ACCEPTABLE INDOOR ENVIRONMENTAL QUALITY AT REDUCED ENERGY CONSUMPTION FOR SUSTAINABLE SCHOOLS IN HOT CLIMATE

BY

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TO FATHER, MOTHER, GRANDFATHER, FRIENDS

AND ALL MY FAMILY MEMBERS

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First and foremost I thank ALLAH (SWT) for helping me complete this work. Thereafter, I acknowledge the faculty of the Architectural Engineering Department, KFUPM for supporting and guiding me throughout my research.

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LIST OF ABBREVIATIONS

IEQ	:	Indoor Environment Quality
IAQ	:	Indoor Air Quality
LED	:	Light Emitting Diode
EDS	:	Envelope Design Strategies
WWR	:	Window to Wall Ratio

ABSTRACT

Full Name : Ahmed Abdaljaleel Abdalnabi Kattlo

Thesis Title : Acceptable Indoor Environmental Quality at Reduced Energy Consumption for Sustainable Schools in Hot Climate

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Buildings are designed with the aim of providing a comfortable living environment for the occupants. The comfort factors include thermal, visual and acoustical comfort as well as the indoor air quality. The indoor environment quality (IEQ) refers to the performance of a building in delivering an indoor environment to its occupants that meet the expectations of maintaining the occupants' health, comfort, and productivity.

Schools have an important function that necessitates careful design and operation to achieve a good learning environment that enhances students' performance. In order to achieve this, and to reduce absenteeism due to building sickness, schools have to be maintained at the acceptable indoor environment quality. Maintaining a school's functions and operating at acceptable conditions may requires a considerable amount of energy if not properly designed.

This research aims at formulating guidelines for sustainable school design and operation by achieving acceptable indoor environmental quality at reduced energy consumption rates. In order to achieve this, a typical school was modeled as the base case. Assessment of the design operational strategies that contribute to sustainability by reducing energy consumption and maintaining acceptable IEQ was done. Typical school buildings in Al-Dammam, Al-Dhahran and Al-Khobar were evaluated for IEQ taking into consideration the energy performance by taking advantage of different opportunities for reducing energy consumption. This was achieved by using the energy simulation program Design-Builder. Optimization for window to wall ratio (WWR), glazing type, air infiltration, and roof and wall thermal insulation was carried out, followed by investigating the impact of lighting type and HVAC systems on the energy consumption and discomfort hours. After conducting optimization for the WWR, glazing type, roof and wall insulation the cooling energy consumption was reduced by 8.7% and the discomfort hours reduced to 213 hours. After upgrading lighting from fluorescent to LED, the reduction in the cooling energy reached 16.5%. While using the DX-Packaged system with optimum parameters reduced the energy consumption by 41% and reduced the discomfort hours to 129hours.

ملخص الرسالة

الاسم الكامل: احمد عبد الجليل قتلو

عنوان الرسالة: تحسين البيئة الداخلية للمدارس المستدامة ضمن الاستهلاك الادنى للطاقة الكهربائية في المناخ الحار.

التخصص: الهندسة معمارية

تاريخ الدرجة العلمية: 2016

صممت المابني بهدف توفير بيئة معيشية مريحة ومناسبة للسكان. وتشمل عوامل الراحة الحرارية والبصرية والصوتية بالاضافة الى نوعية الهواء الداخلي. نوعية البيئة الداخلية هي مؤشر لاداء المبنى في توفير بيئة داخلية مناسبة للسكان والتي تلبي الحاجات الاساسة من الحفاظ على الصحة والراحة والانتاجية للمستخدمين. تعتبر المداس من المباني ذات الوظائف الهامة التي تستوجب تصميم دقيق وعملي لتتحقيق بيئة تعليمية مناسبة لتعزيز ونطوير اداء الطلاب. من اجل تحقيق ذلك والحد من الغياب بسبب المرض يجب أن يتم الحفاظ على جودة البيئة الداخلية في المدارس. المحافظة على البيئة الداخلية للمدارس قد يتطلب قدرا كبيرا من الطاقة اذا لم تكن مصممة بشكل صحيح.

يهدف هذا البحث إلى وضع مبادئ توجيهية لتصميم المدارس المستدامة للحصول على البيئة الداخلية مناسبة مع الاخذ في الاعتبارخفض معدلات استهلاك الطاقة. من أجل تحقيق هذا الهدف، تم نمذجة مدرسة لتمثل نموذج للدراسة والبحث . تم اجراء تقييم لاستراتيجيات تصميم مكونات البنى التي تساهم في الاستدامة عن طريق خفض استهلاك الطاقة والحفاظ على بيئة داخلية مقبولة ومناسبة.

تم تقييم مجموعة من المباني المدرسية في الدمام، الظهران و الخبر من ناحية البيئة الداخلية مع الأخذ بعين الاعتبار استهلاك الطاقة للاستفادة من الفرص المختلفة للحد من استهلاك الطاقة. وقد تحقق ذلك عن طريق استخدام برنامج محاكاة الطاقة للمباني. تم اجراء تحليل باستخدام برنامج المحاكاة لاختيار افضل نسبة نوافذ إلى الجداران، نوع الزجاج، تسلل الهواء، العزل الحراري للجدران والسقف . يلي ذلك دراسة تأثير نوع أنظمة الإضاءة والتكييف على استهلاك الطاقة ومستوى الراحة للبيئة الداخلية. بعد إجراء التحليل لنسبة الزجاج للمباني،ونوع الزجاج ،واستخدام العازل للسقف والجدار تم تخفيض استهلاك الطاقة المستخدمة في التبريد بنسبة 8.7٪ وساعات عدم الراحة إلى 213 ساعة. وبعد تغيير الإضاءة من الفلورسنت لاضاء الصمام الثنائي انخفضت الطاقة بمقدار 16.5٪. وبعد تغيير نظام التكييف تم تخفيض استهلاك الطاقة بنسبة 41٪ وتخفيض ساعات عدم الراحة الى 129ساعة.

CHAPTER 1

Introduction

1.1 Background

The building sector is an important component of an economy and is a significant indicator of economic growth. Buildings are the largest consumer of energy, water, and material resources; hence their potential to impact the economy and the environment is highly significant. According to the U.S. Green Building Council (USGBC), in the United States, buildings account for 36% of the total energy usage and 65% of electrical energy consumption, 30% of the emissions of greenhouse gases, 30% of the usage of raw materials, and 12 % of potable water consumption. Accordingly, there have been increasing efforts through environmental organizations to develop suitable actions and strategies to make the building industry and its activities more sustainable (Akadiri, et al. 2012).

The American Society for Testing and Materials (ASTM) considers a sustainable building to be a 'green building' and defines it as – "a building that provides the specified building performance requirements while minimizing disturbance to and improving the functioning of local, regional, and global ecosystems both during and after its construction and specified service life". A green building is also defined as the one that "optimizes efficiencies in resource management and operational performance; and, minimizes risks to human health and the environment" (BEAM, 2012).

Leadership in Energy & Environmental Design (LEED) developed a Green Building Rating System, which is a consensus standard established by the U.S.Green Building Council (USGBC) for improving and developing sustainable buildings that have a considerable impact in the areas of sustainable energy efficiency, site development, selection of materials, water savings , and the quality of indoor environment. According to LEED, there are different criteria for analyzing the building to assess its sustainability with regards to site, energy system, resource, material, and the quality of indoor environment.

In order to contribute to sustainable building design, the indoor environment quality should be maintained at acceptable levels while consuming the minimum amount of energy. Generally, in harsh climates such as the one prevailing in Saudi Arabia, a significant portion of energy production is used for cooling buildings. According to (SAMA, 2012), government buildings consume 13% of the energy in Saudi Arabia. Schools have an important function and a unique operation, hence, they need to be well designed and carefully operated to achieve their intended function and contribute to sustainability. Furthermore maintaining an acceptable indoor environment in classrooms is a significant factor in improving the learning and achievement of students, (Haverinen, et al., 2015) and (Jurado, et al., 2014) and others. Maintaining the indoor environment requires energy, however, in the quest for improving sustainability by reducing energy consumption, it is important to ensure that IEQ is not negatively impacted and is maintained at acceptable levels. The pattern of operation in schools possesses a high potential to conserve energy and reduce energy wastage without affecting the IEQ requirements.

1.2 Objective of the research

- The main objective of this research is to formulate guidelines for sustainable school design by achieving acceptable indoor environmental quality at reduced energy consumption. This can be achieved through the following:
    - Investigating the status of indoor environmental quality and energy performance in existing schools.
    - Assessing design strategies that contribute to sustainability by reducing energy consumption and maintaining acceptable IEQ.

1.3 Problem Statement

Schools have an important function that necessitates careful design and operation to create a good learning environment and improve student's achievement. In order to perform their function effectively, schools have to be maintained at the acceptable indoor environment quality. This may require a considerable amount of energy if not properly designed. When the building or its components are improperly designed or operated, IEQ is unlikely to be maintained at acceptable levels. At the same time, unnecessary amounts of energy can be consumed particularly in hot climates. Given the uniqueness of the functional characteristics of schools, maintaining an acceptable IEQ at reduced energy consumption is a challenge that needs to be investigated.

1.4 Significance of the study

Schools are considered as buildings with high intermittent occupants containing a unique function. Classrooms need to be maintained at acceptable indoor environment to sustain and improve the learning abilities of the students. Maintaining the indoor environment of schools in a hot climate at acceptable conditions requires a considerable amount of energy. If not properly designed and operated the building may consume unnecessary large amount of energy particularly in hot climates. This calls for higher attention in the design and operation stages of schools to make sure that indoor environment quality is achieved with reduced energy use. This will contribute towards sustainability and provide a sustainable environment in schools in a hot climate. Additionally, being an educational facility, a school should be presented as a model for contribution towards sustainability, and that will have a positive impact on the environment.

1.5 Scope and Limitations

The scope of the study is to investigate energy performance and indoor environmental quality in typical schools built and administrated by the Ministry of Education in Saudi Arabia. The study will be limited to the cities of Al-Dammam, Al-Dhahran, and Al-Khobar as these represent hot humid climates. Five to ten schools were considered for this investigation. The indoor environmental quality investigation was limited to thermal comfort and lighting conditions. Cost analysis was not considered in the study.

1.6 Research Methodology

The methodology of this study is divided into four phases to achieve the aforementioned objectives, and is discussed below:

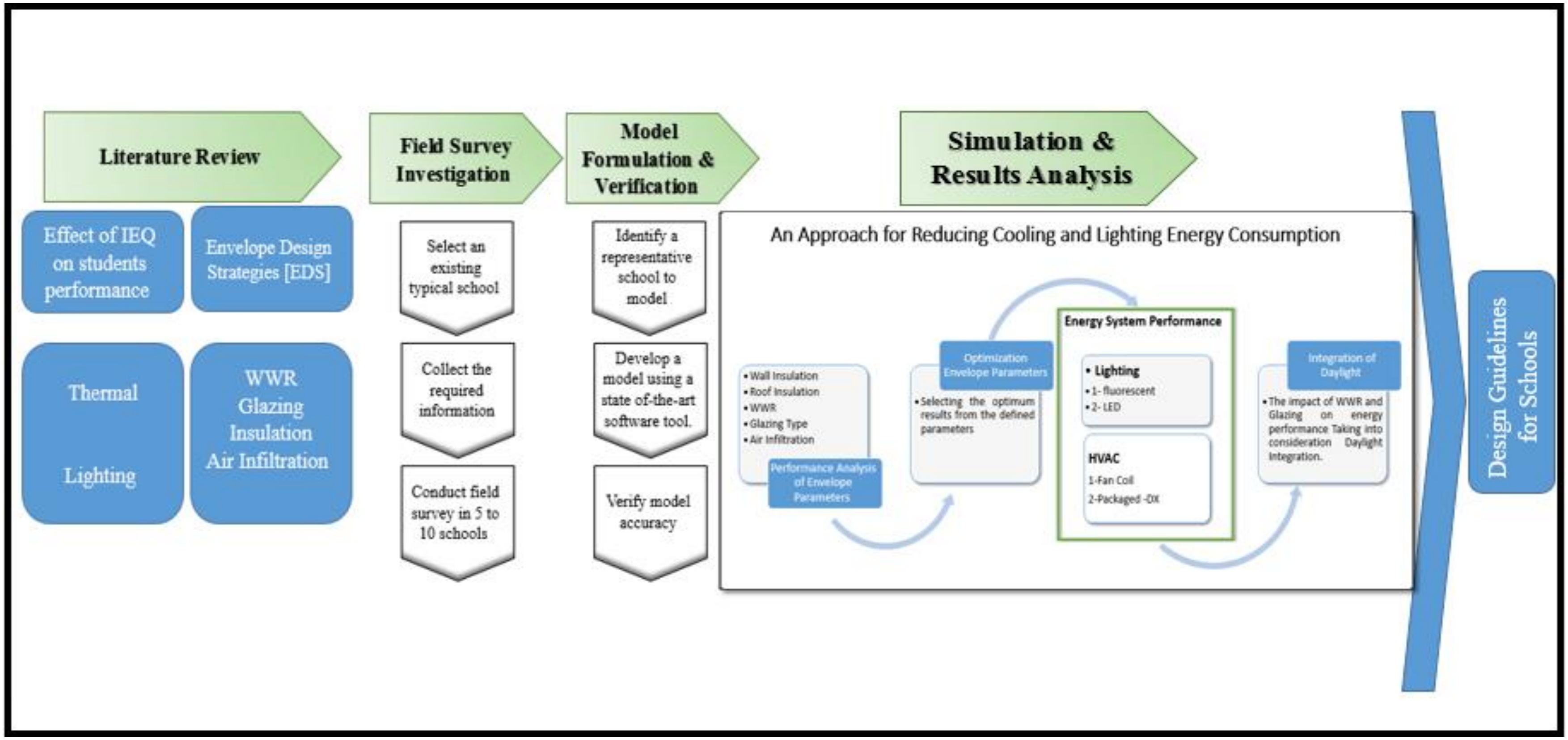


Figure 1. 1 Flow Chart of Research Methodology

Phase-1: Literature Review

- General review of factors that constitute a sustainable building.
- Review the importance of maintaining the indoor environment quality in terms of thermal comfort and lighting on the students' academic achievement in schools.
- Review the effect of different envelope design strategies on energy efficiency in schools.
- Review state-of-the-art building performance simulation (BPS) tool. Select the appropriate tool depending on its capability to provide an accurate result for prediction.

Phase-2: Field Survey Investigation of Energy Status and IEQ of an Existing School

- Review and identify a typical existing school design that is approved by the Ministry of Education in Saudi Arabia.
- Identify schools located in the eastern province for modeling and further investigation.
- Conduct field measurement in 5 to 10 schools to measure the lighting, indoor air quality and energy consumption to assess the indoor environmental quality and energy consumption in the schools.
- Collect the required information about the building thermal characteristics as well as energy consumption from the relevant sources.

Phase-3: Model Formulation

- Identify a representative and suitable school to model.
- Develop a model for the selected case based on the collected information using a state-of-the-art software tool.

- Verify model accuracy.

Phase-4: Optimization Analysis of Resulting Energy Consumption and IEQ

- Investigate the impact of the different envelope design strategies on energy consumption.
- Conduct optimization simulation to assess the effect of envelope parameters on energy consumption and IEQ.
- Compare the results of energy consumption between the post-modified case and the base case model simulation.

Phase-5: Conclusions and Recommendations

- Conclusions, recommendations, and guidelines will be stated to help the designers to design an energy efficient school building utilizing envelope design strategies to improve the energy performance of schools in a hot humid climate in Saudi Arabia.

CHAPTER 2

Literature Review

2.1 Sustainability and Building Design

Sustainability is a term that refers to "the need to develop the sustainable models necessary for both the human race and planet Earth to survive". It also "acknowledges that human civilization takes resources to sustain our modern way of life". In the building context, sustainability refers to buildings that cannot consume materials unless they can be easily extracted, used and returned to nature, cannot consume non-renewable energy, cannot destroy the natural habitat, and cannot release pollutants in quantities that could destroy the natural ecosystem.

Sustainable buildings consist of elements which determine the degree of sustainability. Different organizations have developed systems and principles to enhance a building's performance and to make buildings more sustainable. "BEAM", is an example of such an organization that ensures elements such as a building site.

To improve sustainability especially in the future building industry, Asif, et al., (2007) suggested an assessment approach aimed at producing sustainable buildings with environmental friendly traits and identified three general objectives for providing a framework for developing sustainable building design. This approach covers different fields including; saving energy, enhancing the use of materials, minimization of material waste, control of pollution etc. This can ultimately create sustainable buildings with environment-friendly practices. The three general objectives include resource conservation, cost efficiency and design for human adoption.

The meaning of “Resource Conservation” is natural resource management to obtain maximum advantages of present generations while preserving the capacity to provide for the needs of generations in future. Figure 2.1 shows different strategies that could be implemented to sustain energy conservation with a different method for each one.

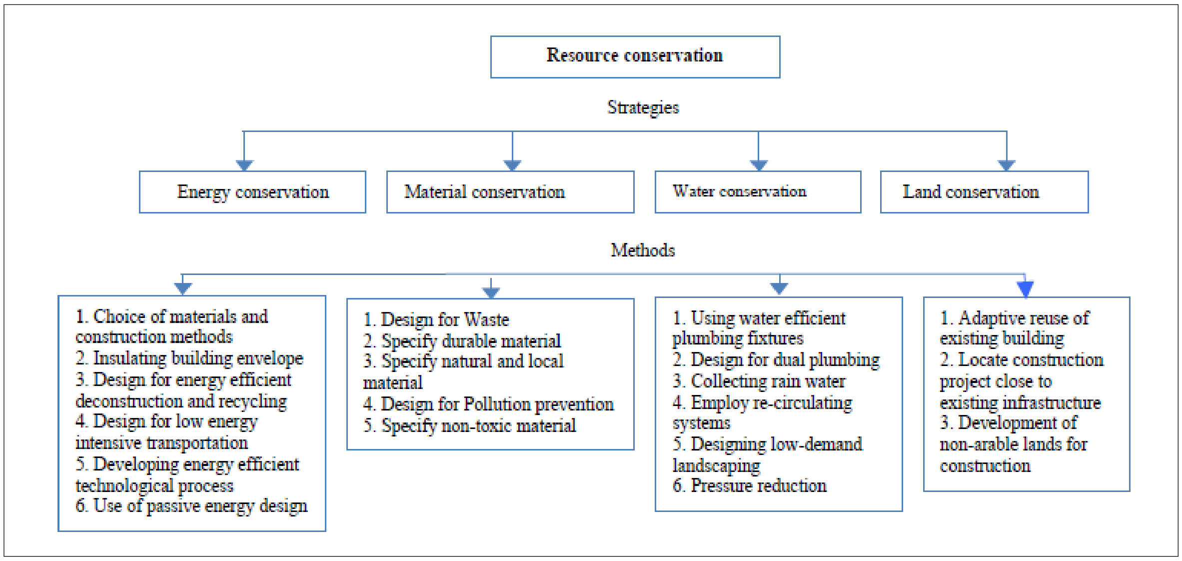


Figure 2. 1 Strategies and methods to achieve resource conservation. (Asif et al., 2007)

2.2 Indoor Environmental Quality in Schools

The main role of buildings is to provide a comfortable living environment for their occupants. This includes thermal, visual and acoustic comfort as well as indoor air quality. IEQ refers to the performance of a building in delivering an indoor environment to its occupants that meets the expectations of maintaining the occupants' health, wellbeing, and productivity (Liang, et al., 2014).

The Indoor environment quality of schools has a significant impact on students' productivity, comfort and safety. Studies have indicated that poor indoor environmental quality may have a negative impact on students' health, attendance, and academic achievement. Thermal comfort, indoor air quality, and lighting are significant parameters to create a suitable indoor environment for students to improve their learning abilities.

2.2.1 Thermal Comfort

Thermal comfort can be defined as "that condition of mind, which expresses satisfaction with the thermal environment" (ISO Standard 7730, 2005). Fanger provided six parameters that have effects on thermal comfort. Metabolism refers to all chemical reactions that occur in living organisms, it is also related to the amount of activity. And the amount of clothing resistance also affects thermal comfort, the relative humidity, and the air velocity where heat loss can increase by convection.

According to ASHRAE Standard 55, to achieve thermal comfort for the occupants, the temperature during the winter season should range between 20-24^{o}C, and in summer spring and autumn should range between 23-26^{o}C. The relative humidity limit for comfort should range between 30%-60% for all seasons.

Different studies were conducted to assess thermal comfort in classrooms. Wong et al., (2003) investigated thermal comfort in schools in Singapore. They revealed that the range of acceptable temperature is between 27.1- 29.38^{o}C.

Fong, et al., (2011) evaluated thermal comfort in classrooms in Hong Kong schools. They revealed that the neutral temperature varies between 24.6 and 27.4^{o}C depending on the ventilation method that they assessed. de Dear, et al., (2015) provided a summary of previous field studies thermal comfort in classrooms to define the thermal comfort range as shown in Table 2.1.

Table 2. 1Summary of Previous Thermal Comfort Field Study in Classroom. (de Dear, et al., 2015)

Study	Location	Climate	Season	Type of Ventilation	Age group	Neutral temperature
Kwok (1998)	Hawaii, US	Tropical	Winter summer	NV and AC	19-13	NV: 26.88 ºC AC: 27.48 ºC
Wong and Khoo (2003)	Singapore	Tropical	Summer	NV	17-13	28.88 ºC
Hwang, Lin,Chen, and Kuo (2009)	Taiwan	Subtropical	Autumn	NV	17-11	24.8-23 ºC
Liang, Lin, and Hwang (2012)	Taiwan	Subtropical	Autumn	NV	17- 12	29.28- 22.4 ºC
Teli, Jentsch, and James (2012)	England, UK	Temperate	Spring	NV	11-7	20.58 ºC

NV: Non-Ventilated AC: Air Conditioned

As an important factor of indoor environment quality in classrooms, thermal comfort was the focus of various studies to investigate the effect of thermal comfort in classrooms on student’s learning skills, and how the performance of students can be affected when the temperature of the classroom exceeds the acceptable range of temperature.

Wargocki et al., (2007) investigated the effect of the temperature and ventilation rate on students' learning performance in the classroom in Sweden. The study included students from 10-12 years old in two classrooms. They found out that adjusting the temperature between 20 and 25ºC improves student performance in numerical tasks, and language-based tasks, by improving their speed

Haverinen et al., (2015) assessed the effects of the temperature and ventilation rate on students’ performance (academic achievement). The study was conducted in 70 elementary schools in the USA, They found out that student academic achievement was enhanced when they maintained the temperature within the range of 20 to 25°C.

2.2.2 Indoor Air Quality

Indoor air quality (IAQ) in classrooms improves the students' learning ability and teachers' productivity according to the research (Mumovic, D., et al, 2009), (Yang, et al ,2009), and (Kosonen, et al, 2004). IAQ includes the ventilation rate and the effects of various pollutant concentrations such as CO_2, sulphur dioxide, nitrogen dioxide, particulate matters etc.

ASHRAE Standard 62, (2007) provides recommendations for the ventilation rate in educational facilities. According to the standard, the ventilation rate should be between 3.8-5 L/s/ person for classrooms and lecture rooms (as shown in Table 2.2) with occupant density between 25 and 35 /100m^2.

