission is the same. (Table 4.15).

- Hence to improve thermal performance, glazing material of higher LSG value is chosen for external openings. Since LSG = VT/ SHGC, a material with high visible transmittance or with low SHGC can be chosen depending on site requirements.
- Changing the LSG ratio does not have any effect on the light energy required. as can be seen from Table 4.15.

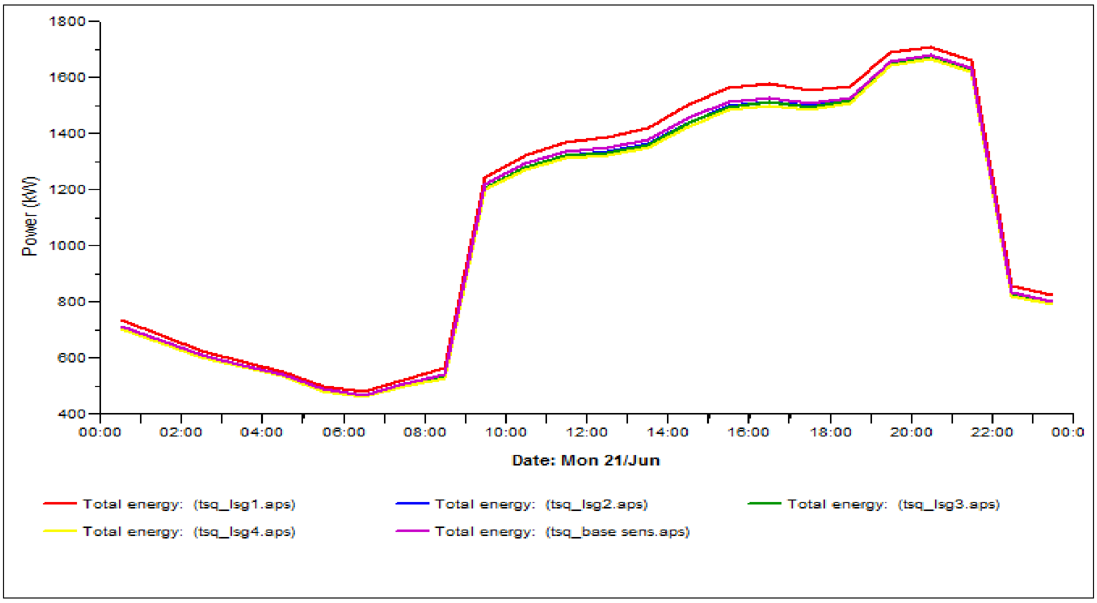


Fig 4.31 : Energy consumption graph for external openings with different glazing material (IES-VE Vista)

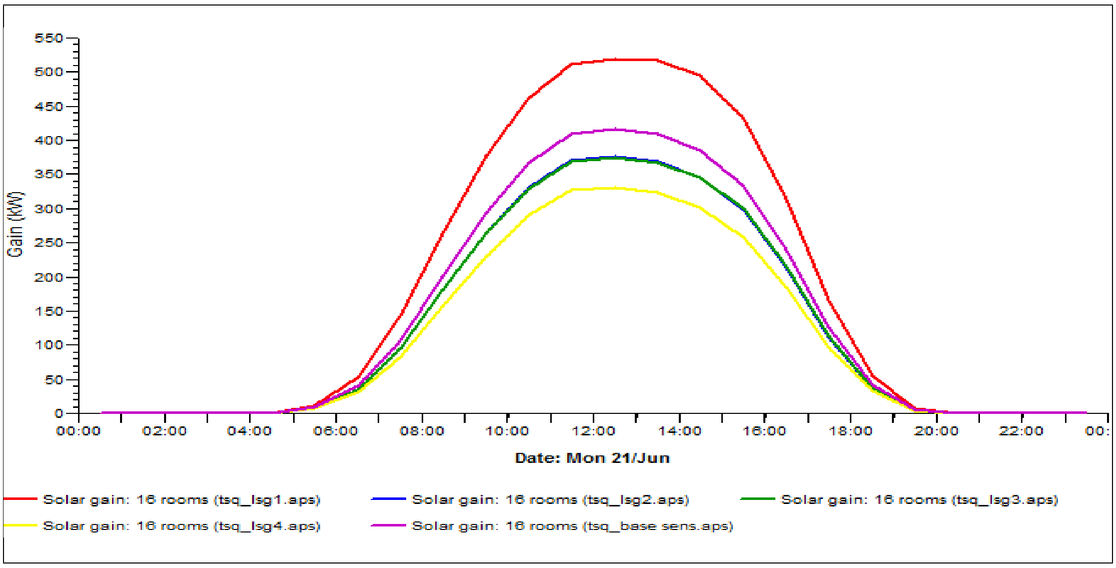


Fig 4.32 : Solar gain graph with options of external glazing material of varying LSG value (IES-VE Vista)

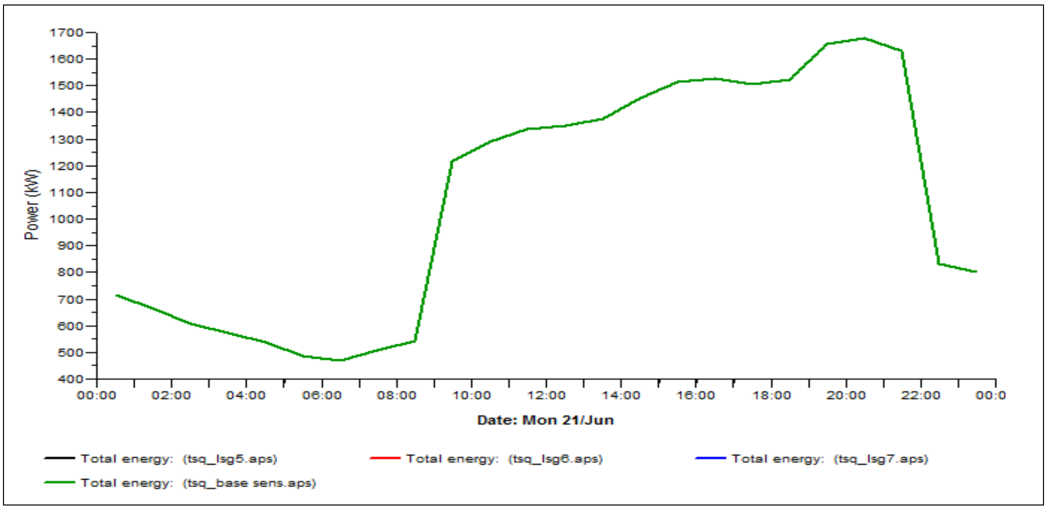


Fig 4.33 : Energy consumption graph for internal openings with different glazing materials (IES-VE Vista)

From Table 4.15 it is seen that external glazing material of higher LSG value of 1.5 will improve thermal performance by 1.32% from base case and LSG 1.3 will reduce by 0.68%. The difference is only 0.64%. To achieve this higher value, low e triple glazing 10mm has to used instead of low e double 10mm or low e triple 6mm. This will increase the construction cost considerably. Hence any glazing material with LSG above 1.3 will be recommended for external glazing and it will be taken as the best value for the optimal case. For internal openings, since LSG value does not affect the thermal performance, the base case value will be retained as such for optimal case.

4.4.5 Variable – U value of envelope

In a hot climate such as Dubai the outside dry bulb temperature keeps rising in the daytime and the building interior also gets heated up soon due to direct exposure of walls and roof to solar radiation. A material with low U value resists this heat transfer and reduces the heat buildup inside. Thus U value is one of the major parameters that can affect the thermal performance of a building. U value is expressed as w/m^{2}K and it depends on the thickness and the thermal conductivity of the material used in construction of wall or roof. It decreases when thermal conductivity of material decreases and when thickness increases. The mall building is tested with various U values for the external walls and roof to determine the percentage reduction in energy consumption that could be achieved.

The most common insulating materials used in UAE are the Polyurethane board, Mineral fiber slab, Phenolic foam, extruded Polyurethane which are available in varying thickness. For this analysis the base case of external wall and roof is taken without insulation. Then varying U values obtained by adding an insulating material to the base case are tested. The insulating materials are selected from the construction data base manager in ApacheSim in IES-VE which gives list of insulating materials and their characteristics. Table 4.16 gives details of the different materials selected for the analysis - the type of insulating material, their thickness and thermal conductivity.

It can be seen from the table that the same material can give different U values when thickness is changed.(case 1&2, case 6&7). Even though the thermal conductivity is same for different materials such as Polyurethane board and Dense EPS slab (case 1&4, case 6&10), their U value is different due to the change in their thickness. Also it can be noted that adding a light weight metallic cladding on the external wall does not affect the U value much.(case 2&3). Fig 4.34 shows the construction materials chosen for the base case roof and the U-value from the construction data base manager.

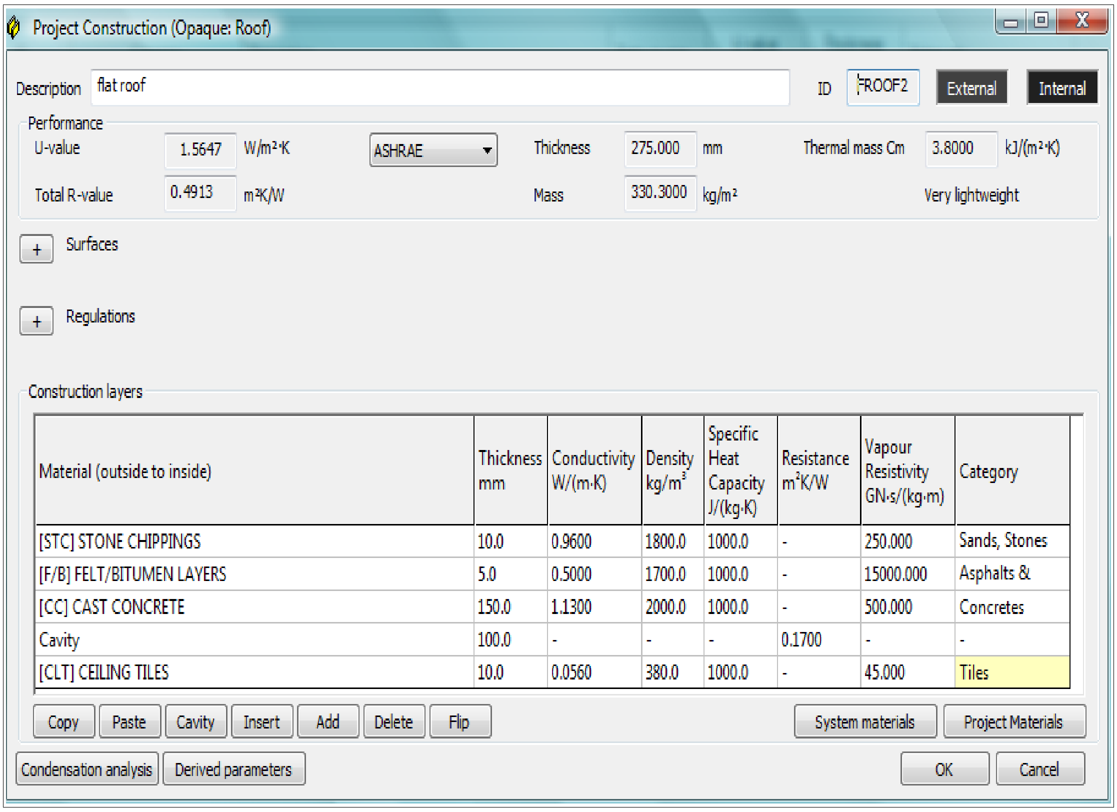


Fig 4.34 : Base case roof construction materials and its U-value (IESVE APcdb)

Table 4.16 : U value of external wall and roof chosen for analysis and their properties (IES-VE APcdb)

EXTERNAL WALL				
Options	**Insulating material**	**Thickness mm**	**Thermal conductivity w/m.K**	**U value w/m^2.K**
Base case	Concrete block wall with plastering (overall thickness 130mm)			2.3969
Case 1	Polyurethane board	70	0.025	0.3074
Case 2	Polyurethane board	32	0.025	0.5771
Case 3	light weight metallic cladding + Polyurethane board	15 32	0.29 0.025	0.5603
Case 4	Dense EPS slab-styrofoam	20	0.025	0.8120
Case 5	Mineral fibre slab	20	0.035	1.0115
ROOF				
Options	**Insulating material**	**Thickness mm**	**Thermal conductivity w/m.K**	**U value w/m^2.K**
Base case	Flat concrete roof as shown in fig1 (overall thickness 275mm)			1.5647
Case 6	Dense EPS slab-styrofoam	120	0.025	0.1839
Case 7	Dense EPS slab-styrofoam	70	0.025	0.2908
Case 8	Phenolic foam	110	0.04	0.2951
Case 9	Phenolic foam	50	0.04	0.5294
Case 10	Polyurethane board	25	0.025	0.6101

Case by case, each material as shown in table 4.16 is applied to the base case model keeping all other variables constant (i.e., glazing profile, number of floors, LSG value of glazing and roof ventilation openable area) and simulation is done in ApacheSim.

Simulation results obtained in IES-Vista showing the monthly breakup of energy consumption, cooling load, dehumidification load lights energy and carbon emission for all cases is shown in Appendix H. The results are summarized in Table 4.17.

Table 4.17 : Comparison of cases for U value analysis in ApacheSim (ISE VE)

Options	**U value**	**Yearly energy consumption (MWh)**	**Room cooling plant load (MWh)**	**Dehum. pl.load (MWh)**	**Light energy (MWh)**	**Total Carbon emission (kgCo2)**
External Wall :						
Base case	2.3969	7406.80	7880.16	1500.48	2716.48	3844127
Case 1	0.3074	7099.17 (- 4.15%)	7265.30 (- 7.80%)	1500.08	2716.48	3684470 (- 4.15%)
Case 2	0.5771	7139.62 (- 3.61%)	7346.17 (- 6.78%)	1500.09	2716.48	3705460 (- 3.61%)
Case 3	0.5603	7136.59 (- 3.65%)	7340.11 (- 6.85%)	1500.09	2716.48	3703887 (- 3.65%)
Case 4	0.8120	7174.92 (- 3.13%)	7416.75 (- 5.88%)	1500.12	2716.48	3723781 (- 3.18%)
Case 5	1.0115	7204.68 (- 2.73%)	7476.26 (- 5.13%)	1500.13	2716.48	3739229 (- 2.73%)
Roof :						
Base case	1.5647	7406.80	7880.16	1500.48	2716.48	3844127
Case 6	0.1839	6800.19 (-8.19%)	6667.39 (-15.39%)	1500.03	2716.48	3529300 (-8.19%)
Case 7	0.2908	6848.13 (- 7.54%)	6763.25 (-14.17%)	1500.04	2716.48	3554177 (- 7.54%)
Case 8	0.2951	6849.93 (- 7.52%)	6766.86 (-14.13%)	1500.04	2716.48	3555114 (- 7.52%)
Case 9	0.5294	6953.61 (- 6.12%)	6974.21 (- 11.5%)	1500.05	2716.48	3608926 (- 6.12%)
Case 10	0.6101	6991.52 (- 5.61%)	7050.00 (-10.54%)	1500.06	2716.48	3628596 (- 5.61%)

Results Analysis:

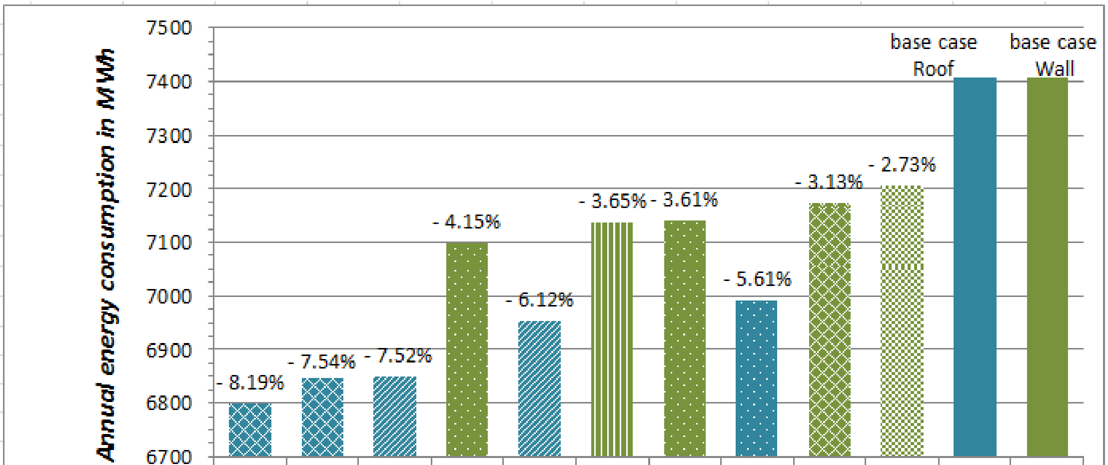
The results obtained from simulation of 5 cases of exterior wall and 5 cases of roof for the variable – U value of envelope is analyzed for thermal and daylight performance. Following observations were made from the results.

