PERFORMANCE ASSESSMENT OF A "DO IT YOURSELF" DOUBLE SKIN GREEN FAÇADE FOR AN EXISTING OFFICE BUILDING

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PREFACE

This thesis is a part of the MSc program in Building Engineering with specialisation on Building technology and Physics, from the faculty of Civil Engineering and Geosciences.

Various courses on building physics, façade design and sustainable design developed my interest in this field, thus leading me to do my masters thesis on this topic. The construction industry is constantly developing with a focus on sustainable projects, in order to maintain a healthy environment for the future. Sustainable construction methods can be drawn out as a result of multiple aims such as energy efficiency, lower carbon emission and the prevention of depletion of renewable materials.

Some sustainable construction methods are undertaken based on circularity. A concept that can be achieved with the reuse and recycle of materials. Upcycling is a method that is used in the building industry, which involves the direct reuse of old materials. The biological aspect of circularity can involve the repeated growth of vegetation in buildings. Vertical farming is one such concept, which involves the placement of vegetation in the envelopes of buildings, commonly known as 'Green Façades'.

This research gave an insight on the practical aspects that need to be considered while adopting such sustainable construction methods. As a result, this research was predominantly a series of practical experiments that lead to "real time" evaluation. Moreover, this project enabled me to expand my knowledge on multiple fields of research.

This research could not have been done without help and guidance obtained from various people who were great sources of motivation. I would like to thank my committee members Prof.ir.P.G. Luscuere, Dr.ir.H.R. Schipper, Dr.ir.W.H. van der Spoel and ir.M. Öğüt for accepting to be a part of this commission and guiding me to carry the research forward throughout the period of the thesis. I would like to thank Ms. Karin Dorrepaal, along with all the members of DOOR Architecten for providing me the opportunity of working on this project, along with helping me gain experience in an office environment.

I would also like to thank faculty members and professionals outside the graduation committee for helping me tackle obstacles and overcome technical difficulties. These include Dipl.ing. B. Bähre, from the faculty of Architecture and the Built Environment, for helping me with the development of measuring sensors with the help of microcontrollers, ing. M. Verwaal, from the faculty of Industrial Design Engineering, for assisting me with the use of the climate chamber, and ir. Menno Spierenburg from Cauberg Huygen for consulting design and experimental strategies for the project.

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ABSTRACT

This project is based on two sustainable construction methods, namely upcycling (reuse of materials) and vertical farming (green facades). These two concepts are combined to form a 'Do It Yourself' double skin façade, a double skin façade made with re-used sliding doors, which is aimed to be capable of developing 'Edible Green', which refers to the placement of edible vegetation in the façade of an office building.

As two sustainable methods are combined into one project, the investigation of the performance of this 'Do It Yourself' double skin façade arose as an objective. Hence the aim of this research was to investigate the climatic performance of the façade for the growth of plants, as well as its influence in the indoor environment of the office.

The façade was divided into 6 modules across two floors, capable of accommodating vegetation individually. These modules were assigned different design strategies based on ventilation, shading system, watering system and the placement of plants. Five different types of plants were placed on each module. Three types of ventilation strategies were adopted as parameters for the modules, namely minimally ventilated, naturally ventilated and mechanically ventilated. The configuration of plants were such that all modules had a total of 9 plants, with 7 short growing and 2 tall growing plants. The watering strategy was adopted in the form of drip irrigation system, where the modules in the top floor received constant rate of irrigation whereas the modules in the bottom floor received varied rate of irrigation.

A measurement system was developed using a microcontroller, namely the Arduino UNO. The parameters were evaluated by the placement of measurement sensors in each of the modules. The measurement was done over a period of three weeks where the temperature, relative humidity, illuminance, CO_2 and Total Volatile Organic Compounds (TVOC) were measured. The obtained values were studied and analysed based on the expected behaviour from the literature. The condition of the plants in the cavities were evaluated by determining the yield produced by each of the module, and also by a visual inspection of the plants.

It was observed that the plants play an influential role in increasing the humidity in the cavity, especially in the cavities of the non-ventilated modules. This was evaluated by comparing the relative humidity and absolute humidity of all the modules. It was found that the humidity in the minimally ventilated modules was higher compared to the rest. Moreover, it was found that the shading in the façades highly influence the temperature in the cavity. The performed experiments suggested that the use of plants in the double skin façade, along with an external shading strategy can decrease the temperature in the cavity by up to 13°C and can increase the relative humidity of air in the cavity by 38%. Moreover, the experiments with respect to mechanically ventilated modules show that the cavity preheats the air by up to 6°C during night time and pre cools the air by up to 10°C during high outdoor temperatures (summer afternoons).

Based on the theoretical and real time evaluation, it was concluded that the minimally ventilated modules perform relatively better with respect to the condition of the plants, whereas the mechanically ventilated modules perform better with respect to the indoor environment in the office. However, the influence of the double skin façade alone on the indoor environment of the office could not be determined, as there were external influences on the climatic conditions inside the office building.

Based on the results, a design strategy was successfully formulated and the performance of each module was investigated. The research answered the question with respect to maintenance of the double skin façade for the growth and health of the vegetation. Moreover, the research helps to provide ideas on different design strategies that can be used, based on different sustainable design requirements.

CONTENTS

CHAPTER 1 – INTRODUCTION

1.1 CONTEXT

1.1.1 Indoor environment in offices

In the western world, most people spend 80 to 90% of their lives indoors. This could either be in places such as a school, an individual's house or an office. (Bluyssen, 2013). Looking at this statistic, it can be said that it is important to maintain the wellbeing of an individual regarding comfort levels in the indoor environment.

The indoor environment is comprised of four determining factors, namely Thermal Comfort, Lighting quality, Indoor Air Quality and Acoustical quality (Bluyssen, 2013). Each of these factors vary depending on characteristics such as the location, the function and type of a building, the number of occupants and the rate of occupancy. This research focuses on an office building and hence the characteristics of an office building is taken into account.

According to (Bluyssen & Cox, 2002), the indoor environment quality is considered to be ideal when all the occupants do not have anything to complain regarding comfort, and are not subject to risks of illness or injury. The indoor environment quality in an office building links to the wellbeing and productivity of the occupant. A poorly maintained indoor environment can cause a decrease in the productivity and performance of a worker inside a building (Fisk & Rosenfeld, 1997).

The air quality inside a building determines the pollutants in the air which occupants are exposed to. This is either indicated through discomfort such as bad odour, or an increased risk of diseases or illness (Bluyssen, 2013). The air quality inside a building can be improved by controlling the ventilation between the inside of the building and the outdoor air (Bluyssen & Cox, 2002). Hence it is clear that ventilation is an important factor in the design of a building. The aim of achieving a good air quality in terms of comfort and health in a building by maintaining sufficient ventilation has been and is being researched (Bluyssen, 2013).

The thermal comfort for occupants in a building varies from region and its corresponding outdoor temperature. Thermal comfort can be controlled by passive measures such as the use of insulating materials during the design of the building, or active measures such as heating, cooling and air conditioning systems. It is achieved by regulating temperature through conduction, convection and radiation, and by regulating the relative humidity in the environment with the help of humidifiers and dehumidifiers in air conditioning systems (Bluyssen, 2013). Moreover, the thermal comfort is should also be seen from an individual's perspective, based on the work being performed and the clothing worn by an individual. (Bluyssen, 2013) stated "Thermal stress occurs when one is not able to regulate its thermal balance or when one believes or perceives it isn't possible. The psychological effect of expectations and the perceived individual level of control seems important."

Lighting in a building is also an important factor to consider. It comprises of variables such as illuminance, luminance ratio and light colour. Inadequate or disproportionate lighting can lead to visual discomfort, that can cause stress, eye strain and headaches (Bluyssen, 2013). The lighting in a building is controlled by either daylighting, i.e. getting maximum use of natural light, or controlling the amount of light in a building, or with the use of artificial lighting (conventional lamps or LED's). A combination of the use of daylighting such as lighting systems and solar screens can achieve the desired lighting quality in a building (Bluyssen, 2013).

The stresses and discomfort with respect to the parameters mentioned can cause effects related to the indoor environment of a building, such as Sick Building Syndrome (SBS) and productivity loss. Hence it can be stated that it is important to maintain a good indoor environment quality in a building, in order to prevent negative effects on the occupants in the building.

Although the indoor environment quality of a building defines the comfort level of the occupants, it also determines the energy consumption of the building, and hence it plays a role in defining the sustainability of the building (Nicol & Humpfreys, 2002). According to (Bluyssen, 2013), different energy efficient measures have been taken to tackle climate change which has led to consequences with respect to indoor environment. Hence it should be noted that although the comfort of the occupants is seen as a priority, the performance of the building with respect to sustainability should also be taken into account.

1.1.2 Sustainability aspect

The growth of population and the amount of time spent indoors over the years have contributed to high energy demands from buildings. Globally, buildings account for 20% to 40% of the energy consumption, with 40% energy consumption in Europe. (Lombard, et al., 2007), (Zhao & Magoulès, 2012). One of the prime contributors to the energy consumption in buildings is the use of HVAC systems, accounting for up to 50% of the energy consumption in buildings, followed by lighting and appliances (Lombard, et al., 2007). It can be said that this is a result of the indoor comfort requirements of occupants inside a building.

The energy consumption for buildings is determined by various factors such as the function and occupancy of the building, the exterior weather condition, the characteristics of the building and the usage of systems and appliances in the building (Zhao & Magoulès, 2012). The excessive use of systems as per demands increases the energy consumption.

It is not only energy consumption that is a cause of concern but also CO_2 emissions. Buildings significantly play a role in the emission of CO_2 with contributions of total CO_2 emissions of 36% in Europe (European Commission, 2019). The growing energy consumption and CO_2 emissions have increased the importance for decreasing the energy efficiency in buildings while maintaining indoor comfort levels inside a building in order to reduce the environmental impact (Zhao & Magoulès, 2012).

The European Community recognizes the impact of buildings on the physical, social and aesthetic environment in Europe (Melchert, 2007). The Netherlands have come up with sustainable building approaches in order to reduce the environmental impact by buildings, by adopting green building solutions that are looking to achieve a better environmental performance (Melchert, 2007). The ideology used behind this approach was the connection between the nature and the indoor environment, leading to sustainable ideas such as the use of green roofs and passive techniques to improve insulation. An example of such an approach is De Kleine Aarde, which was built to maximise the use of passive solar energy and the reuse of raw materials (Melchert, 2007).

Another example of a building designed to increase its energy efficiency is the ING bank headquarters in Amsterdam, which adopted a mixture of active and passive construction methods, such as the shape of the building and orientation of the façade and the use of passive insulation systems, thus making the building 80% energy independent (Melchert, 2007).

The overview of such examples makes it clear that sustainable approaches including passive and low technological approaches in buildings can help reduce the energy demands of the building without compromising the need for indoor comfort. A few sustainable approaches are discussed briefly in the next section.

1.2 SUSTAINABLE CONSTRUCTION METHODS

1.2.1 Overview

The high energy consumption and emissions in buildings has led to necessities in going towards a sustainable approach as mentioned earlier. Some concepts regarding sustainability are explained in the following section. A brief information on broad approaches with respect to circularity, such as upcycling and cradle to cradle design is mentioned. Furthermore, the concept of sustainable design with respect to façades is also elaborated.

1.2.2 Upcycling and Cradle to cradle (C2C) concept

Many environmental problems such as natural calamities, greenhouse effect and pollution are a result of the excessive consumption of natural resources (Ali, et al., 2013). Some methods practiced to avoid excessive usage of recourses are recycling and reusing. In the construction industry, upcycling is a form of reuse, where waste materials are converted to useful products, with which functional and distinctive spaces can be created (Ali, et al., 2013).

Upcycling is a form of reusing a material in such a way that the material of the existing product does not get degraded (Goldsmith, 2009). In this way, old products are made new. Recycling mainly involves the degrading or breaking down of a used material to form a new material. This leads to the consumption of energy. This is not the case for upcycling as the material is directly reused into something else, which reduces the consumption of energy. This process would have a long term positive effect on the environment as waste is being used again where it prolongs the life spent and productivity of those materials (Ali, et al., 2013).

Upcycling can be used to lower the amount of total waste. The process involves turning a used material into a new source, which can be repeated (Caine, 2010) . This is different from recycling. Recycling only prolongs the formation of wastes, which would eventually impact the environment negatively (Ali, et al., 2013). The concept of upcycling provides a short way of decreasing the total amount of production of household wastes (Richardson, 2011).

Although the concept of reusing the materials bring an advantage in terms of sustainability, it is important to keep some factors into account while choosing an object. This can include the type of material, its nature, strength and durability and the amount of time it has been used. Some more aspects to consider are how the material can be preserved and how it can blend in with the space given, whether it's outdoor or indoor and the condition of the material when it is left ((Ali, et al., 2013). Upcycling offers more appreciation of things and protecting the original state of the item for long as it possible. Since upcycling is a method used as a reduction of waste, it is beneficial for the environment as well as for humans, as it not only helps in reducing negative environmental impact, but also creates awareness to people on the necessity of conservation of the environment (Ali, et al., 2013). Sustainable design ideas can be suggested through the use of upcycling, such that materials are used in an effective way and on the large scale, it is one step closer to conserve natural resources (Ali, et al., 2013).

Another sustainable approach which governs the functioning of circularity in buildings is the cradle to cradle (C2C) concept (Niero, et al., 2017). The cradle to cradle design creates a framework for designing products and l processes that convert materials into nutrients by enabling their flow within one or two distinct metabolisms (Braungart, et al., 2007). This concept propounds that environmental impact reduction can provide a positive economic impulse to stakeholders, in contrast to current sustainable approaches, which are costly investments. This concept has been practices internationally by multinational companies and is also being embraced by the Dutch building industry (van Dijk, et al., 2013).

These concepts can be used in the building sector in terms of circularity, where ideas such as reused materials can be used for construction. The incorporation of such practices to buildings could reduce the total energy demand as buildings account for 40% of total energy consumption.

1.2.3 Façade Design

There are quite a few sustainable concepts in buildings which is determined by the design of the façade of the building. One example of such designs is the ABN AMRO global headquarters in Amsterdam, which was recognized by the American Institute of Architects as one of the most sustainable construction projects in 2001 (Melchert, 2007). The building uses a combination of a ventilated double skin façade with blinds such that airflow is maintained through the façade, while sun shading is provided, thus reducing the cooling load in the building (Melchert, 2007). The façade also works in winters as the cavity provides high thermal insulation, preventing heat losses from the building and as a result, reduce the heating demands (Melchert, 2007).

Another example of a passive sustainable façade design is Studio Gang's Solstice on the Park in Chicago (Oldfield, 2019). The south façade in this building is glazed at an such that it reduces solar gain in the building during summer season, and increases the solar gain during winter season (Oldfield, 2019).

The example mentioned above highlights the functioning of a Climate façade. There are also other designs which are implemented such as Vertical Green Systems. In general, a good amount of plants in office buildings can lead to a reduction in the energy consumption of the building and can also reduce the carbon emission rates. This is possible as long as the temperature set point is to be adjusted as per summer and winter (Mangone, et al., 2014).

According to (Pérez, et al., 2011) vertical green systems are comprised of green façades and Living Wall Systems (LWS). (Pérez, et al., 2011) also stated that green façades are systems in which plants are developed from the ground or from individual planters to cover a desired area.

Green façades have the capabilities of improving the insulation of the building in summers as well as in winters, along with improvements in aesthetics, indoor & outdoor climate and air quality in the building (Ottelé, 2015). Green façades and living wall systems improve the environment in cities by providing possibilities of various ecological and economic benefits, purification of air quality, reduced Urban Heat Island (UHI) effect, improved longevity of building materials and an aesthetically pleasing working environment.

(Ottelé, 2015) stated "Green building strategies not only stand for sustainable materials in their construction (e.g., reused, recycled-content, or made from renewable resources), but also by using of natural processes (e.g., shading effect of trees, insulation capacities of green roofs and green façades, mitigation of urban heat due to evapotranspiration)."

(Stec, et al., 2005) made a comparison of the performance of green façades with a double façade with blinds and concluded that the thermal performance of green façades is better compared to a façade with blinds due to the lower temperature of the leaves, as a result of latent heat transfer from the leaves of the plants. Moreover, vegetation in façades also bring in advantages such as improved thermal and acoustic insulation, purification of air through filtering of dust and chemicals, reduction of CO_2 and the reduction of the occurrence of Sick Building Syndrome (Stec, et al., 2005).

Although there are many advantages, there are also some disadvantages by green façades which mainly relate to the control of light entering the building, and the maintenance and growth requirements for the vegetation in the building (Stec, et al., 2005). Moreover, some other disadvantages include the inconvenience of integrating proper irrigation systems for the plants in the building, as well as the cost of installing a vertical green system (Mir, 2011).

However, it can be noted that the advantages outweigh the disadvantages with respect to green façades. The next section describes the purpose of this project and how the discussed sustainable approaches have been implemented in the project.

1.3 DO IT YOURSELF FAÇADE

1.3.1 Description

The specific case used for this graduation project is the PITLAB, which is one of the pavilions in Tuin van Bret, a garden located near the Amsterdam Sloterdijk station. The garden consists of multiple pavilions, home to different offices. This building functions as an office for the architectural firm DOOR Architecten. The building is oriented in such a way that the front façade is facing towards the south east direction. The envelope of the building consists of nine re-used sea containers, stacked in a grid of three by three pattern, in which a double façade is installed out of reused sliding doors respectively.

The double façade contains two sliding doors, parallel to each other with a distance of 420 mm. The outer and inner sliding doors are composed of double glazing respectively. The inner and outer sliding doors of each of the façades can be opened and adjusted. The exterior of each façade contains container doors which can be opened up to a perpendicular orientation to the sliding doors. A greenhouse is also proposed to be constructed on the roof of the PITLAB for the growth of vegetation, however that is not focused on this project. The main focus of this project will be on the upper six segments of the façade, as they correspond to the two different work spaces inside the office building. These segments will be made as different modules, isolated from each other.

Figure 1 a) Façade of the PITLAB

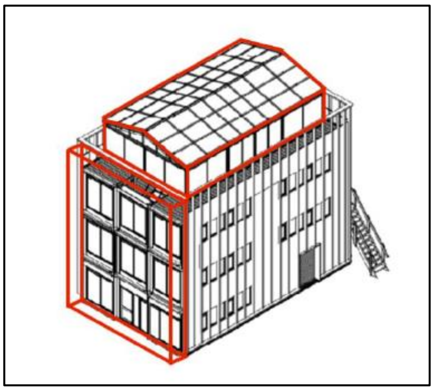


Figure 1 b) Representation of the façade

1.3.2 Vision

The purpose of this project is to maximise the advantages of the building in terms of sustainability. The envelope of the building consists of nine re-used sea containers, stacked in a grid of three by three pattern, in which a healthy, energy efficient double façade is installed respectively. This façade is made out of used materials and is made with a 'Do It Yourself' (DIY) approach. The idea is to place vegetation in the cavity of the double façade and create the concept of 'Edible Green'. In other words, the façade acts as a greenhouse, capable of producing edible plants. This concept aims to show that such a design can be available in any common dwelling, increasing the possibilities of urban agriculture. Some existing examples of urban agriculture are De Dakakker in Rotterdam and Zuidpark in Amsterdam (Ottelé, 2015). The sustainability aspect in the building is aimed to be achieved in terms of circularity. The fact that this building is made up of re-used sea containers and the façade is made of used sliding doors, it is a form of upcycling as it contributes to the reduction of construction waste.

Figure 1 c) Visualisation of the office from inside

Figure 1 d) Artistic representation of the PITLAB

Moreover, the edible plants will be grown which will be used to make food. The waste from the food will be processed in the garden of Tuin van BRET, in which the PITLAB is located. This processed food will be turned into manure. In this way, food waste is reduced. With this idea, the building aims to connect different parts of the food chain, namely production, processing and consumption.