Table 2. 2 Ventilation rate in the educational facility. ASHRAE Standard 62-2007

	People Outdoor Air Rate R_P		Area Outdoor Air Rate R_A			Default Values		
						Occupant Density (see Note 4)	Combined Outdoor Air Rate (see Note 5)	
Occupancy Category	cfm/person	L/s•person	cfm/ft^2	L/s•m^2	Notes	#/1000 ft^2 (#/100 m^2)	cfm/person	L/s•person
Correctional Facilities								
Cell	5	2.5	0.12	0.6		25	10	4.9
Day room	5	2.5	0.06	0.3		30	7	3.5
Guard stations	5	2.5	0.06	0.3		15	9	4.5
Booking/waiting	7.5	3.8	0.06	0.3		50	9	4.4
Educational Facilities								
Daycare (through age 4)	10	5	0.18	0.9		25	17	8.6
Classrooms (ages 5-8)	10	5	0.12	0.6		25	15	7.4
Classrooms (age 9 plus)	10	5	0.12	0.6		35	13	6.7
Lecture classroom	7.5	3.8	0.06	0.3		65	8	4.3
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3		150	8	4.0
Art classroom	10	5.0	0.18	0.9		20	19	9.5
Science laboratories	10	5.0	0.18	0.9		25	17	8.6
Wood/metal shop	10	5	0.18	0.9		20	19	9.5
Computer lab	10	5	0.12	0.6		25	15	7.4
Media center	10	5	0.12	0.6	A	25	15	7.4
Music/theater/dance	10	5.0	0.06	0.3		35	12	5.9
Multi-use assembly	7.5	3.8	0.06	0.3		100	8	4.1

According to UK Bulletin 101 for Building Regulations, the recommended average of CO_2 concentrations in schools should not exceed 1500 (ppm) for learning and teaching zones. Each level of CO_2 concentration inside buildings can have direct effects on the occupants as shown in Table 2.3.

Table 2. 3 The Effects of CO_2 Concentrations on the Occupants.

CO_2 concentrations	**The effect of CO_2 concentration**
250-350 ppm	Normal background concentration in outdoor ambient air
350-1,000 ppm	Concentrations typical of occupied indoor spaces with good air exchange
1,000-2,000 ppm	Complaints of drowsiness and poor air.
2,000-5,000 ppm	Headaches, sleepiness and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present.

Jurado, et al., (2014) assessed indoor air quality in Brazilian universities. The study compares thirty classrooms; 15 air-conditioned (AC) and 15naturally ventilated (NV). They studied the indoor concentration of carbon dioxide (CO_2), relative humidity (RH), temperature, airborne dust levels, and wind speed. The results showed that the concentration of CO_2 was higher in the air conditioned classroom as compared to the ventilated (1433.6 ± 252.8ppm), and exceeded the recommended value specified in the Brazilian standards which is less than 1000 ppm. This increase in concentration is associated with an increase in the ratio of a specific symptom such as a headache, difficulties in concentration, lethargy and eye irritation.

In an attempt to assess the impact of indoor air quality in the classroom on the students' performance, Twardella, et al., (2012) studied twenty classrooms in Germany that use mechanical ventilation systems. They found that a high concentration of CO_2 levels as an indicator of low indoor air quality in classrooms does not decrease the overall short-term concentration performance of the students, but they did show an increased error rate.

Teachers can also be affected by the IAQ which in turn will reflect on students learning achievement. Satish, et al., (2012) assessed the direct impact of CO_2 on decision making. The study was conducted on 22 participants, who were exposed to different CO_2 concentrations of 600, 1,000, and 2,500 ppm in the office. The participants were divided into 6 groups with each group exposed to different conditions and then asked to answer a test on decision-making performance. The results showed that a significant reduction occurred in decision-making performance when the CO_2 concentration reached 2,500 ppm. It was concluded that CO_2 has an adverse impact on human performance.

2.2.3 Lighting

Lighting systems are usually designed based on the levels of light which are required by users to perform tasks in each building space. The Illuminating Engineering Society of North America (IESNA) had provided the appropriate values for illuminance for each building type. The (IESNA) provides a handbook containing comprehensive guidance that provides knowledge and tables for suitable illuminance as shown in Table 2.4

Table 2. 4 The Recommended Illuminance for Educational Building According to (IESNA 2009)

Building Type	**Space Type**	**Maintained Average Illuminance at working level (lux)**	**Measurement (working) Height (1 meter = 3.3 feet)**
Educational buildings	Classrooms	300	at 0.8 m
	Classrooms for adult education	400	at 0.8 m
	Lecture hall	400	at 0.8 m

In Table 2.5 the recommended illuminance and lighting power density for different types of spaces according to ASHRAE 90.1 are specified. According to the standard, classrooms require a 30 foot-candle (322 lux) with a 1.4 w/ft^2 (15.1W/m^2) lighting power density.

Table 2. 5 The Recommended Illuminance and Lighting Power Density for Different Space. ASHRAE 90.1

Space Type	Illuminance (fc)	LPD (W/ft²)
Open Offices	30 to 50 (5 to 10 with task lighting)	1.1
Private Offices	50	1.1
Conference Rooms	30	1.3
Corridors	5	0.5
Restrooms	10	0.9
Lobby	10	1.3
Copy Rooms	10	
Classrooms	30	1.4
Gymnasiums	100	1.1
Dining Areas	10	0.9
Kitchen	50	1.2
Labs	50	1.4

Many studies have investigated the impact of the color and quality of lighting on students' performance related to students' skills and academics performances. Knez, (1995) studied the impact of indoor lighting on the cognitive performance of the students. They used different lighting levels in each experiment and different color temperatures. They found that the level of lighting and color temperature could affect the performance of long-term memory and task solving ability. Haverinen, et al., (2015) focused their study on the effects of various types of lighting used in elementary schools on students' performance. They examined different variables such as students' attendance, development, and academic achievement under different types of artificial lighting. The study was conducted on 327 students and continued for two years. The results of the study show that the students present in classrooms housed with spectrum fluorescent lamps show improved attendance and academic achievement. The students in classrooms with the other types of lights such as high-pressure sodium lamps, suffered from low levels of development, achievement and lower attendance.

In addition to the quality of artificial lighting, daylighting can also have a major impact on students learning achievement and teachers performance. Different studies reveal that the daylight utilization in classrooms may have a significant impact on students test scores and promote academic achievement. A study done by Loisos et al., (1999) in Washington, California, and Colorado analyzed the effect of daylight on human performance for 21,000 students. Results showed that students who are in classrooms with daylighting progressed on math tests 20% faster and in reading tests 26% faster, when compared to students in classrooms with either no or less daylight.

2.3 Energy Consumption in Buildings

A building's energy end use varies depending on the building type. In buildings, the end use of energy is distributed between HVAC, lighting, DHW, equipment, refrigerating and other uses. Umberto, et al. (2002) performed an energy audit analysis for schools. They studied both thermal and electric energy consumption. Energy analysis of the schools showed that thermal consumption contributed up to 80% of the total annual energy consumption. Hani Hussain, (2013) conducted a study on educational buildings in Jeddah. He found that air conditioning systems consumed 91% of the total energy consumption.

It can be seen that Saudi Arabia consumes the highest amount of energy in HVAC systems due to the high level required to achieve thermal comfort. The present buildings in Saudi rely strictly on air conditioning system for the purpose of cooling, and therefore consume large amounts of electricity. Furthermore, Saudi Arabia is totally dependent on fossil fuels (unsustainable sources of energy) for the generation of electricity, which will always have a considerable effect and impact on the environment air, water, climate, and land.

According to SAMA, (2012) more than 12% of generated electrical energy was consumed by government buildings in 2011 which also includes schools as shown in Figure 2.5. This is compared to 7.8% of the total energy consumption in 2005.

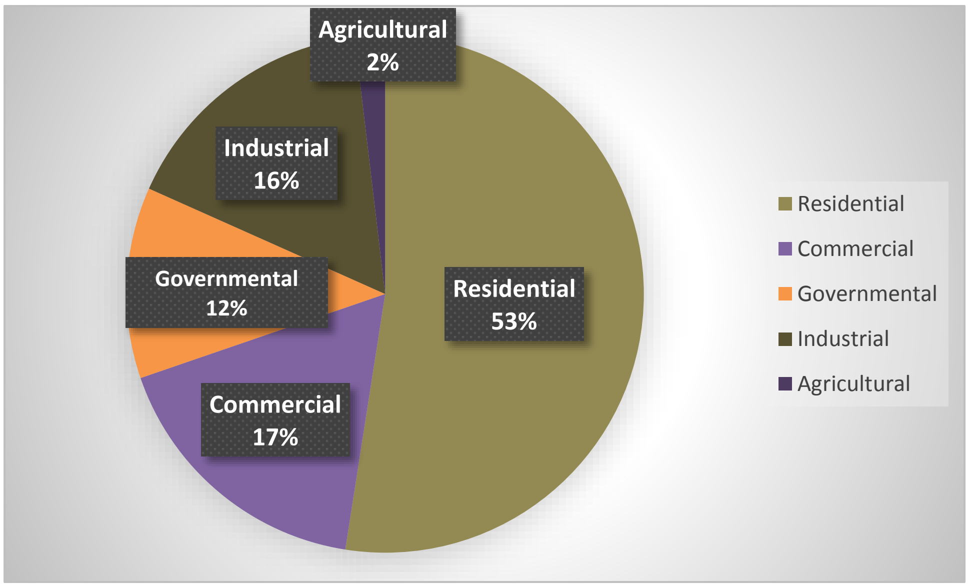


Figure 2. 2 Demand Ratio for Different Sector in the Kingdom. (SAMA, 2015)

The schools are occupied during a typical day for about seven hours, for five days a week. Additionally, schools are generally unoccupied during the summer season. The consumed energy in schools is usually for different purposes, such as heating systems, cooling systems, lighting, and equipment. Maintaining the indoor environment at acceptable conditions is the chief consumer of energy in schools, especially in hot climates. According to Desideri, et al., (2002) maintaining the indoor environment consumes more than 80 % of the overall energy consumption in harsh climates. Room lighting is also a significant factor for energy consumption in schools, therefore it is important to have energy efficient lighting systems in schools and to utilize daylight.

Different studies on energy conservation in schools have been conducted in many countries. For example, a study was conducted by Kim, et al., (2012) on ten schools in South Korea to quantitate the optimal energy consumption of schools with regards to maintaining a pleasant environment and effective energy use. They revealed that the consumption of energy per unit study area in South Korean schools in 2010 reached about 1040 MJ/m^2 y for electricity, 325 MJ/m^2 for gas, and 92 MJ/m^2 y for oil. The highest proportion of the energy was used for heating, then for cooling and lighting.

2.4 Opportunities for Reducing Energy Consumption in Buildings

In the design stage, different factors need to be assessed to improve the sustainability of the building in terms of energy consumption. These factors include the shape, orientation, shading elements, and window to-wall ratio. Many studies have been conducted to investigate various measures for improving the energy performance of buildings. Florides, et al., (2002) investigated measures to reduce the thermal load. They revealed that the annual energy savings as a result of reducing cooling load reached 24 %,(3050 – 5000 KWh/ year). They used a shading element overhang of 1.5 m in length over windows to improve savings by 7% of the annual cooling load. They also found that elongated shapes increase the heating load between 8.2 -26.7% depending on the construction type. In regards to the effect of orientation, they revealed that the best orientation for an elongated house is to orient the longer side of the building to the south, while for a square shape the best orientation is to face the four cardinal points.

2.4.1 Envelope Design Strategies

As mentioned earlier, the development of sustainable buildings needs the adoption of more than one discipline, covering a number of features such as energy use, use of materials, wastage of materials, and control of pollution and emissions. Energy-efficient design does not only depend on energy-efficient equipment, but also on the way the building systems interact and respond to the conditions of the local climate.

The basic idea of envelope design strategy refers to measures that reduce the building's dependence on energy systems such as, mechanical systems and lighting, and utilize other renewable sources such as solar energy, to achieve the building's requirements and maintain it at acceptable indoor conditions. In a hot climate like Saudi Arabia, the energy for maintaining the indoor environment can be reduced by using passive cooling strategies. Using these strategies could help reduce the GHG emissions that are produced as a result of cooling, lighting, and heating, and to improve the indoor environment quality. Passive cooling is a design approach for buildings that focus on the control of heat gain and heat removal in buildings in order to achieve a thermally comfortable indoor environment with minimum energy consumption. According to Samuel, et al., (2013) passive cooling strategies are techniques described as energy-efficient and sustainable when used to improve the thermal comfort of the buildings with either no or less energy consumption.

Passive cooling strategies depend mainly on preventing the transfer of heat from the external sources to the living space or by eliminating heat from the spaces of the buildings. There are various passive cooling techniques, which vary in the principle of their operation and their efficiency such as thermal mass, external shading, window glazing, window wall ratio, passive ventilation and color of the external wall. The performance of these strategies depends mainly on the local climate. Some of the envelope design strategies that can be used to improve the energy efficiency of the building will be discussed further.

Rubaih, (2008), conducted a study to explore the impact of envelope parameters on the energy consumption for schools. Different wall compositions, roof insulations, glazing types, WWR and air infiltration rates were explored using parametric analysis, to select the combination with the lowest energy consumption. The effect of HVAC, lighting systems and the integration of daylighting on the energy consumption and IEQ were not considered in the study.

4.1.1 Shading Elements

Shading elements on the building facade control the quantity of solar radiation that falls onto the exterior surfaces and penetrates the building. This strategy provides better results when the designer aims at reducing the heat gain through the openings of the building facade which are considered as the weakest area of resistance to solar radiation. Control of solar radiation is essential to ensure that thermal comfort and visual comfort are achieved inside the building. The use of proper shading elements could provide a significant reduction in peak cooling load and lighting energy.

Many studies have been conducted in this field to explore the impact of the shading elements on energy consumption and the heat performance of buildings. Kim, et al. (2012) conducted an experimental study on exterior shading devices and compared the energy performance of different types of shading devices using the energy analysis program, IES_VE. Results reveal that using shading devices showed a significant variation in performance with the slat angle. The study was performed on a prototype unit in a residential building in Korea which was around 20-storied high.

It was evident that the external shading elements are highly effective as compared to any other type of internal shading devices since these absorb solar heat and re-radiate it into space. The percentage of the cooling energy that can be conserved in the hot season could reach 10% by using conventional blinds with declining slat angle and reach 7% with the slat at an angle of 60 degrees. On the other hand, the shading device located outside provides an 11% energy saving, even in the case where the slat is at 60 degrees. The minimum consumption of energy is achieved when the slat is at zero degrees, and the maximum is achieved at 60 degrees.

Al-Tamimi, et al. (2011) studied the impact of shading elements in a high-rise residential building on the indoor temperature in the hot–humid climate in Malaysia. The objective of the study was to explore the impact of solar heat gain on the indoor environment and how the internal air temperature is affected by the external shading elements. The researchers used the IES-VE simulation tool and conducted a thermal performance simulation for different types of shading elements, including vertical, horizontal and egg-crate shading. Results revealed that egg-crate shading has a significant effect on reducing the hours of thermal discomfort compared to other shading elements. Additionally, it has been found that using egg-crate shading elements contributes in increasing the number of hours from 1821 to 3947 hours with a temperature of less than 28.6^{o}C.

Ali, (2012) conducted a study aimed at exploring the impact of the length of vertical louvers as a shading element for the thermal performance of residential buildings in New Assiut in

Egypt. A climatic analysis of the city was performed and a typical residential building design was identified and simulated for the four cardinal orientations. The study concludes that vertical louvers with a prominence of 38 cm or more reduce the internal temperature of 2 °C for the four orientations. Nevertheless, for the northern part of the building, a slight effect on the internal temperature is observed when the prominence is increased by more than 38 cm. Vertical louvers of a length of one meter provide an indoor temperature with the lowest values for all cardinal orientations. The study concludes that there is a considerable effect of increasing the length of the vertical louvers in the western, eastern, and southern façade on energy savings.

4.1.2Window Wall Ratio (WWR)

Windows can have a significant impact on building energy performance. If not properly designed windows can have a negative impact on the energy consumption. On the other hand, they can positively contribute to building energy performance when correctly designed. Increasing the Window Wall Ratio (WWR) could provide suitable daylighting and visual comfort; but on the other hand, it allows more solar radiation to enter and increases heat transfer, resulting in increased cooling energy consumption. It is important to assess the WWR for the building façade in the early design stages to improve the energy saving potential, taking into consideration the utilization of daylighting. Many studies have been conducted to investigate the relation between energy consumption and WWR. Persson, et al., (2006) aimed at investigating the impact of the size of the window in the south and north facades on energy consumption in residences, with the maximum power needed to maintain the indoor house temperature between the range of 23 and 26 °C. The results revealed that window size does not have a major effect in winter for heating, but dose have an effect during the summer cooling demand. Mehdi, et al., (2014) presented a paper to investigate the relationship between energy consumption and WWR in office buildings in the climatic conditions of Tehran. The authors used eQUEST software to simulate the energy consumption of the selected base case model. They selected the base case model with 100% WWR Then, they reduced the WWR to 80%, 60%, 40%, and 20% and conducted the tests for each. The results revealed that the annual energy consumption was directly influenced by window-wall ratio. For example, a 20% W.W.R reduced by 17% the annual energy consumption of the selected base-case model. Moreover, the results show that the impact of WWR on energy consumption varies according to the various sides of the selected model. It was found that the suitable WWR for the southern and northern sides is around 40%, and for the western and eastern sides it is around 30%.

4.1.3 Window Glazing Type

The energy performance of a window depends on its thermal transmittance, the glazing's solar transmittance, and air leakage due to the frame and installation airtightness. Solar gains can largely influence the thermal energy balance of a building both in the summer and winter seasons. The designer of the building needs to consider the most effective thermally insulated glazing systems. This will be efficient during the summer to control solar gain, thus reducing the cooling energy demand. In cold areas in winter, this could increase the demand for energy for heating purposes due to the reduction in solar gains. Also, glazing type and transmittance have a significant effect on lighting energy.

Bodart, et al., (2002) studied the impact of window size on the energy required for lighting. Results indicate that the performance of window area with regards to lighting depends on the visible transmittance of the glazing. For instance, increasing the area of a window from

16% to 32% can decrease lighting energy consumption by 12% for 20% visible transmittance glazing, while glazing with an 81% visible transmittance reduced lighting energy by 36%. Karlsson, et al., (2001) explained the significance of the properties of the solar transmittance of glazing and revealed that using low emittance and low thermal transmittance glazing has a significant impact on the energy consumption of the buildings in cold climates that require heating.

Abd, et al., (2005) studied the effect of glazing type, daylighting control, window size, and building size, on daylighting efficiency. They used five types of glazing with various characteristics of light transmittance. The results showed that a WWR of 0.2 reduced the total energy consumption of the building for all types of glazing.

4.1.4 Surface Reflectance and Envelope Color Effect

The surface color and reflectance could have a considerable effect on reducing the heat gain through the building envelope. Different studies have been conducted to investigate the effect of color and reflectance on energy consumption. Suehrcke, et al., (2008) conducted a study in north Australia and found that a roof with a light color reduced the total heat gain about 30% compared with a roof with a dark color. Moujaes, et al., (2003) investigated the thermal performance of reflective paint applied to the outer surface of walls and the roof. The results showed a decrease in energy consumption for cooling, which reached 33.6% when highly reflective paint covered the roof and walls, while reduction reached 11% when the reflective paint was applied to the roof only.

4.1.5 Thermal Insulation

Thermal insulation can be considered to be the most significant factor to improve the energy performance of buildings. The basic properties of thermal insulation are summarized by, reducing heat transfer through the building's envelope, and sealing the building envelope; thereby maintaining the indoor environment quality. The use of insulation is an important factor to achieve a thermally comfortable space in buildings in addition to reducing the energy demand for cooling and heating.

Fang, et al., (2014) investigated the effect of wall insulation in summer for experimental chambers. Two chambers were used, one with thermal insulation and the other without. The energy consumption of the insulated chamber was lower than the basic chamber, offering a savings of up to 23.5% in cooling energy during the test period.

Al-Homoud, et al., (2004) investigated the effect of thermal insulation on energy consumption. The study revealed that in residential buildings in Riyadh, the energy consumption reductions for a building with thermal insulation walls and roof varies from 23.69% to 45.51%, while the reduction in the cooling loads for the same building ranged between 21.59 - 37.65%.

4.1.6 Air Infiltration

Building air infiltration is defined as "the air that enters or exits the building in unplanned, unmanaged ways - basically through holes in the building envelope" (Kearns, T. 2009). Jokisalo, et al,. (2008) defined infiltration as, “uncontrolled airflow through a building envelope, depends on the air permeability of the building envelope and the air pressure difference between indoor and outdoor air across the building envelope".

Managing air infiltration is essential to make buildings more comfortable and healthier places. Suitable indoor air quality includes clean healthy air and suitable temperatures which are the two core elements to design interior spaces of the building with high air quality. These elements are directly affected by the conditioned air inside the building. As a result, unmanaged air infiltration can have different consequences on the interior environment of the buildings. Other reasons for controlling air infiltration in buildings are classified by Solupe, et al., (2014) as moisture control, saving energy, comfort, and health.

The major effect of air infiltration is about the impact on the energy consumption of the buildings. Air infiltration increases the load on the air conditioning system for heating or cooling purposes. This leads to an increase in energy consumption, or in exceeding the air-conditioning system's ability for heating cooling, or ventilating a building; thus leading to an uncomfortable internal environment (Kearns, et al., 2009).

Different studies also mentioned that air infiltration adds about 25%–50% of the heating load in residential buildings (Jokisalo, et al., 2008). Juha, et al., (2009) mentioned that infiltration can cause about a 15%-30% increase in the energy used for heating and ventilation in houses. Similarly, Hassouneh, et al., (2012) found that air infiltration could increase the consumption of the energy required for both heating and cooling by 30%.

2.4.2 Lighting System Design

Lighting is one of the major electric consumers of a building. Generally, lighting consumes between 20- 50 % of the total electricity consumption. Effective use of lighting can offer a major reduction in energy consumption. This can be achieved by using efficient lamps, lighting control systems and by utilizing daylight.

The combination of artificial light and daylighting is one of the significant techniques to help reduce energy consumption, considering that buildings nowadays are heavily dependent on artificial lighting. Good lighting design is essential to provide a suitable level of lighting to perform tasks with comfort and to reduce energy consumption at the same time. Different factors need to be considered during the design of the artificial lighting such as the type of lighting, the use of space in the building, and the window area taking into consideration the orientation and glazing type. To improve the performance of the lighting system in space a suitable energy efficient lamp and control system needs to be used.

Various studies have been conducted to investigate the relationship between lighting control systems and energy savings in buildings. Li, et al., (2006) conducted a study on an air-conditioned office building. One of the elements that the researchers analyzed was the lighting energy consumption. The results showed that the electrical lighting energy saving up to 30% when high-frequency dimming controls system is used.

Williams, et al., (2012) conducted a study on an office, open office, and a classroom. They found that the energy savings of lighting vary from 6% to 70% depending on the type of space and control systems used. They also explained that daylight in a building is influenced by many factors such as the orientation of the building, weather conditions, location, and reflectance. The challenge here is to utilize daylighting and at the same time avoid gaining heat gain in hot seasons, especially in harsh climates.

2.4.2 HVAC System Design

To maintain the indoor environment quality of the building a heating air conditioning (HVAC) system is required. The main purpose of this system is to maintain the dry-bulb air temperature, air quality, and humidity. Different types of HVAC system are available, such as a constant air volume (CAV) system, Variable air volume (VAV) system, fan coils system and single zone system. The HVAC systems can also be classified into central, packaged and split systems.

As mentioned earlier, the building system that consumes the highest value of energy is the HVAC system, especially in harsh climates such as Saudi Arabia. This calls for more attention with regards to the design and selection of the HVAC system for buildings to conserve more energy without affecting indoor environment quality. Types of HVAC include:

4.3.1 Split-System

A split system consists of two elements; the outdoor condensing unit and the indoor air handling unit. The Indoor air handling unit contains a cooling coil, a supply air fan, and an expansion device. The condensing unit contains a condenser coil and a compressor. Split-systems are usually used in small commercial and residential buildings.

4.3.2 Packaged-System

This system is a combination of all the components (outdoor condensing unit and indoor air handling unit) in a single unit. The packaged system is placed outside the building and the air is distributed through ducts to all zones by an air distribution system.