- It can be observed from the results that the thermal performance of the building improves as the U value decreases (Table 4.17).
- For external walls, U value of 0.3074 (case 1) gives the best performance (- 4.15%) and U value of 0.5771 (case 2) improves thermal performance by -3.61%. But it can be seen from table 4.16, that to achieve that U value, the thickness of the polyurethane board has to be doubled from 32mm to 70mm while the reduction in energy consumption is only 40.45 mWh. The cost of insulation doubles to achieve 0.30 U value. Moreover, as per Dubai municipality regulations (DM 2014) 0.57 is the recommended value for external wall. Hence 0.57 will be taken as the recommended value for optimal case.
- Similarly, for roof, U value of 0.1839 (case 6) gives the best performance (-8.19%) and U value of 0.30 (case 7) improves thermal performance by -7.54%. But to achieve that U value, the thickness of dense EPS slab has to be increased from 70mm to 120 mm as can be seen from case 6 and 7 in table 4.16. The cost of insulation increases considerably while the reduction in energy consumption is only 47.94 mWh. Moreover, as per Dubai municipality regulations (DM 2014) 0.30 is the recommended value for roof. Hence 0.30 will be taken as the recommended value for optimal case.
- It is also observed from that the impact of U value on the roof is much more than that on the walls. Figure 4.35 shows the energy consumption of building when U values are applied on the external wall (marked Green) and Roof (marked Blue). It can be seen that columns 2,3 and 4 have the same U value of around 0.30, but total energy consumption of roof is much lesser value than that of wall. Similarly, in columns 5,6 and 7 the same value of around 0.56 achieves a much less energy consumption for roof.
- It can be seen from case 1 and 7 in table 4.17, the same U value of 0.30 reduces the energy consumption by - 4.15% and -7.54% on the external walls and roof respectively. The total external wall area is 6147m^2 and roof area is 18351m^2 for the mall building. The total roof area is much greater – almost 3 times than the wall area. Is the impact on roof more because the roof area is more? To find this percentage reduction in energy consumption per m^2 is calculated in Table 4.18.

Table 4.18 : Percentage reduction in energy consumption per m² for wall and roof

	Options	Yearly energy consumption (MWh)	Total area	Yearly energy consumption per m2 (MWh /m²)	% reduction in energy consumption per m²
External Wall	Base case	7406.80	6147 m²	1.205	Base case
	Case 1(U=.30)	7099.17		1.155	- 4.15%
Roof	Base case	7406.80	18351 m²	0.4036	Base case
	Case 7(U=.30)	6848.13		0.3732	- 7.54%

It is clear from the above table that the same U value of 0.30 reduces energy consumption per m² by - 4.15% and -7.54% on the external walls and roof respectively. So the effect on roof is much more than that of walls. This is due to the reason that it gets direct radiation from sun while the walls get the radiation at an inclined angle. Hence more care should be taken for roof insulation without any compromise to enhance the thermal performance of the building.



	1	2	3	4	5	6	7	8	9	10	11	12
U-value	0.18	0.29	0.29	0.3	0.53	0.56	0.58	0.61	0.8	1	1.56	2.4
Energy MWh	6800	6848	6850	7099	6954	7137	7140	6992	7175	7205	7407	7407

Fig 4.35 : U value analysis - Energy consumption in MWh for external walls and roof (IES- Vista)

Further observations from table 4.16 :

- The same material can give different U values when thickness is changed.(case 1&2, 6&7 - table 4.17). Similarly, 2 materials with same thermal conductivity such as Polyurethane board and Dense EPS slab (case 1&4, 6&10), can give different U values by altering the thickness.
- A particular U value could be achieved by using different materials and altering their thickness.(case 2&3, 7&8). Hence for thermal performance, any insulation material available easily in market could be used but achieving the desired U value is the important factor.
- Also it can be noted that adding a light weight metallic cladding on the external wall does not affect the U value and hence thermal performance much. (case 2&3).
- Changing U-value does not have any effect on light energy required (Table4.17)

4.5 Summary

4.5.1 Day light performance

Day light performance is analyzed in terms of lighting energy required. In this section, daylight performance of all variables tested are summarized. The different variables analyzed in this research are Glazing profile, LSG ratio, Roof ventilation, Number of floors and U value. From the analysis in section 4.4, it is seen that the light energy required for various cases tested under roof ventilation, U value and LSG ratio is 2716.48 MWh and it remains constant. Hence it can be inferred that these 3 variables do not have an impact on day light performance.

The light energy required for the various roof profiles varies as shown in Figure 4.36. It can be seen that light energy required for closed roof is highest. This is because the natural light coming inside atrium is null and in north light cases also it is a higher value because glazing area of north light cases is only 20-40% of original vault glazing area. Hence natural light penetrating into the building is reduced significantly which necessitates the need for artificial lighting throughout which in turn increases light energy consumption.

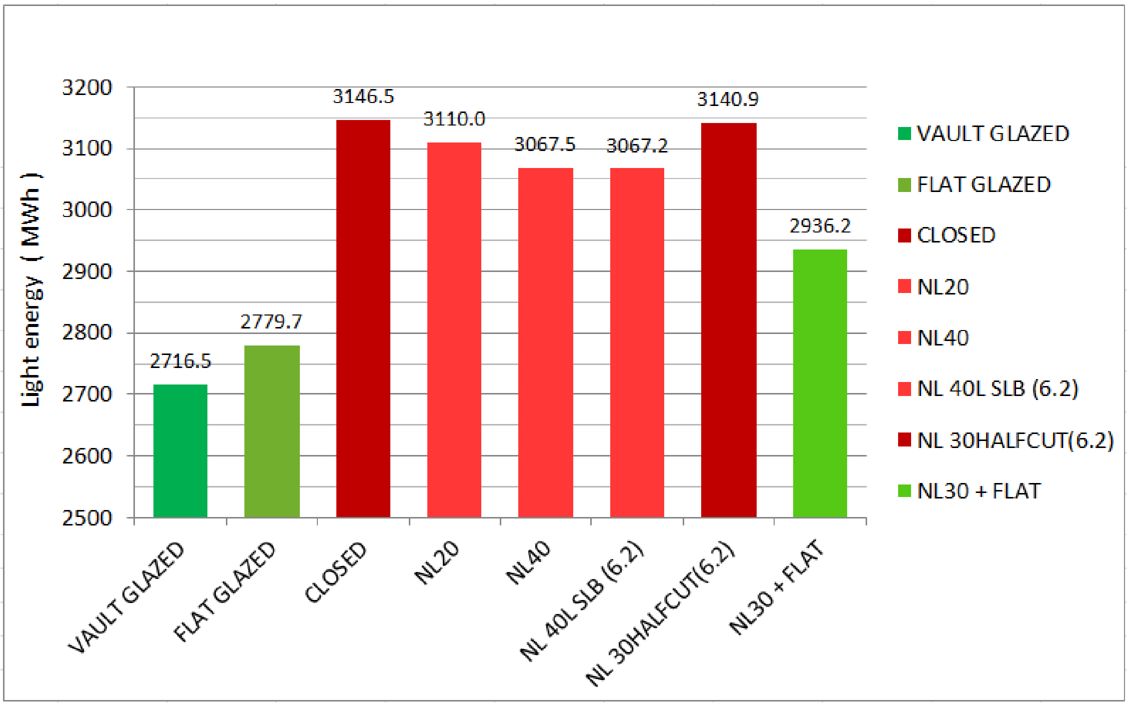


Fig 4.36 : Variable Roof profile – Annual Light energy consumption

In case of flat glazed and vault roof profiles more natural light come into the building. But the sensors in the building will cut off the lights when daylight illumination reaches 500 Lux and hence lighting load will be much lesser in these 2 cases. In case of north light & flat combined roof, lighting gain is reduced by the small flat glazed area which allows more natural light into the building hence the performance of this roof is better than the other north light roofs.

For the variable number of floors, lighting energy required increases as number of floors increase. The overall energy required for lights increases from the base case by 6.87% and 10.95% in 4 and 8 floor building respectively.(Table 4.19 and figure 4.37). As the height of building increases the daylight reaching ground floor decreases and hence ground floor rooms will need more lights leading to higher light gain.

Table 4.19 : Lighting energy required for 2,4 and 8 floor building

Number of Floors	**2 (base case)**	**4**	**8**
Total Lights energy in MWh	2716.48	5700.71	11725.83
Lights energy per m2 in kWh	76.71	81.98 (+6.87%)	85.11 (+10.95%)

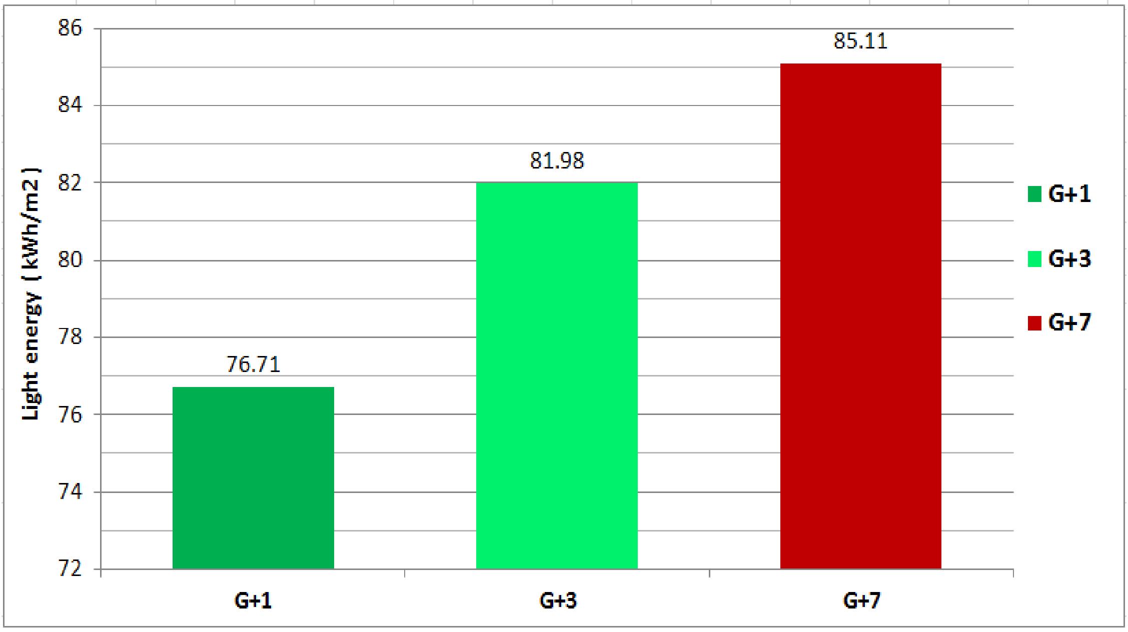


Fig 4.37 : Variable Number of floors – Annual Light energy consumption per m^2

Fig 4.38 shows the light gain needed in the adjoining floors surrounding the atrium in ground, first floor and second floor level of a 4 storey building. It can be seen that the ground floor level needs much more light than that of the higher floors in a multi storeyed building.

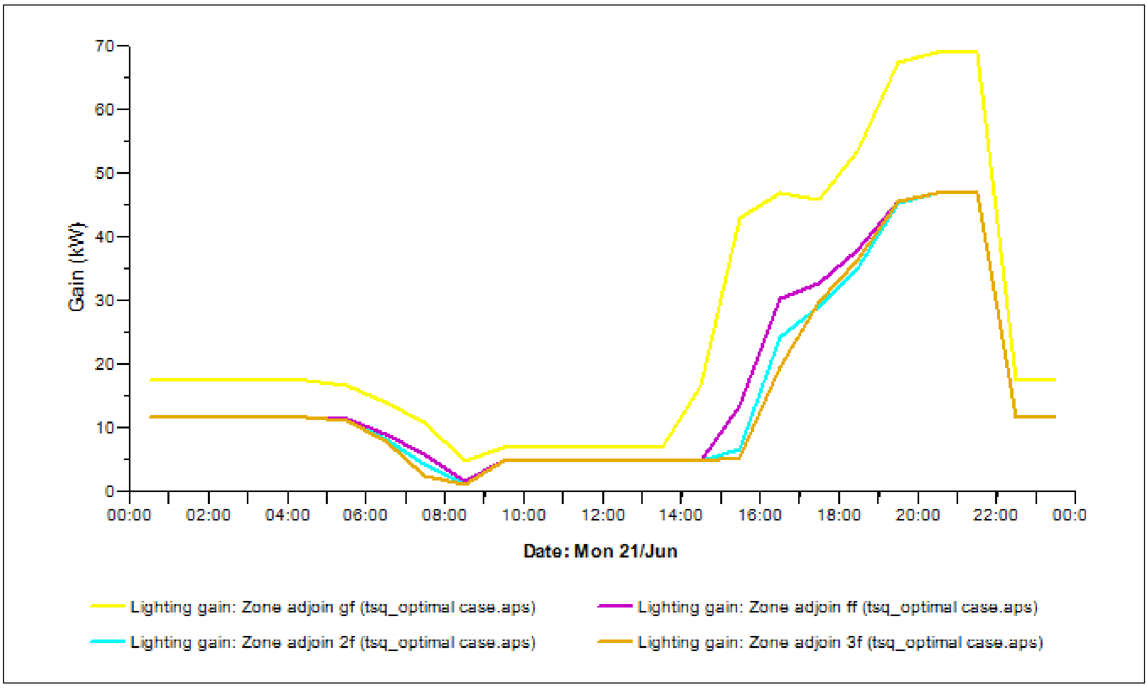


Fig 4.38 : Light gain in adjoining area in GF,1st, 2nd,3rd floor for a 4 storeyed building (IES-VE Vista)

Further, as discussed in Section 4.3, the energy consumption is reduced by 8.47% by placing a dimming sensor inside the building which cuts down the lights when the lux level reaches the required value of 500 Lux. The base case model when simulated without sensor and with sensor showed energy consumption reduction from 228.5 kWh/m2 to 209.2 kWh/m2. i.e., 8.47% (Table 4.3). Hence from this day light analysis it can be seen that,

- Variables - LSG ratio, Roof ventilation and U value do not impact day light performance.
- Variables - number of floors and roof profiles have an effect on day light performance.
- Lighting energy required increases as number of floors increase. (i.e., + 7% and + 11% in 4 and 8 floors respectively).
- Vault roof profiles followed by flat glazed roof gives the least lighting energy consumption.
- Sensors play a vital role in atrium in cutting down the artificial lighting and can reduce energy consumption by 8.47%

4.5.2 Overall performance

The overall performance of the building is analyzed in terms of its total energy consumption and carbon emission. From the analysis of variables applied individually, the percentage reduction obtained by applying the optimal value of each variable is illustrated in figure 4.39. It can be noted sensor plays a significant role in the atrium buildings energy conservation. The main purpose of having an atrium inside a building is to bring in natural sunlight and utilizing this natural light for illuminance and cutting down the artificial lighting by placing a sensor. Hence sensor is vital in any atrium building and it can reduce energy consumption by about 8.47%.

Next, U value plays a major role especially for the roof. The direct solar radiation on the roof on this hot arid climate, heats up the building to a great extent and this is reduced by applying proper insulation on the roof, thus reducing the energy consumption of the building by 7.5%. Likewise, proper insulation on external walls also reduce energy consumption by 3.61%.

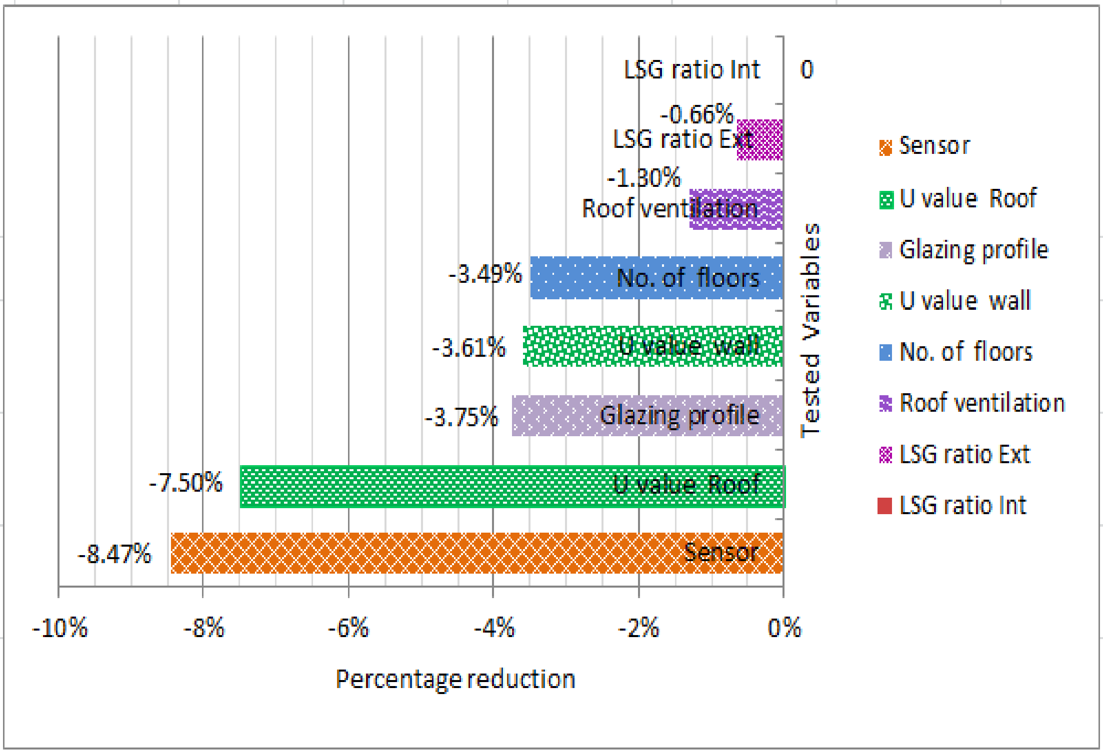


Fig 4.39 : Percentage reduction in energy consumption obtained by applying the optimal value for each variable

The vault roof while compared to closed roof could reduce energy consumption by 3.75%. By increasing the number of floors to 4 and 8, the energy consumption is reduced by 3.5 and 5% respectively. But addition of floors will depend on municipality regulations and client desire's. Having an automated roof which opens roof glazing under favorable outdoor climatic conditions and provides roof ventilation reduces energy consumption to a small extent. Roof ventilation of 40% roof openable area reduces energy consumption by 1.30%.

