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# ANALYSIS OF THE RELATIONSHIP BETWEEN IEQ AND ENERGY CONSUMPTION IN UAE UNIVERSITY BUILDING: IMPACT OF THERMAL AND LIGHTING COMFORT ON ENERGY USAGE

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UAEU
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College of Engineering

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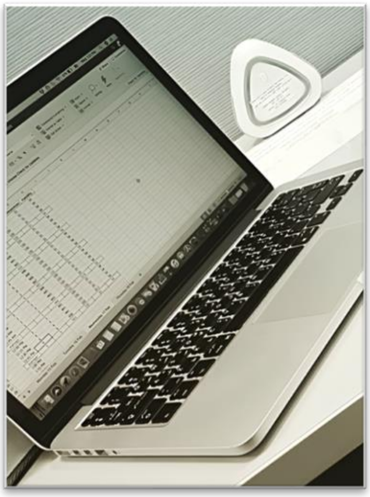

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Architectural Engineering

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Cover: Data Gathering During Monitoring Experiments Using AirMentor Sensor and Excel Software

(Photo: By Salama Abdulla Rashed Suwaid AlGhaithi)



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# Declaration of Original Work

I, Salama Abdulla Rashed Suwaid AlGhaithi, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Analysis of the Relationship Between IEQ and Energy Consumption in UAE University Building: Impact of Thermal and Lighting Comfort on Energy Usage*", hereby, solemnly declare that this is the original research work done by me under the supervision of Dr. Young Ki Kim, in the College of Engineering at UAEU. This work has not previously formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

Student's Signature: ____________________

Date: 01/10/2022

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# Abstract


The Indoor Environment Quality (IEQ) of buildings becomes increasingly critical as people spend more than 90% of their time inside buildings based on the National Human Activity Pattern Survey (NHAPS) (Klepeis et al., 2001). The quality of the indoor environment in a building has been shown to have a significant impact on users' productivity and energy consumption. Further, if tenants are working in a comfortable indoor environment, absenteeism rates and incidental expenses, such as medical expenses, will be reduced. For instance, a comfortable workplace increases productivity by 10-15% and reduces absenteeism by 2.5% (Leyten & Boerstra, 2003). According to the Intergovernmental Panel on Climate Change (IPCC) recent climate report, UAE residents are experiencing higher temperatures and harsher weather conditions (UAE MOCCAE, 2021). Research over the last years concluded that the longer people stay inside buildings, the more likely they are to be exposed to unhealthy environments. Which means more physical and psychological problems such as Sick Building Syndrome (SBS). The overtime spent inside also means more demands for energy inside the buildings.

This thesis studied the relationship between Indoor Environmental Quality (IEQ) and energy use in a UAE university building. To assess IEQ levels, one of the university buildings was selected, and several IEQ parameters such as temperature, Relative Humidity (RH), Indoor Air Quality (IAQ), and illuminance were monitored. An online occupancy survey was distributed to users of the case study building to conduct a Post Occupancy Evaluation (POE) study. Dynamic simulation methods were applied to validate proposed changes based on monitoring and POE findings to improve comfort and energy efficiency, especially lighting and temperature.

The main results of the survey can be summarized as follows: over 40% of students feel neutral on most parameters and are satisfied with their overall IEQ. However, students feel uncomfortable with the dry, stuffy air and the cold room temperature. When considering lighting comfort, 49% of students complain of too much artificial lighting and 32% complain of not enough daylight, and 51% are uncomfortable with glare and reflections. Regarding the results for Sick Building Syndrome (SBS), some students showed symptoms such as a runny nose, dry skin, headache, and fatigue. These symptoms are related to low room temperature, relative humidity, airflow from the AC system, and poor lighting.

As a result of the monitoring experiment, lighting and temperature were found to be the most noticeable issues, which supports the results of the survey. The temperature in most classrooms was below 24 °C. Although most classrooms have plenty of natural light from morning to noon, daylight is not well utilized, resulting in the need for artificial lighting. It has also been observed that in most classrooms with tables and smartboards that are perpendicular to windows, factors such as glare and reflection arise. These factors reduce reliance on daylight and increase the use of artificial light.

Simulation studies results show that the optimal solution to reduce energy consumption and improve occupant comfort is to increase the room temperature based on standards, change the classroom layout, increase daylight use and create artificial lighting zones. These changes result in saving 39% of the cooling load, 92% of artificial lighting, and 51% of total energy consumption.

All the research findings are discussed in full detail in this thesis. The findings could be implemented in other UAE university buildings to improve IEQ, user comfort, and energy consumption.

**Keywords**: IEQ Analysis, POE Study, User Comfort, Dynamic Simulation, University Buildings.

# Title and Abstract (in Arabic)

## تحليل العلاقة بين جودة البيئة الداخلية واستهلاك الطاقة في إحدى مباني جامعة الإمارات: تأثير الراحة الحرارية والإضاءة على استخدام الطاقة


***الملخص***

تصبح جودة البيئة الداخلية للمباني حرجة بشكل متزايد حيث ينفق الناس أكثر من 90% من وقتهم داخل المباني بناءً على المسح الوطني لنمط النشاط البشري. وثبت أن جودة البيئة الداخلية في المبنى لها تأثير كبير على إنتاجية المستخدمين واستهلاك الطاقة. علاوة على ذلك، إذا كان المستأجرون يعملون في بيئة داخلية مريحة، فسيتم تخفيض معدلات التغيب والنفقات العرضية، مثل النفقات الطبية. على سبيل المثال، يزيد مكان العمل المريح الإنتاجية بنسبة 10-15٪ ويقلل من التغيب بنسبة 2.5٪.

وفقًا لتقرير المناخ الأخير الصادر عن الهيئة الحكومية الدولية المعنية بتغير المناخ، يعاني سكان الإمارات العربية المتحدة من درجات حرارة أعلى وظروف مناخية أكثر قسوة. خلصت الأبحاث على مدى السنوات الماضية إلى أنه كلما طالت مدة بقاء الأشخاص داخل المباني، زاد احتمال تعرضهم لبيئات داخلية غير صحية. مما يعني المزيد من المشاكل الجسدية والنفسية مثل متلازمة البناء المرضي. والعمل الإضافي الذي يتم قضاؤه في الداخل يعني أيضًا المزيد من استهلاك الطاقة داخل المباني.

درست هذه الأطروحة العلاقة بين جودة البيئة الداخلية واستخدام الطاقة في مبنى جامعي في جامعة الإمارات العربية المتحدة. لتقييم مستويات جودة البيئة الداخلية، تم اختيار أحد مباني الجامعة، وتم رصد العديد من معايير البيئة الداخلية مثل درجة الحرارة والرطوبة النسبية وجودة الهواء الداخلي والإضاءة. تم توزيع استبانة عبر الإنترنت على مستخدمي المبنى لإجراء دراسة تقييم ما بعد الإشغال. وتم تطبيق طرق المحاكاة الديناميكية للتحقق من التغييرات المقترحة بناءً على تجارب المراقبة ونتائج الاستبانة لتحسين الراحة وكفاءة الطاقة، وخاصة الإضاءة ودرجة الحرارة.

يمكن تلخيص النتائج الرئيسية للمسح على النحو التالي: يشعر أكثر من 40٪ من الطلاب بالحياد في معظم المعايير وهم راضون عن جودة البيئة الداخلية الشاملة. ومع ذلك، يشعر الطلاب بعدم الارتياح للهواء الجاف والخانق ودرجة حرارة الغرفة الباردة. عند التفكير في راحة الإضاءة، يشكو 49٪ من الطلاب من الكثير من الإضاءة الاصطناعية و32٪ يشكون من عدم كفاية ضوء النهار، و51٪ غير مرتاحين للوهج والانعكاسات. فيما يتعلق بنتائج متلازمة البناء المرضي، أظهر بعض الطلاب أعراضًا مثل سيلان الأنف، وجفاف الجلد، والصداع، والتعب. قد ترتبط هذه الأعراض بانخفاض درجة حرارة الغرفة والرطوبة النسبية وتدفق الهواء من نظام التكييف وضعف الإضاءة.

نتيجة لتجارب المراقبة، تبين أن الإضاءة ودرجة الحرارة هي أكثر المشكلات الملحوظة، والتي تدعم نتائج المسح. كانت درجة الحرارة في معظم الفصول الدراسية أقل من 24 درجة مئوية. على الرغم من أن معظم الفصول الدراسية تحتوي على الكثير من الضوء الطبيعي من الصباح إلى الظهر، إلا أن ضوء النهار لا يستخدم بشكل جيد، مما يؤدي إلى الحاجة إلى الإضاءة الاصطناعية. وقد لوحظ أيضًا أنه في معظم الفصول الدراسية التي تحتوي على

طاولات وألواح ذكية متعامدة مع النوافذ، تنشأ عوامل مثل الوهج والانعكاس. تقلل هذه العوامل الاعتماد على ضوء النهار وتزيد من استخدام الضوء الاصطناعي.

تظهر نتائج دراسات المحاكاة أن الحل الأمثل لتقليل استهلاك الطاقة وتحسين راحة مستخدمي المبنى هو زيادة درجة حرارة الغرفة بناءً على المعايير، وتغيير تخطيط الفصل الدراسي، زيادة استخدام ضوء النهار وإنشاء مناطق إضاءة اصطناعية. تؤدي هذه التغييرات إلى توفير 39٪ من حمل التبريد و92٪ من الإضاءة الاصطناعية و51٪ من إجمالي استهلاك الطاقة.

تمت مناقشة جميع نتائج البحث بالتفصيل الكامل في هذه الأطروحة. يمكن تنفيذ النتائج في المباني الأخرى في جامعة الإمارات لتحسين جودة البيئة الداخلية وراحة المستخدم واستهلاك الطاقة.

**مفاهيم البحث الرئيسية:** تحليل البيئة الداخلية للمبنى، دراسة تقييم ما بعد الاشغال، راحة المستخدم، المحاكاة الديناميكية، مباني الجامعة.

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My special thanks go to my advisor Dr. Young Ki Kim who introduce me to the field of well-being inside the buildings and got me to start to search more and understand this topic. I'm thankful for his patience when listening to my research ideas and his endless encouragement and support.

I would like to thank my committee for their guidance, support, and assistance throughout my preparation of this thesis.

My thanks are extended to the Facility Management Department for providing me with most of the building's materials.

Finally, I express my appreciation to my family and friends who encouraged me to continue my master's degree.

# Dedication

*To my beloved parents and family*

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# List of Abbreviations

| | |
|---|---|
| ADHD | Attention Deficit Hyperactivity Disorder |
| ASHRAE | American Society of Heating, Refrigerating, and Air-Conditioning Engineers |
| BIM | Building Information Model |
| BREEAM | Building Research Establishment’s Environmental Assessment Method |
| BRI | Building Related Illness |
| CLA | Circadian Light |
| $CO_2$ | Carbon Dioxide |
| CS | Circadian Stimulus |
| EML | Equivalent Melanopic Lux |
| ESTIDAMA | Arabic Word for Sustainability |
| GBRSs | Green Building Rating Systems |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IAQ | Indoor Air Quality |
| IEQ | Indoor Environment Quality |
| IEQ-GA | Indoor Environment Quality-Global Alliance |
| IHME | Institute for Health Metrics and Evaluation |
| IPCC | Intergovernmental Panel on Climate Change |
| LEED | Leadership in Energy and Environmental Design |

| | |
|---|---|
| NIHL | Noise-Induced Hearing Loss |
| $PM_{2.5}$ | Fine Inhalable Particles / Fine Particulate Matter |
| $PM_{10}$ | Inhalable Particles / Respirable Particulate Matter |
| PMV | Predicted Mean Vote |
| POE | Post-Occupancy Evaluation |
| PPD | Predicted Percentage of Dissatisfied |
| PPM | Part Per Million |
| RH | Relative Humidity |
| SAD | Seasonal Affective Disorder |
| SBS | Sick Building Syndrome |
| TVOC | Total Volatile Organic Compound |
| USEPA | United States Environmental Protection Agency |
| WHO | World Health Organization |

# Chapter 1: Introduction

This research work is based in part on the previously published article [Analysis of Indoor Environment Quality (IEQ) in UAE University Campus Building, UAE]. I have permission from my co-author/publisher to use the work listed below in my thesis/dissertation. (AlGhaithi, S. A., & Kim, Y. K. (2022). Analysis of Indoor Environment Quality (IEQ) in UAE University Campus Building, UAE. ZEMCH 2021 International Conference, 271–284 http://zemch.org/proceedings/2021/ZEMCH2021.pdf)

## 1.1 Overview

According to Roberts's study, people nowadays spend around 90% of their time in buildings. For students, educational buildings such as schools and universities are where they spend most of their time. Indoor Environment Quality (IEQ) can affect students' productivity by a certain amount for each of the parameters such as temperature, Relative Humidity (RH), $CO_2$, lighting, noise level, and Indoor Air Quality (IAQ), and based on the students' age range (Klepeis et al., 2001). For instance, a calming indoor environment could reduce the students' blood pressure by around 17%. In addition, naturally lit classrooms could improve test scores by around 25% (Education Technology Solutions, 2018). A classroom design including acoustics, lighting, furniture, décor and soft furnishing, and configurations could impact learning by 25% (Admin, 2021). Moreover, the occupants' comfort may influence the energy consumption of a building through their behavior. For example, when there is enough natural lighting the occupants will not depend 100% on artificial lighting, which can reduce the energy consumption inside the building. Several studies have shown that users' comfort, actions, and operation patterns determine a building's energy performance. An analysis of the energy consumption of commercial buildings in the United States found that lighting, Heating, Ventilation, and Air Conditioning (HVAC) account for 20% of the total energy consumption. This could be related to the poor assumptions of the systems' operation during the design and commissioning phases. Also, another study has mentioned that in commercial buildings poorly operated equipment is responsible for 10% to 30% of the used energy. Also, other studies found that some of the users' actions, such as leaving lights on or other equipment running for hours after they have been used, could result in significant energy consumption inside the building (Al Amoodi & Azar, 2018). Previous studies have shown that buildings that don't provide users with enough comfort consume more energy. This is another reason why studying the IEQ of the building is critical. According to a recent study conducted in the UAE in an educational building in Abu Dhabi city, human activities can alter energy usage by 25% (Al Amoodi & Azar, 2018).

Furthermore, climate change is a growing issue throughout the whole world. As the temperatures rise, people spend more time indoors. Additionally, diseases such as Corona Virus Disease 2019 (COVID-19) have also pushed people to spend more time indoors, bringing further attention to the Indoor Environment Quality (IEQ) of the buildings.

Buildings are the largest end-use sector for energy consumption around the world, with a percentage of around 35%, followed by 31% for industry, and 30% for transportation. Most of the building electricity, around 80% is used for operating the buildings, not for construction, therefore it is critical to provide comfortable indoor environments to help save energy (Zeiss, 2015). 80% of the energy used in the UAE is consumed by buildings; 70% of this is consumed by cooling systems (Rodriguez-Ubinas et al., 2020). In 2017, Abu Dhabi's total electricity consumption is 60,158 GWH; 48.2% for commercial, 26.8% for domestic, 11.2% for industry, 8.1% for government, 5.7% for agriculture, and 0.1 for other sectors (SCAD, 2017). A growing population, an expanding economy, and climate change are contributing to increased energy consumption. Therefore, it is imperative that energy is utilized more efficiently throughout the country for all sectors, including the building sector (U.AE, 2020).

This study examined the relationship between IEQ and energy consumption. It monitored classrooms in a university building for some of the IEQ parameters such as temperature, RH, IAQ, and illumination. And distributing an online survey to determine the level of student comfort and satisfaction. As well as using a dynamic simulation to figure out the impact of improving the layout, temperature, and lighting of classrooms on energy consumption.

## 1.2 Statement of the Problem

- The effects of climate change, daily lifestyles, and pandemics force people to stay indoors even longer, which exposes them to the indoor environment of buildings more.
- IEQ is critical for productivity, students' records, and energy consumption. The quality of buildings' occupants' comfort causes direct and indirect-health related economic issues; the direct issue stems from the increase in diseases and tiredness, which will cause the overuse of the health sector, which will cost the government a lot of money to provide for the people's needs. Indirectly, the building's users will have a lower level of productivity at work or study, which will have an impact on the general economy.
- United Arab Emirates University (UAEU) classrooms' IEQ needs to be studied since it affects the learning levels of the students. The comfort inside the learning spaces, particularly in terms of heating and lighting, can affect how much energy is used by the building. As I have experienced inside the building, the classrooms are cold during the summer months, so this building needs to be examined regarding indoor thermal comfort. And based on the classrooms' layout, most of the classrooms use artificial lighting more than daylight.

## 1.3 Research Questions

As the primary concern of this study is the IEQ of the classrooms within one of the UAE University buildings, the following questions were asked to guide the study:

Main question:

- How does the Indoor Environment Quality (IEQ) of a university building affect the satisfaction and comfort of students and how does it impact energy consumption?

Sub-questions:

- Considering the literature, what are the most common IEQ parameters to measure, and what methods can be used to evaluate IEQ?

- Considering the results of the Post Occupancy Evaluation (POE) study of the case study building and selected classrooms, how can these findings be used to reduce energy consumption and improve IEQ?

## 1.4 Research Objectives

By analyzing a building's IEQ, using an online survey to evaluate students' comfort, and using dynamic simulations to improve energy use, this study explored and examined the relationship between building users and energy consumption. This research objective can be summed up as follows:

- Evaluating the IEQ of the case study building, and students’ satisfaction level with the classrooms’ IEQ.
- According to the findings from the POE and IEQ studies, provide the optimal solutions to improve lighting and thermal environments as well as energy consumption.

## 1.5 Scoop and Limitations

Some factors affected the scoop of the study. The main limitation was the COVID-19 pandemic, it affected this study a lot. In the beginning, this research was supposed to consider three university buildings, two of them lecture buildings (one on the female side and the other on the male side) and the third one the female residence building, but because the buildings were almost empty and not used a lot since most of the classes are online, as well as for safety reasons (especially at the female residence building), this study focused on only one building. Added to that, some of the parameters were ignored (such as measuring the noise level) inside the classrooms because the building is supposed to be normally occupied so the readings will be accurate. There were also some parameters supposed to be measured using specific sensors during class time, but since there were no face-to-face classes, those parameters were ignored such as noise. So, the study focused on one building only (the lecture building on the female side) with only a few parameters being monitored (temperature, RH, $PM_{2.5}$, $PM_{10}$, $CO_2$, TVOC, and illuminance). Regarding the methods, it would be better if interviews were conducted in classrooms. This would be to get clear answers about the different IEQ parameters of each classroom and at a certain time to understand the IEQ of each classroom in a more thorough way. In the future, researchers could examine the same study area using interviews as well as devices or sensors during class times when classes are full.

While the building wasn't fully occupied, it still operated according to the building's normal schedule. Therefore, all systems, such as HVAC, worked according to the schedule of the building except for the lighting system since users monitor the lighting system. In addition, there were a few classes with a specific number of students who attended face-to-face classes.

### 1.6 Summary of Chapters

This thesis studied the relationship between Indoor Environment Quality (IEQ) and energy consumption in a university building. To assess IEQ levels, one of the university buildings was selected and IEQ parameters such as thermal comfort, IAQ, and lighting were monitored. An online occupancy survey was distributed among the building's users to conduct a Post Occupancy Evaluation (POE) study. Dynamic simulation methods were applied to validate proposed changes based on monitoring and POE findings to improve comfort and energy efficiency, especially lighting and thermal comfort.

This research is divided into chapters; each chapter represents one of the research phases.

- Chapter 1: Gives the main idea and objectives of the research as well as explains the importance of studying such a topic.
- Chapter 2: Presents relevant literature about climate change, Indoor Environmental Quality (IEQ) in buildings, an overview of some Green Building Rating Systems (GBRSs), and methods previously used to analyze IEQ and users' perceptions.
- Chapter 3: Explaining in detail the methodology of this research by going through each of the used methods, which are the online survey, monitoring experiments, and dynamic simulation.
- Chapter 4: Discussing the results and the main findings from all the methods mentioned in Chapter 3 which are online survey, monitoring experiments, and

dynamic simulation, and compare the values from the monitoring experiments to the standards mentioned in Chapter 2 (ESTIDAMA, ASHRAE, etc.).

- Chapter 5: Gives a summary of the research in general, as well as the limitations of this study and further research suggestions.

# Chapter 2: Literature Review

## 2.1 Climate Change and COVID-19 Pandemic

Since climate change affects the whole environment, it is recognized as a global challenge that threatens the nation's economic and social stability. Climate change has a different level of effect for each region due to the difference in the climate and weather in these regions (UAE MOCCAE, 2021). This issue is more severe in hot, dry countries. These countries already have high temperatures and dry weather that make simple outdoor activities like walking difficult, causing people to prefer staying indoors.

The UAE is considered one of those countries with harsh weather and is impacted by climate change on a regular basis. UAE's heat is unbearable because of the Arabian Gulf's humidity. The UAE is considered one of the countries that have the highest possibility of being affected by climate change. This will result in warmer weather and other related issues such as biodiversity loss. There has been a warming trend in the weather as indicated by temperature increases between the past few years and the maximum temperature record (UAE MOCCAE, 2021). There is a prediction by the Emirates Wildlife Society and World Wildlife Fund (EWS-WWF) that there will be an increase in temperatures by 2 °C by 2050 with a rise in the humidity by 10% in a report titled "UAE Climate Change: Risks and Resilience". The rise in temperature will be responsible to increase the energy used for cooling systems by 20% or more. This will increase the annual energy consumption inside the buildings by 11%, which will rise the costs to building owners and end-users for the whole UAE building sector by over $834 million per year (EWS-WWF & Acclimatise, 2017).

Figure 1 shows the change in the surface temperature in UAE, the left Y-axis represents the recorded mean annual temperatures while the right Y-axis shows the deviation of each point in relation to 1951-1980. According to this figure, the annual temperature increased from 26.5 °C in 1930 to almost 28.8 °C in 2019, which is the highest recorded annual temperature based on the figure.

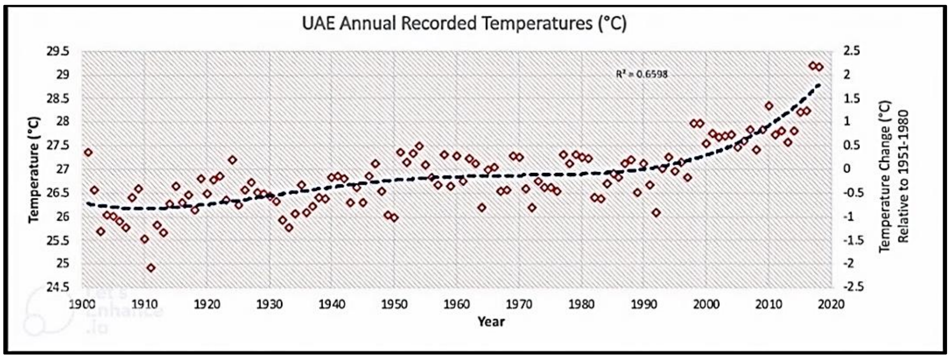



Figure 1: UAE's Annual Temperature Changes, 1900-2020. Source: (UAE MOCCAE, 2021)

In fact, climate change, especially global warming, will force people to stay inside buildings longer and it would impact increasing energy consumption to maintain the indoor environment as comfort (UAE MOCCAE, 2021). It means longer staying indoors and more dependence on Air Conditioning (AC). The second one is about the increase in people's exposure time to indoor environmental pollution such as indoor air pollution. Figure 2 represents results from a survey in a study that looked at where people spend most of their time these days. From the figure, people spend 20-30% of their time from 7 am to 5 pm in schools and public buildings, and this shows the importance of providing a high-quality indoor environment in these places. Additionally, the figures show that people spend most of their time in residences during the day. In addition, around 40% of respondents spend time in the office or factory between 7 am and 5 pm.

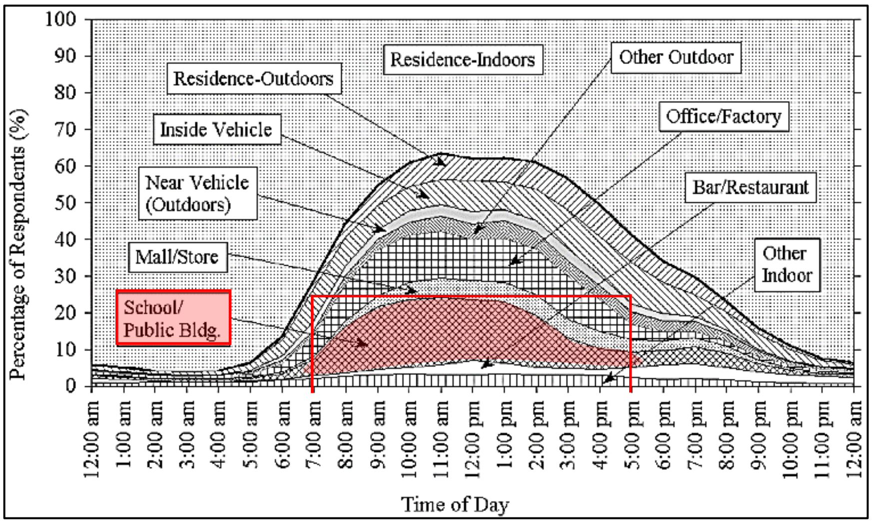



Figure 2: Amount of Time Respondents Spend in Each Place. Source: (Klepeis et al., 2001)

## 2.2 Indoor Environment Quality (IEQ)

Indoor Environment Quality (IEQ) involves the situations inside the building (such as indoor air quality, thermal, visual, and acoustic conditions) and their influence on people's well-being and satisfaction (Mujeebu, 2019).

As the green building concept has become more popular to encompass not just the environment, but also the well-being of the residents, the methods of classifying the IEQ have expanded as well. To address a concept such as this, ensuring people's health, safety, and comfort, enhancing their quality of life, and reducing users' chances of having physical and mental issues inside the buildings are key. A better IEQ can ensure higher productivity and performance levels since that will make the experience of using and interacting with the building's indoor environment more professional (Mujeebu, 2019).

### *2.2.1 International and National Level of IEQ*

It seems that air-related issues are the most popular out of all the other issues (thermal, acoustic, and visual), mainly due to the diverse illnesses caused by polluted indoor air. To show the size of the indoor air pollution issue here is an example, there are around 6.5 million people die each year due to indoor and outdoor air pollution. It is estimated that around 3 million are caused by outdoor air pollution and 3.5 million by indoor air pollution. The air pollution issue is not only considered health-related but also a social and economic issue such as a reduction in productivity and performance level as well as an increase in the absenteeism rate (IEA, 2016).

Based on the data in Figure 3 the World Health Organization (WHO) and the Institute for Health Metrics and Evaluation (IHME) determined that approximately 7 million and 6.7 million people, respectively, die every year because of indoor and outdoor air pollution. From these numbers, indoor air pollution is responsible for 3.8 million and 2.3 million based on WHO and IHME respectively. Figure 4 illustrates several studies on the fatalities caused by air pollution and divides them into two categories, indoors and outdoors. Based on these studies, the parameter responsible for most of the deaths is Particulate Matter (PM).

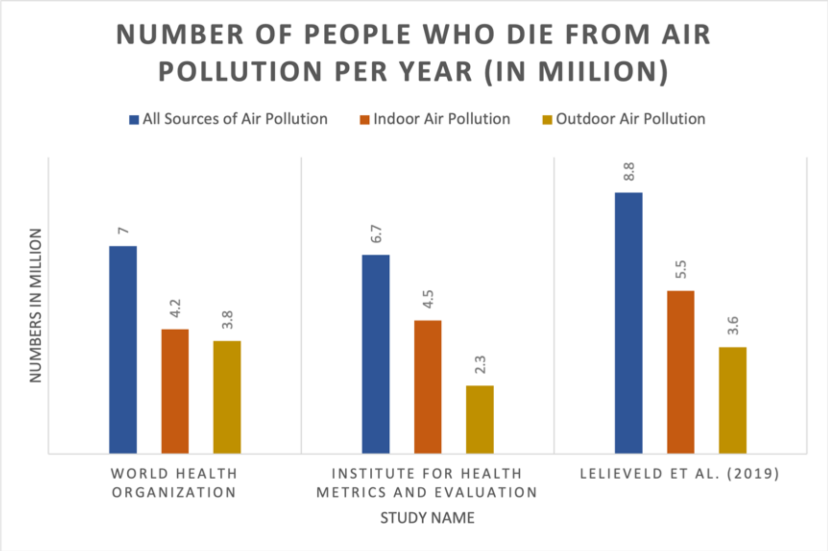



Figure 3: Deaths Related to Air Pollution Around the World. Source of Data: (Roser, 2021)

A diverse range of health problems might be caused by poor IEQ. The most known ones are those related to poor IAQ such as lung cancer, respiratory syndrome, legionnaires' disease, and many others. An ideal IEQ can improve occupants' health, productivity, learning, and working performance (Mujeebu, 2019). Today, 14% of healthcare costs are driven by conditions related to IEQ (Underwriters Laboratories, 2016). The IEQ of a building affects the productivity of users, according to previous studies. It found that a comfortable indoor temperature, an adequate ventilation rate, and less indoor pollution result in a performance increase of 5% to 10%. In addition, there is a 1% decrease in productivity when dissatisfaction increases by 10% (Olesen, 2018). A meta-analysis performed in 2005 found that there was a 1% to 3% improvement in productivity for each additional 10 L/s-person of ventilation, from approximately 6.5 L/s-person up to 65 L/s-person. Also, when the temperature reaches 30 °C only 91.1% of relative productivity is observed (Seppanen et al., 2006). A study in the United Kingdom showed that an optimal IEQ could increase productivity by about 20%. Another study showed that indoor temperatures between 18 °C and 30 °C could improve performance for certain workplace tasks such as typing, reading, and learning, while temperatures between 21 °C and 25 °C could be considered stable for general office productivity. Furthermore, productivity decreases by 2% when indoor temperatures rise by 1 °C in the range between 25 °C and 30 °C (Al Horr et al., 2017).

In the UAE, people spend nearly 95% of their time indoors. This is due to the high outdoor temperatures, dust events, and limited outdoor activities in some areas of the country (Bani Mfarrej et al., 2020). Nowadays, people have become more curious about the different factors, effects, and issues related to IEQ. They want to know how to have better and safer spaces to live in without feeling the pressure of this problem. This is because people realize the importance of what they face every day inside those buildings (Funk et al., 2014).

The COVID-19 pandemic, for instance, is affecting most of the world as most people are working and studying inside buildings, mainly from their houses, which means many are using their houses (or the small spaces that ensure they are protected from others and the outside) as shelters, and this exposes them to indoor pollution as some of the indoor pollutants are is 2 to 5 times higher than the outdoor concentration (US EPA, 2021).

Regarding the effect of occupants' comfort and performance on energy consumption, the following examples are gathered from previous studies:

- Based on a study in South Korea, it has been noticed that the occupants with a high level of perceived control over the thermal environment felt that the summer temperature is comfortable more than the occupants with low perceived control by 0.9 °C. Also, simulation using EnergyPlus showed that the cooling energy consumption could be reduced by 9% by increasing the occupants' perceived level of control over the thermal environment (Yun, 2018).
- In a study done in the Netherlands in the 1980s of 145 households, it was concluded that some human factors such as attitudes of residents towards energy based on prices, environmental concerns, health concerns, and comfort, might impact up to 5% of the variation in consumption (Van Raaij & Verhallen, 1983).
- Based on a study in an Australian educational lecture theatre, comfortable setpoint temperatures and roof construction might result in a 14.2% and 20% reduction in operative temperature, respectively. Resulting in fewer thermal discomfort hours as well as a 43.7% and 41% reduction in energy consumption, respectively (Alghamdi et al., 2022).

## 2.3 IEQ-Related Terms and Aspects

The concept of IEQ has related terms that make it easier for the public to understand it. These terms are related to the different aspects that shape the IEQ. So, there are various parameters (including IAQ, thermal, acoustic, and visual) that need to be considered when studying the IEQ of a building and the related well-being issues. Some of those will be discussed below in detail.

### *2.3.1 Sick Building Syndrome (SBS) and Building Related Illness (BRI)*

Sick Building Syndrome can be defined as the matter in which people in a specific building or space feel unwell or sick due to their exposure to the interior environment. It can be related to the type of furniture and its toxicity, as well as to materials used inside, such as paints and lighting, or even to gasses in the indoor air, such as Volatile Organic Compounds (VOCs). These can cause some simple types of tiredness and fatigue or some serious diseases. Based on previous studies, designers and engineers must design buildings in a way to reduce occupants' exposure to indoor toxic chemicals. This is mainly done by monitoring indoor air and water piping, as well as choosing the most appropriate materials for the interiors (Horr et al., 2016).

Building Related Illness is a term that considers all the health effects and disorders that have a clear link with a specific building or indoor space. Those illnesses are mostly happening in the skin and respiratory tract since it is easy for IEQ parameters to be in direct contact with these tissues (Lara, 2022). Four main mechanisms describe how the factors that cause BRI are induced, and these are immunologic, infectious, toxic, and irritant. Some of those factors that cause BRI can work through more than one mechanism (Tran et al., 2020).

Table 1: Sick Building Syndrome Verses Building Related Illness (Lara, 2020)

| | Sick Building Syndrome | Building Related Illness |
|---|---|---|
| Both Are | - Illnesses associated by buildings due to the indoor environment parameters. | |
| Main Different | - Effects that linked to time spend inside the building.<br>- No specific illness or cause can be specified. | - Effects can be occurred even outside the space.<br>- Symptoms of diagnosable illness identified. |
| Indicators | - Occupants complains of symptoms regarding severe discomfort.<br>- Unknown cause.<br>- Complains usually gone or reduced after leaving the space. | - Clinically defined and identifiable causes.<br>- Complains take long time to recover after leaving the building. |
| Diseases/Illness | - Headache.<br>- Eye, nose, and throat irritation.<br>- Dry cough.<br>- Dry/itchy skin.<br>- Dizziness and nausea.<br>- Difficulty in concentrating.<br>- Fatigue.<br>- Sensitivity to odors. | - Cough.<br>- Chest tightness.<br>- Fever.<br>- Chills.<br>- Muscle aches.<br>- Legionella infection.<br>- Occupational asthma.<br>- Hypersensitivity pneumonitis.<br>- Inhalational fever. |
| Causes | - Inconvenient ventilation.<br>- Indoor and outdoor sources or chemical contaminants.<br>- Biological contaminants such as showers. | - Mechanical ventilation systems. |
| Solutions | - Remove or modify pollutant sources.<br>- Increasing ventilation rates.<br>- Air cleaning.<br>- Education and communication | - Making sure that all the building systems and elements that been used inside the building is safe to use for human health.<br>- Reduce exposure.<br>- Treating symptoms.<br>- Remove the pollution sources.<br>- Improving ventilation. |
| Building Investigation Procedure | - IAQ investigation: HVAC system, possible pollutant pathways and contaminants sources. | |

### *2.3.2 Indoor Air Quality (IAQ)*

According to the United States Environmental Protection Agency (USEPA, 2021), IAQ refers to "the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants." The IAQ includes Particles ($PM_{2.5}$ and $PM_{10}$), $CO_2$, TVOC, Temperature, RH, and other parameters. A favorable IAQ can be defined as:

- Ensuring adequate ventilation (introduction and distribution of clean indoor air).

- Controlling contaminants traveling in the air.
- Zero-emission materials (source control).

Giving an example from (Government of Ras Al Khaimah Green Building Regulations, 2018); ensure a high level of IAQ for building occupants by following these requirements: All air-conditioned buildings must comply with the minimum ventilation rates of ASHRAE Standard 62.1-2013: All particular matter filters or air cleansers shall have a Minimum Reporting Efficiency Rating (MERV) of 6.

The IAQ could be impacted by multiple factors such as indoor activities, ventilation conditions, as well as the effect of outdoor air on the IAQ. Figure 4 shows indoor air pollutants, the sources of these pollutants, and their effects on health.

| | | |
|---|---|---|
| PM | Cooking stoves; fireplaces; smoking; outdoor air | Respiratory and cardiovascular illnesses |
| $SO_2$ | Cooking stoves; fireplaces; outdoor air | Impairment of respiratory function |
| $NO_2$ | Cooking stoves; fireplaces; outdoor air | Irritate the lungs and lower resistance to respiratory infection |
| CO | Cooking stoves; fireplaces; water heater; outdoor air | Highly toxic and fatal at a conc. 700 ppm |
| Ozone | Air cleaning device with high voltage; outdoor air | Asthma and allergic triggers |
| VOCs (such as formaldehyde, turpenes) | Building materials including carpet, plywood (emit formaldehyde); Paint and solvents; Clothing (after dry cleaning) (emits tetrachloroethylene, or other dry cleaning fluids); air fresheners, incense, other scented items; certain plants (emit turpenes) | Some are carcinogenic; can also trigger the formation of photochemical oxidants, such as peroxyacyl nitrates (PAN) and aldehydes, which cause eye irritation |
| Radon | Exuded from earth and rocks such as granite and gneiss in certain locations with low ventilated air and trapped inside houses | Radioactive; leading cause of lung cancer in non-smokers |
| Biological air pollutants (gasses and airborne particulates) | Pets (dander), human (dust from minute skin flakes and decomposed hair), dust mites (enzymes and μm-sized fecal droppings), inhabitants (methane), wall and air-duct (mold) | Increase risk for people with breathing problems, such as asthma sufferers, and with compromised or underdeveloped immune systems |

Figure 4: Indoor Air Pollutants, Sources, and Health Impact. Source: (Leung, 2015)

Indoor air pollution can cause a variety of short- and long-term health problems, ranging from simple to serious. It is therefore imperative that designers and engineers ensure early in the design process that the building will provide and contain high-quality air for its occupants. It is possible to improve IAQ by increasing the rate of ventilation inside buildings. As a result, the level of pollution in the indoor air will decrease. Another method is to reduce the sources of pollution within, inside, and outside of the building. It may be possible to address this issue by providing filters, air cleaners, and other equipment (Horr et al., 2016).

Table 2 represents some examples of the possible health effects of indoor air pollution:

Table 2: Health Effects Related to Indoor Air Pollution

| Parameters | Effects |
|---|---|
| Particles ($PM_{2.5}$ and $PM_{10}$)<br><br>(Xing et al., 2016; Morakinyo et al., 2016) | - Particles deposited on the lung surface can induce tissue damage and lung influence.<br>- Associated with premature mortality, increased hospital admissions for heart or lung causes such as lung cancer, acute and chronic bronchitis, asthma attacks, cough, emergency room visits, respiratory symptoms, and restricted activity days. |
| $CO_2$<br><br>(Annesi-Maesano et al., 2013) | - Impairs attention span and academic performance.<br>- Increases concentration loss and tiredness.<br>- Increase the probability of communicable infection, asthmatic symptoms, and absenteeism. |
| VOC<br><br>(Annesi-Maesano et al., 2013) | - Cause dry throat and runny nose or illnesses such as cancer and asthma attacks. |

Poor $CO_2$ concentration which is an indicator of the ventilation rate inside a space that is occupied by people has effects on occupants. For instance, low outdoor air ventilation rates and thus high indoor concentrations of $CO_2$ impair attention span and cause concentration loss and tiredness. There is evidence that if the ventilation rates were increased from 5 liters per second for each occupant (L/s-p) to 15 L/s-p it improves the academic performance of the occupants by 7%. Further, when the $CO_2$ levels are around 1000 Parts Per Million (PPM) cognitive performance might be affected. Moreover, higher rates of communicable infection, asthmatic symptoms, absenteeism, and impaired academic performance are all linked to high levels of $CO_2$. On the other hand, studies showed that every reduction in indoor $CO_2$ levels by 100 ppm is linked with a relative reduction in illness absence of students by at least 1.0% to 2.5% (Chatzidiakou, Mumovic, & Dockrell, 2014). As shown in Figure 5, air containing different amounts of $CO_2$ (air 0%, low 9%, medium 17.5%, and high 35%) affects healthy people in different ways.

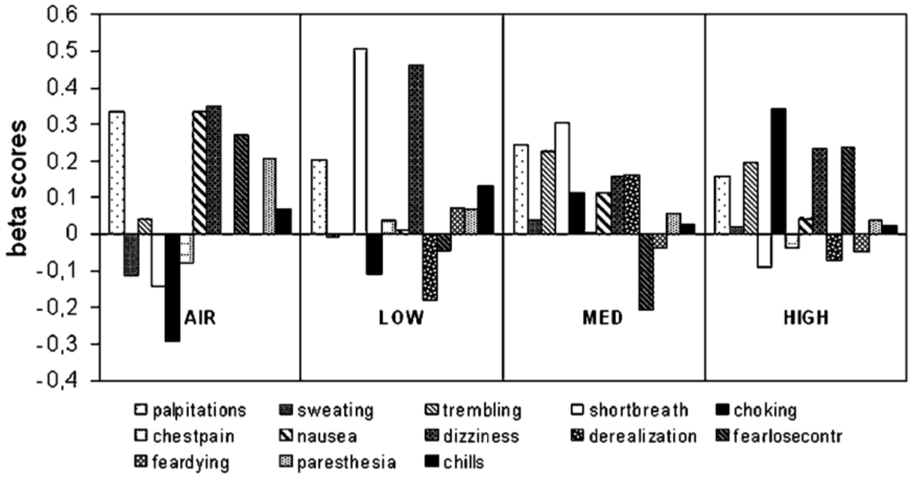



Figure 5: Carbon Dioxide Inhalation Effects on Healthy People. Source: (Colasanti et al., 2008)

*2.3.3 Thermal Environment*

According to (ASHRAE Standards 55, 2020), thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment."

It is known that thermal comfort is one of the most critical factors that can affect the productivity of occupants. At the same time, it is very easy to achieve if a specific procedure is followed. There is a comfort zone for each one, it can be different depending on age and gender (Horr et al., 2016).

It is imperative to assure comfortable indoor thermal conditions because students spend each day around 20-30% of their time inside educational buildings (percentage based on Figure 3), where they need to be productive and hard-working. Thermal comfort in educational buildings has been closely related to energy saving which has been the focus for the past few years. The previous studies on the thermal environment in educational buildings showed that many buildings are not meeting the standards for thermal comfort (Zomorodian, Tahsildoost, & Hafezi, 2016). A common issue encountered in hot countries like the UAE is the AC system's high electricity consumption. More than 80% of the total electricity demand of buildings is required to meet the cooling demand (Aldawoud et al., 2020). Figure 6 is based on a study of different buildings in the UAE. In all the different buildings the energy used for the HVAC is the highest. In the classroom building, the energy used to operate the HVAC system is 62.46% of the total energy consumption.