4.3.3 Heat Pump

Heat pumps are similar to cooling only systems with one exception: a special valve in the refrigeration piping, which allows the refrigeration cycle to be operated in reverse. A cooling only system cools the indoor air and rejects heat to the outdoors. A heat pump can also cool the indoor air, but when the valve is reversed, the indoor air is heated. A supplementary electric resistance heater may also be used to assist the heat pump at lower outdoor temperatures. In colder climates, heat pumps require a defrost period. During defrost times the electric heater is the only means of heating the interior of the building. These units are manufactured as either split or packaged systems.

4.3.4 Chilled Water System

In a chilled water system, liquid water is pumped throughout the building to “chilled water coils”. A “cooling plant” is required for cooling the water. This plant is also known as a chiller plant.

4.3.5 Window Air Conditioners

This system usually serves small areas. The window conditioner is used for either cooling or heating. For air ventilation, this system could provide fresh air from dampers in the unit. This system can be installed in special openings in the wall.

4.3.6 Packaged Terminal Heat Pump

Packaged terminal heat pumps (PTHP) are similar to a window-mounted air conditioner. These units are typically installed in a sleeve passing through the outdoor wall of an apartment, hotel, school classroom, etc. PTHPs are completely self-contained and require only an electrical connection in addition to the opening in the building shell. They also can provide air for ventilation. Flexibility and lower installation costs are the primary advantages of the PTHP. Disadvantages include in-room maintenance, higher operating cost, relatively short life, imprecise "on-off" temperature control, and they can be rather noisy.

2.4.3 Other Opportunities

Building Shape and Orientation

Building shape is an important factor that needs to be considered in the design stage to reduce the energy required to maintain the indoor environment. Reducing the exterior surface area will not only reduce the exposure to solar radiation but additionally, reduces conduction heat transfer across building surfaces. Furthermore, proper building orientation can significantly influence the amount of solar radiation falling on an exterior surface.

Different studies were conducted to explore the effect of shape on energy performance for residential and office buildings in various climatic zones. Sergey, (2014) aimed to investigate the energy performance of buildings in relation to their architectural design in Sweden. They concluded that the shape can have a direct effect on the energy performance of the buildings. AlAnzi, et al., (2008) investigated the effect of the shape of an office building on energy conservation in Kuwait. The study was conducted using different shapes (U shape, T shape, L shape and rectangle shape). They also considered the building aspect ratio, glazing type, window wall ratio and relative compactness. The results revealed that energy consumption decreases as relative compactness increases for all buildings shapes.

Furthermore, the effect of shape on energy consumption can be more pronounced when combined with the orientation. Aksoy, et al., (2005) explored the effect of shape and orientation of the building on the heating energy. A city in Turkey was considered to conduct the investigation. , using a computer software with an hourly calculation. The results showed that buildings with square shape have the highest impact on energy conservation. Additionally, it was found that the shape factor (the ratio of the length of the building to the depth) of the building has a direct impact on energy savings, taking into consideration the effect of the orientation.

Building orientation is one of the parameters that is considered in a passive solar design strategy for buildings. According to Morrissey, et al., (2011) orientation is the most significant factor that affects the energy performance of buildings. The amount of solar radiation received on the facade of the building depends on the orientation angle of the building. The orientation of the building facade can affect other envelope design parameters, such as the shading elements. Different advantages can be derived from the optimal orientation of the building such as, a reduction in the energy consumption, reduction in the use of complex passive systems, increasing the efficiency of other envelope design strategies, improving daylight utilization and thus reducing the energy consumption for the artificial lighting.

According to several studies conducted in this area, the southern orientation generally is optimal in the summer for controlling solar radiation and in the winter for gaining heat.

Aksoy, et al., (2005) assessed the relationship between the orientation of the building and heating demand by studying three different buildings; with and without insulation and having various shape factors (1/1, 1/2, 2/1). Each model was simulated with 8 different angles from 0^o to 80^o (in 10^o intervals). By combining the effect of orientation, shape, and insulation, energy savings of up to 36% were achieved. The best orientation for the building with a rectangular shape is orienting the longer side towards the south. Energy saving in buildings with different shapes and without insulation reached between 1-8 % depending on the orientation.

Joseph, (2003) investigated the effect of the orientation on the façade's surfaces relative to the intensity of the indirect and direct solar radiation. He concluded that the lowest solar intensity is in the north which diverges from 43.6 W/m^2 in October to 65.5 W/ m^2 in July. The intensity of the solar radiation on the west and east façade is similar with the mean solar intensity over a 6-month period being 86.1 W/ m^2 for the east and 89.6 W/ m^2 for the west surfaces. Meanwhile, the mean intensity for the south surface over the 6-month period is 74.5 W/ m^2.

CHAPTER 3

IEQ Status in Existing Schools

3.1 Introduction

IEQ in schools has an important impact on students' productivity, health, attendance and academic achievement. Thermal comfort, indoor air quality, and lighting are significant parameters that create a suitable indoor environment for students to enhance their learning abilities

The main aim of this assessment is to investigate indoor environment quality in terms of temperature, relative humidity, illumination level, CO_2 concentration and air velocity for the schools. Furthermore, this will help in defining ranges of different design parameters for the building.

In this study, an audit form was developed to assess the indoor environment quality in the selected schools. The audit form was used to collect information and measured data in the classrooms of the selected schools. The air temperature, relative humidity, air velocity, illumination levels and CO_2 concentrations were measured.

3.2 Collecting Information

Data was collected from selected schools which are a representation of typical schools built in the eastern province of Saudi Arabia. The data was collected through reviewing drawings, sites visits, interviews and by carrying out measurements. For each school, data was collected in two categories. The first category of data was related to the building components and physical elements, which were collected by a walkthrough of the sites and reviewing building drawings. The second category is represented in an objective assessment of IEQ by measuring the air temperature, air velocity, relative humidity, illumination level and CO_2 concentration in selected classrooms each building.

3.3 General Schools Characteristics

According to the ministry of education different layouts of schools exist which include L shape, I shape and rectangular shape with a court. The rectangular shape is the most common design and approved by the ministry of education for future schools, accordingly schools with a rectangular shape were selected. After conducting meetings, reviewing drawings and making site visits, eight schools were selected in different locations in Dammam, Dhahran and Al-Khobar to cover different areas. The school buildings are two and three stories high, built between 2005 and 2008. The average number of students that a single school can accommodate is between 233 and 510. The buildings usually take a rectangular shape with classrooms, laboratories, and teachers' offices distributed around a central courtyard. All spaces are therefore in contact with an external envelope and the courtyard, as shown in Figure 3.1. The only difference found between the schools was usually in the distribution of the spaces, stairs, and entrances.

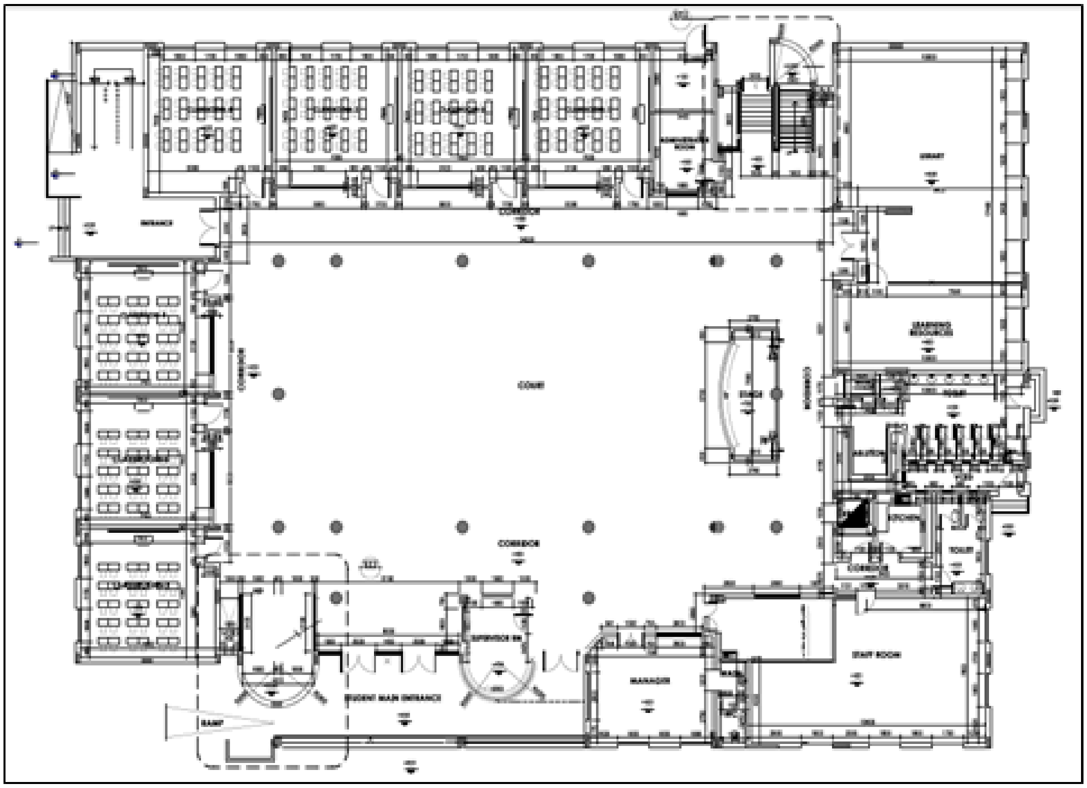


Figure 3. 1 Ground Floor of the Governmental School

Table 3. 1 Schools Areas, Conditioned, and Non-conditioned Areas

Schools	Number of floors	Total Area m^2	Air-conditioned area m^2	Non-conditioned area m^2
(A)	2	3090	1994	1096
(B)	4	3880	2416	1464
(C)	2	3280	1537	1743
(D)	4	3880	2416	1464
(E)	3	4758	2265	2493
(F)	3	4380	1794	2586
(G)	3	4758	2265	2493
(H)	2	3048	1594	1454

Table 3.1 shows the schools areas', divided into conditioned and non-conditioned areas. Schools (F), (G) and (E), consist of three floors with almost the same layout and

dimensions. Schools (A), (H) and (C), have the same layout and dimensions and consist of two floors, and schools (D) and (B) have the same layout comprising four floors.

3.3.1 Envelope Components

According to the drawings by the Building Department of the Ministry of Education and schools ', the selected schools have the same specifications. The drawings also revealed that the school's structures were made of reinforced concrete.

- **Wall Components**

The walls of the schools consist of concrete blocks sandwiched between an outside and an inside layer of plaster. The total thickness of the wall is 300 mm with a U-value of 1.403W/m^2-K.

- **Roof System**

The roof of the schools consists of reinforced concrete, a waterproof membrane, concrete screed, sand screed and a finishing material. The overall U-value of the roof was 1.626 W/m^2-K.

- **Floor**

The flooring system of the schools consists of Mosaic tiles, screed, sand screed and reinforced concrete slab. The overall U-value is calculated to be 0.446 W/m^2-K.

- **Window System**

The windows of the schools are sliding panel type. They consist of double glazing with 6mm glass layers with a 13 mm air cavity in the center. The total thickness adds up to 25 mm with an overall U-value of 1.757 W/m^2-K.

3.3.2 Cooling System

In the selected school, the air conditioning system used is "window unit 2 tons capacity". The units were distributed with two in each classroom, laboratory and shared teachers offices and one unit in each administration room. The units are designed to be positioned in the external wall with a separate thermostat for each unit which is used only for the purpose of cooling. The courtyard, corridors, entrances, lobbies, water closet and staircases are unconditioned and represent 55% of the school area. The units are usually operated between 6:00 am and 1:00 pm to maintain the temperature of the indoor environment.

3.3.3 Lighting System

Based on the collected data, the total wattage and the lighting power density for each zone of the schools are included in this section. From the selected eight schools four schools were selected to gather data about the schools' equipment and lighting due to the reliability and completeness of the electricity bill data from these schools. The lighting in the school can be divided into the ceiling fluorescent lamps and the exterior lighting. The wattage of each type appears in Table 3.2.

Table 3. 2 Schools Lighting Data for Four Schools

	Space type	Lighting Power Density (W/m^2)	Type of lighting	Total lighting load
School (B)	Classrooms	18.6	Florescent lamp (40 W)	37,280 W
	Labs	16.7	Fluorescent lamp (40 W)	
	Offices	16.1	Fluorescent lamp (40 W)	
	Corridors, courtyards, and toilets	5.3	Fluorescent lamp (40 W)	
School (C)	Classrooms	13.9	Florescent lamp (40 W)	23,560
	Labs	10.6	Florescent lamp (40 W)	
	Offices	13.2	Fluorescent lamp (40 W)	
	Corridors, courtyards, and toilets	4.6	Fluorescent lamp (40 W)	
School (G)	Classrooms	13.9	Florescent lamp (40 W)	29,360
	Labs	13.9	Fluorescent lamp (40 W)	
	Offices	13.2	Fluorescent lamp (40 W)	
	Corridors, courtyards, and toilets	4.5	Fluorescent lamp (40 W)	
School (H)	Classrooms	13.9	Florescent lamp (40 W)	17,320
	Labs	10.7	Fluorescent lamp (40 W)	
	Offices	11.3	Fluorescent lamp (40 W)	
	Corridors, courtyards, and toilets	4.7	Fluorescent lamp (40 W)	

3.3.4 The Equipment Summary

In this part, a description of the equipment used in the schools based on the power requirements is listed. Table 3.4 shows a summary of the equipment used in the schools and their respective electrical load represented by school (B) as an example.

Table 3.3 shows the rated electrical load for the equipment, where the recommended load is usually lower than the recommended power. This will reflect on the accuracy of the electrical load calculation. In this case the difference between the recommended and the rated load was ignored, since the total energy consumption for the equipment does not exceed 10 % of total annual energy consumption.

Table 3. 3 Summary of Equipment Electrical Load

Equipment	Equipment Load (W)
Projector	100
Coffee and Tea Water Boiler	1200
Computer	200
TV	100
Water Boiler	1400
Big printer	1100
Small printer	300
Fan	100
Exhaust fan	100

Table 3. 4 Maximum Rated Load of the Energy Consumption for School (B).

School (B) Al shawkani		lighting			Equipment's		AC		
Space type	#	wattage	Area(m^2)	W/m^2	Wattage	W/m^2	wattage	W/m^2	Total
Classrooms	8	27*40 =1080	49	22	2*100=200	4	2*5000= 10000	204	90240
Classrooms	8	16*40 =640	42	15.2	2*100+1*100 1*200=500	11.9	2*5000= 10000	238	89120
offices	1	12*40= 480	45.5	10.5	200*2+1*200 +1*1100+1*5 00+2*100 =2400	52.7	2*5000= 10000	219	12880
offices	3	6*40=2 40	17	14.1	1*100+200 =300	17.6	1*5000= 5000	294	16620
Shared office	2	27*40 =1080	45	24	200*2+2*100 +2*500+1000 =2600	58	2*5000= 10000	222	27360
Shared office	3	18*40= 720	45	16	3*1000+2*10 0=3200	71	2*5000= 10000	222	41760
Shared office	1	18*40= 720	42	16	2*100+1*200 =400	9.5	2*5000= 10000	238	11120
Shared office	1	18*40= 720	49	16	200*1+2*100 +2*300+50=1 050	21.4	2*5000= 10000	204	11770
Laboratories	2	27*40 =1080	45	24	2*100=200	4.4	2*5000= 10000	222	22560
Laboratories	2	18*40= 720	70	10.3	1*200+1*200 =400	5.7	4*5000= 20000	285	42240
Laboratories	1	18*40= 720	48	15	100*2+1*200 +1*500=800	16.7	2*5000= 10000	208	11520
Laboratories	2	27*40 =1080	45	24	2*100=200	4.4	2*5000= 10000	222	22560
Laboratories	1	27*40 =1080	45	24	100*2+1*200 +1*200=600	13.3	2*5000= 10000	222	11680
Holy Quran	1	18*40= 720	73.5	9.7	1*100+1*200 =300	4	4*5000= 20000	272	21020
Computer lab	1	18*40= 720	73.5	9.7	21*200+1*50 0+2*100=490 0	66.8	4*5000= 20000	272	25620
Toilets	4	8*40=3 20	45	7.1	3*150+1*140 0=1850	41			8680
` Toilets	1	6*40=2 40	13.8	17.4	1200	87			1440
Corridors and courtyard		106*40 +4*400 +4*50= 6040	1207	5					6040
Maximum Demand (W)									383990

3.4 IEQ ASSESMENT

Conducting IEQ assessment is an important step for different reasons, firstly to be familiar with the IEQ of existing schools, and to assess the IEQ by assessing thermal comfort, visual comfort, and air quality. Secondly to assess the potential for improving IEQ and energy consumption. Measuring the thermal comfort by measuring the temperature and the relative humidity inside the classrooms will be an important indicator as to whether the classroom indoor environment is acceptable or not. In addition, measuring the illumination level helps in determining if the visual comfort is intended or not and provides a opportunity for reducing the energy for lighting. Measuring CO_2 is a good indicator regarding IAQ to identify if the indoor environment is suitable for teaching or not and what actions can be taken regarding HVAC system selection.

The measurement of indoor environment quality parameters in classrooms were conducted during regular classroom sessions. The measurements were conducted in four classrooms in each of selected schools, at the beginning of February, the end of April and the beginning of May representing summer day and winter day for each school to record data under different weather conditions. The measurements were carried out in each classroom at three different time intervals (8:30 – 10:00 – 11.30) (am) approximately representing the start of occupancy, the middle of occupancy and towards the end of occupancy. The availability of the equipment and the time limitation were the main constraints for conducting the measurements over several days. The selected classrooms in each school represent the following conditions:

- Two classrooms are selected from the last floor in the east and south direction, one of them being a corner classroom.
- The other classrooms are selected from the ground and first floors, one of them being a corner classroom.

Classrooms on the top floor had higher heat gain from the sun as compared to the classrooms on other floors. Also, the orientation of the classrooms was taken into consideration. For example, classrooms in the southeast direction had the highest surface area exposure to the sun. The location was also an important factor to consider e.g., the corner classrooms having two walls exposed as compared to a central classroom with just a single wall exposed. Therefore at least one classroom was selected with exposure to the external environment from two directions (corner wall).

3.4.1 Audit Plan

An audit plan was developed to collect data such as temperature, relative humidity, air velocity, illumination level and CO_2 concentration using three type of instruments. These instruments are VILOCI CALC PLUS, GOSSEN, and GD444 as shown in Figure 3.2.

(A) (B) (C)

Figure 3. 2 Measurements Instruments: (A) GOSSEN for illumination level (B) VILOCI CALC PLUS for temperature, relative humidity and air velocity. (C) GD444 for CO2 concentration.

The developed audit form as shown in Appendix A was used to collect data related to construction and energy consumption. Figure 3.3 shows the location of the measurement in the classrooms where the measurements of different environmental parameters were carried out. The locations for measuring indoor parameters except CO_2 were selected at five points one meter from each corner and one in the middle of the classroom, to have a reasonably accurate assessment of the average condition in the classroom. The CO_2 level was measured at one point in the middle of the classroom as no variation was expected within the space.

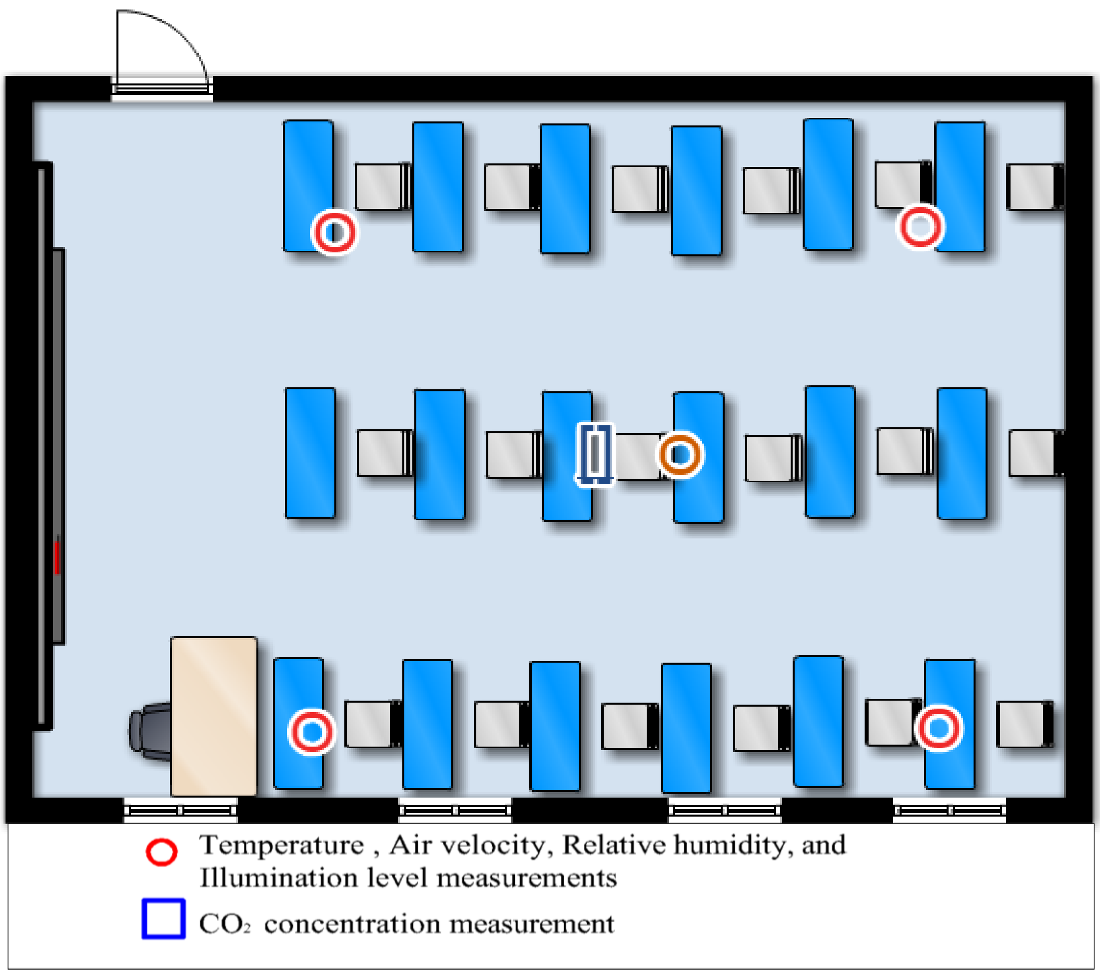


Figure 3. 3 (Location) of the Measurements in the Classroom

Measurements of the five indoor parameters of the indoor environment quality (temperature, relative humidity, illumination levels, CO_2, and air velocity) are as shown as follows:

- **Temperature**

The temperature was measured in five locations at three different times (8.45-11-12.30 (am)). The average indoor temperature during the teaching hours for each classroom shown in Table 3.1. The temperature in the classrooms varied between18 and 25.8^{o}C during winter. For example, in schools (A) and (H) the temperature in the fourth classroom ranged between 23-25.8^{o}C, which is high when compared to other schools as shown in Table 3.1, but in schools (B) and (C), the temperature ranged between 18 to 21^{o}C. In the remaining schools the temperature was between 22^{o}C and 23.9^{o}C, which is almost acceptable. During measurements in the summer, the temperature range increased to vary between 24 and 26^{o}C despite the air conditioning system being in operation. This range is almost within the acceptable comfort zone as shown in Figure3.5.

Table 3. 5 Measured Temperature in the Selected Schools

Time		Temperature (^{o}C) in schools								Average
		A	B	C	D	E	F	G	H	
Winter	8:30	23.4	19.6	19.5	22.4	23.7	23.2	22.6	23.3	
	10:30	25.4	18.3	19.3	22.9	22.5	23.4	23.1	24.4	
	12:00	25.8	21	19.8	22.77	23.4	23.2	22.9	24.6	
	Daily Average	24.9	19.6	19.5	22.7	23.2	23.3	22.9	24.1	22.5
Summer	8:30	25.7	24.6	25.9	-	25.8	-	25.8	25.9	Average
	10:30	26	24.1	25.6	-	24.7	-	25.1	25.8	
	12:00	26.1	24.6	25.4	-	24.7	-	24.6	25.7	
	Daily Average	25.9	24.4	25.6	-	25.1	-	25.2	25.8	25.3

As shown in Figure 3.4 and 3.5, the temperature difference between the classrooms in winter and summer is evident. This can be a result of the time for carrying out the measurements and the classroom location. The temperature at the beginning of the study day (8:30 am) is always the lowest because the temperature outside is still low compared to midday (12:00 am). For the corner classrooms, the temperature shows a higher reading compared to the classrooms with a single external wall as a result of heat gain from the two exposed walls.