Hence, the overall product will be a building, constructed with reused materials, which has a double façade in the form of sliding doors, where vegetation will be grown. With this way, the three sustainable approaches are aimed to be fulfilled. The idea of using reused façade materials reduces construction waste and the processing of food into manure reduces biological waste. This concept of circularity will be implemented in the building, aiming to create a positive environmental impact. The vegetation in the double façade would act as a green façade, thus reducing the energy consumption by increasing the indoor comfort in the building throughout the year. Moreover, a healthy indoor environment will also be maintained as the plants would also act as a purifier to improve the air quality in the building.

1.4 PROBLEM STATEMENT

The placement of vegetation in between the two sliding doors is the sustainable approach taken in terms of circularity, where maintaining a good indoor environment inside the office is aimed. However, this may not be straightforward as the two conditions could be interdependent on each other, but also contradictory at the same time. The placement of vegetation in sliding doors makes it a 'Do It Yourself' green double façade. The temperature in a cavity of a double skin façade can range between -10 and 40 °C, which can be extreme for temperature required for plants (Stec, et al., 2005). If the conditions are not suitable for the plants to grow, then it is not possible to determine what influence the plants in the double skin façade have on the indoor environment of the building. Hence it is important that the façade should be designed such that the climatic conditions do not affect the plants. More importantly the indoor environment in the office should not be compromised in order to maintain the climatic conditions for in the cavity for the plants.

Multiple researches so far have found the behaviour of plants in a double skin façade in general. This case specifies to an edible plant in a façade made out of re-used materials. Hence, the measures taken to maintain the growth and wellbeing of the plant is not yet known. Moreover, it is also not known how the plants would behave based on the condition in the façade. For example, one plant may have higher leaf density, which is good as a shading element for the indoor environment, but produce less yield, which is not favourable in terms of circularity. Hence, it is important to find out how the 'Do It Yourself' façade performs in terms of the growth of the plants, as well as the indoor environment in the office.

1.5 OBJECTIVE

The purpose of this project is to investigate the performance of the 'Do It Yourself' double skin façade, which contains internal and external sliding doors to accommodate vegetation. The investigation is done such that the condition in a green double skin façade and the indoor comfort of an office building is evaluated.

1.6 RESEARCH QUESTION

1.6.1 Main research question

How does a 'Do It Yourself' double skin façade perform with respect to conditions for growing edible vegetation and for the indoor environment in an office building?

1.6.2 Sub research questions

- What factors are considered to evaluate the indoor environment of the building?
- What parameters are considered for the configuration of the double skin façade modules?
- How is the performance of the double skin façade evaluated?
- Which type of edible plant shall be placed in the double skin façade of the building?
- How do the plants influence the climatic conditions in the cavity and the office?

1.7 RESEARCH CONSTRAINTS

- As the influence of plants on the building is not known yet, and the experiment is to be done in an active working environment, the indoor environment in the office is taken as priority. In this case, when the office gets too hot in the summer, the external container doors will be used as a shading device. This may hinder the possibilities of determining the role of the plants on the indoor environment in the office.
- Since the façade modules are based on a Do It Yourself concept, it is important to make sure that each façade module is isolated from the other. This way, the conditions of one module would not affect the conditions in the other. This includes the space in the cavity of the module as well as the space in the office corresponding to each façade module.
- Due to the availability of measurement tools, the evaluation will be constrained to temperature, relative humidity, illuminance and air quality level (CO_2 and VOC)
- Based on the ventilation system in the PITLAB, this research and experiment conducted for this project is specific to the conditions in this office building.

1.8 METHODOLOGY

1.8.1 Preliminary research

In order to answer the research questions, it is clear that a basic understanding of a few concepts need to be known beforehand. As indoor environment of offices is involved in the experiment, a brief study on the basics of indoor environment is reviewed. This includes the parameters involved to define indoor environment and the required conditions for each parameter to be evaluated.

To determine the type of plant to be installed in the double skin façade, a study is conducted on different types of plant species and their growth and behaviour towards different climatic conditions throughout the year. The type of plant is chosen based on the time period the experiment would take place (Spring – Summer).

Moreover, the behaviour of double skin façades in offices and the different configurations adopted for multiple climatic conditions is reviewed. This includes the various mechanisms involved in a double skin façade with respect to building physics. The performance of a green double skin façade is also compared with the performance of a double skin façade with conventional shading (Climate Façade). This includes the influence of plants in the cavity with respect to heat and moisture transfer, and how it would differ from conventional shading devices. Based on the this, the configuration of each façade module and the parameters that are to be evaluated are determined.

1.8.2 Module configuration

The envelope of the building is comprised of nine façade modules in a grid like pattern, where the upper six modules correspond to the offices in the building. The research and experiment is conducted in the upper six modules. Each module is distinguished by certain constant and variable parameters. Ventilation acts as a variable parameter across both the upper and lower three modules, with the plant density being constant in all the modules. The watering system is constant in the upper three modules, and is variable in the lower three modules depending on the behaviour of the modules with constant watering. Each module is described in detail in chapter 3, including the parameters set to it and its expected mechanism.

1.8.3 Measurement Method

Three factors are used to evaluate the performance of the façade, namely, Thermal conditions (temperature & relative humidity), lighting (illuminance) and air quality. These factors are evaluated by the use of sensors, which work with the help of a micro-controller. The microcontroller used for this experiment is based on the Arduino platform. Each sensor is developed and coded with the Arduino IDE.

These sensors are placed in each module, including the space inside the cavity and inside the building and are connected to a common microcontroller with the help of wires. The sensors are placed based on what needs to be measured and evaluated at a particular location. A detailed overview on the configuration of measurement sensors is explained in chapter 4. These sensors are developed and configured such that it can take the readings and simultaneously log the data.

1.8.4 Experimental Analysis

The configuration of the sensors is set to read and log data every ten minutes from each façade module. These readings are logged continuously on an SD card, from which the readings from the measurements are taken and recorded once a week. Through this, it would be possible to determine the trend of each measurement over a weeks' time. This includes temperature, relative humidity, illuminance and air quality.

These measurements are taken simultaneously for the upper and lower three modules. The measurement period is over a course of two months, from May 2019 to July 2019. The change of trend in data is noted over the course of this period. This includes the preliminary measurements on each module without the placement of the plants in the double skin façade.

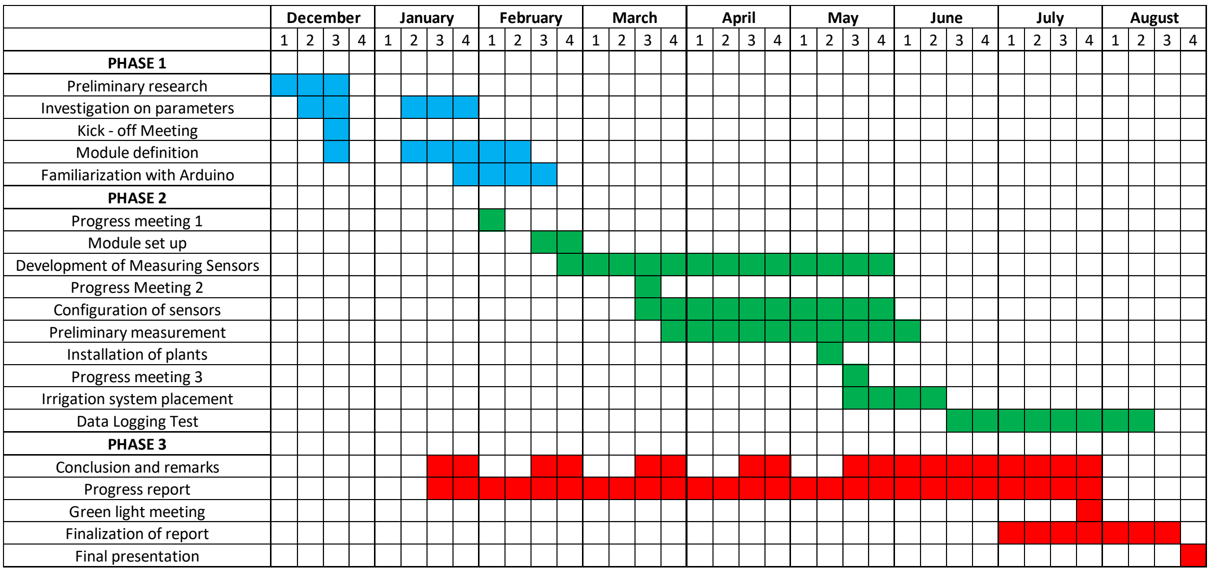
1.8.5 Evaluation and remarks

The results obtained from the experimental analysis are evaluated with a defined comfort criteria, obtained by various sources of literature. The required climatic conditions for the growth of plants is studied and is compared to the actual conditions for the plants, obtained by the experiment.

The differences of the trend in data, over the course of the measurement period is highlighted and the expected outcome and inference is drawn accordingly. Moreover, the indoor environment with respect to comfort will be evaluated by conducting a survey by the occupants in the building.

Based on the experimental result, the effect of the different design of each module on the plants on indoor comfort will be studied, and subsequently, the extent of the influence of the double façade shall be determined, with respect to sustainability and indoor environment.

1.9 RESEARCH SCHEDULE



CHAPTER 2 – PRELIMINARY RESEARCH

2.1 OVERVIEW

This chapter contains the literature review done so far for the experiment. This was done based on two conditions. The first condition is the environment for the indoor office spaces on both the first and second floors of the PITLAB. This was done by first taking three parameters into account: Thermal comfort, Lighting and Air quality. An overview on these parameters were studied to find information such as climatic conditions in workspaces, people's response to different comfort levels with respect to the three parameters and factors that influence the conditions in the indoor environment.

The second condition is the region in the cavity in the double façade in each of the six different modules in the first and second floor. As the study involves the placement of plants in the double façade, a study on the general behaviour of double skin façades, along with its comparison to green façades was done. Moreover, properties of different plants with respect to aspects such as resistance to climatic conditions and maintenance requirements were compared to find which plants are capable of growth in a double façade.

2.2 INDOOR ENVIRONMENT

2.2.1 Thermal comfort

The thermal comfort in an indoor environment depends on certain factors such as temperature, air velocity and relative humidity. As far as temperature is concerned, the air temperature and mean radiant temperature needs to be taken into account. The energy balance of a person is also an important factors that determines the comfort level of a room with respect to temperature. This is the balance between the heat gained and lost in the human body. This can be associated with certain discomforts such as heat discomfort. This depends on the humidity of the skin and its evaporation. This relates to the saturation rate of the surrounding air (Bluyssen, 2009). Hence in this way, relative humidity is also taken into account. Moreover, exchange of radiant energy between surfaces in the indoor environment is important for the thermal comfort of a person (Bluyssen, 2009). Some other forms of discomfort are draught discomfort due to air velocity.

The indoor environment in terms of temperature can be classified as healthy as long as the occupants feel comfortable and the productivity increases. The highest productivity of occupants occurs when temperatures in an office building range between 23 to 24°C (Seppänen, et al., 2006).

One way to determine the comfort in the room is to calculate the Predictive Mean Vote (PMV) (Bluyssen, 2009). Predicted Mean Vote (PMV) can be used as a thermal comfort index which is done in a 7 point scale (+3 to -3 corresponds to hot to cold). This can be used to determine whether a given thermal environment complies with the comfort criteria specified (Bluyssen, 2009).

Comfort zone can also be determined graphically with the help of a psychrometric chart. The comfort zone according to air temperature, relative humidity, air velocity and radiant temperature is given below (Roshan , et al., 2017). In the figure, the curved lines represent the trend of different relative humidity levels corresponding to different temperatures in the horizontal axis.

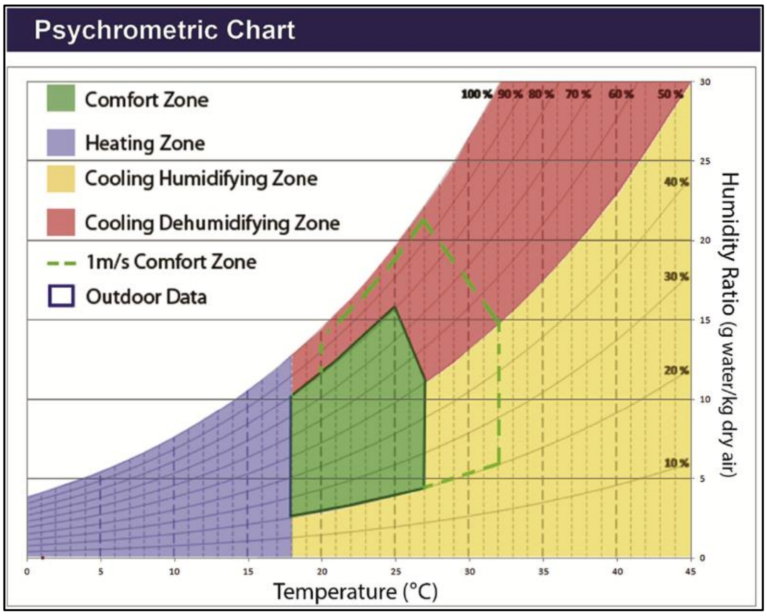


Figure 2 Psychrometric Chart ***Source:*** **(Roshan , et al., 2017).**

2.2.2 Lighting

The quality of light in an indoor space is determined by the sources of light present, the distribution and the way light is perceived (Bluyssen, 2009). The intensity of light can be expressed by its illuminance, which is the amount of light spread over the area receiving the light and is expressed in lux (lumen/m^2) (Bluyssen, 2009). According to the standard (EN 12464-1, 2002), in places where people are continuously present, a minimum level of 200 lux is recommended.

An area of a working space is considered to be day light when it receives at least 300 Lux of illuminance for over 50% of the working year (Shameri, et al., 2011). When luminance ratios are too large, they can cause visual discomfort. Ratios for 1:20 to 1:30 is generally acceptable (Bluyssen, 2009). Visual discomfort can occur when the object to be viewed has a lower illuminance than the background (glare) (Bluyssen, 2009). The luminance of each surface area is important and is determined by reflectance and lighting level on the workspace (Bluyssen, 2009). According to (EN 12464-1, 2002), the following reflectance of indoor surfaces is acceptable

- Ceiling: 0.6-0.9
- Walls: 0.3-0.8
- Work Surfaces: 0.2-0.6
- Floor: 0.1-0.5

Moreover, lighting with frequency of 50 to 100 Hz can increase the eye tiredness of a person (Bluyssen, 2009). Illuminances of less than 1500 lux provide the best results related to less tiredness and productivity (Aries, 2005).

2.2.3 Air quality

Parameters that determine air quality are production of pollutants in a space, ventilation rate of space and concentration of pollutants in ventilation air (Bluyssen, 2009). Some common air pollutants are CO, CO_2, and Volatile Organic Compounds (VOC) (Bluyssen, 2009). Sources of pollution are outdoor sources, office activities (Laser printing leads to release of O_3) , building materials and furnishings (insulation, plywood etc), ventilation system components (air filters and ducts) (Bluyssen, 2009).

Air ducts filters generally produce Volatile Organic Compounds. This may be due to the growth of microorganisms, dust/debris in air ducts that can be sources of pollution in air ducts (Bluyssen, 2009). Air change rate in ventilation systems is a factor for fresh air which increases air change efficiency (unit – h^{-1}). Natural ventilation is the passive way of exchanging air with outdoors, in order to evacuate indoor air contaminants (Bluyssen, 2009). Wind and air density differences due to temperature difference between indoor and outdoor air create pressure that drive the indoor air outside, thus increasing the air change rate (Bluyssen, 2009). However, this can only be the solution for rooms with openings on both sides or with depth to height ratios of less than 3. The high concentrations of VOC including VVOC and SVOC can cause symptoms of Sick Building Syndrome (Bluyssen, 2009). According to (Bluyssen, 2013), CO_2 should also be taken as an indicator for air quality. The recommended minimum ventilation rates over the course of 200 years is given below.

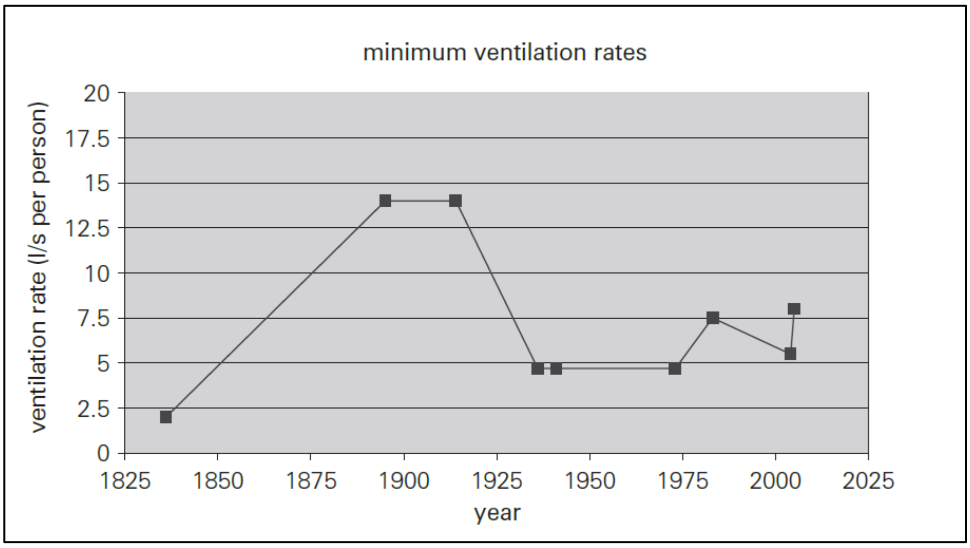


Figure 3 Recommended ventilation rates over 200 years ***Source:*** **(Bluyssen, 2009)**

2.3 DOUBLE SKIN FAÇADES

The envelope of a building acts as a thermal barrier between the indoor and outdoor environment, and it determines the level of thermal comfort, natural lighting, ventilation and energy demands for heating, cooling and air-conditioning (Anđelković, et al., 2015). As it was mentioned earlier that the building sector accounts for 40% of the total energy consumption in Europe, it is important to know how designing with a double skin façade can be beneficial to reduce energy consumption in a building. With increasing demands for energy efficient envelopes, the double skin façade was proposed as an idea for reducing the energy consumption in a building while maintaining a healthy indoor environment (Ghaffarianhoseini, et al., 2016).

A double skin façade is a combination of two types of glazing, where an external glazing is placed at a certain depth in front of the internal glazing, forming an air cavity in between. (Chan, et al., 2009) stated the following,

"Double skin facade refers to a building facade covering one or several stories with multiple glazed skins. The skins can be air tight or naturally/mechanically ventilated. The outer skin is usually a hardened single glazing and can be fully glazed. Inner skin can be insulating double glazing and is not completely glazed in most applications. The width of the air cavity between the two skins can range from 200mm to more than 2m. An air-tightened double skin facade can provide increased thermal insulation for the building so as to reduce the heat loss in winter season. On the other hand, moving cavity air inside a ventilated double skin facade can absorb heat energy from the sun-lit glazing and reduce the heat gain as well as the cooling demand of a building".

According to (Anđelković, et al., 2015) a double skin facade consists of a multi-layered façade envelope, which has an external and internal layer that contains a buffer space used for controlled ventilation and solar protection. This type of facade is able to utilize external environment to maintain indoor comfort.

Double skin façades are used in urban areas subject to external noise, as it functions to diminish external sounds from the external surroundings and also give the building an aesthetic appeal (Gratia & De Herde, 2004). Some advantages of double skin façade include improved sound insulation, thermal comfort in moderate climates and possibility of natural ventilation in the building without being exposed to high wind speeds and noise (Gratia & De Herde, 2004). Glazed double skin façades perform better compared to conventional façades in terms of natural ventilation, daylighting, thermal comfort and energy efficiency (Ghaffarianhoseini, et al., 2016). They are expected to fulfil functions such as energy consumption reduction, ventilation air flow and thermal comfort enhancement, daylighting and glare control, sound insulation, noise reduction and acoustic enhancement and aesthetic enhancement (Ghaffarianhoseini, et al., 2016).

A double skin façade can be used and operated dynamically corresponding to the type of climate the building is located, however bad operation of a double skin façade could lead to an unfavourable indoor environment (Gratia & De Herde, 2004). These passive dynamic strategies enable the double skin façade to reduce the energy consumption, thus improve the sustainability of the building (Ghaffarianhoseini, et al., 2016).