LSG value of external glazing plays a minor role compared to other variables while that of internal glazing does not have an impact on thermal performance. By providing LSG value of 1.30 on the external glazing, the energy consumption is reduced by 0.66%.

The total carbon emission of the building is a derivative of the total energy consumption and the percentage reduction is same as that of reduction in total energy consumption.

Chapter 5

Optimal case Vs Base case

5.1 Optimal case modeling and Simulation

Base case model is altered with different values for each variable and simulated in ApacheSim and the results obtained is analyzed and best case value or the best parameter for each variable is arrived at, in the previous chapter. The following values are taken as the optimal case values.

- Sensor – addition of sensors
- Glazing profile – vault roof
- LSG ratio of glazing – for external glazing any value above 1.30 and internal glazing value does not affect thermal performance
- U value of envelope – for external wall 0.57 and Roof 0.30
- Roof ventilation – 40% openable area
- Number of floors – when number of floors increased the performance improved. But as discussed in section 4.4.2, most of the malls in UAE have a wide floor plan and not more than 2 to 4 floors. Constructing higher number of floors will depend on the municipality approval for that specific location and the client's desires. However for optimal case analysis, all 3 values (2,4 and 8 floors) are tested to analyze the impact on building's performance when all variables are changed together.

The next step involves modelling the optimal case with the best parameter for each variable. So the base case IES model is altered into a G+3 building as shown in Figures 5.1 and 5.2. The roof profile for this analysis is not changed since the best parameter for roof profile vault glazing is provided in the base case itself. LSG Value of glazing and U value of envelope altered with suitable construction materials. Figure 5.3 shows the construction template used in the building template manager for the optimal case. In IES-MacroFlo module, the roof openable area is changed to 40% as can be seen in Figure 5.4. Then sensors are added in this optimal case model as shown in Figure 5.5 in IES Radiance module and simulated. Finally, the model is simulated in ApacheSim with MacroFlo and Radiance link and the results are recorded. Similarly the optimal values are applied to G+1 and G+7 model to check if height has an impact on other optimal values and the results are recorded. Figures 5.6 and 5.7 shows the interior view of atrium in G+1 and G+7 model respectively.

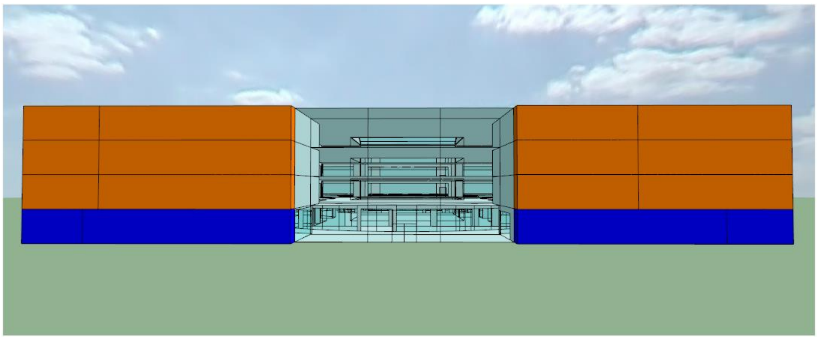


Figure 5.1: Exterior view of Optimal case G+3 model (IES-VE)

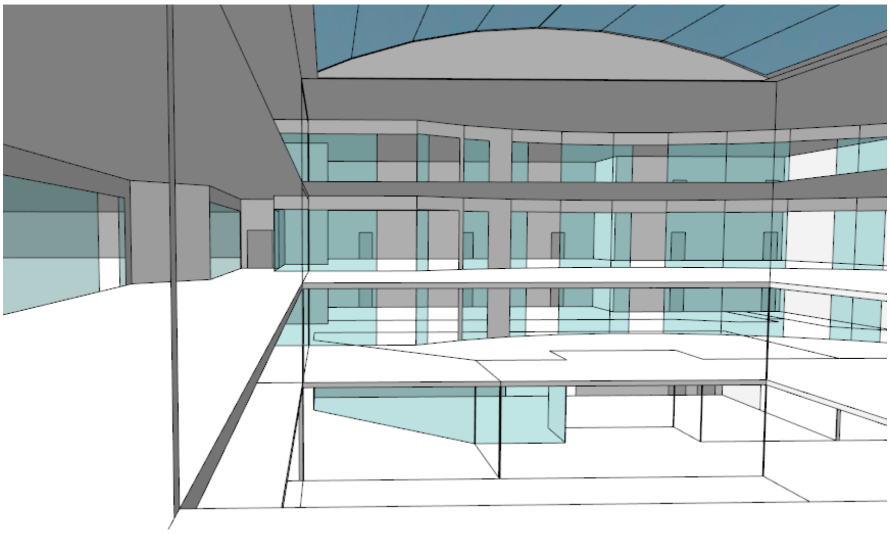


Figure 5.2 : Interior view of Atrium for Optimal case G+3 model (IES-VE)

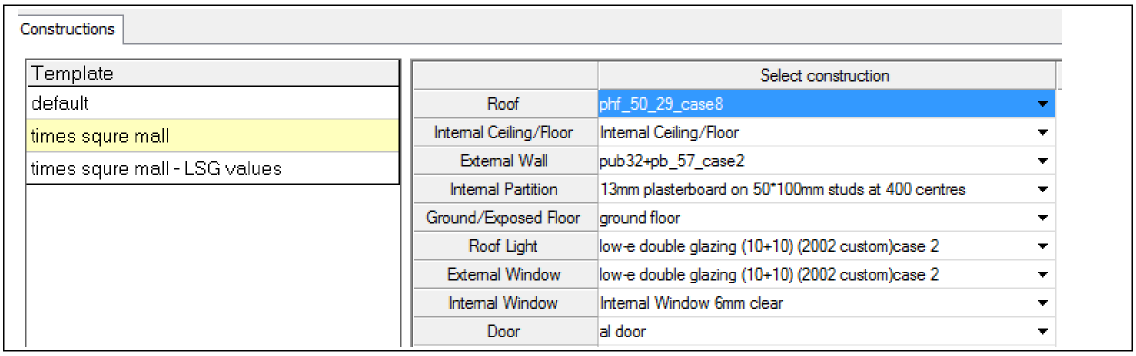


Figure 5.3: Construction template for Optimal case (IES-VE Apcdb)

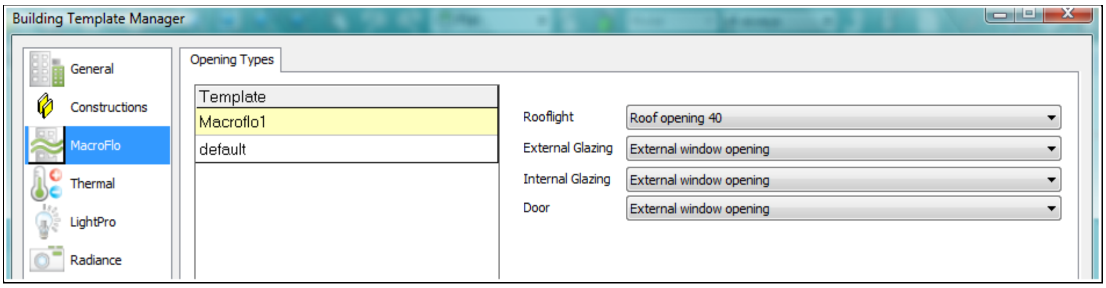


Figure 5.4 : Roof openable area setting in IES MacroFlo for Optimal case (IES-VE)

Room	Sensor ID	Position	Direction	On/Off
[ZN000001] zone 8 gf	ZN000001:1	-104.867, -48.000, 5.228	0.00, 0.00, -1.00	ON
[ZN000015] Zone adjoin gf	ZN000015:1	-104.775, -100.000, 5.228	0.00, 0.00, -1.00	ON
[ZN000000] Zone Atrium	ZN000000:1	-104.500, -79.384, 21.675	0.00, 0.00, -1.00	ON
[ZN000006] Zone adjoin ff	ZN000006:1	-102.000, -98.000, 10.675	0.00, 0.00, -1.00	ON
[ZN000007] Zone lobby	ZN000007:1	-104.500, -134.724, 21.675	0.00, 0.00, -1.00	ON
[ZN000014] Zone adjoin 2f	ZN000014:1	-104.000, -98.000, 16.228	0.00, 0.00, -1.00	ON
[ZN00001B] Zone adjoin 3f	ZN00001B:1	-104.000, -98.000, 21.675	0.00, 0.00, -1.00	ON

Figure 5.5 : Sensor settings in IES Radiance for Optimal case (IES-VE)

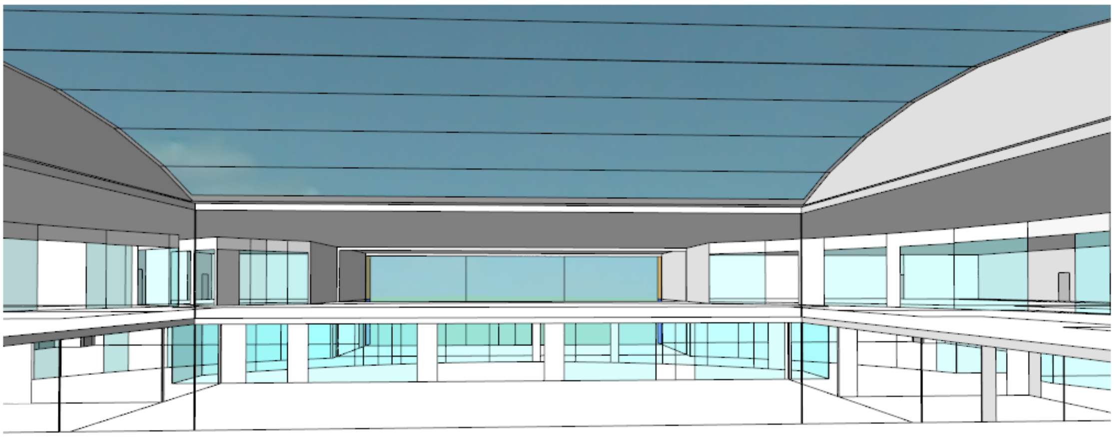


Figure 5.6 : Interior view of Atrium for Optimal case G+1model (IES-VE)

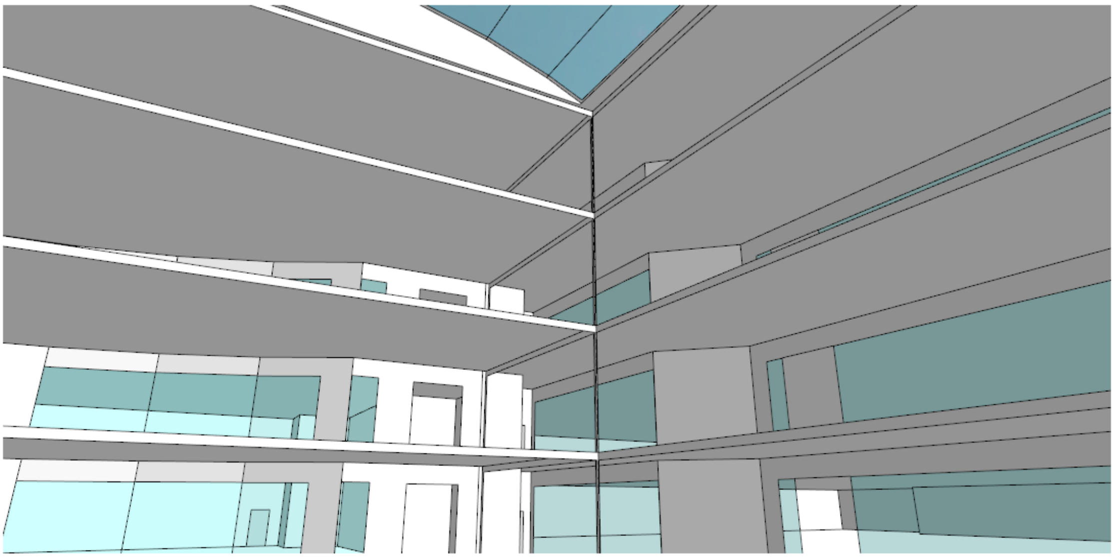


Figure 5.7 : Interior view of Atrium for Optimal case G+7 model (IES-VE)

5.2 Optimal case Vs Base case Analysis

In this final research analysis stage, performance of the base case without sensor which is the as-in-site case is compared to the optimal cases which has the best parameter for each variable applied. The overall performance is analyzed in terms of reduction in energy consumption and carbon emission ; the thermal performance in terms of cooling plant load and dehumidification plant load ; the day light performance in terms of lights energy reduction that could be achieved in the tested cases. Since the floor area of the 3 cases vary, the values are calculated per m^2. Simulation results obtained in IES-Vista showing the monthly breakup for the 3 cases is shown in Appendix I. The results are summarized in Table 5.1.

Table 5.1 : Comparison of results for Base case and Optimal cases

BASECASE VS OPTIMAL CASE G+1, G+3 AND G+7							
PER m^2		**OVERALL PERFORMANCE**		**THERMAL PERFORMANCE**		**DAYLIGHT PERFORM -ANCE**
	Options	**Yearly energy consumptio n (kWh/m^2)**	**Total carbon emission ($kgCo2/m^2$)**	**Cooling plant load (kWh/m^2)**	**Dehumid. plant load (kWh/m^2)**	**Lights energy (kWh/m^2)**
	Base case with no sensor (35413.45 m^2)	228.509	118.596	235.121	42.369	89.764
	Optimal Case G+1 (35413.45 m^2)	181.05 (-20.77%)	93.964 (-20.77%)	164.974 (-29.83%)	43.706 (+3.16)	76.708 (-14.54%)
	Optimal Case G+3 (69536.14 m^2)	182.336 (-20.21%)	94.632 (-20.21%)	157.612 (-32.97%)	43.093 (+1.71%)	81.982 (-8.67%)
	Optimal Case G+7 (137781.52m^2)	183.842 (-19.55%)	95.414 (-19.55%)	154.527 (-34.28%)	42.946 (+1.36)	85.105 (-5.19%)

Results Analysis:

Optimal values of all variables are applied together on the G+1, G+3 and G+7 building and compared with base case and the results are analyzed. Following observations were made from the results.

The results show that the optimal cases when compared to the base case model, reduces the cooling plant load by about 30 to 34% and lights energy by 5 to 15% and increases dehumidification plant load by 1 to 3%. It can be seen that the overall performance in terms of energy consumption and carbon emission is almost the same. i.e.,- 20 to 21% even though the number of floors vary from 2 to 8 floors in the 3 cases. Figure 5.8 illustrates the comparison of percentage reduction that could be achieved in cooling plant load, dehumidification plant load, light energy and yearly energy consumption per m^2 area of the building.

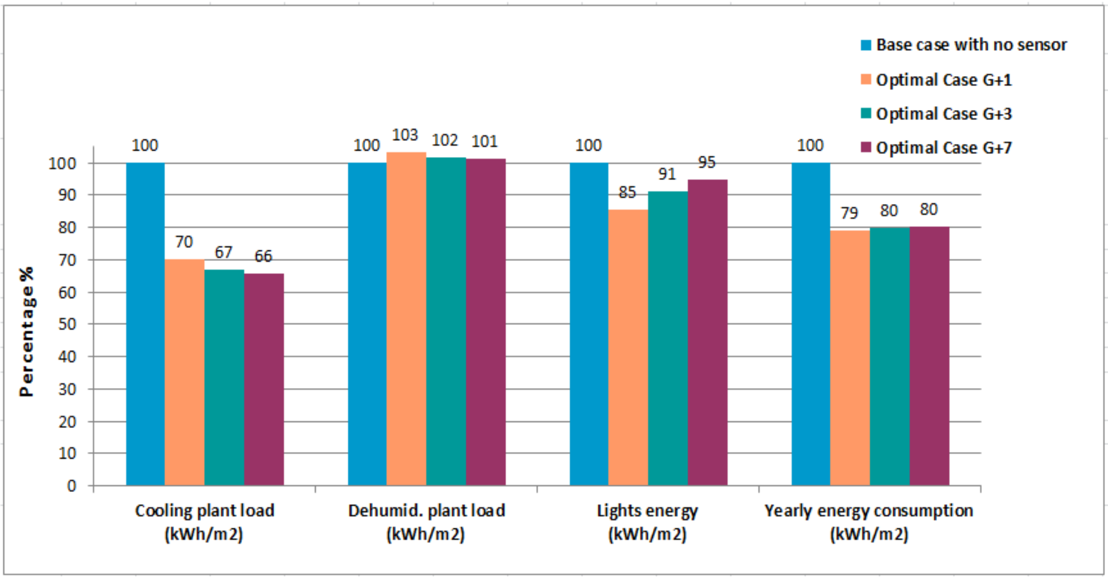


Figure 5.8 : Percentage reduction of results in base case VS optimal cases

5.2.1 Thermal performance

It can be seen from table 5.1 and figure 5.8 that the cooling load of building will be reduced 30-34% in the optimal cases when all optimal values are applied. The reduction is better when number of floors are increased. This is because the compactness of the building which is surface area to volume ratio decreases as the number of floors increase. In hot climates when surface area to volume ratio decreases, the solar gain and the external conduction gain decreases thus decreasing the cooling load of the building.

Similarly, it can be seen that the dehumidification load performance decreases when number of floors are increased. The increase in dehumidification load drops from

+3.16% in G+1 building to +1.36% in G+7 building (table 5.1). Again this is because the ratio of openable roof area to total volume ratio decreases as number of floors increase. This decreases the dehumidification load. The performance of building with more number of floors is better in terms of cooling and dehumidification load.