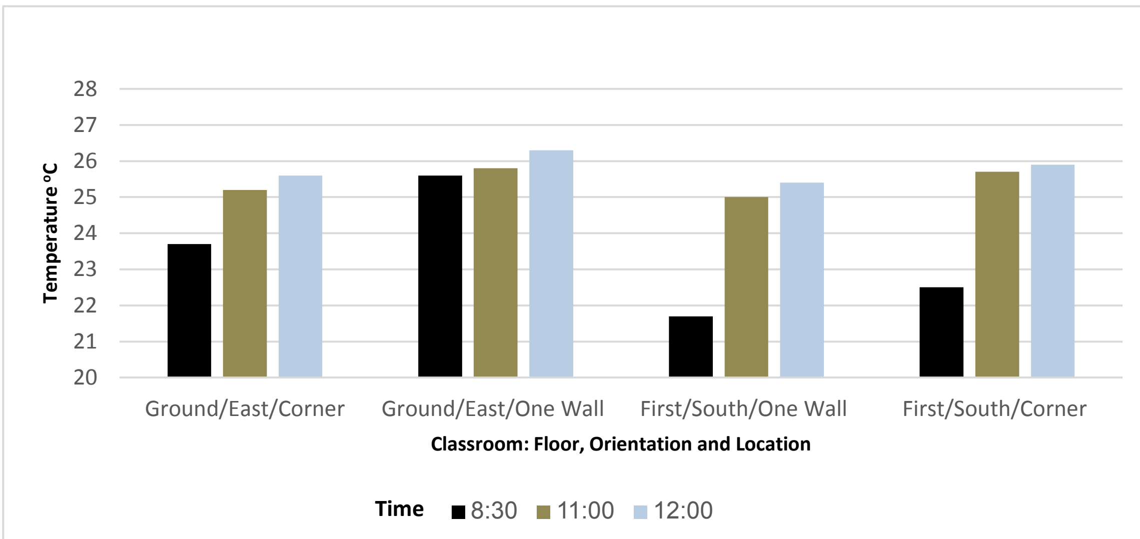


Figure 3. 4 Temperature in Winter at Different Classrooms

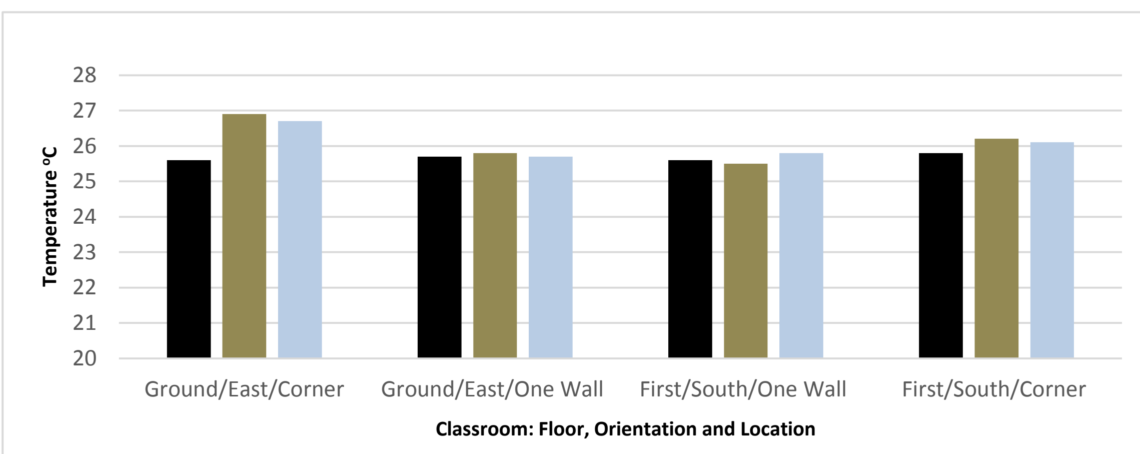


Figure 3. 5 Temperature in Summer for Different Classrooms

- **Relative Humidity**

Table 3.6 shows the relative humidity for the selected schools. It ranged between 34% and 67%, the lowest measurements were recorded in school (C) which ranged between 34% and 36.8. The measured relative humidity in the classrooms was almost within the acceptable ranges, except for one classroom in the Abdulrahman school which exceeded the acceptable level of relative humidity, reaching up to 67%. In summer, when the air conditioning system is in operation and the windows are closed, the relative humidity remains around 40%, which is considered within acceptable ranges as shown in Figure 3.6.

Table 3. 6 Measured Relative Humidity in the Selected Schools

Time		Relative Humidity (RH) in schools								
		A	B	C	D	E	F	G	H	
Winter	8:30	53.1	49.1	38	48.8	59	55.7	46	52	Average
	10:30	45	42.8	40.3	49.5	56.8	53.2	47.75	54	
	12:00	47.7	37	40.3	49.3	61.7	50.8	47.5	49	
	Daily Average	48.6	43.0	39.5	49.2	59.2	53.2	47.1	51.7	48.9
Summer	8:30	39.75	39	37.5	-	40	-	40.3	36.3	Average
	10:30	39.75	38.7	41.6	-	38.8	-	39	36	
	12:00	39.7	40	35.9	-	39	-	39.5	39.5	
	Daily Average	39.7	39.2	38.3	-	39.3	-	39.6	37.3	38.9

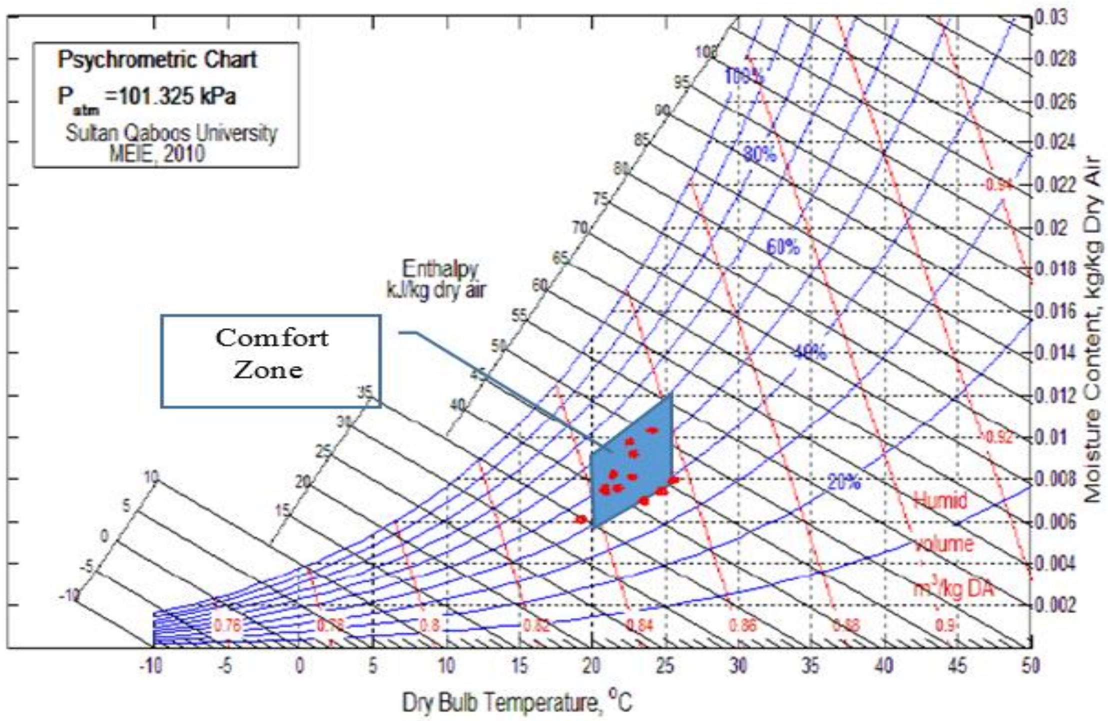


Figure 3. 6 Assessed Schools in Comfort Zone in Psychrometric chart

- **Lighting**

The illumınatıon level was measured in five locations at three different times (8.45-11-12:00 (am)) in the selected classrooms in each school at the study desk level. The recorded illumination level in the schools ranged from an average of 533 Lux at 8:30 am and 5012 Lux at 12:00 on the reading level as shown in Table 3.7. The highest reading was recorded in school (A) with an average of 3365 Lux, where the classrooms were directed to the south and east direction without any shading elements. In school (B) the measurement was conducted for classrooms in the west with an average of 533 Lux. Meanwhile, the illumination levels in the other schools were directly affected by the type of the curtains used in classrooms that shade the window glass. The illumination level in all schools was higher than 500 lux, which falls between the recommended levels of 300 Lux and 500 Lux.

In some classrooms, the illumination level caused glare on the reading level, especially, near the window. Table 3.7 shows the average illumination level in classrooms of the different schools for three periods in the summer and winter. As seen from Table 3.7 the illumination level in classrooms in the summer is less than in winter. This is as a result of two factors:

- The altitude of the sun in winter is lower as compared to summer.
- The use of the curtains in summer.

Table 3. 7 Measured Illumination level in the Selected Schools

Time		Illumination level (Lux) in schools							
		A	B	C	D	E	F	G	H
Winter	8:30	3367	533	597	1241	1318	722	965	495
	10:30	6759	553	760	1312	1100	667	1335	587
	12:00	5012	573	725	866	1188	602	777	735
	Daily Average	5046.0	553.0	694.0	1139.7	1202.0	663.7	1025.7	605.7
Summer	8:30	864	686	873	-	1107	-	918	715
	10:30	845	629	817	-	950	-	794	613
	12:00	781	633	705	-	598	-	847	711
	Daily Average	830.0	649.3	798.3	-	885.0	-	853.0	679.7

- **CO_2 Concentration**

The concentration of CO_2 was measured three times in each school in four classrooms. The concentration ranged between 650 PPM and 2650 PPM. It was noticed that the concentration of CO_2 decreased when the windows were opened as shown in the winter time. The concentration of CO_2 in the A, D, E and F schools was recorded to be more than 1000 PPM. These values exceed the recommended values as mentioned in the ASHRAE Standard 62, which recommends 500 PPM for lecture halls and classrooms. A summary of the average CO_2 concentration in the selected schools during teaching hours is shown in Table 3.8.

Table 3. 8 Measured CO_2 (Concentration) in the Selected Schools

Time		CO_2 concentration (PPM) in schools							
		A	B	C	D	E	F	G	H
Winter	8:30	1002.5	1150	666	1100	1492	805	1330	517
	10:30	905	704	603	1183	1500	650	1563	628
	12:00	1425	888	675	1046	1567	800	1112	515
	Daily Average	1110.8	914.0	648.0	1109.7	1519.7	751.7	1335.0	553.3
Summer	8:30	2572	925	1525	-	2133	-	1913	1650
	10:30	2700	1113	1863	-	1666	-	1950	1767
	12:00	2330	1088	2088	-	2075	-	2200	1700
	Daily Average	2534.0	1042.0	1825.3	-	1958.0	-	2021.0	1705.7

- **Air Velocity**

Air velocity was measured at five different locations in three different time slots (8.45-11-12.00 (am)) in the selected classrooms in each school. The reading of air movement in the selected schools ranged between 0.02 m/s and 0.1m/s. These values were measured in the schools during the teaching hours. The acceptable range of air movement is between 0.15-0.25 m/s. Four schools had no ceiling fans and no mechanical ventilation techniques were adopted in the classrooms.

In conclusion, as observed through measurements, the indoor environmental quality in terms of CO_2 concentration and illumination levels in the classrooms in government schools do not lie in the comfort zone. In terms of the relative humidity and temperature, schools like (A) and (I) were found to outrange the comfort zone; this can directly impact the learning performance and productivity of students.

CHAPTER 4

Base Case Formulation (School Modeling)

4.1 Introduction

To enhance the indoor environmental quality and improve energy performance, reducing the demand for air conditioning system is a must. Reduction in energy consumption can also be achieved by applying design strategies such as, designing an energy efficient envelope and choosing and designing the HVAC system efficiently. To achieve these goals at a reduced cost, Usage of Building Simulation software is essential. To obtain better results, an evaluation of the building needs to be conducted. This can be achieved by a comparison with a reference building. A model of a government school was developed to conduct a simulation and analyze the energy performance of the current schools. Then optimization was conducted on the envelope parameters to improve the energy consumption.

To improve the simulation results and to have more accurate findings, a validation was conducted on the results of energy consumption for the model with the actual energy consumption of the schools.

4.2 Base Case Modeling

In this section, a description of the base case model development by using Design-Builder software will be introduced. This software provides advanced modeling tools in an easy-to-use interface. This enables to use the software to develop comfortable and energy-efficient building designs from concept through to completion. Design-Builder Simulation provides a powerful and accurate environmental performance analysis capability based on the widely respected EnergyPlus simulation program. The software allows for the calculation of heating and cooling system sizes, thermal comfort, energy consumption and CO_2 emissions for both naturally ventilated and air-conditioned buildings. The work using design-builder starts with selecting the location, then using the tools to create the geometry of a building, and then using the parameters to define the internal loads, windows, doors, material selection, construction types, lighting, and HVAC systems. Design-Builder provides parameters to build up the model as a first step using the DXF file of the floors plans to develop the model. Then the zones of the building were created, where the zones were divided into classrooms, offices, labs, toilets, corridors and courtyard.

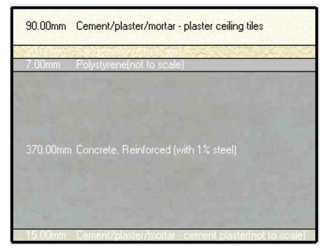
The detailed school plan that was used to develop the base case was a design approved by the Ministry of Education in AL Dammam. This design almost has the same shape as the selected school, but the difference between the schools is the stairs' shape, location and the distribution of the spaces around the courtyard. All the information and specification was obtained from the Building Department of the Ministry of Education in AL Dammam and used to model the base case.

- **Building Envelope Details**

Table 4.1 shows descriptions of the building envelope for the schools in Saudi Arabia which are usually built as a concrete structural building. The external walls are built from concrete block and the slabs of reinforced concrete.

Air infiltration is an important factor, as mentioned before, with regards to energy consumption. As such, in the Design-Builder software, air infiltration can be defined by the air change per hour for each zone. The value of air infiltration in the zone depends on different factors such as the number of openings and the usage of the zone. Different floors can have different values of air infiltration. According to the ASHRAE HANDBOOK 2009 Fundamental, the value of air infiltration is assumed to be between 0.5 and 2 ACH for commercial and residential buildings. While in ASHRAE HANDBOOK 1981 Fundamental the spaces were divided into groups depending on the openings number in the spaces, which includes space with no openings (windows or exterior doors) with 0.5 ACH air tightness, spaces with an opening on one wall with 1 ACH air tightness, space with openings on two sides with an 1.5 ACH air tightness, and spaces with an opening on three side with a 2 ACH air tightness. Since the windows and the doors in schools spaces were on two sides the appropriate value for the ACH is 1.5.

Table 4. 1 Composite of the Construction Elements

Envelope Elements	Composite of the Elements	Thickness (M)	U-value (W/m²-K)	illustration
Wall	Plaster	0.019	1.403	
	Medium Concrete Block	0.25		
	Plaster	0.019		
Roof	Plaster	0.019	1.626	
	Reinforced Concert	0.37		
	Waterproof membrane	0.007		
	sand	0.04		
	Cement Screed	0.1		
Internal Floors	Terrazzo tile	0.025	0.446	
	Mortar	0.02		
	Sand	0.1		
	Reinforced concrete	0.32		
Ground Floor	Terrazzo Tile	0.03	0.816	
	Mortar	0.02		
	Sand	0.07		
	Reinforced concrete	0.15		
	Gravel and Soil	0.4		

- **Cooling System Details**

An HVAC system can be defined in Design-Builder with various options, and the complexity of the system is the main factor that affects the selection of the system. Design-Builder also provides the opportunity to design the HVAC system for each zone in the building separately or to design the system for all the zones based on the standards.

For the base case model, according to the collected information, a simple HVAC definition was selected with a manual design for the system. In this case, the design capacity (KW) for each zone was defined based on the collected information.

Different parameters need to be defined in Design-Builder with regards to the HVAC system. Firstly, the HVAC system – "Window Unit", which is used only for cooling, the COP (1.83), and the operation schedule for the system as shown in Figure 4.1. The school consists of three floors - ground, first and second. The zones of the school are defined as classrooms, laboratory, offices, toilets and circulation areas. Each zone schedule was defined individually for the operation and occupancy.

The occupational density in the school was defined based on the zone. For instance, the classrooms' zone density was defined with 0.5 people/m^2, offices defined with 0.1 people/m^2, laboratory-defined with 0.2 people/m^2 and circulation areas and corridors defined with 0.1 people/m^2.

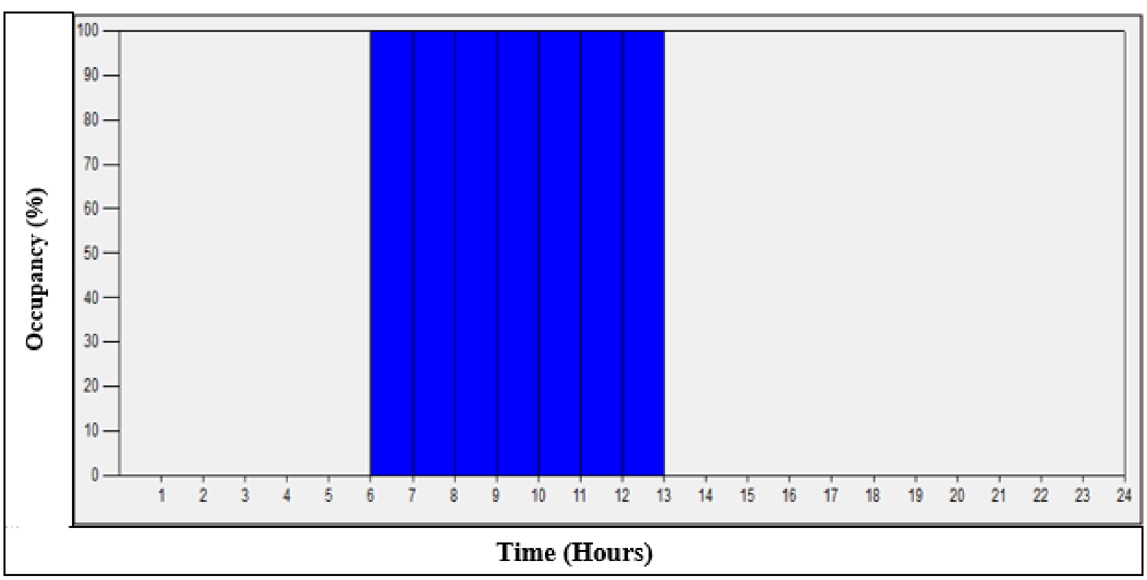


Figure 4. 1 HVAC Operation Schedule

Lighting System Details

In Design-Builder, the lighting input information is divided into general lighting, exterior lighting, display lighting and lighting control system. In the base case model, no lighting control systems were used and the display lighting in the schools had the least importance. consequently, these elements were neglected in the model.

From the collected information, general lighting data such as lighting power density and lighting type were defined by taking into consideration the schedules of the occupancy that represent the operation time as shown in Figure 4.2. The same applies to the exterior lighting. In Design-Builder, the general lighting requirement was entered by W/m^2 for each zone e.g., the classroom, labs (14 W/m^2) and common area (5 W/m^2).

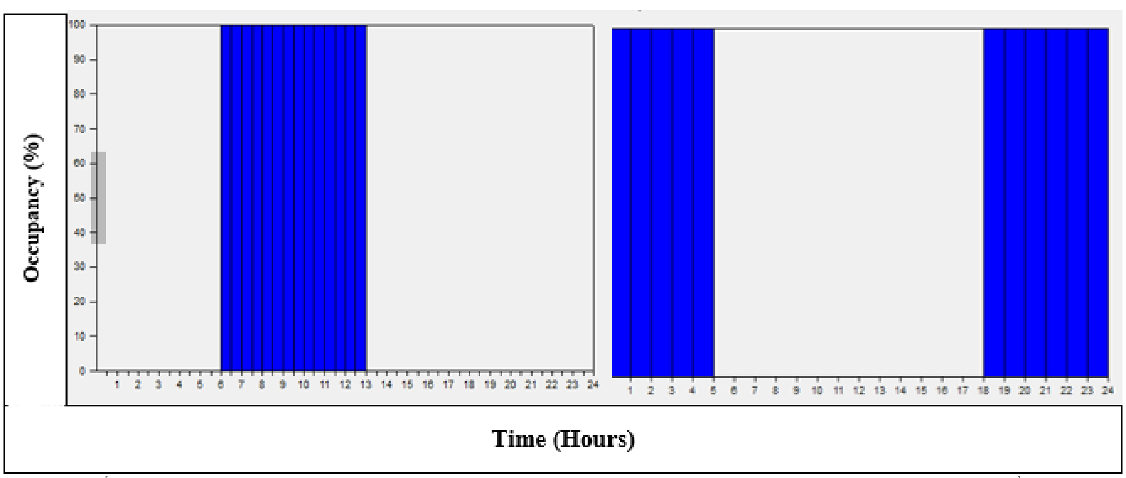


Figure 4. 2 Lighting Operation Schedules for the Internal Lighting and Exterior Lighting

4.3 Schools' Utility Bills

The utility bills of the selected schools were obtained from the Saudi Electrical Company (SEC). These bills were available for three years for each school 2013, 2014 and 2015. These bills were used to analyze and explore the energy consumption pattern in the schools. Table 4.2 shows the annual energy consumption for each school.

Table 4. 2 Schools Annual Energy Consumption

School Name		Location	Year	Annual Energy Consumption
Alqadisia School	(A)	Al Khobar	2013	93,666.4
			2014	147,690.9
			2015	213,974.4
Alshawkani School	(B)	Al Dhahran	2013	197,740.4
			2014	188,936.6
			2015	190,307.4
Alkaramah School	(C)	Al Khobar	2013	266,051
			2014	290,410
			2015	309,421
Alsaudia School	(F)	Al Khobar	2013	341,406.6
			2014	412,851.8
			2015	481,183.4
Saeed School	(G)	Al Dammam	2013	239,171.7
			2014	281,198.5
			2015	300,072.2
Mosab School	(H)	Al Dammam	2013	131,831.3
			2014	156,338.1
			2015	154,116.4

The collected utility bills were dated according to Al Hijri calendar. Therefore, these were converted based on the Gregorian calendar to use them as a valid input, since the current study and the simulation software is based on the Gregorian calendar. The conversion from Al Hijri to Gregorian calendar was carried out by the following steps:

- Distribute the total energy consumption for each period, which could be for a month or more or less on the number of the day of the period to find the average daily consumption.
- Find the monthly average consumption in the Gregorian form. Table 4.3 shows an example for changing the Al Hijri calendar to the Gregorian calendar.