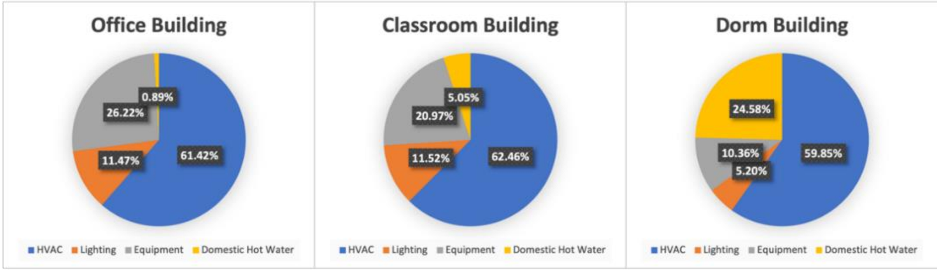



Figure 6: Baseline Energy Consumption Distribution by End Use. Source: (Al Amoodi A. & Azar E., 2018)

In the event that a suitable temperature value is not achieved, it might present health risks due to the high density of people occupying the same environment or a certain hyper-sensitivity of students to higher temperatures (Zomorodian et al., 2016). Moreover, thermal comfort in classrooms needs to be considered carefully because of their high occupant density, and the adverse effects that uncomfortable or unsatisfactory thermal environments have on learning performance and outcomes. The quality of the indoor thermal environment in educational buildings is directly associated with student health and productivity (Ali & Al-Hashlamun, 2019). In addition, thermal comfort is linked to our health, well-being, and productivity and it is ranked as one of the biggest contributing factors influencing overall human satisfaction in buildings. Due to its influence on the integumentary, endocrine, and respiratory body systems, thermal comfort can impact multiple health outcomes. For example, exposure to cold air and sudden temperature changes can cause asthma in adults. Thermal discomfort is also known to play a role in Sick Building Syndrome symptoms, which will similarly cause decreases in productivity (WELL Standards, v2).

Some related facts from previous studies:

- In a study of 75,000 New York City students, there was a 0.2% reduction in test scores for every 1 °F increase in temperature (WORLD GBC, 2018).
- When students felt their classroom ‘was comfortable’ they get 4% more correct answers in a math test compared to those who were hot, based on surveying more than 4,000 Finnish students (WORLD GBC, 2018).
- Each 1 °C decrease in classroom temperature showed a 12–13 point increase in math scores in a study of more than 3,000 US students (WORLD GBC, 2018).

- Leading research indicates employees perform 6% and 4% less efficiently when the office is overheated and cold, respectively (WELL Standards).
- In 2016, a study of more than 4,000 Finnish students showed that respiratory complaints increased when the indoors were "too hot" or "too cold" (WELL Standards).
- Higher humidity levels increased the incidence of Sick Building Syndrome symptoms in a study of over 1,000 Polish students (WELL Standards).
- There is evidence that lower temperatures in the range between 25 °C to 20 °C enhanced students' performance by 2% to 4% for every 1 °C reduction (Chatzidiakou et al., 2014).

According to a study that investigated the effects of indoor thermal environment and IAQ on students' health, comfort, and cognitive performance. The following figures show the relation between users' performance with air temperatures and with thermal sensation, both from a previous study that was conducted in London in 2014.

Figure 7 shows the relationship between PMV and PPD. The PMV index is ranging from (-3) cold to (+3) hot, with (0) being neutral (comfortable). PPD represents the satisfaction level of the people in a space. When people feel neutral and comfortable (PMV = 0) the PPD is 0, which means that in the comfort zone, people feel 100% satisfied. On the other hand, when it is too cold (-3) or too hot (+3), the PPD reaches 100%, meaning that all the people in this space are not comfortable and unsatisfied.

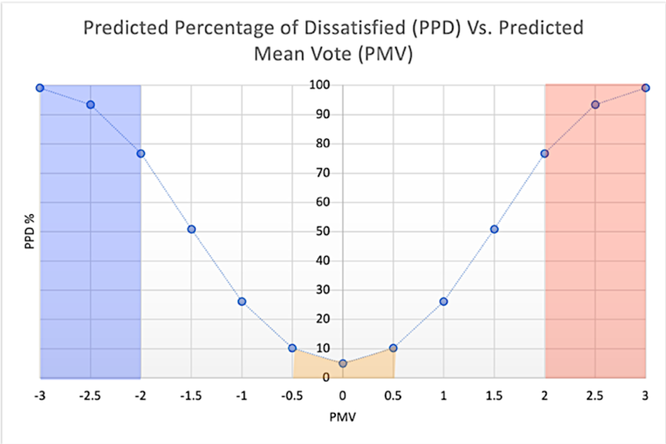



Figure 7: Predicted Mean Vote Verses Predicted Percentage of Dissatisfied

Table 3 shows the health effects of different temperatures (too cold and too hot) and humidity (dry and wet) levels.

Table 3: Illnesses Related to Different Levels of Temperature and Humidity

| Parameter | Level | People Affected | Effects |
|---|---|---|---|
| Temperature (°C) | Too Cold<br>(4 – 8 or less) | - People with certain diseases.<br>- Newborn babies.<br>- Outdoor workers and homeless. | - Direct Effects: Heart attack, stroke, asthma, respiratory disease, influenza, falls and injuries, sore throat, and hypothermia.<br>- Indirect Effects: Mental health and social isolation, and carbon monoxide poisoning. |
| | Too Hot<br>(40 or higher) | - Outdoor workers, student athletes, and homeless.<br>- Young children, pregnant women, older adults, and people with certain medical conditions. | - Heat stroke and dehydration, cardiovascular, respiratory, and cerebrovascular disease.<br>- Increase numbers of deaths for diabetes patients. |
| Relative Humidity (%) | Too Dry<br>(Below 30) | - People with breathing illnesses (ex. asthma). | - Dry eye and skin, sore throat, and nosebleeds.<br>- Asthma symptoms, especially spasms.<br>- Fluid that hydrates bronchial tubes can quickly evaporate; this can leave airways vulnerable to irritation.<br>- Symptoms of bronchitis, sinusitis, and other respiratory illnesses can worsen.<br>- Higher stress level. |
| | Too Wet<br>(Above 70) | - All people. | - Increases the rate of SBS symptoms.<br>- Cause mold growth which causes health issues such as headache. |

Figure 8 - Top shows that when air temperatures are 21 °C and 24 °C, no performance decrement occurs; however, when the air temperature is too cold (for example, 15 °C) or too hot (for example, 35 °C), there is a performance decrement of 25% and 21%, respectively. Figure 8 - Down illustrates that when thermal sensation is approximately 0, which refers to comfort level, the relative performance percentage is the

highest (almost 100%). When the sensations are in the too-cold level (-3) or in the too-hot level (+3), the relative performance percentages are the lowest (around 60%).

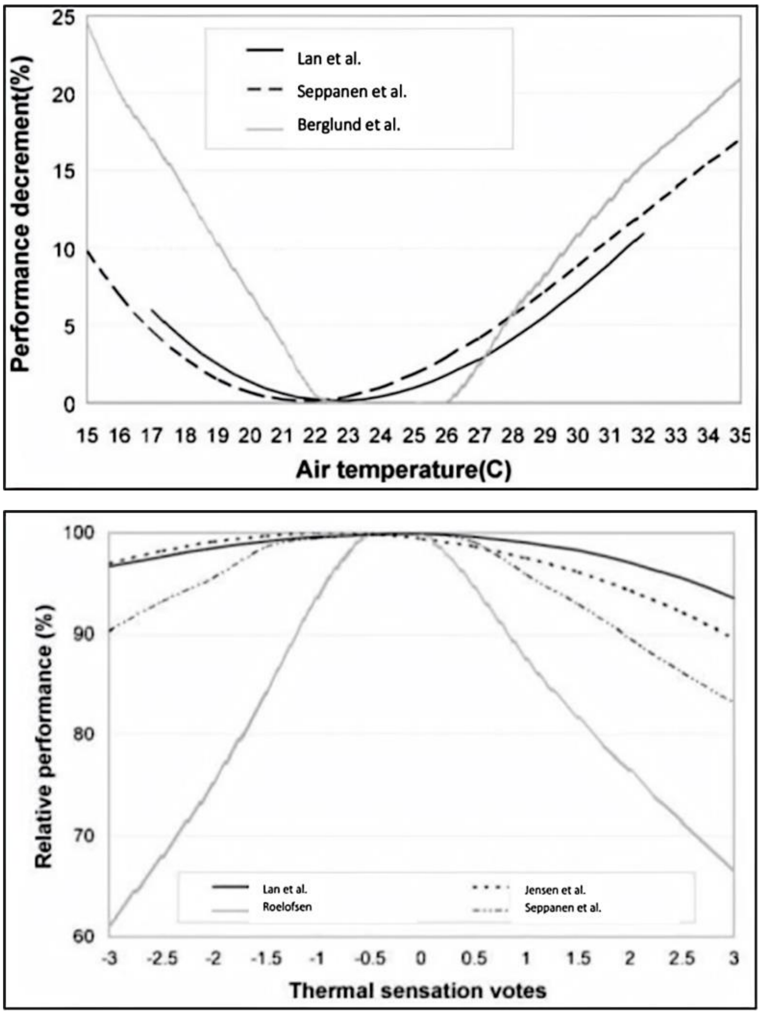



Figure 8: Comparison of the Relationship Between Air Temperatures (Top) and Thermal Sensation Votes (Down) with Relative Performance Developed in Three Studies in Office Workers. Source: (Chatzidiakou et al., 2014)

### *2.3.4 Acoustic Comfort*

The concern for acoustic comfort relates to how to protect buildings' occupants from outside noise, such as traffic noise. It also relates to how to keep inside noises from transferring from one place to another or to the outside (Horr et al., 2016). Selecting the right construction materials and following certain standards, can be accomplished. Moreover, it ensures the acoustic performance and specification of the insulation used for the different elements of the building, such as the walls, the roof, and the windows (Ricciardi & Buratti, 2018).

Noise generally has a negative impact on human health. It can cause irritability and fatigue in the entire body, especially hearing (Witkowska & Gladyszewwska-Fiedoruk, 2018). In addition, student health and behavior can be negatively affected by poor acoustics in classrooms. It can stimulate hearing loss, changes in heart rate, higher blood pressure, higher stress responses, and Attention Deficit Hyperactivity Disorder (ADHD). Moreover, poor acoustics results in lower student achievement. In Florida, a study of students at schools with loud HVAC systems had lower achievement rates than students in quieter classrooms. Students in a UK school located on a flight path misheard one in four words, affecting language acquisition skills (WORLD GBC, 2018).

Figure 9 shows some of the health effects that occur when people are exposed to certain noise levels (dB) over a period. It shows that a noise level of less than 60 dB has no major harm. However, once it reaches 60 decibels, simple symptoms such as stress and annoyance start to occur.

| level | Noise source | Health effects |
|---|---|---|
| 140dB | Jet plane take off, firecracker, gun shot | Sudden damage to hearing |
| 130dB | Pain threshold exceeded | |
| 120dB | Ambulance siren, pneumatic drill, rock concert | |
| 110dB | Night clubs, disco | |
| 100dB | Motorcycle at 50km/h | |
| 90dB | Heavy goods vehicle at 50km/h | |
| 85dB | Hearing protection recommended in industry | Hearing loss, tinnitus |
| 75dB | | Cardiovascular effects |
| 70dB | | Sleep disturbances |
| 65dB | | Stress effects |
| 60dB | | Annoyance |
| 55dB | Desirable outdoor level | |
| 50dB | Normal conversation level | |
| 40dB | Quiet suburb | |
| 30dB | Shoft whisper | |
| 20dB | Normal conversation level | |

Figure 9: Examples of Health Effects Related to Noise Exposure. Data Source: (Schneider et al., 2006)

*2.3.5 Lighting Comfort*

In educational buildings, lighting comfort is one of the main factors affecting occupant productivity, especially where computers or other electronic devices are required to complete the work. These factors include illumination, glare, reflection, flicker, and color. Lighting comfort can also have an impact on occupants' well-being, because it may cause them some sort of eye discomfort and tiredness which can lead to headaches and other related vision diseases and issues (Horr et al., 2016).

Lighting results in both positive and negative effects on users in buildings. This is dependent on how it is used, and the details are taken into consideration when designing the lighting system for the building. There are multiple ways for lighting to affect the building's users' mood, concentration, productivity, and energy. For instance, students in the US showed a 36% improvement in oral reading fluency when exposed to high-intensity light, whereas those in regular lighting conditions enhanced by only 16% (WORLD GBC, 2018).

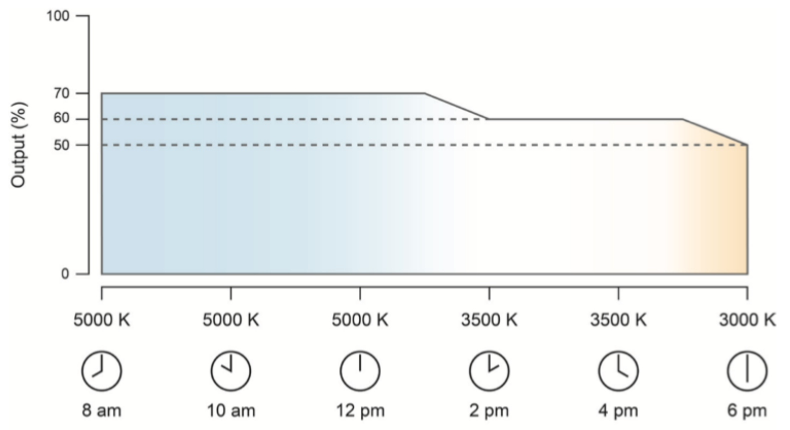
The low average light level (illuminance) in the area could cause slow reading, and decreased concentration, while the excessive variation of the average light level is related to reduced visual performance, hyperactivity, and discomfort. To avoid distraction and contrast a uniform level of illumination should be achieved in the area. Glare and reflections are strongly correlated with symptoms like headaches, diminished productivity, eyestrain, and diminished concentration. Furthermore, flicker could cause visual disturbance, irritation, and discomfort. The last factor of lighting comfort is color. The color of the light is significant because it plays a major role in the learning environment, and it could lead to an effective learning environment (Baeza Moyano et al., 2020; Schweitzer et al., 2004).

Added to that, people's moods and attitudes can be affected by lighting. For example, daylighting is related to enhancing moods, reducing eyestrain, reducing fatigue, and improving morale. The "Seasonal Depression" illustrates the relationship between daylight and the human endocrine system. This depression is caused by the lack of daylight. In Finland, 10% of the population suffers from seasonal depression, and in the United States, 6% of the population does (Shishegar & Boubekri, 2016).

Another term that can be directly related to lighting comfort is Circadian Rhythms, which refers to "24-hour cycles that are part of the body's internal clock, running in the background to carry out essential functions and processes." The sleep/wake cycle is considered one of the most significant and well-known circadian rhythms. Various systems in the human body are regulated by the circadian rhythm that synchronizes with the brain's primary clock. This clock is directly affected by the environment it is surrounded by, especially light. This is why circadian rhythms are connected to the cycle of day and night (Rijo-Ferreira & Takahashi, 2019).

Students' health and academic performance can be adversely affected by poor lighting in schools, with the level of impact depending on how inadequate the visual environment is. Poor lighting can affect the sleep/wake cycles of the building's occupants and their circadian rhythm. That's why when designing the lighting for a space the Circadian Stimulus (which is a metric that was proposed to help achieve healthy buildings in the field of lighting designs) must be taken into consideration (Baeza Moyano et al., 2020; Figueiro et al., 2016; Schweitzer et al., 2004).

Figure 10 shows an example of a customized Circadian Stimulus (CS) dosage schedule, with the x-axis showing different lighting colors (in Kelvin), and the y-axis representing the intensity (in %).




| | | | | | | |
|---|---|---|---|---|---|---|
| CS | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.15 |
| $E_H$ | 400 | 400 | 400 | 350 | 350 | 300 |
| $E_V$ | 280 | 280 | 280 | 245 | 245 | 210 |

Figure 10: An Example of Customized CS Dosage Schedules. (EH) Horizontal Lux amount, (CS) Circadian Stimulus, and (EV) Vertical Lux. Source: (Figueiro et al., 2016)

High levels of electric lighting have been found to have psychological and physiological effects. Higher alertness and physiological arousal, as well as better performance, faster response times, and enhanced accuracy under high illuminance (1000 lux) compared with low illuminance (200 lux) white (4000 K color temperature) lighting in non-daylit workplaces. Increased daily light exposure by office workers led to improved sleep quality at night. Light exposures over 1000 and 2500 lux improved sleep quality, implying that bright light is beneficial for circadian entrainment (Baeza et al., 2020; Figueiro, 2017; Figueiro et al., 2016; Schweitzer et al., 2004).

Light is known to be the primary factor affecting the human sleep-wake cycle and other physiological rhythms. The biological effects of light are measured by the equivalent melanopic lux. This is measured at the vertical level of the occupants. The EML can be calculated using the following formula (Visual Illuminance (Lux) X Melanopic Ratio), where Melanopic Ratio is the ratio of melanopic response that helps control circadian rhythms. Later, this can be converted to Circadian Light (CLA), comparable to conventional photopic illuminance. The values of CLA can be used to determine the Circadian Stimulus (CS). The main difference between measuring lux and menapolic lux is that the illuminance lux is how well an area is illuminated. It could be written as one lumen per square meter. In contrast, melanopic lux is the biological effect of light on people (WELL Standards, 2020).

Melanopic Light Intensity in Learning Areas must meet one of the following requirements (WELL Standards, 2020):

- Models of light (including daylight): On the vertical plane facing forward (1.2 m) above the finished floor, 75% of desks or more should have at least 125 equivalent melanopic lux which equals 215 visual lux. This should at least be present for 4 hours a day for each day of the year.
- Ambient lights supply preserved illuminance on the vertical plane of equivalent melanopic lux equal to or greater than the lux recommendations, taking the age group category most suitable for the people serviced by the school.

Table 4 summarizes some of the issues that can affect people's well-being if the IEQ parameters are not at the comfort level.

Table 4: Issues Related to Indoor Environment Quality Parameters

| IEQ Parameters | Issues if Not Achieved |
| --- | --- |
| Thermal Comfort (Temperature and Relative Humidity) | - Thermal-related factors influence the heat transfer from the body to the environment, that's why maintaining those factors in the comfort zones is required growth (EPA, 2014).<br>- Based on Energy Protection Agency the indoor RH percentage should be maintained between (30 and 60) to reduce mold growth (US EPA, 2022).<br>- Uniformity of temperature is important to comfort (EPA, 2014). |
| IAQ | - Poor IAQ could cause several of non-specific symptoms (not clearly defined illness). (EPA, 2014) Some of the main effects are:<br>- Headache and Fatigue.<br>- Shortness of breath.<br>- Sinus congestion.<br>- Cough and Sneezing.<br>- Eye, nose, and throat irritation.<br>- Skin irritation.<br>- Dizziness and Nausea. |
| Acoustic Comfort | - Loud or inescapable sounds could cause stress, high blood pressure, heart disease, and sleep disturbances. Sometimes it might also cause impairments in memory, attention level, and reading skills (Jafari et al., 2019; Munzel et al., 2014).<br>- Sounds that exceeded 85 decibels might harm a person's ears. The most known health problem related to noise pollution is Noise Induced Hearing Loss (NIHL) (NIDCD, 2022). |
| Visual Comfort | - Poor indoor lighting could affect human health mentally and physically. Physical illness such as eye strain, headaches, and fatigue. While mental illnesses such as stress and anxiety. (Ticleanu, 2021; Osibona et al., 2021).<br>- Lack of the natural lighting inside the buildings has a negative effect on the mind and body, and might lead to conditions like Seasonal Affective Disorder (SAD) (Brown & Jacobs, 2011). |

Furthermore, the different IEQ parameters and conditions may have a wide range of effects on human health and well-being ranging from simple to dangerous illnesses, and from short-term to long-term symptoms. These physical and mental effects will lead to a decrease in the performance and productivity levels of building occupants.

## 2.4 IEQ-Related Terms and Aspects

To study the IEQ and its impacts on the occupants' comfort and well-being, different types of research and experiments have been carried out. Surveys and interviews have been conducted to study the satisfaction of the buildings' users. Also, to compare the perception of occupants with the real conditions, a monitoring experiment was conducted for thermal, IAQ, acoustic, and visual comfort. This was done by using special sensors to collect data in specific locations and then analyze the results. In the design stage, a simulation using specific programs and BIM tools can be used to avoid any complaints from the occupants after the building is occupied and operated. In addition, some researchers look at previous works and then make connections to sustainable building standards and regulations to see where the standards align well with well-being and where there are conflicts.

Depending on the study type, purpose, and main objective, the methods varied. Some choose to work with quantitative methods, others with qualitative methods, and even there are studies that use a mix of the two types of methods.

There are many different studies happening in this area of study in different types of buildings and different countries. Most studies that have been found are outside the UAE. As the study is focusing on IEQ, the difference in climate will not have a huge effect on the study. But one of the few effects of the climate is that the weather is hotter in the UAE. This means people will spend even more time than in colder places, as well as more use of mechanical systems for ventilation.

(Appendix A) shows a summary of several global and local case studies done previously using different methods to measure the different parameters of the indoor environment. The analysis of these studies concludes the following:

- Most of the studies showed issues related to indoor temperature and daylight, for instance, according to the Triantis et al. Study, 64% of the users rated the indoor temperature as warm or hot. In addition, 28% were not pleased with the air temperature (Triantis, Bougiatioti & Oikonomou, 2006). Regarding the lighting issues, in one of the studies, the lighting level is slightly low (251 lux) which is below the Malaysian standard (300-500 lux) (Sulaiman et al., 2013).
- The other clear issue in most of the studies was IAQ. For example, in a study, 73% of users found the IAQ to be unacceptable or barely acceptable (Triantis et al., 2006).
- Most of the studies showed good noise and acoustic levels and the users felt neutral or comfortable regarding this parameter. Only a few studies showed some issues with the acoustic environment such as Lee et al. study concluded that sound

pressure was higher than the background noise level in all teaching rooms (Lee et al., 2012). In one of the studies, it has been found that the sound intensity is 76.4 dB, which is higher than the Malaysian standards (50-70 dB) (Sulaiman et al., 2013).

- In some of the studies such as Lee et al., the users' complaints have a comparable impact on learning performance and there is a good and clear correlation between learning performance and the number of complaints (Lee et al., 2012). In Wang & Zamri's study, all IEQ parameters and overall satisfaction are significantly correlated with the occupants' study/work performance. The thermal and acoustic quality were the main parameters that contribute to the overall study/work performance (Wang & Zamri, 2013).
- Another important point from the studied previous research is that there is a clear relationship between the Green Building Rating Systems (GBRS) and the occupants' comfort and well-being. However, green buildings are not always guaranteed high occupants' comfort and well-being. There could be conflicts between the building's performance (such as energy efficiency) and the occupants' comfort and well-being. Moreover, the plan layout, the geometry of the building, and the materials used can affect the IEQ and occupants' comfort.

Table 5 gives a summary of the most used methods in previous studies, and the purpose of using each one.

Table 5: Used Methods in Previous Studies.

| Method Used | Purpose and Parameters | The Process |
|---|---|---|
| Literature Review | - Gathering information about the different parameters of the indoor environment (thermal, acoustic, visual, etc.).<br>- Searching the available standards, codes, and regulations (LEED, WELL Standard, ESTIDAMA). | - Search will be depending on the year of publication, journal's reputation, and top-cited papers. |
| Physical Measurements | - Using special devices to examine the indoor environment, such as the $CO_2$ level, IAQ, acoustic (dB), visual (lux), and temperature (ºC). | - Placing the devices in the place that is examined, then record all the readings. |
| Interviews | - Occupants' perception of the indoor environment and the level of comfort they feel it. | - Gathering information from occupants, then arrange it based on the issue or indoor environment-related parameter. Some researchers do coding using multiple categories to organize the information. |
| Questionnaires / Surveys | - Collecting data about certain things, such as the overall percentage satisfaction of the indoor environment.<br>- The average comfort level about each indoor environment parameter (thermal, acoustic, visual, air quality, etc.). | - Write the form of the questionnaire/survey, and make sure to first put personal questions information (age, gender, etc.). After that let a considerable number of building's users to fill in the questions. Analyze the findings and conclusions. |
| Simulation | - Evaluate different settings for space. | - Do a model of the space in one of the software, then change one parameter (window size, window location, lights arrangement, etc.), after that calculate the new recording to space and see the difference depending on the type of change. |

## 2.5 IEQ Issues in Green Building Rating Systems (GBRSs)

Currently, sustainability is one of the most important topics in the world. This is because people desire a healthier environment to live in. Since buildings are one of the most significant factors that affect humans and the environment locally, regionally, nationally, and globally, the focus becomes more intense on them. So, the UAE's government began importing and publishing some building regulations and standards. These building regulations and standards will be safer for their users and have less of a negative impact on the environment. A rating system was introduced in 1990 by Building Research Establishment Environmental Assessment Method (BREEAM) in the UK, then followed by others in different years and countries. The rating systems were initially focused mainly on environmental and economic aspects, but then they were improved to consider human health and well-being. Currently, there are standards and regulations that only instruct designers and engineers on how to make better living spaces and areas. Here is a brief description of some of the rating systems in use in the UAE.

### *2.5.1 ESTIDAMA*

ESTIDAMA means sustainability in Arabic. Abu Dhabi created this rating system to achieve sustainable urbanization by balancing the four pillars of sustainability: environmental, economic, cultural, and social. In an era in which the built environment is changing rapidly, ESTIDAMA focuses on reducing the use of resources, making sure the building has fewer negative impacts on the environment, improving the quality of life for people, and finally saving energy and water. All of these will help in providing a comfortable, healthy, and happy life for the occupants (ESTIDAMA).

### *2.5.2 LEED*

LEED stands for Leadership in Energy and Environmental Design. Buildings have a huge impact on the planet and people's health and well-being. This is because they consume many resources, generate a lot of waste during construction and operation, and cost too much to maintain and operate. Buildings with LEED will result in improved design, construction, and operation, resulting in improved health and productivity for users, resulting in less waste and negative impacts on the environment, and resulting in a reduction of the building's life cycle cost. It is available for different types of buildings, so it contains specific criteria for the different types. LEED consists of several categories such as sustainable sites, energy efficiency and atmosphere, water efficiency, innovation, and operations, IEQ, waste reduction for resources and materials, and awareness and education. A LEED-certified building provides a healthier and safer indoor environment for its occupants. LEED has different rating systems so that designers and engineers can choose the most appropriate one for their project types. It has levels depending on the points that have been achieved starting with certified, then silver, gold, and platinum (LEED).

*2.5.3 WELL Standards*

The Standard aims at enhancing people's health and well-being in buildings, and it lists many criteria for creating a healthy interior with a high IEQ. Its mission is to improve human health and well-being through the spaces that it has created for the community. It has ten aspects related to air, water, light, thermal comfort, sound, materials, movement, mind, community, and nourishment. It is important for buildings to be healthy, productive, and enjoyable places for people to live, work, rest, and enjoy their time. WELL standards offer steps to improve the interiors and exteriors of these buildings. The information contained in the WELL standards is the result of a great deal of research and experimentation in this field. The WELL standard has three levels, which are silver, gold, and platinum. Buildings will be measured for all the points covered by the standard, and then a certificate will be issued (WELL Standards).

*2.5.4 ASHRAE*

The American Society of Heating, Refrigerating and Air-Conditioning Engineers is an American professional association seeking to advance heating, ventilation, air conditioning, and refrigeration systems design and construction. Their vision is to build healthy and sustainable spaces for the people to serve them and ensure a high-quality life for everyone (ASHRAE).

*2.5.5 BREEAM*

BREEAM states for the Building Research Establishment Environmental Assessment Method. It was established in 1990 in the United Kingdom, and it is a voluntary GBRS. Its main role is to assess the buildings' environmental performance over a wide range of issues to achieve a rating of either pass, good, very good, excellent, or outstanding. The main criteria for this GBRS are the following: energy and water use, health and wellbeing, pollution, transport, materials, waste, ecology, and management processes. The health and wellbeing category contributes to a user's comfort, health, and safety. This category includes visual comfort, air quality, acoustic performance, etc. (BEEARM).

Table 6 compares the most used systems in UAE focusing on the different IEQ parameters such as thermal, IAQ, lighting, and acoustic.

Table 6: Comparison Between the Four GBRSs

| | ESTIDAMA | LEED | WELL Standards | ASHRAE |
|---|---|---|---|---|
| Thermal Environment | - Ventilation Exceeds minimum requirements by 15%. | - Thermal Comfort.<br>- Use of efficient air conditioning.<br>- Controllability of systems - thermal. comfort.<br>- Thermal comfort design.<br>- Thermal comfort verification. | - Thermal Performance.<br>- Enhanced Thermal Performance.<br>- Thermal Zoning.<br>- Individual Thermal Control.<br>- Radiant Thermal Comfort.<br>- Thermal Comfort Monitoring.<br>- Humidity Control. | - Elevated air speed comfort zoon.<br>- Operative temperature.<br>- Metabolic rate.<br>- Clothing insulation.<br>- Air temperature.<br>- Radiant temperature.<br>- Humidity. |
| Indoor Air Quality | - $CO_2$ sensors at all return points. | - Pre: Minimum IAQ Performance.<br>- Pre: Environmental Tobacco Smoke Control.<br>- IAQ Management Program.<br>- Enhanced IAQ Strategies. | - Fundamental Air Quality.<br>- Smoke Free Environment.<br>- Ventilation Effectiveness<br>- Construction Pollution Management.<br>- Enhanced Air Quality.<br>- Enhanced Ventilation.<br>- Operable Windows.<br>- Air Quality Monitoring and Awareness.<br>- Pollution Infiltration Management.<br>- Combustion Minimization.<br>- Source Separation.<br>- Air Filtration.<br>- Active VOC Control.<br>- Microbe and Mold Control. | - Air quality standards: carbon monoxide, lead, nitrogen dioxide, ozone, particle pollution, and sulfur dioxide.<br>- Air tightness.<br>- Inadequate ventilation rates.<br>- Ineffective filtration and air cleaning.<br>- Moisture in building assemblies.<br>- Moisture and dirt in ventilation systems.<br>- Indoor contaminant sources.<br>- Contaminants from indoor equipment and activities. |
| Acoustic Comfort | - Indoor noise pollution. | - Sound transmission.<br>- Background noise.<br>- Sound isolation.<br>- Room noise.<br>- Acoustical finishes.<br>- Site exterior noise.<br>- HVAC noise.<br>- Exterior noise.<br>- Reverberation time. | - Sound Mapping.<br>- Maximum Noise Levels.<br>- Sound Barriers.<br>- Sound Absorption.<br>- Sound Masking. | - Sound tests (diffusers and grills).<br>- Terminal unit testing. |

Table 6: Comparison Between the Four GBRSs (Continued)

| | ESTIDAMA | LEED | WELL Standards | ASHRAE |
|---|---|---|---|---|
| Visual Comfort | - Daylight and glare. | - Interior Lighting.<br>- Daylighting and Quality Views.<br>- Use of natural light.<br>- Light pollution reduction.<br>- Controllability of systems - lighting. | - Light Exposure and Education.<br>- Visual Lighting Design.<br>- Circadian Lighting Design.<br>- Glare Control.<br>- Enhanced Daylight Access.<br>- Visual Balance.<br>- Electrical Light Quality.<br>- Occupant Control of Lighting Environment. | - Daylight metrics: Daylight autonomy (DA), Continuous DA, Spatial DA, Annual Sun Exposure (ASE), and Useful Daylight Illuminance (UDI).<br>- Glare metrics: Daylight Glare Probability (DGP) and Annual Daylight Glare Probability (Annual DGP). |

## 2.6 Standards Based on the Previous GBRSs

Here are the standards for the relevant parameters based on the GBRS mentioned above in Table 7. In Chapter 3 (Methodology) and Chapter 4 (Results and Discussion), this table will be summarized and used to explain if the gathered data from the monitoring experiments are acceptable or not based on the thresholds.

Table 7: IEQ's Parameters Standards in the Mentioned GBRS.

| IEQ's Parameters | ESTIDAMA | LEED | WELL |
|---|---|---|---|
| Temperature (ºC) | - Depending on ASHRAE 62.1 2007 (21 or 25)<br>- Depending on ASHRAE 55-2004: the temperature must be (19–29) | - Depending on ASHRAE 62.1 2016 (25)<br>- Depending on ASHRAE 90.1 2016 (26-32) | - Depending on ASHRAE 55-2013 (20-25) |
| Relative Humidity (%) | - Depending on ASHRAE 62.1 2007 section 4.2 (Occupied space RH shall be limited to 65 or less) | - Depending on ASHRAE 62.1 2016 (Occupied space RH shall be limited to (65 or less) | - (30 - 60) |
| **$CO_2$ (PPM) ASHRAE recommends indoor $CO_2$ levels not exceed the outdoor concentration by more than about 600 ppm. | - The $CO_2$ level must not be allowed to exceed (1000), different from outdoor concentration by 650 | - Depending on ASHRAE 62.1 2016: No greater than about (700) | - Less than 800, different from outdoor concentration by 600 |
| $PM_{2.5}$ (µg/m$^3$) | - Depending on ASHRAE 62.1 2007 (15) | - Depending on ASHRAE 62.1 2016 (12-15) | - Less than 15 |
| $PM_{10}$ (µg/m$^3$) | - Depending on ASHRAE 62.1 2007 (50) | - Depending on ASHRAE 62.1 2016 (50) | - Less than 50 |
| Acoustic Environment – Noise Level (dB) | - Demonstrate that internal ambient noise levels do not exceed 50 in the area to be occupied.<br>- All spaces within the school must be designed to meet the requirements laid out in Building Bulletin 93 (35-40) | - Depending on ANSI Standard S12.60-2002: (35-40)<br>- Using Standard S12.60-2002, maximum background noise level in classrooms and other primary learning spaces of 45 | - For Classrooms (35-60) |
| Visual Environment (Lux) | - Demonstrate a minimum daylight illuminance of 300 on the working plane | - Depending on ASHRAE 90.1 2016: For classrooms LPD=1.2 w/m$^2$, using 300-500 | - Depending on EN 12464-1: 2011 (Classrooms 300) |

**A previous study conducted in one of the UAE University buildings over a period of one year (2019), focused on the energy gap by examining the building to determine the source of the discrepancy with dynamic energy performance. The $CO_2$ levels are within the comfort and safe ranges based on WELL Building Standard recommendations (Kim et al., 2020).

## 2.7 Summary of Chapter

Several aspects of Indoor Environment Quality (IEQ) were discussed in this chapter. The chapter began by mentioning the importance of studying IEQ based on international issues such as climate change and COVID-19, and how these issues affect the amount of time people spend in buildings. Going from there to the related issues of the indoor environment such as Sick Building Syndrome (SBS), Building-Related Illnesses (BRI), and how those can impact buildings users. Moving on to the Green Building Rating Systems (GBRS) and the way they affect the social category of the buildings that are related to occupants' comfort and well-being.

The chapter takes readers through a clear and detailed explanation of the IEQ meaning, the related parameters such as thermal, IAQ, lighting, and acoustic, and each parameter-related impact on human comfort and health. And to support the previously written information, various worldwide studies that focus on different building types and different methodologies were studied in detail in Appendix A and a summary of the table is written in this chapter.

After reading previous literature reviews and various journal articles, it became apparent that the aspects of the IEQ that will affect the occupant's comfort and well-being need to be studied and considered at the design stage of the building to avoid problems when the building is occupied and operated, and to avoid additional costs to fix the issues related to the user complaint. Additionally, sustainability cannot be achieved by considering environmental and economic aspects alone; the building needs to consider social health and well-being. Lastly, it has been concluded that making people satisfied is not as easy as it sounds, since they have different personalities and different needs. In general, however, an effort to provide high IEQ that protects occupants' comfort and well-being is possible and can have positive results.

# Chapter 3: Methodology

## 3.1 Overview of Research Methodology

In general, the research methodology can be defined as “the systematic approach to resolve research issues or a specific problem”. Research methodology determines how the research will be conducted scientifically. Research methodology involves a well-structured procedure for describing, explaining, and predicting a phenomenon, in addition to laying out a clear method for reaching a conclusion on a specific topic within the study. Another term that is directly connected to research methodology is research methods, which can be defined as "the various procedures, schemes, and algorithms used during research". When planning for a research methodology it is critical to consider the most appropriate method for the study or topic, the efficiency of the selected method/s, and the results’ accuracy (Rajasekar et al., 2006). Research methodology is a significant step in the research process. This is because it shows the level of confidence in the author's ideas and goals, as well as an appropriate understanding of the selected topic. A well-planned research methodology helps to explain research and results in a better way for people, which will lead to more efficient use and benefit of research results in future studies. There are a variety of research methods that can be used separately or together to achieve a successful study. These methods include literature review, case study, survey or questionnaire including interviews, laboratory including monitoring experiments, and dynamic simulations using various types of software.

## 3.2 Overview of the Research and the Selected Methods

To plan a proper research methodology and to select the most appropriate methods it is first necessary to limit the topic to a specific area by writing a main research question and objectives and doing a comprehensive literature review in the same study area to learn from previous studies and see what the most used methods in this topic are. By doing this, the research process will be clearer.

Three different methods were used to explore the IEQ of a university building: the online survey, monitoring experiments, and dynamic simulation. The online survey focused on the students’ satisfaction level and perception of the different parameters, such as indoor temperature, RH, air movement, IAQ, and lighting. In the monitoring experiment, two devices were used to gather data about temperature, relative humidity, $PM_{2.5}$, $PM_{10}$, $CO_2$, TVOC, and lighting intensity. They then compare that data to GBRSs to get an overall picture of the IEQ in the selected classrooms. Taking the information from the previous two methods, simulation scenarios were prepared. The scenarios focused on the issues that have been identified and relate to classroom layouts and desk directions, daylighting and artificial lighting zones, as well as indoor temperature. These scenarios were explored using software to see the change and the reduction in energy consumption. Furthermore, some of these changes may improve students' comfort, such as their circadian rhythm.

In this study, three different methods were used to gather data and collect information. The variety of methods helps in finding a relation between the actual values from monitoring experiments and the occupants' perceptions from the online survey. This gives a more comprehensive understanding of the IEQ of the case study building. While the simulation method reflected the possible changes using different scenarios, and their percentage of improvement in energy consumption. Figure 11 summarizes the research process.

- Phase 1: A literature review (information gathering by doing a background study using different online resources such as journals and books to get general ideas from previous research and their findings, results, and solutions to improve the issues of IEQ. This step was needed to build a clear research question and methodology.
- Phase 2: Online Surveying.
- Phase 3: Monitoring Experiments (for thermal, IAQ, and lighting).
- Phase 4: Simulation (for total energy consumption).
- Phase 5: Results and discussion (analyzing and discussing the results and relating them to each other to find the relationship between what users feel and the data from experiments). Also, discussing in detail how the different selected scenarios helped in reducing energy consumption using the simulation findings.

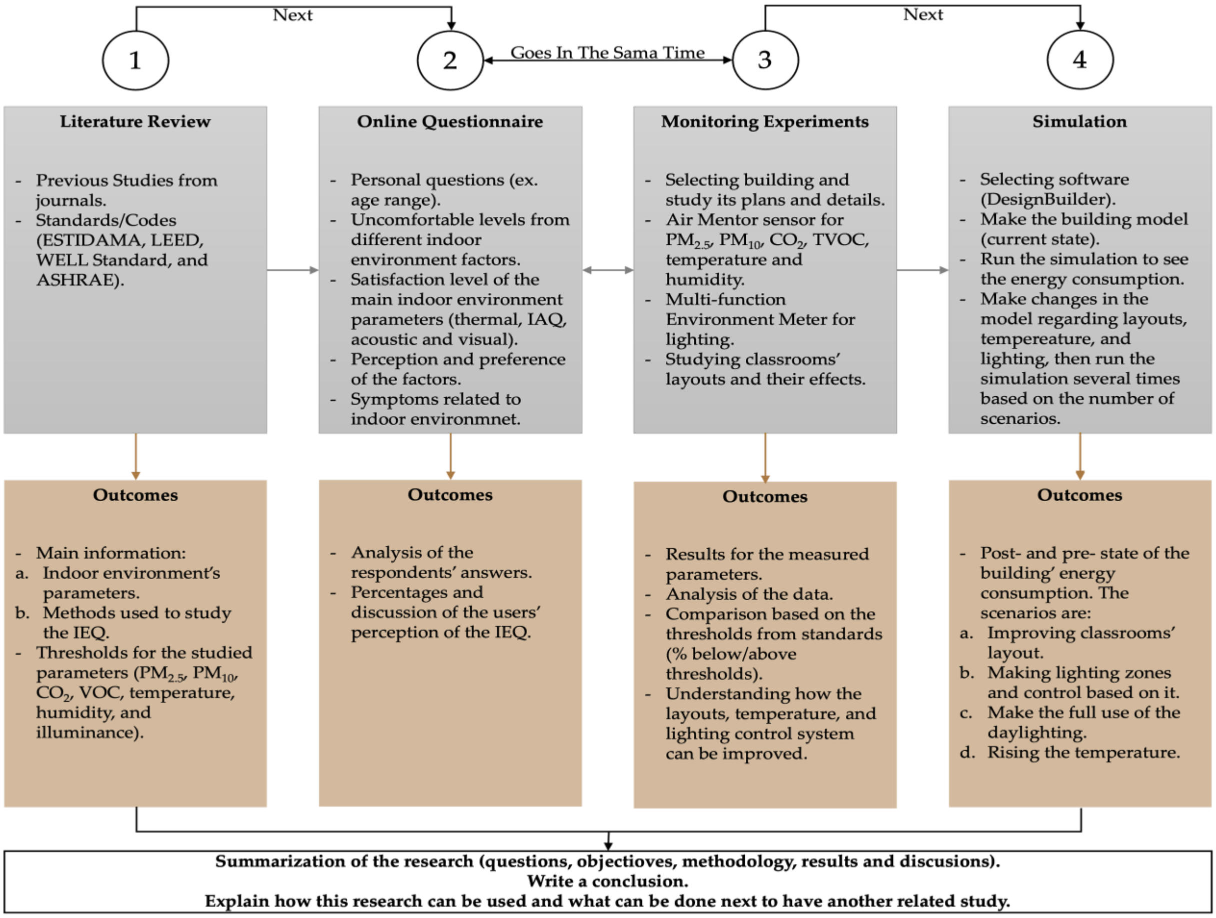



Figure 11: Research Procedure with Four Main Methods

### *3.2.1 Survey Methodology*

The survey/questionnaire can be a subjective study (qualitative) such as interviews, or an objective study (quantitative) such as gathering data using a written form of different questions. The most suitable type should be chosen by considering what will assist in achieving this research and how it will assist in achieving it. Before selecting a survey form or writing one, try to think of the main reason for doing the survey. Consider the focus of the questions, as well as the desired results.

The survey should be planned in detail, and to do this the following procedure could help:

- The objective of the survey: What to include and what to exclude.
- The frame of the survey: What is the limit of the needed data?

- The sampling design: Searching the available tools that can help in this study, looking for some examples of surveys done before in this area of research such as Building Use Studies (BUS) and European Audit.
- The design of the survey questionnaire: What are the groups of questions and how many parts the questionnaire should have, what type of questions to ask and what to avoid, and how to organize the full questionnaire?
- Data collection: How data will be collected from participants (for example, using a form or online link).
- Analyzing the gathered data: Summarization of the answers using numbers or percentages.
- Documentation: Write a detailed discussion about the collected data and the main findings.

#### *3.2.2 Monitoring Experiments Methodology*

In monitoring experiments, the research objective should define a case study building (or a specific sample that is to be analyzed) and then choose suitable ways to conduct the field study, for example, placing sensors in the case study to gather measurements and values that may be useful to the goal of the study. Observing the case study and collecting actual data can help in explaining the main topic in a better way to people since it uses an example. People who are unfamiliar with the research area can gain a clearer understanding of the phenomenon through observation and close-up study of the case study.