5.2.2 Day light performance

The main purpose of Atrium is to bring in natural light into the building and to utilize this natural daylight, to reduce energy required for lighting. The sensors placed in Atrium will cutoff lights when daylight illuminance reaches 500Lux. Hence the day light performance of Atrium is analyzed in terms of light energy required. It can be seen from table 5.1and figure 5.8 that the light energy reduces 14.5% in G+1 building. As the number of floors are increased the reduction in light energy is only 8.7 and 5.2% in G+3 and G+7 building respectively. The performance of building with less number of floors is better in terms of light energy since the penetration of the natural sunlight is better when building height is less. As the height of building increases the daylight reaching lower floors decrease, thus increasing the light energy required for the building.

5.2.3 Overall performance

The overall performance is analyzed in terms of reduction in energy consumption and carbon emission. It can be noted from table 5.1 that although the cooling plant load and dehumidification plant load is reduced as the height of building increases, the total energy consumption of the building is almost the same in all 3 cases. This is due to the fact that the light energy increases when height of building is increased as discussed in section 5.2.2. Hence the decrease in cooling load is balanced by the increase in light energy. Thus we note that when optimal values for all strategies discussed in chapter 4 is applied to the base case, the reduction in energy consumption is about 20%, irrespective of the number of floors.

The total carbon emission of the building is relative to the total energy consumption as discussed in section 4.2 and the percentage reduction in optimal case is about 20%, same as the reduction in total energy consumption.

Chapter 6

Conclusions and Recommendations

Chapter 6 :   Conclusions and Recommendations

This research focusses on the efficiency of the Atrium in a mall building in context to a hot arid climate and investigates on how its efficiency could be increased with regard to its thermal and daylight performance. It also looks into the important variables impacting the efficiency and the best values for each variable that could be incorporated in the design of Atrium in a hot arid climate and thus saving on the total energy consumption. A literature review was conducted initially to study the history of Atrium, its characteristics, variables impacting its efficiency and the methodology used by other researchers. Based on the literature review, computer simulation is identified as the best feasible methodology to investigate on this research question. IES-VE Software is chosen for computer modeling and simulation.

An existing Atrium in Dubai – Times square center shopping mall is selected for this study. The existing parameters at site are studied with existing drawings and site visits. A virtual model with real dimensions and existing parameters and working profile at site is constructed in IES-VE ModelIT module. The weather data EPW file for United Arab Emirates is loaded. The model is simulated in IES-ApacheSim module and the results are recorded. Then this base case model is altered with one variable at a time, keeping all other variables constant and then simulated as before and the results are recorded for each case. In the data analysis stage, the results are analyzed with their energy consumption, cooling load, dehumidification load, light gain and carbon emission and also solar gain, external conduction gain, infiltration gain and MacroFlo gain when necessary. The optimal parameter/value for each variable which gives the most efficient energy consumption is analyzed. Next an optimum case model is constructed by applying the optimal values of each variable to the base case G+1 model. These optimal values are applied to G+3 and G+7 models also to check whether height has an impact on other optimal values and the results are recorded. These 3 optimal case models are simulated and their performance is recorded for analysis. In the final research analysis stage, thermal and daylight performance for the base case without sensor which is the as-in-site case is compared to the optimal cases. The reduction in energy consumption, cooling load, dehumidification load, light energy and carbon emission that could be achieved by applying the optimal case is studied.

Hence this research analyzes the percentage reduction in energy consumption of the building achieved by each variable, optimal values for each variable and the most effective variable or strategy that could be applied in the design and construction of an atrium in a shopping mall in a hot arid climate and thus answers the research question that were put forward initially.

6.1 Conclusions

Glazing profile, Number of floors, LSG ratio of glazing system, U value of envelope and Roof ventilation are identified as variables impacting the efficiency of atrium in terms of its thermal and daylight performance and analyzed in this research. The following conclusions were arrived from this research.

- Initial analysis revealed that the placement of a dimming sensor inside the building which controls the lights when room illumination level by day lighting goes above 500 Lux, reduces energy consumption and carbon emission by 8.47%.
- Variable roof ventilation was tested with openable roof which functions under comfortable climatic conditions outside – i.e., outside dry bulb temperature < 22ºC and outside air humidity < 90 %. It was found that as the openable area increases bringing more cool and humid air in winter, the latent dehumidification plant load increases due to humidity of air while the cool air decreases the sensible cooling load. So the cooling plant load keeps decreasing while dehumidification plant load keeps increasing and at 40% openable area, they reach a point where the energy consumption starts to increase.
- The difference in energy consumption between a model with dynamic opening and one with 40% openable area is only 0.09% of total energy. Considering this negligible reduction and the cost for automated controls for dynamic opening, 40% openable area which reduces energy consumption by 1.30% is taken as the optimum value for roof ventilation openable area.
- Variable roof profile was analyzed by changing the original vault roof with 7 different options including north light, flat glazed and closed roof. Vault roof followed by flat glazed roof profile gave the best performance in terms of energy consumption. Although their cooling plant load and thus system energy was

highest due to high solar gain, their final energy consumption was lowest. This is because of reduction in lighting load due to more natural light coming in. Hence when system energy and lights energy were added, their total energy consumption was the lowest among all the roof profiles tested. Similarly, although the cooling plant load was lowest for closed roof and North light cases, their final energy consumption was highest. This is because natural light penetrating into the building is reduced significantly due to null roof glazing area in closed roof case and only 20-40% of original vault glazing area in north light cases hence increasing artificial lighting needed. Finally when system energy and light energy is added up, the total energy consumption goes much higher. It is also noted that providing a vault roof instead of a closed roof can reduce energy consumption by 3.75%.

- Variable LSG ratio of glazing was analyzed for internal glazing and external glazing separately. Out of all variables tested LSG ratio has minimal impact on energy consumption. LSG ratio above 1.3 is recommended for external glazing (external window and Roof light) and it will reduce energy consumption by 0.68%. For internal openings changing LSG value of glazing does not an impact.
- It is also noted that different glazing materials can give the same performance if their LSG value is same. Since LSG = VT/ SHGC, a material with high visible transmittance or with low SHGC can be chosen depending on site requirements.
- Variable U value of envelope tested values ranging from 0.18 to 2.39 for the external walls and roof separately. It was noted that the lowest U values tested gave the best performance and U value of 0.57 for external walls improved performance by -3.61%. and 0.30 for roof improved performance by -7.52%. But considering that the cost of insulation doubles to achieve the lowest U value and that the recommended value according to Dubai municipality regulations is 0.57 for external wall and 0.30 for roof, 0.57 and 0.30 are taken as the optimal values for external wall and roof respectively.
- It was noted that the impact of U value on the roof is much more than that on the walls. So more care is to be taken for good roof insulation.
- Any insulation material available easily in market could be used but achieving the desired U value by altering their thickness is the important factor. Also it was

noted that adding a light weight metallic cladding on the external wall does not affect the U value and hence thermal performance much.

- Variable number of floors was tested with 2,4,8 floors. As the height of building increases the daylight reaching ground floor decreases, leading to higher light gain in lower level floors but external conduction gain and solar gain becomes lesser leading to reduction in cooling load. Hence a building with more number of floors reduces energy consumption by 5% in a G+7 building and 3.5% in a G+3 building when all other variables are constant.
- Optimal values obtained for each variable where applied together to the base case G+1 model and also G+3 and G+7 models to analyze its impact on buildings performance when all optimal values are applied together. It was noted that as height of building increased, the performance in terms of cooling load and dehumidification load increased but in terms of lighting load, the performance decreased. The performance of cooling load and lighting load balanced each other and when they were added up for final energy consumption, it was noted that the percentage reduction achieved is almost the same value of about 20% in all 3 cases, irrespective of the number of floors.
- The energy consumption of base case is 228.5 kWh/m2. The energy consumption finally achieved after applying optimal values is 181 kWh/m2. Thus about 20% reduction in energy consumption is achieved in this research by applying all the optimal values for the variables. This percentage reduction will depend on the base case which is being analyzed and it may vary according to the base case conditions.
- The total carbon emission of the building is a derivative from total energy consumption and the percentage reduction will be always the same as that of total energy consumption.
- By applying all the optimal values, 20% reduction is achieved in this research. It is also noted that when all strategies are applied together on a building, the effective reduction in energy consumption achieved need not be equal to the sum of reduction achieved when the strategies are applied individually due to the effect of variables on each other.
- Thus it is concluded that a final energy consumption of 181 kWh/m2 could be achieved by applying optimal values.

6.2 Recommendations

6.2.1 Recommendations for an optimal Atrium

This research aims to arrive at optimal values for each variable, the percentage reduction in energy consumption of the building achieved by each variable and the most effective variable or strategy that could be applied in the construction of an atrium in a shopping mall in a hot arid climate. This will help the designers, builders and promoters to incorporate atrium in their buildings in a more effective way and thus enhancing the building's efficiency. If all buildings constructed with atriums comply with some basic standards, it will increase the buildings efficiency and an efficient atrium in a building saves on the total energy consumption of the building, thus playing a significant role in the total savings on the energy consumption in UAE.

Out of all the strategies tested, placing a sensor inside the building can reduce energy consumption by 8.47% and is noted to be the most effective strategy. As explained earlier the main purpose of having an atrium inside a building is to bring in natural sunlight for illuminance. Unless artificial lighting is cut down by placing a dimming sensor, the purpose of natural daylight through atrium will go waste. Hence sensor is vital in any atrium building and it could be incorporated into the building with lesser effort than the other strategies.

Next, U value plays a major role especially for the roof. The direct solar radiation on the roof in this hot arid climate, heats up the building to a great extent and this is reduced by applying insulation of U value 0.57 on the roof, thus reducing the energy consumption of the building by 7.5%. Similarly insulation on external walls with U value 0.30 can reduce energy consumption by 3.61%. These U values could be achieved by choosing any locally available insulating material in the market and changing its thickness to achieve the particular value.

Providing automated roof opening with 40% openable area which opens under favorable climatic conditions can save energy consumption by 1.30%. LSG value of external glazing plays a minor role compared to other variables providing a reduction of 0.66% only, with a glazing of LSG ratio 1.30 on external walls and roof while that of internal glazing does not have an impact on thermal performance. Since LSG = VT/

SHGC, a material with high visible transmittance or with low SHGC can be chosen depending on site requirements.

Application of all above mentioned variables together can reduce the energy consumption of Atrium by about 20%, irrespective of the number of floors. In this research the roof profile of base case is vault roof which is the best parameter. Hence it is not changed in the optimal case. However, a vault roof while compared to closed roof could reduce energy consumption by 3.75%. Finally, by applying all these optimal values the energy consumption of atrium building can be brought down to 181kWh/m2.

6.2.2 Recommendations for future study

This section recommends the scope for further study in the field of atrium. From the literature review conducted, geometry of atrium was identified as one of the variable impacting the atrium's efficiency. The well opening size could be altered and further research done to study the optimal value for this variable.

Different forms of atrium are defined by the number of sides the atrium abuts the building namely one sided, two sided, three sided, four sided, enclosed or linear atriums. The atrium analyzed in this research is a four sided or enclosed atrium. The other forms of atrium could be studied in further research.

This research is done specifically for a shopping mall situated in a hot arid climate. Further studies can be conducted with the same virtual model but in different climatic zones to analyze the modifications that should be adapted for the various strategies studied.

Many of the malls nowadays have multiple atriums within their interior space and further study could be done to analyze their impact over one another.

Indoor plants and water features will have an impact on the micro climate inside the atrium. This study could be extended to analyze that aspect of design.

This research is done on an Atrium in a shopping mall. Usually, shopping malls have large open spaces, i.e., a large adjoining area around the atrium and showrooms with mostly open or glazed frontages. But other building sectors such as Office towers and Residential towers and health sector buildings will be planned mostly with closed rooms around the atrium. The research could be continued for other building types to find the best design parameters.

Finally, this research concludes that a well-designed atrium in a shopping mall with optimal values for the variables can lower the energy consumption to 181 kWh/m2. Atrium being one of the common design feature nowadays in malls can contribute much to the energy savings of that region if properly designed. This implies the need for further research in the field of atriums.

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APPENDIX

APPENDIX A

ASHRAE standards for energy calculations :

Table A.1 : People gain – Latent and Sensitive gain standards (ASHRAE)

Heat gain from people in conditioned spaces (from ASHRAE *Handbook of Fundamentals*, Chap. 26, Table 3)

Degree of activity	Typical application	Total heat, W* Adult male	Total heat, W* Adjusted M/F/C[1]	Sensible heat, W*	Latent heat, W*
Seated at theater	Theater—matinee	115	95	65	30
Seated at theater, night	Theater—evening	115	105	70	35
Seated, very light work	Offices, hotels, apartments	130	115	70	45
Moderately active office work	Offices, hotels, apartments	140	130	75	55
Standing, light work; walking	Department or retail store	160	130	75	55
Walking, standing	Drug store, bank	160	145	75	70
Sedentary work	Restaurant[2]	145	160	80	80
Light bench work	Factory	235	220	80	80
Moderate dancing	Dance hall	265	250	90	90
Walking 4.8 km/h (3 mph); light machine work	Factory	295	295	110	110
Bowling[3]	Bowling alley	440	425	170	255
Heavy work	Factory	440	425	170	255
Heavy machine work; lifting	Factory	470	470	185	285
Athletics	Gymnasium	585	525	210	315

Note: Tabulated values are based on a room temperature of 24°C (75°F). For a room temperature of 27°C (80°F), the total heat gain remains the same but the sensible heat values should be decreased by about 20 percent, and the latent heat values should be increased accordingly. All values are rounded to nearest 5 W. The fraction of sensible heat that is radiant ranges from 54 to 60 percent in calm air ($V < 0.2$ m/s) and from 19 to 38 percent in moving air ($0.2 < V < 4$ m/s).

*Multiply by 3.412 to convert to Btu/h.

[1]Adjusted heat gain is based on normal percentage of men, women, and children for the application listed, with the postulate that the gain from an adult female

Table A.2 : Occupancy area standards (ASHRAE)

Classifications	Occupancy Sq Ft/Person Lo	Av	Hi
Apartment, High Rise	325	175	100
Auditoriums, Churches, Theaters	15	11	6
Educational Facilities	30	25	20
Schools, Colleges, Universities			
Factories Assembly Areas	50	35	23
Light Manufacturing	200	150	100
Heavy Manufacturing*	200	250	300
Hospitals Patient Rooms	70	50	25
Public Areas	100	80	50
Hotels, Motels, Dormitories	200	150	100
Libraries and Museums	80	60	40
Office Buildings (General)	130	110	80
Private Offices	150	125	100
Stenographic Department	100	85	70
Residential Large	600	400	200
Medium	600	360	200
Restaurants Large	17	15	13
Medium			
Shopping Centers, Department Stores and Specialty Shops			
Beauty and Barber Shops	45	40	25
Malls	100	75	50
Refrigeration for Central Heating and Cooling Plant			
Urban Districts			
College Campuses			
Commercial Centers			
Residential Centers			

To convert imperial to metric system, use 10.76 sq ft = 1m2

Table A.3 : Lighting load standards (ASHRAE)

Table 1. ASHRAE/IES 90.1 lighting power allowances using the Building Area Method.