Table 4. 3 Example for Data Conversation of the from Al-Hijri – Gregorian Calendar for the Electric Bills

Average Daily consumption	Georgian Date	Al-Hijri Date
372.4	1/11/2013	1/ Rabi awal/ 1434
372.4	1/12/2013	2
372.4	1/13/2013	3
372.4	1/14/2013	4
372.4	1/15/2013	5
372.4	1/16/2013	6
372.4	1/17/2013	7
372.4	1/18/2013	8
372.4	1/19/2013	9
372.4	1/20/2013	10
372.4	1/21/2013	11
372.4	1/22/2013	12
372.4	1/23/2013	13
372.4	1/24/2013	14
372.4	1/25/2013	15
372.4	1/26/2013	16
372.4	1/27/2013	17
372.4	1/28/2013	18
372.4	1/29/2013	19
372.4	1/30/2013	20
372.4	1/31/2013	21
372.4	2/1/2013	21
372.4	2/2/2013	22
372.4	2/3/2013	23
372.4	2/4/2013	24
669.8	2/5/2013	25
669.8	2/6/2013	26
669.8	2/7/2013	27
669.8	2/8/2013	28
669.8	2/9/2013	29
669.8	2/10/2013	1/rabi althani/ 1433
669.8	2/11/2013	2
669.8	2/12/2013	3
669.8	2/13/2013	4

Some information regarding energy consumption for the selected schools was missing for some of the months in the collected years. In such a case, if the monthly energy demand is available for two years, the average daily consumption of a month is taken and multiplied by the number of working days.

In some cases, the electrical consumption for some schools was summed for more than five months and data for some of these months was missing, but the total yearly consumption was available. As a result, this information was used to analyze the total energy consumption between schools.

For all the selected schools, the required data was comprehensively available for the year 2013, which thereby served as a reference year for the study. On the other hand weather, data file that is utilized by the simulation software was available for the year 2012 for the city of Al-Dhahran.

Figure 4.3 and Table 4.4 show the energy consumption KWh/ m^2 for each month for four schools (schools with reliable and available data), as shown in Figure 4.4. The data can be divided into two groups:

- The first group consists of schools with low energy consumption/ m^2, like schools (G) and (H)
- The second group consists of schools with high energy consumption/ m^2 per month, such as schools (B) and (C).

It is evident that the energy consumption/ m^2 for the schools is convergent for most of the months and the differences arise in September, April and May.

A variety of reasons can be attributed to these differences such as the ratio of the conditioned area to the total area of the school; the student's density/ m^2 in the conditioned area; type of the window; the air infiltration in the conditioned areas and the construction year of the school.

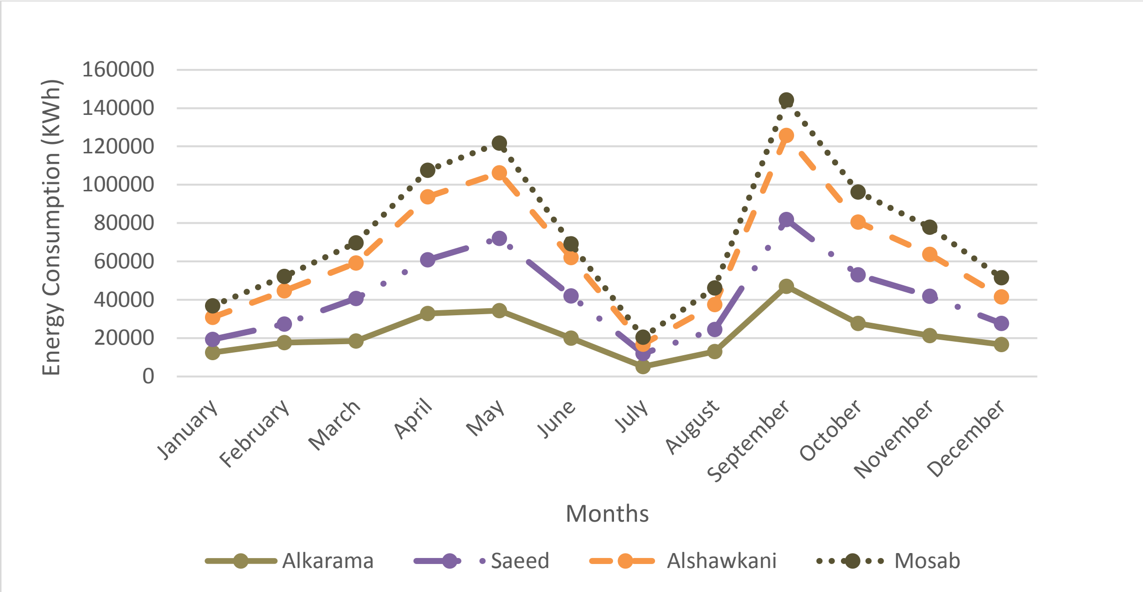


Figure 4. 3 Schools Energy Consumption During 2013

Table 4. 4 Energy Consumption (KWh)/ m^2 for the four Schools During 2013

KWh	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
School (B)	2.96	4.49	4.76	8.47	8.84	5.15	1.24	3.32	11.3	7.10	5.62	3.54	66.79
School (C)	2.60	3.69	3.88	6.90	7.21	4.21	1.05	2.72	9.88	5.82	4.45	3.48	55.89
School (G)	1.43	2.04	4.64	5.86	7.91	4.60	1.44	2.42	7.31	5.30	4.33	2.33	49.61
School (H)	1.97	2.43	3.47	4.59	5.05	2.38	1.22	2.87	6.09	5.17	4.64	3.30	43.18

Figures 4.4, 4.5, 4.6 and 4.7 show the energy consumption for four schools, and the events during the academic year for the schools based on data from the Ministry of Education in Saudi Arabia. As seen, the energy consumption in the months of January, February, and December (winter months) is lower compared to other study months, where the temperature is usually moderate. In June, July and August the energy consumption is lower despite the high outside temperature due to the allotted summer vacation.

We can also notice that the energy consumption, in January for all schools over three years, portrays the lowest value due to the low outside temperature and midterm vacation which is 10 days. For the month of March, the outside temperature is higher than February, but the increase in energy consumption was witnessed with a low ratio in some cases, such as schools (C), (B) and (G) as a result of the midterm vacation, which is 10 days.

May and September have the highest demand for energy due to the high outside temperature. However, it is also noticed that the energy consumption in October 2015 was higher than September due to the shifting of Al-Adha vacation which is around two weeks as shown in Table 4.5.

It is also noticed that in August 2015, the energy consumption for the schools increased for most of the schools by a different ratio due to two reasons, the first being a shift of the end of summer vacation from the 1st of September to the 23rd of August instead, and the second being the occupation of the school by teachers 20 days before the beginning of the study term. In June the energy consumption showed a high ratio despite the commencement of the summer vacation. This is due to the occupation of the school by the teachers 10 days after the examination period. In schools (B) and (H), the energy consumption in 2014 and 2015 in the summer vacation was high compared to other schools due to the summer activities in these schools in the same period.

Table 4. 5 Events and Vacation During the Academic Year

Year	Middle vacation	Midterm vacation	Summer vacation	Al Adha vacation
2013	16/Jan – 26/Jan	20/Mar –30/Mar	5/Jun – 31/Aug	9/Oct – 21/Oct
2014	16/Jan – 26/Jan	20/Mar –30/Mar	5/Jun – 31/ Aug	28/ Sep – 12/Oct
2015	15/Jan – 25/Jan	19/Mar –29/Mar	4/Jun – 23/Aug	17/Sep – 29/Sep

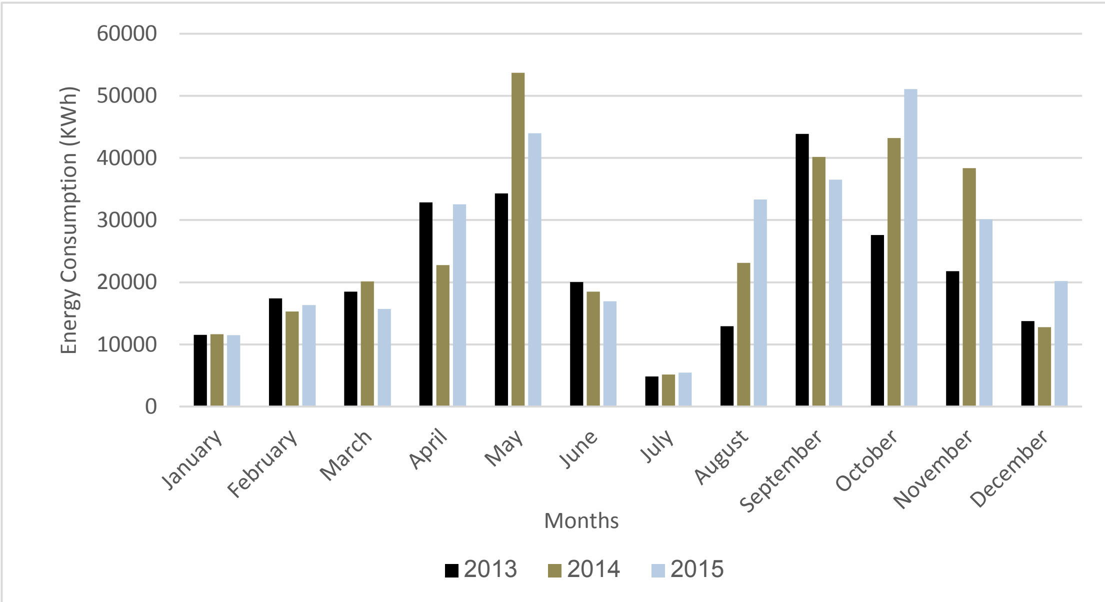


Figure 4. 4 The Energy Consumption for Three Years for school (B)

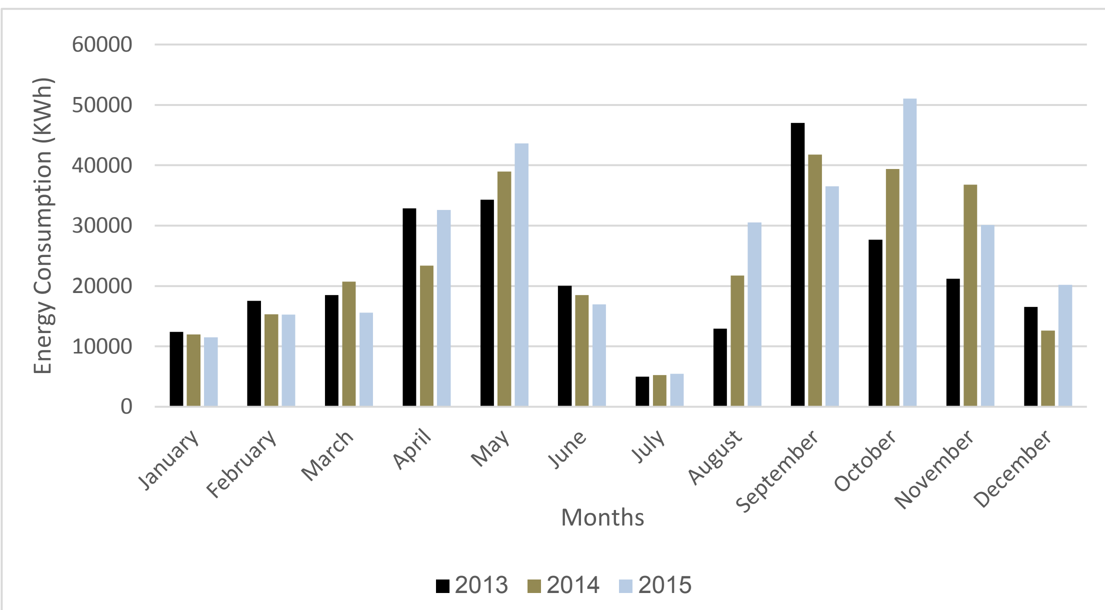


Figure 4. 5 The Energy Consumption for Three Years for school (C)

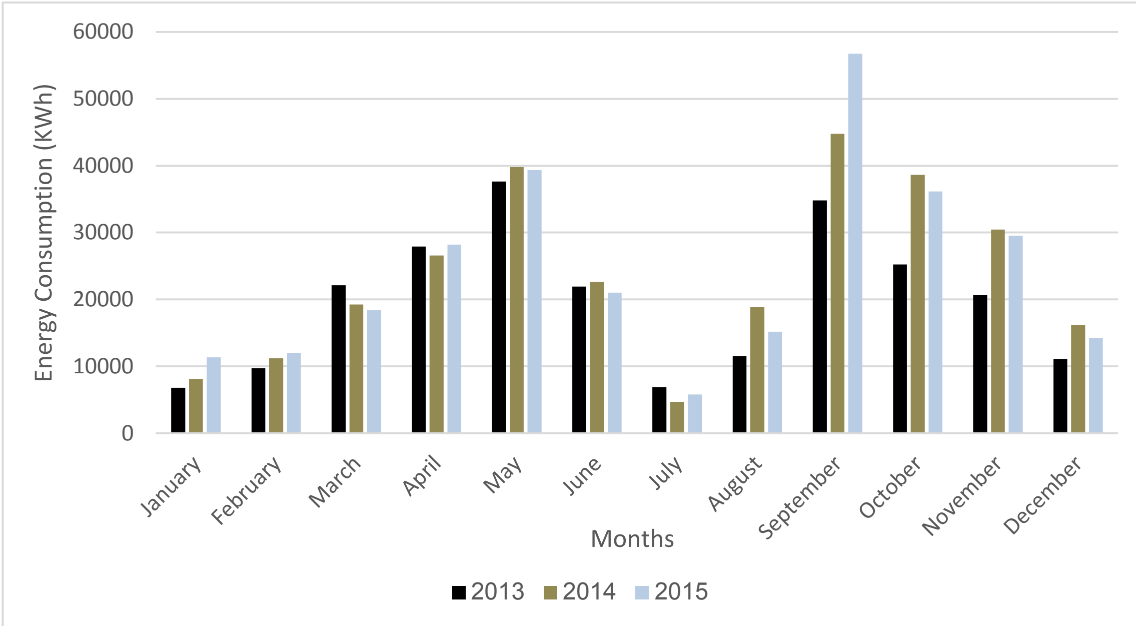


Figure 4. 6 The Energy Consumption for Three Years for school (G)

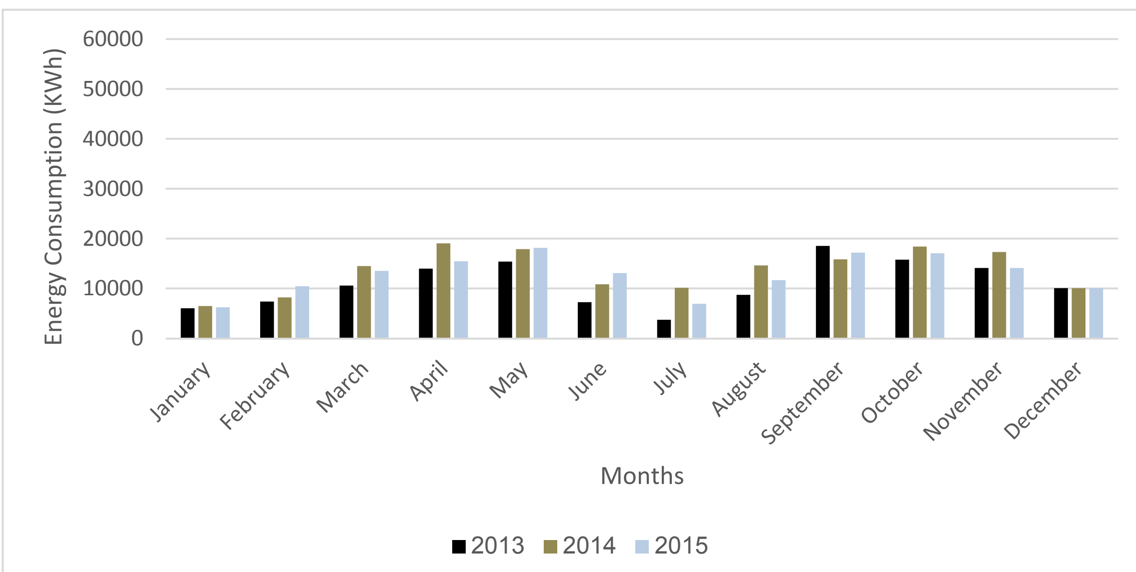


Figure 4. 7 The Energy Consumption for Three Years for school (H)

4.4 Base Model Validation

The results of the initial simulation of the base case illustrate the following: the total annual energy consumption for the modeled school was found to be 246813 KWh. The energy consumption reached 57,378 kWh for lighting, 25,344 kWh for equipment, 162083 KWh for cooling and 2007 KWh for exterior lighting. Figure 4.8 shows the annual electrical energy use summary for the base case (initial simulation). It is evident that most of the energy that is consumed by the school is for cooling purposes with a total consumption of 66%of the total, while lighting consumes 22 % and equipment consumes 10% of the total energy demand of the school.

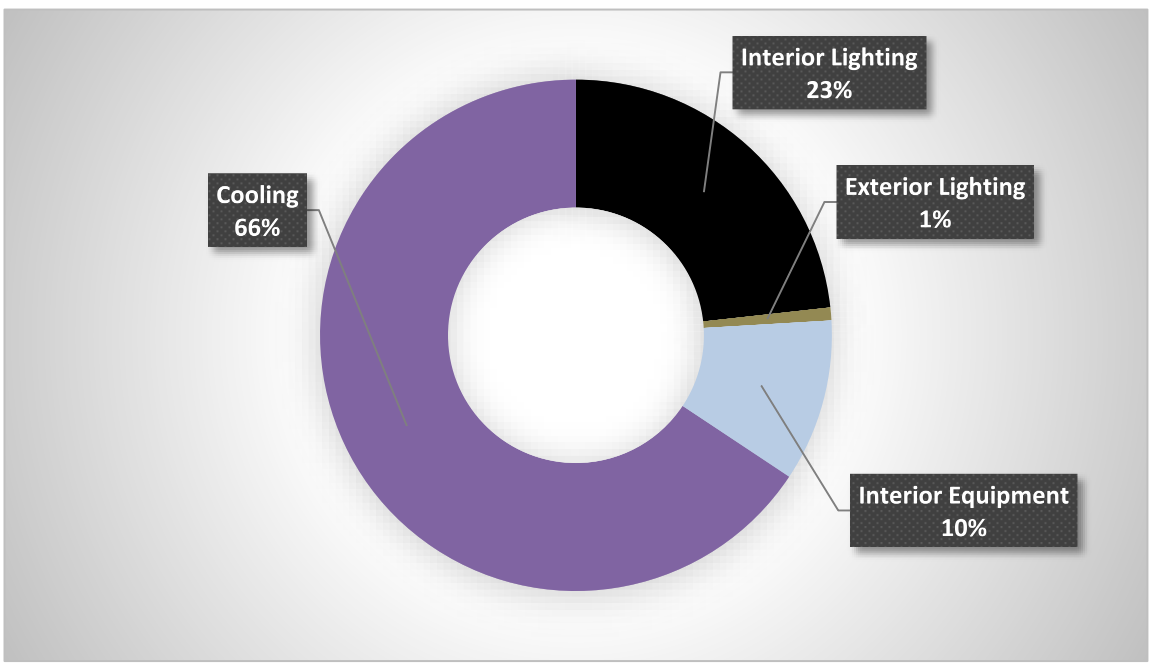


Figure 4. 8 Annual Electrical Energy Use Summery for the Base Case

To ensure that the base case model results represent the actual energy consumption of schools, a comparison was done based on electrical utility bills for the selected schools as analyzed previously. The average energy consumption for the four schools per square meter (KWh/m^2) and for the base case model was compared and it was found that the differences did not exceed 15%. Table 4.6 shows the monthly energy consumption per square meter for the school and the base case.

Table 4. 6 Monthly Energy Consumption KWh/m^2 for (2013)

KWh	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
School (B)	2.96	4.49	4.76	8.47	8.84	5.15	1.24	3.32	11.3	7.10	5.62	3.54	66.79
School (C)	2.60	3.69	3.88	6.90	7.21	4.21	1.05	2.72	9.88	5.82	4.45	3.48	55.89
School (G)	1.43	2.04	4.64	5.86	7.91	4.60	1.44	2.42	7.31	5.30	4.33	2.33	49.61
School (H)	1.97	2.43	3.47	4.59	5.05	2.38	1.22	2.87	6.09	5.17	4.64	3.30	43.18

As seen from the Table 4.6, there are variations in the energy consumption between the schools. These variations are as a result of many factors, such as the area of the schools, the energy consumption pattern, the activities that are conducted in each school, difference in the spatial distribution, orientation of the building, occupational density in the schools (people /m^2), and the summer activities. The deviation between the actual consumption and the base case model varies from 2% to 14% as shown in the Figure 4.9 and Table 4.7.

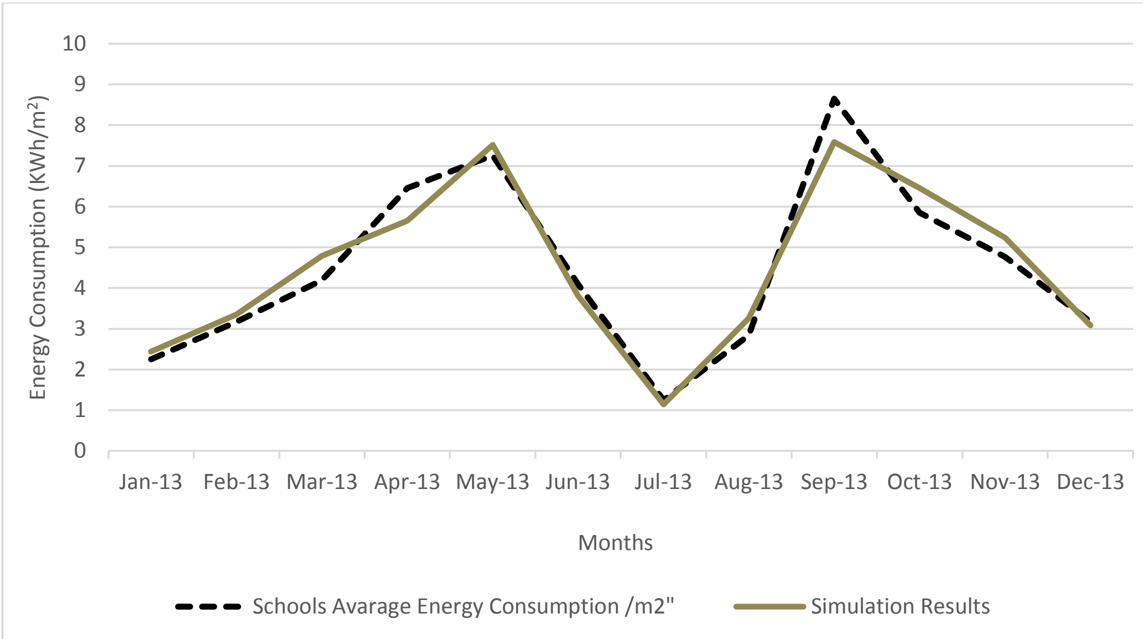


Figure 4. 9 Deviation Between the Actual and the Base Case Model Consumption for (2013)

Table 4. 7 Deviation Between the Actual and the Base Case Model Consumption

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Average energy consumption for the 4 schools(KWh/m^2)	2.2	3.1	4.2	6.4	7.2	4.1	1.2	2.8	8.6	5.8	4.7	3.1
Simulation Result (KWh/m^2)	2.4	3.3	4.7	5.6	7.5	3.8	1.1	3.2	7.5	6.4	5.2	3.0
Deviation %	-8.5	-5.9	-14.2	12.5	-3.6	7	8.3	-14.7	12.3	-10.3	-9.9	2.6

CHAPTER 5

Energy Performance and IEQ in Schools: Analysis and Discussion

5.1 Introduction

Reducing the energy consumption can be achieved by applying different energy saving strategies; however, some of these strategies may conflict with one another or may negatively impact IEQ. Furthermore, better energy performance and IEQ can be achieved if proper combination and/ or investigation between the different strategies are carried out. In this chapter, the impact of envelope design strategies, HVAC systems, and lighting systems on energy consumption and IEQ are analyzed as part of an approach to reduce the energy consumption and maintain acceptable IEQ in schools.

The results of the initial simulation after model validation showed the energy consumption for cooling reached 66% of the total energy consumption and 23% for lighting in schools. Building envelope plays an important role in regulating interior temperatures. Also, it helps in determining the amount of energy required to maintain the thermal comfort within the building. Furthermore, in order to minimize the need for space heating and cooling, it is essential to reduce the heat transfer through the building envelope. HVAC and lighting consume an important amount of energy to maintain the indoor environment, these systems were analyzed taking into consideration their impact on energy consumption and IEQ.