#### *3.2.3 Simulation Methodology*

Dynamic simulations could aid in understanding an assumption or idea better by displaying percentages and numbers, along with images and graphs. Also, it helps in showing various scenarios of the same case study at the same time, which can give a comparison between pre- and post-changes, and between different scenarios at the same time. A dynamic simulation can be carried out using one or more software programs that were made for the purpose.

### 3.3 Data Gathering

This research used an online survey and monitoring experiments to collect data on students' satisfaction and the building's current state, respectively. As a result of these findings, a simulation was used to see how some simple changes in the IEQ of the classroom, especially temperature, lighting, and layout, affect occupant satisfaction and energy consumption. The following sections give details about the methods and explain how each method is being applied in this research.

#### *3.3.1 Survey Study*

A survey was conducted using (QuestionPro) to gather information on how occupants perceive IEQ and the level of satisfaction with each parameter and the overall IEQ. When comparing the results of the monitoring experiments with the results of the questionnaire, it is vital to know if the occupants feel the IEQ or if their feelings do not represent the actual state of the IEQ. It targeted students who studied in the buildings and had experience in them; there were 217 respondents to the survey. The survey started in April 2021 and closed in August 2021. This questionnaire was based on (TOBUS) software, an interactive decision aid tool for building retrofit studies. The questionnaire is from (The Indoor Environment Handbook: How to Make Buildings Healthy and Comfortable) (Bluyssen, 2015).

The survey aimed at understanding students' feelings about the buildings' classrooms by using different groups of questions that focused on different areas related to comfort and satisfaction level. Figure 12 shows the questionnaire's main parts with examples of the scales used and the parameters in focus.

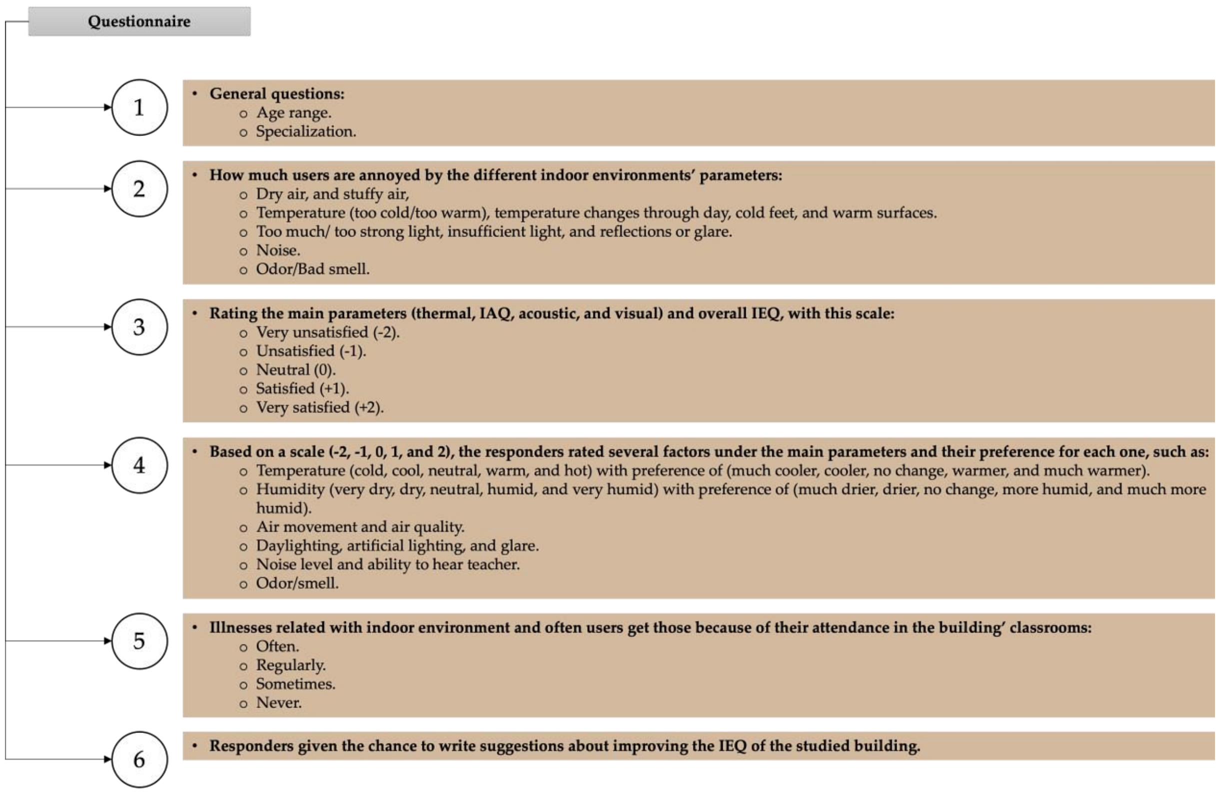



Figure 12: Questionnaire' Main Parts

Figure 13 shows some examples of the questions from different parts of the online questionnaire that was made using QuestionPro software. The whole questionnaire is shown in (Appendix B).

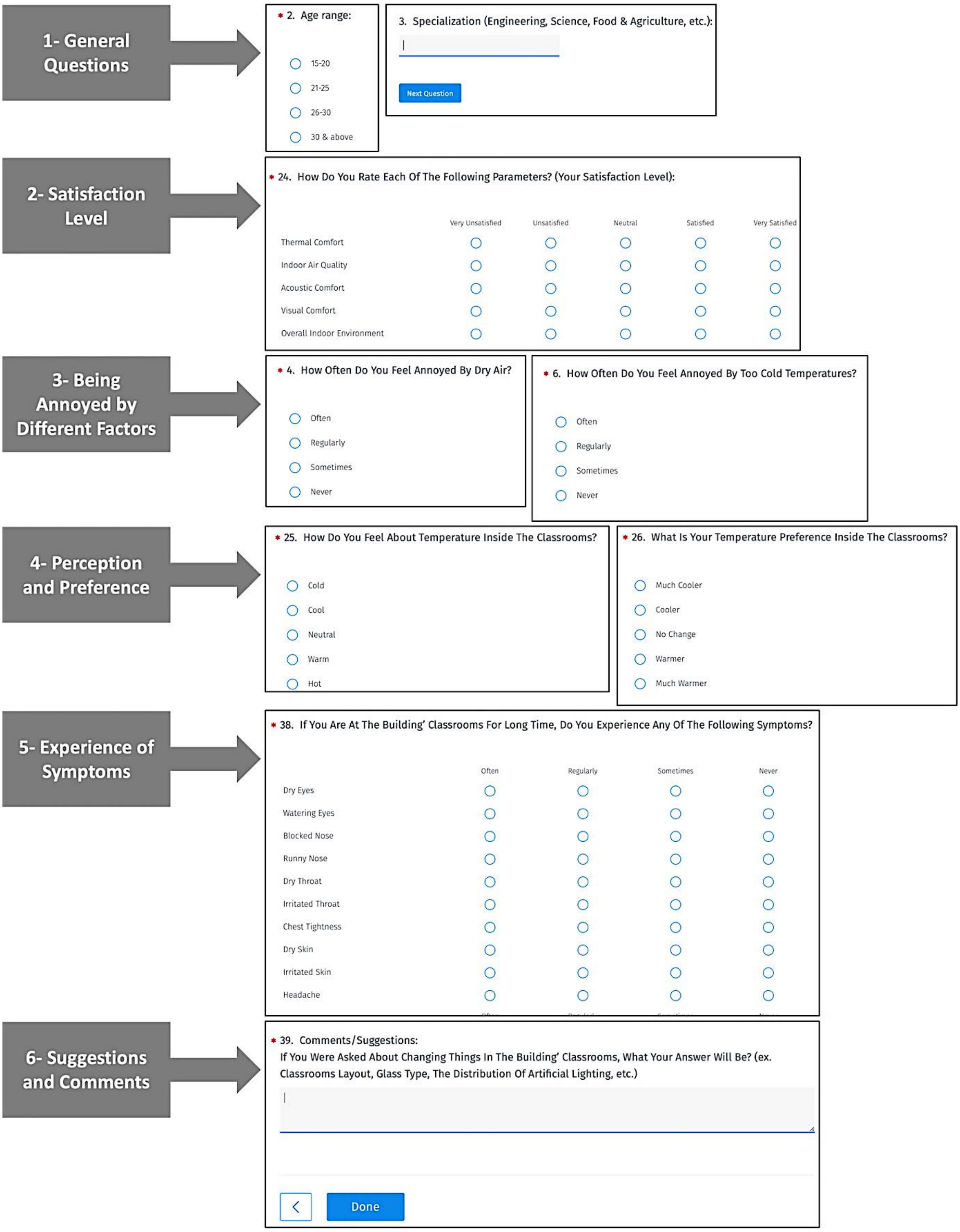



Figure 13: Questionnaire Screenshots from QuestionPro Software. Full Questionnaire is in Appendix B

The final step of the survey is the analysis of the results. So, after getting all the answers from the questionnaire, first, each section of the questionnaire was analyzed and discussed in detail with some graphs, tables, and words. For example, pie charts are used in Chapter 4 to show the percentage of satisfied people and unsatisfied people for each of the main IEQ parameters (thermal, IAQ, and lighting). A summary and a general conclusion are written to summarize and describe the main findings of the case study. This is later used to see the relation between what people feel and what the monitoring experiments find.

*3.3.2 Monitoring Experiments Study*

Monitoring experiments are a valuable tool for studying the current state of the IEQ of the building since it provides values for each of the studied parameters.

It should be noted that the case study building and classrooms were mostly unoccupied during the monitoring experiments due to the COVID-19 pandemic. And it could impact some records, especially artificial lighting. But in general, the building was operated on its normal schedule, so all the systems such as the HVAC system are working based on the everyday schedule of the building.

These experiments are divided into sections based on the type of the measured parameters, which are thermal-related, IAQ-related, and lighting-related.

After doing all the experiments and collecting all the readings, each parameter will be evaluated on its own based on the range used to evaluate the comfort level Table 7 in Chapter 2. Tables and charts were drawn to show the relationship between the gathered results and the standards. This makes it easier to identify the difference between the standards that were set as comfort levels and the actual situation of the building.

Table 8 outlines the monitoring devices and their specifications where they have been used as part of this research to gather data and to evaluate the level of IEQ.

Table 8: Details of the Monitoring Experiments for this Study

| | Thermal and IAQ Experiments | Lighting Experiments |
|---|---|---|
| Device Used | Air Mentor | Multi-Function Environment Meter |
| Device' General Information | - Dimension: 106 x 115 x 44.5 mm (HxWxD), and weight 205.5 g.<br>- Input Power: Micro USB 5V/1A.<br>- Battery: 3.7 V, 1500 mAh.<br>- Communication: BT 4.0 Low Energy (Bluetooth Smart).<br>- Operation Temp: 5 – 40 ℃.<br>- Temperature Sensor Range: 0 ~ 80 ℃.<br>- Humidity Sensor Range: 0 ~ 100 %.<br>- $PM_{2.5}$ Sensor Range: 0 ~ 300 µg/m3.<br>$PM_{10}$ Sensor Range: 0 ~ 300 µg/m3.<br>- TVOC Sensor Range: 125 ~ 3500 PPB.<br>- $CO_2$ Sensor Range: 400 ~ 2000 PPM. | - Measures RH as %, temperature in ºC or ºF, sound levels in dB, and light levels in Lux.<br>- All results are clearly displayed on the large LCD.<br>- Simple to operate with individual probes for each measurement parameter.<br>- has a data hold and max hold switch plus a low battery indication and it auto powers off to save batteries.<br>- Ideal for health and safety and environmental testing measurements in the offices, factories, workshops, councils, industrial units, and all sporting events. |
| Considered Parameters and Their Thresholds<br><br>Based on (Table 8 - Chapter 2) | - Indoor air parameters:<br>- $PM_{2.5}$: Thresholds ≤ 15 µg/m3.<br>- $PM_{10}$: Thresholds ≤ 50 µg/m3.<br>- $CO_2$: Thresholds ≤ 1000 ppm.<br>- TVOC: Thresholds ≤ 312 ppb.<br>- Thermal parameters:<br>- Temperature: Thresholds 21-25 °C.<br>- Humidity: Thresholds 30-65 %. | - Illuminance: Thresholds 300-500 lux. |
| When It Done | - In 2 periods:<br>- From (Monday 15/02/2021) until (Thursday 15/04/2021).<br>- From (Sunday 18/04/2021) until (Thursday 29/04/2021). | - Each classroom in different day:<br>- 0034: Sunday 21/02/2021.<br>- 0021: Sunday 25/04/2021.<br>- 1012: Wednesday 28/04/2021.<br>- 1015: Monday 19/04/2021.<br>- 1036: Tuesday 27/04/2021.<br>- 1037: Wednesday 21/04/2021. |
| Time Interval | - Workdays From 8 am until 4 pm every 15 minutes, then taking the average for each hour. | - For every classroom 3 readings in 1 day at 9 am, 12 noon, and 3 pm. |
| Examined Classroom | - First time: 0031, 0032, 0033, and 0034.<br>- Second time: 2 students sitting areas, 0006, 0021, 0034, 1015, 1037, and 1059. | - 0021.<br>- 0034.<br>- 1012.<br>- 1015.<br>- 1036.<br>- 1037. |
| Conditions | - No specific conditions. | - 4 conditions:<br>- Blinds open and lights on.<br>- Blinds open and lights off.<br>- Blinds closed and lights on.<br>- Blinds closed and lights off. |
| Device' Location | - 1 device per classroom was fixed on table and connected to app in iPad. | - 1 device used for all the classrooms, located on tables based on classrooms' layout. |

Figure 14 shows the locations of the monitoring devices to monitor the IEQ for one of the selected classrooms. Room (0021) is located on the ground floor. Light bulbs are represented by green squares with (F2), and intersections between 4 light bulbs are represented by red circles. The sensor was placed at these intersections (not directly under the lights) and on the desk. The arrangement of tables in classrooms (how students sit) is also considered. Regarding the thermal and IAQ experiments the AirMentor device was fixed on the back of the classroom (blue square) and the readings were collected on the iPad using an app.

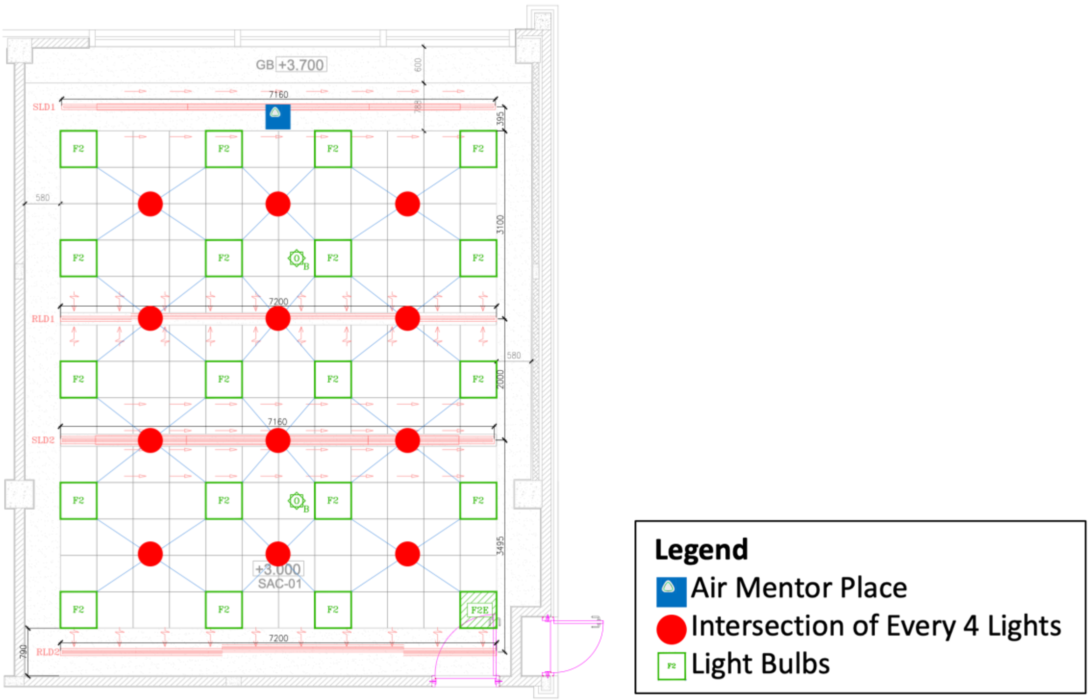



Figure 14: Classroom 0021 (Ground Floor)

Analyzing the data is the last step in monitoring experiments. Analyzing the gathered data clearly and scientifically is critical to draw meaningful conclusions from the research. So, for temperature, humidity, and IAQ factors ($PM_{2.5}$, $PM_{10}$, $CO_2$, and TVOC) results were used to draw graphs using Excel software to show where the results fall below/above thresholds and where they stay in the comfort level.

Below are the lighting results represented by the plans of the selected classrooms and the different colors of the lux levels to display where reading conditions were comfortable (300 to 500 lux) and where they were not. Also, for lighting calculation, the

Equivalent Melanopic Lux (EML) will be calculated with the following formula (EML = Visual Lux (L) X Melanopic Ratio (R)) to find if the circadian stimulus is at the average level that is required for a proper circadian rhythm. Figure 15-a represents the Melanopic Ratio (R) for the different light sources. In this case, the used type is the fluorescent type with 4000 K CCT. Figure 15-b shows the design recommendations for the various spaces (the recommendation for the learning area is used here and it is 125 lux or more).

**Melanopic Ratio by Light Source**

| CCT (K) | Light Source | Ratio |
|---|---|---|
| 2700 | LED | 0.45 |
| 3000 | Fluorescent | 0.45 |
| 2800 | Incandescent | 0.54 |
| 4000 | Fluorescent | 0.58 |
| 4000 | LED | 0.76 |
| 5450 | CIE E (Equal Energy) | 1.00 |
| 6500 | Fluorescent | 1.02 |
| 6500 | Daylight | 1.10 |
| 7500 | Fluorescent | 1.11 |

* Source: WELL Building Standard

a

**Design Recommendations**

Some recommendations shown in Feature 54 of WELL Building Standard are listed as followings. Equivalent Melanopic Lux is measured on the vertical plane.

| | |
|---|---|
| Work Areas | 250 Equivalent Melanopic Lux or more for at least 4 hours per day for every day of the year |
| Living Environments | Daytime - 250 or more Equivalent Melanopic Lux<br>Evening - Not more than 50 Equivalent Melanopic Lux |
| Breakrooms | 250 Equivalent Melanopic Lux or more |
| Learning Areas | 125 Equivalent Melanopic Lux or more |

b

Figure 15: WELL Building Standards Recommendations for Lighting Factors

### *3.3.3 Simulation Study*

Simulation is useful in showing how IEQ and user comfort may affect energy consumption inside classrooms. DesignBuilder software is used to build simulation models that evaluate the effect of reducing energy consumption. These models evaluate the effect of changing classroom layouts, adjusting room temperature targets, redesigning electric lighting zones, and adding interior windows.

*3.3.3.1 About DesignBuilder Software*

The simulation was done with DesignBuilder software version 6.2 which targets an internal version of EnergyPlus that has an extended data definition file to allow a surface of up to 330 vertices, shading surfaces of up to 33 vertices, and up to 400 zones in compact HVAC systems. Using DesignBuilder, users can simulate energy consumption, daylighting, CFD, cost, and carbon using heating and cooling designs. Also, it enables the user to get a visualization of the building (https://designbuilder.co.uk/software/for-architects).

DesignBuilder software has the latest ASHRAE worldwide weather data and locations (4429 data sets) and contains 1258 EnergyPlus hourly weather files. This software makes it easy for engineers to quantify performance accurately in the fastest way possible. DesignBuilder comprises a core 3-D modeler and 11 modules that work together to provide in-depth analysis for any building. EnergyPlus' most established and advanced user interface is DesignBuilder. It also provides access to all the most required simulation capabilities covering building fabric, thermal mass, glazing, shading, renewables, HVAC, and financial analysis (https://designbuilder.co.uk/35-support/tutorials/96-designbuilder-online-learning-materials).

*3.3.3.2 Simulation Model and Input Data*

DesignBuilder software users must enter the main details for the building, such as weather data, and north direction, and then draw the building, adding different details such as construction details (such as glazing types, door types, walls, floors, and roof layers), electrical details (such as lighting types and their distributions), and mechanical details (such as AC type). In addition, the type of building and the activity in each zone. Table 10 - Section 3.4 contains the information needed to build the model in the software. Figure 16 shows the model created using DesignBuilder software with details of classroom 0034. The input data in DesignBuilder software for the building activity, construction details, lighting, HVAC, and other details are presented in Appendix C.

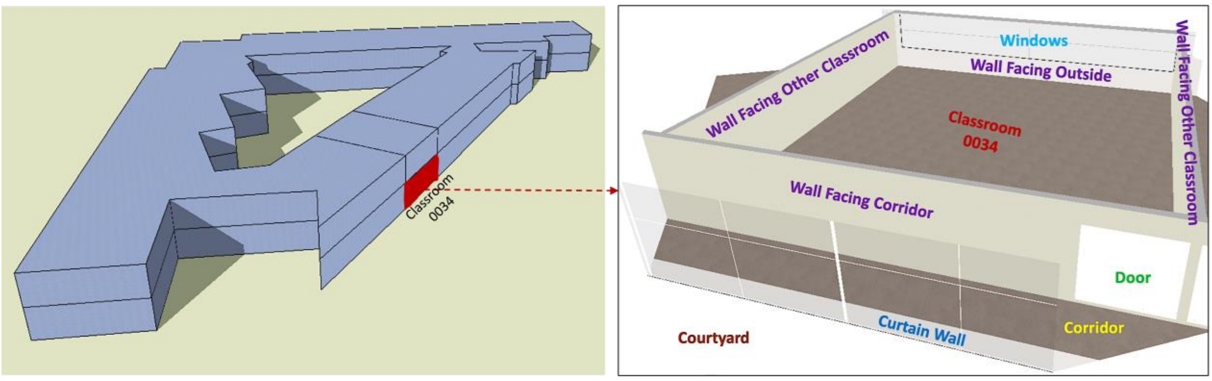



Figure 16: 3D Model and Classroom 0034 Created in DesignBuilder Software

*3.3.3.3 Simulation Scenarios and Analysis*

Several models were done using this software. These models show the difference in energy consumption between the original state of the building and the other suggested situations or improvements. Different classrooms in different orientations were selected to examine. The first model is the current state of the building. Then, other models were created by making some changes to improve the building's layout, lighting, and thermal conditions. Table 9 provides an explanation of the different scenarios created in the simulation. All the scenarios were built to compare the pre-and post-states of the building to determine the impact on the total energy consumption. The total energy consumption for each scenario was calculated by the software. All the calculated data was gathered in a graph to clearly show the improvements and differences between all the scenarios. This graph also showed how much each scenario affected the total energy consumption.

Each scenario was created due to a specific finding from either the online survey, monitoring experiments, or both. So, the following points explain clearly how or why each scenario is included in this research:

- Scenario A (Internal target temperature change): Due to the monitoring experiments, most of the classrooms have a very low temperature (below comfort level – below 24 $^{o}$C). In addition, based on the online survey students complain about the cold indoors. So, when the classrooms' internal temperature is raised to the comfort level (24 $^{o}$C), the occupants' satisfaction and comfort level increase, and the energy needed for the air conditioning is reduced.

- Scenario B (Classroom desk layout change): Based on studying the buildings' classrooms, most of the classrooms' desks and blackboard direction were perpendicular to the windows which causes issues such as glare and reflections on the screens. Furthermore, the layout of the students' desks made it possible for half of them to use natural lighting. By making the desks parallel and closer to the windows, two issues related to glare and reflection of screens, and the use of natural lighting inside the classroom could be reduced.
- Scenario C (Create lighting zoning): Currently, the lighting in the classroom can be controlled in 2 zones (the panel in Table 11), which results in high energy consumption due to the limited control over the artificial lighting, but this could be drastically reduced by creating 3 zones to control the artificial lighting in the classroom.
- Scenario D (Open window through the corridor and lighting zoning): As some classes have a corridor that is lined with a curtain wall (full of natural lighting), opening a window with a specific window-to-wall ratio will increase the amount of natural lighting in the classroom; when this method is combined with the lighting zoning method, it is now possible to have most of the classrooms (around 70%) depend on natural lighting in the morning hours, thereby reducing the demand for artificial lighting.
- Scenario E (Combine scenarios A, C, and D): Using all the previously described scenarios together, a noticeable amount of energy is being saved through simple strategies and wisely utilized areas.

Table 9: The Detailed Scenarios for Simulation Part

| Scenario | Parameters to change | Consideration |
|---|---|---|
| Scenario A:<br>Internal target temperature change | From Below 24 ºC to 26 ºC | Cooling energy consumption and user thermal comfort improvement. |
| Scenario B:<br>Classroom desk layout change | Bring the desks near the window and facing parallel to sunshine to avoid glare/reflection | Increasing daylight inside classroom, reduce lighting energy consumption, and improve lighting comfort. |
| Scenario C:<br>Create lighting zoning (Control for each row of luminaires)<br><br>(Current lighting control divided into 2 zones) | Areas, where daylight can reach, will need less artificial lighting during the daytime (9 am and 12 pm) | Reducing lighting energy consumption. |
| Scenario D:<br>Open window through the corridor and lighting zoning | Increase amount of daylight inside and change the desk directions to be parallel with daylighting. | The increase of daylight and desk directions help in saving energy and affect lighting comfort. |
| Scenario E:<br>Combine scenario A, C, and D | The combination of all changes | Improvement on energy consumption and users' thermal and lighting comfort. |

### 3.4 Case Study Building

The case-studied building is the C6 Building (College of Engineering, Food and Agriculture, and Science Building). This study focuses mostly on classrooms that are used by students during the day (8 am to 5 pm). The number of selected areas for the thermal and IAQ experiments was 9 classrooms and 2 student sitting areas. For the lighting experiments, 6 classrooms were studied each in a different orientation of the building. The building is located on the female side of the UAE University in Al Ain, UAE. It is a three-story building (the ground floor and the first floors are mostly classrooms and computer labs, while the second floor is offices). The building's shape looks like a triangle with an open courtyard in the middle. The building is covered with lots of glass and has an additional layer of glass on the windows and curtain walls from the outside for extra shading. In addition, it is surrounded by some trees and other shading objects as well. Figure 17 shows the building's shape and images from the outside, while Figure 18 shows images from the inside and the classrooms that were studied. Table 10 shows some details and images for materials, electrical and mechanical systems.

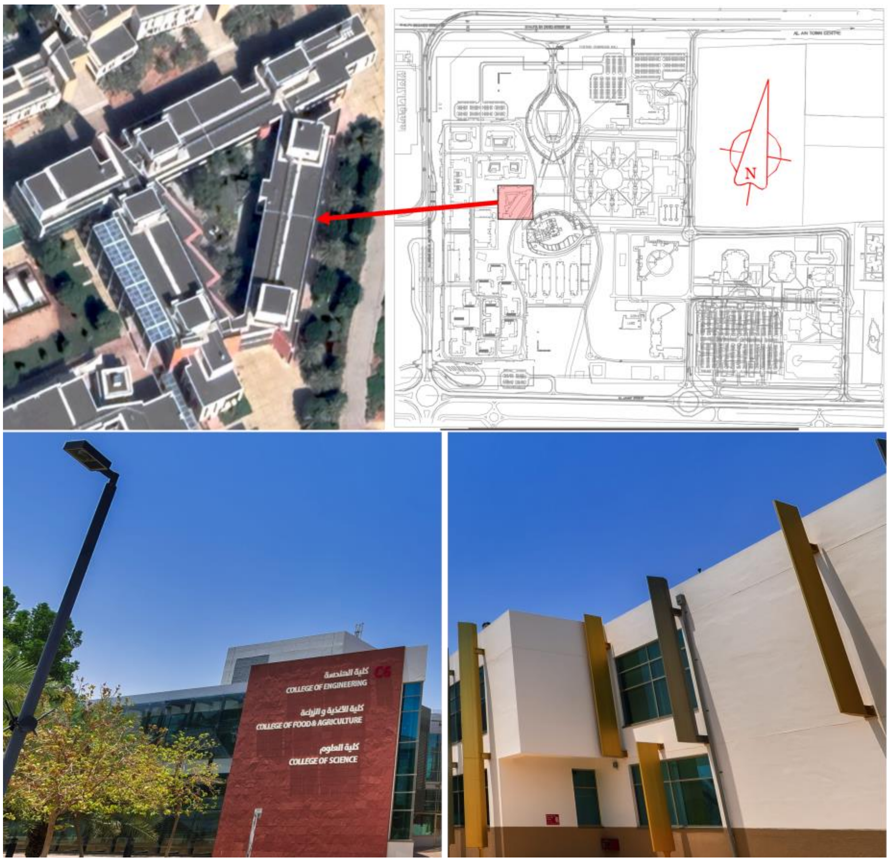



Figure 17: Female Faculty of Engineering, Science, Food and Agriculture [C6 Building], Female Side, UAEU, Al Ain, UAE


Figure 18: C6 Bding’s Ground and First Floors Plans with Images from Indoor

Table 10: Building’s Materials and Systems Details

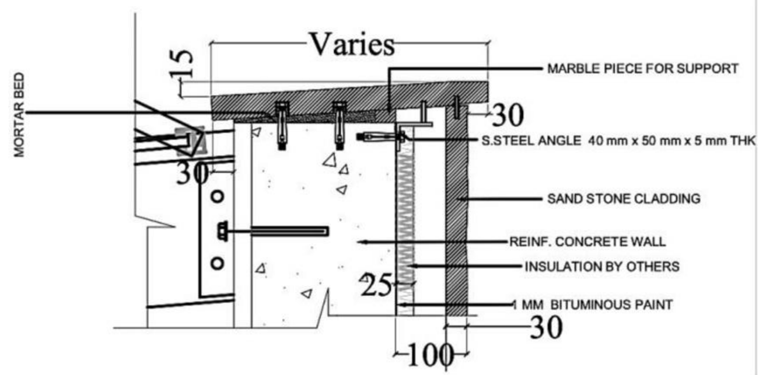
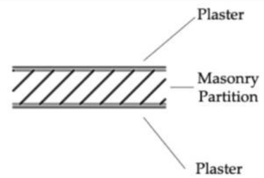
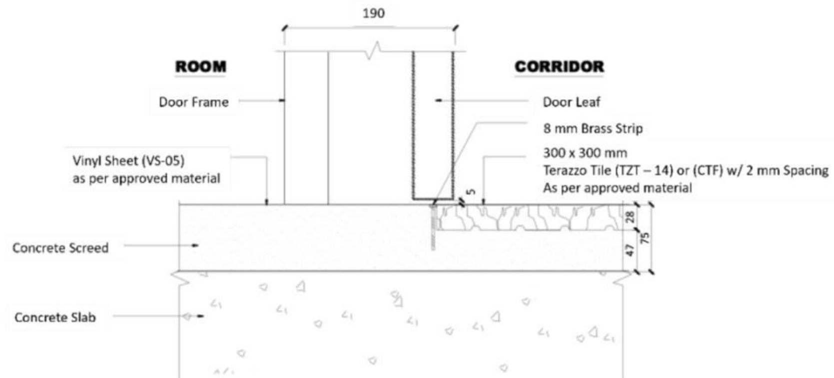
| Element | Details | Details Images |
| --- | --- | --- |
| External Walls Layers<br><br>U-Value = 9.224 W/m$^2$.K | - 30 mm sandstone cladding.<br>- 45 mm gap.<br>- 25 mm insulation.<br>- 1 mm bituminous paint.<br>- RC concrete wall.<br>- 25 mm plaster. |  |
| Internal Walls Layers<br><br>U-Value = 0.54 W/m$^2$.K | - Concrete plaster on 2-sides.<br>- 150 mm masonry partition. |  |
| Ground Floor Layers<br><br>U-Value = 4.1732 W/m$^2$.K | - Carpet<br>- 8 mm thick ceramic.<br>- Screed.<br>- Water proofing membrane.<br>- Structural RC slap. |  |

Table 10: Building's Materials and Systems Details (Continued)

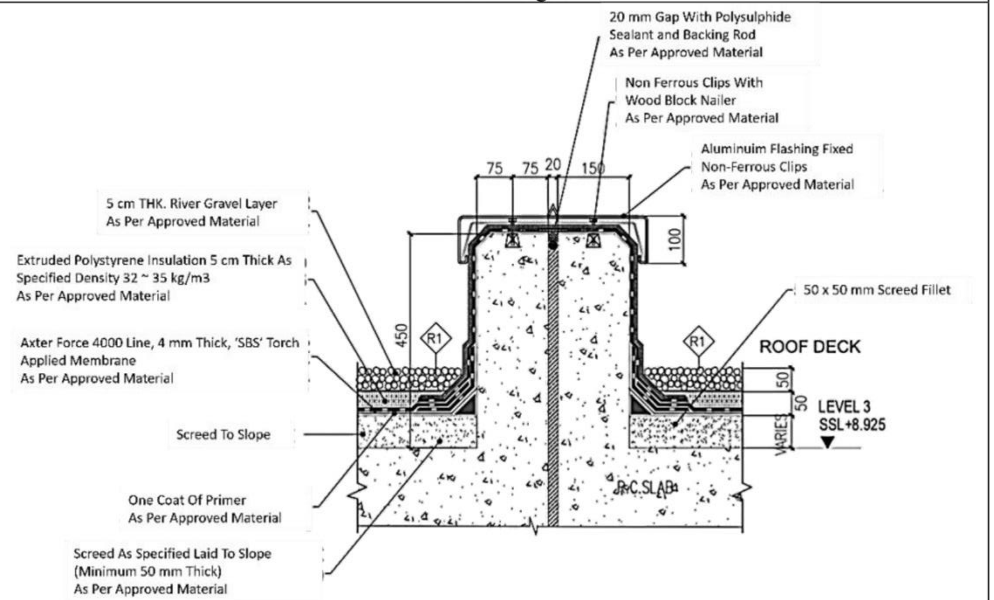
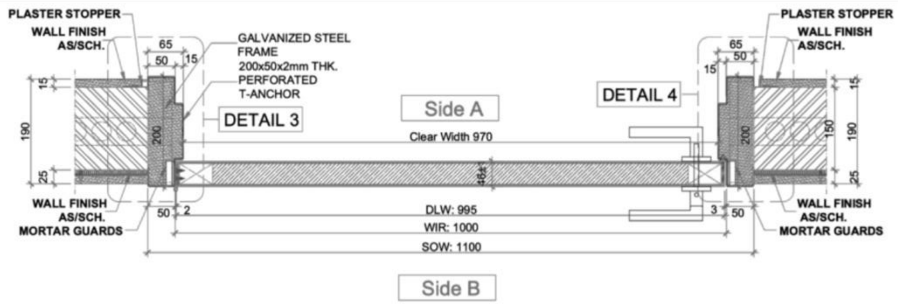
| Element | Details | Details Images |
| --- | --- | --- |
| Flat Roof Layers<br><br>U-Value = 1.341 W/m$^2$.K | - 50 mm gravel.<br>- 5 cm geotextile filter membrane.<br>- 5 cm extruded polystyrene insulation.<br>- 4 mm Geotextile separation layer.<br>- One coat of primer.<br>- 50 mm cement screed.<br>- RC slap. |  |
| Doors<br><br>U-Value = 0.64 W/m$^2$.K | - Wooden doors with aluminum frames (Indoors).<br>- Glass doors (Main – Exterior). |  |

Table 10: Building's Materials and Systems Details (Continued)

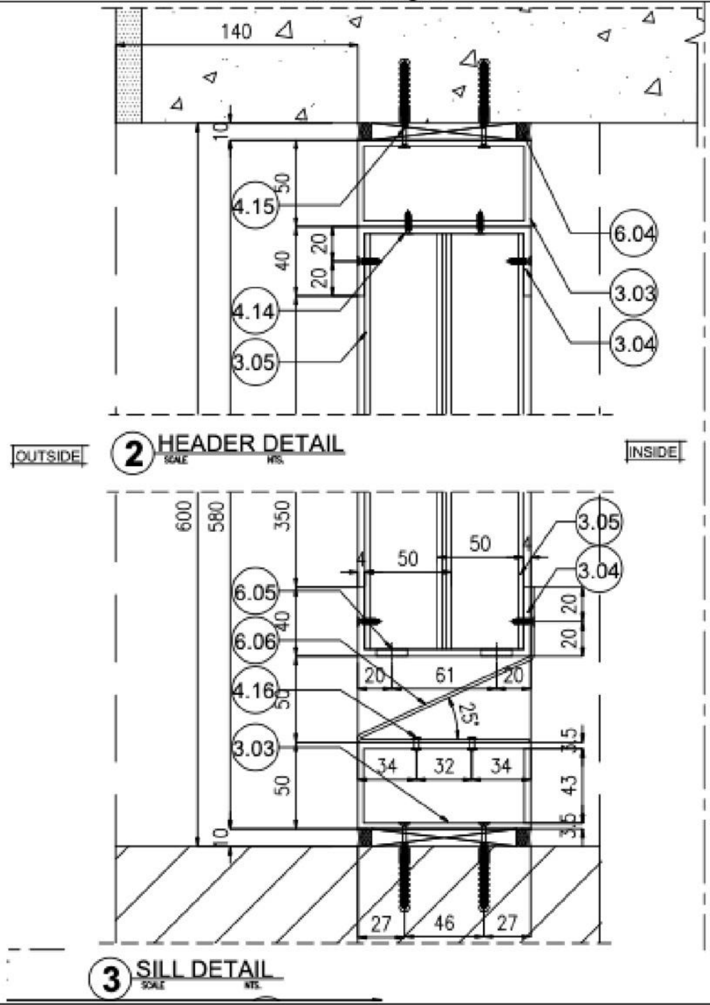
| Element | Details | Details Images |
|---|---|---|
| Windows<br><br>U-Value = 2.71 W/$m^2$.K | - Rooms: High performance double glazed; green tinted; high performance low-e with 12 mm air space and 6 mm clear.<br>- Curtain Wall: 6 mm green tinted; single glazed; polyester powder; insulation back pan. |  |

Table 10: Building's Materials and Systems Details (Continued)

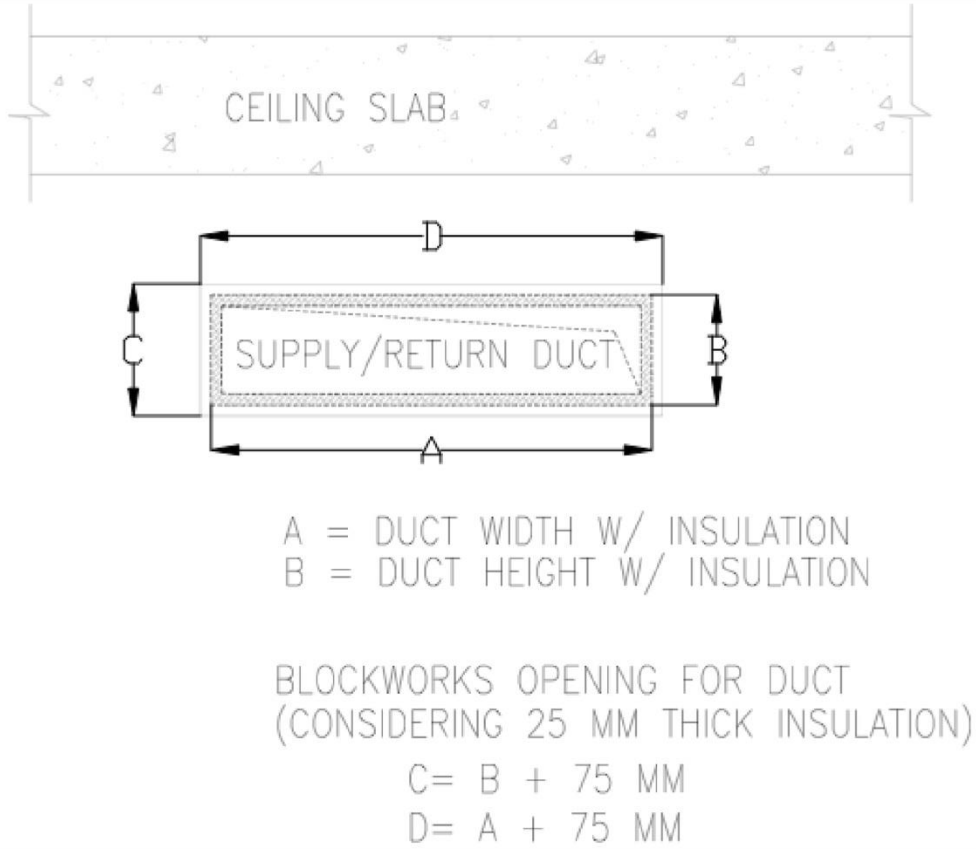
| Element | Details | Details Images |
| --- | --- | --- |
| Mechanical System | - Chilled water system on each floor.<br>- VAC (AC Vacuum Pump) |  |
| Lighting (for classrooms) | - Type: 4 x 14 W IP-20<br>- Description: TL-5 Fluorescent Normal Light Fitting Recessed Mounted Luminaire.<br>- Mounting: Ceiling. | |

Figure 19 shows the building's electricity consumption (kWh) for three years (2019, 2020, and 2021).

- In 2019, all classes were held offline (Face-to-Face).
- In 2020, the first half of the year were offline classes (Face-to-Face), and the other half were online classes due to the start of the COVID-19 pandemic.
- In the year 2021, all the classes were online.

Among the other years, 2019 had the largest electricity consumption (more than 1,200,000 kWh), while in the year 2020, the amount of electricity used decreased (less than 1,000,000 kWh) when half of the year was online, and in the year 2021 the electricity consumption was the most minimal (about 800,000 kWh). And since all the other systems such as HVAC were working normally except for the lighting, it is likely that the lighting affected most of this decrease. It is then clear why it was beneficial and worthwhile to study the lighting in the classrooms by creating different scenarios for simulation. This is to minimize the use of artificial lighting. The lighting system has an impact on the total electricity consumption of the building. Therefore, this study was worthwhile. Appropriate lighting can help reduce the building's electricity consumption.