The advantage in a double skin façade is the versatility behind the usage of the air cavity. In summer, the air cavity can be used as a space to keep a shading device to avoid heating from sunlight whereas in winter, the air in the cavity can be used as an insulation to prevent heat loss from the building (Gratia & De Herde, 2004). Though the double skin façade has possibilities of overheating in summer, the temperature can be reduce by enabling ventilation through the cavity with the help of openings (Gratia & De Herde, 2004). A ventilated cavity can act as a thermal buffer, which reduces undesired heat gain during the summer, heat loss during winter and thermal discomfort due to asymmetric radiation (Ghaffarianhoseini, et al., 2016).

The performance of the double skin façade depends on parameters such as the technical composition of the cavity and the glazing, information on the type of building and the type of environment the building is situated (Ghaffarianhoseini, et al., 2016). Certain factors that are to be considered while designing a double skin façade are geometric parameters, glazing type, shading, ventilation type, cost and maintenance (Shameri, et al., 2011).

(Gratia & De Herde, 2004) experimented on the different strategies that can be used in a double skin façade at different climatic scenarios, in an office building in Belgium, and concluded the following,

- On a sunny winter day, temperatures in a non-ventilated cavity reached up to 42°C. This temperature was reduced to 26°C by keeping openings of 2.5 cm in the double façade and enabling high ventilation rates. Thus, the thermal conditions in the cavity is influenced by the size of the opening.
- On a sunny summer day, the temperature in a non-ventilated cavity went to 52°C. The presence of blinds inside the cavity for shading emits radiative heat inside the cavity, which creates a mini greenhouse effect. This can be avoided by ventilating the cavity such that the air does not enter the building. The double façade can be used as an exhaust, however, it depends on the orientation of the wind.
- On a cloudy winter day, the double façade should remain closed such that the cavity acts as an insulation to prevent heat loss from the building. This is because the temperature outside is less than the temperature inside.
- The strategy used on a sunny spring day is similar to the one used on a sunny summer day whereas the strategy used on a cloudy spring day is similar to the one used on a cloudy winter day.
- In the case of a cloudy summer day, the cavity is ventilated depending on the temperature outside. No shading devices are used as sunlight is diminished. This may be problematic in the case of plants as they do not provide a controlled shading.

Hence, it can be seen that the double skin façade can be operated in a different manner in order to suit the indoor environment in offices across different climatic scenarios.

Another advantage of double skin façades in winter is the minimal difference between the temperature of the air inside the room and the inner glazing, which reduces the heat losses from the building to the outside and thus, reduces heating demands (Gratia & De Herde, 2004). Moreover, the glazing of the double skin façade can maximise the use of sunlight in order to reduce artificial lighting and heating loads (Ghaffarianhoseini, et al., 2016). This is due to the fact that double skin façades enable the entrance of daylight in the building without glare (Shameri, et al., 2011). In the case of their research (Gratia & De Herde, 2004) concluded that the use of a double-skin facade decreases the heating loads and increases the cooling loads. Hence, it would be interesting to see how the placement of plants in a double skin façade can decrease the cooling loads.

There are four types of double skin façades, namely box window façade, shaft box façade, corridor façade and a multi storey façade (Ghaffarianhoseini, et al., 2016). A box façade is a type where the internal skin of each level of the building is covered by its own external skin, in which the cavity of that particular level is separated from the others (Ghaffarianhoseini, et al., 2016). Since the PITLAB consists of individual modules isolated from one another, it can be classified as a box window façade.

Double façades can be ventilated in multiple ways. They can be non-ventilated (closed), they can be used as a mechanical intake and exhaust as well as natural intake and exhaust (Ghaffarianhoseini, et al., 2016). These different methods of ventilation are considered for the façade modules in the PITLAB, which is further explained in chapter 3.

With the ventilation strategy adopted, double skin façades can also work to improve the air quality of the building by replacing contaminated air by clean air, and create a room climate without draught problems (Shameri, et al., 2011). Fresh air can be provided by different types of double skin façades corresponding to different climates, orientations and location (Shameri, et al., 2011). Looking at the ventilation strategies provided by double skin façades, it can be integrated as a part of the HVAC system in a building (Stec & van Paassen, 2005). Double skin façades can be used to integrate natural ventilation in a building to improve the air quality and comfort conditions in urban areas (Anđelković, et al., 2015).

The parameters such as the orientation of the façade, type of glazing, solar radiation level and the shading devices used can lead to a greenhouse effect in a double skin façade (Gratia & De Herde, 2007). This happens when a part of the solar radiation is transmitted to the interior glazing, warming it up and thus making it re-emit radiation inside the double skin façade. This radiation is trapped and as a result, the air temperature in the cavity increases due to convection from the glazing to the air inside the double skin (Gratia & De Herde, 2007). This phenomenon is dominant in a south glazing façade, and is not favourable in summer if the façade is oriented in the east or west direction due to overheating in the morning (Gratia & De Herde, 2007). Since the façade of the PITLAB is oriented towards south east direction, it is important to consider that greenhouse effect is a possible phenomenon to occur, especially in a non-ventilated cavity. This may be a disadvantage in summer but be beneficial during sunny winter days, where the double façade can act as a preheating element. A schematic representation of the greenhouse effect in facades is given below.

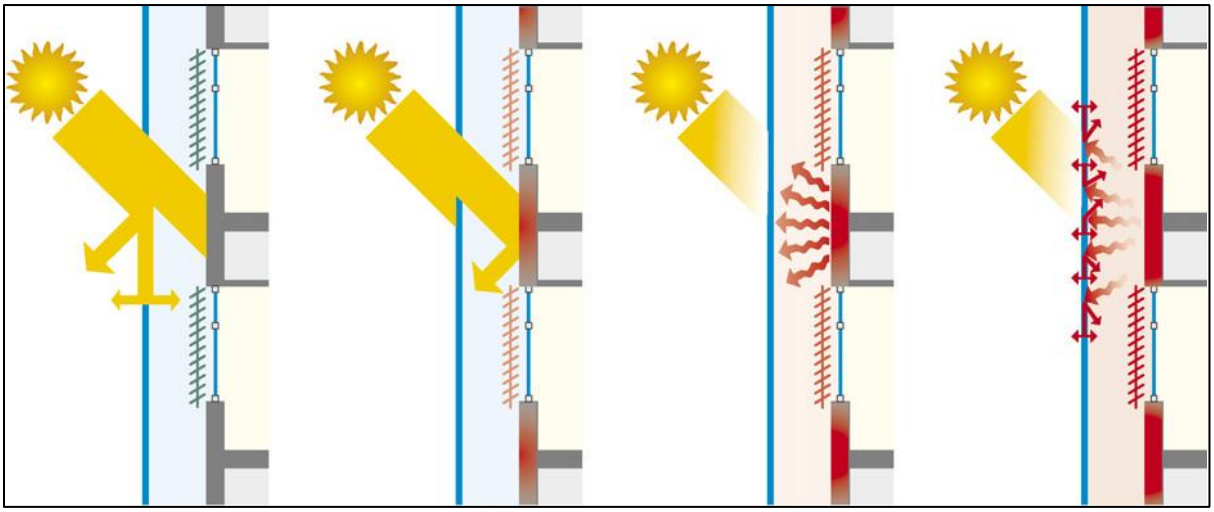


Figure 4 Greenhouse effect in a closed double skin façade ***Source:*** **(Gratia & De Herde, 2007).**

2.4 GREEN FAÇADES

The behaviour of double skin façades and strategies for its design with respect to different climatic conditions were examined. However, the concept of green façade was mentioned as a sustainable method of construction, but its performance with respect to indoor climate was not looked at. This section contains the advantages of placing vegetation in structures, and the influence of placing vegetation in a double skin façade.

One of the differences shown by green façades to conventional façades is the behaviour of the plants with respect to climatic conditions. For example, a surface of a building material (shades or walls) react to global radiation by either reflecting them or transforming them into heat flux, whereas, plants can not only convert radiation into latent heat, but also convert solar energy into biomass, oxygen and humidity (Ottelé, 2015). With this process, plants tend to create their own microclimate, which is beneficial for the thermal comfort in cities (Ottelé, 2015).

In a microclimatic scale, plants help to increase the quality of air by filtering out particulate matter and other forms of pollutants such as NO_3 and CO_2 (Ottelé, 2015). This filtration ability is due to the leaf structure and respiratory mechanisms of the plants in the microclimate (Ottelé, 2015).

Due to the fact that plants create their own microclimate, green façades can cause great temperature fluctuations in the building if they are exposed to a constant sunlight and wind speed (Ottelé, 2015). However, plants are durable to UV radiation and can keep the façade from reaching high temperatures during the day, with the effect increasing as the density of plants increase (Ottelé, 2015).

Studies have shown that vegetation in façades bring a positive effect in summer as well as in winter. In summer, direct solar radiation is blocked by vegetation due to the shading effect of leaves, which not only regulates the lighting, but also regulate the temperature inside the building (Ottelé, 2015). Moreover, the plants utilize the direct solar radiation for its growth. Due to the function of evapotranspiration in plants, the temperature in the façade decreases, thus radiating much less temperature to the rest of the building and as a result gives a cooling effect in buildings especially in urban areas (Ottelé, 2015). In winter, the plants act as an insulating agent, preventing heat to exit from the building, as the plants will act as a thermal buffer which keeps internal air trapped inside within the plant foliage in the building (Ottelé, 2015).

In the case of a double skin façade, the effect of plants can be compared to general shading devices. (Stec, et al., 2005) found that when a plant and a shading blind device is exposed to the same type of radiation, the temperature of the blinds is twice of that of the plants. As a result, plants would emit less convective heat to the air in the cavity compared to the blinds. Additionally, (Stec, et al., 2005) found out that the temperature of the plants do not exceed 35°C whereas the blinds can go up to 55°C. This is an advantage in the case of summer when the cavity is not expected to overheat. This would make the building more efficient with respect to cooling energy consumption. The average temperature of air in a cavity is less with the presence of plants compared to an empty cavity as well (Stec, et al., 2005).

However, this may be a disadvantage in winter as vegetation does not provide controlled shading, when sunlight is needed during winter. Moreover, due to its less heat emission towards the cavity air, the air would be less preheated as compared to the double skin façade with blinds. Moreover, space requirements for plants and frequent maintenance due to pruning of plants also act as a disadvantage.

To conclude, the functions of vegetation in façades with respect to thermal comfort, lighting and air quality has been highlighted. It is seen that the shading effect of plants do not only prove to be beneficial in terms of lighting, but is also an advantage for thermal comfort due to blockage of sunlight and due to the release of latent heat due to evapotranspiration. Similarly, the leaf density of the plants do not only act as a shading device, but also has the ability to improve the air quality by filtering out pollutants. Due to these advantages, thermal comfort, lighting and air quality have been considered to be parameters to evaluate the performance of vegetation in double skin façades.

2.5 PLANTS AND THEIR GROWING CONDITIONS

As mentioned in the problem statement, that the range of climatic conditions in a double skin façade is large (temperature ranges can go from -10°C to 40°C), it is important to take into account that there is a limitation for the amount of plants that can be grown and placed in a double skin façade. Moreover, this project involves the growth of edible plants, hence the quality of each plant is also an aspect to take into account. Taking these factors and the measurement period (spring-summer) into account, the requirements of climatic conditions for different types of plants were compared, in order to check which plant can be placed in the façade of the PITLAB.

A comparison between 5 different plant species was studied. A summary of the properties for each of the plants are briefly listed below.

2.5.1 Cucumber

Cucumber is a plant with a growing season of an average of 3 to 4 months, where the first fruit appears after 5 weeks of cultivation followed by more fruit production for the next 4 to 8 weeks (NaanDanJain Ltd., 2014) . The optimum growing conditions in the day is 20 – 22°C during day and 19-20°C at night with a soil temperature should be a minimum of 15°C (NaanDanJain Ltd., 2014). Maximum temperature for growth without of cucumber flower degeneration is 35°C due to which growth will take a longer time (NaanDanJain Ltd., 2014). The humidity conditions should be low with a spacing of 30 to 50 cm, due to the fact that cucumbers are prone to diseases due to mildew, which develops due to high humidity (NaanDanJain Ltd., 2014).

2.5.2 Pepper plant

The germination temperature of pepper plants ranges from 23 to 30°C with an optimum growing condition of 21 to 28°C in the day and 15 to 20°C in the night (Starke Ayres, 2014). Peppers tend to grow better in spring and summer and their growth rate is reduced at temperatures below 15°C with cold damage occurring at temperatures below 6°C (Starke Ayres, 2014). Soil temperature ranges from 15 to 35°C. However, with soil temperatures between 20 to 30°C, and a plant density of 3-4 plants per m^2 germination takes place between 8 to 13 days (Starke Ayres, 2014). Relative humidity for a pepper plant varies between 65 to 85% (High relative humidity) and a relative humidity higher than 85% can lead to foliar diseases (Starke Ayres, 2014). Low relative humidity with high temperature can lead to wilting of growth tip which can cause rot.

2.5.3 Tomatoes

Tomatoes have an optimum growth temperature of 21 to 28°C during the day and 15 to 18°C during the night, with a soil temperature of 15°C (Snyder, 2014). The quality with respect to colour deteriorates at higher temperatures. At temperatures above 30°C, lycopene which is the pigment that makes tomatoes red, stops developing (Snyder, 2014). Relative humidity for tomatoes is 60 to 70 % but with high light intensity, as temperature fluctuations with high moisture content and low light intensity can cause blotchy ripening (Snyder, 2014). Insufficient watering of the plants can cause the plant to wilt and rot and lack of CO_2 at low temperatures can lead to puffiness during the growth of the tomato plants.

2.5.4 Carrots

Carrots are plants which are grown predominantly during the heating season. This is due to the fact that carrots grow in relatively lower temperatures with a minimum growth temperature of 5°C and the optimum growth temperature of 16 to 25°C with a minimum soil temperature of 10°C (Suojala, 2000). As a result, carrots need to be grown at high relative humidity of around 95% (Suojala, 2000). The growing period for carrots is roughly 2 to 4 months and the yield quality of carrots decrease when temperatures are above 25°C and below 10°C (Suojala, 2000).

2.5.5 Spinach

Spinach germination has a high temperature range between 7°C and 24°C (Ernst, et al., 2012). The optimum growth temperature for spinach is between 15 to 24°C and temperatures below 15 and above 24°C result in slow growth with a minimum temperature of 2°C and maximum of 29°C (Ernst, et al., 2012). If temperatures are below or above this range the plants have possibilities of dying. The relative humidity range is between 50 to 70% and high moisture can cause diseases in leaves and formation of pests such as aphids and slugs (Ernst, et al., 2012). During high moisture content, the roots will absorb water leaving the leaves unable to transpire, causing guttation (growth of liquid water from leaves) (Ernst, et al., 2012).

2.5.6 Conclusion

From the properties above, it is seen that each plant has different responses and requirements. Although some aspects are similar, its overall requirements vary. For example, the optimum growing temperature in pepper and tomatoes fall in the same range. However, the relative humidity requirements contradict each other. In the case of peppers, the optimum growing condition falls in a limited range, however its resistance to temperature is high. i.e. if temperatures are beyond the optimum range, they will grow slowly but will not die. Moreover, the measurements are going to be done over the span of spring to summer season, which might suit the requirements for it to grow. Hence, Habanero peppers are considered to be placed in the façade modules of the PITLAB.

2.6 SUMMARY – PEPPER PLANTS

2.6.1 Overview

The chilli pepper plant (*Capsicum L.*) is a single stem plant with around 8 to 15 leaves, which can grow up to 150 cm. (Sape & Owk, 2005). There are many types of pepper plants, ranging from sweet peppers (*Capsicum Annum*) to Habanero Chilli peppers (*Capsicum Chinese*). The Habanero Chilli pepper plant size ranges between 30 and 150 cm depending on the environmental condition, and the average height of the plant is around 60 cm (DeWitt & Bosland, 2009). The leaves of the plant can go up to 15 cm in length and 10 cm in width, with each individual pod going up to a length of 5 cm and a width of 1.5 to 3 cm. They are green in colour during early stages and can turn yellow, orange or red upon maturity (DeWitt & Bosland, 2009). Most habaneros typically have a lantern or blocky shape, 3-5 cm in length, and 2-3 cm in width (Crosby, 2008).

2.6.2 Climatic requirements and soil conditions

During germination, the ideal temperature conditions for pepper plants range from 23 to 30°C, with 21 to 28°C in the day and 15 to 20°C in the night. Pepper plants can withstand lower temperatures with a slower growth rate. However, cold damage occurs at temperatures below 6°C (Starke Ayres, 2014). Soil temperature ranges from 15 to 35°C. However, with temperatures between 20 to 30°C, germination takes place between 8 to 13 days (Starke Ayres, 2014).

The growth aspects of a plant such as root and shoot growth, biomass accumulation, photosynthesis, chlorophyll content, nutrient uptake and yield are dependent on container size (NeSmith & Duval, 1998). The root and shoot growth are interdependent on each other and this balance is disturbed or affected if the plants are kept in small containers (NeSmith & Duval, 1998). In the case of pepper plant, it is suitable to have planter with a depth of at least 20 cm, and each plant should be kept at a distance of 35 to 40 cm apart (Albert, 2010).

Most plants tend to grow better at higher relative humidity. However, mineral deficiencies, disease outbreaks, smaller root systems and softer growth are possible consequences of excess humidity (British Columbia Ministry of Agriculture, 2015). The relative humidity for a pepper plant varies between 65 to 85% (Starke Ayres, 2014).

Peppers are susceptible to rot, blossom end rot, anthracnose, tobacco mosaic virus, bacterial spot, and mildew. Relative humidity higher than 85% can lead to Folier diseases. Low relative humidity with high temperature can lead to wilting of growth tip which can cause rot (Albert, 2010). Fertilizers should be added such that the soil is rich in contents such as Nitrogen, Phosphorous, Sulphur and Zinc (Biratu, 2018). The soil should also be in a slightly acidic state with a pH content of 6.5 to 6.8, along with other nutrients such as Magnesium, Sodium, Calcium and Potassium (Starke Ayres, 2014). The general moisture content and water requirements for the different stages of growth of pepper plants are given in the figure below.

WEEKS AFTER PLANT	ROOT DEPTH (mm)	SOIL MOISTURE %	CROP FACTOR	DAYS BETWEEN IRRIGATION	AMOUNT NEEDED (mm)
0 - 2	400	20	0.3	2	10 - 15
3 - 6	500	30	0.4	3 - 5	15 - 25
7 - 15	600	40	0.6	5 - 7	30 - 40
16 - +	700	50	0.8	7 - 10	20 - 30

Figure 5 Irrigation requirements for pepper plants. ***Source:*** **(Starke Ayres, 2014)**

2.6.3 Lighting requirements

Pepper plants are day-neutral plants, i.e. the growth is unaffected by the amount of natural or artificial light in a certain photoperiod. Pepper plants need at least 5 hours of sunlight, with an optimum amount of sunlight ranging between 8 to 12 hours (Allman, n.d.). In order to achieve this, it is ideal to place the plants in a south facing façade (Allman, n.d.). Some other methods to increase the amount of light includes the usage of aluminium foils, or artificial lighting (Allman, n.d.). Advanced covering materials could also be used, such as white, low-iron glass (light transmission increase +1-2%), modern anti reflection coatings on glass (+5-8%), new plastic films like ETFE material (+3%) or new nano-sized surface structures (+5-8%) (Hemming, 2009).

The growth of plants in general is also affected by the wavelength of light. The range of wavelength of light used for photosynthesis is between 400 – 700 nm (Mattson, 2014). The day light integral is a factor to determine the photosynthesis for plants. Plants such as peppers require a Day Light Integral of 20-30 mol/m2/day (Mattson, 2014).

In the Netherlands, the total Light Integral received in a regular greenhouse in a year is 6200-6500 mol/m^2/year (Hemming, 2009). In cases with high humidity levels (80%) a higher amount of light is tolerated by the plants, as well as recommended. Crop distribution increases by adding diffuse light. For example, cucumber plants showed an increase in production of about 6.5-9.7% (Hemming, 2009).