Building Type	Maximum Lighting Power Density (W/sq.ft.) Allowed Per Version of the ASHRAE/IES 90.1 Standard			
	1989	1999/2001	2004/2007	2010
Automotive Facility	0.96	1.5	0.9	0.982
Convention Center	2.07	1.4	1.2	1.08
Court House	1.44	1.4	1.2	1.05
Dining: Bar Lounge/Leisure	1.37	1.5	1.3	0.99
Dining: Cafeteria/Fast Food	1.37	1.8	1.4	0.90
Dining: Family	1.37	1.9	1.6	0.89
Dormitory	1.15	1.5	1.0	0.61
Exercise Center	2.07	1.4	1.0	0.88
Gymnasium	2.07	1.7	1.1	1.00
Healthcare Clinic	1.44	1.6	1.0	0.87
Hospital	1.44	1.6	1.2	1.21
Hotel	1.15	1.7	1.0	1.00
Library	1.29	1.5	1.3	1.18
Manufacturing Facility	0.96	2.2	1.3	1.11
Motel	1.15	2.0	1.0	0.88
Motion Picture Theater	2.07	1.6	1.2	0.83
Multi-Family	1.15	1.0	0.7	0.60
Museum	2.07	1.6	1.1	1.06
Office	1.26	1.3	1.0	0.90
Parking Garage	1.03	0.3	0.3	0.25
Penitentiary	1.44	1.2	1.0	0.97
Performing Arts Theatre	2.07	1.5	1.6	1.39
Police/Fire Station	1.44	1.3	1.0	0.96
Post Office	1.44	1.6	1.1	0.87
Religious Building	2.07	2.2	1.3	1.05
Retail	2.25	1.9	1.5	1.40
School/University	1.29	1.5	1.2	0.99
Sports Arena	2.07	1.5	1.1	0.78
Town Hall	1.44	1.4	1.1	0.92
Transportation	2.07	1.2	1.0	0.77
Warehouse	1.03	1.2	0.8	0.66

To convert imperial to metric system, use 10.76 sq ft = 1m2

APPENDIX B

Energy consumption break up from IES (IES VE Vista manual, pp18,20-21)

Method of derivation of total energy consumption for Flat glazed roof :

Cooling plant sensible load is sum of the following as shown in Table B.1

Table B.1 : Cooling Plant load breakup

	Lighting gain (MWh)	People gain (MWh)	Equipment gain (MWh)	Solar gain (MWh)	External conduction gain (MWh)	Internal conduction gain (MWh)	Aux vent gain (MWh)	Natural vent gain (MWh)	Infiltration gain (MWh)	Cooling plant sensible load (MWh)
	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms
Date	tsq_flat	tsq_flat	tsq_flat	tsq_flat	tsq_flat	tsq_flat	tsq_flat	tsq_flat	tsq_flat	tsq_flat
Jan 01-31	241.9233	115.1008	0.0000	50.8622	-120.6991	0.2824	0.0000	0.0000	-57.5154	229.9723
Feb 01-28	214.9361	103.6233	0.0000	58.7535	-48.7843	-1.1304	0.0000	0.0000	-32.0786	295.2891
Mar 01-31	237.5586	114.0509	0.0000	70.8590	22.3266	0.0925	0.0000	0.0000	-8.2617	436.6163
Apr 01-30	229.9720	111.6250	0.0000	81.8015	159.1000	-0.4534	0.0000	0.0000	43.4923	625.5331
May 01-31	231.4879	114.5759	0.0000	100.7304	316.0974	-0.6935	0.0000	0.0000	99.2801	861.4752
Jun 01-30	220.8947	110.5751	0.0000	100.1010	384.2450	0.2918	0.0000	0.0000	120.7073	936.8118
Jul 01-31	231.6666	115.6258	0.0000	98.6272	455.3113	-0.5135	0.0000	0.0000	145.4846	1046.1981
Aug 01-31	231.0194	114.0509	0.0000	94.0589	466.0278	0.2748	0.0000	0.0000	150.0067	1055.4357
Sep 01-30	226.6096	111.1000	0.0000	81.4153	377.6257	0.1896	0.0000	0.0000	117.4947	914.4321
Oct 01-31	238.5548	115.1008	0.0000	70.2298	235.7473	0.5988	0.0000	0.0000	70.8644	731.0933
Nov 01-30	232.3479	110.5751	0.0000	52.9486	75.9460	0.4749	0.0000	0.0000	16.8380	489.1270
Dec 01-31	242.7057	115.1008	0.0000	46.8330	-68.3775	0.5735	0.0000	0.0000	-33.7844	303.0455
Summed	2779.6763	1351.1045	0.0000	907.2204	2254.5664	-0.0125	0.0000	0.0000	632.5281	7925.0293

Chiller load = [Room cooling plant load + room dehumidification plant load] / cooling delivery efficiency . So, Chiller load = 7925.03 + 1493.88 = 9418.91 / 1.08 = 8721.21

Table B.2 : Chiller load breakup

	Room cooling plant sens. load (MWh)	Room dehum. plant load (MWh)	System air sens. clg. load (MWh)	System air lat. clg. load (MWh)	Aux vent sens. clg. load (MWh)	Aux vent lat. clg. load (MWh)	Chillers load (MWh)
	tsq_flat fi.aps	tsq_flat fi.aps	tsq_flat fi.aps	tsq_flat fi.aps	tsq_flat fi.aps	tsq_flat fi.aps	tsq_flat fi.aps
Date							
Jan 01-31	229.9723	21.5467	0.0000	0.0000	0.0000	0.0000	232.8879
Feb 01-28	295.2891	21.3312	0.0000	0.0000	0.0000	0.0000	293.1668
Mar 01-31	436.6164	69.7527	0.0000	0.0000	0.0000	0.0000	468.8604
Apr 01-30	625.5331	58.4014	0.0000	0.0000	0.0000	0.0000	633.2720
May 01-31	861.4752	107.2951	0.0000	0.0000	0.0000	0.0000	897.0099
Jun 01-30	936.8118	179.8406	0.0000	0.0000	0.0000	0.0000	1033.9377
Jul 01-31	1046.1981	255.5142	0.0000	0.0000	0.0000	0.0000	1205.2897
Aug 01-31	1055.4358	243.5907	0.0000	0.0000	0.0000	0.0000	1202.8031
Sep 01-30	914.4321	255.5813	0.0000	0.0000	0.0000	0.0000	1083.3452
Oct 01-31	731.0933	141.3002	0.0000	0.0000	0.0000	0.0000	807.7712
Nov 01-30	489.1270	105.2113	0.0000	0.0000	0.0000	0.0000	550.3133
Dec 01-31	303.0455	34.5182	0.0000	0.0000	0.0000	0.0000	312.5589
Summed total	7925.0298	1493.8835	0.0000	0.0000	0.0000	0.0000	8721.2168

Chiller energy = chillers load / chiller seasonal efficiency

Hence, Chiller energy = 8721.21 / 2.5 = 3488.484

Total system energy = chillers energy + fan/pumps energy. i.e,4709.454 = 3488.484+1220.97

Table B.3 : System energy breakup

	Boilers energy (MWh)	Chillers energy (MWh)	Ap Sys aux + DHW/solar pumps energy (MWh)	Ap Sys heat rej fans/pumps energy (MWh)	Total system energy (MWh)
	tsq_flat fi.aps	tsq_flat fi.aps	tsq_flat fi.aps	tsq_flat fi.aps	tsq_flat fi.aps
Date					
Jan 01-31	0.0000	93.1552	0.0000	32.6043	125.7595
Feb 01-28	0.0000	117.2667	0.0000	41.0433	158.3101
Mar 01-31	0.0000	187.5443	0.0000	65.6404	253.1846
Apr 01-30	0.0000	253.3090	0.0000	88.6582	341.9671
May 01-31	0.0000	358.8041	0.0000	125.5813	484.3850
Jun 01-30	0.0000	413.5749	0.0000	144.7513	558.3262
Jul 01-31	0.0000	482.1159	0.0000	168.7405	650.8564
Aug 01-31	0.0000	481.1212	0.0000	168.3925	649.5134
Sep 01-30	0.0000	433.3384	0.0000	151.6683	585.0067
Oct 01-31	0.0000	323.1087	0.0000	113.0880	436.1967
Nov 01-30	0.0000	220.1253	0.0000	77.0439	297.1692
Dec 01-31	0.0000	125.0236	0.0000	43.7582	168.7817
Summed total	0.0000	3488.4873	0.0000	1220.9701	4709.4565

Total energy consumption = System energy +Lights energy + Equipment energy

= 4709.454 + 2779.68 = **<u>7489.1349</u>** (page 21 manual)

Table B.4 : Total energy breakup

Summary

Month	Heating (boilers etc.)	Cooling (chillers etc.)	Fans, pumps and controls	Lights	Equip.
A-Z	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo
Jan	0.0	93.2	32.6	241.9	0.0
Feb	0.0	117.3	41.0	214.9	0.0
Mar	0.0	187.5	65.6	237.6	0.0
Apr	0.0	253.3	88.7	230.0	0.0
May	0.0	358.8	125.6	231.5	0.0
Jun	0.0	413.6	144.8	220.9	0.0
Jul	0.0	482.1	168.7	231.7	0.0
Aug	0.0	481.1	168.4	231.0	0.0
Sep	0.0	433.3	151.7	226.6	0.0
Oct	0.0	323.1	113.1	238.6	0.0
Nov	0.0	220.1	77.0	232.3	0.0
Dec	0.0	125.0	43.8	242.7	0.0
Total	0.0	3,488.5	1,221.0	2,779.7	0.0

MWh

The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted

Total Yearly Energy Consumption = 7,489.1MWh

Total Yearly Energy Consumption per Floor Area = 211.9KWh/m^2

APPENDIX C

BASECASE with and without sensor - IES Simulation Results monthly breakup

Table C.1 : Basecase with and without sensor - Energy consumption monthly breakup (IES-VE Vista)

	Total energy (MWh)	Total energy (MWh)
	tsq_BC_sens.aps	tsq_base_no sensor.aps
Date		
Jan 01-31	359.9607	409.2103
Feb 01-28	365.3307	415.6718
Mar 01-31	482.8168	537.3322
Apr 01-30	564.4525	620.3171
May 01-31	708.9504	774.0001
Jun 01-30	772.9509	839.9877
Jul 01-31	875.7981	943.7924
Aug 01-31	875.2495	939.1577
Sep 01-30	806.8715	865.3366
Oct 01-31	668.6136	723.3422
Nov 01-30	522.6172	571.8223
Dec 01-31	403.1876	452.3119
Summed total	7406.7998	8092.2822

Table C.2 : Basecase with and without sensor - Cooling load and Dehumidification plant load monthly breakup (IES-VE Vista)

	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)
	tsq_BC_sens.aps	tsq_base_no sensor.aps	tsq_BC_sens.aps	tsq_base_no sensor.aps
Date				
Jan 01-31	224.4498	255.8619	21.5476	21.5288
Feb 01-28	289.9168	322.3772	21.3284	21.3227
Mar 01-31	431.4677	466.9084	69.9206	69.9149
Apr 01-30	621.3385	657.8311	58.5094	58.5062
May 01-31	858.3467	900.8873	107.6766	107.6766
Jun 01-30	934.2919	978.1360	180.7307	180.7307
Jul 01-31	1043.5782	1088.0607	256.9008	256.9008
Aug 01-31	1053.7716	1095.5814	244.8934	244.8934
Sep 01-30	912.7680	951.0045	256.9661	256.9661
Oct 01-31	727.9705	763.7590	141.8955	141.8953
Nov 01-30	484.8942	516.9969	105.5541	105.5376
Dec 01-31	297.3658	329.0504	34.5514	34.5442
Summed total	7880.1592	8326.4551	1500.4747	1500.4172

Table C.3: Basecase with and without sensor - Carbon emission monthly breakup (IES-VE Vista)

	Total CE (kgCO2)	Total CE (kgCO2)
	tsq_BC_sens.aps	tsq_base_no sensor.aps
Date		
Jan 01-31	186819	212380
Feb 01-28	189607	215733
Mar 01-31	250582	278875
Apr 01-30	292951	321944
May 01-31	367945	401706
Jun 01-30	401161	435954
Jul 01-31	454539	489828
Aug 01-31	454254	487423
Sep 01-30	418766	449110
Oct 01-31	347010	375414
Nov 01-30	271238	296775
Dec 01-31	209254	234750
Summed total	3844127	4199894

Table C.4 : Basecase with and without sensor - Light energy monthly breakup (IES-VE Vista)

	Total lights energy (MWh)	Total lights energy (MWh)
	tsq_BC_sens.aps	tsq_base_no sensor.aps
Date		
Jan 01-31	236.9612	270.5142
Feb 01-28	209.7077	243.8214
Mar 01-31	232.1223	268.9204
Apr 01-30	224.5281	262.1478
May 01-31	225.9386	269.7173
Jun 01-30	215.4386	260.5542
Jul 01-31	225.5585	271.3109
Aug 01-31	225.9164	268.9204
Sep 01-30	222.0044	261.3510
Oct 01-31	233.6799	270.5142
Nov 01-30	227.3929	260.5542
Dec 01-31	237.2286	270.5140
Summed total	2716.4773	3178.8398

Table C.5 : Basecase with and without sensor - Cooling load Break up (IES-VE Vista)

	Solar gain (MWh)	Solar gain (MWh)	External conduction gain (MWh)	External conduction gain (MWh)	Internal conduction gain (MWh)	Internal conduction gain (MWh)	Infiltration gain (MWh)	Infiltration gain (MWh)	Lighting gain (MWh)	Lighting gain (MWh)	People gain (MWh)	People gain (MWh)
	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms
Date	tsq_BC_ser	tsq_base_r	tsq_BC_ser	tsq_base_n	tsq_BC_ser	tsq_base_n	tsq_BC_ser	tsq_base_n	tsq_BC_ser	tsq_base_n	tsq_BC_ser	tsq_base_r
Jan 01-31	50.7712	50.7712	-121.1101	-122.9193	0.2851	0.2649	-57.7849	-58.1068	236.9612	270.5142	115.3056	115.3056
Feb 01-28	58.7724	58.7724	-48.9787	-50.4576	-1.1435	-1.1292	-32.2202	-32.4147	209.7077	243.8214	103.8077	103.8077
Mar 01-31	70.9138	70.9138	22.3790	21.0895	0.0907	0.0977	-8.2834	-8.3619	232.1223	268.9204	114.2538	114.2538
Apr 01-30	81.7872	81.7872	159.8626	158.7434	-0.4601	-0.4641	43.8011	43.7984	224.5281	262.1478	111.8236	111.8236
May 01-31	100.6855	100.6855	317.6600	316.4258	-0.6969	-0.7003	99.9821	99.9821	225.9386	269.7173	114.7797	114.7797
Jun 01-30	100.0657	100.0657	386.1640	384.8969	0.2948	0.2895	121.5609	121.5609	215.4386	260.5542	110.7718	110.7718
Jul 01-31	98.5605	98.5605	457.6334	456.3588	-0.5155	-0.5103	146.5133	146.5133	225.5585	271.3109	115.8315	115.8315
Aug 01-31	93.8712	93.8712	468.3898	467.1921	0.2751	0.2781	151.0673	151.0673	225.9164	268.9204	114.2538	114.2538
Sep 01-30	81.4693	81.4693	379.4807	378.3669	0.1928	0.1971	118.3256	118.3256	222.0044	261.3510	111.2977	111.2977
Oct 01-31	70.1247	70.1247	236.8928	235.8397	0.6043	0.6120	71.3654	71.3653	233.6799	270.5142	115.3056	115.3056
Nov 01-30	52.9787	52.9787	76.3022	75.2676	0.4822	0.4800	16.9688	16.9471	227.3929	260.5542	110.7718	110.7718
Dec 01-31	46.7932	46.7932	-68.5926	-70.0261	0.5779	0.5729	-33.9438	-34.1122	237.2286	270.5140	115.3056	115.3056
Summed	906.7935	906.7935	2266.0833	2250.7778	-0.0130	-0.0117	637.3521	636.5642	2716.4773	3178.8398	1353.5084	1353.5084

APPENDIX D

Variable Roof ventilation - IES Simulation Results monthly breakup

Table D.1: Roof ventilation - Energy consumption monthly breakup (IES-VE Vista)

	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)
	tsq_v100.aps	tsq_v80.aps	tsq_v60.aps	tsq_v50.aps	tsq_v40.aps	tsq_v30.aps	tsq_v20.aps	tsq_v10.aps	tsq_base
Date									
Jan 01-31	331.1623	326.8727	324.1950	323.9262	324.7293	327.2491	332.0532	340.7813	359.9607
Feb 01-28	346.5895	343.0877	340.8871	340.5975	341.0936	342.8527	346.3790	352.5739	365.3307
Mar 01-31	482.4754	476.9595	472.4500	470.7343	469.6421	469.4037	470.5981	474.1045	482.8167
Apr 01-30	571.9747	568.8004	565.9625	564.7423	563.7139	562.9710	562.6221	562.9335	564.4525
May 01-31	709.3380	709.1907	709.0613	709.0052	708.9588	708.9249	708.9089	708.9131	708.9505
Jun 01-30	772.9500	772.9500	772.9500	772.9500	772.9500	772.9500	772.9500	772.9500	772.9510
Jul 01-31	875.7985	875.7986	875.7985	875.7985	875.7986	875.7986	875.7986	875.7985	875.7983
Aug 01-31	875.2499	875.2499	875.2499	875.2499	875.2499	875.2498	875.2499	875.2499	875.2496
Sep 01-30	806.8713	806.8713	806.8713	806.8713	806.8713	806.8713	806.8713	806.8713	806.8715
Oct 01-31	672.2438	671.2501	670.3159	669.8806	669.4750	669.1112	668.8119	668.6149	668.6135
Nov 01-30	537.0726	532.7866	528.6680	526.7220	524.9061	523.3068	522.0864	521.5734	522.6171
Dec 01-31	386.3109	381.5397	377.9765	377.0097	376.8267	377.9716	381.2468	387.9721	403.1875
Summed total	7368.0371	7341.3569	7320.3857	7313.4873	7310.2153	7312.6602	7323.5757	7348.3359	7406.7998

Table D.2 : Roof ventilation - Cooling load monthly breakup (IES-VE Vista)

	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)
	tsq_v100.aps	tsq_v80.aps	tsq_v60.aps	tsq_v50.aps	tsq_v40.aps	tsq_v30.aps	tsq_v20.aps	tsq_v10.aps	tsq_base
Date									
Jan 01-31	135.5293	139.6362	145.5470	149.6277	154.9501	162.2407	172.8120	189.7641	224.4498
Feb 01-28	221.2233	224.9794	230.3164	233.9375	238.5477	244.7010	253.3032	266.0941	289.9168
Mar 01-31	379.1163	382.0141	386.0613	388.7936	392.3015	396.9175	403.4800	413.3584	431.4676
Apr 01-30	605.9748	607.1683	608.7593	609.7773	611.0049	612.5238	614.4803	617.1638	621.3384
May 01-31	857.5735	857.6496	857.7462	857.8046	857.8737	857.9575	858.0613	858.1878	858.3465
Jun 01-30	934.2932	934.2932	934.2932	934.2932	934.2932	934.2932	934.2932	934.2932	934.2919
Jul 01-31	1043.5781	1043.5782	1043.5781	1043.5780	1043.5780	1043.5782	1043.5781	1043.5780	1043.5782
Aug 01-31	1053.7722	1053.7721	1053.7722	1053.7722	1053.7722	1053.7722	1053.7721	1053.7722	1053.7716
Sep 01-30	912.7675	912.7675	912.7675	912.7675	912.7674	912.7674	912.7674	912.7675	912.7679
Oct 01-31	724.9965	725.2524	725.5901	725.8013	726.0525	726.3604	726.7501	727.2581	727.9705
Nov 01-30	469.2145	470.3728	471.8924	472.8820	474.0859	475.5811	477.5653	480.3284	484.8939
Dec 01-31	218.4491	222.4424	228.0018	231.7995	236.6669	243.2465	252.8000	267.9023	297.3658
Summed total	7556.4883	7573.9258	7598.3267	7614.8340	7635.8945	7663.9399	7703.6626	7764.4683	7880.1592