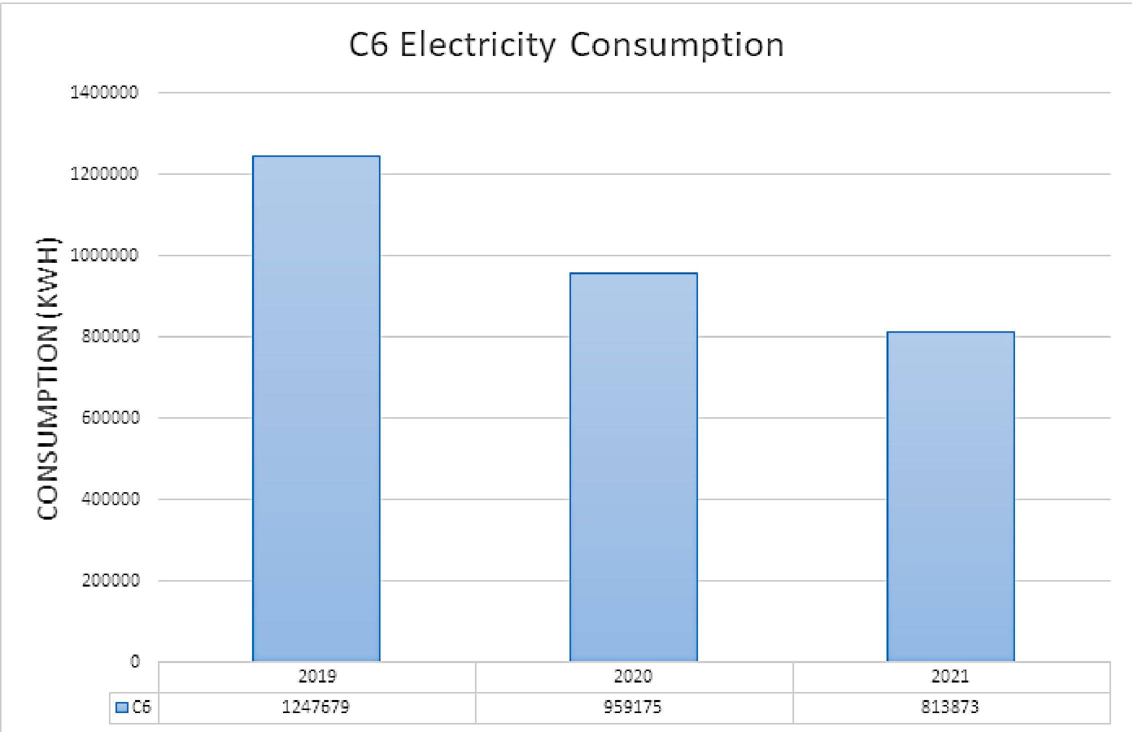



Figure 19: Summary of the Case Study Building Electricity Consumption, 2019-2021.
Source: (Khadamat Facility Management)

## 3.5 Limitations of Study

There were several barriers, most of which related to the COVID-19 pandemic, which resulted in some changes in the overall study, especially in the case study buildings. After that, the face-to-face interviews and survey were changed into an online survey due to the small number of students coming to the university. Additionally, the number of devices was reduced to only two. This is because the use of other sensors was supposed to be done during class time with the full number of students inside the classroom. Also, the acoustic parameter was excluded from the experiments since the building wasn't 100% occupied.

# Chapter 4: Results and Discussion

Chapter 4 presents the details, results, and discussion of all the used methods to accomplish this research. And as explained in Chapter 3, there are two main methods (online questionnaire and monitoring experiments) and a supportive method (simulation), the results and discussion chapter were designed to have three sections, and each one of the main sections presents one method with sub-sections to explain in full details all the different parts and divisions of the method. These methods are related to one another to see the connection between occupants' perception and the actual state of the buildings, it is important to see the connection because the monitoring experiments give support to the survey findings, which makes the whole study clearer and more understandable.

## 4.1 Overview of the Survey

The online questionnaire was distributed among building users from April 2021 to August 2021, which is part of the spring and summer seasons in the UAE, so the weather ranges from warm to hot. The respondents were mainly students, and the total number of participants was 217. The COVID-19 condition has prevented students from attending the university every day and made it hard for students to remember the indoor environmental condition of the case study building. So, it affected the total number of participants in the survey.

The questionnaire focused on the level of satisfaction with the different IEQ parameters and the perception of the comfort and well-being of the students. The participants are all female students (since the building is on the female side of the campus) and under 25 years old (the age ranges of 15-20 (43%) and 21-25 (57%)).

Based on the response, provides a better understanding of the current state of the IEQ for the case study building and which indoor environmental parameters affect occupants' comfort. And the findings provide which indoor environmental parameters need to adjust to improve the IEQ.

The detailed questionnaire is presented in Appendix B. The following sub-sections show the results from the online surveying and the summary of each part of the survey.

- Part 1: The results show that most students are satisfied with the overall IEQ. However, there is a small percentage of unsatisfaction that can be related to some indoor issues, such as 9% felt bad about the overall IEQ this percentage might be related to the other IEQ parameters such as thermal comfort since there is 12% of students who felt bad about it, and this could be related to the cold indoor temperature. Another IEQ parameter that got 15% of bad responses is the IAQ, and it might be related to some feeling of dry and study air inside the classrooms.
- Part 2: The results show that students are annoyed by dry and stuffy air, also low temperatures during the summer, especially students who sit under the AC diffusers. The annoyance of the low indoor temperature during the summer season is understandable because in UAE the outdoor temperatures during the summer can reach up to 49 $^{o}$C, so when people suddenly get into a cold building, they feel uncomfortable, and some may get some illness symptoms such as headache or heavy breathing. Regarding the level of the lighting, students complain about too much artificial lighting, and a lack of daylight, and this is due to the classrooms' layout that makes the use of natural lighting beneficial only for parts of the classroom while the other parts should depend on the artificial lighting.
- Part 3: Shows that students mostly felt neutral about the IEQ parameters, but there are a few complaints about some factors such as the indoor temperature (around 40% think that the temperature is leaning toward cool), this might feel uncomfortable for some of the students especially at summer season because the outdoor temperature is very high and if the indoor temperature is low then a sudden feeling of temperature changing might occurs. This section also presents the students' preferences for some of the IEQ parameters.
- Part 4: Shows some students have symptoms related to SBS symptoms such as dry eyes, and skin, runny nose, headache, and tiredness, these might be related to some of the IEQ parameters. But this part cannot give 100% data on the related SBS, because it needed a deep study of students' health and observation of them during their time spent inside the classrooms.
- Part 5: This last part collected some of the students' preferences and see their ideas about improving the IEQ of the classrooms. Some of the most repeated suggestions

were the classrooms' layout (students prefer the screen and tables to be parallel to the window to factors such as glare and reflection). Another one was about adding an air diffuser and humidifier inside the classroom to improve the IAQ. There are more suggestions such as removing the carpet to decrease the indoor smell and dust that come from it.

More detailed analysis and discussion are presented in related sub-sections. The results that are presented in the tables are only the ones related to the temperature, RH, lighting, and IAQ. All the other parameters such as noise and odor/smell, get neglected in this research since in the part of monitoring experiments the focus was only on temperature, lighting, and IAQ since the building is almost empty and parameters such as noise cannot be studied.

### *4.1.1 Part 1 Survey Results*

The first part of the questionnaire focused on the overall IEQ and the general level of satisfaction of each main IEQ parameter in the case study building.

Table 11: Part 1 of the Questionnaire

| Parameters | Very Unsatisfied (%) | Unsatisfied (%) | Neutral (%) | Satisfied (%) | Very Satisfied (%) |
|---|---|---|---|---|---|
| Thermal Comfort | 1.84 | 10.14 | 44.24 | 35.48 | 8.29 |
| Indoor Air Quality | 3.69 | 11.52 | 36.87 | 37.79 | 10.14 |
| Visual Comfort | 3.69 | 6.91 | 42.86 | 35.48 | 11.06 |
| Overall Indoor Environment | 2.76 | 6.45 | 34.56 | 41.01 | 15.21 |

From Table 11, people seem to feel neutral about most parameters (thermal comfort 44.24%, and visual comfort 42.86%), and some lean toward satisfaction level (IAQ 37.79%). And the overall satisfaction of the IEQ seems to be ranging between neutral (34.56%) and satisfaction (41.01%). Later, these answers were compared to the results from the monitoring experiments to see if the occupants' perception meets the actual situation of the building.

*4.1.2 Part 2 Survey Results*

The second part tried to see the factors that make the students annoyed or uncomfortable inside the classrooms with some details such as When this mostly happens? Where does this happen? Why does this happen? What are the causes?

Table 12: Part 2 of the Questionnaire

| Parameters | Q. How Often Do You Feel Annoyed by The Followings? | | | |
|---|---|---|---|---|
| | Often (%) | Regularly (%) | Sometimes (%) | Never (%) |
| Dry Air | 16.59 | 23.5 | 40.55 | 19.35 |
| Stuffy Air | 15.67 | 29.49 | 35.02 | 19.82 |
| Too Cold Temperatures | 13.82 | 19.35 | 50.23 | 16.59 |
| Cold Feet | 14.29 | 24.42 | 36.87 | 24.42 |
| Warm Surface During Summertime | 9.22 | 19.35 | 39.63 | 31.8 |
| | Where? (%)<br>- (6.21 Ceiling)<br>- (35.86 Windows)<br>- (20.34 Walls Facing Outdoor)<br>- (10.69 Walls Facing Indoor)<br>- (20.69 Floor)<br>- (6.21 Other such as Chairs and Tables) | | | |
| Temperature Changes Through the Day | 11.98 | 28.11 | 36.87 | 23.04 |
| Too Much or Too Strong Artificial Light | 13.36 | 18.43 | 39.17 | 29.03 |
| Insufficient or Too Little Natural Light | 5.99 | 17.51 | 39.63 | 36.87 |
| Reflections or Glare | 8.29 | 10.6 | 51.15 | 29.95 |

From Table 12, students were mostly annoyed by variables related to temperature, and some were annoyed with air quality. 50.23% of the students sometimes feel cold mostly in the winter season, meaning the indoor temperature needs to adjust to recommend temperature for students to feel comfortable. Sometimes 40.55% of students feel that the indoor air is dry and 35.02% feel stuffy indoor air, so based on these the air quality needs to be checked inside when the classrooms are fully occupied to see if there is a need to add an amount of air to reduce these issues and it shows that the classroom would need to install a humidifier with the mechanical ventilation system. For lighting factors, glare and reflection sometimes make the students uncomfortable. Sometimes 39.17% (or 40%) of students complain that there is too much/too strong lighting in their classrooms, and 48.84% (or 50%) of them blame artificial lighting. When it comes to reflections and glare, 51.15% feel sometimes annoyed, and among this percentage, 58.82% feel it is because of the windows.

### *4.1.3 Part 3 Survey Results*

The third part asked how the students feel about each factor such as (temperature, RH, air, etc.) and what are the preferences of these factors (change or stay the same).

Table 13: Part 3 of the Questionnaire

| Parameters | -2 (%) | -1 (%) | 0 (%) | 1 (%) | 2 (%) |
|---|---|---|---|---|---|
| Temperature | 16.59<br>Cold | 40.09<br>Cool | 35.94<br>Neutral | 6.45<br>Warm | 0.92<br>Hot |
| Relative Humidity | 2.3<br>Very Dry | 21.2<br>Dry | 66.82<br>Neutral | 8.29<br>Humid | 1.38<br>Very Humid |
| Relative Humidity Preference | 1.38<br>Much Drier | 12.44<br>Drier | 74.19<br>No Change | 11.52<br>More Humid | 0.46<br>Much More Humid |
| Air Movement | 3.69<br>Very Weak | 23.5<br>Weak | 59.91<br>Neutral | 11.52<br>Strong | 1.38<br>Very Strong |
| Air Stuffiness | 3.69<br>Very Stuffy | 17.05<br>Stuffy | 57.14<br>Neutral | 19.82<br>Fresh | 2.3<br>Very Fresh |
| Dust in Air | 1.84<br>Very Dusty | 6.91<br>Dusty | 54.84<br>Neutral | 30.41<br>Clean | 5.99<br>Very Clean |
| Light Level | 0.46<br>Very Dark | 5.99<br>Dark | 64.52<br>Neutral | 26.73<br>Bright | 2.3<br>Very Bright |
| Glare | 1.84<br>Too much Glare | 9.68<br>Glare | 64.98<br>Neutral | 19.35<br>Little Glare | 4.15<br>No Glare at All |
| Daylight | 2.3<br>No Daylight | 17.97<br>Little Daylight | 40.09<br>Neutral | 35.02<br>Satisfied | 4.61<br>Very Satisfied |

As Table 13 shows, people's perceptions and preferences of the indoors are different from one to another, for example, 44.7% prefer the temperature to be cooler while 17.51% prefer it to be warmer, this shows two main things; the first one is that designing the indoors needs a detailed study about the occupants (genders, age ranges, etc.) and the building type to specify the type of works that will be done inside. Secondly, the importance of having controllers inside the classrooms so that people can change them based on their preferences. The table also concludes that students do have not much of complaints about relative humidity and 74.19% prefer to keep it as it is. The air movement answers are varying, and this can be due to the used type of AC inside the classrooms (linear shape – 2 inlets and 2 outlets) Figure 22 shows examples of three classrooms (1 as a 2D plan and 2 as images), which make students who set under it feel colder, drier, and annoyed more about air movement while the rest of the students can feel comfortable or opposite. The results also show that the students feel good about the IAQ. Due to glare issues by the orientation of classroom layouts and windows, the blinds and the electrical lighting are always on to improve the lighting comfort, even it has enough daylight (sub-heading 4.2.3 shows the level of daylights in the selected classrooms from 9 am to 3 pm, the average of the data near the windows (half of the classroom) for the classrooms 0021 and 1037 in Figure 20 are 426 lux and 665 lux respectively). These impact the energy consumption in the building and health issues for the students such as circadian rhythm. The dependence in the daytime must be on daylighting because the amount of natural light that enters the classrooms can light up at least half of the classroom (rows near the windows).

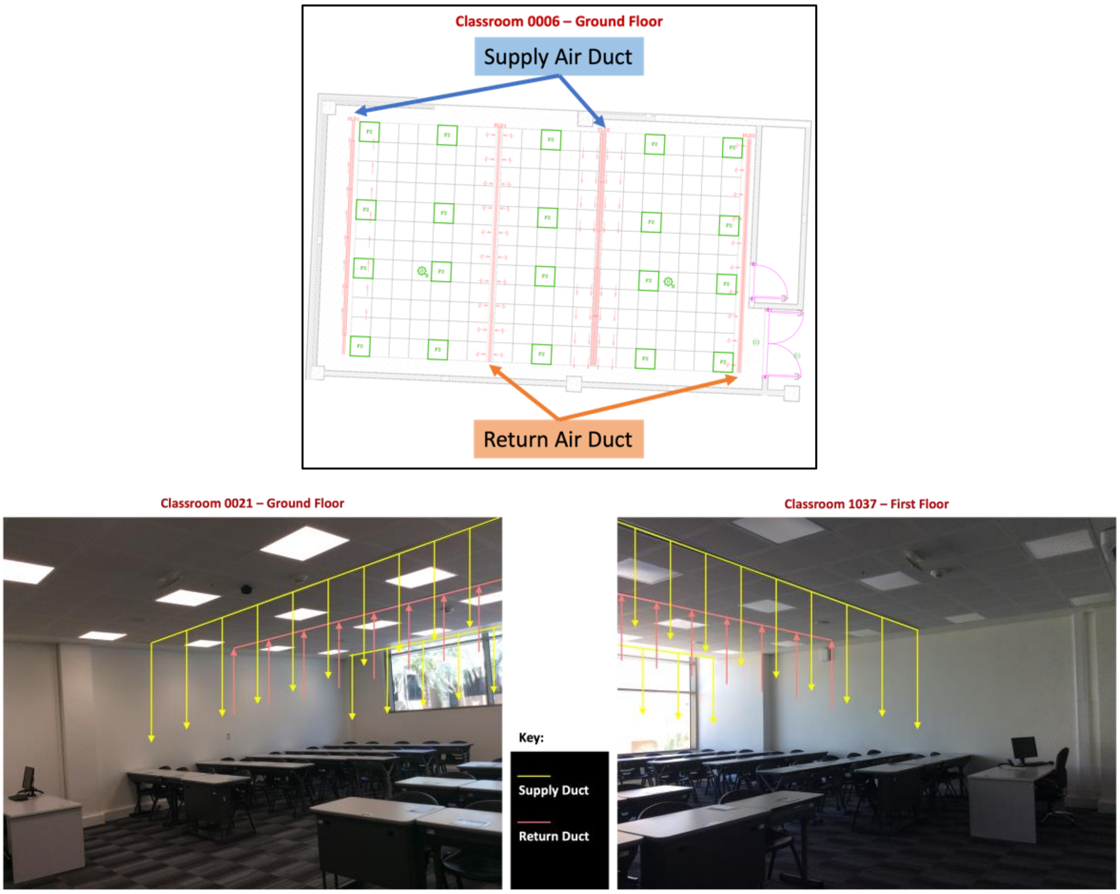



Figure 20: Showing the Supply and Return Air Ducts in Three Classrooms

*4.1.4 Part 4 Survey Results*

The fourth part of the survey asked about the symptoms of SBSs from the case study building. Based on the literature review, these symptoms can be related to some of the IEQ's parameters as shown in Table 14, but to know exactly if the occurrence of these symptoms was caused by the indoor environment, then a deep study considering the occupants' health state should be done.

Table 14: Part 4 of the Questionnaire

| Parameters | Q. If You Are at The Classrooms for Long Time, Do You Experience Any of These Symptoms? | | | | Parameters |
|---|---|---|---|---|---|
| | Often (%) | Regularly (%) | Sometimes (%) | Never (%) | |
| Dry Eyes | 11.06 | 13.36 | 33.64 | 41.94 | RH |
| Watering Eyes | 4.61 | 17.51 | 20.74 | 57.14 | RH, Dust |
| Blocked Nose | 5.07 | 15.21 | 29.49 | 50.23 | Temperature |
| Runny Nose | 5.99 | 15.21 | 41.01 | 37.79 | Direct air movement, Temperature, TVOC |
| Dry Throat | 6.91 | 12.44 | 35.94 | 44.7 | RH, TVOC |
| Irritated Throat | 4.61 | 6.45 | 29.49 | 59.45 | $CO_2$, Temperature |
| Chest Tightness | 4.61 | 11.52 | 26.27 | 57.6 | $CO_2$, PM |
| Dry Skin | 9.22 | 13.82 | 38.71 | 38.25 | Low RH, Air movement |
| Irritated Skin | 5.07 | 9.68 | 24.42 | 60.83 | TVOC, PM |
| Headache | 14.29 | 21.2 | 41.47 | 23.04 | Poor IAQ (such as $CO_2$), Poor lighting quality, high RH |
| Tiredness | 15.21 | 22.58 | 45.62 | 16.59 | Poor IAQ (such as $CO_2$), poor lighting |

Based on Table 14, some health issues such as runny nose, dry skin, headache, and tiredness are reported sometimes with percentages of 41.01%, 38.71%, 41.47%, and 45.62% respectively. A Runny nose could happen when students sit directly under the air conditions. Dry skin issues could be related to a lower level of RH and air movement which would be happened like a runny nose issue. A headache could happen when the IAQ is bad, poor lighting quality, and the relative humidity is too high (above 70% - too wet). Lastly, tiredness can be related to poor IAQ and poor lighting. There are not many complaints about students' health issues. Another thing these illnesses could also be related to the person itself, so to know exactly about the BRI that happens to the students because of the building itself a deep study of the students' health needs to be done. In addition, there are psychological health issues that can happen when the IEQ is poor such as stress and anxiety, but it needs a professional in this area of study to evaluate these types of health issues.

#### *4.1.5 Part 5 Survey Results*

Finally, the participants were asked to write some suggestions to make the classrooms' IEQ better for them. Some of the answers were:

- Changing the classroom layout (such as the boards shouldn't face the windows to reduce the glare).
- Adding air diffusers and air humidifiers is related to air quality preference.
- Change the AC type, this is mainly because of the air distribution inside the classroom.
- Increase the daylight instead of the artificial lights, increase the number of windows or their sizes and make them operable to enter fresh air from outside, change the glass type, and re-distribute the artificial lights.

#### *4.1.6 Summary of Survey*

To summarize the findings of the survey Figure 21 is shown below and the IEQ' parameters' issues are explained. Figure 21 is divided the data of each parameter between good, neutral, and bad to show the general thought of students about each parameter. The summary results indicate that 12% of the students feel bad about thermal comfort, 15% about IAQ, 11% about visual comfort, and about 9% of the students feel bad about the overall IEQ.

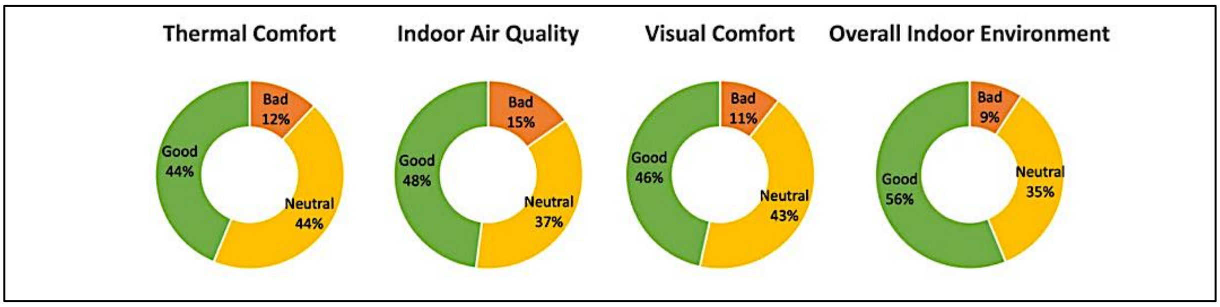



Figure 21: Summary of the Satisfaction Level of Each Parameter

Based on the percentage shown in Figure 21, the following points are an explanation of the related issues with the overall bad percentage:

- Thermal comfort: 12% of the students felt bad about thermal comfort due to the cold temperatures, and the change in temperatures throughout the day Figure 21. It is also related to the AC type in the classrooms (the strip type) which make the air distribution inside the classroom not even which causes different feeling among the students (some feel cold, and others feel warm).
- IAQ: 15% of the students feel bad about the IAQ because of the dry air and stuffy air feeling inside the classrooms, that is why some of the students also recommend having air diffusers and air humidifiers inside the classrooms.
- Visual: 11% of the students feel bad about visual comfort and this is because of the overuse of artificial lighting and the less use of natural lighting, also students feel that there are reflections and glare on the screens, and it is mainly from the window.
- Others and Overall IEQ: 9% of the students that feel bad about the overall IEQ are related to some factors such as the classrooms' layout (the placing of the furniture and its directions).

### 4.2 Overview of the Monitoring Data

The monitoring experiments were done using two main devices, which are Air Mentor Pro and Multi-Function Environment Meter. Table 15 shows the standards that are considered as a baseline to analyze the results.

Table 15: The Different IEQ Parameters Based on Standards

| IEQ's Parameters | Standards |
|---|---|
| Temperature (°C) | - Based on ASHRAE 55 2007: 24 - 26 |
| Relative Humidity (%) | - Based on ASHRAE 55 2007 section 4.2: 30 – 60 |
| $CO_2$ (PPM) | - Based on ESTIDAMA: Must not exceed 1000 |
| $PM_{2.5}$ ($\mu g/m^3$) | - Based on ASHRAE 62.1 2007: 15 or less |
| $PM^{10}$ ($\mu g/m^3$) | - Based on ASHRAE 62.1 2007: 50 or less |
| TVOC (PPB) | - Based on WELL Standards: 312 or lower |
| Light Level (Lux) | - Based On ESTIDAMA: A minimum illuminance of 300<br>- Based on ASHRAE 90.1 2016: 300 – 500 |

Several devices (of the Air Mentor) were placed in different classrooms across the building based on considering orientation and activities (classroom), these are shown in Figure 22. The gathered data were taken from 8:00 am till 4:00 pm. The Air Mentor devices helped in collecting data about the Particles ($PM_{2.5}$ and $PM_{10}$), Carbon Dioxide ($CO_2$), the Total Volatile Organic Compound (TVOC), Temperature, and humidity. The data that gathered by Air Mentor are presented in sections 4.2.1 and 4.2.2. While the data was gathered using the Multi-Function Meter represented in section 4.2.3 which is the lighting lux.

It is important to say that all those measurements were done at a time the building was almost empty due to COVID-19 Pandemic. However, except for lighting and acoustic, the operating systems of the case study building such as HVAC operated the same as before the pandemic.

Based on the monitoring data, the indoor temperature and lighting operation have noticeable issues. For example, a lower indoor temperature than recommended temperature leads to too much energy waste to maintain the lower indoor temperature. Not wisely operating the daylights and artificial lights leads to a waste of lighting energy. In addition, some classrooms have glare and reflection issues such as desk layout and room orientation especially, east oriented classrooms. It seems these classrooms would be better to change the desk layout to parallel to daylighting to avoid glare and reflection and to improve lighting comfort and artificial lighting usage. Problems found in monitoring are consistent with problems found in user surveys. Examples include low room temperature and the use of too much artificial light and too little natural light.

The survey and monitoring findings were reflected to create the simulation scenarios to improve energy consumption and user comfort as can be seen in Section 4.3.

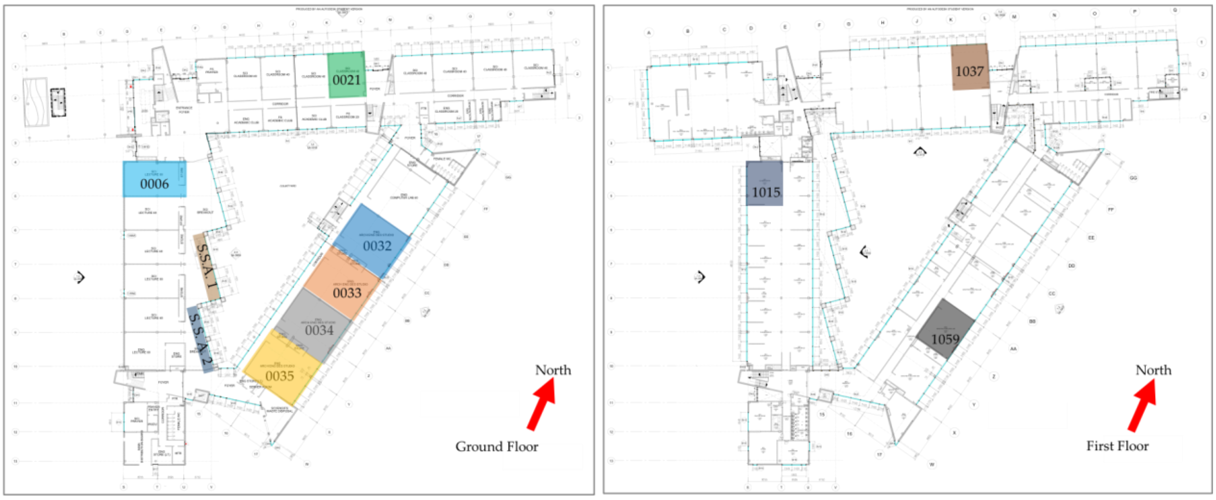



Figure 22: Selected Classrooms on the Ground and First Floors, C6 Building

*4.2.1 Thermal Comfort Monitoring Results*

The gathered data on the temperature shows that most of the time the classrooms are cold (under 24 ºC) with a percentage of 93.3 for the whole gathered data, which means there is a need to increase the indoor temperature to be inside the comfort zone (24 – 26 ºC), it is also better to consider that these data were taken during the warm season which means that the outdoor temperature is high (above the 30 ºC) and if the difference between the indoor and outdoor temperature is so high then this could affect occupants' comfort and health. Based on Chapter 2, some of the main health issues related to this are headaches, tiredness, heavy breathing, and nose and eye irritations. While the data related to the relative humidity shows that there is a little issue regarding the RH, only 0.253 of the readings are below the minimum standard (30%) and 0.676% above the maximum (65%), this gives a total of 0.929% of data out of the comfort zone for RH. The following sub-sections show detailed data for temperature and relative humidity.

*4.2.1.1 Temperature*

Figure 23 shows the results for Temperature in ºC in all selected classrooms. The area between the red lines in the graph is the comfort zone based on the standard (from ASHRAE) and all the points outside this area mean they are not matching the standard requirements. Standards-based on (Table 15 - Section 4.2).

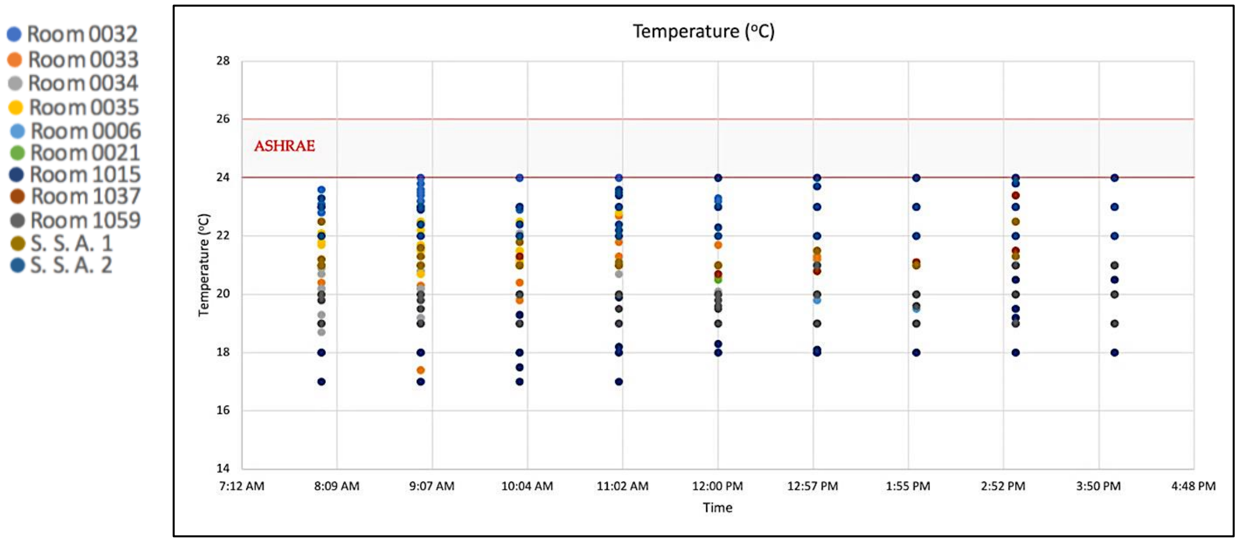



Figure 23: Hourly-Based Temperature Data

As seen in Figure 23, there are several readings under the comfort level (24 – 26 ºC) for temperature, and those are mainly in the early mornings, the lowest readings were 17 ºC in room 1015 and 17.4 ºC in room 0033, followed by 19.2 ºC in room 0032 and room 0034, 19.3 ºC in room 0034, and 19.8 ºC in room 0033. None of the readings for above the comfort level for the temperature. Table 16 gives a summary of the readings that are not in the comfort zones. Based on the table, the repetition percentage is 93.3%, which means the indoor temperature has issues.

Table 16: Temperature Readings Above/Below the Standards Summary

| Classroom No | Temperature | | | Average Temperature ºC | Remarks |
|---|---|---|---|---|---|
| | Below (%) | Within (%) | Above (%) | | |
| 0006 | 100 | 0 | 0 | 19.02 | - Total number of readings = 1182<br>- Total below average = 1103<br>- Percentage of total below average = 93.3 |
| 0021 | 100 | 0 | 0 | 20.36 | |
| 0032 | 56.25 | 43.75 | 0 | 23.45 | |
| 0033 | 100 | 0 | 0 | 21.16 | |
| 0034 | 100 | 0 | 0 | 20.95 | |
| 0035 | 100 | 0 | 0 | 22.19 | |
| 1015 | 100 | 0 | 0 | 18.56 | |
| 1037 | 98.67 | 1.33 | 0 | 22.26 | |
| 1059 | 100 | 0 | 0 | 20.13 | |
| S. S. A. 1 | 100 | 0 | 0 | 21.79 | |
| S. S. A. 2 | 88.57 | 11.43 | 0 | 22.86 | |

*4.2.1.2 Relative Humidity*

Figure 24 shows the results for Relative Humidity for all the selected classrooms. The two red lines in the graph show the maximum and the minimum preferred values based on the standard (from ASHRAE and WEL Standards) and all the points below or above these lines are not matching the standard requirements. Standards-based on (Table 15 - Section 4.2).

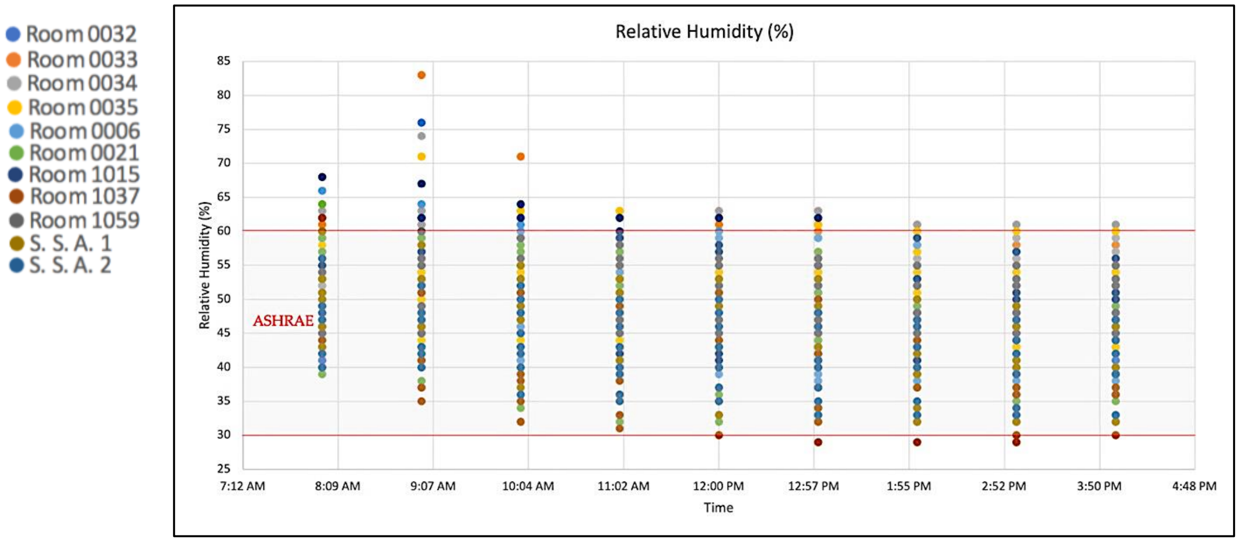



Figure 24: Hourly-Based Relative Humidity Data

As seen in Figure 24, For the relative humidity, there were only three readings below the standard and that was 29% all in room 1037, there are also 53 readings above the standards, and the highest readings were 83% in room 0033 followed by 76% in room 0032. Table 17 gives a summary of the readings that are not in the comfort zones. Based on the table, the repetition average is low (4.733%), which means there are not many issues related to the RH.

Table 17: Relative Humidity Readings Above/Below the Standards Summary

| Classroom No | Relative Humidity | | | Average Relative Humidity % | Remarks |
|---|---|---|---|---|---|
| | Below (%) | Within (%) | Above (%) | | |
| 0032 | 0 | 98.75 | 0.625 | 47.19 | - Total number of readings = 1182<br>- Total below average = 3<br>- Percentage of total below average = 0.253<br>- Total above average = 53<br>- Percentage of total above average = 4.48 |
| 0033 | 0 | 93.60 | 1.16 | 52.20 | |
| 0034 | 0 | 90.28 | 0.57 | 53.19 | |
| 0035 | 0 | 97.15 | 0.56 | 49.63 | |
| 0006 | 0 | 95.89 | 1.86 | 49.29 | |
| 1015 | 0 | 81.42 | 2.85 | 51.77 | |
| 1037 | 4 | 94.66 | 0 | 41.55 | |
| 0021 | 0 | 98.70 | 0 | 45.03 | |
| 1059 | 0 | 100 | 0 | 48.76 | |
| S. S. A. 1 | 0 | 100 | 0 | 44.68 | |
| S. S. A. 2 | 0 | 100 | 0 | 42.56 | |

### *4.2.2 IAQ Monitoring Results*

The gathered data shows that in general the IAQ is good for the building's users, the few issues that were noticed are mostly related to particles. But again, the readings were taken during the COVID-19 pandemic which means classrooms are empty, so there could be more issues if the classrooms were full of students. For example, if the classrooms were full then this could increase the number of indoor air issues since the students might carry some things that can cause an increase in particles and $CO_2$ levels such as perfumes or any personal care products. Also, students might bring more dust inside the classrooms by their shoes and that will cause an increase in the percentage of students who feel sometimes annoyed by stuffy air (35.02% as Table 13) and those who feel that the air inside the classrooms contains some dust (8.75% as Table 14). The following sub-sections show the detailed data for IAQ factors.

*4.2.2.1 $PM_{2.5}$ and $PM_{10}$ Monitoring Results*

Figure 25 a and b show the results for particles ($PM_{2.5}$ and $PM_{10}$) for all selected classrooms. The red line in the graphs shows the standard (from ASHRAE) and all the points above it mean they exceed the standard requirements. Standards-based on (Table 15 - Section 4.2).

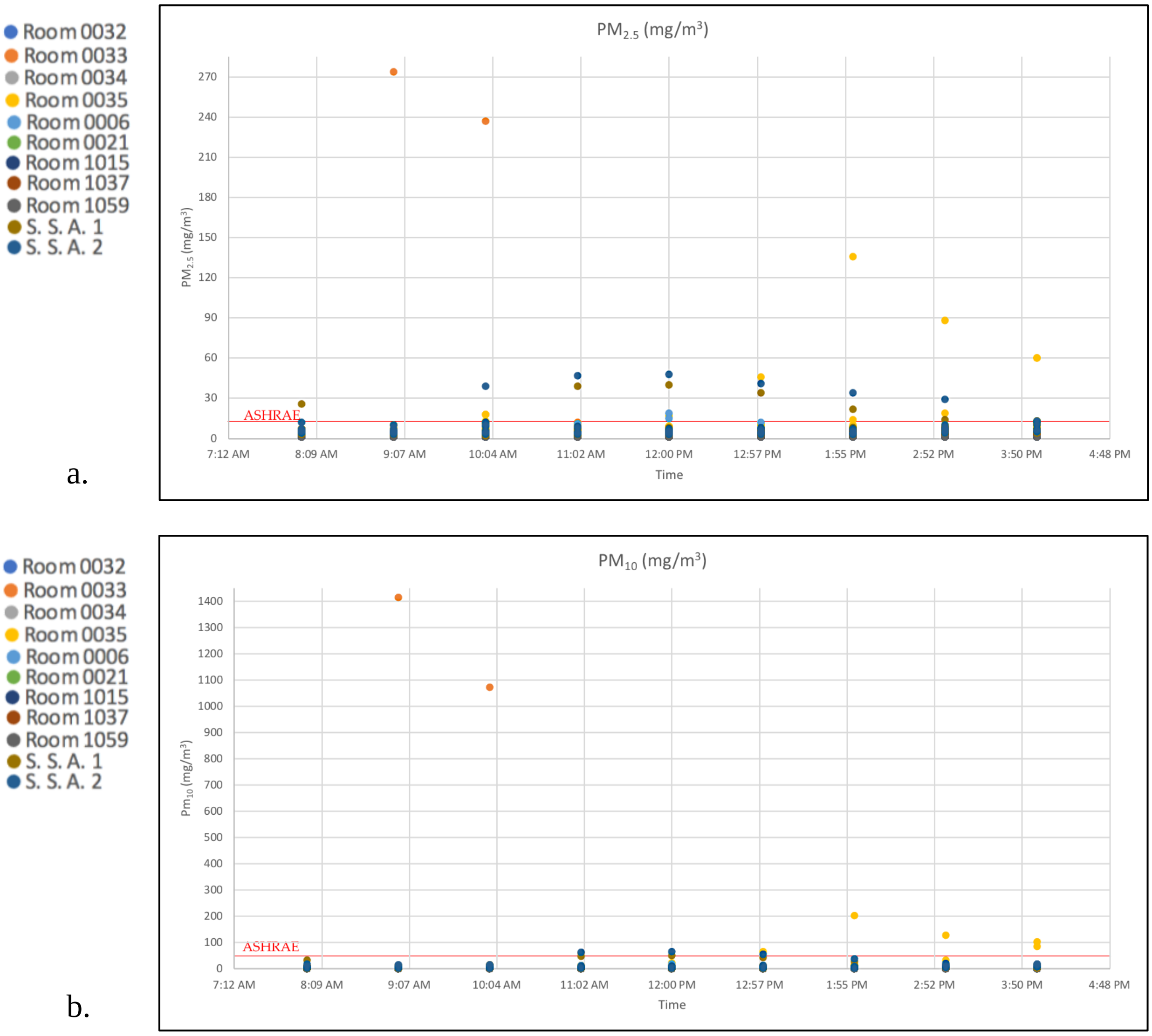



Figure 25: Hourly-Based Data For (a) PM2.5. (b) PM10

From Figure 25, there are a few issues with particles ($PM_{2.5}$ and $PM_{10}$) in classrooms 0033 and 0035 as well as in the students' sitting areas. For $PM_{2.5}$, the highest results were 274 and 237 both in classroom 0033. For $PM_{10}$, the highest results were 1416 and 1072 both in classroom 0033. Table 18 shows the repetition percentage of the reading above the standards. Based on the table, the percentage of repetition is not bad (1.94% and 1.01%) for $PM_{2.5}$ and $PM_{10}$ respectively.

Table 18: $PM_{2.5}$ and $PM_{10}$ Readings Above the Standards Summary

| Classroom No | $PM_{2.5}$ (15 µg/m$^3$ or less) Above (%) | Average $PM_{2.5}$ µg/m$^3$ | Remarks |
|---|---|---|---|
| 0006 | 1.36 | 4.96 | - Total number of readings = 1182<br>- Total above average = 23<br>- Percentage of total above average = 1.94 |
| 0033 | 1.16 | 6.43 | |
| 0035 | 5.11 | 7.77 | |
| S. S. A. 1 | 7.69 | 7.69 | |
| S. S. A. 2 | 8.57 | 8.74 | |
| **Classroom No** | **$PM_{10}$ (50 µg/m$^3$ or less) Above (%)** | **Average $PM_{10}$ µg/m$^3$** | **Remarks** |
| 0033 | 1.74 | 18.98 | - Total number of readings = 1182<br>- Total above average = 12<br>- Percentage of total above average = 1.01 |
| 0035 | 2.84 | 10.65 | |
| S. S. A. 1 | 1.53 | 9.42 | |
| S. S. A. 2 | 4.28 | 10.47 | |

*4.2.2.2 $CO_2$ Monitoring Results*

Figure 26 show the results for $CO_2$ in the selected classrooms. Red lines in the graph show the standard (from ESTIDAMA and WELL Standards). Standards-based on (Table 15 - Section 4.2).

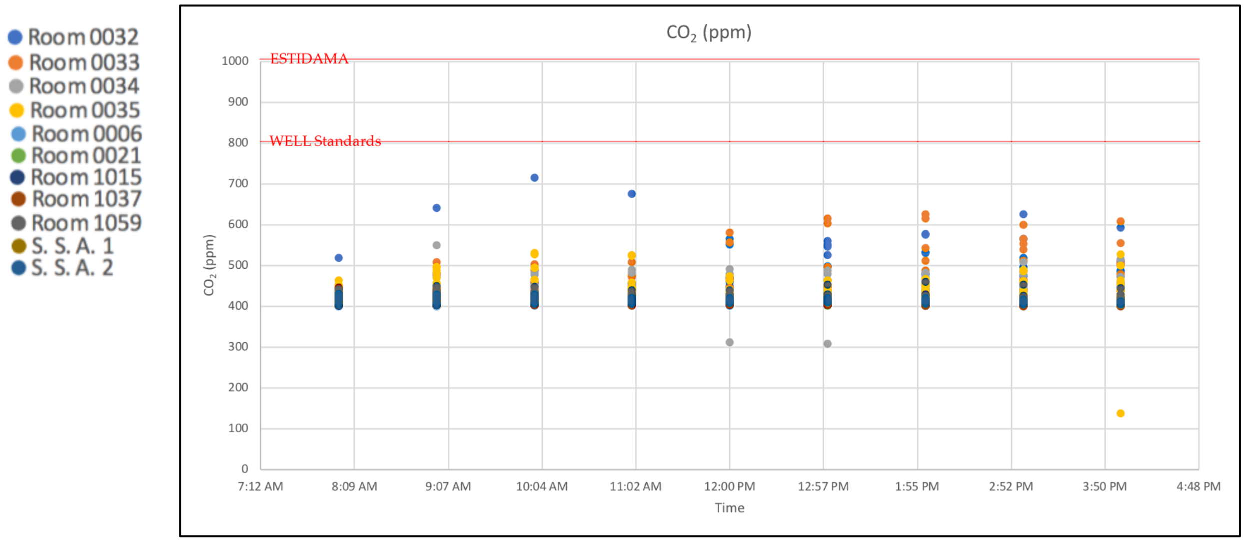



Figure 26: Hourly-Based $CO_2$ Data

Based on Figure 26, The $CO_2$ seems to be good everywhere all under the maximum allowed values by WELL Standards 800 ppm and ESTIDAMA 1000 ppm.