Varying the densities of the plants may increase the light use efficiency of the plants. For example, high density plants under HPS lamps increases the plant yield compared to low density plants (Hemming, 2009). Different wavelengths are suitable for different plants. For example, blue light (400-500nm) is suitable for potatoes and lettuce, whereas red light (700 nm) is suitable for peppers and cabbage. However, several experiments have shown that the mixing of light spectrum cause an increase in vegetable growth and nutritional value (Hemming, 2009). In this case, it seems suitable to adopt grow-light (combination of red blue and white LED) for artificial lighting.

From the requirements mentioned above, it can be said that artificial lighting is an option to consider in the case of winter, when the amount of sunlight is not much. Moreover, the power produced by the light can act as a heat source for the plants when temperatures in the cavity get too low. Since the experiment is going to take place throughout the spring and summer season, the concept of artificial lighting as a parameter is being overlooked. An alternative option for a parameter is the use of different peppers in the double skin façade. One plant in the bottom will be a tall growing plant and the one on the top will be a short growing plant.

2.7 BEHAVIOUR OF PLANTS WITH RESPECT TO HUMIDITY

It is known that the climatic conditions surrounding the plants affect the growth of the plant. However, it can also be said that the vice versa is true. One of the main parameters affected in the indoor environment is the humidity levels. Humidity levels change with changes in air temperature. Moreover, plants add moisture content to the surrounding environment through a process known as evapotranspiration. Since the amount of water vapour present in the air is defined by the ability of free water in the air to evaporate, the maximum available moisture content in the air increases as the temperature of the air increases. Due to this phenomenon, water vapour tends to move from areas of high concentration, such as leaves of plants, to areas of low concentration, such as the air surrounding it. This is how evapotranspiration occurs through plants (British Columbia Ministry of Agriculture, 2015).

Due to this phenomenon, it is important that the humidity is controlled in the environment. Relative humidity near the dew point can lead to condensation, which can cause moisture to settle in the plants. This can lead to various diseases (British Columbia Ministry of Agriculture, 2015). Moreover, in the case of pepper, it is necessary to prevent relative humidity levels to reach 85%.

One method to evaluate the relation between the plants and its surroundings is to measure the Vapour Pressure Deficit (VPD). Vapour Pressure Deficit is the difference between the amount of water vapour in the plant surfaces and the amount of water vapour in the air at constant relative humidity (British Columbia Ministry of Agriculture, 2015). The Vapour Pressure Deficit increases with an increase in temperature. This quantity measures the difference between the amount of water vapour that can be held in saturated air at a given temperature, and the actual amount of water that is held in a sample of air that is not saturated (British Columbia Ministry of Agriculture, 2015). This quantity is measured in millibar (mb). A common range of setpoint for Vapour Pressure Deficit for different relative humidity is given below

Temp °C	Relative Humidity										
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%
15	0.0	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6	8.5
16	0.0	0.9	1.8	2.8	3.7	4.6	5.5	6.4	7.3	8.2	9.1
17	0.0	1.0	2.0	2.9	3.9	4.9	5.8	6.8	7.8	8.8	9.7
18	0.0	1.0	2.0	3.1	4.1	5.1	6.2	7.2	8.2	9.3	10.3
19	0.0	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0
20	0.0	1.2	2.4	3.5	4.7	5.9	7.0	8.2	9.4	10.6	11.7
21	0.0	1.2	2.4	3.7	4.9	6.2	7.4	8.6	9.9	11.1	12.4
22	0.0	1.3	2.6	3.9	5.3	6.6	7.9	9.2	10.5	11.9	13.2
23	0.0	1.4	2.8	4.2	5.6	7.0	8.5	9.9	11.3	12.7	14.1
24	0.0	1.5	3.0	4.5	5.9	7.4	8.9	10.4	11.9	13.4	14.9
25	0.0	1.6	3.2	4.8	6.4	8.0	9.5	11.1	12.7	14.3	15.9
26	0.0	1.7	3.4	5.1	6.7	8.4	10.1	11.8	13.4	15.1	16.8
27	0.0	1.8	3.5	5.3	7.1	8.9	10.7	12.4	14.2	16.0	17.8
28	0.0	1.9	3.8	5.7	7.6	9.5	11.4	13.3	15.1	17.0	18.9
29	0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0
30	0.0	2.1	4.2	6.4	8.5	10.6	12.7	14.8	17.0	19.1	21.2

Figure 6 Vapour Pressure Deficit set point in millibars *Source:* (British Columbia Ministry of Agriculture, 2015)

The vapour transfer deficit can also be found by determining the saturated vapour pressure from the leaf of the plant and the vapour pressure of air. The VPD is obtained by calculating the difference between the saturated vapour pressure of the leaf and the vapour pressure of the air. The formula to calculate the VPD is mentioned below (Metsaots, 2018)

$$SVP_{leaf} = 6.107 \times 10^{(7.5 \times T_{leaf}) / (237.3 + T_{leaf})}$$

$$VP_{Air} = 6.107 \times 10^{(7.5 \times T_{Air}) / (237.3 + T_{Air})} \times \frac{R.H_{Air}}{100}$$

$$VPD = SVP_{leaf} - VP_{Air}$$

Where,

SVP_{leaf} = Saturated Vapour pressure of the leaf in millibar

T_{leaf} = Temperature of the leaf in °C

VP_{Air} = Vapour pressure of air in millibar

$R.H_{Air}$ = Relative humidity of air in %

VPD = Vapour transfer deficit in millibar

In figure 7, the blue shaded region in the left denotes vapour transfer deficit values below 5 millibar, indicating that the air is too humid for the plants. The blue shaded region in the right denotes values above 12.5 millibar which shows that the air is too dry. The blue shaded region in the middle covers values between 8 and 10 millibar, which is considered ideal for plants (British Columbia Ministry of Agriculture, 2015).

2.8 CONCLUSION

This chapter contains the literature done on different aspects, to evaluate the building's performance with respect to the façade as well as the indoor environment of the building. The factors involved to define indoor comfort were discussed in order to find out on what parameters can the performance of the double skin façade be evaluated. Three parameters are considered namely thermal comfort, lighting and indoor air quality.

Sustainable methods of construction were reviewed in order to find how energy demands of a building can be reduced without compromising the need for indoor comfort. Since the façade of the PITLAB is considered as a double skin façade, various literature on the types and performances of double skin façades in different climatic conditions were reviewed. Strategies for improving the indoor environment of the building through different operations of double skin façades were also reviewed.

The project involves the placement of vegetation in a 'Do It Yourself' double skin façade in order to maximise sustainability in terms of circularity and sustainability. Due to this, the concept of green façades and its performance was important to be mentioned. More importantly, the comparison of green façades with conventional façades were also made to get an idea of the expected behaviour of green façades, with respect to the three comfort parameters.

The literature not only dealt with the influence of green façades on the indoor environment of the building, but also the influence of the plants in the double skin façade on the environment in the cavity of the façade, and vice versa. Looking at the wide range of climatic conditions inside a double skin façade, it can be said that the objective was to create a 'greenhouse' within each double skin façade module for the growth of the edible plants. Hence, a few species of plants were considered where the climatic requirements of each species was evaluated. Moreover, the microclimatic behaviour of plants, with respect to thermal and moisture conditions was also studied, mainly due to the process of evapotranspiration in plants.

Overall, this research was done to determine what strategies can be used in the double façade, depending on the growth requirements of the plants, as well as the requirements for indoor comfort. These strategies include the determination of the constant and variable parameters to be used on each façade, differences in the configuration of each façade module, maintenance strategies and evaluation methods. These are discussed in the following chapter.

CHAPTER 3 – MODULE DEFINITION

3.1 OVERVIEW

This chapter includes the details with respect to the façade of the building. As mentioned earlier, this façade can be classified as a box window façade. In order to determine the performance of the double skin façade, each of the six modules were distinguished by a set of constant and variable parameters, across the two storeys of the office building. One basic façade module is described as per its characteristics and dimensions. Then the configuration of each façade module is mentioned. Moreover, the characteristic, working mechanism and expected behaviour of each individual module is also mentioned.

3.2 DESCRIPTION OF THE BASIC MODULE

The frontal double skin façade of the building is oriented towards south east direction. Each double skin façade module is 1.9 m in length and 2.4 m in height. Both the skins of each module is glazed with a height of 2 m (84% glazed), leaving 0.4 m of height opaque for plants to be placed. The width of the cavity in the double skin façade is 0.42 m. Both the inner and outer skins are present in the form of sliding doors, where the inner sliding doors are openable, whereas the outer one is to be fixed. A schematic representation of the double skin façade is given below in figure 8.

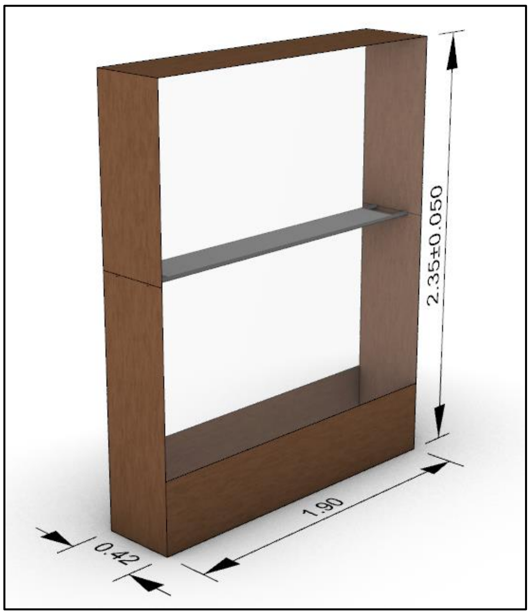


Figure 7 Basic representation of a double skin facade module

The inner and outer skin of the façade is double glazed with HR++ glazing. Each double façade contains external shading which is in the form of container doors, which can either be opened or closed. They can be open up to an angle of 90°. Due to the orientation of the façade, the container doors act as a complete shading device when it is closed and partial shading device when it is open. The sides of the cavity in the module is cladded with timber which is painted in black. The vertical and horizontal sections of one of the façade modules in the PITLAB are shown below in Figure 9 and 10.

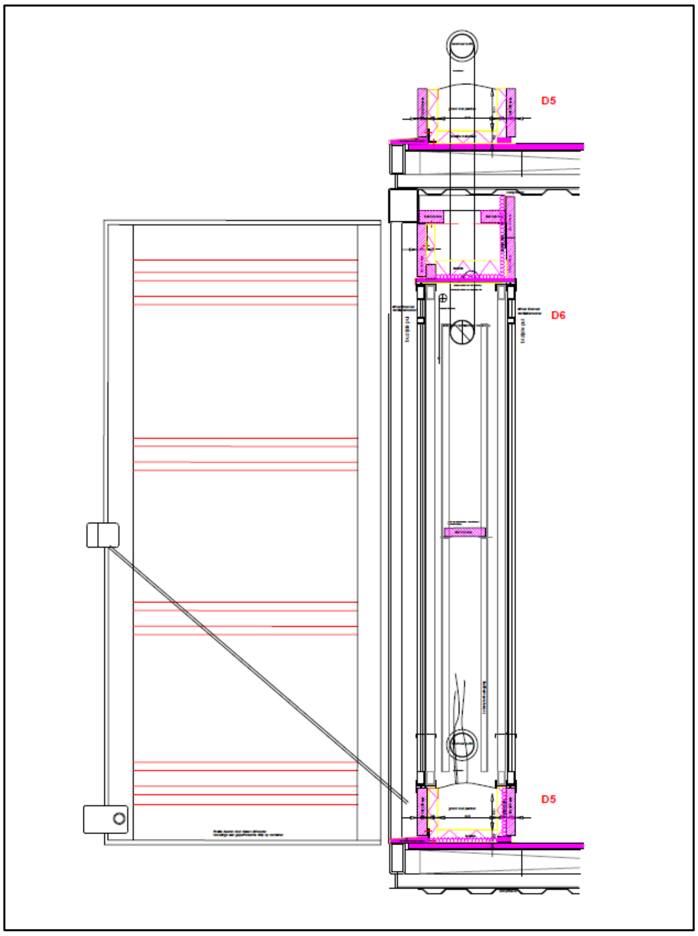


Figure 8 Vertical section of one of the façade modules *Source:* (Door Architecten, 2018)

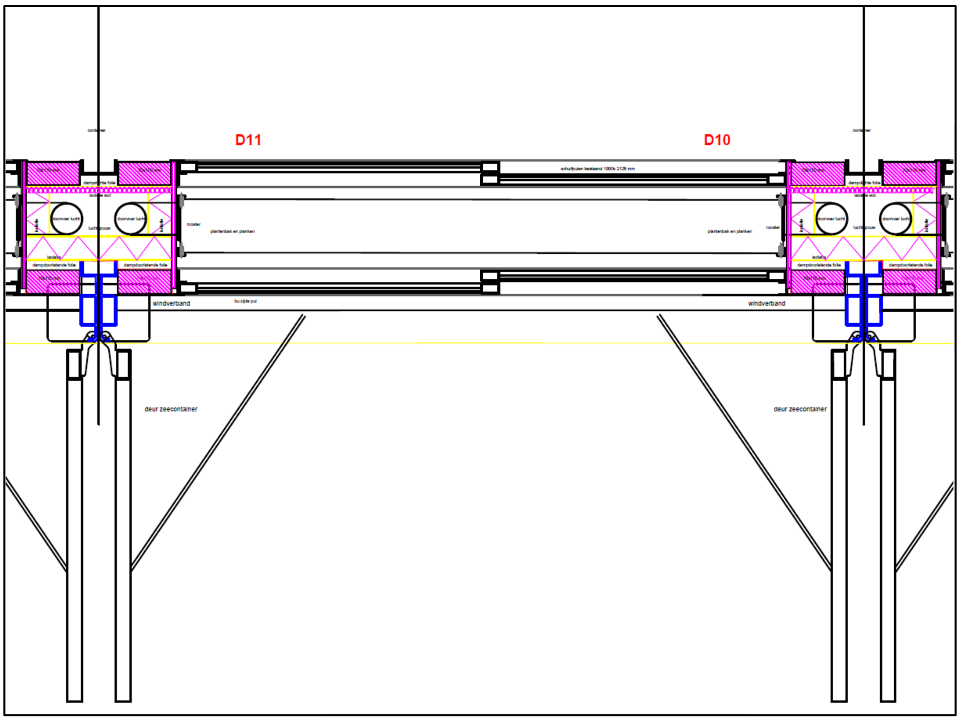


Figure 9 Horizontal section of one of the facade modules *Source:* (Door Architecten, 2018)

Every façade module is insulated on all four sides and each module is separated by a distance of 0.3 m from the adjacent module. These separations contain insulation and is cladded with timber. This is done mainly to ensure the isolation of one module from another. It is important that the conditions inside the cavity of one module does not affect the condition in the other. A rack is placed at a height of 1.4 m from the base of the cavity, to place the pepper plants in individual planters. The base of the module has a depth of 0.4 m, which contains a coating made of a black waterproof layer of textile. This is because the base will be covered with a layer of soil, to accommodate a row of plants. Moreover, it is important that there should not be a common space outside the cavity. This is because the three modules will influence the space as a whole, and it would be difficult to determine the effect of each module on the space outside the cavity. Hence, the space outside the cavity should be divided into zones. This will be done with the help of curtains, which will separate the zones and create an individual environment.

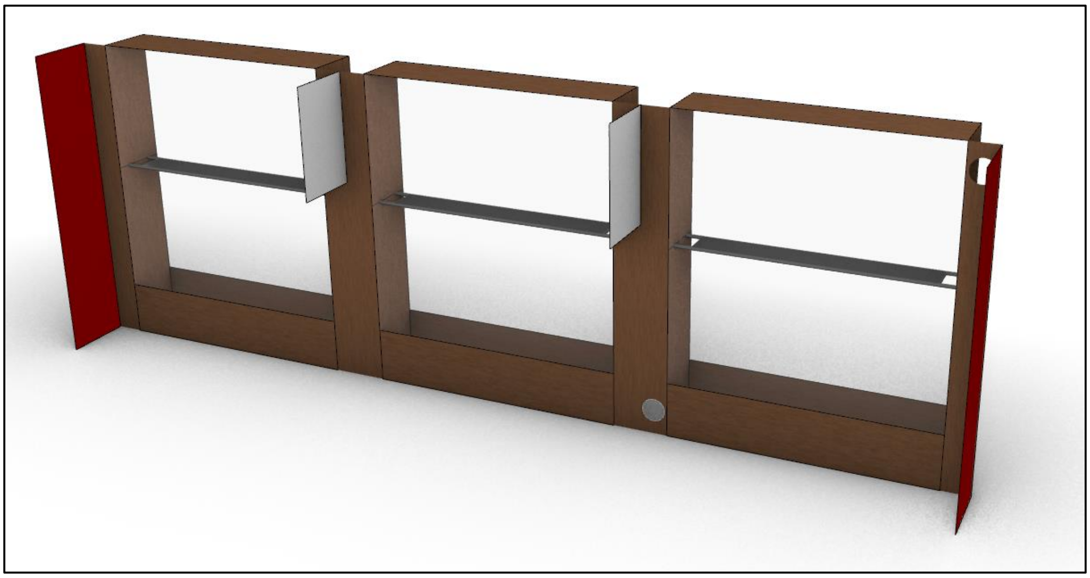


Figure 10 Segregation of zones in one floor

3.3 MODULE CONFIGURATION

3.3.1 Parameters involved

To distinguish the function of each of the six façade modules, a few parameters were considered, namely ventilation, watering system for the plants, the type of plants and its arrangement, and the shading involved by the external container doors. The ventilation parameter was set to be constant between the two floors, but variable across one floor, i.e. the method of ventilation used in each of the façade module in the top floor is different, but is duplicated in the bottom floor as well. The watering system for the plants was set to be constant in one floor for each module and variable in the bottom floor. The plant density and type were variably distributed based on its availability, and the shading through the container doors were variable based on the temperature.

The aforementioned strategies adopted in each module define the experimental set up of this graduation project. The similarities and differences in each module with respect to these modules are mentioned in the following sections.

3.3.2 *Ventilation based module*

In the previous chapter, different ventilation strategies used for double skin façades in different climates were mentioned. The main function of ventilating the façade is to achieve the desired thermal comfort according to different climatic regions and reduce the contaminants in the air by replacing it with fresh air, thus improving the air quality in the building (Ghaffarianhoseini, et al., 2016). In the case of the experiment, the objective was not only to check the thermal comfort of the building, but also the conditions in the double skin façade for plants. Hence the ventilation types were distinguished accordingly

The modules in each floor were functioned based on three types of ventilation mechanisms. These were mechanical ventilation, natural ventilation by the opening and closing of sliding doors and minimal ventilation with closed sliding doors. The configuration of each façade module from inside the building is given below in Figure 10.

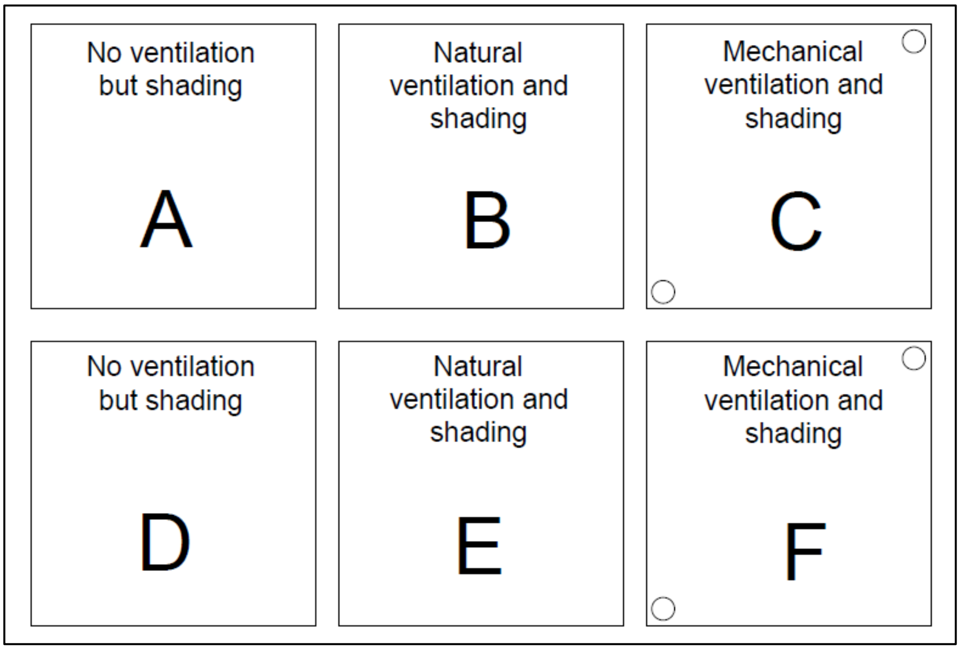


Figure 11 Ventilation configuration for each module across two floors

The figure above shows the arrangement of the façade modules with a view from inside the building. These modules were assigned variables as shown in the figure, for experimental purposes. The variables A and D refer to the non-ventilated modules in the top and bottom floor respectively. The variables B and E refer to the naturally ventilated modules and the variables C and F are assigned to the mechanically ventilated modules in the top and bottom floor respectively.