Table D.3:Roof ventilation-Dehumidification plant load monthly breakup (IES-VE Vista)

	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)
	tsq_v100.aps	tsq_v80.aps	tsq_v60.aps	tsq_v50.aps	tsq_v40.aps	tsq_v30.aps	tsq_v20.aps	tsq_v10.aps	tsq_base
Date									
Jan 01-31	52.8720	40.1860	28.9192	24.3012	20.5850	18.3335	17.3704	17.8749	21.5476
Feb 01-28	51.9796	41.3522	31.7400	27.6086	24.0607	21.4740	19.9714	19.6122	21.3284
Mar 01-31	121.5897	107.6596	94.5933	88.4292	82.7377	77.6444	73.4711	70.6047	69.9206
Apr 01-30	88.9177	81.3759	74.1078	70.6505	67.3653	64.3612	61.7069	59.6466	58.5094
May 01-31	109.2252	108.8541	108.4986	108.3280	108.1660	108.0142	107.8791	107.7608	107.6766
Jun 01-30	180.7307	180.7308	180.7307	180.7307	180.7308	180.7307	180.7307	180.7307	180.7307
Jul 01-31	256.9007	256.9009	256.9008	256.9008	256.9008	256.9007	256.9008	256.9008	256.9008
Aug 01-31	244.8933	244.8935	244.8934	244.8934	244.8934	244.8934	244.8934	244.8934	244.8934
Sep 01-30	256.9660	256.9661	256.9661	256.9661	256.9661	256.9660	256.9660	256.9661	256.9661
Oct 01-31	152.1312	149.8860	147.6817	146.5990	145.5358	144.5018	143.5132	142.6111	141.8955
Nov 01-30	150.1438	140.4135	130.6565	125.7756	120.9400	116.2456	111.8211	108.0318	105.5541
Dec 01-31	79.7153	66.1792	53.4925	47.7621	42.5282	38.2394	35.2348	33.5837	34.5514
Summed total	1746.0652	1675.3978	1609.1805	1578.9452	1551.4099	1528.3049	1510.4589	1499.2168	1500.4747

Table D.4: Roof ventilation - Carbon emission monthly breakup (IES-VE Vista)

	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)
	tsq_v100.ap	tsq_v80.aps	tsq_v60.aps	tsq_v50.aps	tsq_v40.aps	tsq_v30.aps	tsq_v20.aps	tsq_v10.aps	tsq_base_se
Date									
Jan 01-31	171873	169647	168257	168117	168534	169842	172335	176865	186819
Feb 01-28	179795	177998	176874	176735	177003	177923	179760	182982	189607
Mar 01-31	250405	247542	245202	244311	243744	243620	244241	246060	250582
Apr 01-30	296855	295207	293734	293101	292567	292182	292001	292162	292951
May 01-31	368147	368070	368003	367974	367950	367932	367924	367926	367945
Jun 01-30	401161	401161	401161	401161	401161	401161	401161	401161	401161
Jul 01-31	454539	454539	454539	454539	454539	454539	454539	454539	454539
Aug 01-31	454254	454254	454254	454254	454254	454254	454254	454254	454254
Sep 01-30	418766	418766	418766	418766	418766	418766	418766	418766	418766
Oct 01-31	348895	348378	347894	347668	347457	347269	347113	347011	347010
Nov 01-30	278741	276516	274379	273369	272426	271596	270963	270697	271238
Dec 01-31	200495	198019	196170	195668	195573	196167	197867	201357	209254
Summed	3823925	3810098	3799233	3795663	3793975	3795251	3800923	3813781	3844127

Table D.5 : Roof ventilation - Light energy monthly breakup (IES-VE Vista)

	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)
	tsq_v100.ap	tsq_v80.aps	tsq_v60.aps	tsq_v50.aps	tsq_v40.aps	tsq_v30.aps	tsq_v20.aps	tsq_v10.aps	tsq_base_se
Date									
Jan 01-31	236.9612	236.9612	236.9612	236.9612	236.9612	236.9612	236.9612	236.9612	236.9612
Feb 01-28	209.7077	209.7077	209.7077	209.7077	209.7077	209.7077	209.7077	209.7077	209.7077
Mar 01-31	232.1223	232.1223	232.1223	232.1223	232.1223	232.1223	232.1223	232.1223	232.1223
Apr 01-30	224.5281	224.5281	224.5281	224.5281	224.5281	224.5281	224.5281	224.5281	224.5281
May 01-31	225.9386	225.9386	225.9386	225.9386	225.9386	225.9386	225.9386	225.9386	225.9386
Jun 01-30	215.4386	215.4386	215.4386	215.4386	215.4386	215.4386	215.4386	215.4386	215.4386
Jul 01-31	225.5585	225.5585	225.5585	225.5585	225.5585	225.5585	225.5585	225.5585	225.5585
Aug 01-31	225.9164	225.9164	225.9164	225.9164	225.9164	225.9164	225.9164	225.9164	225.9164
Sep 01-30	222.0044	222.0044	222.0044	222.0044	222.0044	222.0044	222.0044	222.0044	222.0044
Oct 01-31	233.6799	233.6799	233.6799	233.6799	233.6799	233.6799	233.6799	233.6799	233.6799
Nov 01-30	227.3929	227.3929	227.3929	227.3929	227.3929	227.3929	227.3929	227.3929	227.3929
Dec 01-31	237.2286	237.2286	237.2286	237.2286	237.2286	237.2286	237.2286	237.2286	237.2286
Summed	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773

Table D.6 : Roof ventilation - MacroFlo gain monthly breakup (IES-VE Vista)

	MacroFlo ext vent gain (MWh)	MacroFlo ext vent gain (MWh)	MacroFlo ext vent gain (MWh)	MacroFlo ext vent gain (MWh)	MacroFlo ext vent gain (MWh)	MacroFlo ext vent gain (MWh)	MacroFlo ext vent gain (MWh)	MacroFlo ext vent gain (MWh)
	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms	16 rooms
Date	tsq_v100.aps	tsq_v80.aps	tsq_v60.aps	tsq_v50.aps	tsq_v40.aps	tsq_v30.aps	tsq_v20.aps	tsq_v10.aps
Jan 01-31	-118.6418	-112.1422	-103.0241	-96.8817	-89.0418	-78.5985	-63.9210	-41.3188
Feb 01-28	-85.0639	-79.9761	-72.8308	-68.0599	-62.0662	-54.1559	-43.2814	-27.4236
Mar 01-31	-62.9160	-59.1394	-53.9244	-50.4312	-46.0020	-40.2402	-32.1958	-20.2945
Apr 01-30	-16.7292	-15.3646	-13.5596	-12.4136	-11.0399	-9.3492	-7.1906	-4.2841
May 01-31	-0.7035	-0.6362	-0.5511	-0.4989	-0.4373	-0.3630	-0.2713	-0.1556
Jun 01-30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Jul 01-31	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Aug 01-31	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sep 01-30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Oct 01-31	-3.2212	-2.9264	-2.5437	-2.3065	-2.0257	-1.6863	-1.2660	-0.7295
Nov 01-30	-17.3878	-16.0043	-14.2056	-13.0440	-11.6417	-9.9202	-7.6656	-4.5917
Dec 01-31	-103.5982	-97.7082	-89.6110	-84.1463	-77.2134	-68.0172	-55.0627	-35.2915
Summed total	-408.2615	-383.8973	-350.2505	-327.7820	-299.4682	-262.3304	-210.8544	-134.0893

APPENDIX E

Variable Number of Floors - IES Simulation Results monthly breakup

Table E.1 : Number of Floors - Energy consumption monthly breakup (IES-VE Vista)

	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)
	tsq_base sens.aps	tsq_4floorss.aps	tsq_8floorss.aps
Date			
Jan 01-31	359.9607	770.0237	1599.7377
Feb 01-28	365.3307	753.4970	1537.8668
Mar 01-31	482.8167	959.2085	1914.2256
Apr 01-30	564.4525	1072.1182	2085.4597
May 01-31	708.9505	1302.2789	2493.9111
Jun 01-30	772.9510	1409.0256	2686.2229
Jul 01-31	875.7983	1589.9471	3023.3457
Aug 01-31	875.2496	1581.1985	2996.7983
Sep 01-30	806.8715	1476.0210	2816.9236
Oct 01-31	668.6135	1253.8971	2429.8376
Nov 01-30	522.6171	1026.1858	2041.5148
Dec 01-31	403.1875	842.9726	1728.8083
Summed total	7406.7998	14036.3740	27354.6543

Table E.2 : Number of Floors - Cooling plant load and Dehumidification load monthly breakup (IES-VE Vista)

	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)
	tsq_base sens.aps	tsq_4floorss.aps	tsq_8floorss.aps	tsq_base sens.aps	tsq_4floorss.aps	tsq_8floorss.aps
Date						
Jan 01-31	21.5476	42.5802	84.8774	224.4498	508.1458	1081.4799
Feb 01-28	21.3284	42.2758	84.4449	289.9168	585.7059	1180.6731
Mar 01-31	69.9206	138.0894	274.8338	431.4676	809.7197	1565.2269
Apr 01-30	58.5094	115.3504	229.5467	621.3384	1087.1143	2013.8899
May 01-31	107.6766	212.8658	423.6008	858.3465	1438.9172	2599.1282
Jun 01-30	180.7307	358.2037	713.2704	934.2919	1544.5121	2763.4763
Jul 01-31	256.9008	509.7520	1015.5135	1043.5782	1714.1251	3054.2244
Aug 01-31	244.8934	485.8604	967.9056	1053.7716	1726.0847	3069.0322
Sep 01-30	256.9661	509.8283	1015.6226	912.7679	1512.5741	2709.8042
Oct 01-31	141.8955	280.7525	558.6788	727.9705	1252.6188	2301.9565
Nov 01-30	105.5541	208.3541	414.1275	484.8939	894.6840	1717.2764
Dec 01-31	34.5514	68.3395	136.2049	297.3658	624.8418	1282.8608
Summed total	1500.4747	2972.2520	5918.6270	7880.1592	13699.0430	25339.0293

Table E.3: Number of Floors - Carbon emission monthly breakup (IES-VE Vista)

	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)
	tsq_base sens.aps	tsq_4floorss.aps	tsq_8floorss.aps
Date			
Jan 01-31	186819	399643	830265
Feb 01-28	189607	391064	798142
Mar 01-31	250582	497829	993483
Apr 01-30	292951	556430	1082354
May 01-31	367945	675883	1294340
Jun 01-30	401161	731284	1394149
Jul 01-31	454539	825183	1569116
Aug 01-31	454254	820642	1555339
Sep 01-30	418766	766054	1461982
Oct 01-31	347010	650772	1261086
Nov 01-30	271238	532591	1059546
Dec 01-31	209254	437503	897251
Summed total	3844127	7284877	14197053

Table E.4: Number of Floors - Light energy monthly breakup (IES-VE Vista)

	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)
	tsq_base sens.aps	tsq_4floorss.aps	tsq_8floorss.aps
Date			
Jan 01-31	236.9612	494.6591	1016.5645
Feb 01-28	209.7077	439.5042	905.2759
Mar 01-31	232.1223	485.3025	994.1977
Apr 01-30	224.5281	470.8846	963.7452
May 01-31	225.9386	476.3860	982.5507
Jun 01-30	215.4386	457.6662	947.8535
Jul 01-31	225.5585	478.0080	988.4786
Aug 01-31	225.9164	475.2246	978.3340
Sep 01-30	222.0044	464.8182	954.2109
Oct 01-31	233.6799	487.2091	999.5248
Nov 01-30	227.3929	474.6652	975.8154
Dec 01-31	237.2286	496.3808	1019.2795
Summed total	2716.4773	5700.7085	11725.8301

Table E.5 : Number of Floors - Cooling load Break up (IES-VE Vista)

	Solar gain (MWh)	Solar gain (MWh)	Solar gain (MWh)	External conduction gain (MWh)	External conduction gain (MWh)	External conduction gain (MWh)	Infiltration gain (MWh)	Infiltration gain (MWh)	Infiltration gain (MWh)
	16 rooms	28 rooms	52 rooms	16 rooms	28 rooms	52 rooms	16 rooms	28 rooms	52 rooms
Date	tsq_base	tsq_4floorss.	tsq_8floorss.	tsq_base	tsq_4floorss.	tsq_8floorss.	tsq_base	tsq_4floorss.	tsq_8floorss.
Jan 01-31	50.7712	56.9275	67.4174	-121.1100	-151.3101	-210.9555	-57.7849	-119.1152	-241.2979
Feb 01-28	58.7724	65.7259	77.4656	-48.9787	-55.5074	-69.6736	-32.2202	-65.9965	-133.3024
Mar 01-31	70.9138	81.3689	99.9446	22.3790	35.6322	60.7990	-8.2834	-17.1716	-34.7224
Apr 01-30	81.7872	94.6623	117.4527	159.8626	215.5715	324.8859	43.8011	87.3185	174.4523
May 01-31	100.6855	116.8690	146.2585	317.6600	421.9215	627.1667	99.9821	199.2623	397.8245
Jun 01-30	100.0657	117.2821	147.7837	386.1640	509.3523	752.4798	121.5609	242.2684	483.6826
Jul 01-31	98.5605	114.8762	144.3954	457.6334	602.7173	889.4139	146.5133	291.9982	582.9673
Aug 01-31	93.8712	107.5876	132.4106	468.3898	617.2439	911.4050	151.0673	301.0742	601.0876
Sep 01-30	81.4693	91.8699	109.6474	379.4807	501.3850	742.1035	118.3256	235.8203	470.8095
Oct 01-31	70.1247	78.0868	91.4335	236.8928	317.6677	476.5760	71.3654	142.2356	284.0029
Nov 01-30	52.9787	59.0388	69.2320	76.3022	108.8247	172.1921	16.9688	33.8785	67.7463
Dec 01-31	46.7932	52.6216	62.6507	-68.5926	-81.7707	-108.0962	-33.9438	-69.4958	-140.3873
Summed	906.7935	1036.9166	1266.0922	2266.0833	3041.7278	4568.2964	637.3521	1262.0769	2512.8633

APPENDIX F

Variable Roof Profile - IES Simulation Results monthly breakup

Table F.1 : Roof Profile - Energy consumption monthly breakup (IES-VE Vista)

	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)
	tsq_NL30 slb	tsq_NL30 slb	tsq_NL 40	tsq_NL40	tsq_NL 20	tsq_closed	tsq_flat fi.aps	tsq_BC_sens
Date								
Jan 01-31	384.6261	388.5835	386.1551	386.1139	387.4555	388.5928	367.6826	359.9607
Feb 01-28	373.3929	391.4895	387.2956	387.3853	389.5197	390.8063	373.2459	365.3307
Mar 01-31	485.6908	509.3811	503.4020	503.8459	505.7867	507.3011	490.7432	482.8168
Apr 01-30	564.4203	588.2198	580.9788	581.8403	583.1700	584.8986	571.9390	564.4525
May 01-31	705.7823	734.0882	723.3540	724.5663	726.4979	729.1161	715.8732	708.9504
Jun 01-30	773.5643	799.7966	788.3061	790.0829	792.1501	794.3356	779.2208	772.9509
Jul 01-31	877.0844	905.0183	893.8829	896.8367	896.7120	898.1399	882.5224	875.7981
Aug 01-31	872.8091	902.2104	893.4873	895.9227	895.1658	894.9789	880.5325	875.2495
Sep 01-30	804.6175	832.5746	827.0905	829.2925	827.8417	826.3741	811.6163	806.8715
Oct 01-31	668.6010	694.4542	691.1579	692.5312	691.2083	690.3368	674.7509	668.6136
Nov 01-30	544.7908	549.6213	547.9113	548.5663	548.1277	547.6103	529.5170	522.6172
Dec 01-31	429.2485	432.8637	430.7900	430.8755	431.7157	432.3742	411.4872	403.1876
Summed	7484.6284	7728.3013	7653.8110	7667.8594	7675.3516	7684.8647	7489.1313	7406.7998

Table F.2 : Roof Profile - Cooling plant load monthly breakup (IES-VE Vista)

	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)
	tsq_NL30 slb	tsq_NL30 slb	tsq_NL 40	tsq_NL40	tsq_NL 20	tsq_closed	tsq_flat fi.aps	tsq_BC_sens
Date								
Jan 01-31	217.6817	219.1258	217.6955	217.5746	218.1142	218.7231	229.9723	224.4498
Feb 01-28	269.0319	278.8069	276.9031	277.1156	277.1760	277.0133	295.2891	289.9168
Mar 01-31	405.6973	416.2081	414.1564	414.7915	413.2003	411.9528	436.6164	431.4677
Apr 01-30	592.7268	599.7330	598.7144	600.3228	595.7061	592.3361	625.5331	621.3385
May 01-31	823.7158	829.0779	828.0061	830.6929	823.3134	817.9924	861.4752	858.3467
Jun 01-30	903.9641	907.2317	905.9358	909.2394	901.1208	894.8557	936.8118	934.2919
Jul 01-31	1014.5121	1019.4387	1018.1924	1022.6164	1012.3820	1005.0851	1046.1981	1043.5782
Aug 01-31	1021.5466	1029.2106	1029.0631	1033.2573	1022.9261	1014.8345	1055.4358	1053.7716
Sep 01-30	880.9150	891.9475	892.0822	895.6359	887.1971	880.0743	914.4321	912.7680
Oct 01-31	698.1198	711.7427	711.9855	714.4088	708.3071	703.4469	731.0933	727.9705
Nov 01-30	475.3314	477.4226	477.3605	478.4809	475.6359	473.2386	489.1270	484.8942
Dec 01-31	293.4388	294.6593	293.6419	293.7770	293.4786	293.3083	303.0455	297.3658
Summed	7596.6812	7674.6045	7663.7363	7687.9126	7628.5576	7582.8613	7925.0298	7880.1592