### *4.2.2.3 TVOC Monitoring Results*

Figure 27 show the results for TVOC in all the selected classrooms. The red line in the graph shows the standard (from WELL Standards). Standards-based on (Table 15 - Section 4.2).

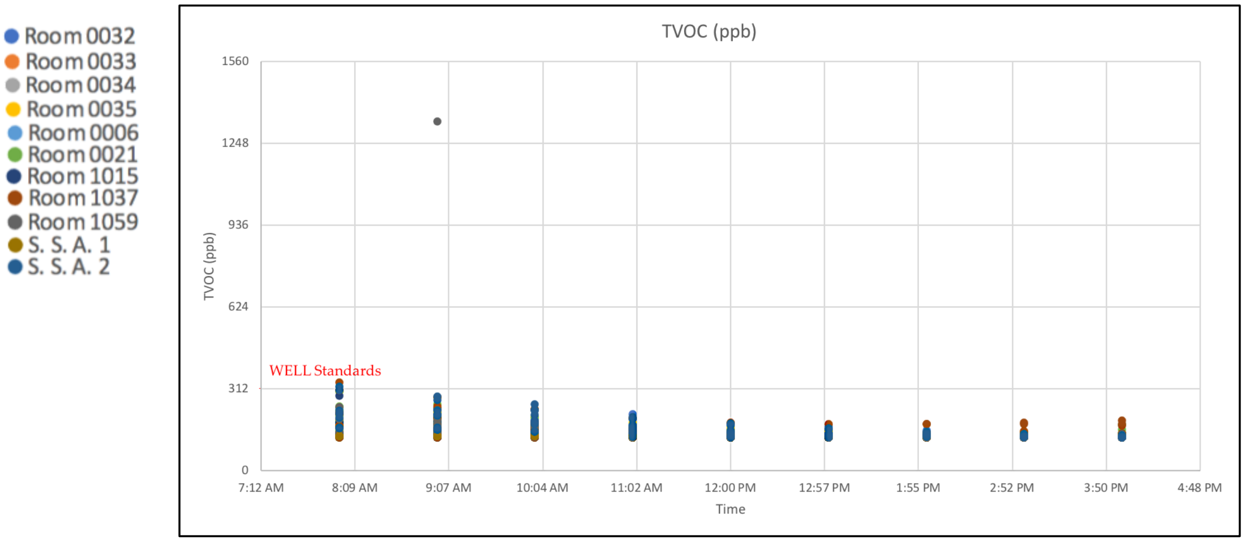



Figure 27: Hourly-Based TVOC Data

Based on Figure 27, The TVOC is good except for three readings, the highest one was 1331 in classroom 1059. (Table 19) shows the repetition percentage of the reading above the standards. As from the table, the percentage of the readings that exceed the standard is only 0.25% which means the overall TVOC inside the classrooms is within the limit.

Table 19: TVOC Readings Above the Standards Summary

| Classroom No | TVOC (312 ppb or less) | Remarks |
|---|---|---|
| | Above (%) | |
| 1037 | 1.33 | - Total number of readings = 1182<br>- Total above average = 3<br>- Percentage of total above average = 0.25 |
| 1059 | 1.44 | |
| S. S. A. 2 | 1.42 | |

### *4.2.3 Lighting Comfort Monitoring Results*

For lighting comfort monitoring experiments, the Multi-Function Environment Meter was used. The classrooms that were selected are in different orientations and floors of the building. The measurements for each classroom were taken four times, each time by changing a variable that affects the indoor visual comfort; (1) blinds open and lights on, (2) blinds open and lights off, (3) blinds closed and lights on, and (4) blinds closed and lights off. These different situations helped in concluding if the natural lighting is enough, or if it is used well, as well as helped in seeing if the layout of the classrooms is good or needs to be changed. Under normal operation in most classrooms the blinds are usually closed to avoid the glare and reflection on the screens, so for that, there is not enough daylight can pass through the blinds which means that there is usually a need for artificial lighting even in the daytime when there could be enough daylight. In addition of that, the artificial lighting zoning inside the classrooms is divided into two zones (columns moving from the window to the front of the classrooms), which makes it hard to control the artificial lighting wisely in a way that the rows beside the windows turned off and the one far away from the window turned on. Figure 28 shows the selected classrooms for conducting the lighting monitoring experiments.

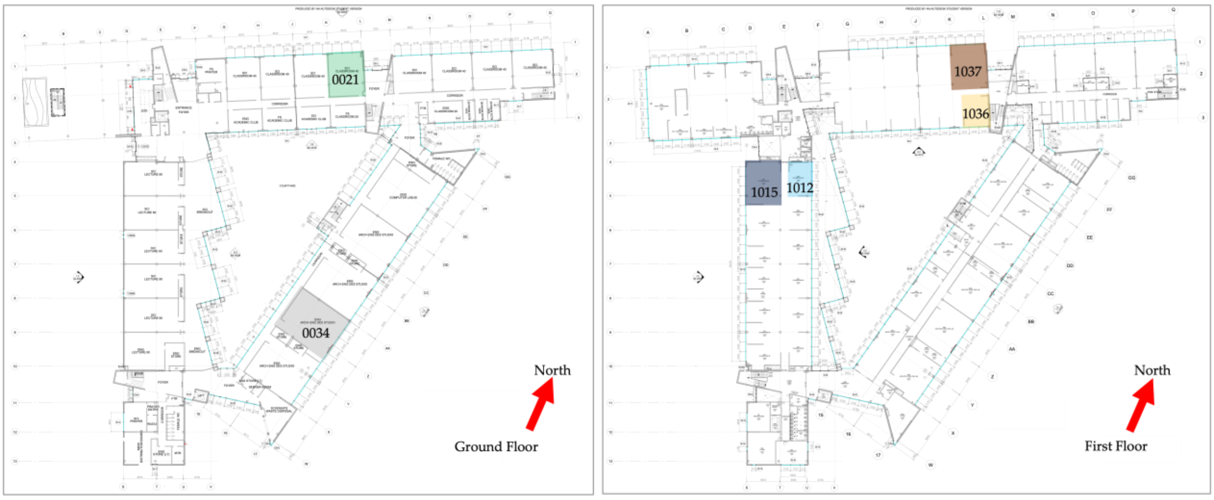



Figure 28: Selected Classrooms on the Ground and First Floors

As mentioned in Table 15 in Section 4.2, the lighting level for classrooms based on ESTIDAMA should not be less than 300 lux, and based on ASHRAE 90.1 2016 should be between 300 and 500 Lux. Following is the lux level shown in colors based, the "light green color" means the light level is in the comfort range (300 – 500 Lux).

In each of the classrooms, the device was placed based on the classrooms' layouts (students' tables). The readings for each classroom were taken at three different times (9 am, 12 noon, and 3 pm). At each time there were four different situations related to blinds (open/close) and lights (on/off). From previous literature it is best to have:

- 0.3 circadian stimulus which is equal to (500-600 lux) in the morning, wakes the human body and makes students more active.
- 0.2 circadian stimulus which is equal to (400 lux) in the afternoon, to comfort the human body and let it be in the comfort level of activeness.
- 0.1 circadian stimulus which is (less than 300 lux) in the evening/night, to prepare the body for nighttime to sleep well.

To calculate the Circadian Stimulus (CS) the following information from Chapter 3 is used, Equivalent Melanopic Lux (EML) = Visual Lux (L) X Melanopic Ratio (R). The melanopic ratio for the fluorescent light sources is 0.58 (CCT = 4000 K for a neutral white color). And the recommended EML for the learning area is 125 lux or more. If the visual lux is calculated based on these recommended and given values, then it is supposed to be 215 lux or more. Table 20 below shows a summary of the selected classrooms for lighting and the main findings.

Table 20: Summary of the Main Findings of Lighting Experiments

| Classroom | Orientation | Glass Details | Daylighting |
|---|---|---|---|
| 0034 | Ground Floor (East) | Windows in the east facing outside | There is enough amount of daylight for almost half of the classroom in daytime. |
| 0021 | Ground Floor (North) | Windows in the north facing outside | The last rows of students' tables have enough daylight from morning until 3 pm. |
| 1012 | First Floor (Middle) | Windows in the east facing glazed corridor | The classroom doesn't have enough daylight to depend on. |
| 1015 | First Floor (West) | Windows in the west facing outside | Two columns of students' tables can depend on daylight from morning until 12 noon. |
| 1036 | First Floor (Middle) | Windows in the south facing courtyard | High amount of daylight (in some areas more than the standard) from morning until 3 pm. |
| 1037 | First Floor (North) | Windows in the north facing outside | Three rows of students' tables have enough daylight from morning until 3 pm. In some areas it is more than standard. |

More detailed readings for all the selected classrooms are shown in the following figures.

Starting with classroom 0034 (Architectural Engineering Design Studio), the class plan is shown in Figure 29. The classrooms area is in the East south direction from the outer side of the building.

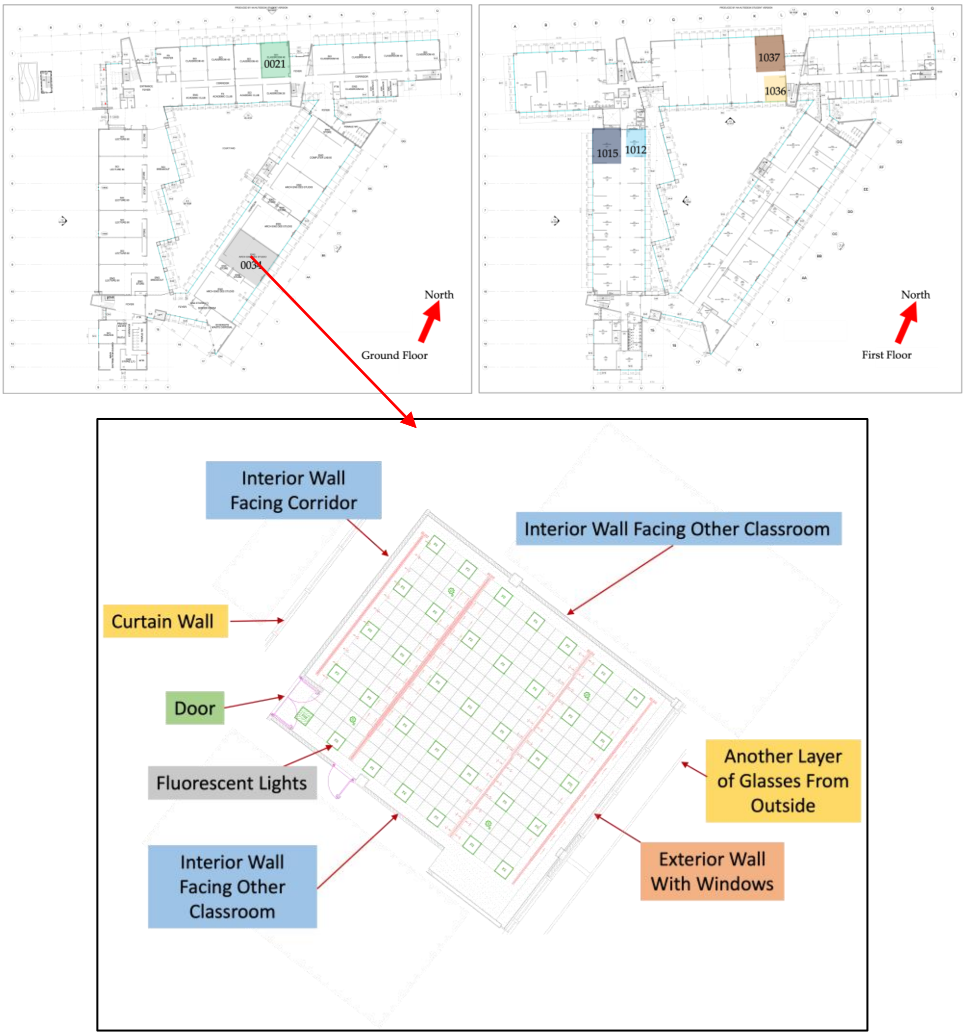



Figure 29: Classroom 0034 Layout (Ground Floor)

From Figure 30 when the (blinds are open and lights are off) almost half of the rows can depend on daylighting from 9 am till 12 pm, while at 3 pm it is hard to do so. But at noon and evening (3 pm), some readings exceed 400 lux (0.2 CS) and 300 lux (0.1 CS) respectively, which means it might be not comfortable for occupants' circadian rhythm. In the case of (blinds open and lights on), the readings are too high during all day long, which mean the students' body will stay too active in the afternoon and evening and this might lead to stress or inability to sleep well at night.

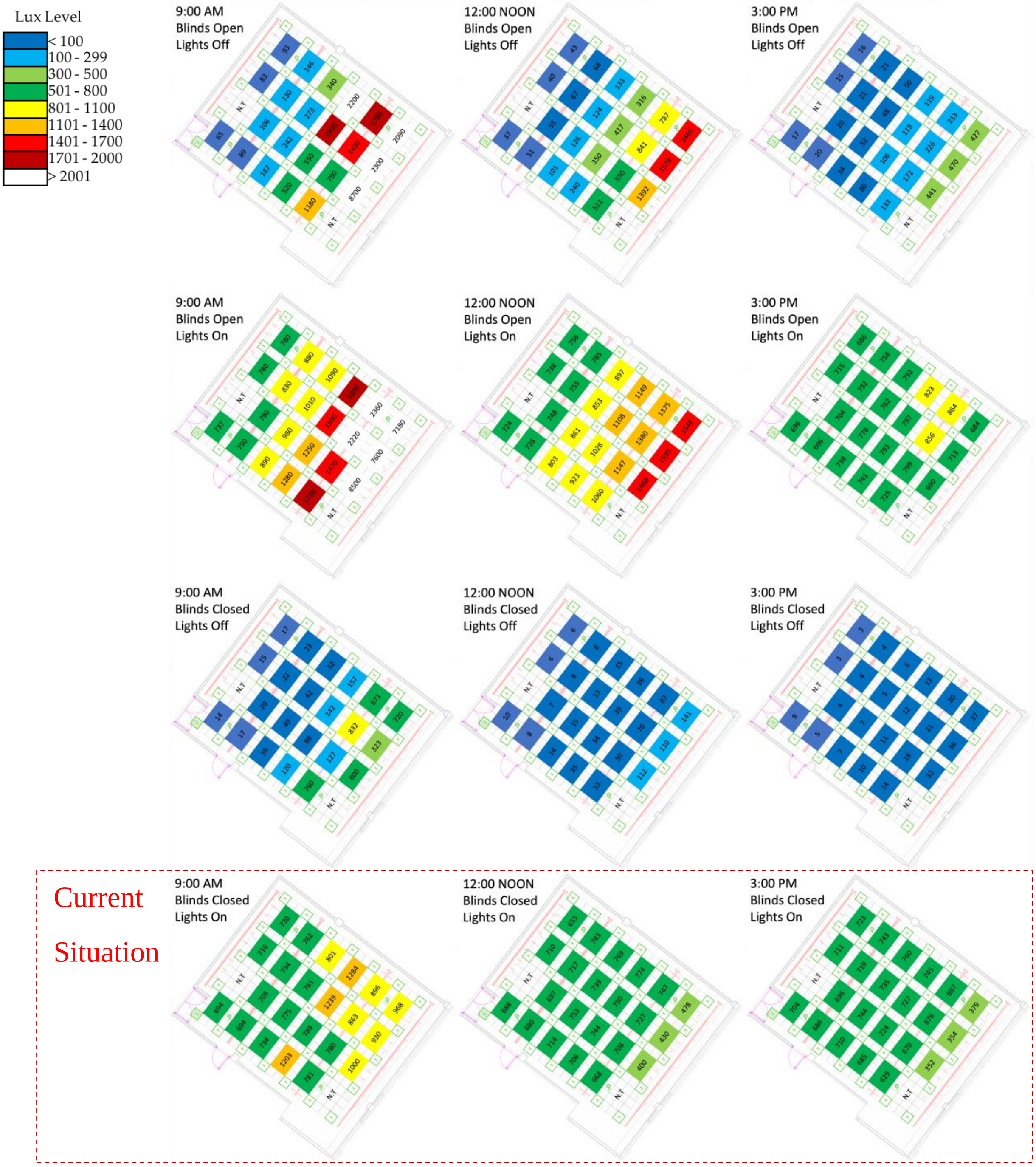



Figure 30: Lighting Levels Measurements for Classroom 0034 (Ground Floor)

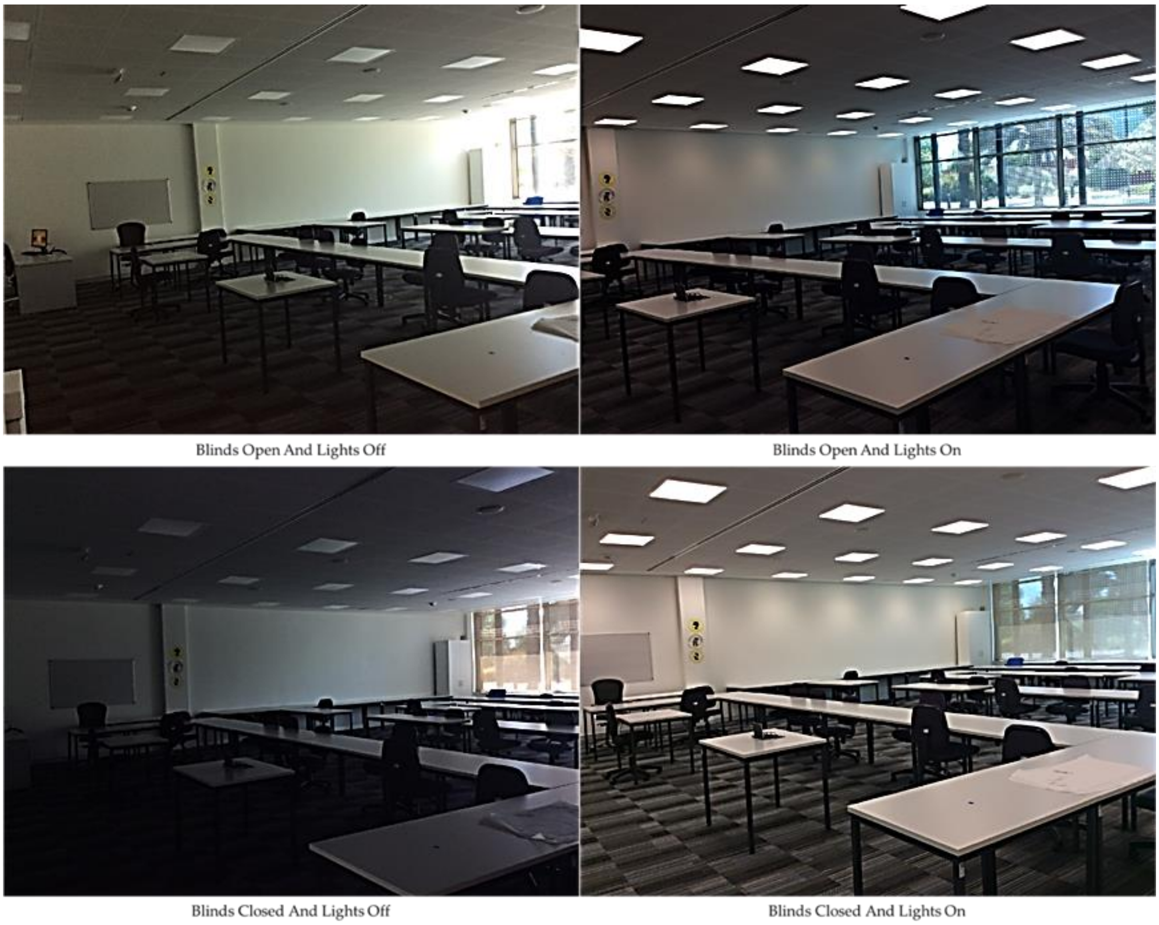



Figure 31: Blinds and Artificial Lights Different Cases in Classroom 0034

As seen in Figure 31, the windows can provide enough daylight for almost half of the class in the daytime; so, this can give an idea of changing the class layout or providing different controls for lighting.

The readings for classroom 0021 (Lecture Classroom) are shown below, the class plan is shown in Figure 32. The classroom area is in the Northwest direction from the outer side of the building.

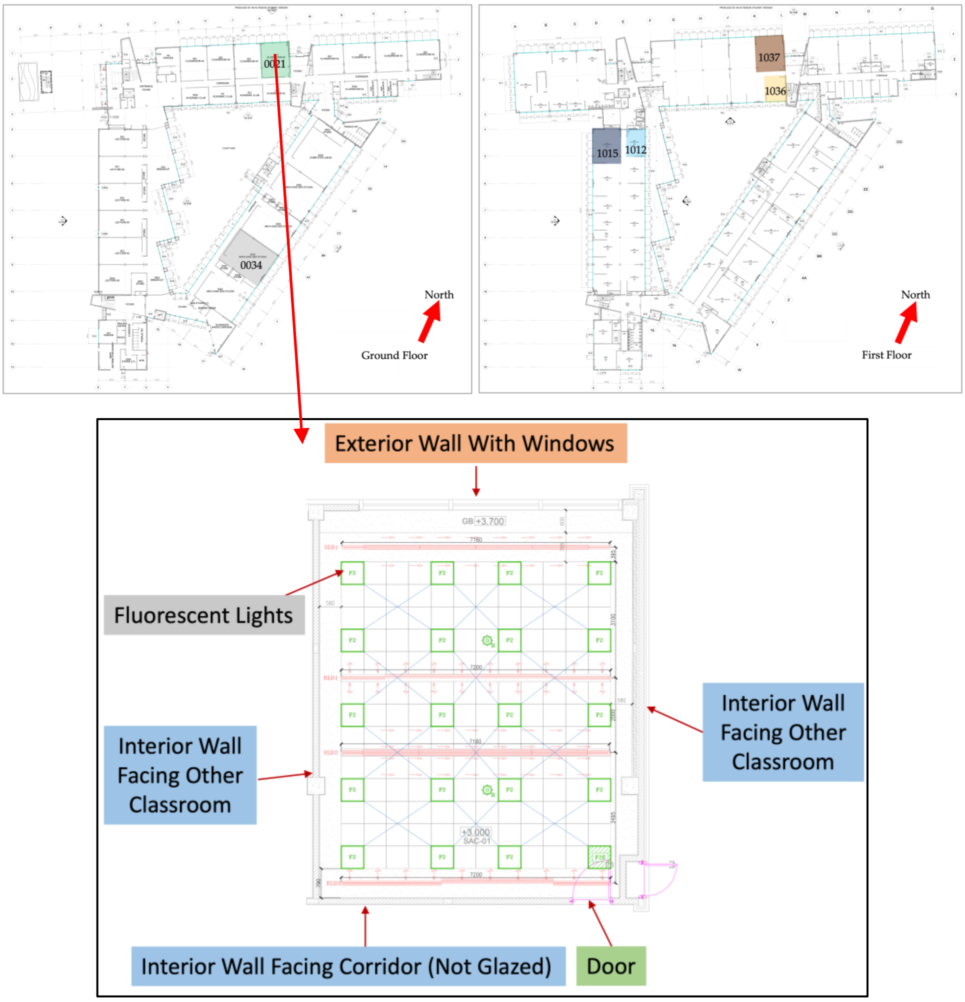



Figure 32: Classroom 0021 Layout (Ground Floor)

From Figure 33 when the (blinds are open and lights are off), the last two rows (near the windows) have enough daylight to depend on from 9 am to 3 pm. In this classroom as well some of the readings during the afternoon (noon) and evening (3 pm) is exceeding the best level of CS for the human body to maintain a good circadian rhythm.


Figure 33: Lighting Levels Measurements for Classroom 0021 (Ground Floor)

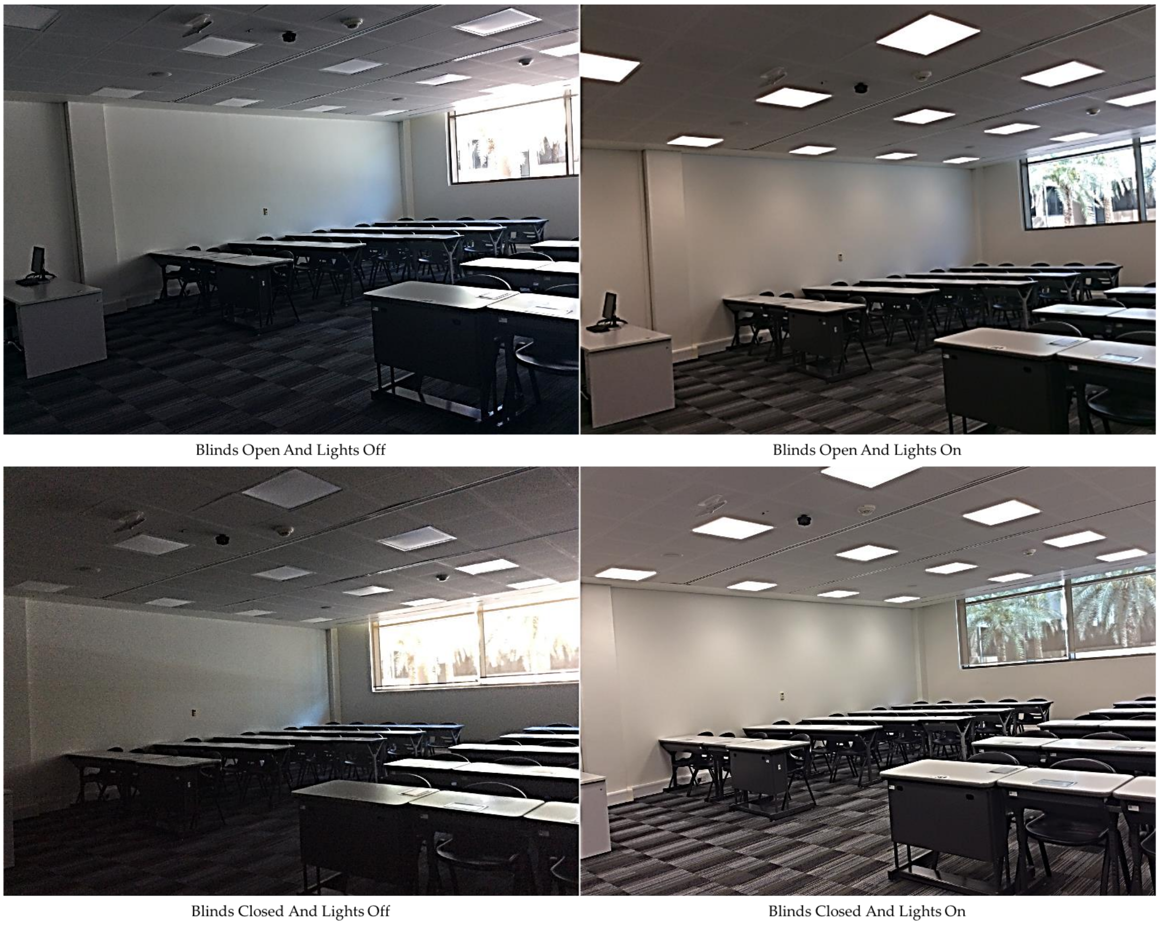



Figure 34: Blinds and Artificial Lights Different Cases in Classroom 0021

The readings for classroom 1012 (Lecture Classroom) are shown next, and the class plan is shown in Figure 35. The classrooms area is in the West south direction from the inner side of the building where the windows facing the courtyard. This classroom has no blinds that’s why there are only two situations that were recorded (blinds open-lights on and blinds open-lights off).

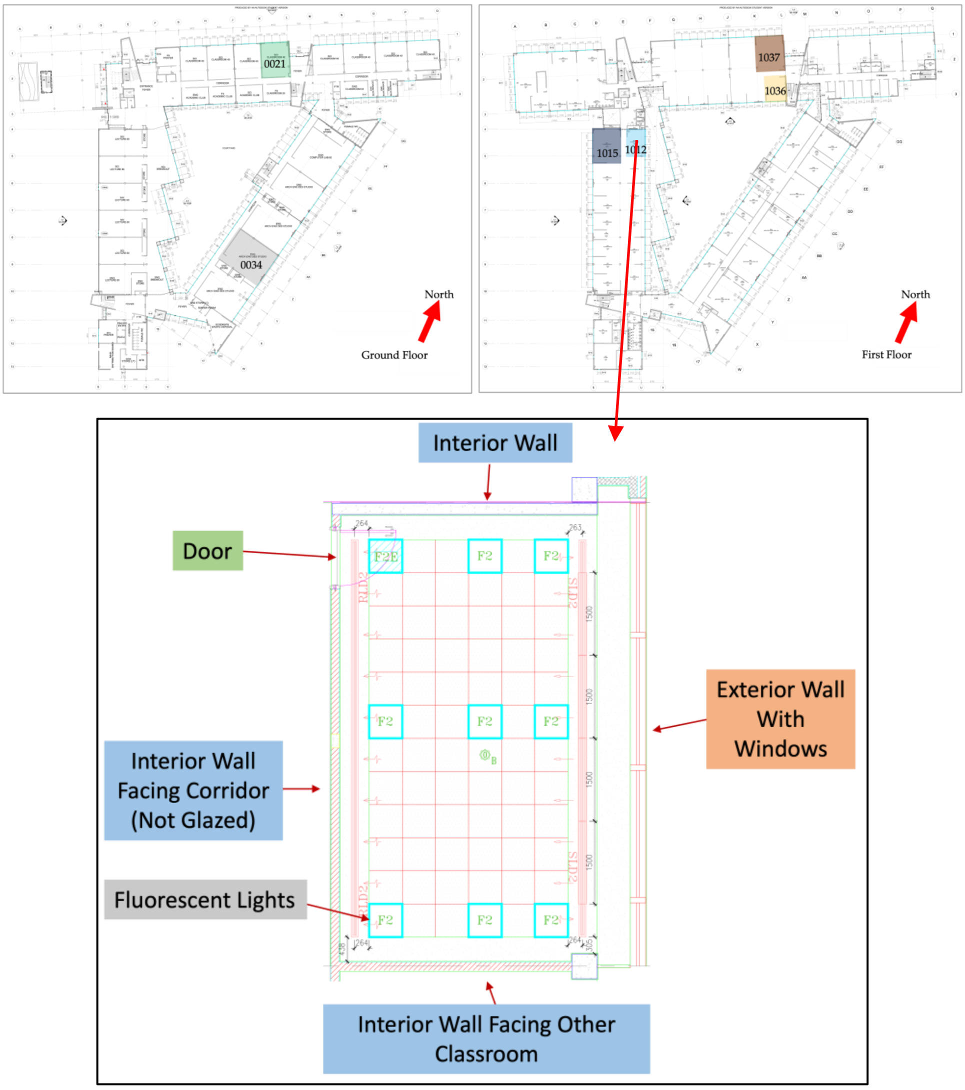



Figure 35: Classroom 1012 Layout (First Floor)

From Figure 36 when the (blinds are open and lights are off) the classroom doesn’t have enough daylight to depend on, this might be because of the classroom location in the building. Based on daylighting only, the amount of lux doesn’t match the best level of CS for morning and afternoon where the readings of lux are supposed to be (500-600 lux) and (400 lux) respectively, but for the afternoon the lux readings are below 300lux (0.1 CS) which is good for sleep/wake cycle.


Figure 36: Lighting Levels Measurements for Classroom 1012 (First Floor)

Blinds Open And Lights Off | Blinds Open And Lights On

Figure 37: Blinds and Artificial Lights Different Cases in Classroom 1012

Following are the readings for classroom 1015 (Lecture Classroom), the class plan is shown in Figure 38. The classrooms area is in the West south direction from the outer side of the building.

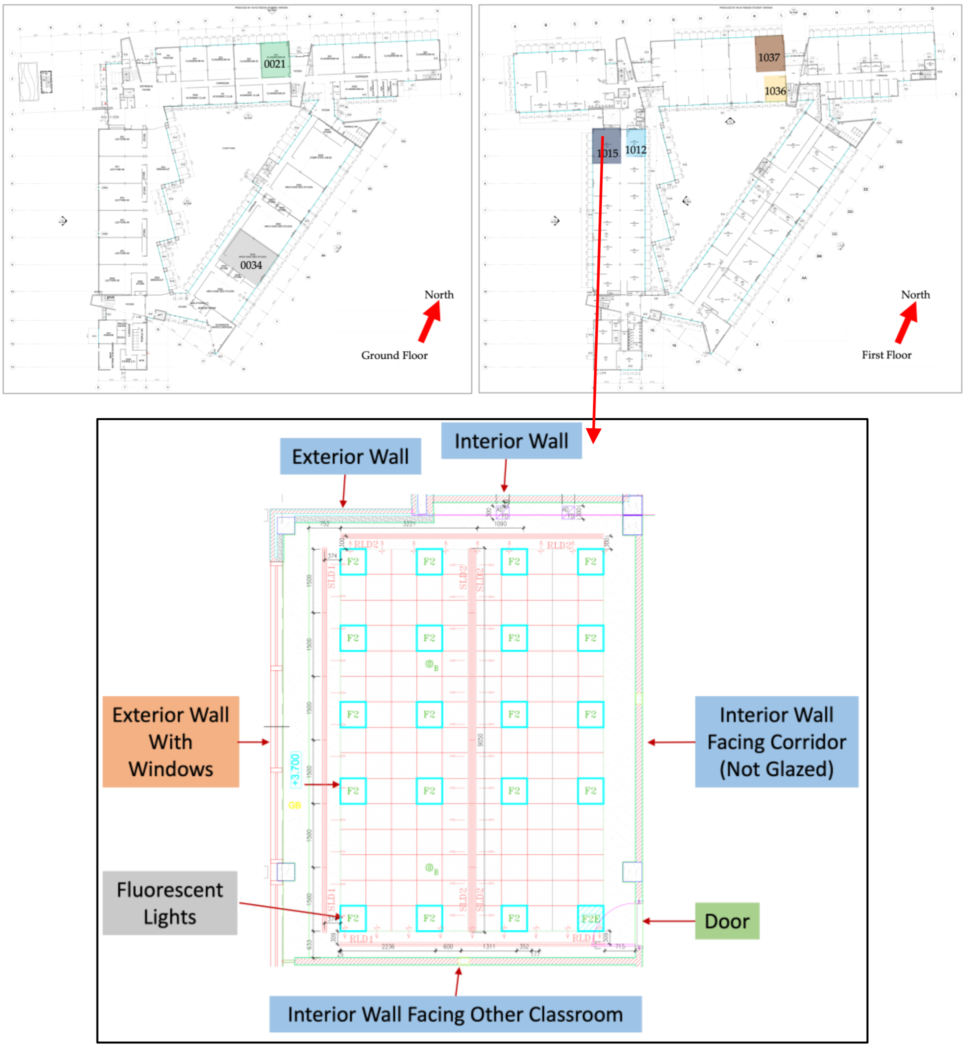



Figure 38: Classroom 1015 Layout (First Floor)

From Figure 39 when the (blinds are open and lights are off) two of the columns can depend on the daylighting in the time range of 9 am to 12 noon, while at 3 pm it is hard to do so. But the good side of this is that at 3 pm most of the readings are below 300 lux (0.1 CS) except for eight readings. When the (blinds are open and lights are on) most of the lux readings are above the standards for classrooms (300-500 lux), and at the same time it is more than the required levels for circadian rhythm.


Figure 39: Lighting Levels Measurements for Classroom 1015 (First Floor)

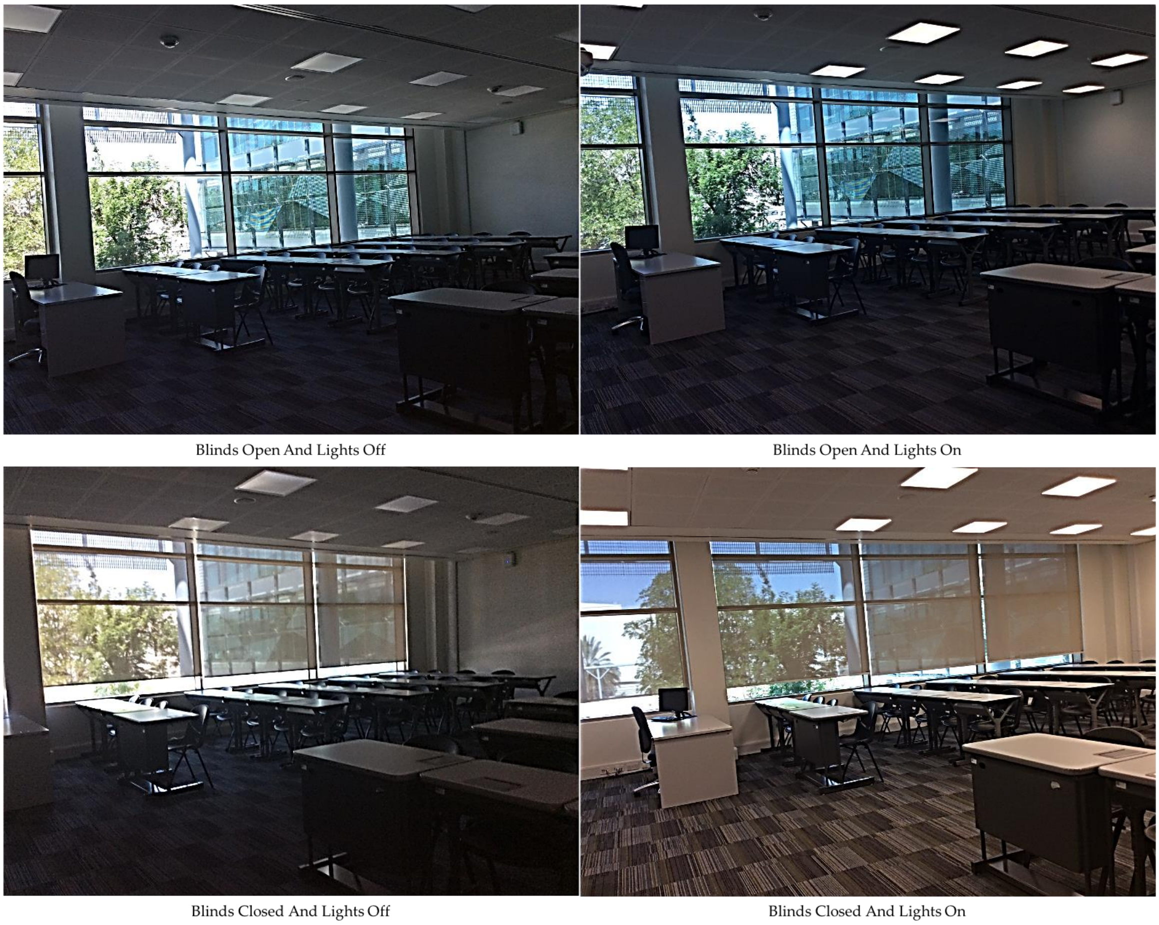



Figure 40: Blinds and Artificial Lights Different Cases in Classroom 1015

Next are the readings for classroom 1036 (Lecture Classroom), the class plan shown in Figure 41. The classrooms area is in the Northwest direction from the inner side of the building where the windows facing the courtyard.

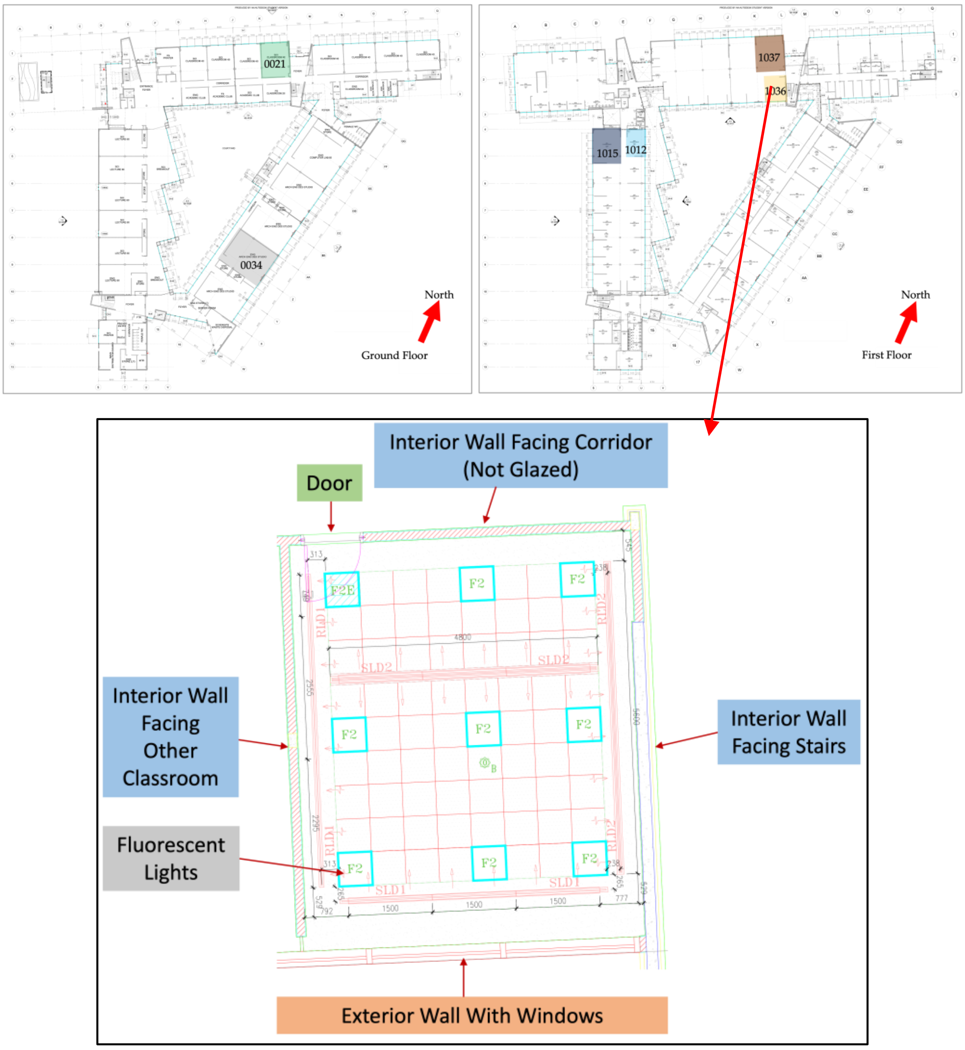



Figure 41: Classroom 1036 Layout (First Floor)

From Figure 42 when the (blinds open and lights are off) the amount of daylight that can enter the classroom from 9 am to 3 pm is higher than both the required standards for the classrooms (300-500 lux) and circadian stimulus. This could be because of the classroom location inside the building, so it might be better to change the glass type or provide more shading. Or even provide lighting intensity controls for each row.