The purpose of this experiment is to investigate how the module performs due to the presence of vegetation in the cavity. Hence the strategy adopted for mechanically ventilating the façade (C and F) was the mechanical intake of air from the outside, along with the mechanical supply of the circulated air into the office.

In other words, air which enters the building through windows will be taken by the fan in the bottom, the air is then circulated back to the indoor of the building with the help of a fan from the top of the module. The external sliding door is closed and the module does not act as an exhaust, but as a supply mechanism for air. In this case, it would be possible to determine how the plants in the cavity influence the temperature of air that is being circulated. For example, it would be possible to investigate whether this mechanism preheats or pre cools the air which is to be supplied in the building.

The naturally ventilated modules (B and E) are done with the help of opening and closing the sliding doors. The idea is similar to the mechanically ventilated modules, however in this case, there are no fans, but air is expected to be circulated in the cavity and is supplied with the help of the internal sliding door. In this case, the external sliding door is closed and the internal sliding door is open, which acts as an inlet for air to ventilate the cavity as well as an inlet to allow the air to enter the building. In this case, the circulation of air is driven by the temperature difference between the cavity and the office, unlike what is described in the mechanically ventilated modules. This configuration is also used to determine whether the incoming air is preheated or pre cooled in the cavity due to the placement of the plants. Hence, a comparison can be made between the naturally ventilated mechanism and the mechanically ventilated mechanism. The modules with minimal ventilation (A and D) rely on the infiltration caused due to the sliding doors and the position of the external shading device. This configuration remains constant throughout the year. The configuration for the ventilation strategy adopted in all the module is given below.

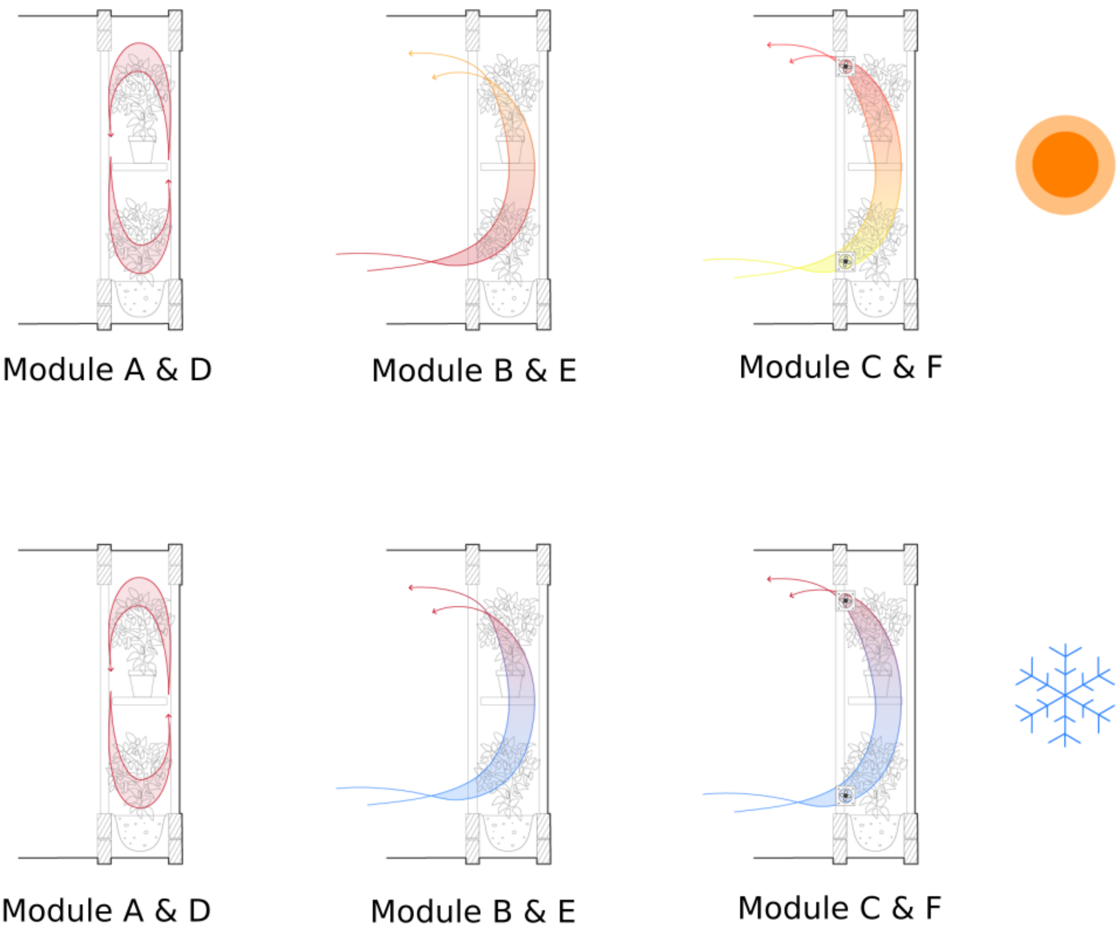


Figure 12 Ventilation strategy applied for all the modules during summer and winter

3.3.3 Placement of plants

The plants were placed such that there are different types of pepper plants placed in the cavity of each module, stacked in two rows, one row on top of the other. The top row is placed at a height of 1.4 m to accommodate short growing peppers, whereas the base contains a combination of short growing peppers as well as tall growing peppers.

Each module contains nine plants. Each module in the top floor contains seven planters of short growing peppers (five at the top and two at the bottom), one mid- size growing pepper plant and one tall growing pepper plant, which have similar transpiration rates. The configuration in the mechanically ventilated module of the bottom floor (module F) is the same as the ones in the top (module C), similarly, the configuration of the plants in the naturally ventilated modules (modules B and E) are the same. However, the minimal ventilated module in the bottom floor (module D) contains two mid-size pepper plants, and does not have a tall pepper plant. This configuration was made according to the availability of the plant. Figure 11 shows the scheme for the placement of plants is given below.

Figure 13 Placement of plants across six different facade modules

As mentioned before, each module consists of a combination of short growing pepper plants, one mid-size growing pepper plant and a tall growing pepper plant. Three types of short growing pepper plants were taken into account for this experiment, based on the availability of the plants. The three short peppers that were used were called 'Hot Chilli Red' peppers, 'Yellow Pointy' peppers and 'Snack Pepper Orange'. These were provided by Pick and Joy®. The mid-size growing pepper plant which was considered was the 'Bahamian Goat'. The tall growing pepper plant was an unnamed pepper, currently referred to as 'CGN21566'. These pepper plants with fully grown peppers are represented below in Figure 12.

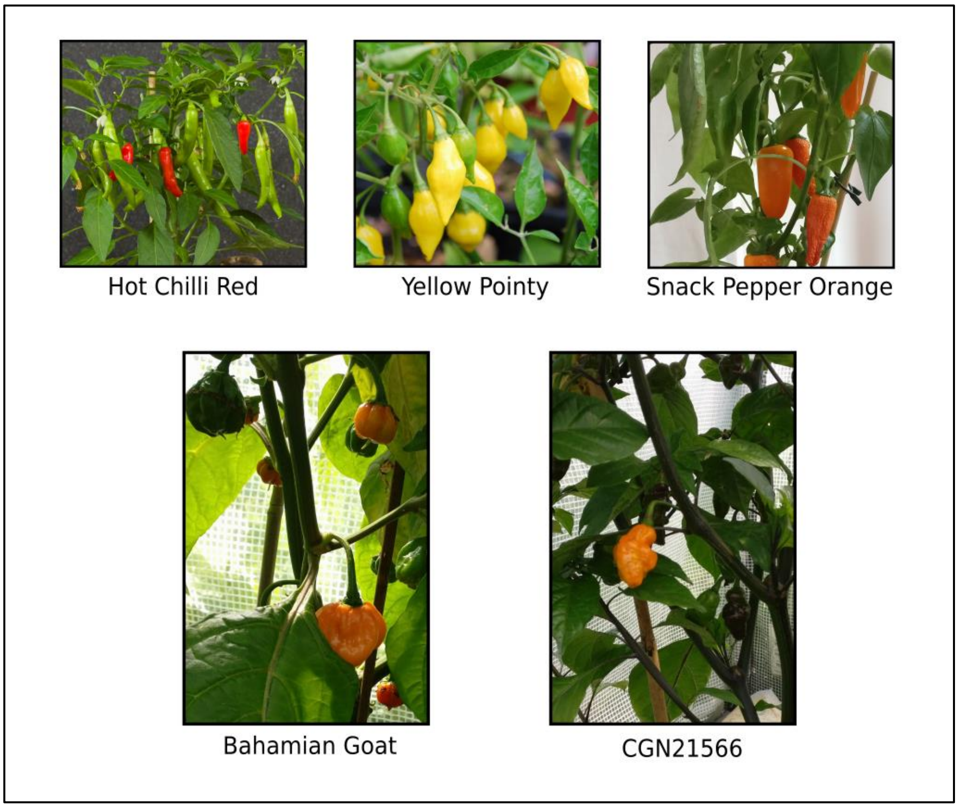


Figure 14 Types of pepper plants adopted. Source: (Diana's mooie moestuin, 2019), (Pick & Joy, n.d.)

As mentioned before in the previous section (Figure 10) that the modules were assigned variables, each plant in in a module was also assigned its own variable during the arrangement. This was done in order to evaluate the growth of each plant during the experimental phase. A schematic representation for the arrangement of plants is given in Figure 16 below.

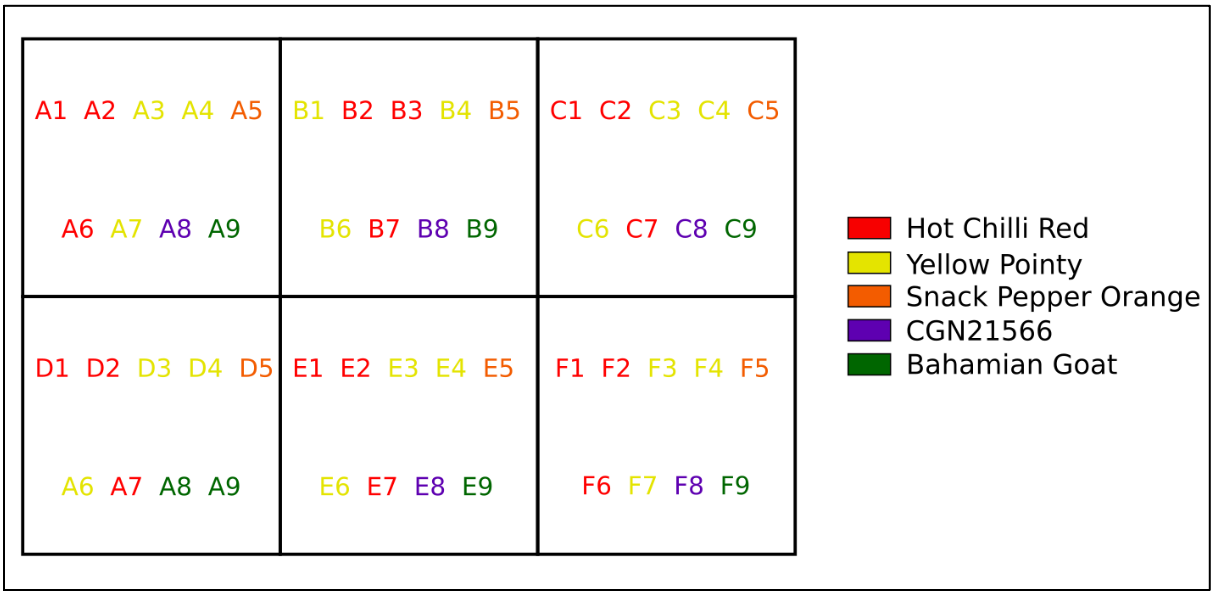


Figure 15 Arrangement of pepper plants per module

The plants were placed on the 10th of May, 2019 in based on the arrangement shown in figure 10. One pepper from each type of plant was taken to be weighed in grams. This was done in order to evaluate the amount of pepper harvested from each module during the end of the experiment. The number of young peppers and ripe peppers were counted in each plant while placing the plants in the cavity. They were recorded and listed. This is tabulated in Appendix C. The weight of one individual young pepper is given in the Table 1 below.

Table 1 Unit weight of different types of pepper

Name of Pepper	Weight (g)
Yellow Pointy	2
Hot Chilli Red	2
CGN21566	0.4
Bahamian Goat	1
Snack Pepper Orange	23

3.3.4 Watering system

As mentioned in the previous chapter, the evapotranspiration of plants can influence the conditions with respect to humidity. Moreover, the rate of evapotranspiration of plants depends on how well they are watered. For example, well-watered crops the evaporation of water from the leaves is high, thus increasing the humidity of the air in the temperature, however high humidity in the cavity can lead to the risk of condensation on the surface of the façade (Stec, et al., 2005). This created an objective to find out how the watering influences the conditions in the cavity for the plants.

The watering system in each module is configured in such a way that it is constant through the three modules on the top floor, regardless of the ventilation, and is variable in the bottom floor. The idea is to have a standard rate of irrigation for the three different modules on the top, and note the behaviour of each module. The irrigation rate will be different for each module in the bottom floor, depending on the humidity level shown in each module. Hence in the case of the top floor, the condition of the plants may be compromised in order to find the humidity conditions in the cavity. Whereas the bottom floor was configured in order to get a clearer idea about the health of plants, regarding factors such as how green the leaves are, how dense the plant grows and how much yield is being produced.

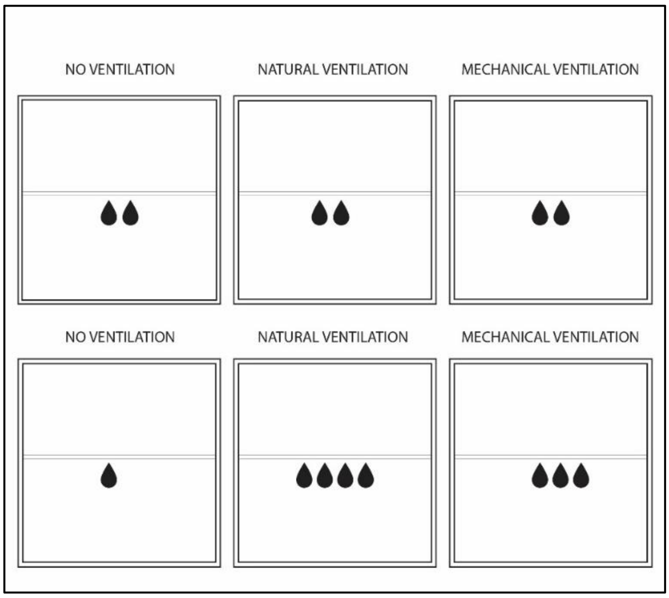


Figure 16 Watering configuration for the six facade modules

The irrigation for each type of module is done with the help of a micro drip irrigation system. A 10 litre tank is added in the top corner of the cavity of each façade and is connected to an irrigation pipe. This pipe contains multiple drippers, which contain valves that can be controlled in order to regulate the amount of water entering the plants. These drippers are distributed across the plants such that each plant contains two drippers. An advantage of this type of system is that the rate of irrigation can be set for each plant, and manual watering and maintenance for each plant is not required. A schematic representation and the implementation of the irrigation system in the cavity is given below in figure 17 a) and b).

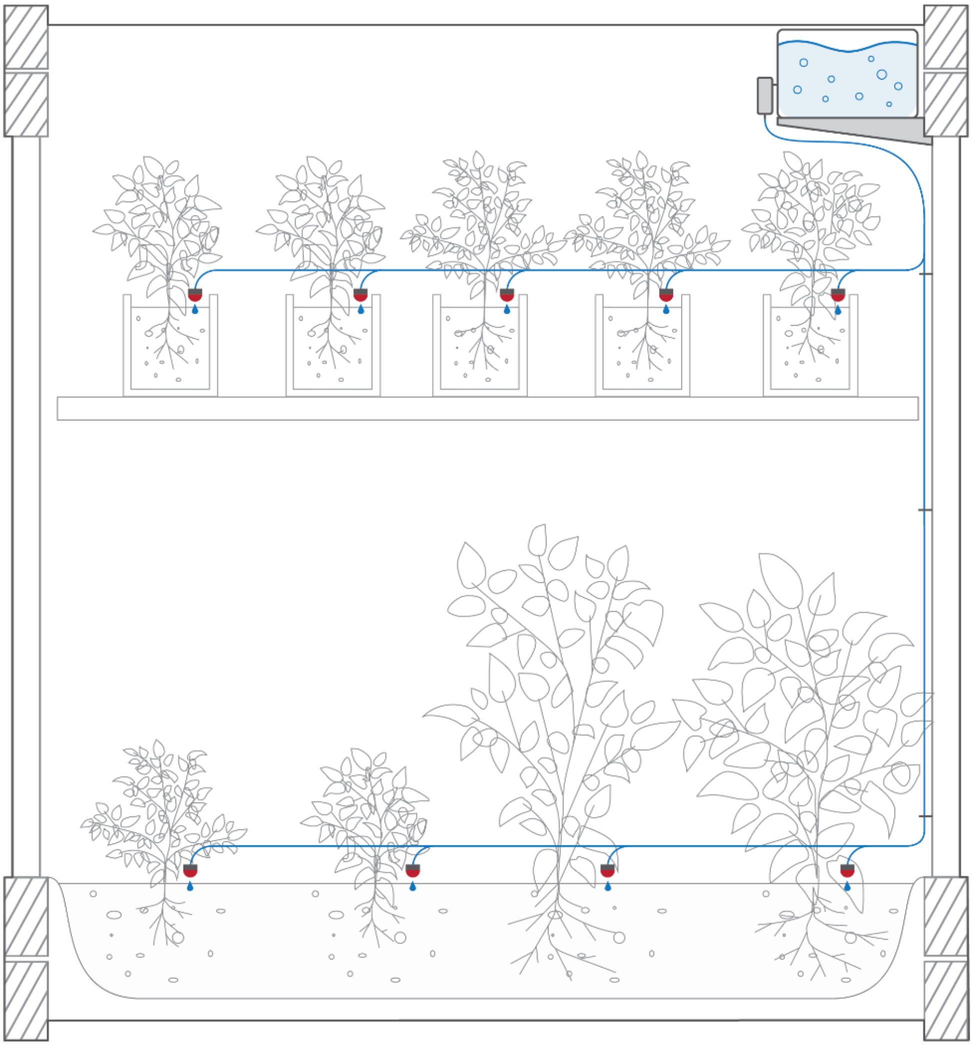


Figure 17 a) Schematic of a micro drip irrigation system in one module

Figure 17 b) Implementation of a micro drip irrigation system in the top row of one module

3.3.5 Shading strategy

The external container doors were used as a means for shading in the façade. Each façade module contains container doors which can be open up to an angle of 90°. The shading strategy through the container doors remains constant for all the modules i.e. they are opened and closed up to the same extent at the same time altogether. This was done to evaluate whether the plants in each module provide extra shading, and if so, which module shall give the highest shading effect. The opening and closing of the container doors were based on the outdoor whether. The shading strategy was planned such that the container doors are open (90° angle) if the outside temperature is below 18°C, to maximise the solar load in the façade. The doors would be partially open (45° angle) when the outside temperature is between 18°C and 24°C, and minimally open (<10° angle) when the outside temperature is above 24°C. A schematic representation of the shading strategy adopted is given below in figure 18.