5.2 The Approach

In order to achieve the study objective, the approach shown in Figure 5.1 was developed to reduce the energy consumption in schools while maintaining acceptable IEQ. The approach is designed to better understand the impact of different building thermal and energy systems on energy consumption and IEQ and to account for the computational constraints of the simulation tool and reduce the simulation time.

The first step was to study the impact of the parameters related to envelope design, to recognize their impact on energy performance and the thermal comfort using optimization simulation. To achieve this, the following procedures were implemented:

1. Identify the envelope design strategies that affect energy consumption and IEQ (Window Wall Ratio, Glazing type, Wall Insulation, Roof Insulation, and Air Infiltration).
2. Conduct parametric analysis for each parameter to define values that have an influential impact on the energy consumption. This will help in defining the range of parameters and make the simulation process more efficient.
3. Conduct optimization simulation for the selected for the selected parameters range To achieve the following objectives:
    1. Reduce the total energy consumption (KWh),
    2. Reduce the discomfort hours (hrs) to improve the IEQ.

The second step was to study the impact of lighting systems on the energy performance and visual comfort in terms of lighting type and design. Thirdly the impact of HVAC systems on the cooling energy consumption and thermal comfort was investigated. Finally, a parametric analysis was conducted on the WWR and glazing type, to analyze its impact on cooling and lighting energy when integrating daylighting with the lighting system.

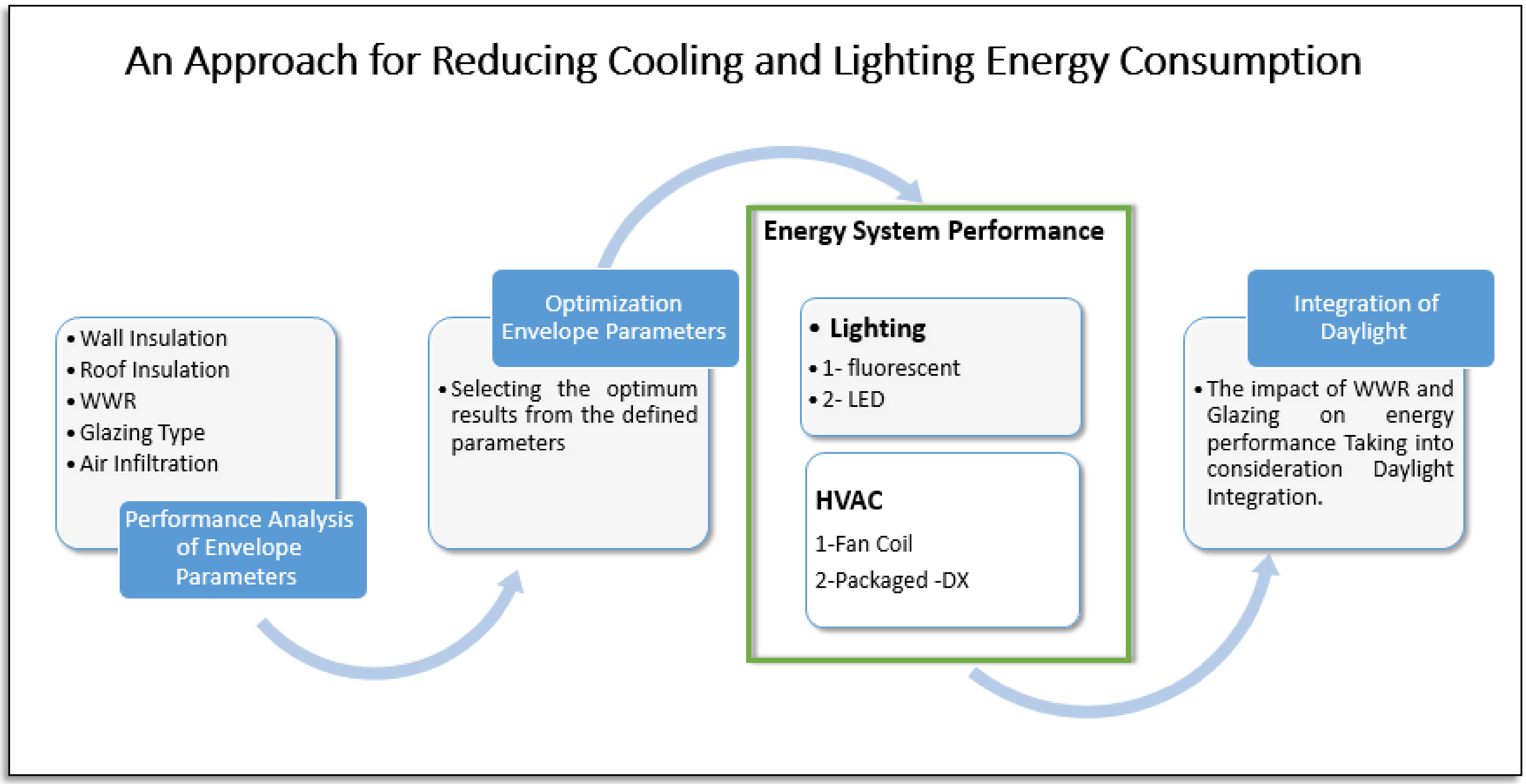


Figure 5. 1 The Implemented Approach for Reducing Cooling and Lighting Energy and Improved IEQ

5.3 Impact of Envelope Parameters on Cooling Energy Consumption

Rubiah, (2008) assessed the impact of envelope parameters on the energy consumption of schools in Dhahran in Saudi Arabia. Different design practices were studied to explore the variation of thermal characteristics. The results revealed that cooling energy is reduced by 30.6 % when the effective envelope design parameters are used.

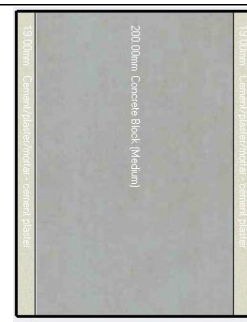
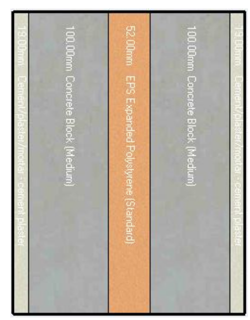
The purpose of this analysis is to have a better understanding of the effect of the envelope parameters on the cooling energy and to define the ranges for the purpose of optimization. The parametric analysis covered wall and roof insulation, WWR, glazing type and air infiltration.

5.3.1 Wall Insulation

The design of the wall system and the proper selection of thermal insulation are important determinants that influence cooling energy consumption, particularly in hot climates. In this part, the impact of thermal insulation on cooling energy consumption is investigated with different thickness layers. Rubaih, (2008) conducted a study to explore the impact of the envelope parameters on the energy consumption for schools. Different wall compositions were explored with a different type of wall insulation and thicknesses. According to the study a wall with a block and extruded polystyrene is the most suitable wall economically and practically. Table 5.1 shows the thermal characteristics of the modeled walls.

Figure 5.2 shows a reduction in cooling energy consumption relative to the base case as a result of increasing the insulation thickness when the insulation was bounded by two block layers. It can be seen that adding insulation resulted in about a 1.4% reduction in cooling energy. A further increase in insulation thickness results in more energy savings. When insulation thickness is increased to 105mm, energy savings show an increase of 2.3%.

Table 5. 1 Thermal Wall Composites

Wall	Insulation	U- value W/m^2.^{0}C	
Base wall	200 mm concrete block +19mm cement plaster on both side	1.626	
Wall(1) Wall(2) Wall(3) Wall(4)	200 mm concrete block +19mm cement plaster on both side+ 28 mm extruded polystyrene 52 mm extruded polystyrene 75 mm extruded polystyrene 105 mm extruded polystyrene	0.695 0.466 0.355 0.270	

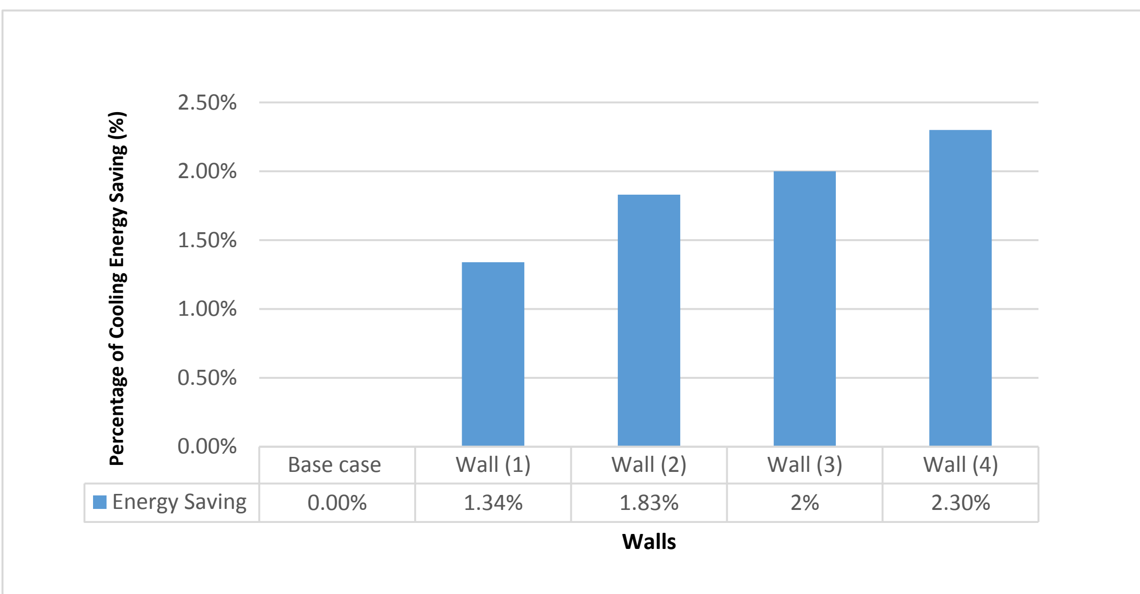


Figure 5. 2 Reduction Cooling Energy due to Wall Insulation

The relatively small reduction in cooling energy consumption as a result of adding wall insulation can be attributed firstly to the fact that the schools are not operated during the summer when heat gain through exterior wall is maximum. Secondly, the wall surfaces are not as exposed to the solar radiation as compared to the roof. For example, walls in the east and the north elevation during class hours are not exposed to the solar radiation.

5.3.2 Roof Insulation

The roof is an important element of the building exterior envelope as it is exposed to solar radiation throughout the day thereby admitting a considerable amount of heat; which in turn reflects on the cooling load. Therefore, it is essential to properly design the system to minimize heat gain through it; and consequently, reduce cooling energy. The thermal characteristics of the roof system and in particular the thermal insulation is of great importance in determining its ability to resist the heat transfer. The impact of thermal insulation of the roof system on the cooling energy for the modeled school is examined. Table 5.2, illustrates thermal characteristics represented by the U-value of different roof systems with an extruded polystyrene insulation thickness ranging from 28-75mm.

Table 5. 2 Roof Design with Different U-Values for the School

	Insulation	U- value W/m^2.^{0}C
Base Case	15mm cement plaster+370 mm concrete block +Water proof 5mm+100mm cement plaster	1.626
Roof (1)	15mm cement plaster+370 mm concrete block+3mm plastic sheet +28 mm extruded polystyrene+50 mm sand+100mm cement plaster	0.672
Roof (2)	15mm cement plaster+370 mm concrete block+3mm plastic sheet +52mm extruded polystyrene+50 mm sand+100mm cement plaster	0.456
Roof (3)	15mm cement plaster+370 mm concrete block+3mm plastic sheet +75mm extruded polystyrene+50 mm sand+100mm cement plaster	0.348

Figure 5.3, shows the percentage of savings in cooling energy resulting from the addition of insulation with different thickness. It is evident that increasing the roof insulation thickness reduces the demand for cooling energy. About a 2.5% reduction in cooling energy is obtained when 25mm of the extruded polystyrene is added compared with the base case. Furthermore increasing the thickness of insulation results in more energy savings; as tested, 75mm thickness of insulations resulted in an energy saving of up to 3.4%.

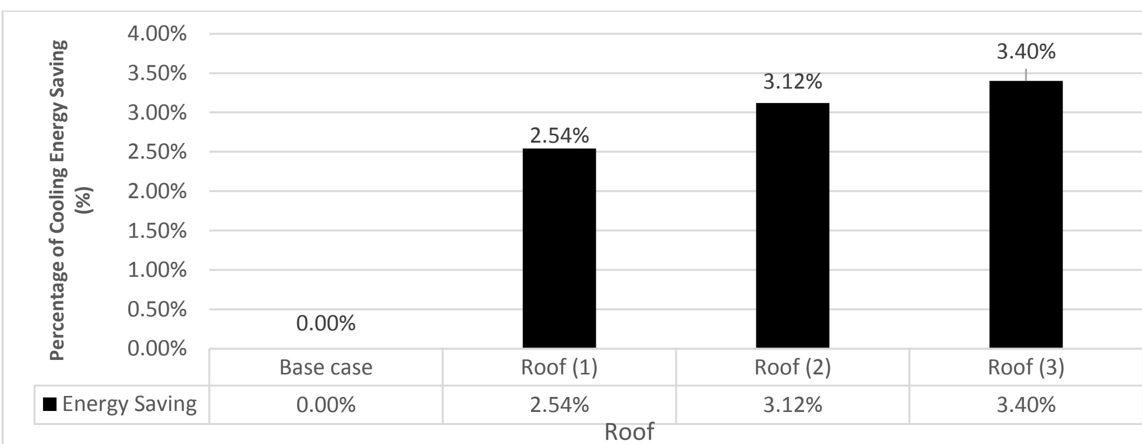


Figure 5. 3 Impact of Type of Roof on the Cooling Energy Consumption of the Base Case School (No Summer)

The result shows that the reduction in the cooling energy didn't exceed 3.4% after applying three inches of insulation. This is due to the school usage since the schools was not used in summer and the school use hours finish by the midday, so the effect of the sun radiation will be low compared to the period after midday. While if the school is used in summer for summer activity or for the summer courses, the effect of the insulation on the cooling energy consumption will be higher as shown in Figure 5.4.

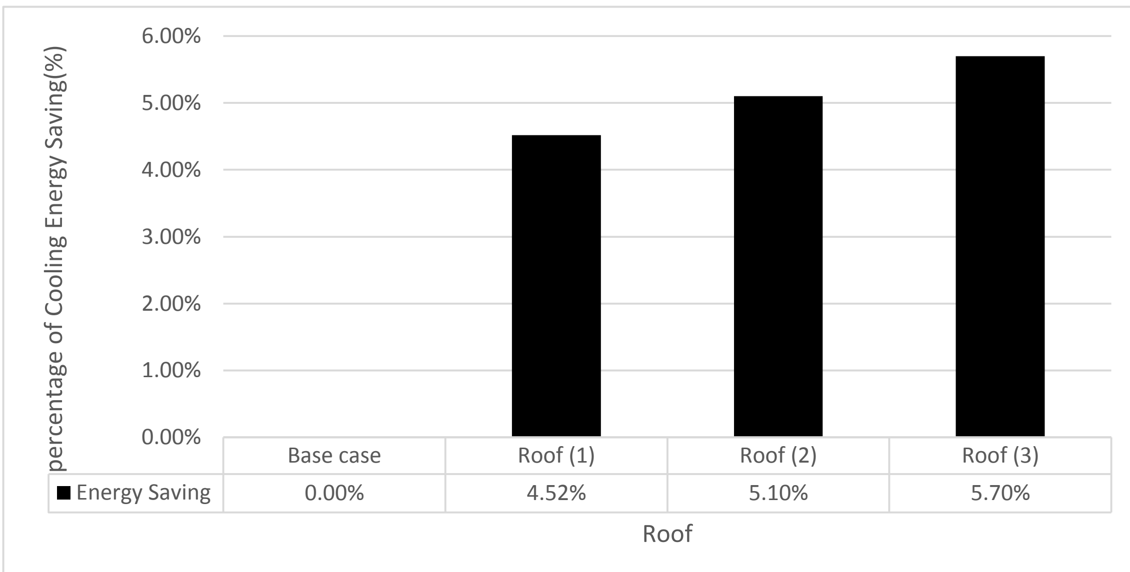


Figure 5. 4 Impact of Type of Roof on the Cooling Energy Consumption of the Base Case School (in Summer)

5.3.3 Glazing Type

Window design, glazing type, and window wall ratio have a considerable impact on the energy performance, particularly in hot climates. The selection of glazing has a major impact on the heat gain both as a result of solar radiation and conduction due to the temperature difference. In this section, the energy performance resulting from usage of different glazing types was evaluated to assess the impact of glazing thermal characteristics on cooling energy. The shading coefficient and the U-value of the glazing are the most important parameters in determining heat gain. Around 210 glazing types are available according to the DOE-2 library, it's not practical to test all these types to investigate their impact on energy savings. Therefore the availability, common use, cost and the solar transmittance / solar heat gain coefficient (**Tvis/SHGC**) were the criteria for selection. The double reflective glazing was selected despite it low value of (**Tvis/SHGC**) because it's commonly used in schools and recommended due to its low heat gain coefficient. Table 5.3 shows the thermal characteristics of glazing types that will be investigated.

Table 5. 3 Glazing Type and its Thermal and Lighting Characteristics.

Glazing Type	Glazing Description	Shading coefficient	Light transmission	U- value $W/m^2.^0C$	Tvis/SHGC
Base case	Double clear 6 mm thickness / 13mm Air	0.703	0.781	2.665	1.1
Type (1)	Single gray 6 mm thickness	0.602	0.431	5.778	0.7
Type (2)	Single reflective clear 6 mm thickness	0.261	0.14	4.664	0.5
Type (3)	Double reflective 6 mm thickness / 13mm Air	0.144	0.045	2.228	0.3
Type (4)	Triple clear 3mm /6mm air	0.682	0.738	2.178	1.1

The percentage of savings of cooling energy for different types of glazings is shown in Figure 5.5. It can be seen that savings in cooling energy relative to the base case are inversely proportional to the values of the shading coefficient. Type (3), which is double reflective glass with 0.144 $W/m^2.^0C$ U- value, provides the lowest energy consumption of around 11.5 % compared to the base case. While the glazing (2), which is single reflective glazing, provides a 9% reduction in the energy consumption. However, the single gray glazing (1) provides a cooling energy saving of up to 7.6 % as shown in Figure 5.4. Light transmittance is also an important factor to be considered while selecting the shading coefficient. Glazing's resulting in a higher reduction in heat gain are normally associated with a low light transmittance coefficient, therefore, a reduced availability of daylight.

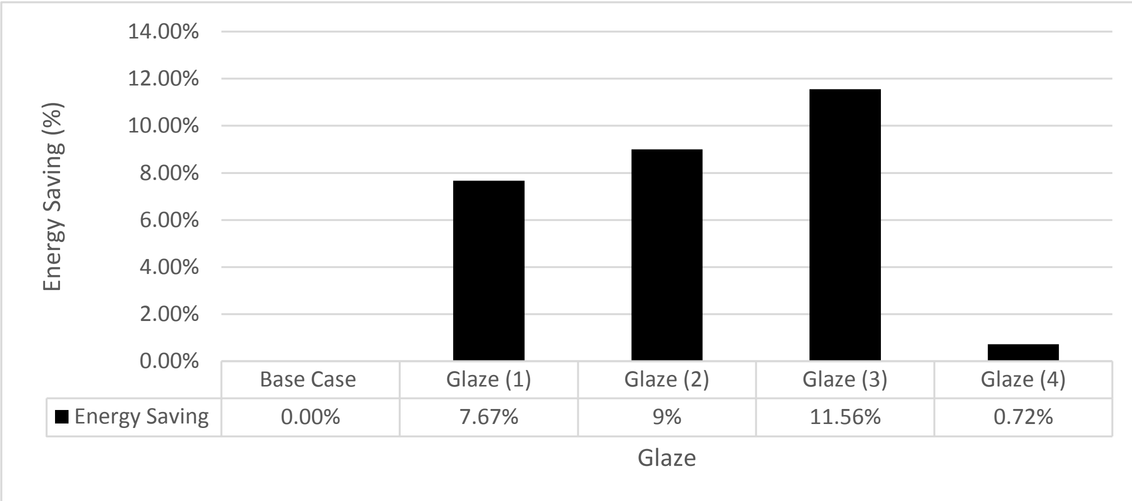


Figure 5. 5 Impact of Shading Coeffecient on Cooling Energy Saving for Base Case School

5.3.4 Air Infiltration Rate

Air infiltration; which is a naturally occurring continuous process can have a direct effect on the building energy consumption and the indoor air quality. Air infiltration occurs through wall cracks, windows and doors of the building envelope. Air infiltration control can be achieved by various strategies, such as automatic door closers, windows with weather stripping and improving sealants.

Air infiltration can have a major impact on the building's cooling energy in hot climates. Savings in cooling energy as a result of a reduction in air infiltration rate is shown in Figure 5.6. The air change rate of 1.5 represents the base case status as mentioned in chapter three is a less tight building, while 1ACH represent typical building tightness, 0.5 ACH represents a tight building and 0.2 ACH represents a very tight building (Timusk, J. 1984).

It can be noticed that a reduction in air infiltration is always associated with a reduction in cooling energy. Reducing the air infiltration rate from 1.5 ACH to 0.6 ACH has resulted in about a 4.45% a reduction in cooling energy, whereas 0.2 ACH resulted in about a 7.3% reduction in cooling energy. However, this value represents very tight spaces which are neither applicable nor practical.

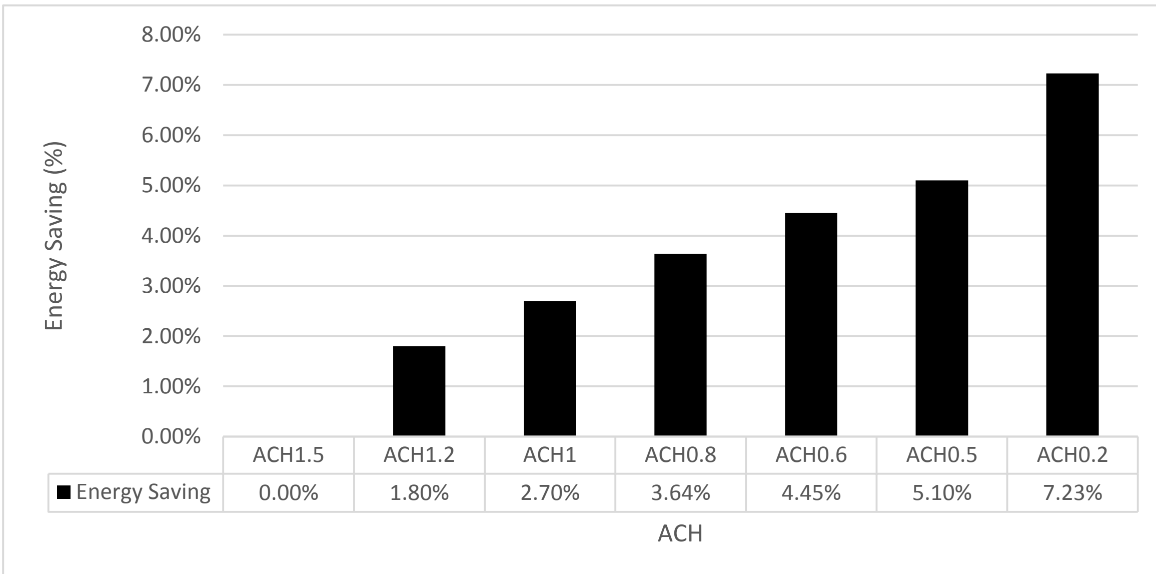


Figure 5. 6 Impact of Air infiltration on Cooling Energy Saving for Base Case School

5.3.5 Window to Wall Ratio (WWR)

Window to wall ratio is achieved by dividing the area of fenestration present in vertical walls by the total wall area. Given the fact that the windows are thermally weak components of the exterior envelope, any reduction in the WWR will result in energy savings. However, it is important to mention that the effect of reducing the WWR will not be the same for differently oriented walls. For example, the effect will be higher for the east and the south walls due to the time of solar exposure. On the other hand, the need for the daylight and views to the outside should be considered when deciding on the WWR during the design stage, especially in educational buildings such as schools.