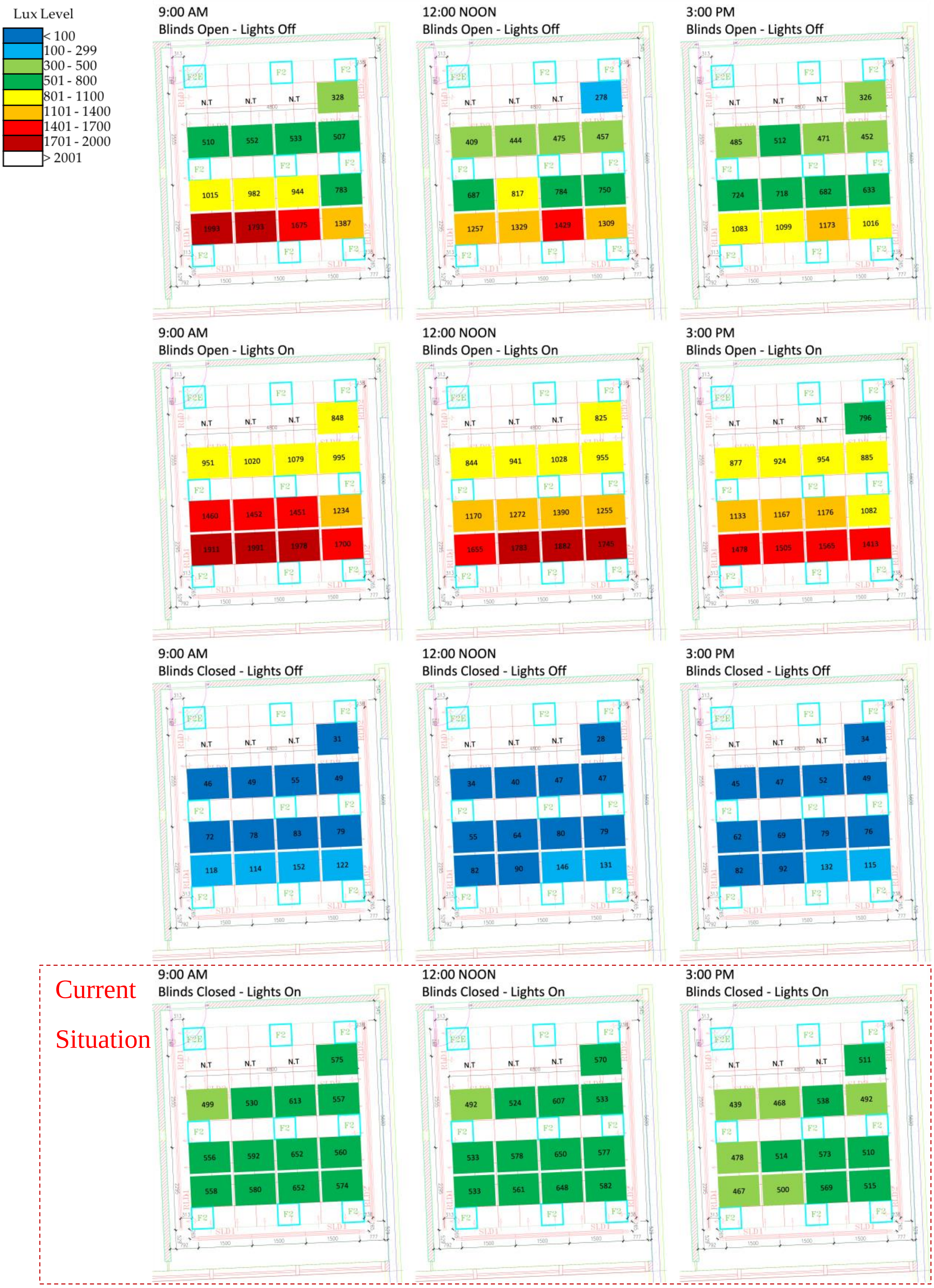



Figure 42: Lighting Levels Measurements for Classroom 1036 (First Floor)

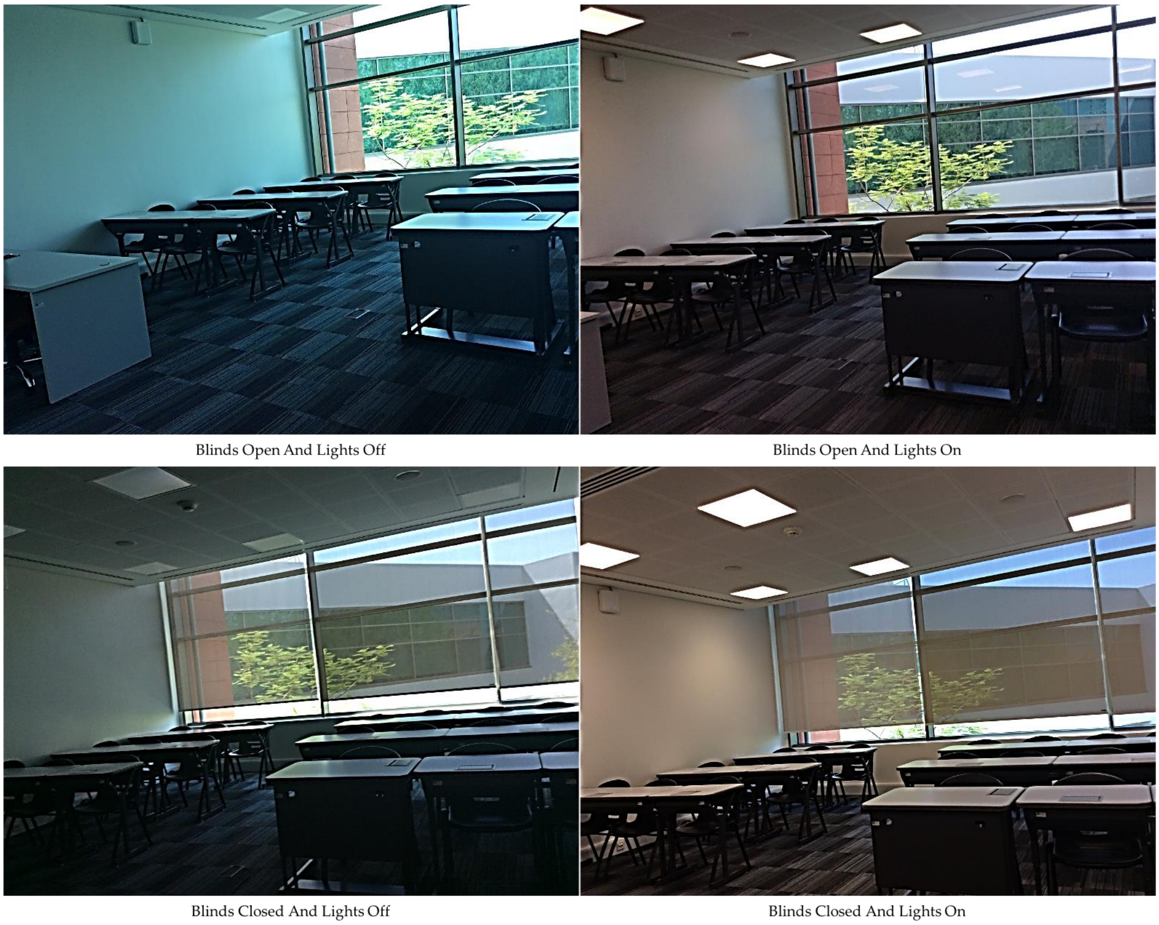



Figure 43: Blinds and Artificial Lights Different Cases in Classroom 1036

Lastly, are the readings for classroom 1037 (Lecture Classroom), the class plan shown in Figure 44. The classroom area is in the Northwest direction from the outer side of the building.

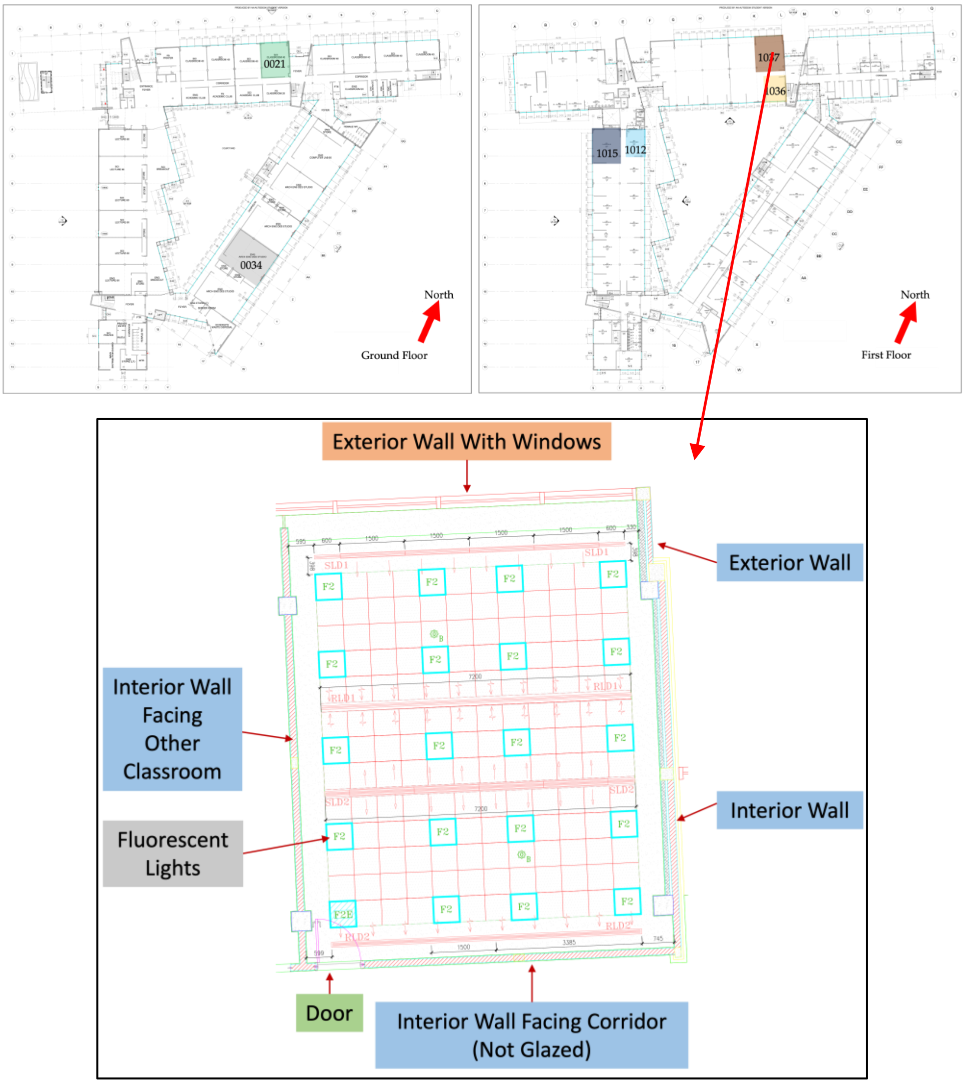



Figure 44: Classroom 1037 Layout (First Floor)

From Figure 45 when the (blinds are open and lights are off) the last 3 rows can depend on the daylighting from 9 am to 3 pm. The last row has more daylighting than the standard level (300-500 lux). This classroom mostly shows very high lux levels in both modes (daylighting) and (mixed mode).


Figure 45: Lighting Levels Measurements for Classroom 1037 (First Floor)

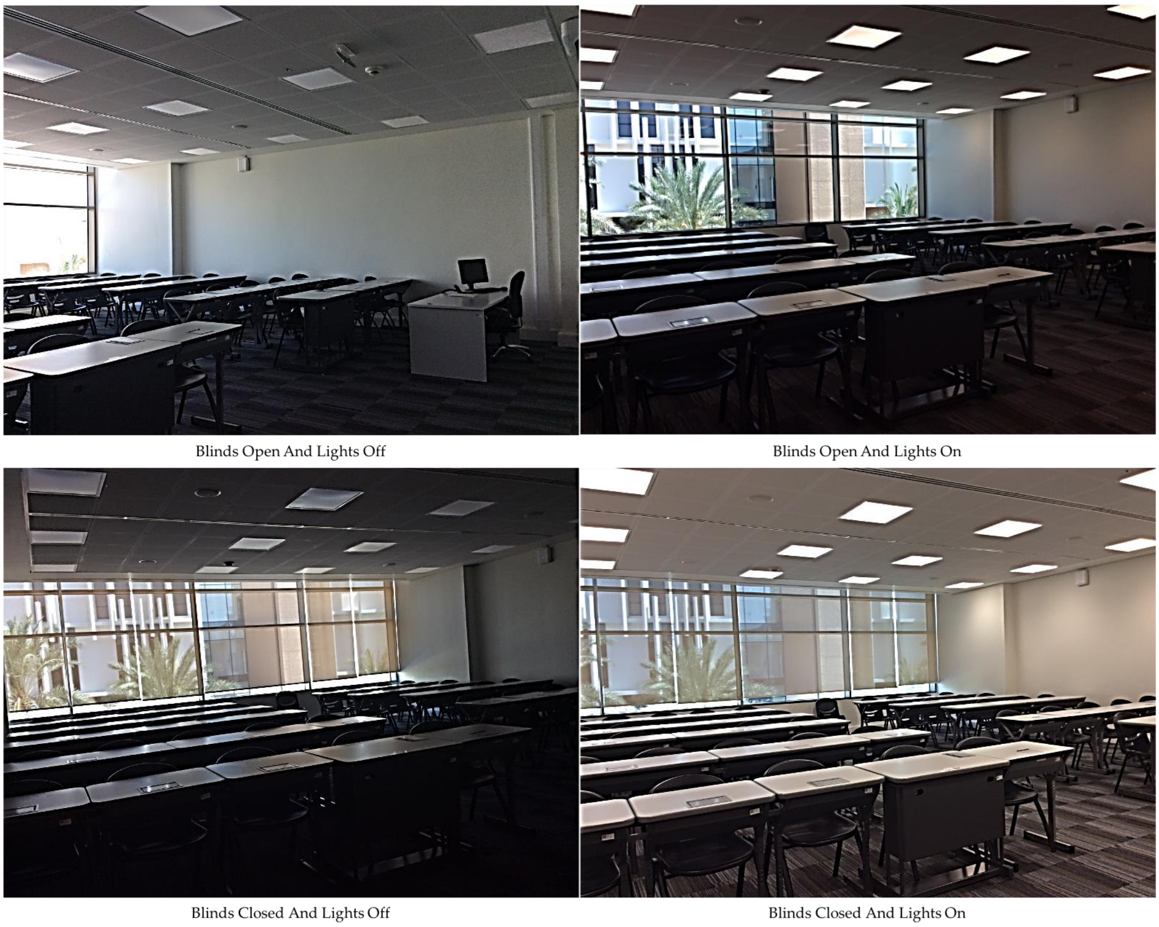



Figure 46: Blinds and Artificial Lights Different Cases in Classroom 1037

All the measurements for the classrooms showed that the classrooms got good (but varying) amounts of daylight each based on the classroom's location in the building. Some of the classrooms exceeded the best level for lux and Circadian Stimulus (CS).

*4.2.4 Summary of Monitoring Experiments*

Write a summary of the main findings as bullet points. The monitoring experiments concluded the following for the studied areas:

- Thermal Comfort: The temperatures inside most of the studied areas about 40.35% were below the comfort range (21 $^{o}$C). For the RH the readings were good, there were only 0.929% of the readings that were below and above the comfort range (30% - 65%).
- IAQ: The IAQ parameters were good almost everywhere, there are only a few readings that weren't in the comfort range (the standard), such as $PM_{2.5}$ with 1.94%

above the standard (15 μg/$m^3$), and $PM_{10}$ with 1.01% above the standard (50 μg/$m^3$). While the $CO_2$ didn't pass the standard anywhere (less than 800 ppm as WELL Standards and less than 1000 ppm as ESTIDAMA). The TVOC was also good except for a small ratio of 0.25% above the standard (312 ppb).

- Lighting Comfort: The amount of natural lighting that enters the classrooms was good almost in all the studied classrooms, but the ratio is different in each classroom due to the classrooms' location inside the building and the size of the classroom, and the wall-to-window ratio. Some of the classrooms could depend on the natural lighting in the daytime if the layout of the classroom were improved and the artificial lighting control designed based on three lighting zones (based on the classroom's layout).

The most common related findings between the survey and the monitoring experiments are the followings:

- Temperature: In the survey students were feeling uncomfortable about the indoor temperature (feeling cold), and it is supported by the monitoring experiments data that showed the indoor temperature in most of the classrooms was below the comfort range.
- Lighting: Students felt that the use of natural lighting inside the classroom is less than the use of artificial lighting which makes them not comfortable inside the classrooms, and as the gathered data from the monitoring experiments most of the studied classrooms get a very good amount of natural lighting throughout the daytime.

From all the common findings of the survey and the monitoring experiments the scenarios of the simulation part have been planned, which are the following:

- Temperature: Indoor temperature is below the comfort range which makes occupants feel uncomfortable, and this is also can be related to the amount of energy consumption, for that, it is better to reduce the indoor temperature to be around the comfort range (24 $^{o}$C).

- Lighting: The use of artificial lighting inside the classrooms is high even in the daytime when there is a good amount of natural lighting, and the layout of the classrooms is not helping with saving energy from the artificial lighting and it give students uncomfortable because it causes glare and reflections on the screens, for that it is better to organize the furniture to be parallel to the window and make it closer to them to increase the use of the natural lighting. It is also helpful if the artificial lighting controls are divided into smaller lighting zones (three zones) to reduce the use of energy for lighting.

These previous findings helped in planning the following section of the simulation.

**4.3 Overview of the Simulation Results**

The main focused parameters of the indoor environment in this research are the classrooms' layout (including desk orientation), indoor temperature, electrical lighting operation, and use of daylight with internal blinds. As discussed before, the temperature in some classrooms is under the comfort level, and this not only affects thermal comfort but also leads to increased cooling energy consumption. Also, as for lighting most of the classrooms are arranged in a way that makes the daylight reach only a few students' desks, which results in using artificial lighting more and consuming more energy, but when the desks are arranged in another way and the classrooms are divided based on lighting zones the amount of used energy for light could decrease. When combining the improvement of increasing the indoor temperature to reach the comfort zone with the improvement of the classrooms' layouts and lighting zoning a good amount of energy could reduce.

In the simulation part, one of the most used classrooms during the COVID-19 Pandemic was selected (classroom 0034), also this classroom is used as Architecture Design Studio and the students always work on printed layouts with lots of details as well as on computers, in this type of classrooms the students should get comfortable especially regarding the lighting parameter because of the type of work they do and also because design studio classes usually last for 3 hours which mean it is a long period comparing to other lecture classes, that's why this classroom was taken as an example for the simulation part.

*4.3.1 Internal Cooling Temperature Change*

Since the temperature in most classes was low (below the comfort level), the simulation was done (in classroom 0034) to see the difference in energy consumption when the temperature was increased to 24 $^{o}$C (which consider a comfort zone). Table 21 shows the results in classroom 0034 on the ground floor. The cooling load has decreased from 13.72 kW to 10.65 kW. This shows a reduction in energy consumption of around 25% in this classroom. This means the cooling load is one of the main consumers of energy in buildings.

Table 21: Readings from DesignBuiler Software for Increasing Internal Temperature

| Classroom 0034 | Current (21 °C) | Suggested (24 °C) |
|---|---|---|
| Use of Cooling Load (%) | 100<br>(13.72 kW) | 68<br>(10.65 kW) |
| Use of Lighting (%) | 100 | 100 |
| Use of Energy (%) | 100 | 75 |
| % Of Saved Energy | 25 | |
| Thermal Comfort | - Indoor temperature at comfort level and energy is saved. | |

Next are Figure 47 screenshots from the software to show the difference in cooling load when the internal temperature is 21 $^{o}$C (upper graph) and when it is 24 $^{o}$C (lower graph).

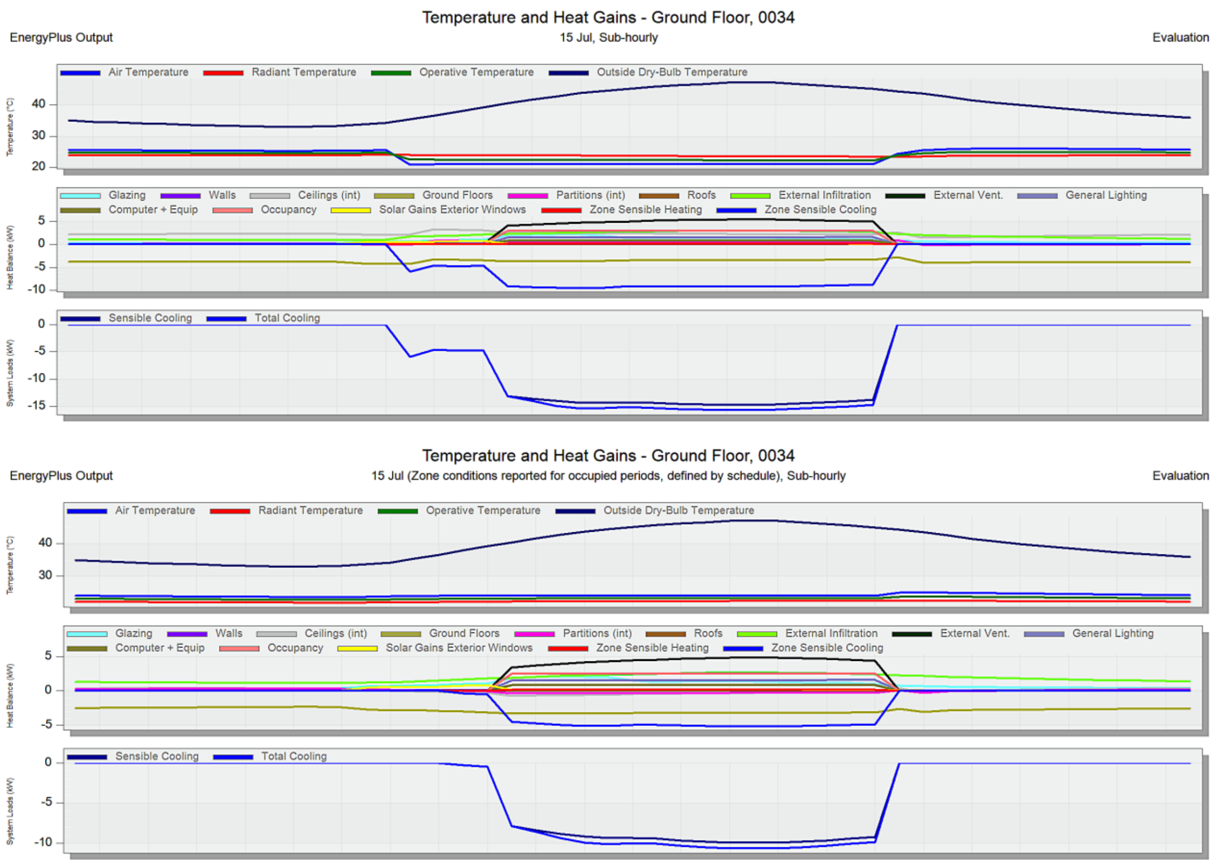



Figure 47: Cooling Load Graphs from DesignBuilder Software for Classroom 0034

### *4.3.2 Desks Layout Change*

The use of artificial lighting was decreased by changing the classroom layout and desk orientations to increase the use of daylighting. The following Table 22 shows the results in classroom 0034 on the ground floor. This results in a reduction of around 19% in the overall energy consumption in one classroom. Figure 48 explains the suggested changes in the selected classroom. This suggestion showed that almost half part of the classroom can rely on daylight from 9 am to 12 pm, while from around 3 pm until evening the use of artificial lighting is again 100% due to the lack of natural lighting.

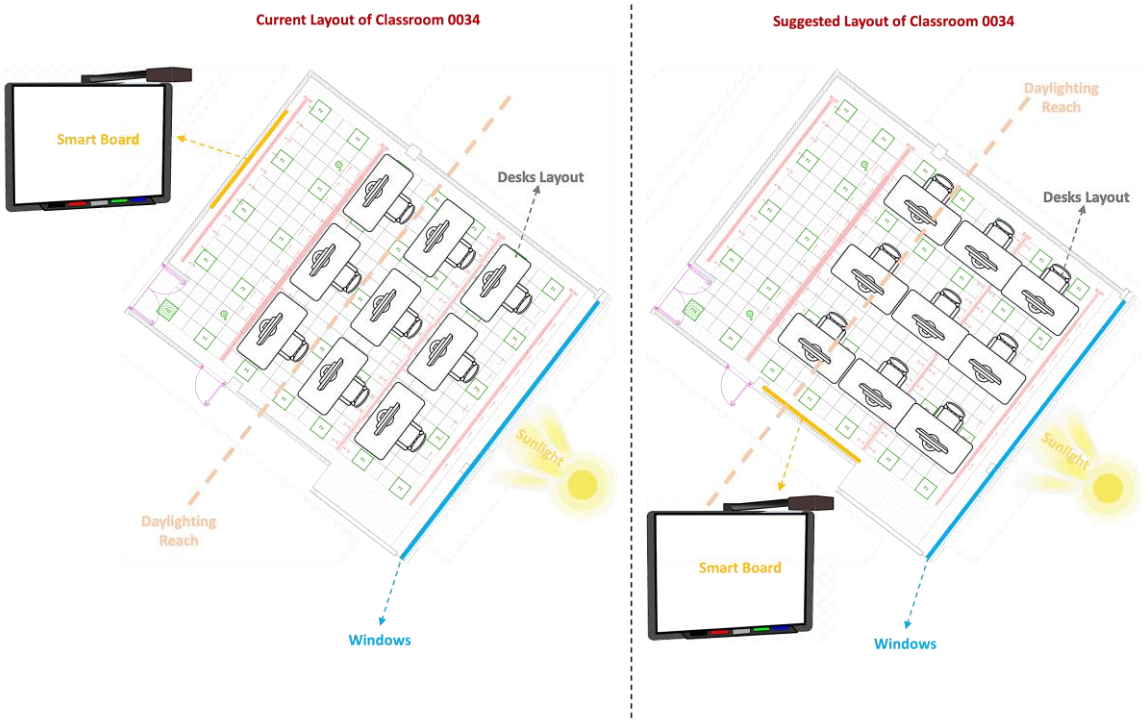



Figure 48: Current and Suggested Desks Layout of Classroom 0034

From Table 22 the reduction in the cooling load happened due to the reduction in the use of artificial lighting which reduces the amount of heat that generates by the light bulbs.

Table 22: The Changes for Desks Layout in Classroom 0034

| Classroom 0034 | Current | Suggested |
|---|---|---|
| Use of Cooling Load (%) | 100 | 95 |
| Use of Lighting (%) | 100 | 90 |
| Use of Energy (%) | 100 | 81 |
| % Of Saved Energy | 19 | |
| Lighting Comfort | - Glare and reflections in screens eliminated. | |

### *4.3.3 Lighting Zoning Change*

Creating lighting zones based on the area that could depend on the daylighting at certain times of the day could result in more reduction in the used energy. Table 23 shows the results from the software. The overall reduction of creating lighting zones could reach

26% in energy consumption. Figure 49 explains the suggested changes in the selected classroom. This suggestion helped in managing the use of artificial lighting in the classroom based on the daylight amount in each zone.

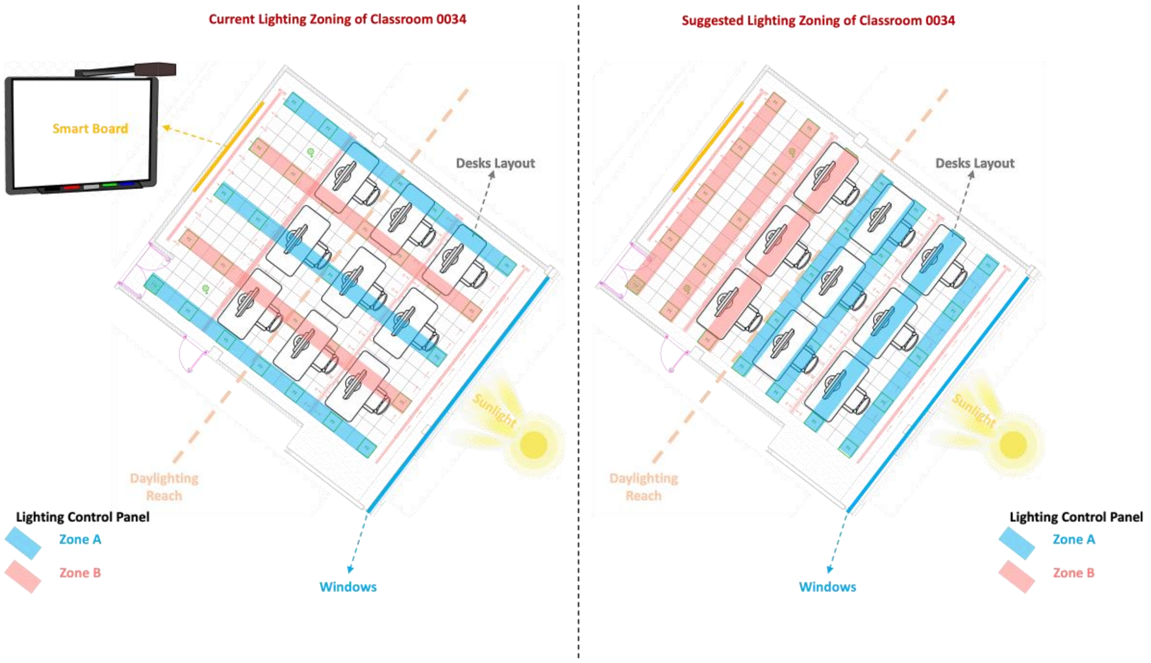



Figure 49: Current and Suggested Lighting Zoning of Classroom 0034

From Table 23 since the amount of artificial lighting is reduced this caused to reduce in the heat that comes from the light which led to a reduction in the cooling load.

Table 23: The Changes for Lighting Zoning Change in Classroom 0034

| Classroom 0034 | Current | Suggested |
|---|---|---|
| Use of Cooling Load (%) | 100 | 78 |
| Use of Lighting (%) | 100 | 94 |
| Use of Energy (%) | 100 | 74 |
| % Of Saved Energy | 26 | |
| Lighting Comfort | - Increase the ability of using daylighting through the day in certain places in the classroom. | |

*4.3.4 Open Window Through Corridor, Desks Layout, and Lighting Zoning*

The opaque wall that faces the corridor was changed to be glazed to make advantage of the natural light that enters the corridor from the courtyard. The lighting zoning for artificial lighting is divided into three zones, and the desk layout is changed to avoid any discomfort such as glare and reflections. Figures 50 and 51 explain this scenario in more detail. While Table 24 presents the results based on the DesignBuilder Software.

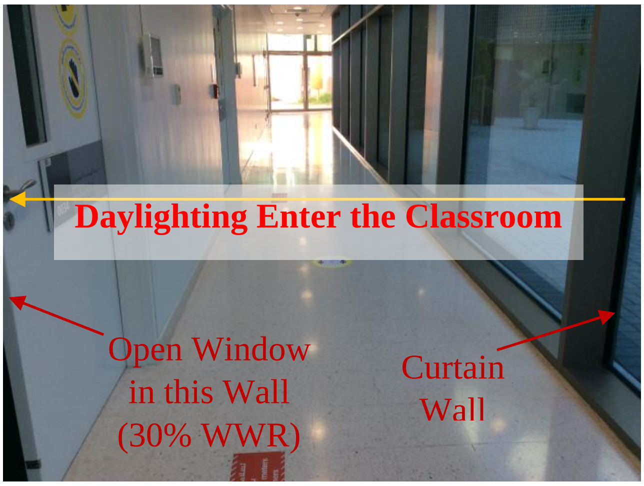



Figure 50: Daylight Comes from the Courtyard Can be Used in Classroom 0034

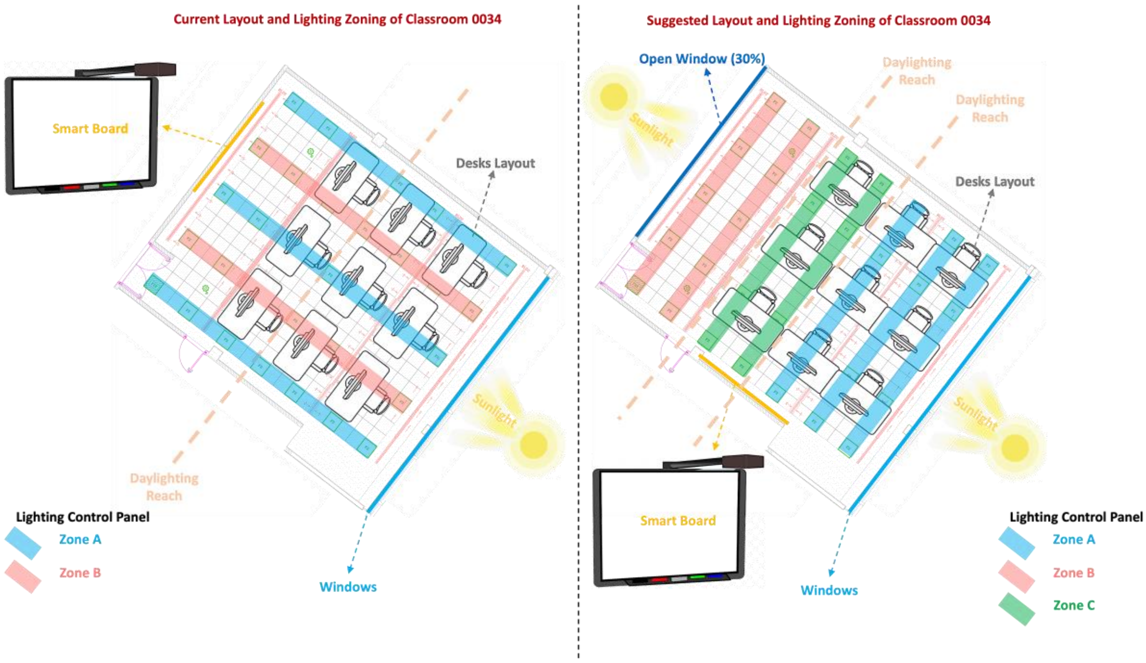



Figure 51: Current and Suggested State of Classroom 0034

Table 24: The Changes for Open Window, Lighting Zoning, and Desks Layout in Classroom 0034

| | Current | Suggested |
|---|---|---|
| Use of Cooling Load (%) | 100 | 94 |
| Use of Lighting (%) | 100 | 16 |
| Use of Energy (%) | 100 | 76 |
| % Of Saved Energy | 24 | |
| Lighting Comfort | - Increase the ability of using daylighting through the day in most places in the classroom.<br>- Eliminate Glare and reflections in the screens. | |

Figure 52 shows that after opening the side window some areas in the classroom can depend on daylighting at certain times of the day, which will reduce the lighting load in the classroom. A small area at the center of the classroom always needed artificial lighting.

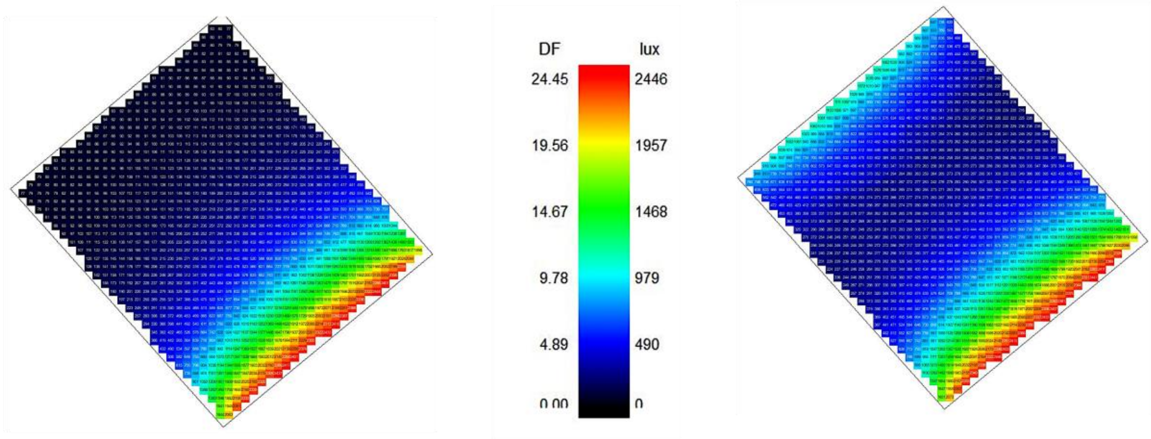



Figure 52: Current State of Lux Distribution in classroom 0034 (Left) and After Opening the Side Window Through the Corridor (Right)

*4.3.5 All Scenarios Combined*

Combining the reduction from changing the indoor temperature, desks layout, lighting zoning, and opening another window in the wall facing the corridor. This will result in a noticeable reduction in energy use in this classroom.

Table 25: The Combination of All Scenarios in Classroom 0034

| | Current | Suggested |
|---|---|---|
| Use of Cooling Load (%) | 100 | 61 |
| Use of Lighting (%) | 100 | 8 |
| Use of Energy (%) | 100 | 49 |
| % Of Saved Energy | 51 | |

Figure 53 shows the summary of the reduction gathered from all the scenarios.

- Scenario A: Change the internal temperature to 24 °C.
- Scenario B: Change desk layout.
- Scenario C: Create lighting zoning.
- Scenario D: Open a side window through the corridor with changing the desks layout and creating new lighting zoning.
- Scenario E: All the scenarios combined.

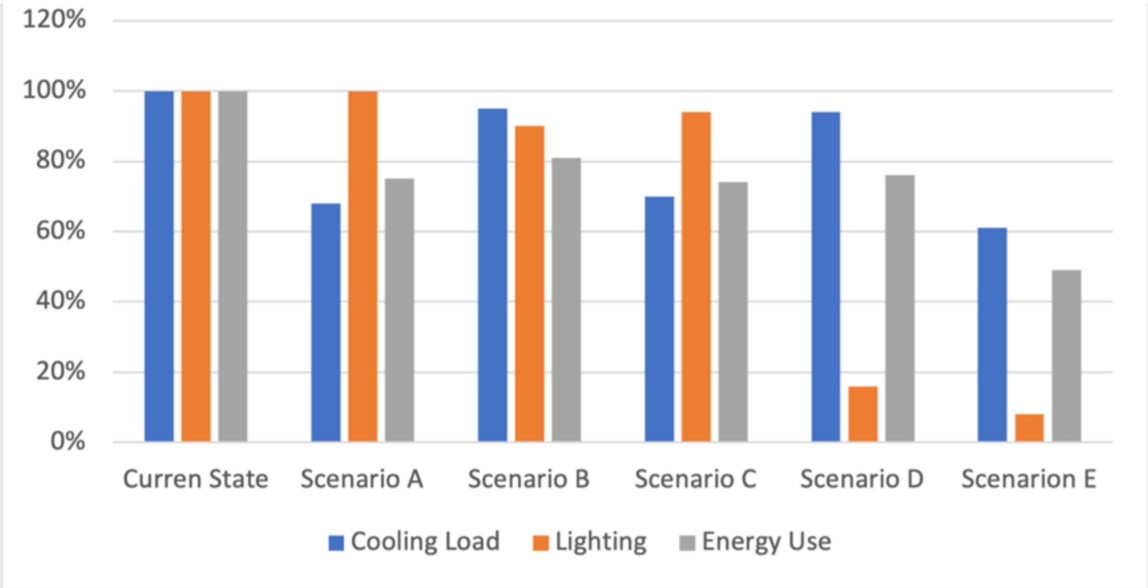



Figure 53: The Reduction in Cooling Load, Lighting, and Energy Use of All the Scenarios

### 4.4 Summary of Research Findings and Discussion

Both subjective and objective measurements helped in understanding the IEQ and how the occupants perceive it.

The questionnaire itself shows that people can have different opinions on each of the parameters of the IEQ, this might be due to multiple variables such as gender, age, health state, etc. When comparing the questionnaire to the monitoring experiments it is also shown that not all people will get annoyed or affected by the IEQ in the same way or at the same level. Because even when the readings weren't good some of the students still find the IEQ good for them, while others are not.

The questionnaire findings showed that the main issues that students feel are low indoor temperatures where around 40% felt cool and another 16.6% felt cold so more than half percentage of the respondents felt that indoor temperatures leaned toward being cold. The second issue is about not enough daylight inside the classrooms because the blinds can't be opened due to the class layout, so when the blinds are opened glare and reflection occur, and there are around 51% of students felt annoyed by glare and reflection. In general, there are 39.5% felt that there is too little daylight inside the classrooms. The monitoring experiments also support the fact that there are issues with indoor temperature since 93.3% of the gathered data were under the comfort level of 24 $^{o}$C. The lighting experiments showed that there is enough daylight in almost all the classrooms when the blinds are opened and the lights off, but the blind in the current situation is being closed to avoid glare and reflection since in most classrooms the smart board is facing the windows and the students' table are perpendicular to the windows.

There are some suggestions based on the results from the questionnaire and monitoring experiments, some of these were taken into consideration for the simulation and some were not. Some of the suggestions are:

- Changing the classroom layout, in a way that will make it use the most daylight, and in some classrooms, the students' tables are perpendicular to the windows which cause glare and reflections so making them parallel to the windows will reduce this issue.

- Making the artificial lighting controlled by rows, will reduce energy consumption because the rows that have enough daylighting will not need to turn on the artificial lights and so on.
- Changing the AC type (linear type) to a type that can distribute the air evenly in the classroom or add shields beneath the ducts to help in distributing the air evenly or change the place of the AC ducts to the edges of the ceiling, walls, or floor. Because with the linear type, the students that are set under the supply air ducts feel colder and drier than the others, while the ones who are set far away from it could feel warmer or more comfortable.

Based on the simulation, the energy consumption could reduce by 51% using a variety of simple methods such as raising the internal temperature to the comfort level (25% saved energy), increasing the daylighting (24% saved energy), creating artificial lighting zones (26% saved energy), and updating the classrooms' layouts (19% saved energy). Those types of changes can be done in each classroom based on its location in the building, then the reduction could be done in almost all the classrooms which means the total consumed energy of the building will reduce by a noticeable value.

# Chapter 5: Conclusion

This study focused on investigating the Indoor Environment Quality (IEQ) for a university building by conducting an online questionnaire, monitoring experiments, and simulation. The main aim was to ensure that the case study building has a proper IEQ that will help in improving productivity during class times. Also, studying the energy consumption inside the studied areas and making scenarios to reduce it. The study did not aim at focusing on studying the students' well-being and health because this will need a separate study and more data about students' physical and physiological health, as well as observations of the students during the time they stayed inside the building. However, the study did use previous studies and research about the effect of the IEQ of the built environment on occupants' health and well-being, to show and explain to the readers of this study the importance of conducting such a study in an educational building that is used by many students and other people to learn, teach, and communicate. Based on this, the study investigates the case study building's IEQ through online surveying, monitoring experiments, and dynamic simulations.