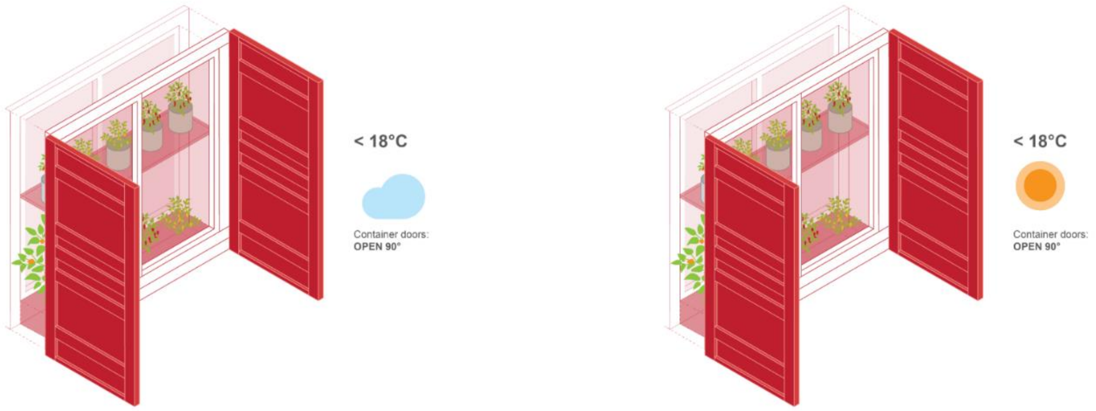


Figure 18 a) Position of container doors for outdoor temperature below 18°C

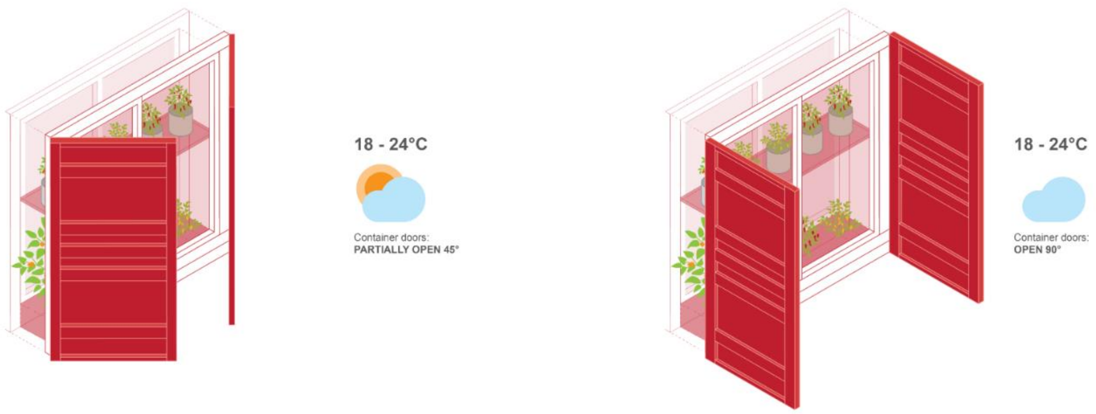


Figure 18 b) Position of container doors for outdoor temperature between 18°C and 24°C

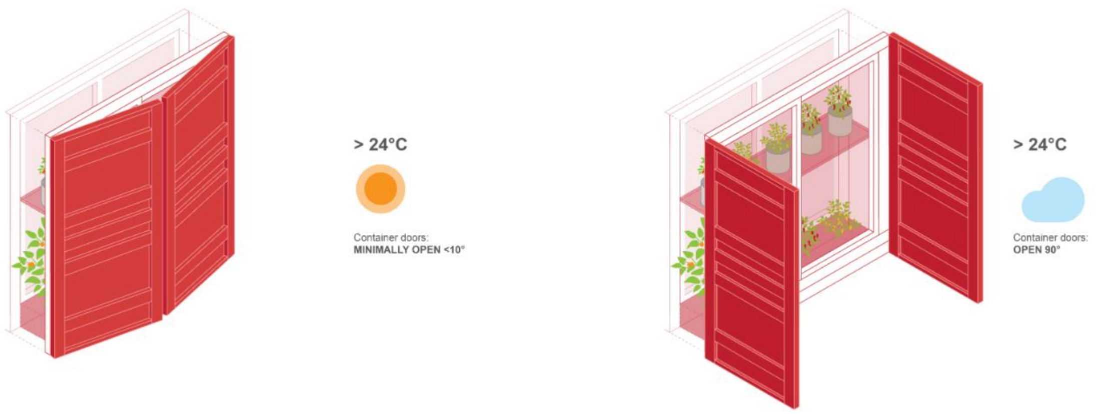


Figure 18 c) Position of container doors for outdoor temperature above 24°C

3.4 CONCLUSION

This chapter contains the steps and strategies involved to carry the experiment forward, based on the literature review performed. The parameters to be evaluated were identified and the configuration of each module was done accordingly. The differences in each module were based on ventilation, to evaluate the performance of the building and the cavity in terms of thermal comfort and air quality. The type of plants, and the watering system were configured such that the performance of plants, with respect to its influence on the cavity in terms of moisture and subsequently its growth could be determined. Moreover, the different densities of the plants would give an idea on how much shading each cavity provides, and subsequently, how it influences the conditions in the office.

For the type of plants, five varieties were chosen based on the colour of the pepper and the size of the plant. Each module accommodated a total number of 9 plants, with 7 short growing plants and 2 tall growing plants. The tall growing plants were placed in the bottom right side of each cavity. Cavity D had two Bahamian Goat plants instead of a CGN21566, due to lack of availability.

The ventilation strategies used were mainly three types, namely minimally ventilated modules (A & D), naturally ventilated modules (B & E) and mechanically ventilated modules (C & F). The idea of ventilation is such that the air is taken in from inside the building, circulated in the cavity and then supplied back into the building. This way, it is possible to find how the air temperature is influenced due to the cavity.

The watering system was decided to be in the form of a drip irrigation system where each plant receives water from two drippers. The irrigation rate was decided to be constant across all the modules in the top floor for all the plants. The irrigation rate was set to be variable in the modules in the bottom floor. This is used as a parameter to check the climatic conditions in the cavities.

The container doors in the double skin façade were used as the shading strategy. The opening and closing of the container doors remained constant for all the modules. This was done in order to ensure that all the modules are exposed to similar outdoor conditions with respect to sunlight. The shading strategy was adopted based on the outdoor temperature and the sky conditions.

CHAPTER 4 – MEASUREMENT METHOD

4.1 OVERVIEW

There are three factors which are to be evaluated in this project, namely thermal comfort in terms of temperature and relative humidity, lighting in terms of illuminance and air quality in terms of CO_2 and Volatile Organic Compounds (VOC). The method chosen to evaluate these parameters was the use of sensors, which were chosen according to the quantities needed to be measured. The idea of using individual sensors and it's connection to a microcontroller (Arduino), in order to get data was adopted as a measurement method.

4.2 SENSORS

4.2.1 Temperature and relative humidity

The sensor adopted to measure temperature and relative humidity is the DHT22 sensor. This is a low cost digital sensor with a wide range of measurement. It's temperature range is -40°C to 80°C, with an accuracy of ±0.5°C (Adafruit Learning System, 2018). It's humidity range is 0% to 100% with an accuracy of ±2 to 5%. (Adafruit Learning System, 2018). It is powered with a voltage of 5V and can be connected to the digital output pin of a microcontroller. In the case of this project, an Arduino microcontroller is used.

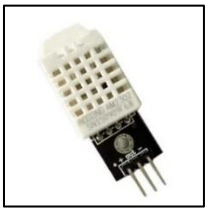


Figure 19 DHT22 Temperature and Relative Humidity sensor

The DHT22 was connected to an Arduino and its initial readings were tested. A code for reading the sensor was uploaded to the Arduino board with the help of Arduino IDE, the official coding software for Arduino based products. The codes uploaded to the microcontroller was based on C++. The program was made such that the temperature and relative humidity is monitored per second as an output from the Arduino IDE. The output of the test is given in the picture below

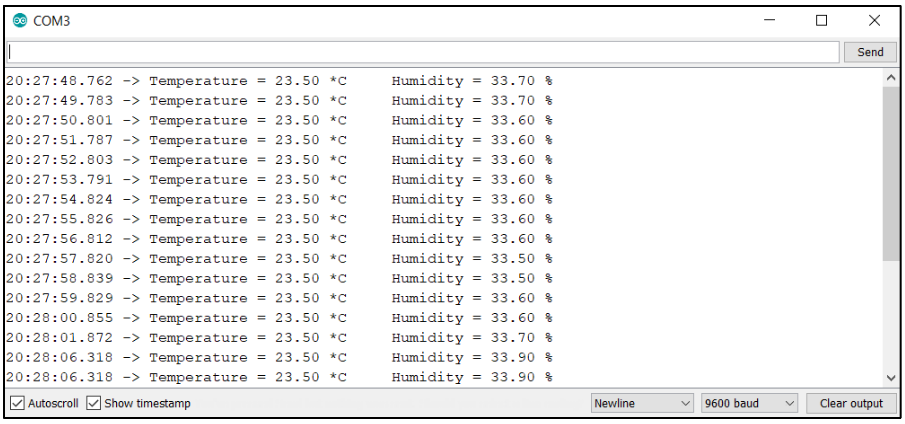


Figure 20 DHT22 sensor output through the Arduino IDE

4.2.2 Illuminance

The purpose of measuring illuminance is mainly to monitor the amount of visible light entering the cavity for the growth of plants that are going to be placed. This is going to be measured with the help of a lux meter, which measures the illuminance of a certain area in lux (lumen/m^2). The sensor used for this is the BH1750. This is an I^2C bus based digital sensor, which gives the illuminance values in lux. It has a measurement range of 1-65535 lux.

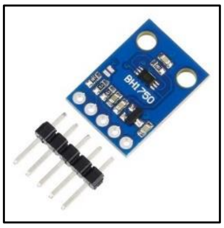


Figure 21 BH1750 Sensor

The BH1750 is also connected to the Arduino board, however it does not connect directly to the digital output pin of the board. It is connected to the Serial Clock (SCL) and Serial Data (SDA) pin of the Arduino. This network is based on an I^2C protocol. An I^2C bus enables a high speed communication between two devices while maintaining a minimum number of input/output pins (Blum, 2013). An I^2C bus is controlled by a master device (usually a microcontroller), and contains one or more slave devices that receive information from the master (Blum, 2013). In this case, the master device is the Arduino and the slave device is the BH1750. A script for the light sensor was written with Arduino IDE and the sensor was tested. The output for one of the tests is given in the figure below

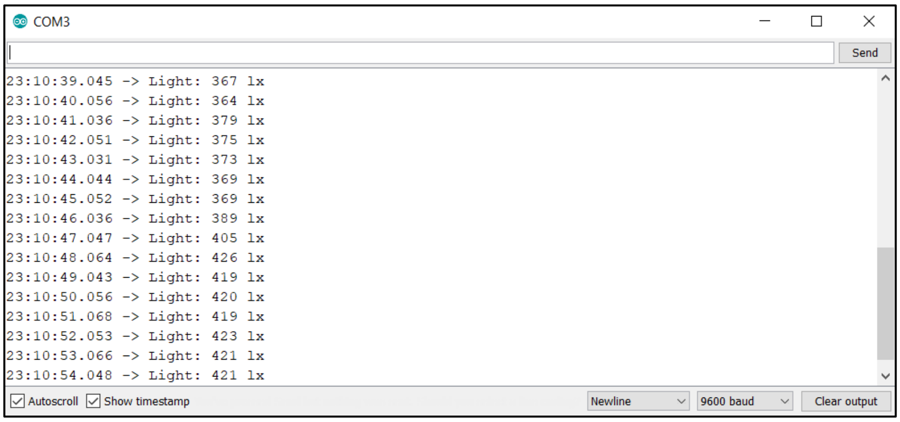


Figure 22 BH1750 output with Arduino IDE

4.2.3 Air quality

The air quality inside the building is to be evaluated by the measurement of two components, namely, the carbon dioxide CO_2 content and the amount of Total Volatile Organic Compounds (TVOC). The sensor to be used for this is the CCS811, which has the capability to read the CO_2 content in the air in parts per million (ppm), as well as the number of TVOC in parts per billion (ppb).

Figure 23 CCS811 Air quality sensor

This sensor works on the I^{2}C protocol, similar to the BH1750 sensor. This sensor was tested and the output was monitored in the Arduino IDE. The CCS811 was hooked to the Arduino board and the output is given below.

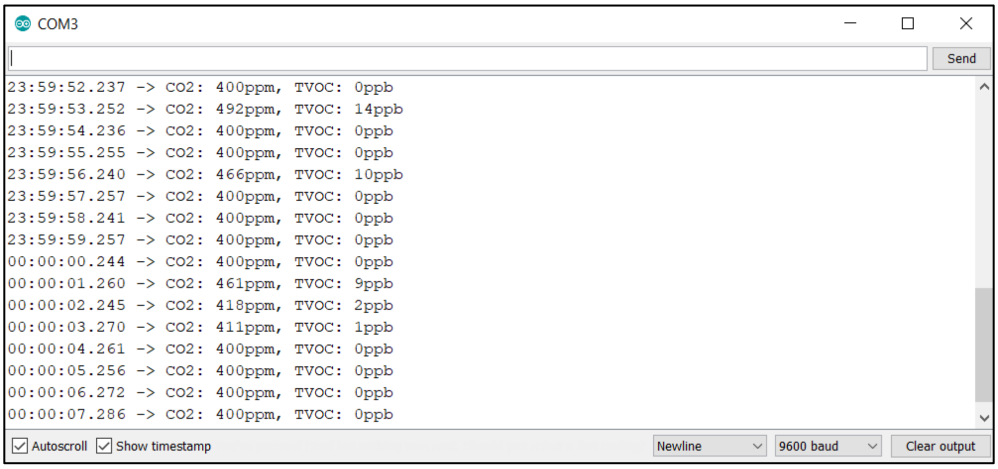


Figure 24 CCS811 output with Arduino IDE

4.3 SENSOR CONFIGURATION

As seen in the previous section, the three sensors were tested and the readings were successfully obtained. However, the next approach done to check whether the different types of sensors can be connected to one microcontroller. Moreover, the output shown before is a monitor which just shows the readings upon the connection between the computer and the microcontroller. The main objective of the measurement set up was to figure out a way to obtain the readings from the individual sensors, and continuously log the data over a period of time. This method would enable the possibility of the long term changing behaviour of the façade with respect to the three parameters of evaluation.

The method adopted to achieve the above is the use of a Data shield, along with a Real Time Clock module on a microcontroller. A data shield is a device which stacked on top of a microcontroller. It has similar input/output pins as the microcontroller and emulates the function of the microcontroller. It comes with an SD card interface, which is connected to the chip select pin of the microcontroller. They designate a chip select (CS) pin, which may or may not be the default CS pin. This pin is 10 on Arduino Uno and 53 on Arduino Mega (Blum, 2013). The Real Time Clock module logs the exact time on the SD card, while the data is being obtained.

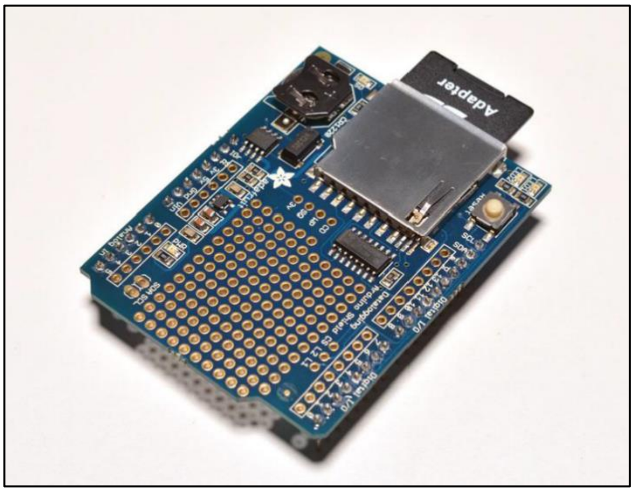


Figure 25 Data Logging shield. *Source:* (Blum, 2013)

A separate code is written when the Arduino is used with the data shield. The code is written such that the readings are obtained from the sensor, and is then logged in the SD card in the form of Comma Separated Value (.csv) files. This file is then exported to an Excel sheet or Google sheets, where the values from each sensor is listed.

This concept is to be adopted for the measurement of the different modules in the floor. For the preliminary measurement, there will be one temperature and relative humidity sensor inside the cavity of the double skin façade for each module, and also in the building, corresponding to each façade module. There will also be three lux meters, one in each cavity to evaluate the amount of sunlight entering the cavity, where the plants will be situated. There will be one air quality sensor inside the building, mainly to measure the amount of CO_2 and VOC in the building.

Hence the sensors in one floor will be configured such that there are 6 temperature and relative humidity sensors, four lux meters and three air quality sensors. There is one temperature and relative humidity sensor placed inside the cavity of each façade module, as well as the zone inside the building behind each module. Since the plants affect the CO_2 and VOC levels, it was important to add three air quality sensors, one in the cavity of each façade module. The light sensors were placed in each zone behind the façade modules, mainly to evaluate the shading provided by the plants. Moreover, there is one light sensor placed in the external glazing to measure the sunlight from outside. All the sensors will be connected to a data shield, which will be stacked on an Arduino Mega. The reason an Arduino Mega is used in this case is because it has more memory and is able to accommodate data from more number of sensors. The sensors are connected to the data shield with the help of jumper wires, with a maximum length of 5 m. The microcontroller will be connected to a power supply throughout the measurement period. A schematic representation of the configuration of sensors is given below

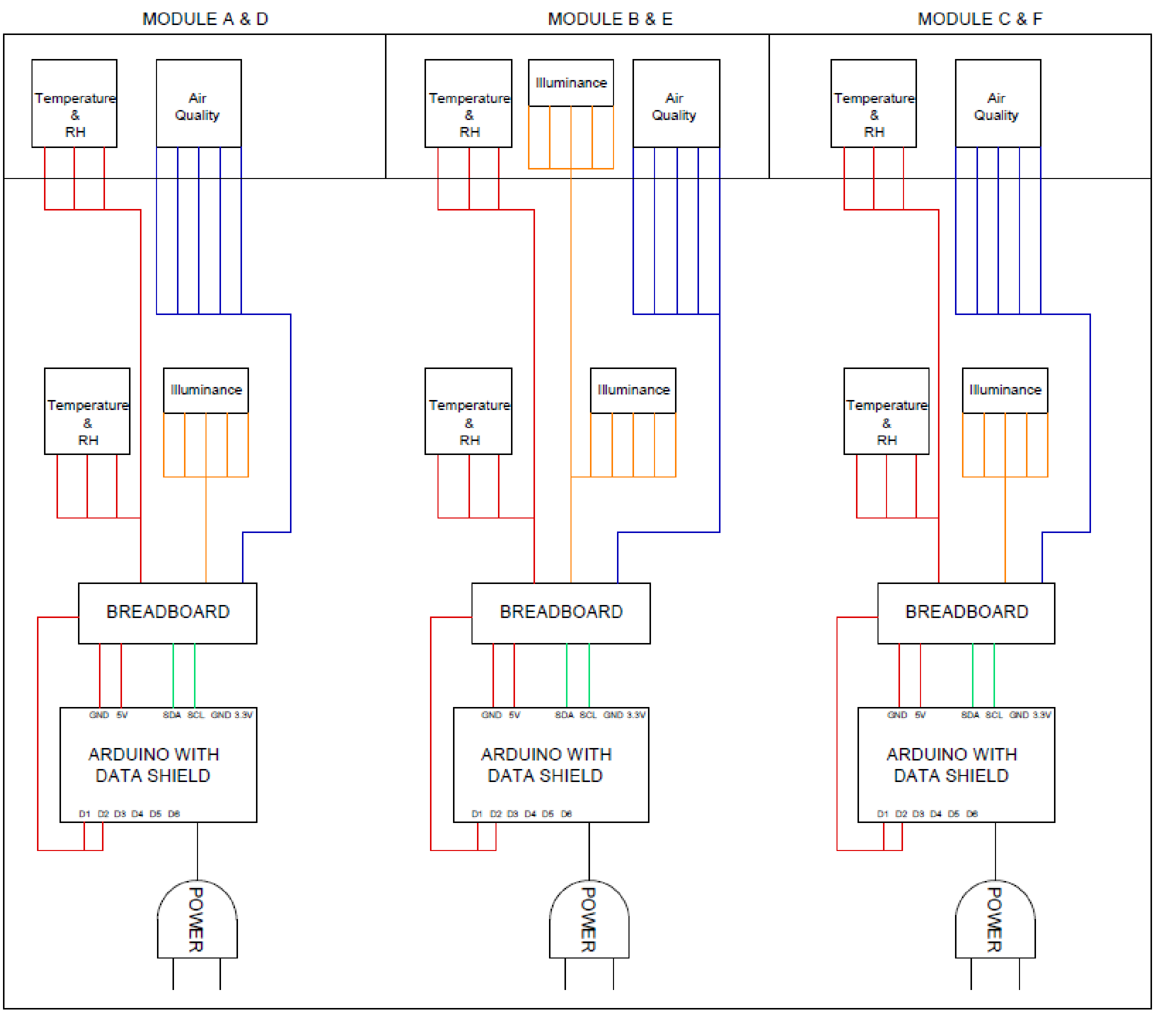


Figure 26 Configuration of sensors in one floor

The sensors in the cavity are attached on the upper half of the height of the cavity. The sensors inside the office are attached such that they are hung from the ceiling of each zone. This was done in such a way that the sensors of each zone are isolated from one another.