Figure 5. 7 Impact of WWR on Cooling Energy Saving for Base Case School

Figure 5.7 illustrates the impact of altering the window to wall ratio equally for all the façades on cooling energy as compared to the base case consumption. It can be seen that the relationship between the cooling energy and the WWR is negative. When the WWR is reduced from 25% to 10% the reduction in the energy consumption reached more than 6%. On the other hand, based on the data collected from the schools, the illumination levels (lux) in all classrooms present in the south and east direction exceed the required level causing glare especially in the area near the exterior wall of the classroom. Therefore, reducing the WWR could be beneficial in terms of saving energy at the same time maintaining suitable visual indoor environment quality for conducting intended activities.

5.4 Optimization of Envelope Parameters

Parametric analysis is a step conducted to reduce the alternative of the parameters to start the optimization process. This is an essential step to reduce the time required for the process of optimization. This process, however, requires high-performance computers and may take several days to complete (could exceed 4 days) depending on the parameters, required objective, and building size. On the other hand, this step is important for better understanding the results of optimization.

The parameters are interrelated and may have a varying impact on energy consumption and the indoor thermal quality. Optimization, therefore, provides a chance to explore the impact of these parameters collectively on the energy consumption and indoor thermal quality.

Optimization simulation in Design-Builder is a new tool developed to provide a combination of cost, energy and comfort analysis. Genetic Algorithm (GA) based on the NSGA-II method, which is widely used as a "fast and elitist multi-objective" method provides a good tradeoff between a well converged and a well-distributed solution set. This can be done by identifying objectives and the required variables to select the optimum combination of these variables with respect to the selected objectives.

Table 5.4 shows the selected parameters to initiate the optimization process with respect to the defined objectives, the cooling energy consumption and the summer discomfort hours in order to identify the best combination that may reduce the cooling energy and the discomfort hours. Discomfort Summer ASHRAE 55 Adaptive 80% Acceptability was selected since the energy that is used for maintaining the thermal comfort during the study year is only for cooling and the energy for heating is a minor use of energy which can be neglected, and this complies with thermal comfort assessment during winter time as mentioned previously in chapter three.

632 simulations were carried out by the software to provide the optimum result of the defined envelope design parameter, the results of which are illustrated in Figure 5.8. Table 5.5 shows the value of parameters associated with the best solution. It can be noticed that the optimum roof and wall insulation is extruded polystyrene with 75 mm thickness.

In regards to WWR, 10% was selected which represents the lowest value. This can be explained by the excess value of the illumination, since the illumination level in all the classrooms is always higher than the recommended value as shown in the IEQ assessment. Therefore, reducing the WWR to 10 % will reduce the illumination level. On the other hand, the heat transfer through the window will decrease due to this reduction, therefore reducing the cooling energy.

Double reflective glazing was selected with a shading coefficient of 0.14 and 0.045 light transmittance. Where this glazing provides the lowest heat transfer among the selected glazing type. While the lowest value of daylight will be affordable due to the low value of lighting transmittance. This could affect on the illumination level and WWR, so a further investigation was conducted in this section to see the best WWR and glazing type taking into consideration the illumination level, type of lighting and lighting control.

The result of the optimization is in harmony with the result of the parametric analysis except for the air infiltration, where the selected value in the optimization simulation was 0.6 instead of 0.2. This can be attributed to the influence of temperature difference where the outdoor temperature is lower than the indoor temperature of the classroom during certain periods and months. For instance, in January and December, the internal heat gain resulting from occupants gets diluted by outdoor air at a lower temperature. This resulted in an optimum value of 0.6 ACH rather than 0.2 ACH for air infiltration.

Table 5. 4 Selected Parameters for the Optimization Process

Roof Insulation	Wall Insulation	WWR	Glazing type	Air infiltration
15mm cement plaster+370 mm concrete block +100mm cement plaster	200 mm concrete block +19mm cement plaster on both side	10%	Double clear 6 mm thickness / 13mm Air	0.5
15mm cement plaster+370 mm concrete block+3mm plastic sheet +28 mm extruded polystyrene+50 mm sand+100mm cement plaster	200 mm concrete block +19mm cement plaster on both side+ 28 mm extruded polystyrene	15%	Single gray 6 mm thickness	0.6
15mm cement plaster+370 mm concrete block+3mm plastic sheet +52mm extruded polystyrene+50 mm sand+100mm cement plaster	200 mm concrete block +19mm cement plaster on both side+ 52 mm extruded polystyrene	20%	Single reflective clear 6 mm thickness	0.7
15mm cement plaster+370 mm concrete block+3mm plastic sheet +75mm extruded polystyrene+50 mm sand+100mm cement plaster	200 mm concrete block +19mm cement plaster on both side+ 75 mm extruded polystyrene	25%	Double reflective 6 mm thickness / 13mm Air	0.8
				0.9
				1

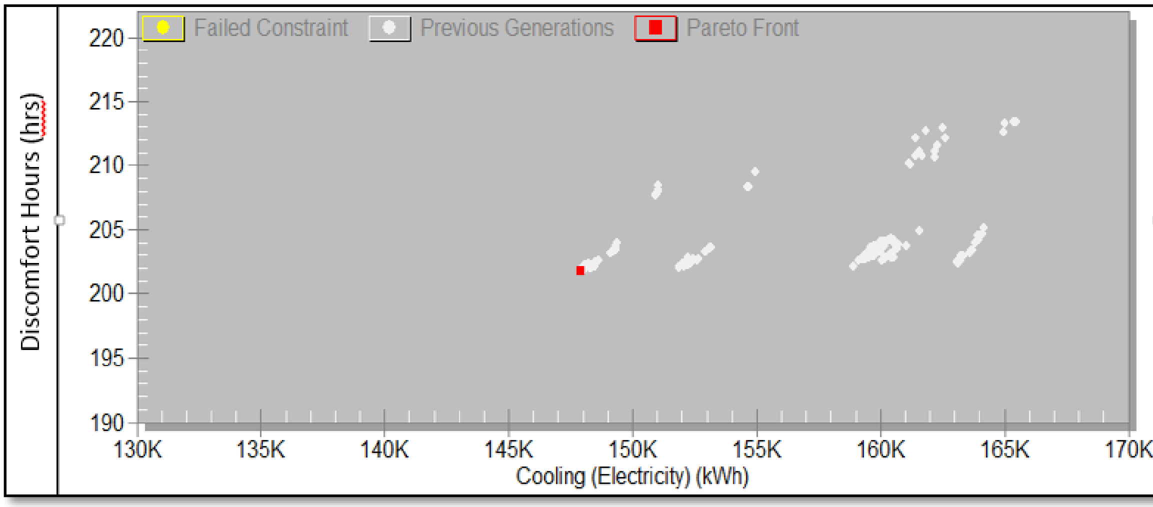


Figure 5. 8 Optimization Simulation

Table 5. 5 Optimum Parameters after Optimization Simulation

External floor construction	WWR (%)	External wall construction	Infiltration (ac/h)	Glazing type	Cooling (Electricity) (KWh)	Discomfort Summer ASHRAE 55 Adaptive 80% Acceptability (hr)
Roof with Extruded Poly. 75mm	10	Wall with Extruded Poly. 75mm	0.6	Dbl Ref-6mm/13mm Air	147910	201

The optimum solution obtained from the simulation resulted in a major reduction of about 8.7%. The energy consumption was reduced from 162,513KWh of the base case to 147,910 KWh for the optimum case. Additionally, the discomfort hours were reduced from 213 (hr) to 201 (hr), which represents a minor change for the average discomfort hours for the building spaces. This slight reduction could be attributed to the ability of HVAC systems to satisfy the thermal load and achieve the set point temperature.

5.5 The Effect of Lighting Systems on the Energy Consumption

Electrical lighting accounts for around 25% of the total energy consumption for buildings according to, Li, et al. (2010). According to the measured data, the illumination level of the artificial lighting in most of the classrooms exceeds the required level and reaches around 1200 Lux. Standard illumination levels recommend a value between 300 and 500 Lux in classrooms as acceptable. The lighting system that was used in the base case schools is a fluorescent 40watt with 3680 lumens. As a rough estimate, the lighting efficacy is 16 fluorescent unit in each class * 40 watts for each unit* 92 lumen for each watt = 58880 lumen. The illumination level in the class was 58880 / the classroom area = 1280 Lux. Also for the base case classroom, the lighting power density = 14 watts/ m^2. Accordingly, 500 Lux can be achieved if the lighting power density is reduced to around 5.5 watts/ m^2.

The previous results were cross-checked by the lighting design software (Relux). As shown in Figure 5.9 the illumination level for the base case model exceeded 750 Lux, while the required level for the classroom and study areas according to the standards was between 300-500 Lux. Figure 5.10 shows the illumination level for the classroom after upgrading the lighting type to LED, and the power density to be 5.5watt/m^2. Thereby the resultant illumination levels now fall between the range of 300 Lux and 500 Lux.

After defining all parameters based on the optimum results, and defining the lighting power density, the lighting type was changed to the LED type with a suitable power density to explore its impact on the energy consumption. The results show a reduction in cooling energy by 7.3 % and 57% for lighting energy as compared to the model with selected envelope parameters and fluorescent lighting, as shown in Table 5.6 and Figure 5.11.

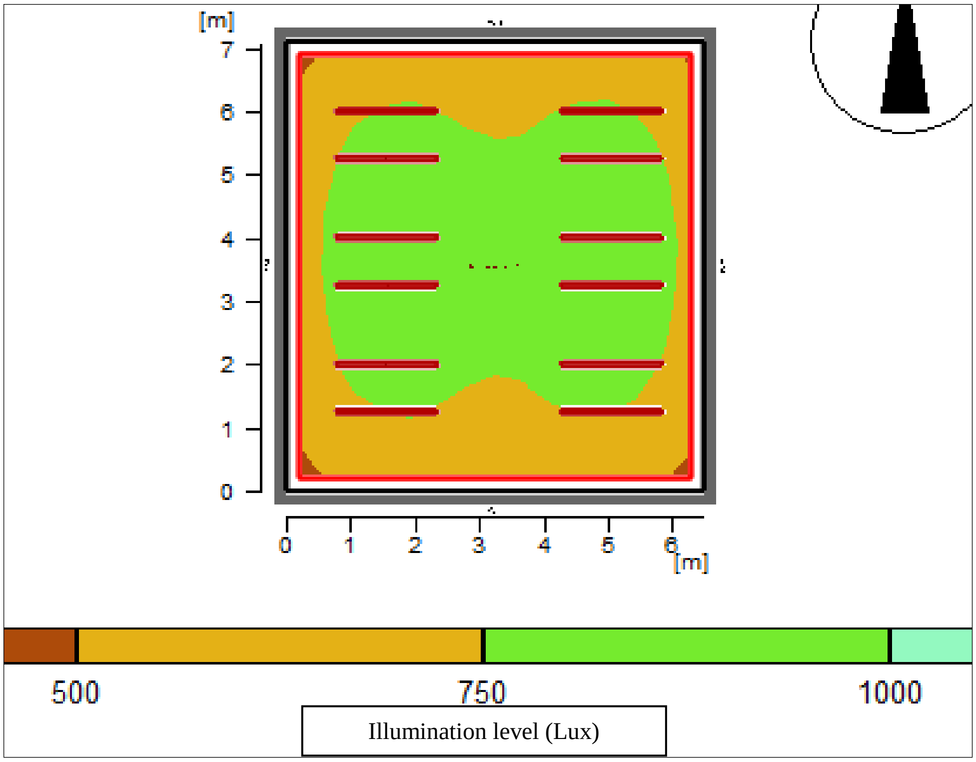


Figure 5. 9 The Illumination Level (Lux) for the Base Case Mode (Fluorescent Light and 14 watt/m²)

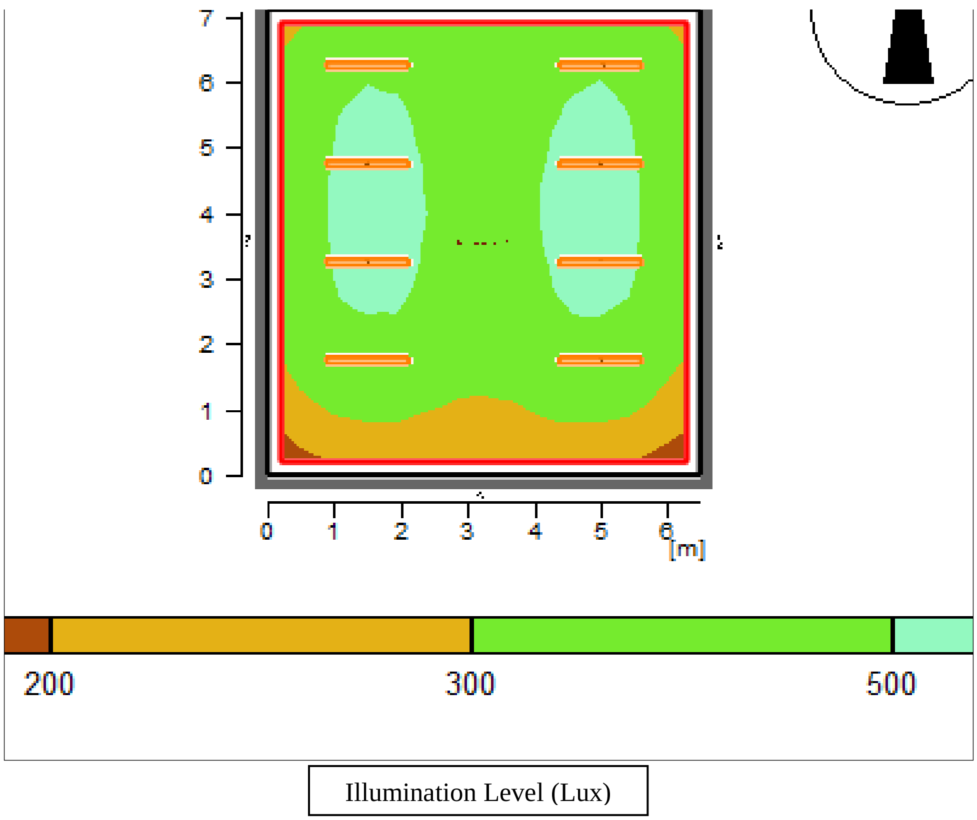


Figure 5. 10 The Illumination Level (Lux) for the Base Case Mode (LED Light and 5.5 watt/m²)

Table 5. 6 The Impact of Using LED Light with Adequate Power Density on Energy Consumption Compared with Base Case

	External Roof construction	WWR (%)	External wall construction	Infiltration (ac/h)	Glazing type	Light type	Cooling (Electricity) (KWh)	Lighting (Electricity) (KWh)	Total (KWh)
Optimum Parameters Of Base Case	Roof with Extruded Poly. 75mm	10	Wall with Extruded Poly. 75mm	0.6	Dbl Ref-6mm/13mm Air	Fluorescent	147910	56829	204739
Suitable Power Density	Roof with Extruded Poly. 75mm	10	Wall with Extruded Poly. 75mm	0.6	Dbl Ref-6mm/13mm Air	LED	137015	24428	161443

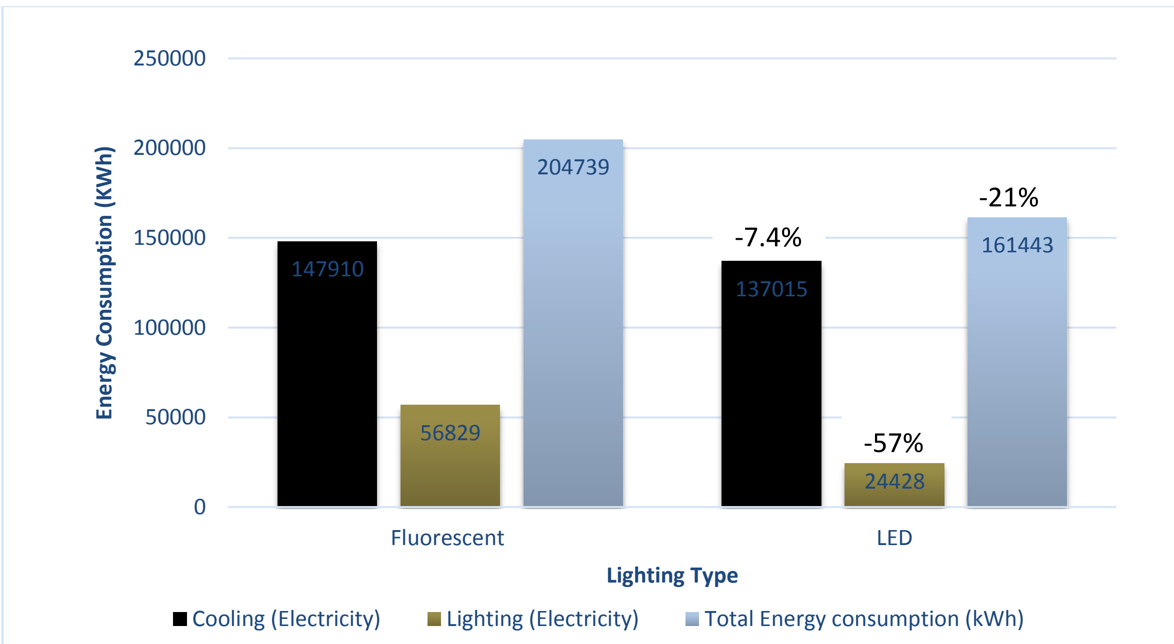


Figure 5. 11 The Impact of Using LED Light with Adequate power density on Energy Consumption Compared with base case

5.6 The Impact of Type of HVAC System on Energy Consumption

In hot climates, HVAC systems are considered an integral part of buildings and play a critical role in providing and maintaining acceptable indoor environmental quality.

According to Pereira et al. (2014), 57% of the total energy consumption in schools is dedicated to maintaining the thermal comfort.

In the base case, the window air conditioning system is a "two tons window unit". The same system was incorporated during the previous analysis of selecting envelope parameters and lighting systems. In this section, savings in cooling energy and the thermal comfort are explored for the schools (with selected parameters and new lighting systems) with a different type of HVAC systems. The HVAC systems that were analyzed are fan coil air cooled chiller and packaged DX. These systems are considered as the most commonly used types of schools according to the advanced energy design guide for school buildings. Also, this system can be integrated with the current architecture design of the schools with minimum alteration. In addition, according to Qi, et al., (2008) this system cost less entail and maintenance cost. On the other hand packaged –DX provide air ventilation for the served spaces since all the assessed classrooms suffered from high level of CO_2 concentration due to the unavailability of ventilation.

After determining the optimum parameters of the model regarding the envelope, and lighting type, the effect of the HVAC system on the cooling energy consumption was investigated. The discomfort hours were reduced from 213 hours of the base case to 129 hours according to the results which are illustrated in Table 5.7. It can be noticed that the packaged DX system consumes the lowest energy at a consumption of 95629 KWh as shown in Figure 5.12 where the reduction reaches 30% compared with the window air conditioning system. This reduction in the energy consumption can be explained by the required energy for starting and operating the system. Since the energy consumption for systems operation (drawn current) could be equal for Packaged-DX and the window type air conditioning system, but the energy consumption for starting operation (starting current) for one unit is less than that required for several units.

Table 5. 7 Cooling, Lighting and Total Energy Consumption for the Optimum Parameters with Alternative HVAC Systems

	External floor construction	WWR (%)	External wall construction	Infiltration (ac/h)	Glazing type	Lighting control	HVAC	Discomfort Hours	Cooling Electricity) (KWh)	Lighting (Electricity) (KWh)	Total Energy consumption (KWh)
Case (1)	Roof with Extruded Poly. 0.75	10	Wall with Extruded Poly 75mm	0.6	Dbl Ref.6 mm / 13mm Air	LED	Packaged DX	129	95629	24428	147168
Case (2)	Roof with Extruded Poly. 0.75	10	Wall with Extruded Poly 75mm	0.6	Dbl Ref.6 mm / 13mm Air	LED	Fan Coil Unit air cooled chiller	129	111343	24365	162818

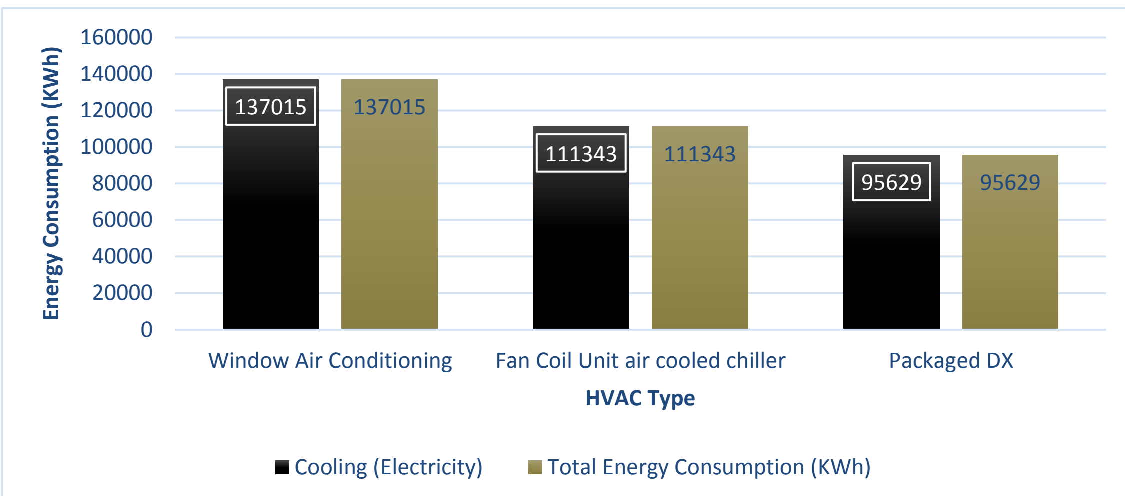


Figure 5. 12 Cooling, Lighting and total Energy Consumption for the Optimum Parameters with Alternative HVAC Systems

5.7 The Effect of WWR and Glazing Type on the Lighting Energy and Cooling Energy

The effect of the WWR and glazing type on the cooling and lighting energy with daylight integration were assessed to derive the optimum WWR and glazing type.

It is worth mentioning that daylight integration is affected by a number of factors. Firstly the location and the number of the sensors placed. The number of sensors was defined by the impact on energy consumption. Two simulations were carried out for the classrooms in the south, west and east elevation with one and two sensors. A minor change in the energy consumption for lighting was observed which reached 6 KWh. As such one sensor was used for each space.

The second factor is the lighting control system. Design builder provides three types of lighting control system, linear control, linear/off control and stepped control. For linear control, the light dims continuously and linearly from the maximum electric power.