## 5.1 Main Findings

First, the online questionnaire aimed at understanding students' feelings about the different parameters of the IEQ such as thermal, IAQ, and visual. It also aimed at understanding how they interact with the current classroom environments, such as the furniture layout and how it affects the use of artificial and natural lighting. Using this method, it has been determined that the internal temperatures are very low. In addition, there are some lighting issues related to glare and reflection due to the classroom furniture layouts. This results in using more artificial lighting inside classrooms and less daylighting because most of the time the blinds are closed. In general, the students showed a neutral satisfaction level with the overall IEQ of the classrooms. (Figure 54) shows a summary of the gathered data from the online questionnaire. Even though the percentage of students who feel unhappy about different parameters seems small, it is wise not to ignore them. Therefore, the next method (monitoring experiments) is performed in this research to verify whether the classrooms' IEQ meets the standards for the main parameters such as temperature, RH, particles, $CO_2$, TVOC, and lighting.

| | Bad | Neutral | Good |
|---|---|---|---|
| Thermal Comfort | 11.98 | 44.24 | 43.77 |
| | | | |
| | Bad | Neutral | Good |
| Indoor Air Quality | 15.21 | 36.87 | 47.93 |
| | | | |
| | Bad | Neutral | Good |
| Visual Comfort | 10.6 | 42.86 | 46.54 |
| | | | |
| | Bad | Neutral | Good |
| Overall Indoor Environment | 9.21 | 34.56 | 56.22 |

Figure 54: Summary of the Main Data from the Questionnaire

Secondly, the monitoring experiments measured the actual state of the IEQ in terms of thermal, IAQ, and visual parameters, but the acoustic parameter was ignored since the building is not occupied as usual due to the COVID-19 pandemic. $PM_{2.5}$ and $PM_{10}$ concentrations have some issues in some classes, with percentages over the standards of about 1.94% and 1.01% respectively. The studied areas have acceptable $CO_2$ and TVOC levels. All the classrooms have low temperatures with 93.3% of the gathered readings under 24 $^oC$, while relative humidity has a smaller percentage (0.929%) of data that deviates from comfort levels (30% - 65%). Lighting is the parameter that presents the most issues compared to all other parameters, and these issues indicate that classrooms have lots of artificial lighting whereas many classrooms can depend on daylighting during the daytime (before 3 pm). However, in most classrooms, it is impractical to open blinds because it could cause glare or reflections on the screens due to the furniture layout that faces the windows. As shown in Chapters 3 and 4, the artificial lighting inside the classrooms has only two zones. These zones are divided into columns rather than rows, which will be more beneficial because it will be possible to turn off the rows beside the windows when there is enough daylight. This will allow them to turn on only part of the classroom lights. This will decrease energy consumption directly.

From online surveying and monitoring experiments, the scenarios for the simulations have been generated. And these scenarios are based on the problems identified.

By focusing on the classroom's furniture layout, indoor temperature, and lighting, the simulation part of the study helps determine whether the suggestions made will help improve the IEQ and decrease energy consumption. It showed that energy consumption could be reduced by doing simple changes like increasing the indoor temperature and making it in the comfort zone as per the standards (24 – 26 $^{o}$C) to reduce the cooling load. Also, increase the use of daylight by changing the furniture layout, and adding a window. And changing the artificial lighting zones to reduce the use of artificial lighting inside the classroom. Table 26 summarize the reduction of cooling load, lighting, and energy consumption when simulating different changes inside the space. Both the cooling load and lighting load have a big effect on the energy consumption of the building.

Table 26: Simulation Scenarios Summary

| | Current State | Scenario A | Scenarios B | Scenario C | Scenario D | Scenario E |
|---|---|---|---|---|---|---|
| Cooling Load (%) | 100 | 68 | 95 | 75 | 94 | 61 |
| Lighting Load (%) | 100 | 100 | 90 | 94 | 16 | 8 |
| Energy Use (%) | 100 | 75 | 81 | 74 | 76 | 49 |

Based on the results of the online questionnaire and the monitoring experiments, there are some issues inside the classrooms, such as the indoor temperature being cold or hot for some students due to the type of AC used (linear type - 2 outlets and 2 inlets) which results in an uneven air flow throughout the classrooms. The reality is that users' perception is not the same for all of them, so it can be seen how valuable it is to understand a building's users before designing it (in terms of gender, age, etc.). Additionally, the monitoring experiments showed more issues than what occupants can feel, which indicates that it is useful to do different types of analysis when studying IEQ since less information about its actual state makes a study not as accurate. The simulation showed how it is useful to use software to see the difference between various scenarios (for example choosing different materials for glazing or changing the light types or as in this study increasing the indoor temperature and reducing the use of artificial lighting in multiple ways), and how each scenario affects the IEQ and the energy consumption as well.

A few Green Building Rating Systems (GBRSs) such as ESTIDAMA, LEED, WELL Standards, ASHRAE, and BREEAM were discussed in this research. Some of these standards and guidelines are used to determine whether the gathered data from monitoring experiments for temperature, RH, IAQ, and illumination is within the comfort level. As per the literature review, the GBRSs are created to ensure a better-built environment taking into consideration nature, humans, the economy, society, and energy. Previous studies have shown that the ideal built environment is the one that balances all these factors since they are linked to each other. About the improvement of IEQ, some of the suggestions based on GBRSs involve increasing the use of daylight and enhancing the control of the occupants within the space to ensure a comfortable indoor environment while conserving energy. This research proved that some of these simple ways could improve occupants' comfort and energy usage by a certain percentage. The GBRSs also show that maintaining a high-quality indoor environment needs detailed studies of two things. The first is the building's occupants because some factors such as age and gender might affect the occupants' interactions with the space. The second study is about climatic conditions.

### 5.2 Research Challenges and Opportunities

The main limitation was the COVID-19 pandemic, which affected this study in a variety of ways. In the beginning, this research was supposed to consider three university buildings, two of them lecture buildings (one on the female side and the other on the male side) and the third one the female residence building, but because the buildings were almost empty and not occupied as usual since most of the classes are online, as well as safety concerns (especially at the female residence building), this study focused on only one building. Adding to that, some of the parameters were ignored when conducting the monitoring experiments (such as measuring the noise level inside the classrooms) because the building is supposed to be normally occupied so that the readings will be accurate, but it is also necessary to say that all the building's systems such as HVAC are operating as normal which means the other measured parameters are not affected by the occupation except for the artificial lighting since it is controllable by users. Further, other types of devices could be more accurate or could be used to support the readings in the monitoring experiments. However, due to the limited time to remain inside the building, this was not feasible. As well, more devices can be operated by sensors during class time while students are present, but this was not feasible. Another limitation can be related to the methods used. A direct interview with the users could be more beneficial to gain a better understanding of how each classroom operates. This is because it would be conducted at a certain time of the day when students would be in the classroom.

### 5.3 Research Gap and Future Study

A future study may use other methods, such as interviews and the use of other types of sensors that work when students are present in classrooms. This might provide more useful information. Furthermore, future research should focus not only on classrooms but also on other spaces such as labs, computer labs, student sitting areas, etc. Added to that, a detailed study of the occupants' physical and psychological states and how those could be affected by the IEQ will support the importance of studying the IEQ of the buildings. Finally, the whole building's energy consumption could be studied in more detail by seeing the decrease in the used energy when applying the different scenarios in the whole building.

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# Appendices

## Appendix A: Case Studies

Table A1: Global and Local Case Studies for Different Types of Buildings

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (1) 2006 | Users' Perception of Comfort and Well-being in University Buildings (Triantis, Bougiatioti & Oikonomou, 2006) | University Building (Greece) | - Questionnaires<br>- Monitoring Measurements | - Obtaining subjective information about the indoor comfort conditions (thermal, visual, acoustic and air quality).<br>- Measuring air temperature, relative humidity, and daylighting. | - High levels of air temperature, due to the building's high thermal mass.<br>- Low levels of daylighting in corridors, while glare issue in Southern offices.<br>- 64% of the users rated thermal comfort in offices as "warm" or "hot". 28% rated the air temperature as "unpleasant".<br>- No significant issues for lighting comfort.<br>- Most users have direct access to windows in their space, so that they can benefit from natural ventilation. This leads to users can fully 36%, or almost fully 55% control ventilation in their space.<br>- 73% of users considers IAQ to be unacceptable to barely acceptable. This could be because of the design of typical office spaces does not allow for cross-ventilation of individual units.<br>- For noise levels and acoustic comfort, users feel the overall performance as satisfactory. |
| (2) 2011 | Student Learning Performance and Indoor Environmental Quality (IEQ) in Air-Conditioned University Teaching Rooms (Lee et al., 2012) | University (Hong Kong) | - Subjective Assessment<br>- Objective Measurement | - Gathering data about air temperature, RH, air speed, mean radiant temperature, $CO_2$, sound pressure level, horizontal illumination level, occupant activity and clothing insulation level measured in 4 classrooms and 4 large lecture halls, self-reported learning performance and perceived IEQ are evaluated. | - Thermal comfort, IAQ and visual environment are of comparable importance, aural environment is the main determining factor.<br>- All IEQ complaints have comparable impact on learning performance and there is a good correlation between learning performance and the number of complaints.<br>- The measured air velocities were higher than those found in some Hong Kong air-conditioned offices, and thus a higher contribution of indoor air temperature to the operative temperature $T_{op}$.<br>- Equivalent sound pressure levels were significantly higher than the background noise levels in all teaching rooms except the lecture hall H3 and classrooms C2 and C3.<br>- Survey results showed that 84% were satisfied with thermal comfort, 76% with IAQ, 91% with visual environment, and 90% with aural environment. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (3)<br><br>2013 | Evaluation of Indoor Environmental Quality (IEQ) on Dense Academic Building: Case Studies Universiti Tun Hussein Onn Malaysia<br><br>(Sulaiman et al., 2013) | Tun Hussein Onn Malaysia University<br><br>(Malaysia) | - Questionnaire: occupants' survey and data collection.<br>- Scientific measurement: investigation, study of building plans, and measuring using devices.<br>- Data analysis. | - Identify frame wok, evaluate IEQ based on users' perception, then measure IEQ.<br>- Experimental studies based on thermal (temperature and RH), IAQ (air movement and $CO_2$), noise and lighting.<br>- Experimental results compared with Malaysian standards. | - The average temperature reading was 23°C (good condition), as per standards (23-27°C).<br>- The total average RH reading is 73% (high), as standards (55-70%).<br>- Sound intensity is at 76.4dB (bad condition), as standards (50-70dB).<br>- The average lighting level is 251 lux intensities (slightly low), as standards (300-500 lux).<br>- The average reading of air movement was 0.4 m/s, as standard (0.15 to 0.50 m/s).<br>- The average reading of $CO_2$ was 513 ppm (good condition) since it must be below 1000 ppm. |
| (4)<br><br>2013 | Effect of IEQ on Occupant Satisfaction and Study/Work Performance in a Green Educational Building: A Case Study<br><br>(Wang & Zamri, 2013) | New Wales University (Tyree Energy Technologies Building)<br><br>(Australia) | - Case study with quantitative (archival records) and qualitative (questionnaire) methods.<br>- Site visits. | - Explore the relationships between IEQ and occupants' study/work performance in a green educational building.<br>- Structured online questionnaire.<br>- Non-probability purposive sampling used to select the sample of participants. Correlation coefficients and multiple linear regressions used to analyze the results. | - Occupants satisfied with the overall indoor environment, but not with space layout and the IAQ.<br>- All indoor environment factors and the overall indoor environment satisfaction are significantly correlated with the occupants' performance.<br>- Thermal and acoustic quality and space layout were the main factors that contribute to the overall performance.<br>- Overall thermal and lighting quality were relatively highly evaluated by the occupants where else IAQ was regarded as the lowest.<br>- Acoustic quality affects occupants' performance the most. Noise can affect work performance and gives negative influence on cognitive work such as logical thinking, memorization ability, concentration, and interrupt these internal processes. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (5)<br>2014 | Comparative Study on the Indoor Environment Quality of Green Office Buildings in China with a Long-term Field Measurement and Investigation<br>(Pei et al., 2014) | Office Buildings<br>(China) | - Case Study Buildings<br>- POE Surveys<br>- Long-Term Objective Measurements | - Searching about 10 buildings case studies built after 2008, and conventional office built in the recent 10 years. Then analyze all the buildings' data.<br>- Evaluation of occupants' habits and satisfaction using a questionnaire of more than 20% of occupants' number. Examining thermal comfort, IAQ, lighting, and acoustic.<br>- Using calibrated quick-response digital instruments, the indoor and outdoor environments were measured (Thermal, IAQ, Visual and Acoustic). | - Green building (GB) possesses significantly higher satisfaction level than the conventional building (CB). The graph indicates that the difference in occupant satisfaction between GB and CB is particularly obvious in the IAQ and thermal comfort. Occupant satisfaction is affected by lots of factors, such as environmental attitudes, knowledge of GB, etc.<br>- Comparing the temperature variety curves in a typical week among 4 buildings, there is no significant difference between GB and CB, with the temperature almost between 20 and 24°C. They both have up to Chinese standard (Public building energy efficiency design standards), which requires the indoor air temperature of the HVAC system up to 20°C.<br>- $CO_2$ is almost 400 and 1100 ppm, gradually getting higher as the number of officers gets larger and the working time gets longer to the peak by the end of working hours in a day. $CO_2$ in these buildings basically achieves the standard line.<br>- Some workplace doesn't achieve the standard request sometimes for the visual environment. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (6)<br><br>2014 | Evaluation of Indoor Environmental Quality Conditions in Elementary Schools' Classrooms in The United Arab Emirates<br><br>(Fadeyi et al., 2014) | Elementary Schools<br><br>(Abu Dhabi) | - Observations.<br>- Investigations.<br>- Monitoring Experiments.<br>- Data Analysis. | - Observations during walkthrough investigations.<br>- Measured IEQ data ($CO_2$, CO, TVOC, RH, Temperature, O3, Formaldehyde, Particle, Acoustic, Light).<br>- Data Analysis. | - The average measured in classrooms were TVOC (815 mg/m$^3$), $CO_2$ (1605 ppm), O3 (0.05 ppm), CO (1.16 ppm), and particle (1730 mg/m$^3$). Whereas the local authority (Dubai Municipality) recommended 300 mg/m$^3$, 800 ppm, 0.06 ppm, 9 ppm, and 150–300 mg/m$^3$, respectively.<br>- Dubai Municipality recommended (22.5ºC to 25.5ºC) for temperature and (30%–60%) for RH. The average temperature and RH measured in the classrooms were 24.5ºC and 40.4%.<br>- The average sound level in the classrooms was 24dB greater than the recommended sound level limit of 35dB.<br>- 6 classrooms had average lux levels in the range of 400–800 lux. Two classrooms had average lux levels in the range of 100–200 lux. The remaining classrooms had lux levels around the recommended 300 lux.<br>- Most of the studied classrooms have high occupancy density.<br>- Poor IEQ conditions in the studied classrooms highlight the need for further research investigation to understand how poor classrooms' IEQ conditions could influence students' health, comfort, attendance rate, and academic performance. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (7)<br><br>2016 | Sustainable Buildings for Healthier Cities: Assessing the Co-benefits of Green Buildings in Japan<br><br>(Balaban & Puppim de Oliveira, 2016) | 7 Office Buildings with different other functions, like: public gallery, commercial facilities, shopping mall<br><br>(Japan) | - Studying the Context of Japan<br>- Literature Review<br>- Case Studies<br>- Semi-Structed Interviews | - Studying the level of GHG emissions in Japan and the main reasons for it. Also, the impacts of sustainable buildings in reducing the GHG emissions.<br>- Find the relationship between the building sector and environment including human health.<br>- 7 case studies located in Greater Tokyo Area. Calculated in terms of environmental benefits, economic benefits, and health benefits (better IAQ, more natural lighting, better ambient air quality and less heat to pedestrians, improved thermal comfort).<br>- Collecting quantitative data and qualitative information from 11 interviews with 24 people. | - Sustainably renovated buildings could yield significant benefits in terms of $CO_2$ reduction and improved health situation for building users.<br>- The case study buildings with the best two performances are found to achieve 38% and 32% reduction in $CO_2$ emissions intensity in comparison to benchmark values.<br>- The top two buildings are found to provide improved healthy environment due to improved indoor and ambient air quality, better thermal comfort, and more natural lighting indoors.<br>- Passive design, natural elements such as airflow and sunlight are used to provide a comfortable indoor environment. These strategies provide a better IAQ, thermal comfort and more daylight in buildings, which in turn may influence the health and wellbeing of the occupants in positive ways. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (8)<br>2016 | Occupant Productivity and Office Indoor Environment Quality: A Review of the Literature<br>(Al Horr et al., 2016) | Office<br>(England) | - Literature Review | - Set a firm base for the research findings.<br>- Outline different IEQ factors (IAQ and ventilation, thermal comfort, lighting and daylighting, noise, and acoustics) that affect occupant productivity in an office environment. | - IAQ parameters such as RH, temperature, and air contaminants are affected by outdoor conditions (climate), building conditions (material, structure, and construction), buildings' HVAC systems, indoor space arrangements (furnishing, furniture, equipment), and occupants' productivity patterns.<br>- Thermal comfort can be affected by clothing, altering activity, changing posture, window location, and mood. And it is influenced by air temperature, air velocity, RH, mean radiant temperature, clothing insulation, and metabolic rate. And plays a significant role in occupant productivity. Dissatisfaction with thermal comfort leads to productivity loss. Temperature change within the 18°C - 30°C range can influence the performance of office occupants in tasks. The temperature range of 21°C - 25°C is a stable range for office productivity. There is a decrease in occupant performance by 2% per 1°C increase in temperature in the range of 25°C - 30°C.<br>- Lighting and Daylighting: Organizations that pay attention to the importance of daylighting achieve higher occupant productivity in their workplaces. Some companies have reported a 15% decrease in absenteeism and a 47% increase in attendance, respectively, in buildings designed to provide maximum daylight for their occupants. A study of office workers focusing on the importance of windows and their benefits reports that almost 99% believed that offices should have windows and that 86% considered daylighting to be the preferred source of light for office tasks.<br>- Noise and Acoustics: Internal and external noise sources, both affect occupants' performance and cause stress and anxiety, and might create long-term health problems. A temperature change of 1°C has the same effect on productivity as a change in the noise of 2.6dB. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (9)<br><br>2016 | Assessment of Indoor Environmental Quality (IEQ): Students Well-Being in University Classroom with the Application of Landscaping<br><br>(Jamaludin et al., 2016) | University<br><br>(Malaysia) | - Classroom Measurement Normal Condition<br>- Classroom Intervention Setting<br>- Measurements<br>- Questionnaires | - Student satisfaction level in their normal classroom environment.<br>- Comparison of IEQ in different classroom environment setting.<br>- Sampling devices to monitor temperature, RH, $CO_2$, VOC, dust particles, lighting, and noise of the classroom.<br>- Based on IEQ elements and current students' satisfaction level. | - From the questionnaire, there were some minor health symptoms that have been identified such as stress, dry skin, itchy eye, blurred vision, and tired eyes.<br>- Most of the students rated it warm. This might be due to the heat transmission through the windows and lack of air circulation, which eventually reduces ventilation rates. The classroom orientation with windows is towards Easts, meaning that the classroom gains higher penetration from sunlight, which can cause heat gain in the classroom. However, few students rated cold in the classroom. Based on the sitting position, students perceived satisfaction with the thermal condition is due to the location in the classroom whether they are sitting near the air conditioner.<br>- The indoor air temperature pattern was observed to be influenced by the outdoor air temperature.<br>- The concentration of $CO_2$ in the classroom is within acceptable standards (700 ppm above the outdoor concentration).<br>- No serious issue regarding dust particles ($PM_{10}$) in the classroom.<br>- TVOC shows a significantly high value (11.7 ppm) beyond the TLV set (3 ppm).<br>- Lower lighting intensity was observed at the right side of the classroom, due to the tinted glass windows, which reduces excessive lighting penetration during a sunny day. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (10)<br><br>2017 | INDOOR AIR QUALITY (IAQ) IN THE UAE RESEARCH IN ENVIRONMENTAL HEALTH AND SAFETY<br><br>(Bani Mfarrej et al., 2017) | Malls (Toilets, Food Courts, Hypermarkets, Gyms)<br><br>(Abu Dhabi, Dubai, RAK) | - Measurements and monitoring. | - Measuring the air pollution and monitoring the dust, carbon monoxide (CO), and carbon dioxide ($CO_2$) found in Abu Dhabi, Dubai, and RAK malls by utilizing TSI IAQ Instruments, and dust monitor.<br>- | - Highest count of $CO_2$ was 2880 and above which found in the toiled zone. Dust was found in the toilet which mean the worst zone was bathroom.<br>- Mazyed Mall CO level in the air was 0.1 ppm which is below the standard (0.9). $CO_2$ level was 1115 ppm as an average which is higher than the standard (800 ppm) and this is due to the high population in this location. 3rd, dust level in the same spot was 65 ug/$m^3$ which is considered a safe level as it`s lower than the standard (150 ug/$m^3$).<br>- Delma mall was the second place to study the IAQ, with 0.1 ppm CO level in the air which is below the standard (0.9).<br>- RAK Mall, CO level in the air and 0.6 ppm are the average and some of the ready was 0 ppm. So, 0.6 ppm it's a normal level in the air and it consider as safe level. |
| (11)<br><br>2017 | A Review of Comfort, Health, and Energy Use: Understanding Daily Energy Use and Wellbeing for the Development of a New Approach to Study Comfort<br><br>(Ortiz et al., 2017) | Different Types<br><br>(Netherlands) | - Extensive Literature Review | - Performed in the topics of health, comfort, and energy use, with a focus on the interactions between the occupant and the environment.<br>- Studied factors are thermal comfort, acoustical quality, air quality, and visual quality. | - Comfort influenced by the different IEQ parameters, such as visual (view, illuminance, and reflection), thermal (air velocity, humidity, and temperature), acoustical (control of unwanted noise, vibrations, and reverberations), and air quality (smells, irritants, outdoor air, and ventilation).<br>- Humans avoid discomfort and unpleasant experiences, and hence they are always striving (whether consciously or unconsciously) to change their present state towards a homeostatic state – thus a more neutral or comfortable one. As a result, many of the actions we do are wellbeing-driven actions that can have effects on both health and comfort. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (12)<br><br>2017 | The Impact of Thermal Environment on Occupant IEQ Perception and Productivity<br><br>(Geng et al., 2017) | Office<br><br>(China) | - Experimental Study.<br>- Questionnaire and Productivity Test. | - Series of Experiments were done to study the way that thermal environment (air temperature, globe temperature, RH, $CO_2$, illuminance, and background noise) affects occupant IEQ perception, productivity, and health.<br>- Conducted to find out the perception of each IEQ factor (thermal comfort, IAQ, lighting and acoustic). | - Thermal sensation vote was predicted to be "neutral" at 24ºC, meanwhile, the percentage of thermal dissatisfaction was expected to be lowest. This prediction was verified, and it showed that 75% of the thermal satisfaction voted concentrate on "neutral" and none of the subjects felt dissatisfied under 24ºC.<br>- Thermal satisfaction votes firstly increased and then decreased with the air temperature moving from 16ºC to 28ºC, and subjects attained highest thermal satisfaction at experimental condition of 24ºC.<br>- The average value of thermal sensation vote had a strong linear relationship with air temperature.<br>- Satisfaction votes were obtained at different air temperature conditions and more than 80% of the participants felt "neutral or satisfied" with IAQ, lighting and acoustic environment. However, the percentage of IAQ, lighting and acoustic dissatisfaction was relatively high at 22ºC and 24ºC.<br>- 70% of participants felt "dissatisfied" with overall environment at 16ºC, while the percentage of overall environment dissatisfaction fell to zero at 24ºC.<br>- When thermal environment was unsatisfactory, it weakened the "comfort expectation" of other IEQ factors, which accordingly resulted in the less dissatisfaction with other IEQ factors. Conversely, when thermal environment was quite satisfying, it raised "comfort expectation" of other IEQ factors, which lowered the evaluation of the real performance of other IEQ factors retroactively.<br>- The optimal productivity was obtained when people felt "neutral" or "slightly cool", and the increase of thermal satisfaction had a positive effect on productivity. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (13)<br>2017 | Indoor Environmental Quality and Occupant Satisfaction in Green-Certified Buildings<br>(Altomonte et al., 2017) | Office Buildings<br>(UK) | - Survey.<br>- Monitoring and Feedback. | - Explores the relationships between the points earned in the IEQ (thermal, acoustic, luminous and IAQ) category and the satisfaction expressed by occupants with the qualities of their indoor environment.<br>- Monitoring of building performance and collection of comprehensive occupant feedback. | - Homogeneous samples were drawn only from buildings that were certified by the LEED product and version featuring that specific IEQ credit.<br>- The achievement of an individual IEQ credit does not have a practically relevant influence on occupant satisfaction with the corresponding IEQ parameter.<br>- The total number of IEQ points earned did not influence workplace satisfaction, independent of the product under which certification was awarded.<br>- Occupant satisfaction with the building and workspace was not affected by the rating level achieved. |
| (14)<br>2018 | Indoor Environment Quality Assessment in Classrooms: An Integrated Approach<br>(Tahsildoost & Zomorodian, 2018) | Educational Buildings<br>(Old, new, retrofitted)<br>(Iran) | - Measurements<br>- Questionnaire | - Temperature, humidity, radiant temperature, air velocity, $CO_2$ level, and illumination were measured in 3 occupation periods every day for a school week in mid-July, mid-November, mid-January, and mid-April.<br>- Students' personal information, satisfaction of thermal, visual, acoustical, IAQ, and overall comfort level was assessed. | - Minimum attention to local standards about IAQ, acoustic, and lighting, especially in the old and retrofitted buildings, seems the main reason of low environmental quality in the studied cases.<br>- The acceptable range of each IEQ parameters, especially regarding thermal and acoustic comfort, is broader in real condition in comparison with the standards.<br>- All 3 measured classrooms in the old building have average PMV values higher than ASHRAE standard requirements (category II—normal level of expectations: $-0.5<PMV<0.5$) in the cooling season. High PMV are due to the uninsulated building envelope, single layer windows, and insufficient ventilation rates. The new and retrofitted buildings are in the TC range. Besides the temperature control, the thermal discomfort of the classrooms in the cooling season was related to draughts caused by cooling system (air velocity>0.8 m/s). |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (14)<br><br>2018 | Continue | | | | - The average PMV values are all in the comfort range (between -0.5 and +0.5, based on ASHRAE 55.1) in November. In April, warm sensations are predicted in the south-faced classrooms in all 3 buildings.<br>- The maximum average SL recorded (74dB) in the old building is much bigger than national standards for classrooms (40 dB). It was concluded that students would feel neutral about the acoustic environment when the SL is lower than 50.8 dB and would be satisfied when the SL is lower than 41.7 dB.<br>- $CO^2$ highest value was recorded (2052 ppm) in the new building during January, while the lowest (417 ppm) was recorded in April in the old building.<br>- According to the CEN Report CR 1752 Ventilation for buildings, if sedentary occupants are assumed to be the only source of pollution, the $CO_2$ concentration above the outdoor level should be for category B: less than 660 ppm.<br>- The maximum value of $CO_2$ levels raised to more than 1200 ppm in most cases in the heating season, which induced overheating from the beginning hours, and odor complaining was intensified with high occupant density, making forced ventilation a mandatory requirement. Considering the high values of $PM_{2.5}$ in winter in Tehran, it is not recommended to provide more ventilation, as far as IAQ is not objected.<br>- Average light levels (lower limit) measured in classrooms ranged between 321 and 480 lux, with minimum and maximum recorded in north and south-faced classrooms, respectively. The average illuminance levels were in line with standard requirements (300 lux) in classrooms during the year. Students felt neutral when the light level reaches 256 lux and feel most satisfied when reaches 646 lux. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (15)<br>2018 | Environmental Quality of University Classrooms: Subjective and Objective Evaluation of the Thermal, Acoustic, and Lighting Comfort Conditions<br>(Ricciardi & Buratti, 2018) | University Classrooms<br>(Italy) | - Questionnaires<br>- Measurements Experiments | - 7 classrooms selected at Pavia University, all the architectural characteristics, systems and other details were reported.<br>- Investigate the students' perception on thermo-hygrometric, acoustic, and lighting comfort and to analyze which are the subjective parameters most correlated with the experimental results.<br>- Measurements of the main descriptors of thermal, acoustical, and visual comfort. | - Among all the acoustic comfort questions, the ones related to background noise present the highest correlation. Other questions were selected considering the intelligibility - comprehension and the overall assessment of the auditory environment in the classrooms. Classroom 5 is the worst in terms of acoustic conditions, and it is confirmed by the correspondent indexes named IBN (Background Noise Index) and ISQ (Sound Quality Index).<br>- The analysis of the lighting questionnaire showed that the average measured illuminance value has a high correlation with the perceived visual comfort. The classrooms annoying glares have a strong relationship to the classroom excessive light contrasts and a good correlation with the measured illuminance values. |
| (16)<br>2018 | A Review of Operating Performance in Green Buildings: Energy Use, Indoor Environmental Quality and Occupant Satisfaction<br>(Geng et al., 2018) | Different Types of Green Buildings<br>(Different Countries) | - Extensive Literature Review | - Review published research on post-occupancy performance of green buildings in terms of IEQ (thermal comfort, IAQ, lighting and acoustic) and occupant satisfaction.<br>- Compared the actual operating performance of green buildings in China and US, with information collected from previous research. | - People in green buildings (GBs) performed better and had fewer SBS than in conventional buildings (CBs).<br>- CBs was about 1°C cooler, had a lower level of illuminance, and 2.5–3 times higher air change rate.<br>- Objective IEQ performance of GBs basically achieve the designed value, and those GBs were perceived more satisfied than CBs.<br>- Several environmental features can improve occupant satisfactions, including lower background noise levels, higher light levels, conditions associated with thermal comfort, and fewer airborne particulates.<br>- Occupant satisfactions with IEQ were positively associated with their environmental senses, which meant that the 'green' occupants were generally better tolerated with IEQ than their 'non- green' counterparts.<br>- Sources of dissatisfaction mainly came from temperature, air quality, lighting, and noise.<br>- GBs generally had higher occupants' satisfaction level than CBs, although U.S. subjective data did not support this inference. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (17) 2018 | Self-Reported Health and Comfort of School Children in 54 Classrooms of 21 Dutch School Buildings (Bluyssen et al., 2018) | School (Netherlands) | - Questionnaires<br>- Survey<br>- Monitoring Experiment | - Distributed among 1,311 school children (8–12 years old, average 10) of 54 classrooms at 21 schools in The Netherlands.<br>- Inspection of the school and its installations using checklists (window frames, glazing, lighting, etc.).<br>- Measuring of some environmental parameters (temperature, RH and $CO_2$) in the classrooms. | - 87% were bothered by noise, 63% by smells, 42% by sunlight when shining, 35% didn't like the temperature in the classroom (too cold or too warm) and 34% experienced temperature changes.<br>- The main diseases reported comprised allergies (26%), rhinitis (17%), hay fever (16%), and eczema (16%).<br>- Health and comfort in non-traditional schools were better than in the traditional schools studied.<br>- Mean $CO_2$ varied from 641 to > 2000 ppm, and 22 of the 37 classrooms monitored had average $CO_2$ above 1000 ppm.<br>- Mean indoor air temperatures varied from 21 to 26°C and outdoor air temperatures from 13 to 30°C.<br>- No statistically relevant relationship was found between indoor and outdoor air temperatures or indoor air temperature and the mean RH.<br>- The mean RH varied between 29 and 53 percent. |
| (18) 2018 | An Indoor Environmental Quality (IEQ) Assessment of a Partially Retrofitted University Building (Zuhaib et al., 2018) | National University of Ireland (Arts and Science Building) (Ireland) | - Short- and long-term surveys.<br>- Physical measurements: using LASCAR data loggers. | - Assess the compliance for thermal, visual, and acoustic, and IAQ.<br>- Relationship between the performance of the building envelope and occupant comfort is described across retrofitted and non-retrofitted zones.<br>- Physical measurements were conducted for: indoor air temperature (°C), RH (%), mean radiant temperature (°C), air velocity (m/s), illumination (lux), $CO_2$ (ppm) and noise level (dBA). | - Retrofitting of the façade did not make any significant difference to IEQ and occupants continued to adapt personally to the existing conditions.<br>- Preferred satisfaction levels were lower than the measured thermal sensation.<br>- The mean PMV results from summer, autumn and spring are below 0 (neutral) and the mean Thermal Sensation Votes from the satisfaction survey are above 0 (neutral) which means that the occupants prefer and satisfied with lower temperatures.<br>- Recommend that future retrofits are adequately planned and optimized to improve both IEQ and energy performance. A whole building retrofit approach must balance and include factors such as human health, building fabric and energy savings to avoid the pitfalls of current practice. |

Table A1: Global and Local Case Studies for Different Types of Buildings (Continued)

| (#) Year | Title of Research | Building Type (Country) | Methodology | Parameters and Procedure | Results |
|---|---|---|---|---|---|
| (19)<br><br>2019 | An Applied Framework to Evaluate the Impact of Indoor Office Environmental Factors on Occupants' Comfort and Working Conditions<br><br>(Andargie & Azar, 2019) | Green University Campus<br><br>(Abu Dhabi) | - Survey.<br>- Performance test.<br>- Monitoring.<br>- Data collection.<br>- Data analysis. | - Subjective evaluation of comfort levels of occupants with various indoor environment parameters.<br>- Objective evaluation of productivity.<br>- Indoor environmental monitoring (Sound Level, Air Velocity, Radiant Temperature, Air Temperature, Illuminance, and RH).<br>- Data collection by the tools developed in the previous stages.<br>- Data analysis using descriptive statistics, spearman's rank correlations, and ordinal logistic regression models. | - Environmental conditions and occupants' personal characteristics have significant impacts on how occupants perceive their indoor environment, affecting their overall satisfaction, reported happiness, reported productivity levels, and basic cognitive abilities.<br>- Demographical factors such as gender and age are significant determinants of most of the studied comfort and performance metrics, confirming the need to further account for the personal characteristics of occupants when assessing the performance of the built environment.<br>- 30.1% increase in the likelihood of a higher satisfaction with temperature for a 1 unit increase in radiant temperature. The measured noise level is, indicating a 6% decrease in the likelihood of satisfaction with noise for a 1 unit increase in noise level.<br>- An increase of 10 lux improves the likelihood of a higher reported happiness level by 4%.<br>- The measured radiant temperature and RH affected the reported levels of satisfaction of respondents with temperature. Even though the average indoor air temperatures were not particularly low (24.2°C and 23.4°C), results indicate that satisfaction will increase with higher temperatures, which might be due to occupants' adaptation to high outdoor temperatures (mean of 31.5°C). |

## Appendix B: Online Questionnaire Draft

The Survey Will Be Used for Studying Purposes Only, And Your Respond Is Voluntary.

Intro: You are invited to participate in our survey [Analysis of Indoor Environment Quality in UAE University Campus Building]. In this survey, you will be asked to complete a survey that asks questions about [The Indoor Environment of Building C6 (College of Engineering, Science, Food & Agriculture) In Female Campus]. It will take Less Than 5 minutes to complete the questionnaire. Your participation in this study is completely voluntary. If you feel uncomfortable answering any questions, you can withdraw from the survey at any point. It is very important for us to know your opinions. Your responses will be reported only for research uses. Your information will be coded and will remain confidential. If you have questions at any time about the survey or the procedures, you may contact [Salama AlGaithi] at [201400426@uaeu.ac.ae]. Thank you very much for your time and support.

Questionnaire Link: https://www.questionpro.com/t/ASTlqZl5PF

1. Have you had a class in the C6 building since joining the university?
   - ☐ Yes
   - ☐ No

   (If Yes, The Questionnaire Will Start. If No the Questionnaire Will End)

Part 1: General Information:

2. Age Range:
   - ☐ 15-20
   - ☐ 21-25
   - ☐ 26-30
   - ☐ 30 & Above
3. Specialization (Engineering, Science, Food & Agriculture, etc.):

Part 2: How Do You Rate Each of The Following Parameters? (Your Satisfaction Level):

| Parameter | -2 Very Unsatisfied | -1 Unsatisfied | 0 Neutral | 1 Satisfied | 2 Very Satisfied |
|---|---|---|---|---|---|
| Thermal Comfort | ☐ Very Unsatisfied | ☐ Unsatisfied | ☐ Neutral | ☐ Satisfied | ☐ Very Satisfied |
| Temperature | ☐ Cold | ☐ Cool | ☐ Neutral | ☐ Warm | ☐ Hot |
| Relative Humidity | ☐ Very Dry | ☐ Dry | ☐ Neutral | ☐ Humid | ☐ Very Humid |
| Relative Humidity Preference | ☐ Much Drier | ☐ Drier | ☐ No Change | ☐ More Humid | ☐ Much More Humid |
| Air Movement | ☐ Very Weak | ☐ Weak | ☐ Neutral | ☐ Strong | ☐ Very Strong |
| Air Stuffiness | ☐ Very Stuffy | ☐ Stuffy | ☐ Neutral | ☐ Fresh | ☐ Very Fresh |
| Dust in Air | ☐ Very Dusty | ☐ Dusty | ☐ Neutral | ☐ Clean | ☐ Very Clean |
| Visual Comfort | ☐ Very Unsatisfied | ☐ Unsatisfied | ☐ Neutral | ☐ Satisfied | ☐ Very Satisfied |
| Light Level | ☐ Very Dark | ☐ Dark | ☐ Neutral | ☐ Bright | ☐ Very Bright |
| Glare | ☐ Too Much Glare | ☐ Glare | ☐ Neutral | ☐ Little Glare | ☐ No Glare at All |
| Daylight | ☐ No Daylight | ☐ Little Daylight | ☐ Neutral | ☐ Satisfied | ☐ Very Satisfied |
| Overall IEQ | ☐ Very Unsatisfied | ☐ Unsatisfied | ☐ Neutral | ☐ Satisfied | ☐ Very Satisfied |

Part 3: How Often Do You Feel Annoyed by The Following? (Tick One Box)

4. Dry Air?
   - ☐ Often
   - ☐ Regularly
   - ☐ Sometimes
   - ☐ Never
5. Stuffy Air?
   - ☐ Often
   - ☐ Regularly
   - ☐ Sometimes
   - ☐ Never
6. Too Cold?
   - ☐ Often
   - ☐ Regularly
   - ☐ Sometimes
   - ☐ Never
7. Temperature Changes During A Day?
   - ☐ Often
   - ☐ Regularly
   - ☐ Sometimes
   - ☐ Never
8. Cold Feet?
   - ☐ Often
   - ☐ Regularly
   - ☐ Sometimes
   - ☐ Never
9. Warm Surface?
   - ☐ Often
   - ☐ Regularly
   - ☐ Sometimes
   - ☐ Never

10 Based On Q.9; From Where?

- ☐ Ceiling
- ☐ Windows
- ☐ Walls Facing Outdoor
- ☐ Walls Facing Indoor
- ☐ Floor

11. Too Much or Too Much or Too Strong Artificial Light?

- ☐ Often
- ☐ Regularly
- ☐ Sometimes
- ☐ Never

12. Insufficient or Too Little Natural Light?

- ☐ Often
- ☐ Regularly
- ☐ Sometimes
- ☐ Never

13. Reflections Or Glare?

- ☐ Often
- ☐ Regularly
- ☐ Sometimes
- ☐ Never

14. Based On Q. 13; What Is The Cause?

- ☐ Windows
- ☐ Artificial Lighting system
- ☐ Other (please specify)

Part 4: If You Are at The Building' Classrooms for Long Time, Do You Experience Any of The Following Symptoms?

| Symptoms | Often | Regularly | Sometimes | Never |
|---|---|---|---|---|
| Dry Eyes | ☐ | ☐ | ☐ | ☐ |
| Watering Eyes | ☐ | ☐ | ☐ | ☐ |
| Blocked Nose | ☐ | ☐ | ☐ | ☐ |
| Runny Nose | ☐ | ☐ | ☐ | ☐ |
| Dry Throat | ☐ | ☐ | ☐ | ☐ |
| Irritated Throat | ☐ | ☐ | ☐ | ☐ |
| Chest Tightness | ☐ | ☐ | ☐ | ☐ |
| Dry Skin | ☐ | ☐ | ☐ | ☐ |
| Irritated Skin | ☐ | ☐ | ☐ | ☐ |
| Headache | ☐ | ☐ | ☐ | ☐ |
| Tiredness | ☐ | ☐ | ☐ | ☐ |

Part 5: Your Suggestions:

If You Were Asked About Changing Things in The Building' Classrooms, What Your Answer Will Be? (ex. Classrooms Layout, Glass Type, The Distribution of Artificial Lighting, etc.)

Thank You for Completing the Survey!

## Appendix C: Screenshots for the Input Data on DesignBuilder Software

DesignBuilder software is used to conduct the dynamic simulation. Most of the input data in DesignBuilder software are based on data gathered and arranged in [Table 2: Building's Materials and Systems Details].

The input data contains the location of the building and orientation, type of building, operating schedule based on local vacations, finally building construction details, and mechanical and lighting system details.

1. Entering the site location of the case study building (C6 building in UAEU) with the weather data and North direction.

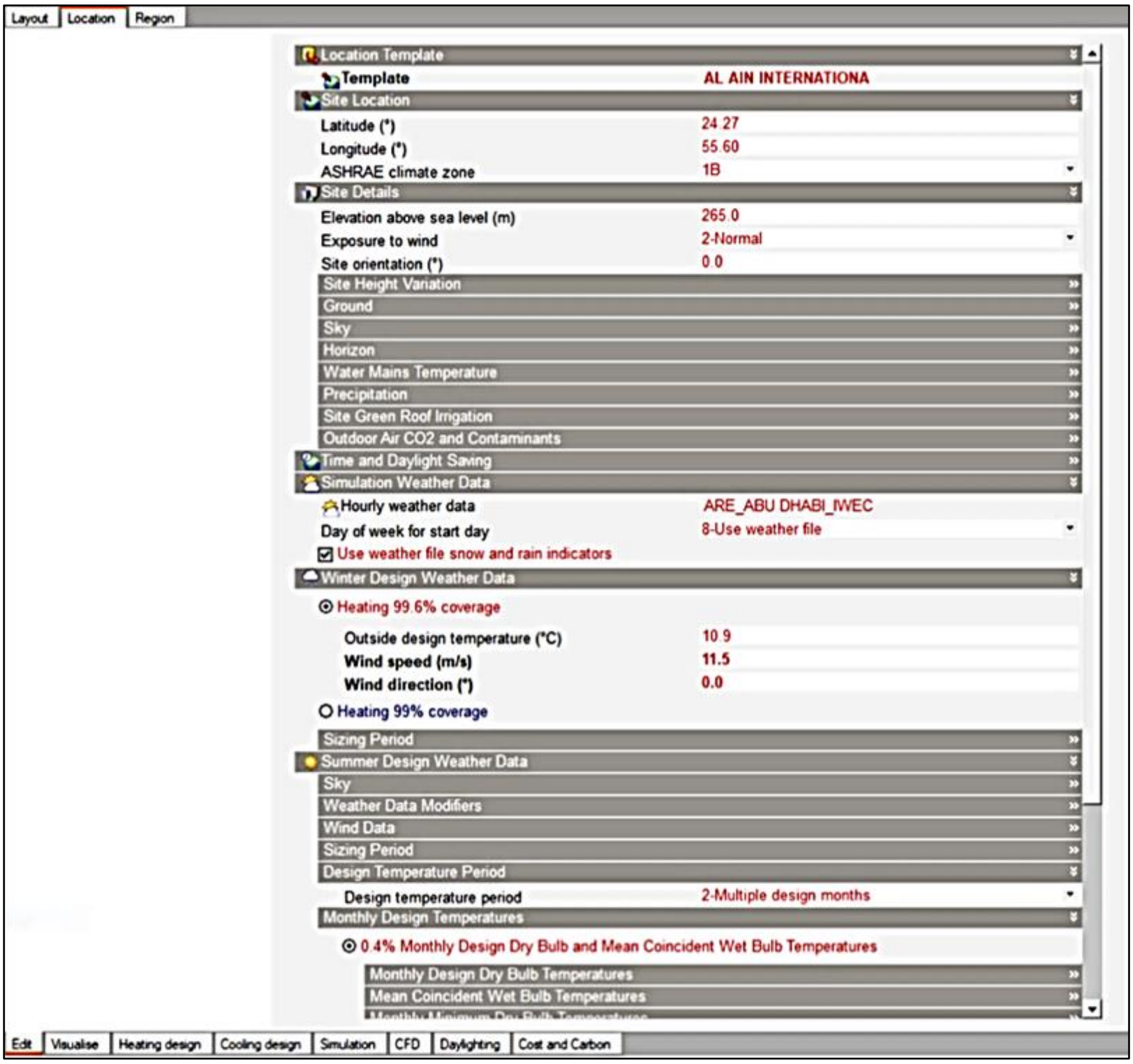


Figure C 1: General Input Data

2. Draw the models based on the building's floor plans and divide them into zones (ex. classrooms, corridors, computer labs, etc.). Draw windows, doors, and shading on windows if exist.