These sensors are attached to the Arduino with the help of jumper wires fixed across the side walls of the cavity and the office. The Arduino's in each zone were attached to the inner wall of the façade, corresponding to the façade modules of each zone. This was done to make the configuration as compact as possible. A schematic representation of the placement of temperature & relative humidity and air quality sensors in all modules, along with light sensors in modules B and E is given as an example to show how the sensors have been placed in the building. This is given in figure 27 below

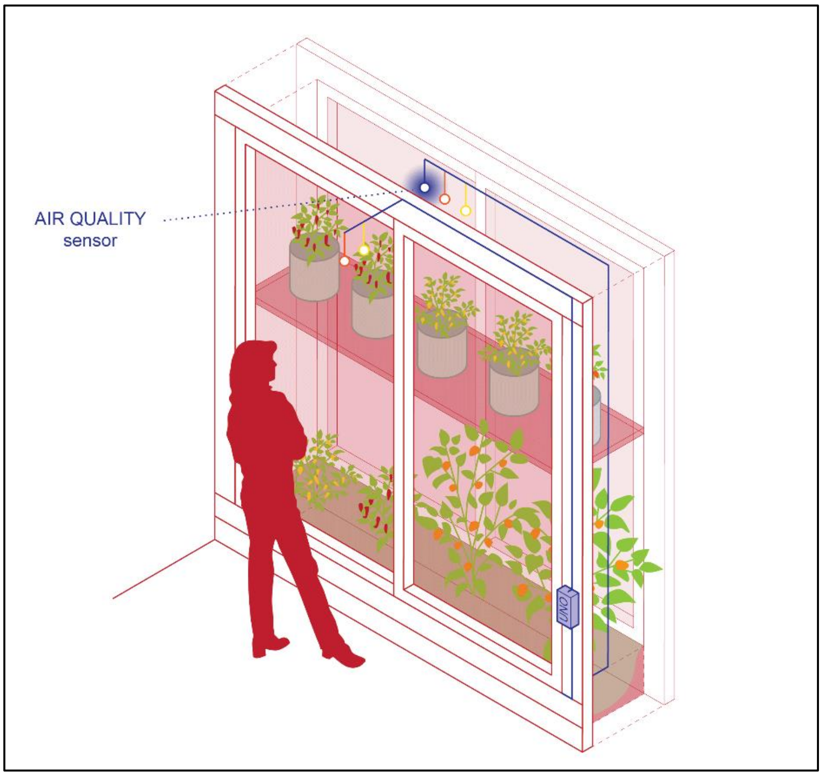


Figure 27 a) Placement of air quality sensors in all modules

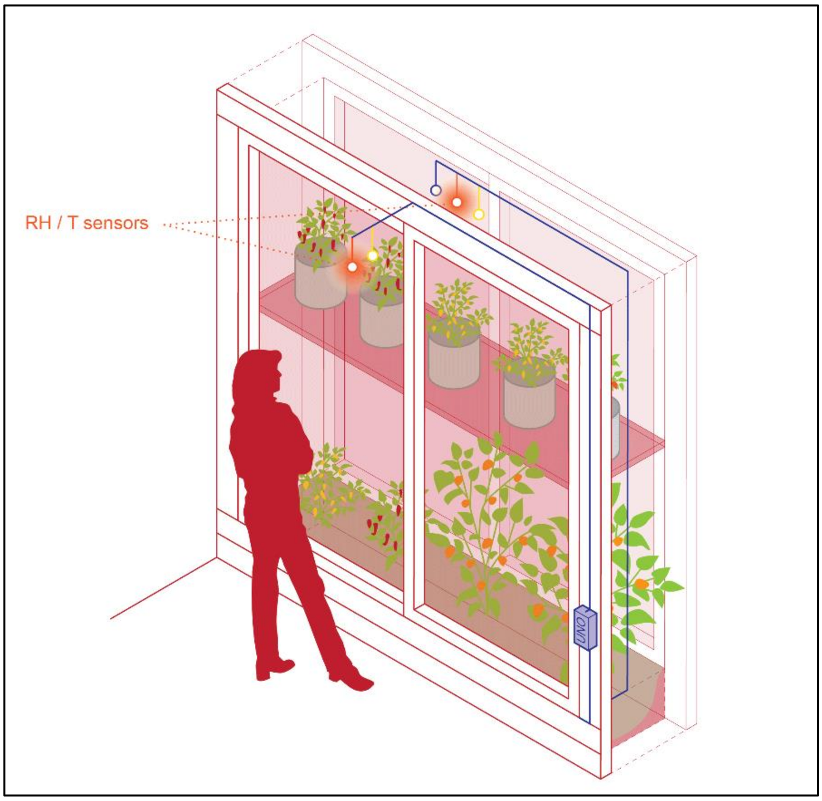


Figure 27 b) Placement of temperature and relative humidity sensors in all modules

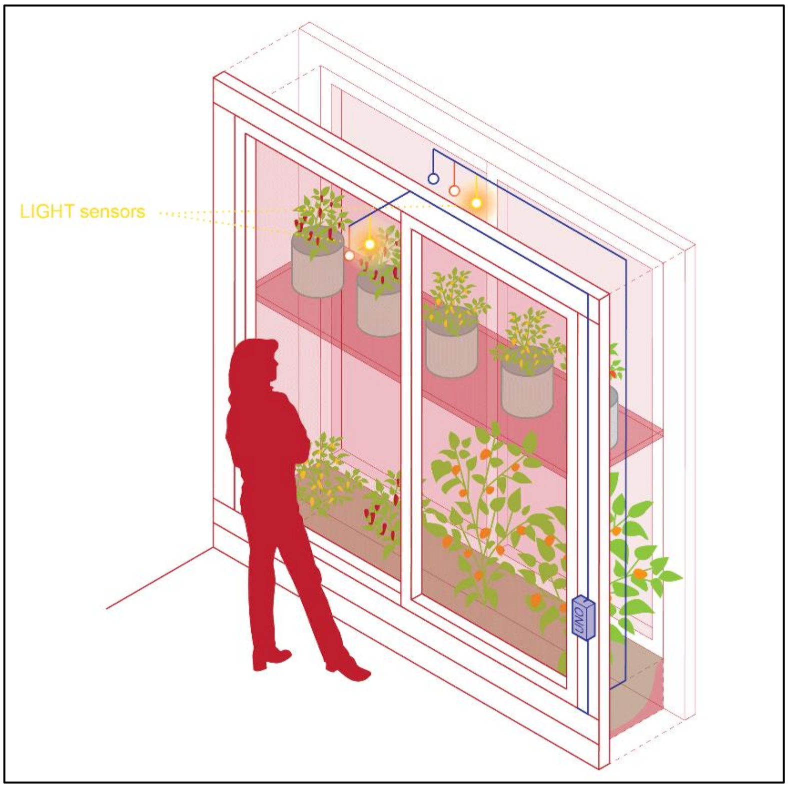


Figure 27 c) Placement of Light sensors in modules B and E

In order to go ahead with the configuration mentioned above, it is necessary to test whether multiple sensors can be connected to one Arduino and if the data from each sensor could be logged simultaneously.

An Arduino Uno and an Arduino Mega was used to connect multiple sensors. With the existing code, it was found that the Arduino Mega could log data from 6 temperature and relative humidity sensors, whereas an Arduino Uno could only log 5 temperature and relative humidity sensors. Two light sensors were also added with the connection.

With the Arduino Mega, so far 6 temperature and relative humidity sensors and two light sensors have been logged successfully over a period of time. This test was however done without the use of a real time clock module. The result was exported to Google Sheets. The output is given below

Table 2 Data logging result of 6 DHT22 sensors and 2 BH1750 sensors

rh1	rh2	rh3	rh4	rh5	rh6	temp_1	temp_2	temp_3	temp_4	temp_5	temp_6	illuminance_1	illuminance_2
39.7	40.7	39.6	39.5	39.2	59	25	25.5	25.9	26.3	26.1	25.2	829	1004
39.3	40.2	39.1	39.3	38.7	37.6	25.1	25.6	26.1	26.6	26.4	24.1	795	991
39.2	40.1	38.8	39	38.3	37.7	25.2	25.8	26.2	26.7	26.6	24.1	786	965
39.1	40	38.7	38.9	38.3	38.7	25.3	25.8	26.3	26.9	26.8	24.1	793	969
39.1	39.9	38.6	38.7	37.9	37.6	25.4	26	26.5	27.1	27	24.2	827	972
39	39.9	38.5	38.6	38	37.7	25.5	26.1	26.6	27.2	27.1	24.2	854	981
39	39.7	38.3	38.4	37.5	37.6	25.5	26.1	26.6	27.2	27.1	24.2	807	974
39	39.7	38.4	38.5	37.8	37.9	25.7	26.2	26.8	27.4	27.4	24.2	865	996

In the above table, rh1 to rh6 represents the relative humidity of the different sensors, temp_1 to temp_6 represents the temperature of the sensors and illuminance_1 and illuminance_2 represents the readings from the lux meter. The values are listed on a minute basis. In the test mentioned above, all the sensors were placed together in the same environment. It was observed that the most of the sensors have similar readings over time, with only deviations of 1 to 2%. However, there were some readings which deviated from accurate readings. Hence it was necessary to check the accuracy of the sensors in a controlled environment. An experiment was done using a climate chamber, where the temperature and humidity sensors were placed and logged. This is explained in detail in the following chapter.

4.4 CONCLUSION

This chapter explains on how the experiment is to be evaluated. This includes on what parameters are to be measured, and what platform is used to evaluate the parameters. The sensors were first tested by their function, and their ability to log data. A strategy was also made to configure the arrangement of sensors, based on the specific parameters needed to be measured in each façade module.

A data logging test was done for six temperature and relative humidity sensors and two light sensors. It was noted that the accuracy of the temperature and the relative humidity readings is a factor to be checked upon. The measures taken for this is explained in the following chapter.

CHAPTER 5 – PRELIMINARY EXPERIMENTS

5.1 OVERVIEW

This chapter contains the practical and experimental approach involved in this project. The temperature and relative humidity sensors were checked for its accuracy with a simple experiment. Moreover, the preliminary set up was made according to the configuration of sensors mentioned in the previous chapter, however, the measurements was restricted only to temperature and relative humidity sensors. The experiment was done over different time periods and the data was logged accordingly. The irrigation system was placed on all the cavities based on the required amount of water for each plant in the cavities.

5.2 ACCURACY CHECK – TEMPERATURE AND RELATIVE HUMIDITY

It was mentioned in the previous chapter that the readings from the initial logging of temperature and relative humidity sensors were deviant. In order to check the accuracy of the sensors, six temperature and relative humidity sensors were connected to an Arduino UNO, along with a data shield. The sensors were placed in a climate chamber, where a constant temperature and relative humidity was set. The experiment was done in the Faculty of Industrial Design Engineering in TU Delft. The temperature in the climate chamber was set to 30°C and the relative humidity was set to 85%. The data was logged for 40 minutes with one reading per minute.

Figure 28 Climate chamber

It was observed that the temperature of five sensors had errors ranging between 0.8 and 1.2°C, however the sixth sensor had an error of almost 2°C. The relative humidity of each sensor was also tested. Three of the sensors showed similar results errors ranging from 0 to 2.5%. The fourth and fifth sensor showed errors of 3%. The sixth sensor deviated quite a bit from the expected value with an error of 9%. The results are graphically represented in Appendix A.

Hence it can be concluded one of the sensors showed inaccurate results. The other sensors showed results as per its expected accuracy. One method to improve the accuracy of the sensors is to calibrate them through coding with the help of the Arduino IDE.

The initial climate chamber test was performed to evaluate the accuracy of each sensor with respect to it's specific value. The performance of six sensors were evaluated as their output was compared to a constant temperature and relative humidity in the climate chamber.

Since the temperature and relative humidity sensors are placed in the façade of the building, they are subject to experience variable temperatures and relative humidity with respect to time. Hence it is important to understand how each sensor reacts to changes in temperature and relative humidity.

As per the configuration of sensors mentioned in Figure 24, a total of 12 temperature and relative humidity sensors are to be placed across both the floors of the buildings. Hence it is important that the performance of each of the sensors are evaluated.

The climate chamber test was performed once again to check the performance of 15 temperature and relative humidity sensors, not only with respect to accuracy, but also with respect to the change in trend of the values, subject to variable temperatures and relative humidity of the climate chamber. This was done by setting a different temperature and relative humidity in the climate chamber at regular intervals.

The test was done in batches of 5 sensors which were connected to an Arduino UNO, with the help of a data logging shield as mentioned in section 4.3. Sensors 1 to 5 were placed in the climate chamber for a period of one hour. The initial temperature and relative humidity were set to 30°C and 80%. It should be noted that the actual temperature and relative humidity in the climate chamber were not as accurate as the set temperature and relative humidity. For example, the relative humidity was set to 80%, however, the actual relative humidity was 76%. The temperature and relative humidity of the climate chamber were varied over an interval of roughly 15 minutes.

This test was performed for the next two batches of five sensors the same way, however it was only performed for a time period of half an hour for each batch, due to time constraints. The interval of change was 12 to 15 minutes, and the actual temperature and relative humidity of the climate chamber were recorded once in three minutes. The results of the sensors are depicted in the figures below.

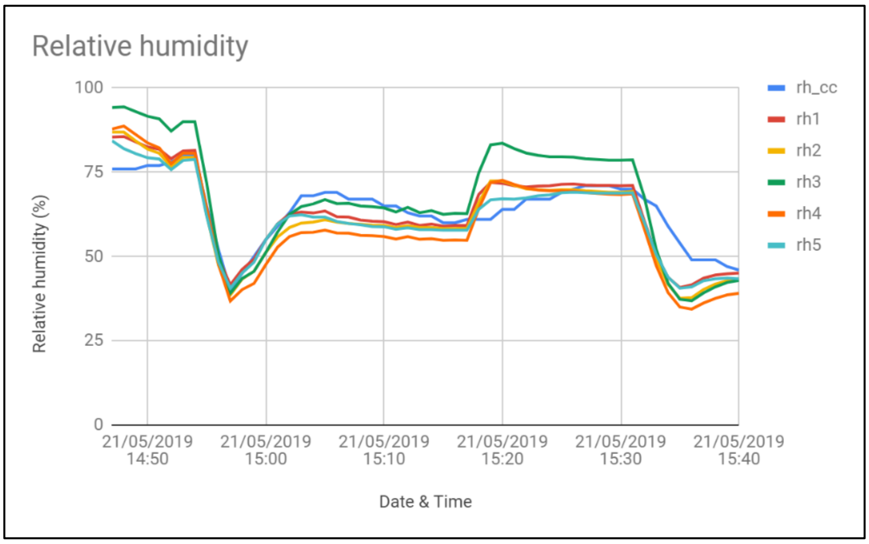


Figure 29 a) Relative Humidity of sensors 1 to 5

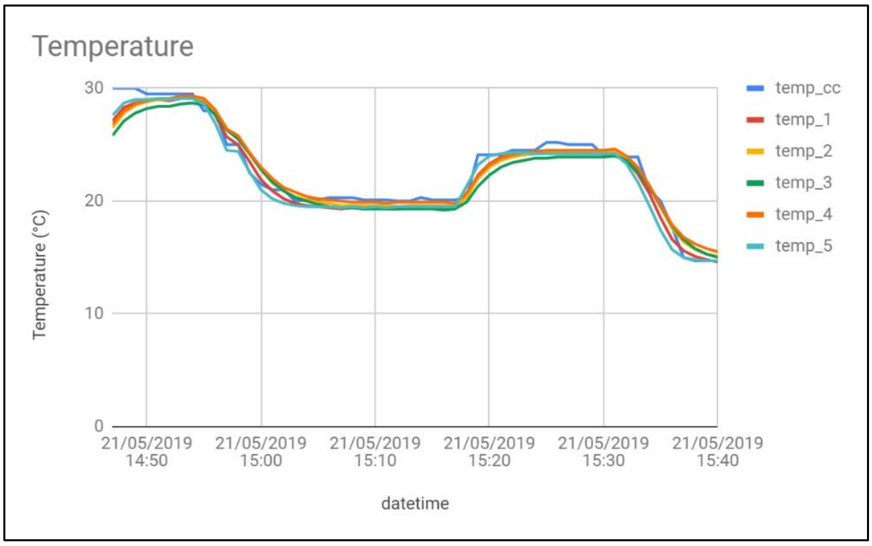


Figure 29 b) Temperature of sensors 1 to 5

Figure 19 a) and b) show the trend of changes in temperature and relative humidity for the first five sensors, along with the conditions of the climate chamber over an interval of one hour. The relative humidity and the temperature of the climate chamber is represented as rh_cc and temp_cc. The variables temp_1 to temp_5 and rh1 to rh5 denote the temperature and relative humidity of the sensors 1 to 5 respectively.

It is observed that both the temperature and relative humidity of all the five sensors follow the same trend of change as compared to the one of the climate chamber. Although the trend of sensor 3 is similar to that of the climate chamber, it's accuracy is less as there are instances where the relative humidity deviates up to 10%. Sensors 1,2,4 and 5 seem to have similar readings with an accuracy range of 2%. In the case of temperature, the values of all the sensors seem to follow that of the climate chamber. The readings of all the sensors are more accurate to each other as well as the climate chamber. Hence, in this case, it can be concluded that sensor 3 is the least accurate of the five sensors. The results of sensors 6 to 10 are given in figure 30 a) and b) below.