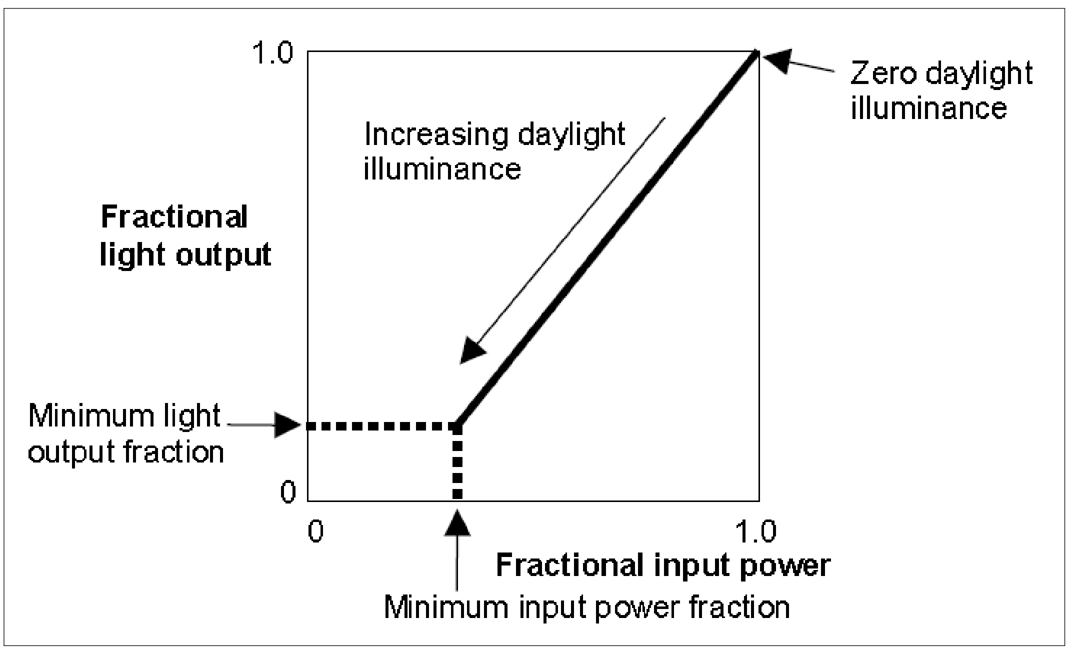


Figure 5. 13 Linear Control for Lighting (WWW.Designbuilder,2016)

Minimum artificial light input as daylight increases until it reaches minimum light output fraction; which is the minimum power the light can dim down to, after this point the light switch off, as shown in Figure 5.13.

The second type of lighting control is linear/off, which works similar to a linear control system except that this system switches off the light completely when the minimum dimming point is reached.

The third type is the stepped control, which allows for switching on/off the light according to the electric lighting requirement. An ideal lighting control mechanism is linear control, which can be useful for calculating the upper limits of potential savings when using natural daylight.

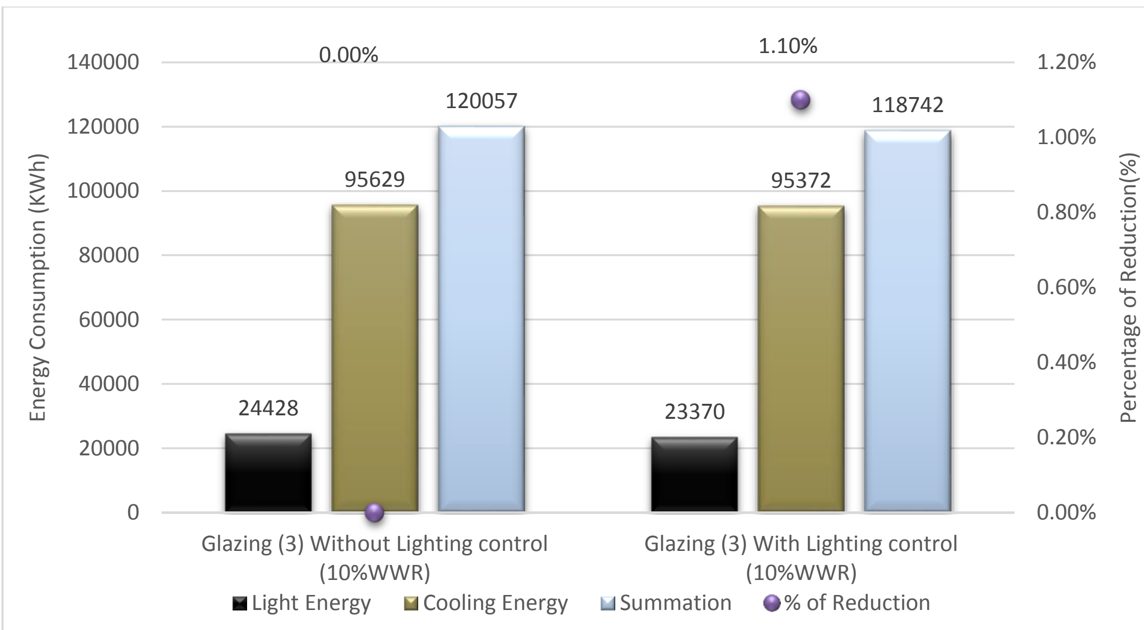


Figure 5. 14 Impact of Lighting Control on Lighting and Cooling Energy Consumption for the Base Case after Selecting e, HVAC and Lighting Systems

Figure 5.14 shows how the energy consumption for cooling and lighting was reduced after applying the lighting control system on the (optimum results) of the envelope parameters, HVAC system and lighting type, where a minor reduction occurs which reached 1.1% as shown in the figure. Therefore a further investigation was done to explore how the WWR and glazing type will reflect on the cooling and lighting energy after implementing the lighting control system, and to identify what is the best type of glazing and WWR that will provide the minimum energy consumption for cooling and lighting.

Table 5.8 shows the result of the parametric analysis of WWR and glazing after implementing the lighting control system. It can be seen that a reduction of 6.9 % is achieved in cooling and lighting energy when double clear glazing with 15 % WWR was used alongside a linear control lighting system as compared to double reflective glazing and 10 % WWR, which represents the base case after implementing the best result of the envelope parameters, HVAC system and lighting type, mentioned in Figure 5.15 in (red box). This is as a result of the integration of daylighting with the artificial light, whereas the double clear glazing allows more light to enter compared with double reflective. In addition a 15%WWR reduces the lighting energy to 10,271 KWh as compared to 23,370 KWh for the double reflective glazing as shown in Figure 5.15. As a result, the cooling energy is reduced to 110,575 KWh due to the reduction of heat gain from lighting. Also, triple glazing with 15% WWR, reduces energy consumption by 6.7 %, but this type of glazing is rarely used due to its high cost as compared to single and double glazing.

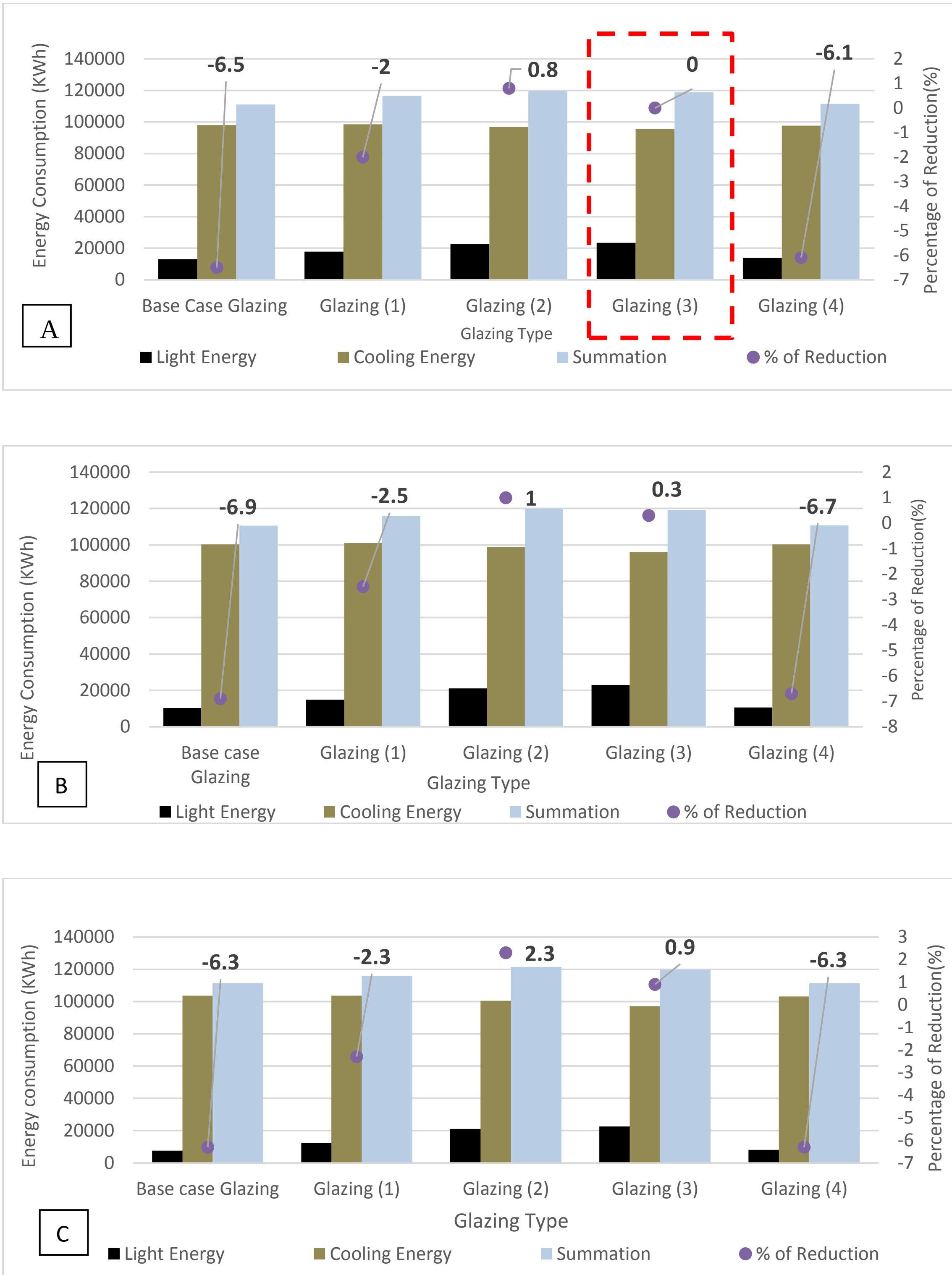


Figure 5. 15 The Effect of Dayligh Integration on the Energy Consumption, (A)10% WWR, (B)15%WWR, (C)20%WWR

Table 5. 8 The Results for WWR and Glazing Type on Reduce Cooling and lighting Energy Consumption while daylight integration is used

10% WWR					
		Light Energy	Cooling Energy	Summation	% of Reduction
Base Case Glazing	Double clear 6 mm thickness / 13mm Air	13115	97933	111048	-6.5
Glazing (1)	Single gray 6 mm thickness	17864	98553	116417	-2.0
Glazing (2)	Single reflective clear 6 mm thickness	22742	96989	119731	0.8
Glazing (3)	Double reflective 6 mm thickness / 13mm Air	23370	95372	118742	0.0
Glazing (4)	Triple clear 3mm /6mm air	13932	97601	111533	-6.1
15% WWR					
Base case Glazing	Double clear 6 mm thickness / 13mm Air	10271	100304	110575	-6.9
Glazing (1)	Single gray 6 mm thickness	14788	100971	115759	-2.5
Glazing (2)	Single reflective clear 6 mm thickness	21135	98739	119874	1.0
Glazing (3)	Double reflective 6 mm thickness / 13mm Air	23006	96151	119157	0.3
Glazing (4)	Triple clear 3mm /6mm air	10576	100205	110781	-6.7
20% WWR					
Base case Glazing	Double clear 6 mm thickness / 13mm Air	7637	103602	111239	-6.3
Glazing (1)	Single gray 6 mm thickness	12334	103623	115957	-2.3
Glazing (2)	Single reflective clear 6 mm thickness	21053	100444	121497	2.3
Glazing (3)	Double reflective 6 mm thickness / 13mm Air	22638	97202	119840	0.9
Glazing (4)	Triple clear 3mm /6mm air	8134	103101	111235	-6.3

CHAPTER6

Conclusions and Recommendations

6.1 Conclusion and Summary

This study was processed in different stages to attain its objectives. Firstly, a literature review on envelope design strategies, and its impact on the energy consumption and thermal comfort was conducted. Based on the literature, it was evident that envelope design strategies have a direct influence on the IEQ and energy consumption. Since, the target area of this study was schools, apart from achieving a reduction in energy consumption, higher attention was given and more effort was made to create a suitable quality of indoor environment as it has a significant influence on the performance of students.

The information and the data about the schools that were collected can be categorized into two groups. The first group is data related to the design of the school, construction characteristics, and energy consumption. This data was used to model and validate the base case. The second group comprises of data regarding indoor environment quality in classrooms, namely relative humidity, air temperature, illumination level, CO_2 concentration and air velocity.

Amongst the eight schools covered, the average temperature and relative humidity found during the wintertime were mostly within the comfort zone, especially before midday (except for some schools), while in summer the temperature mostly remained above 25C^{o}. The CO_2 concentration was found to be higher than the acceptable level during the classes, which was recorded as being higher than 1000 PPM, especially in the summer time. Regarding the illumination level, it was noticed that all schools had illumination levels above the recommended level in both summer (between 600- 1000 Lux) and winter (Higher than 1000 Lux).

After the base case modeling, the simulation was conducted using 'DesignBuilder' software to investigate the energy performance of the schools and the impact of the envelope design strategies and HVAC systems on the cooling energy consumption and thermal comfort.

The annual energy consumption for the base case model was compared with the average energy consumption for four schools based on the electric bills from Saudi Electricity Company (SEC) to validate the base case model. These schools were selected due to the reliability of data. This step was carried out in order to obtain reliable results when envelope design strategies were applied. The maximum difference between the base case result and the average energy consumption bills for the four schools was 15%.

Optimization was conducted to select the optimum result among the defined parameters. The selected parameters provided an obvious reduction in the cooling energy consumption in the school, which decreased from 162083 KWh of the base case to 100,304KWh, resulting in a 38% reduction. Lighting energy consumption reduced to 10,271 KWh from 57,378 KWh of the base case, representing an 82% reduction as shown in Table 6.1.

The reduction in the total energy consumption per square meter after the application of the optimum parameters was around 29.7 % with the consumption decreasing from 76 KWh/m^2 of the base case to 53.4 KWh /m^2 of the optimized case.

Table 6. 1 Evaluation of the Cooling and lighting Energy

Models	**Cooling Energy (KWh)**	**Reduction (%)**	**lighting Energy (KWh)**	**Reduction (%)**	**Total Cooling and Lighting Energy**	**Total Reduction for Cooling and Lighting (%)**
Base Case	162,513		57,378		219,461	
Optimum Parameters	147,910	8.7%	57,378		205,288	6.5 %
Optimum Parameters +LED lighting	137,016	16.5%	24,428	57%	161,444	26 %
Optimum Parameters +LED lighting + packaged-DX HVAC system	95,629	41%	24,428	57%	120,057	45 %
Optimum Parameters with +LED + Packaged-DX HVAC System + Daylight Integration WWR + Glazing Type	100,304	38%	10,271	82%	110,575	49 %

The discomfort hours were reduced from 213 hours to 129 hours. It is important to mention that the reduction in energy consumption after applying the envelope design strategies reached 8.7% and after replacing fluorescent lighting with LED and adequate lighting power density, the reduction reached 16.5 % for cooling energy and 26% for cooling and lighting. After changing the HVAC system to Packaged-DX the total reduction in lighting and cooling energy reached 45%.

When the optimization for the WWR and glazing Type was carried out, daylight integration was applied to explore the lowest value of energy consumption. The cooling energy consumption increased to 100,305 KWh as compared to 95,629 KWh prior to applying daylight integration, while the lighting energy was reduced to 10,271 KWh as compared to 24,428 KWh. This is due to the increase in WWR to 15%. This accelerated heat gain through the window, but on the other hand led to reducing the energy use of the artificial lighting. Therefore double reflective glazing with 10%WWR provides a higher saving in cooling energy if the daylight integration is not applied, while double clear glazing with 15% WWR provides higher energy saving when daylight integration is applied.

Figure 6.1 shows the energy consumption /m^2 for the school after applying the best results of the envelope parameters, HVAC systems and lighting systems with the assumption of what that school used in the summer. It's clear that the energy consumption in the summer months reach the peak point in the assumption if there is summer activity or courses. It's important to mention that the maximum energy consumption didn't exceed 4.5 KWh/m^2 in August after applying the best design strategies compared to 8.3 KWh/m^2 for the base case.

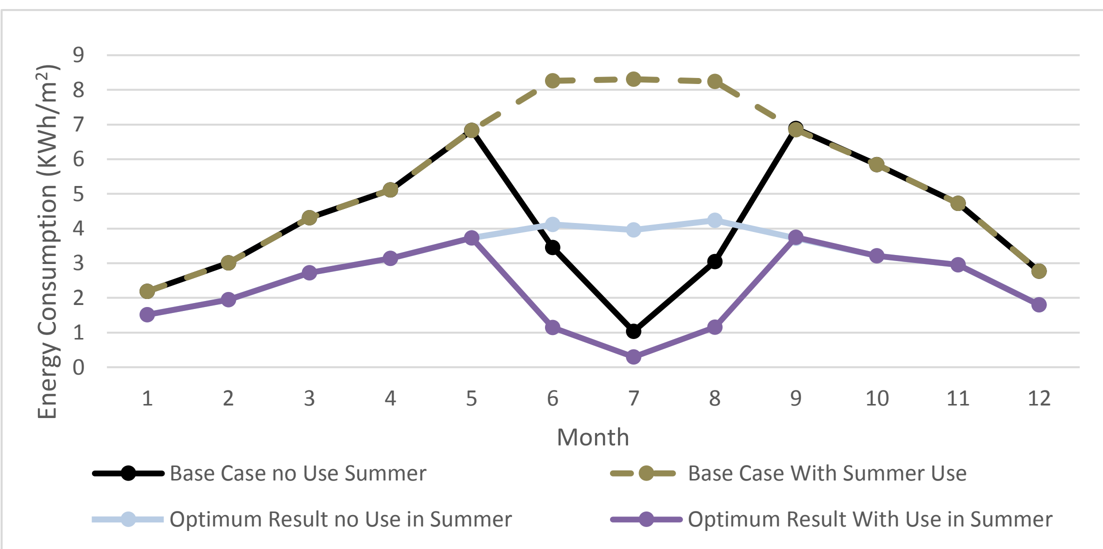


Figure 6. 1 Energy Consumption /m^2 for the School After and Before Applying the Optimum Results (With and Without Summer Use)

6.2 Guidelines

Based on the results and the conclusions the following guidelines have been formulated for schools in the hot humid climates of Saudi Arabia as shown in Table 6.2.

Figure 6. 2 Design Guideline

Design Strategies		Guidelines
Envelope System	Wall and Roof Insulation	Use insulation with high thermal resistance (R-value) in the building envelope. The R-value should be not less than 2 m^{2o}C/W.
	Glazing Type	If there is no daylighting integration, using double reflective glazing 6/13/6 mm with 2.21 m^{2o}C/W U-value and 0.07 light transmittance is more efficient for reducing the cooling energy consumption.
	Window to Wall Ratio (WWR)	WWR should not be used for the school buildings more than 30%, since increasing 5% WWR will increase the cooling energy consumption by around 2%. 15 % WWR reduces the energy for cooling and provides suitable daylighting since all the assessed classrooms suffered from high illumination levels.

	Air Infiltration	Reducing air infiltration to 0.6 ACH has a considerable impact on the cooling energy consumption and provide reduction in cooling energy up to 4.45%.
HVAC and Lighting System	Lighting Type	By using LED lighting and reducing lighting power density to be 6 W/m^2 instead of 14 W/m^2 will reduce the lighting up to 57%.
	Type	Packaged-DX system provides a reduction in cooling energy and reduces the discomfort hours from 201 to 129 during the school operation period. Also this system provides air ventilation compared to a window air conditioning system and heating.

Regarding to lighting control system the fowling guidelines was developed to provide more reduction in the energy consumption.

- If double reflective glazing is selected without daylight integration reduce the WWR to be 10%. If double clear glazing is selected with daylight integration reduce the WWR to be 15%. This will reduce the cooling and lighting energy consumption by .
- If daylighting integration is used double clear glazing 6/13/6 mm with 2.66 m^{2o}C/W U-value and 0.78 light transmittance is more efficient in reducing the energy consumption for lighting and cooling.

6.3 Future research

A future study can be conducted for the same type of building in the same conditions to investigate the optimum window wall ratio with optimum window glazing type for each elevation for different orientations of the schools and with the integration of daylighting. Each elevation can have a different window wall ratio with different glazing type. Economic considerations can also be considered using the optimization simulation to reduce the energy consumption and the initial costs. This study can also be extended to assess other types of buildings, such as office buildings.

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Appendix

Energy Audit Form

School Energy Audit Forms

- **General Information:**

School Name: ___________________Year of Construction:

____

Location:

____

___

Total Occupancy: ______________________________

Conditioned Area (m^2): __________________Unconditioned Area (m^2):

____

Number of Floors: ______________________

Number of classes: ______________________

Class dimensions: _______________________

Number of student in each class: ____________

- **HVAC SYSTEM**

❑ AC Type : Central ☐ Split units ☐ Fan-Coil Units ☐ Window units ☐ Other : -------
❑ Number of units in class: , --------------, --------------------, ------------------, --------------
❑ AC Voltage : 220 ☐ 110 ☐

- **AIR CIRCULATION SYSTEM**

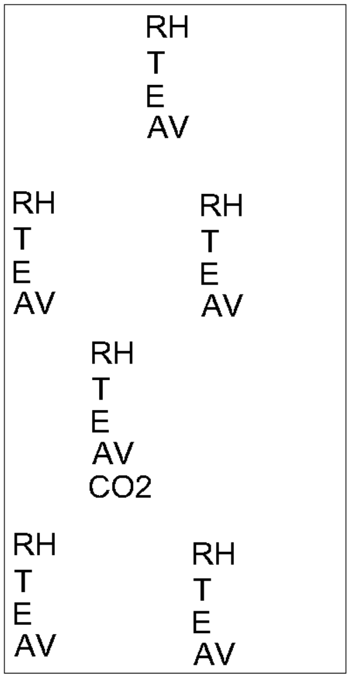
❑ Type : Ceiling Fans ☐ Fixed on the wall ☐ Stand-alone floor Fans ☐
❑ Number: ------------------, ----------------------, -----------------------------

- **LIGHTING SYSTEM**

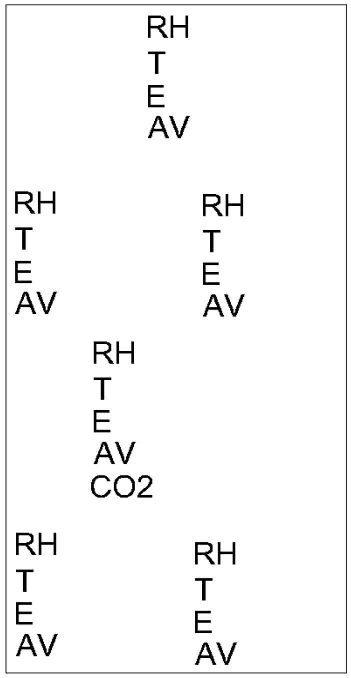
❑ Type of Lighting: Fluorescent ☐ Incandescent ☐ Other --------
❑ Number of Interior Units/Lamps in each class : ----------------- , ------------------, ----------------
❑ Number of Units/Lamps in corridors: ----------------- , ------------------, ----------------
❑ Lighting Voltage: 220 ☐ 110 ☐
❑ Type of curtains: ____________________________
❑ Indoor surface color: __________________________
❑ Location : [Indicate Locations of equipment location on Plan Sketch]

Class location in the school: _______________________________

Type of class: One wall class ☐ Corner class ☐



Time: period:



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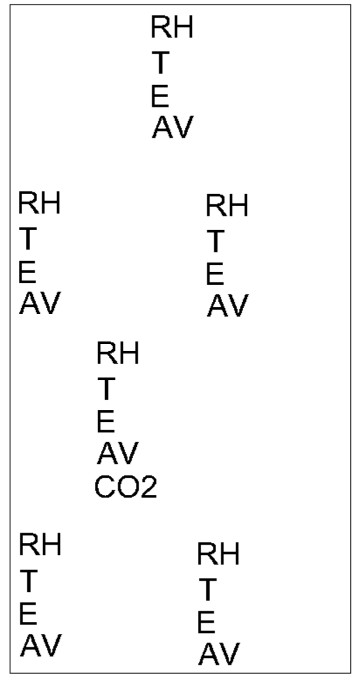

Time: period

Floor#:

Vitae

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