Table F.3 : Roof Profile - Dehumidification load monthly breakup (IES-VE Vista)

	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)
	tsq_NL30 slb	tsq_NL30 slb	tsq_NL 40	tsq_NL40	tsq_NL 20	tsq_closed	tsq_flat fi.aps	tsq_BC_sens
Date								
Jan 01-31	21.5612	21.5491	21.5339	21.5466	21.5301	21.5496	21.5467	21.5476
Feb 01-28	21.3536	21.3328	21.3164	21.3266	21.3115	21.3354	21.3312	21.3284
Mar 01-31	69.8924	69.8841	70.0596	70.1360	69.9044	69.7630	69.7527	69.9206
Apr 01-30	58.4316	58.4326	58.4913	58.5206	58.4408	58.4040	58.4014	58.5094
May 01-31	107.5989	107.5989	108.0738	108.2349	107.7020	107.2951	107.2951	107.6766
Jun 01-30	180.7099	180.7099	182.0195	182.4568	180.9978	179.8406	179.8406	180.7307
Jul 01-31	256.9289	256.9289	259.0558	259.7659	257.3972	255.5142	255.5142	256.9008
Aug 01-31	244.9116	244.9116	246.9017	247.5662	245.3495	243.5907	243.5907	244.8934
Sep 01-30	256.9908	256.9908	259.1089	259.8156	257.4575	255.5813	255.5813	256.9661
Oct 01-31	141.8288	141.8286	142.6317	142.9020	142.0046	141.3002	141.3002	141.8955
Nov 01-30	105.4863	105.4562	105.8249	105.9654	105.5160	105.1918	105.2113	105.5541
Dec 01-31	34.5291	34.5127	34.5183	34.5382	34.5004	34.5153	34.5182	34.5514
Summed	1500.2230	1500.1361	1509.5358	1512.7748	1502.1119	1493.8812	1493.8835	1500.4747

Table F.4 : Roof Profile - Carbon emission monthly breakup (IES-VE Vista)

	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)
	tsq_NL30 slb	tsq_NL30 slb	tsq_NL 40	tsq_NL40	tsq_NL 20	tsq_closed	tsq_flat fi.aps	tsq_BC_sens
Date								
Jan 01-31	199621	201675	200414	200393	201089	201680	190827	186819
Feb 01-28	193791	203183	201007	201053	202161	202829	193715	189607
Mar 01-31	252074	264369	261265	261496	262503	263289	254696	250582
Apr 01-30	292934	305286	301528	301975	302665	303562	296836	292951
May 01-31	366301	380991	375421	376050	377052	378411	371538	367945
Jun 01-30	401480	415094	409131	410053	411126	412260	404416	401161
Jul 01-31	455207	469704	463925	465458	465394	466135	458029	454539
Aug 01-31	452988	468247	463720	464984	464591	464494	456997	454254
Sep 01-30	417596	432106	429260	430403	429650	428888	421229	418766
Oct 01-31	347004	360421	358711	359423	358737	358285	350196	347010
Nov 01-30	282746	285253	284366	284706	284478	284209	274819	271238
Dec 01-31	222780	224657	223580	223625	224061	224402	213562	209254
Summed	3884522	4010988	3972328	3979618	3983507	3988445	3886860	3844127

Table F.5 : Roof Profile - Light energy monthly breakup (IES-VE Vista)

	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)
	tsq_NL30 slb	tsq_NL 40	tsq_NL30 slb	tsq_NL40	tsq_NL 20	tsq_closed	tsq_flat fi.aps	tsq_BC_sens..
Date								
Jan 01-31	265.0051	266.5406	268.2464	266.5537	267.6336	268.4566	241.9232	236.9612
Feb 01-28	228.2004	238.1860	241.4198	238.1642	240.2762	241.6320	214.9361	209.7077
Mar 01-31	247.8960	261.2938	266.3347	261.3821	264.2343	266.4435	237.5586	232.1223
Apr 01-30	238.8415	252.3757	259.1372	252.4186	256.0967	259.5286	229.9720	224.5281
May 01-31	240.1256	255.3142	265.7491	255.1022	260.9909	266.4726	231.4879	225.9386
Jun 01-30	231.2272	244.3281	255.8256	244.2345	251.0914	256.9878	220.8946	215.4386
Jul 01-31	241.3640	255.2584	266.8345	255.6454	261.8231	267.8399	231.6666	225.5585
Aug 01-31	239.5799	255.5045	265.1489	255.5106	261.0274	265.7663	231.0194	225.9164
Sep 01-30	235.6643	251.4952	258.1059	251.5670	255.5146	258.5467	226.6096	222.0044
Oct 01-31	248.6266	263.8492	267.6683	263.8757	266.0528	267.9627	238.5548	233.6799
Nov 01-30	254.3813	256.3190	258.1819	256.3431	257.5519	258.3950	232.3479	227.3929
Dec 01-31	265.2646	266.7099	268.2777	266.7179	267.7263	268.4623	242.7057	237.2286
Summed total	2936.1768	3067.1743	3140.9304	3067.5151	3110.0193	3146.4941	2779.6763	2716.4773

APPENDIX G

Variable LSG Ratio of glazing - IES Simulation Results monthly breakup

External Glazing :

Table G.1 : External Glazing - Energy consumption monthly breakup (IES-VE Vista)

	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)
	tsq_lsg1.aps	tsq_lsg2.aps	tsq_lsg3.aps	tsq_lsg4.aps	tsq_base sens.aps
Date					
Jan 01-31	361.3968	357.9190	358.8032	356.4128	359.9607
Feb 01-28	368.7316	362.7365	363.4468	360.5305	365.3307
Mar 01-31	488.5913	479.4984	480.0828	476.4547	482.8167
Apr 01-30	574.8615	560.3217	560.3747	556.1464	564.4525
May 01-31	726.6266	703.4511	702.8926	697.5725	708.9505
Jun 01-30	792.9769	767.3169	766.3987	761.1039	772.9510
Jul 01-31	897.9922	870.0920	868.7632	863.5827	875.7983
Aug 01-31	897.5367	869.7032	868.2916	863.3338	875.2496
Sep 01-30	825.2356	802.1187	801.0433	796.7091	806.8715
Oct 01-31	681.1865	664.7368	664.3186	660.5457	668.6135
Nov 01-30	529.2003	519.9327	520.1000	517.2645	522.6171
Dec 01-31	405.6056	401.1432	401.8218	399.4514	403.1875
Summed total	7549.9414	7358.9697	7356.3379	7309.1084	7406.7998

Table G.2 : External Glazing - Cooling plant load monthly breakup (IES-VE Vista)

	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)
	tsq_lsg1.aps	tsq_lsg2.aps	tsq_lsg3.aps	tsq_lsg4.aps	tsq_base sens.aps
Date					
Jan 01-31	226.8482	220.3827	222.1799	217.3807	224.4498
Feb 01-28	296.4514	284.7399	286.1780	280.3398	289.9168
Mar 01-31	442.8305	424.8443	426.0250	418.7634	431.4676
Apr 01-30	642.1213	613.0796	613.1879	604.7295	621.3384
May 01-31	893.6984	847.3472	846.2321	835.5914	858.3465
Jun 01-30	974.3459	923.0257	921.1891	910.6000	934.2919
Jul 01-31	1087.9661	1032.1669	1029.5093	1019.1470	1043.5782
Aug 01-31	1098.3466	1042.6807	1039.8563	1029.9409	1053.7716
Sep 01-30	949.4946	903.2625	901.1108	892.4423	912.7679
Oct 01-31	753.1082	720.2170	719.3809	711.8346	727.9705
Nov 01-30	497.7321	479.5334	479.9088	474.2230	484.8939
Dec 01-31	301.8699	293.2917	294.6689	289.9235	297.3658
Summed total	8164.8135	7784.5708	7779.4272	7684.9160	7880.1592

Table G.3 : External Glazing - Dehumidification load monthly breakup(IES-VE Vista)

	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)
	tsq_lsg1.aps	tsq_lsg2.aps	tsq_lsg3.aps	tsq_lsg4.aps	tsq_base sens.aps
Date					
Jan 01-31	22.0213	21.5315	21.5028	21.5204	21.5476
Feb 01-28	21.5955	21.3168	21.2990	21.3048	21.3284
Mar 01-31	70.1074	69.9065	69.8949	69.9006	69.9206
Apr 01-30	58.5451	58.5065	58.5040	58.5059	58.5094
May 01-31	107.6766	107.6766	107.6766	107.6766	107.6766
Jun 01-30	180.7307	180.7307	180.7307	180.7307	180.7307
Jul 01-31	256.9008	256.9008	256.9008	256.9008	256.9008
Aug 01-31	244.8934	244.8934	244.8934	244.8934	244.8934
Sep 01-30	256.9661	256.9661	256.9661	256.9661	256.9661
Oct 01-31	141.9045	141.8951	141.8950	141.8950	141.8955
Nov 01-30	105.8815	105.5457	105.5038	105.5197	105.5541
Dec 01-31	34.8833	34.5376	34.5168	34.5215	34.5514
Summed total	1502.1060	1500.4072	1500.2839	1500.3357	1500.4747

Table G.4 : External Glazing - Carbon emission monthly breakup (IES-VE Vista)

	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)
	tsq_lsg1.aps	tsq_lsg2.aps	tsq_lsg3.aps	tsq_lsg4.aps	tsq_base sens.aps
Date					
Jan 01-31	187565	185760	186219	184978	186819
Feb 01-28	191372	188260	188629	187115	189607
Mar 01-31	253579	248860	249163	247280	250582
Apr 01-30	298353	290807	290834	288640	292951
May 01-31	377119	365091	364801	362040	367945
Jun 01-30	411555	398238	397761	395013	401161
Jul 01-31	466058	451578	450888	448199	454539
Aug 01-31	465821	451376	450643	448070	454254
Sep 01-30	428297	416300	415741	413492	418766
Oct 01-31	353536	344999	344781	342823	347010
Nov 01-30	274655	269845	269932	268461	271238
Dec 01-31	210509	208193	208545	207315	209254
Summed total	3918419	3819306	3817938	3793426	3844127

Internal Glazing :

Table G.5 : Internal Glazing - Energy consumption monthly breakup (IES-VE Vista)

	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)
	tsq_lsg5.aps	tsq_lsg6.aps	tsq_lsg7.aps	tsq_base sens.aps
Date				
Jan 01-31	359.9716	359.9693	360.0110	359.9607
Feb 01-28	365.3431	365.3409	365.3704	365.3307
Mar 01-31	482.8326	482.8302	482.8523	482.8167
Apr 01-30	564.4702	564.4682	564.4790	564.4525
May 01-31	708.9755	708.9724	708.9814	708.9505
Jun 01-30	772.9747	772.9727	772.9822	772.9510
Jul 01-31	875.8260	875.8240	875.8320	875.7983
Aug 01-31	875.2753	875.2729	875.2803	875.2496
Sep 01-30	806.8943	806.8920	806.8976	806.8715
Oct 01-31	668.6306	668.6292	668.6342	668.6135
Nov 01-30	522.6298	522.6282	522.6368	522.6171
Dec 01-31	403.1978	403.1959	403.2210	403.1875
Summed total	7407.0215	7406.9956	7407.1782	7406.7998

Table G.6 : Internal Glazing - Cooling plant load monthly breakup (IES-VE Vista)

	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)
	tsq_lsg5.aps	tsq_lsg6.aps	tsq_lsg7.aps	tsq_base sens.aps
Date				
Jan 01-31	224.4708	224.4662	224.5441	224.4498
Feb 01-28	289.9409	289.9367	289.9922	289.9168
Mar 01-31	431.4983	431.4932	431.5352	431.4676
Apr 01-30	621.3740	621.3693	621.3908	621.3384
May 01-31	858.3966	858.3904	858.4095	858.3465
Jun 01-30	934.3403	934.3368	934.3550	934.2919
Jul 01-31	1043.6322	1043.6293	1043.6451	1043.5782
Aug 01-31	1053.8241	1053.8199	1053.8345	1053.7716
Sep 01-30	912.8126	912.8091	912.8203	912.7679
Oct 01-31	728.0055	728.0020	728.0121	727.9705
Nov 01-30	484.9185	484.9152	484.9298	484.8939
Dec 01-31	297.3863	297.3822	297.4294	297.3658
Summed total	7880.6001	7880.5503	7880.8979	7880.1592

Table G.7 : Internal Glazing - Dehumidification load monthly breakup (IES-VE Vista)

	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)
	tsq_lsg5.aps	tsq_lsg6.aps	tsq_lsg7.aps	tsq_base sens.aps
Date				
Jan 01-31	21.5482	21.5480	21.5544	21.5476
Feb 01-28	21.3287	21.3286	21.3319	21.3284
Mar 01-31	69.9210	69.9209	69.9235	69.9206
Apr 01-30	58.5094	58.5094	58.5098	58.5094
May 01-31	107.6766	107.6766	107.6766	107.6766
Jun 01-30	180.7307	180.7307	180.7307	180.7307
Jul 01-31	256.9008	256.9008	256.9008	256.9008
Aug 01-31	244.8934	244.8934	244.8934	244.8934
Sep 01-30	256.9661	256.9661	256.9661	256.9661
Oct 01-31	141.8955	141.8955	141.8955	141.8955
Nov 01-30	105.5546	105.5545	105.5567	105.5541
Dec 01-31	34.5517	34.5516	34.5544	34.5514
Summed total	1500.4768	1500.4762	1500.4939	1500.4747

Table G.8 : Internal Glazing - Carbon emission monthly breakup (IES-VE Vista)

	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)
	tsq_lsg5.aps	tsq_lsg6.aps	tsq_lsg7.aps	tsq_base sens.aps
Date				
Jan 01-31	186825	186824	186845	186819
Feb 01-28	189613	189612	189627	189607
Mar 01-31	250590	250588	250600	250582
Apr 01-30	292960	292959	292965	292951
May 01-31	367958	367957	367962	367945
Jun 01-30	401174	401173	401177	401161
Jul 01-31	454553	454552	454556	454539
Aug 01-31	454267	454267	454271	454254
Sep 01-30	418778	418777	418780	418766
Oct 01-31	347019	347018	347021	347010
Nov 01-30	271245	271244	271248	271238
Dec 01-31	209260	209259	209272	209254
Summed total	3844242	3844229	3844325	3844127

Table G.9 : Internal Glazing - Light energy monthly breakup (IES-VE Vista)

	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)
	tsq_lsg1.aps	tsq_lsg2.aps	tsq_lsg3.aps	tsq_lsg4.aps	tsq_lsg5.aps	tsq_lsg6.aps	tsq_lsg7.aps	tsq_base_sen
Date								
Jan 01-31	236.9612	236.9612	236.9612	236.9612	236.9612	236.9612	236.9612	236.9612
Feb 01-28	209.7077	209.7077	209.7077	209.7077	209.7077	209.7077	209.7077	209.7077
Mar 01-31	232.1223	232.1223	232.1223	232.1223	232.1223	232.1223	232.1223	232.1223
Apr 01-30	224.5281	224.5281	224.5281	224.5281	224.5281	224.5281	224.5281	224.5281
May 01-31	225.9386	225.9386	225.9386	225.9386	225.9386	225.9386	225.9386	225.9386
Jun 01-30	215.4386	215.4386	215.4386	215.4386	215.4386	215.4386	215.4386	215.4386
Jul 01-31	225.5585	225.5585	225.5585	225.5585	225.5585	225.5585	225.5585	225.5585
Aug 01-31	225.9164	225.9164	225.9164	225.9164	225.9164	225.9164	225.9164	225.9164
Sep 01-30	222.0044	222.0044	222.0044	222.0044	222.0044	222.0044	222.0044	222.0044
Oct 01-31	233.6799	233.6799	233.6799	233.6799	233.6799	233.6799	233.6799	233.6799
Nov 01-30	227.3929	227.3929	227.3929	227.3929	227.3929	227.3929	227.3929	227.3929
Dec 01-31	237.2286	237.2286	237.2286	237.2286	237.2286	237.2286	237.2286	237.2286
Summed total	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773

APPENDIX H

Variable U value of envelope - IES Simulation Results monthly breakup

External Wall :

Table H.1 : External Wall - Energy consumption monthly breakup (IES-VE Vista)

	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)
	tsq_BC_s_u_5.aps	tsq_BC_s_u_4.aps	tsq_BC_s_u_3.aps	tsq_BC_s_u_2.aps	tsq_BC_s_u_1.aps	tsq_BC_sens.aps
Date						
Jan 01-31	363.4025	364.1865	365.2138	365.1996	366.5104	359.9607
Feb 01-28	364.8801	364.9801	365.0992	365.1466	365.4420	365.3307
Mar 01-31	478.4814	477.9094	477.1624	477.2462	476.5281	482.8168
Apr 01-30	550.6835	548.5739	545.8116	546.0522	543.1670	564.4525
May 01-31	683.0358	679.1799	674.2297	674.5964	669.3268	708.9504
Jun 01-30	742.3268	737.7526	731.8930	732.3070	726.0052	772.9509
Jul 01-31	839.7605	834.3671	827.4576	827.9462	820.5135	875.7981
Aug 01-31	838.3530	832.8079	825.6912	826.1992	818.5399	875.2495
Sep 01-30	776.7407	772.1790	766.3083	766.7346	760.4169	806.8715
Oct 01-31	648.6555	645.5939	641.6215	641.9304	637.6853	668.6136
Nov 01-30	514.2074	512.9398	511.2797	511.4248	509.6883	522.6172
Dec 01-31	404.1534	404.4467	404.8189	404.8323	405.3489	403.1876
Summed total	7204.6802	7174.9170	7136.5869	7139.6162	7099.1729	7406.7998