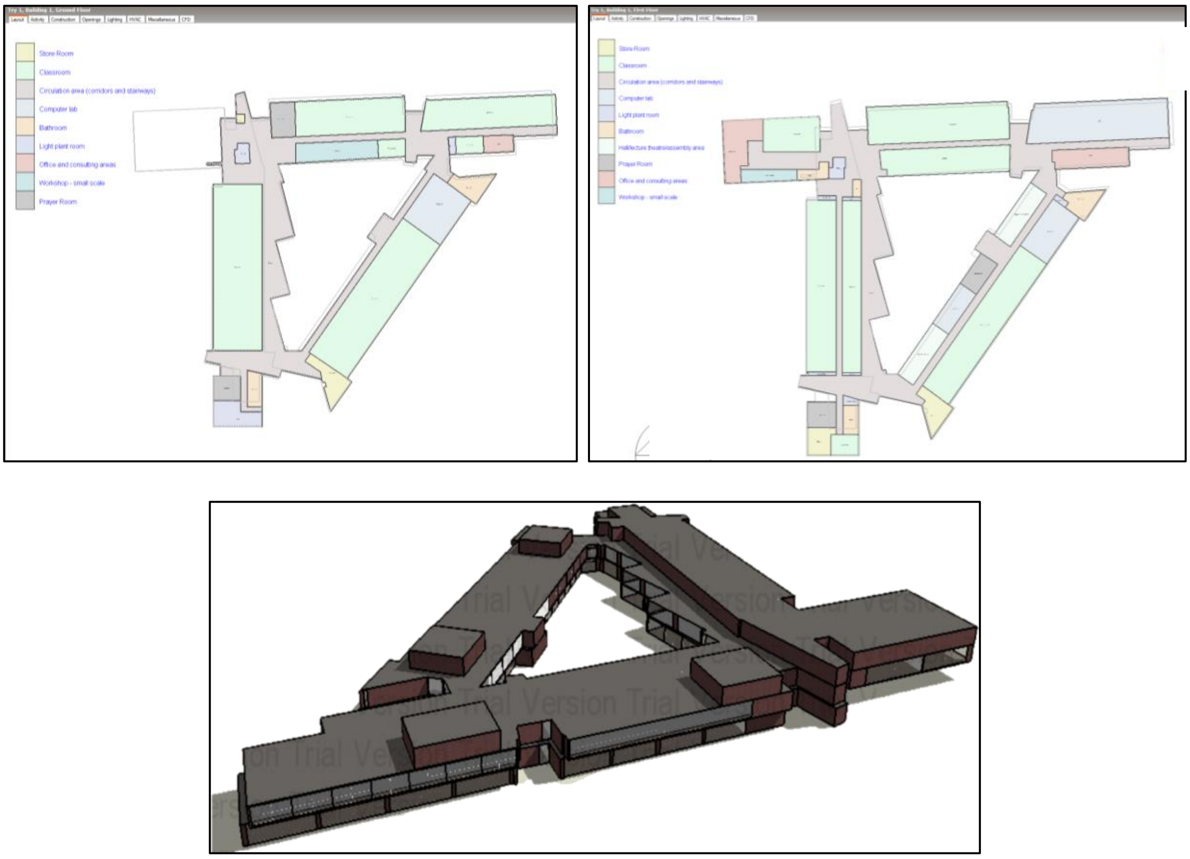


Figure C 2: Building Model in the Software

3. Select the model and input the building type, the holidays per year in UAE, heating setpoint temperatures, and humidity control.

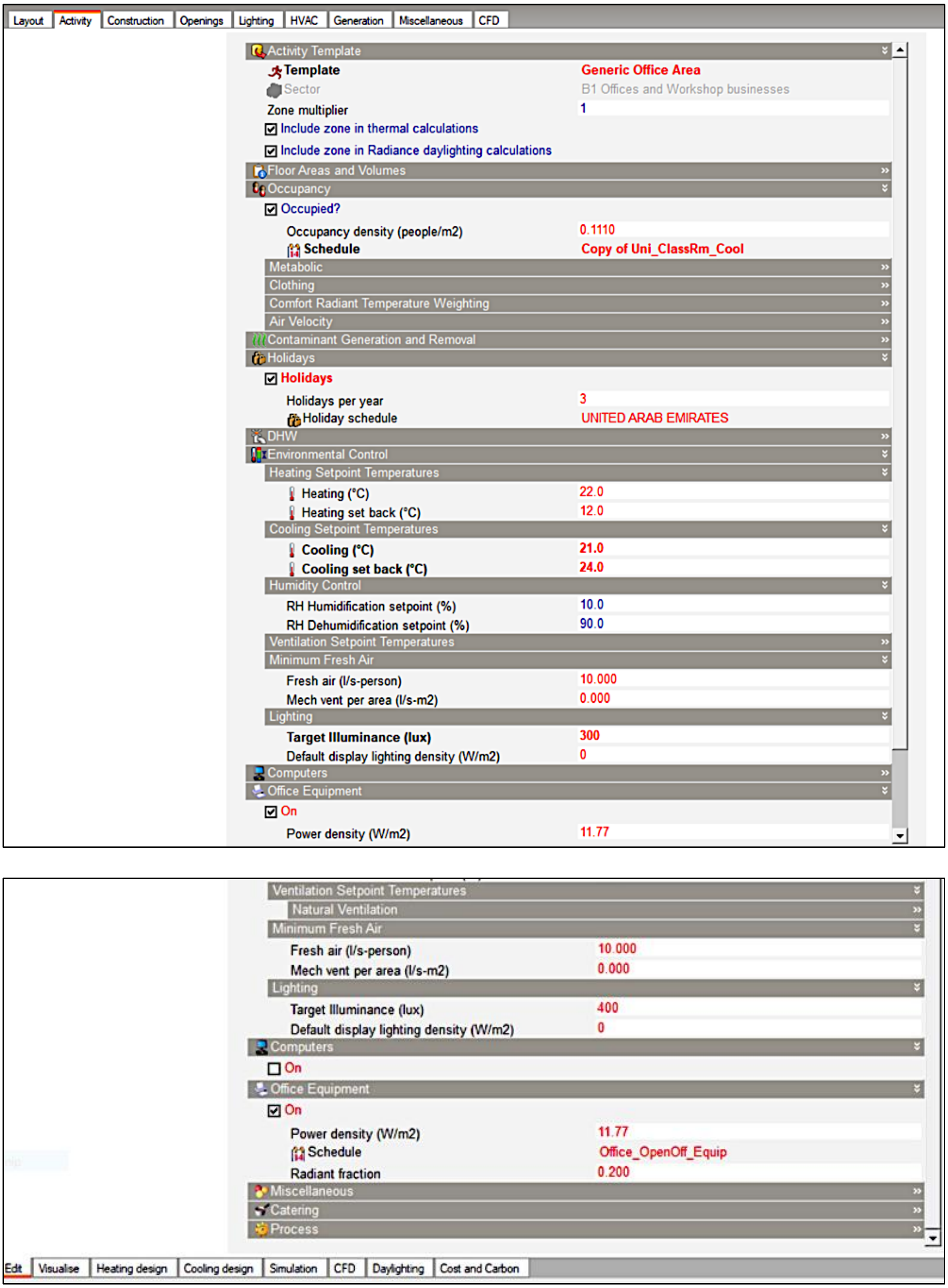


Figure C 3: Activity Data

4. After that input all the required data in the software based on [Table 3: Building's Materials and Systems Details]; the construction details such as external walls, indoor partitions, floors, roof, and openings, alongside the lighting and HVAC details.

A. Construction Details:

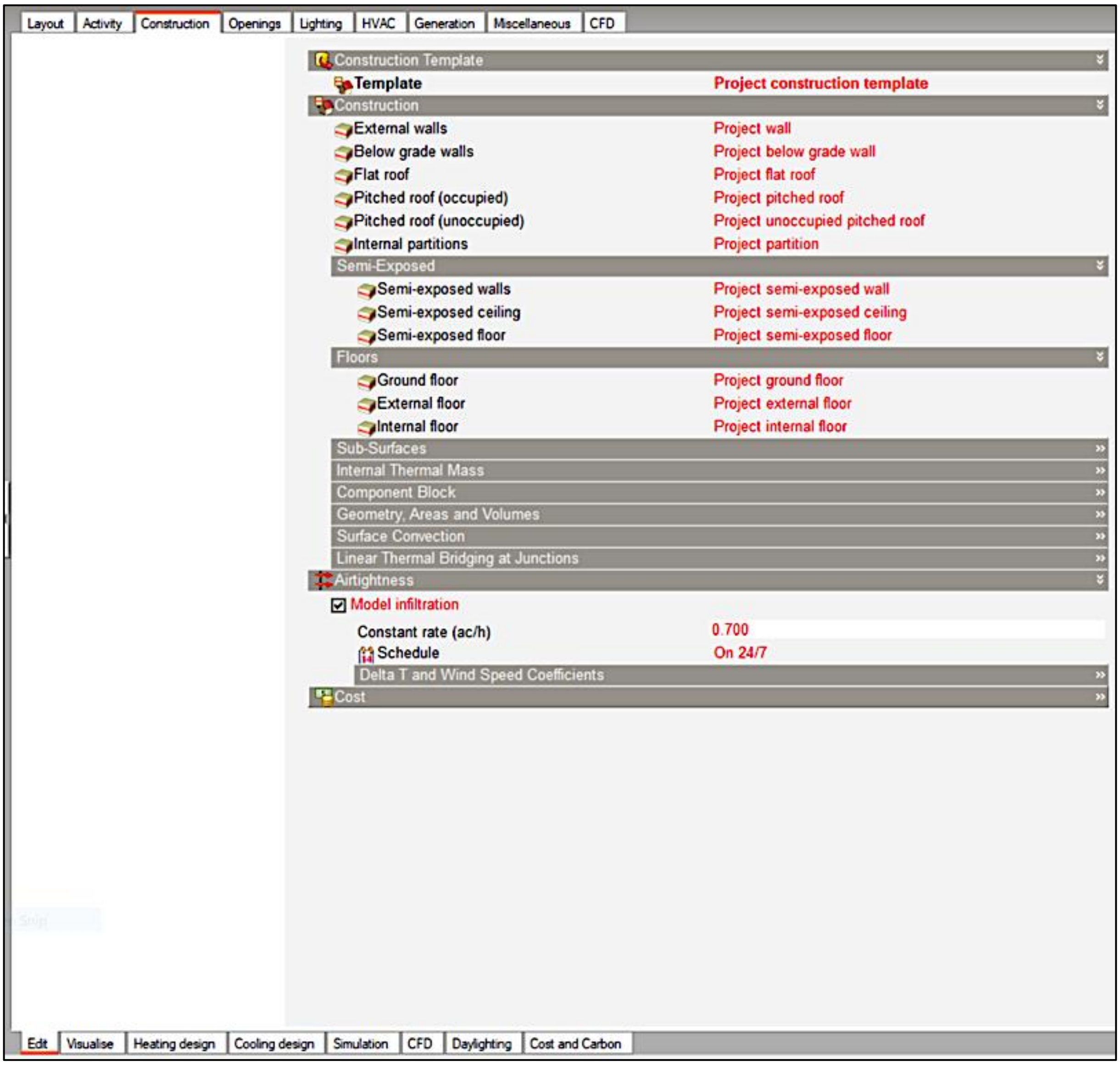


Figure C 4: General Construction Details

- External Walls:

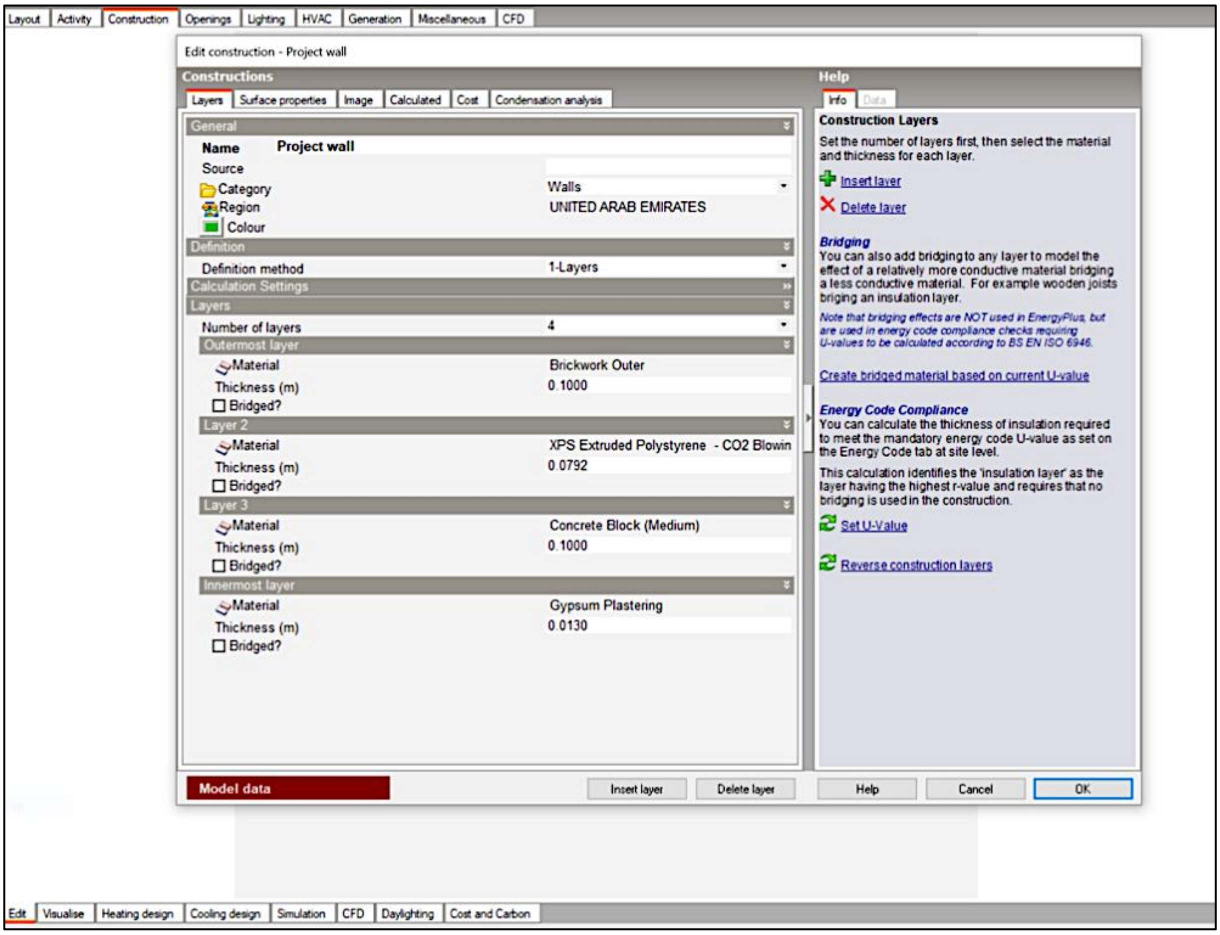


Figure C 5: External Walls Construction Details

- Internal Partitions:

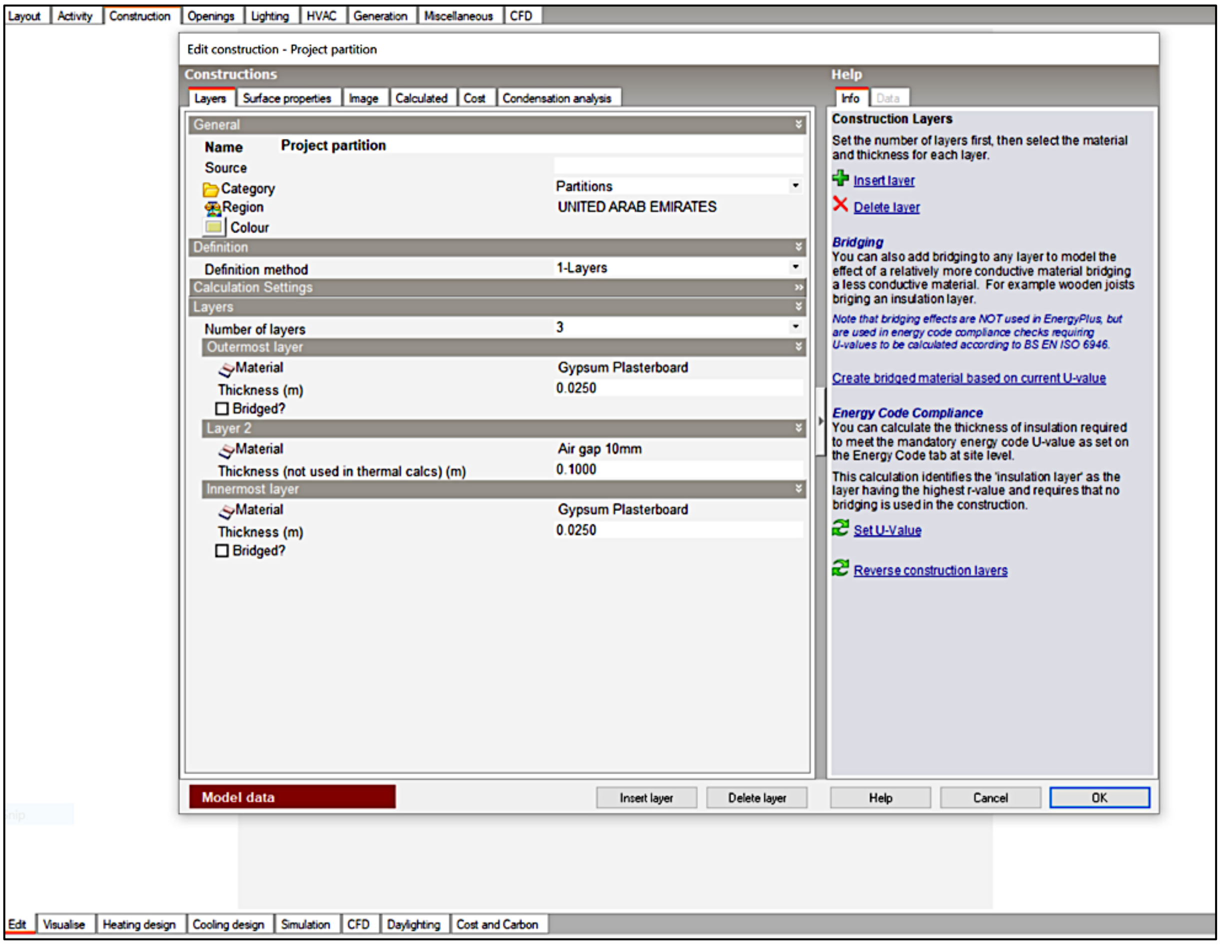


Figure C 6: Internal Partitions Construction Details

- Roof:

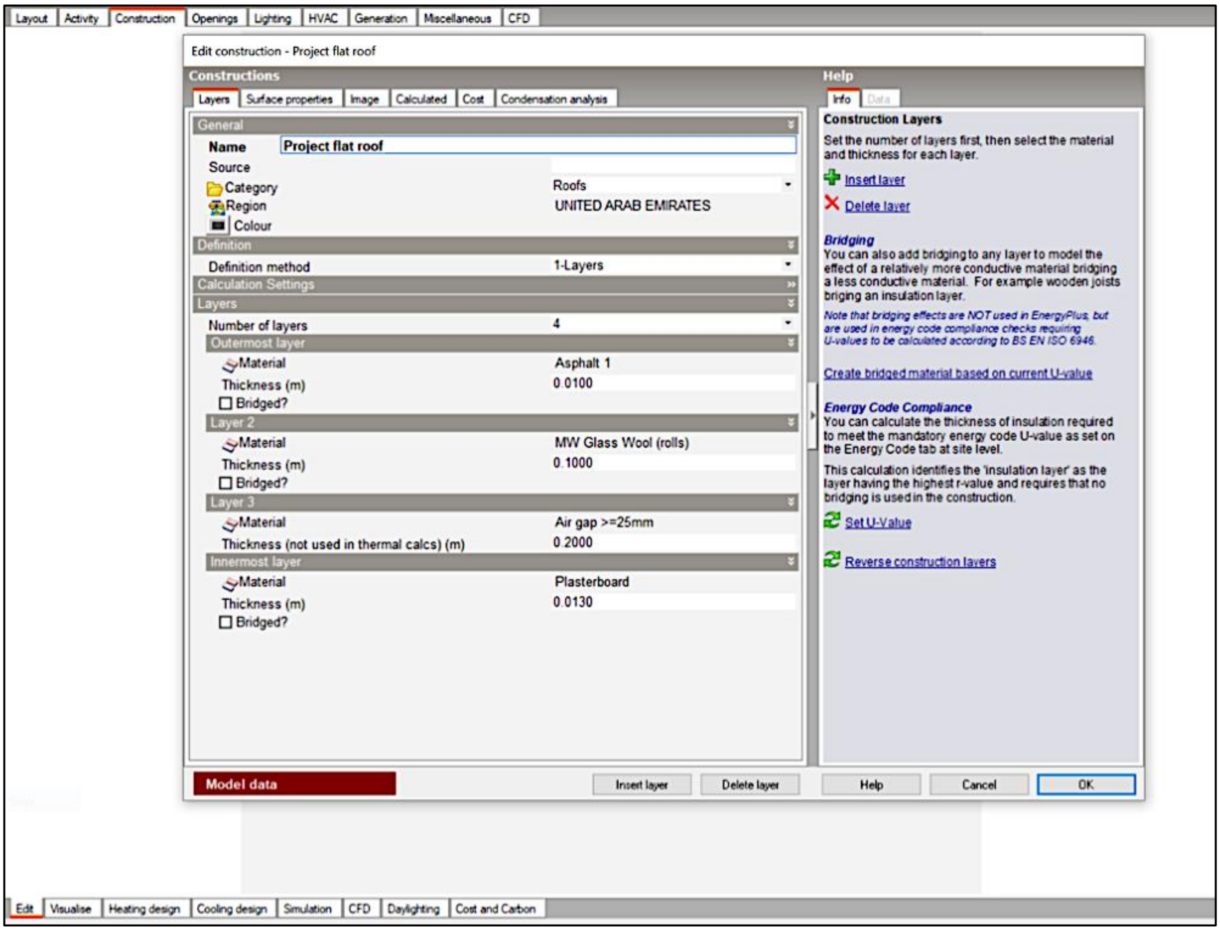


Figure C 7: Roof Construction Details

B. Openings

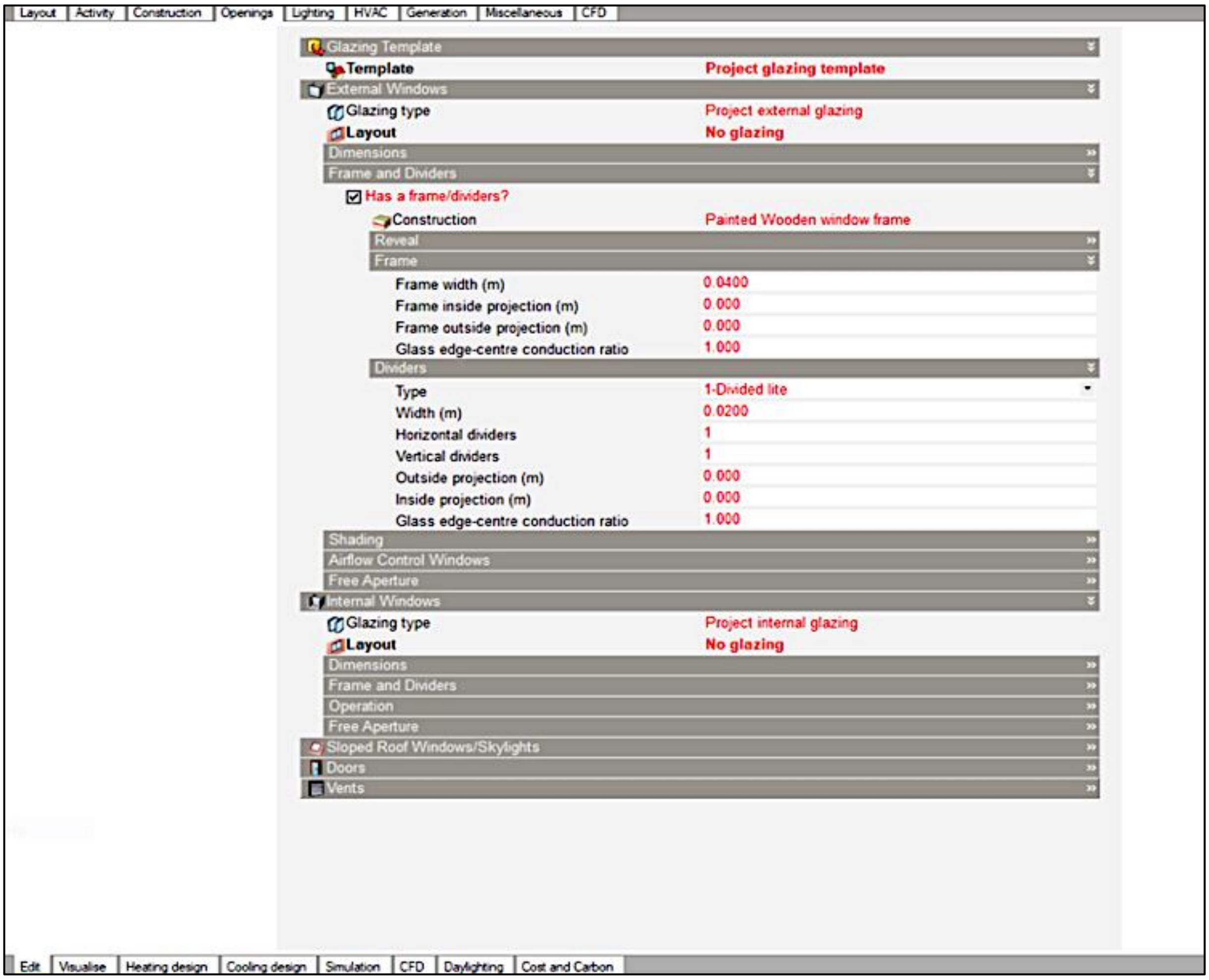


Figure C 8: Openings Construction Details

- External Glazing:

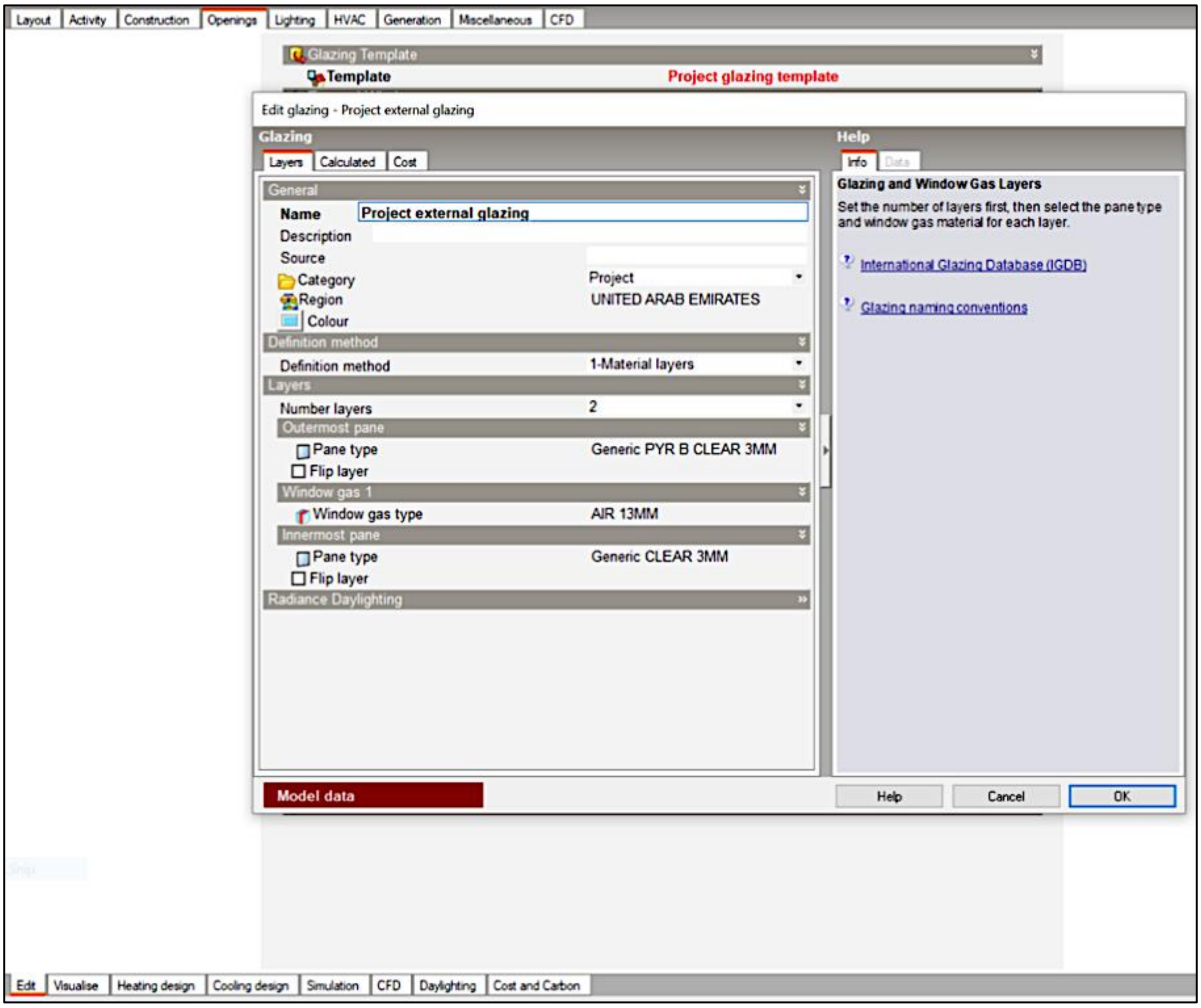


Figure C 9: External Glazing Details

- Internal Glazing:

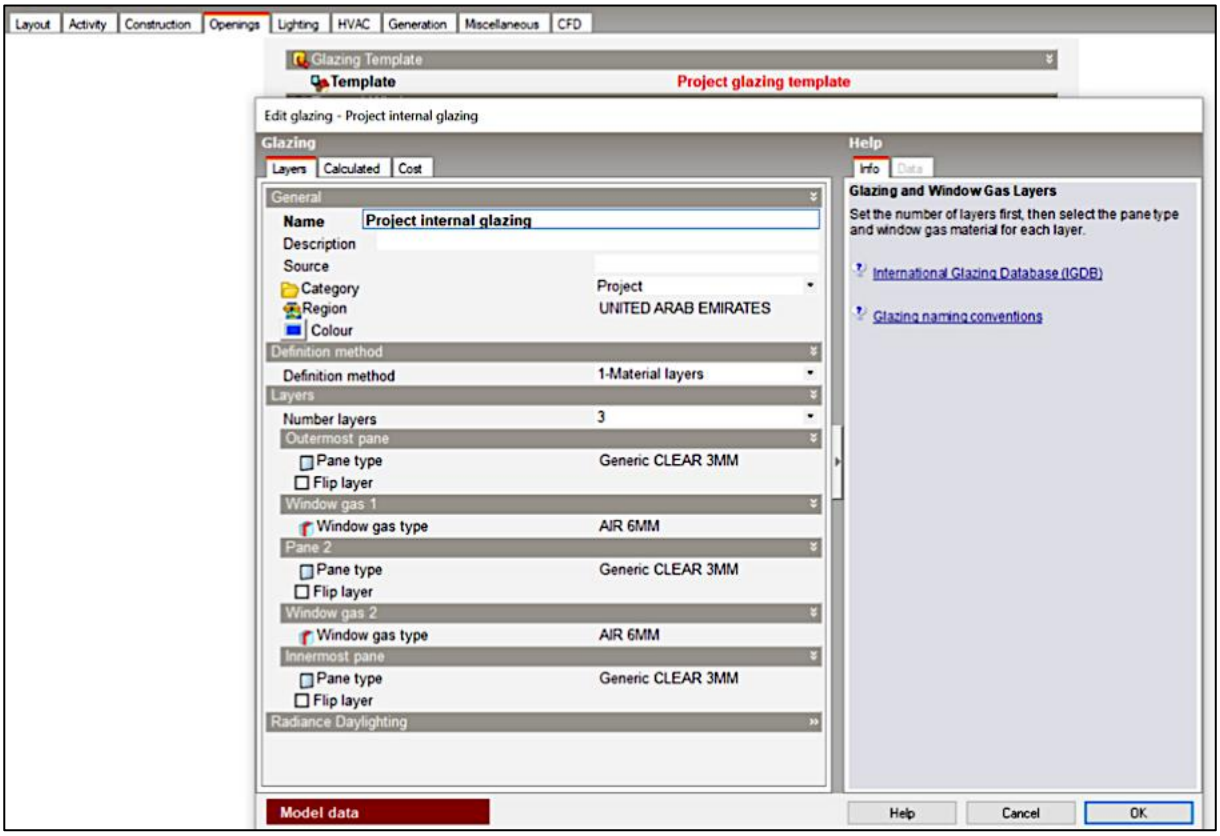


Figure C 10: Internal Glazing Details

## C. Lighting

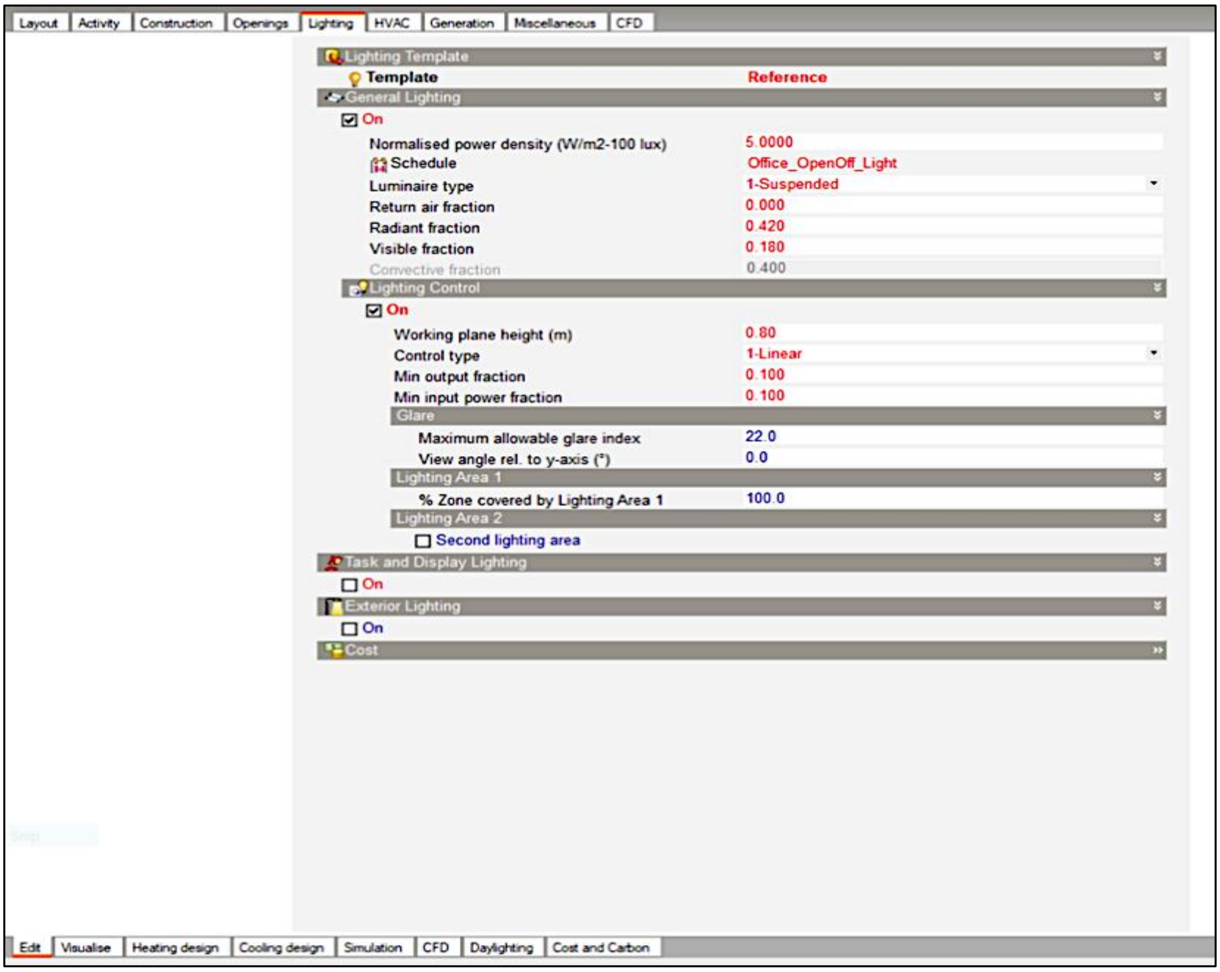


Figure C 11: Lighting Input Data

D. HVAC

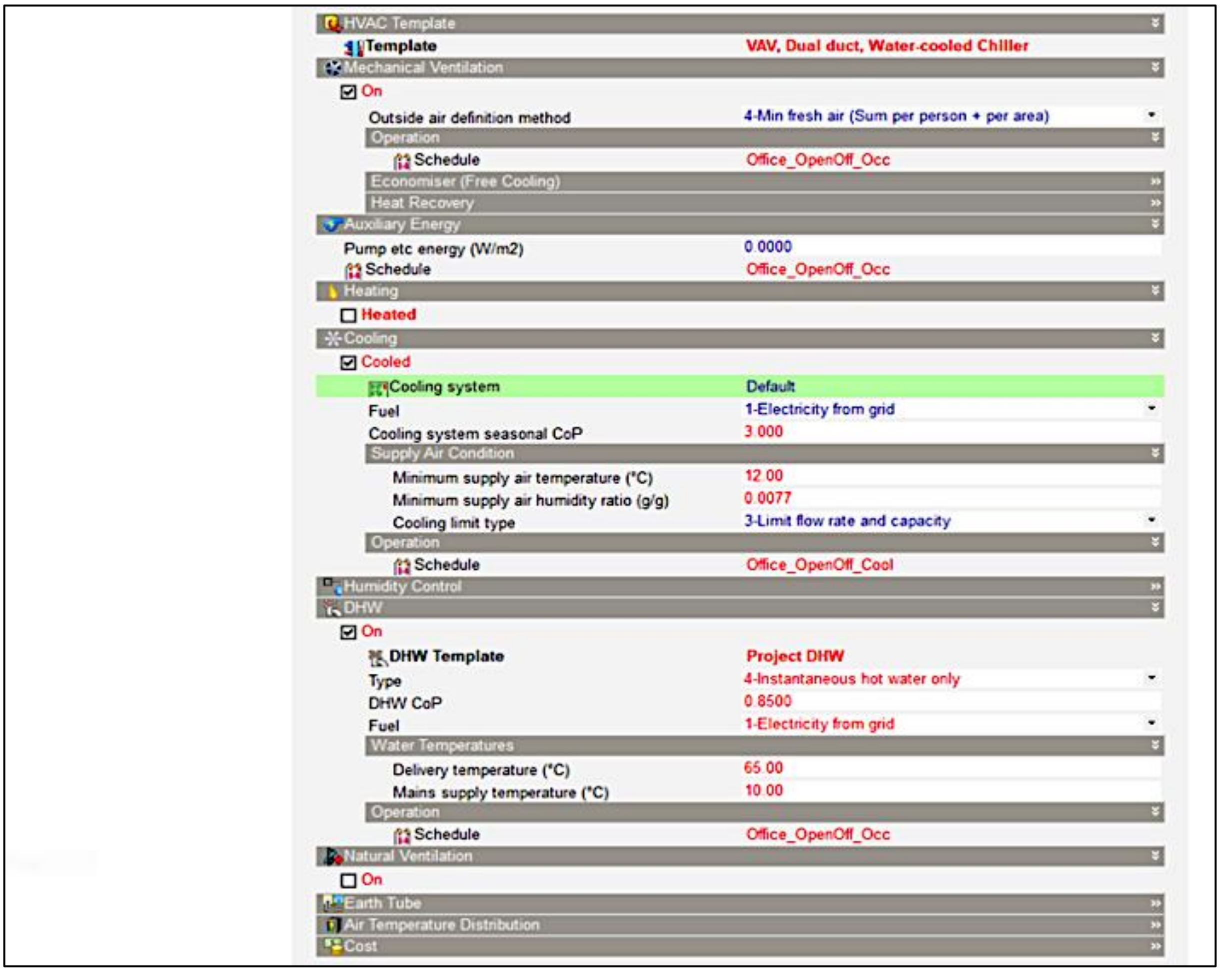


Figure C 12: HVAC Input Data

5. Finally, the scenarios [Table 4: The Detailed Scenarios for Simulation Part] are entered one by one to calculate the cooling load, illuminance, and total energy consumption for classroom 0034 (Architecture Design Studio) on the ground floor in the west direction. The detailed results are presented in Chapter 4.

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This thesis studied the relationship between Indoor Environment Quality (IEQ) and energy use in a UAE university building. To assess IEQ levels, one of the university buildings was selected, and several IEQ parameters such as temperature, relative humidity, indoor air quality, and illuminance were monitored. An online occupancy survey was distributed to building's users to conduct a Post-Occupancy Evaluation study. Dynamic Simulation methods were applied to validate proposed changes based on findings to improve comfort and energy efficiency.

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