Table H.2 : External Wall - Cooling plant load monthly breakup (IES-VE Vista)

	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)
	tsq_BC_s_u_5.aps	tsq_BC_s_u_4.aps	tsq_BC_s_u_3.aps	tsq_BC_s_u_2.aps	tsq_BC_s_u_1.aps	tsq_BC_sens.aps
Date						
Jan 01-31	231.4849	233.0645	235.1296	235.1004	237.7304	224.4498
Feb 01-28	289.0476	289.2487	289.4879	289.5831	290.1743	289.9168
Mar 01-31	422.8493	421.7073	420.2160	420.3836	418.9498	431.4677
Apr 01-30	593.8157	589.5981	584.0742	584.5555	578.7858	621.3385
May 01-31	806.5168	798.8044	788.9037	789.6399	779.0995	858.3467
Jun 01-30	873.0441	863.8975	852.1774	853.0059	840.4009	934.2919
Jul 01-31	971.5023	960.7162	946.8966	947.8740	933.0087	1043.5782
Aug 01-31	979.9777	968.8887	954.6566	955.6702	940.3531	1053.7716
Sep 01-30	852.5059	843.3812	831.6411	832.4927	819.8582	912.7680
Oct 01-31	688.0558	681.9322	673.9858	674.6046	666.1130	727.9705
Nov 01-30	468.1351	465.6036	462.2863	462.5764	459.1052	484.8942
Dec 01-31	299.3244	299.9123	300.6579	300.6847	301.7180	297.3658
Summed total	7476.2593	7416.7544	7340.1128	7346.1704	7265.2964	7880.1592

Table H.3: External Wall - Dehumidification load monthly breakup(IES-VE Vista)

	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)
	tsq_BC_s_u_5.aps	tsq_BC_s_u_4.aps	tsq_BC_s_u_3.aps	tsq_BC_s_u_2.aps	tsq_BC_s_u_1.aps	tsq_BC_sens.aps
Date						
Jan 01-31	21.3960	21.3847	21.3735	21.3748	21.3667	21.5476
Feb 01-28	21.2961	21.2951	21.2942	21.2943	21.2939	21.3284
Mar 01-31	69.8686	69.8659	69.8629	69.8633	69.8610	69.9206
Apr 01-30	58.4936	58.4928	58.4920	58.4921	58.4918	58.5094
May 01-31	107.6766	107.6766	107.6766	107.6766	107.6766	107.6766
Jun 01-30	180.7307	180.7307	180.7307	180.7307	180.7307	180.7307
Jul 01-31	256.9008	256.9008	256.9008	256.9008	256.9008	256.9008
Aug 01-31	244.8934	244.8934	244.8934	244.8934	244.8934	244.8934
Sep 01-30	256.9661	256.9661	256.9661	256.9661	256.9661	256.9661
Oct 01-31	141.8953	141.8953	141.8953	141.8953	141.8953	141.8955
Nov 01-30	105.4927	105.4896	105.4863	105.4869	105.4850	105.5541
Dec 01-31	34.5245	34.5234	34.5222	34.5225	34.5217	34.5514
Summed total	1500.1344	1500.1145	1500.0941	1500.0968	1500.0829	1500.4747

Table H.4 : External Wall - Carbon emission monthly breakup (IES-VE Vista)

	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)
	tsq_BC_s_u_5.aps	tsq_BC_s_u_4.aps	tsq_BC_s_u_3.aps	tsq_BC_s_u_2.aps	tsq_BC_s_u_1.aps	tsq_BC_sens.aps
Date						
Jan 01-31	188606	189013	189545	189538	190219	186819
Feb 01-28	189373	189424	189486	189511	189664	189607
Mar 01-31	248332	248035	247647	247691	247318	250582
Apr 01-30	285805	284710	283276	283401	281904	292951
May 01-31	354496	352494	349925	350116	347381	367945
Jun 01-30	385267	382894	379852	380067	376797	401161
Jul 01-31	435836	433037	429450	429704	425847	454539
Aug 01-31	435105	432227	428534	428797	424822	454254
Sep 01-30	403129	400761	397714	397935	394656	418766
Oct 01-31	336652	335063	333002	333162	330958	347010
Nov 01-30	266874	266216	265354	265429	264528	271238
Dec 01-31	209756	209908	210101	210108	210376	209254
Summed total	3739229	3723781	3703887	3705460	3684470	3844127

Table H.5 : External Wall - Light energy monthly breakup (IES-VE Vista)

	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)
	tsq_BC_s_u_5.aps	tsq_BC_s_u_4.aps	tsq_BC_s_u_3.aps	tsq_BC_s_u_2.aps	tsq_BC_s_u_1.aps	tsq_base_sensor.a
Date						
Jan 01-31	236.9612	236.9612	236.9612	236.9612	236.9612	236.9612
Feb 01-28	209.7077	209.7077	209.7077	209.7077	209.7077	209.7077
Mar 01-31	232.1223	232.1223	232.1223	232.1223	232.1223	232.1223
Apr 01-30	224.5281	224.5281	224.5281	224.5281	224.5281	224.5281
May 01-31	225.9386	225.9386	225.9386	225.9386	225.9386	225.9386
Jun 01-30	215.4386	215.4386	215.4386	215.4386	215.4386	215.4386
Jul 01-31	225.5585	225.5585	225.5585	225.5585	225.5585	225.5585
Aug 01-31	225.9164	225.9164	225.9164	225.9164	225.9164	225.9164
Sep 01-30	222.0044	222.0044	222.0044	222.0044	222.0044	222.0044
Oct 01-31	233.6799	233.6799	233.6799	233.6799	233.6799	233.6799
Nov 01-30	227.3929	227.3929	227.3929	227.3929	227.3929	227.3929
Dec 01-31	237.2286	237.2286	237.2286	237.2286	237.2286	237.2286
Summed total	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773

Roof :

Table H.6 : Roof - Energy consumption monthly breakup (IES-VE Vista)

	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)
	tsq_BC_s_u_r5.aps	tsq_BC_s_u_r4.aps	tsq_BC_s_u_r3.aps	tsq_BC_s_u_r2.aps	tsq_BC_s_u_r1.aps	tsq_BC_sens.aps
Date						
Jan 01-31	385.5376	382.7487	375.4617	377.1611	382.8648	359.9607
Feb 01-28	373.7793	372.5354	369.6411	370.1760	372.5957	365.3307
Mar 01-31	473.1360	473.6465	475.5100	474.8545	473.6374	482.8168
Apr 01-30	521.2037	524.7587	535.0988	532.1956	524.6332	564.4525
May 01-31	625.0421	631.7908	651.0463	645.9357	631.5457	708.9504
Jun 01-30	671.7089	680.2458	704.2263	697.9645	679.9257	772.9509
Jul 01-31	756.4446	766.4844	794.6174	787.3259	766.1097	875.7981
Aug 01-31	754.2427	764.6034	793.4993	786.0255	764.2137	875.2495
Sep 01-30	708.8580	717.4259	741.2149	735.0891	717.1047	806.8715
Oct 01-31	608.2755	613.6445	628.5922	624.6623	613.4441	668.6136
Nov 01-30	503.4582	505.1088	509.7821	508.4723	505.0498	522.6172
Dec 01-31	418.5075	416.9383	412.8264	413.7515	417.0037	403.1876
Summed total	6800.1934	6849.9316	6991.5166	6953.6133	6848.1279	7406.7998

Table H.7 : Roof - Carbon emission monthly breakup (IES-VE Vista)

	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)
	tsq_BC_s_u_r5.ap:	tsq_BC_s_u_r4.ap	tsq_BC_s_u_r3.ap	tsq_BC_s_u_r2.ap	tsq_BC_s_u_r1.ap:	tsq_BC_sens.aps
Date						
Jan 01-31	200094	198646	194864	195746	198706	186819
Feb 01-28	193991	193346	191844	192121	193377	189607
Mar 01-31	245558	245823	246790	246449	245818	250582
Apr 01-30	270505	272350	277716	276210	272284	292951
May 01-31	324397	327900	337893	335240	327772	367945
Jun 01-30	348617	353048	365493	362244	352881	401161
Jul 01-31	392595	397806	412406	408622	397611	454539
Aug 01-31	391452	396829	411826	407947	396627	454254
Sep 01-30	367897	372344	384691	381512	372177	418766
Oct 01-31	315695	318481	326239	324200	318377	347010
Nov 01-30	261295	262151	264577	263897	262121	271238
Dec 01-31	217205	216391	214257	214737	216425	209254
Summed total	3529300	3555114	3628596	3608926	3554177	3844127

Table H.8 : Roof - Cooling plant load monthly breakup (IES-VE Vista)

	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)
	tsq_BC_s_u_r5.ap:	tsq_BC_s_u_r4.ap	tsq_BC_s_u_r3.ap	tsq_BC_s_u_r2.ap	tsq_BC_s_u_r1.ap:	tsq_BC_sens.aps
Date						
Jan 01-31	275.8324	270.2491	255.6511	259.0578	270.4812	224.4498
Feb 01-28	306.8575	304.3687	298.5763	299.6469	304.4897	289.9168
Mar 01-31	412.1707	413.1915	416.9180	415.6066	413.1720	431.4677
Apr 01-30	534.8583	541.9691	562.6508	556.8442	541.7175	621.3385
May 01-31	690.5298	704.0283	742.5376	732.3166	703.5364	858.3467
Jun 01-30	731.8097	748.8828	796.8433	784.3209	748.2424	934.2919
Jul 01-31	804.8701	824.9502	881.2153	866.6343	824.2020	1043.5782
Aug 01-31	811.7589	832.4796	890.2708	875.3234	831.7000	1053.7716
Sep 01-30	716.7405	733.8774	781.4546	769.2033	733.2333	912.7680
Oct 01-31	607.2952	618.0324	647.9280	640.0693	617.6313	727.9705
Nov 01-30	446.6275	449.9304	459.2808	456.6611	449.8116	484.8942
Dec 01-31	328.0399	324.9011	316.6766	318.5270	325.0322	297.3658
Summed total	6667.3911	6766.8599	7050.0034	6974.2109	6763.2495	7880.1592

Table H.9 : Roof - Dehumidification load monthly breakup (IES-VE Vista)

	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)
	tsq_BC_s_u_r5.ap:	tsq_BC_s_u_r4.ap	tsq_BC_s_u_r3.ap	tsq_BC_s_u_r2.ap	tsq_BC_s_u_r1.ap:	tsq_BC_sens.aps
Date						
Jan 01-31	21.3186	21.3244	21.3476	21.3398	21.3243	21.5476
Feb 01-28	21.2840	21.2854	21.2899	21.2886	21.2854	21.3284
Mar 01-31	69.8564	69.8562	69.8568	69.8565	69.8563	69.9206
Apr 01-30	58.4922	58.4915	58.4905	58.4906	58.4916	58.5094
May 01-31	107.6766	107.6766	107.6766	107.6766	107.6766	107.6766
Jun 01-30	180.7307	180.7307	180.7307	180.7307	180.7307	180.7307
Jul 01-31	256.9008	256.9008	256.9008	256.9008	256.9008	256.9008
Aug 01-31	244.8934	244.8934	244.8934	244.8934	244.8934	244.8934
Sep 01-30	256.9661	256.9661	256.9661	256.9661	256.9661	256.9661
Oct 01-31	141.8955	141.8953	141.8949	141.8950	141.8953	141.8955
Nov 01-30	105.5021	105.5002	105.4967	105.4972	105.5004	105.5541
Dec 01-31	34.5167	34.5172	34.5187	34.5182	34.5172	34.5514
Summed total	1500.0331	1500.0377	1500.0626	1500.0535	1500.0381	1500.4747

Table H.10 : Roof - Light energy monthly breakup (IES-VE Vista)

	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)
	tsq_BC_s_u_r5.ap:	tsq_BC_s_u_r4.ap	tsq_BC_s_u_r3.ap	tsq_BC_s_u_r2.ap	tsq_BC_s_u_r1.ap:	tsq_BC_sens.aps
Date						
Jan 01-31	236.9612	236.9612	236.9612	236.9612	236.9612	236.9612
Feb 01-28	209.7077	209.7077	209.7077	209.7077	209.7077	209.7077
Mar 01-31	232.1223	232.1223	232.1223	232.1223	232.1223	232.1223
Apr 01-30	224.5281	224.5281	224.5281	224.5281	224.5281	224.5281
May 01-31	225.9386	225.9386	225.9386	225.9386	225.9386	225.9386
Jun 01-30	215.4386	215.4386	215.4386	215.4386	215.4386	215.4386
Jul 01-31	225.5585	225.5585	225.5585	225.5585	225.5585	225.5585
Aug 01-31	225.9164	225.9164	225.9164	225.9164	225.9164	225.9164
Sep 01-30	222.0044	222.0044	222.0044	222.0044	222.0044	222.0044
Oct 01-31	233.6799	233.6799	233.6799	233.6799	233.6799	233.6799
Nov 01-30	227.3929	227.3929	227.3929	227.3929	227.3929	227.3929
Dec 01-31	237.2286	237.2286	237.2286	237.2286	237.2286	237.2286
Summed total	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773	2716.4773

APPENDIX I

Base case VS Optimal cases - IES Simulation Results monthly breakup

Table I.1 : Base case VS Optimal case - Energy consumption monthly breakup (IES-VE Vista)

	Total energy (MWh)	Total energy (MWh)	Total energy (MWh)
	tsq_optima G+7.aps	tsq_optimal_G+1.aps	tsq_optimal case.aps
Date			
Jan 01-31	1556.3728	345.4214	740.5887
Feb 01-28	1483.5784	342.7444	716.6885
Mar 01-31	1838.5745	449.3928	909.2174
Apr 01-30	1955.4443	500.5834	985.5710
May 01-31	2262.0254	590.4061	1145.7419
Jun 01-30	2411.6108	632.0988	1223.3656
Jul 01-31	2701.6875	710.7947	1372.5110
Aug 01-31	2669.1157	707.8118	1360.1312
Sep 01-30	2549.8120	670.7310	1296.0170
Oct 01-31	2256.3398	582.7618	1138.6256
Nov 01-30	1969.4783	492.9796	981.5423
Dec 01-31	1676.0082	385.8941	808.9629
Summed total	25330.0469	6411.6196	12678.9629

Table I.2 : Base case VS Optimal case - Cooling plant load monthly breakup (IES-VE Vista)

	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room cooling plant sens. load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)	Room dehum. plant load (MWh)
	tsq_optima	tsq_optimal_G+	tsq_optimal	tsq_optima	tsq_optimal_G+	tsq_optimal
Date						
Jan 01-31	1010.9537	197.7195	458.2364	68.6745	19.1994	33.6211
Feb 01-28	1080.2736	242.4171	514.7794	75.8853	23.4571	39.3585
Mar 01-31	1409.2462	352.5870	701.1072	279.5114	81.9524	146.7209
Apr 01-30	1747.4802	484.7665	906.2232	235.9202	67.3434	123.1475
May 01-31	2134.8406	620.7557	1125.3477	424.1141	108.1790	213.3612
Jun 01-30	2214.2463	652.5891	1173.1941	713.2704	180.7307	358.2037
Jul 01-31	2410.9126	713.5715	1279.2500	1015.5136	256.9008	509.7520
Aug 01-31	2413.6624	718.8974	1283.9473	967.9058	244.8934	485.8604
Sep 01-30	2175.5896	640.4859	1152.5665	1015.6228	256.9660	509.8283
Oct 01-31	1951.0341	552.6045	1018.3104	562.6007	145.5580	284.5190
Nov 01-30	1562.1534	410.4015	792.1157	425.1772	120.7714	221.6357
Dec 01-31	1180.5150	255.5111	554.6728	132.9505	41.8192	70.4878
Summed total	21290.9082	5842.3071	10959.7500	5917.1465	1547.7709	2996.4963

Table I.3 : Base case VS Optimal case - Carbon emission monthly breakup (IES-VE Vista)

	Total CE (kgCO2)	Total CE (kgCO2)	Total CE (kgCO2)
	tsq_optima G+7.aps	tsq_optimal_G+1.aps	tsq_optimal case.aps
Date			
Jan 01-31	807759	179273	384366
Feb 01-28	769908	177854	371927
Mar 01-31	954219	233235	471884
Apr 01-30	1014875	259803	511511
May 01-31	1173991	306421	594639
Jun 01-30	1251626	328059	634927
Jul 01-31	1402175	368902	712333
Aug 01-31	1385270	367354	705907
Sep 01-30	1323353	348109	672632
Oct 01-31	1171039	302453	590946
Nov 01-30	1022159	255856	509420
Dec 01-31	869849	200279	419851
Summed total	13146223	3327600	6580345

Table I.4: Base case VS Optimal case - Light energy monthly breakup (IES-VE Vista)

	Total lights energy (MWh)	Total lights energy (MWh)	Total lights energy (MWh)
	tsq_optima G+7.aps	tsq_optimal_G+1.aps	tsq_optimal case.aps
Date			
Jan 01-31	1016.5645	236.9612	494.6591
Feb 01-28	905.2759	209.7077	439.5042
Mar 01-31	994.1977	232.1223	485.3025
Apr 01-30	963.7452	224.5281	470.8846
May 01-31	982.5507	225.9386	476.3860
Jun 01-30	947.8535	215.4386	457.6662
Jul 01-31	988.4786	225.5585	478.0080
Aug 01-31	978.3340	225.9164	475.2246
Sep 01-30	954.2109	222.0044	464.8182
Oct 01-31	999.5248	233.6799	487.2091
Nov 01-30	975.8154	227.3929	474.6652
Dec 01-31	1019.2795	237.2286	496.3808
Summed total	11725.8301	2716.4773	5700.7085