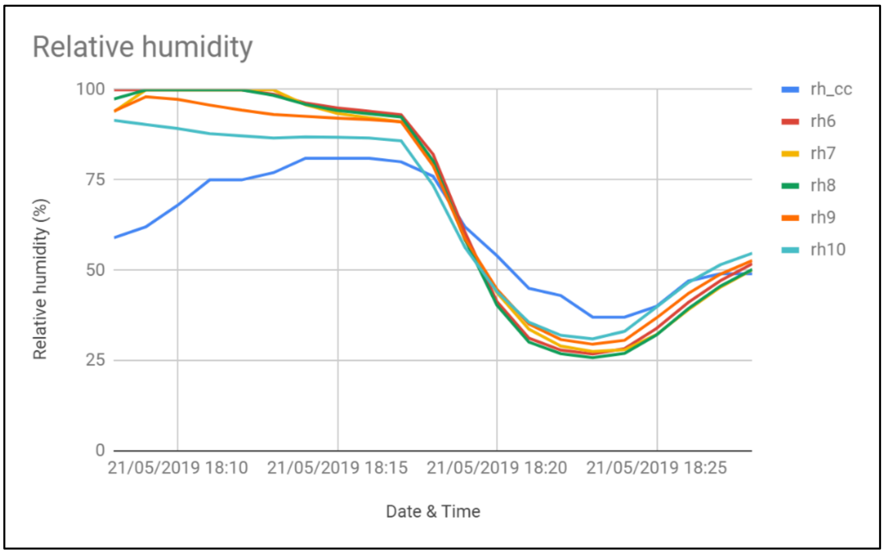


Figure 30 a) Relative humidity of sensors 6 to 10

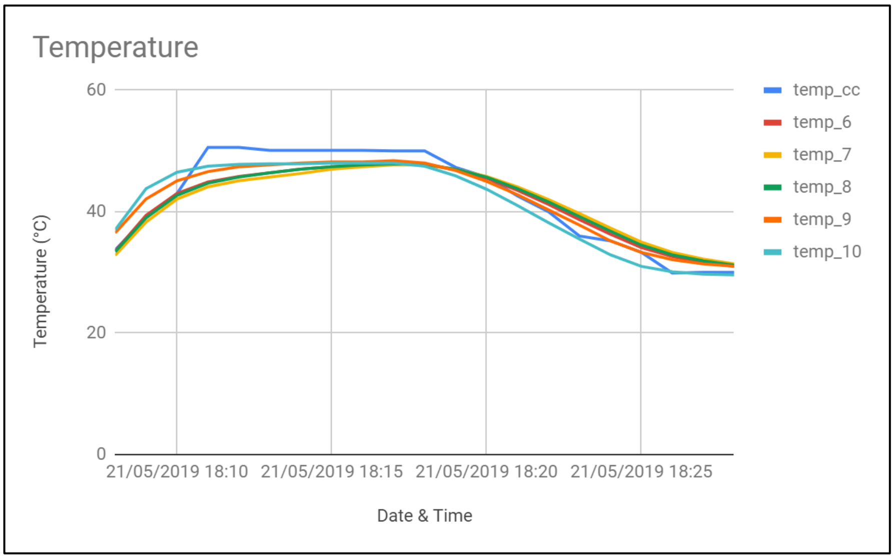


Figure 30 b) Temperature of sensors 6 to 10

The readings from sensors 6 to 10 were less accurate as compared to the first batch (sensors 1 to 5). Although the second batch was only logged for about half an hour, significant changes in the relative humidity of each sensor were observed. The temperature and the relative humidity at the time of logging were 33.7°C and 59% respectively. However, sensors 6 to 8 were at maximum humidity while the humidity of the climate chamber was 59%. It is seen that sensor 10 relatively is more accurate to the condition of the climate chamber. Although the values of the sensors are not accurate to the climate chamber, they are accurate to each other and follow the expected trend of change in temperature and relative humidity. The temperature trend of the five sensors were similar to the trend showed by the climate chamber with sensor 6 and 9 being relatively more accurate. The readings from sensors 11 to 15 are shown below in figure 31 a) and b).

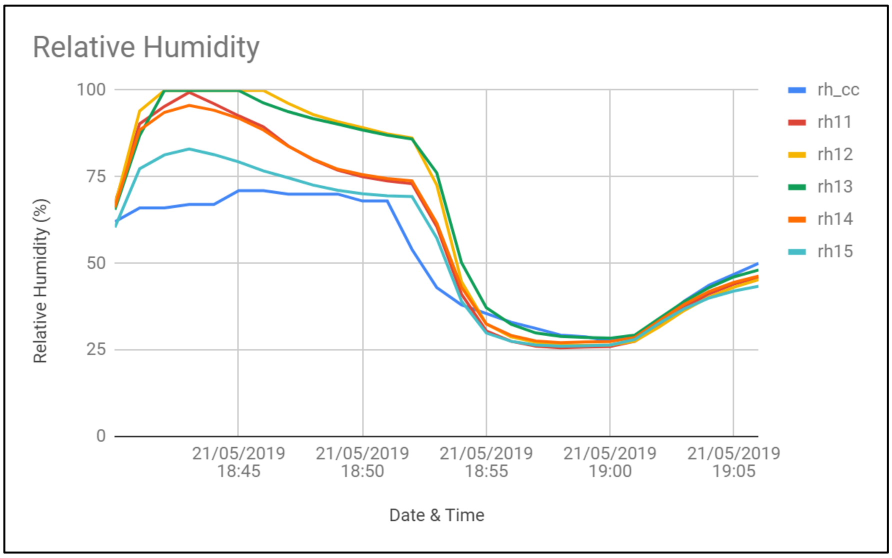


Figure 31 a) Relative humidity of sensors 11 to 15

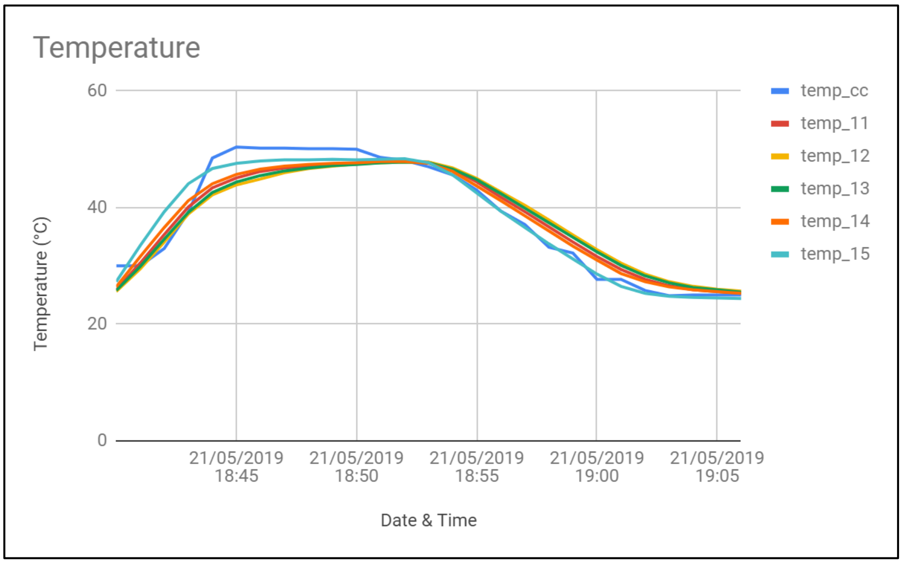


Figure 31 b) Temperature of sensors 11 to 15

The behaviour of the third batch of sensors was similar to that of the second batch. At the time of the logging, the temperature in the climate chamber was 30°C whereas the relative humidity was 60%. However, during the first five minutes of the test, the relative humidity of sensor 11, 12 and 13 were at its peak. The relative humidity of sensor 15 was relatively more accurate to that of the climate chamber, however, there was still a deviation of up to 20%. After the first 10 minutes, the trend of each all the sensors were matching the trend of the climate chamber. The temperatures of all the sensors were observed to be accurate to each other, and follow the change in temperature of the climate chamber over time.

Overall, it can be concluded that batch one seemed to show the most accurate results. The deviation of the relative humidity of sensors 6 to 15 may be due to the fact that needed more time for configuration, as it is observed that the values got more accurate over time. Moreover, it is seen that each sensor has a different response time to the change in temperature and relative humidity of the climate chamber. Although the response time is different for each sensor, they seem to maintain a uniform trend of change in temperature and relative humidity, as compared to that of the climate chamber, when a different temperature and relative humidity is set over a particular period of time. A total of 15 sensors were examined. As the experiment needs a total of 12 sensors, three sensors were omitted. These were sensors 6, 11 and 12, as they relatively seemed to show the least accurate values.

5.3 PRELIMINARY MEASUREMENT

Before the climate chamber test was performed, four temperature and relative humidity sensors were placed in the top floor of the PITLAB based of the configuration of the measurement sensors. This was done such that there is one sensor placed in the cavity of each double skin façade. One more sensor was added in the inside of the building, mainly to check the indoor condition of the building with respect to temperature and relative humidity. The configuration and the setup of the sensors to the Arduino is shown in figure 32 and figure 33 below

Figure 32 Configuration of the sensors

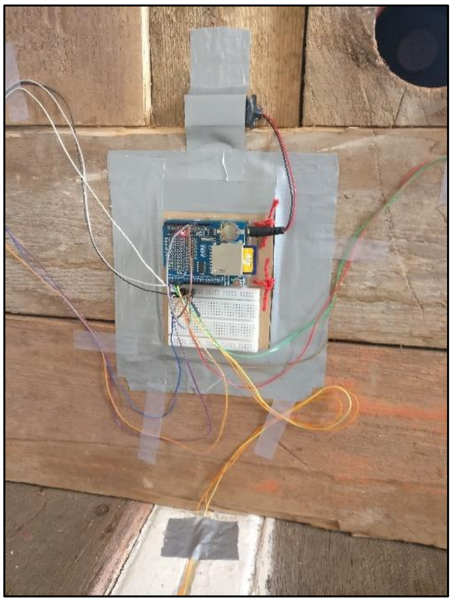


Figure 33 Connection to the Arduino UNO with the data shield

The sensors in each cavity were connected to an Arduino UNO, with the help of jumper wires of 5m length. The Arduino UNO was stacked with a data logging shield. An SD card was attached to the data logging shield so that the readings obtained from the sensors can be logged into it. This set up was attached to a 9V battery for power supply, which enables the data logging. The code was made using Arduino IDE and was uploaded to the microcontroller. The set up was complete on 29th of March in the afternoon. Each façade module was closed, such that there was minimal ventilation in the middle and right module from inside, and the container doors in all the three modules were open to allow maximum sunlight. The right module was mechanically ventilated. The data logging began at 15:48. The readings were taken and the data was logged for around 10 hours, from 15:48 to 30th of March at 02:13. The logged data was then exported to an Excel sheet and the results of the varying temperature and relative humidity is shown below

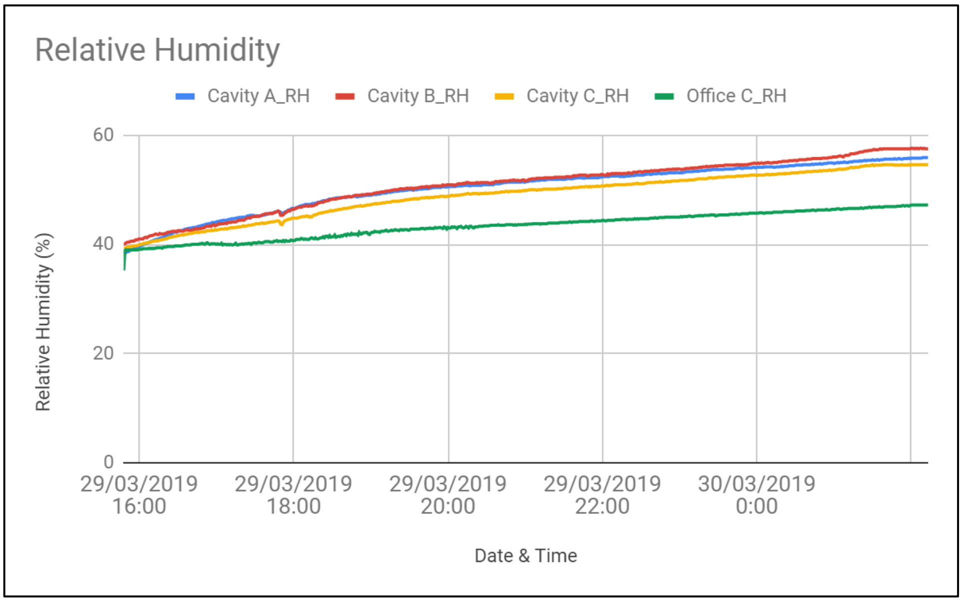


Figure 34 Relative Humidity for the preliminary set up

Figure 25 above shows the variation in the relative humidity for the different modules for a period of 10 hours. In the figure, Cavity A_RH refers to the relative humidity of the left cavity from the inside, Cavity B_RH refers to the middle cavity, Cavity C_RH shows the readings of the right side cavity and Office C_RH represents the relative humidity inside the building. It is seen that there is a constant increase in relative humidity in the three cavities, which range from 40% to 57%. The relative humidity inside the building starts off similar to the cavities, however, the rate of increase is less than that of the cavities. It is observed that the relative humidity inside the building at 2:04 is roughly 10% less than that of the cavities. These readings are a result of the temperatures which are given below

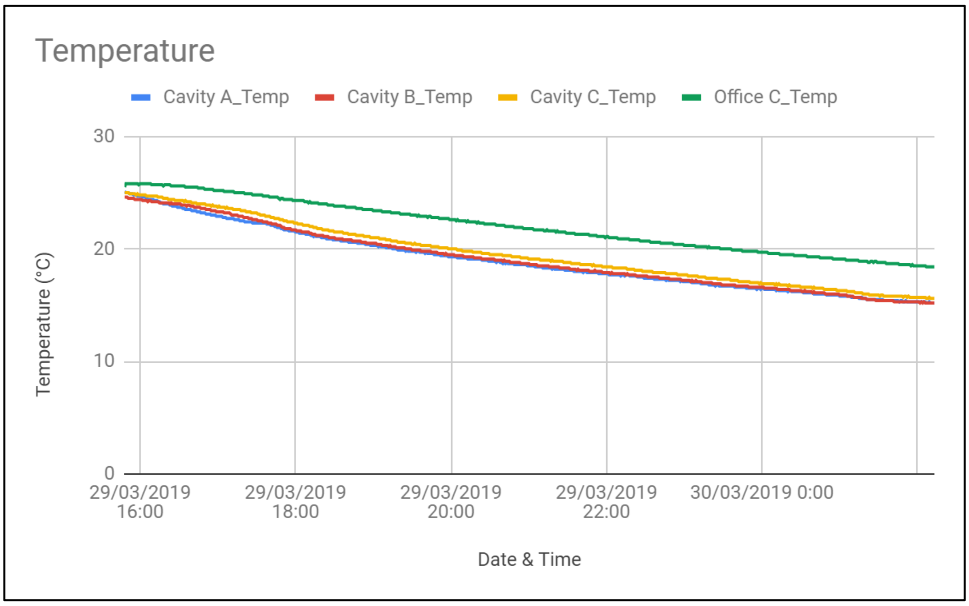


Figure 35 Temperature for the preliminary set up

The temperature decreases at a constant rate. This is the reason for the constant increase in relative humidity. The variables Cavity A_Temp, Cavity B_Temp and Cavity C_Temp represent the temperatures of the cavities from left to right and Office C_Temp is the temperature inside the building. At the beginning, all the temperatures are in the range of 25°C, however over time, the temperature in the cavities were in the range of 15.4 to 15.7°C, whereas the temperature in the building turned out to be 3°C more than the cavities, with a value of 18,4°C. This is due to the insulating properties of the façade, and the fact that it is a double skin with double glazing in both thee floors. The resulting low U-value would lead to a resistance in heat loss from inside the building to the outside.

In the measurements done so far, it was not the air temperature which was being measured, as the temperature of the sensor would have also been affected by the radiant temperature of the glazing. Hence, in order to measure the air temperature, the sensors were placed in a casing, which was wrapped on aluminium foil as it has low emissivity and would thus isolate the sensor from the radiant temperature. Hence, this method was adopted in order to find the air temperature and relative humidity in the cavity as well as in the building.

With this similar configuration of the three modules, data was logged a couple of more times from the sensors, for a longer period of time. The temperature and relative humidity was logged on the 19th of April at 16:30 till 21st of April, 15:30. This was followed by another set of logging from 24th of April at 13:15 till the 26th of April till 13:30.

It was noted that the maximum temperature was logged on the 20th of April, at 12:45, when the temperature in the non-ventilated module reached 51.9°C with a relative humidity of 13%. The outside temperature was 26°C at the time. The temperature in the mechanically ventilated module and inside the building was 24.8°C with a relative humidity of 38%. Hence this shows that ventilating the façade prevents overheating in the cavity of the double skin façade by 50%. The results of the datalogging are represented below.

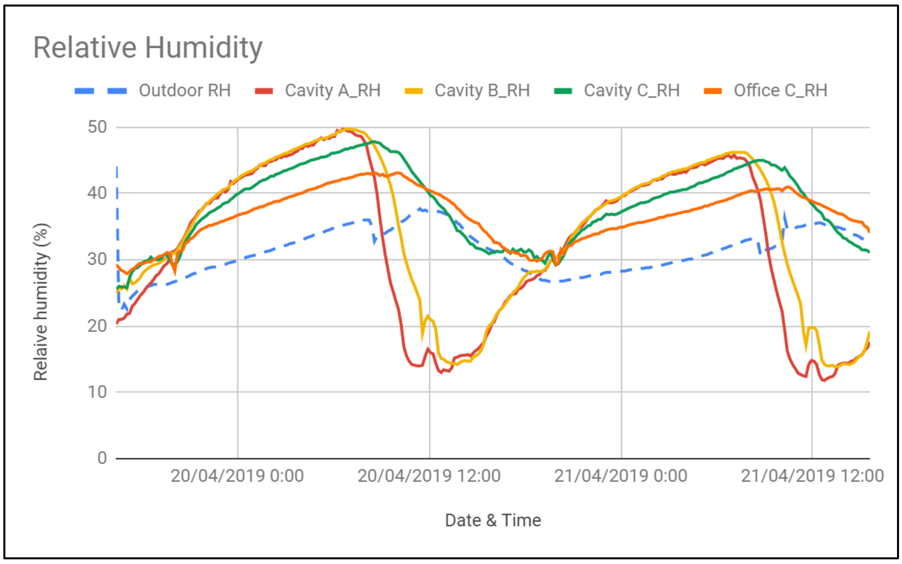


Figure 36 a) Relative Humidity for the preliminary data logging from 19th to 21st of April 2019

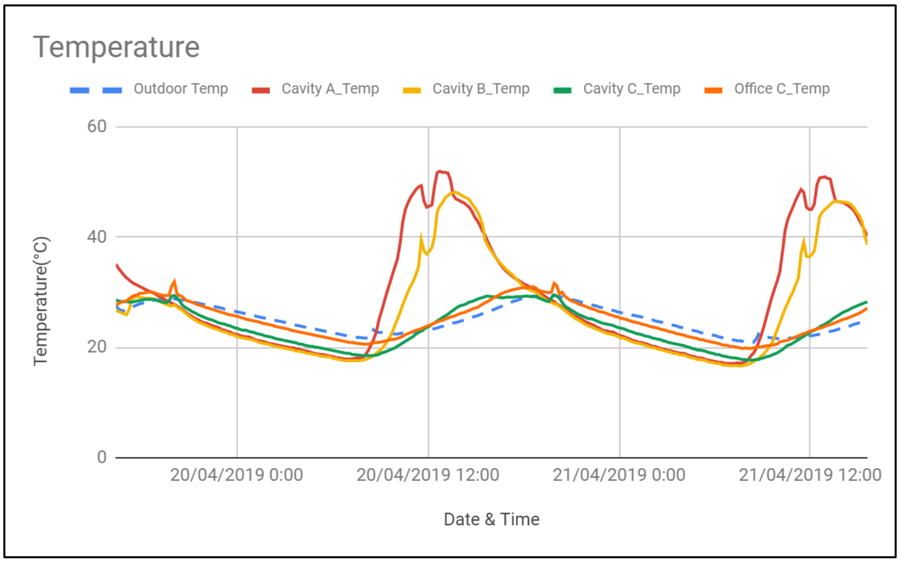


Figure 36 b) Relative Temperature for the preliminary data logging from 19th to 21st of April 2019

5.4 COMPUTATIONAL ANALYSIS

Based on the current configuration of each façade module, the sides of the façade module would create the temperatures to rise in the cavity during days with high solar irradiance. This is due to the high absorption of the black coloured sides. This in return would emit radiative heat to the other components in the cavity. The planks are made with aluminium, which has a low emissivity, but has a relatively high thermal conductivity. Hence it is important that the measuring sensors do not come to contact with the planks. It is also important that the view factor between the sensors and the plants should be minimal, if not zero.

It is also challenging to distinguish between radiative temperature and the air temperature. From the setup of the façade, the emissivity of the surrounding elements in the façade can radiate temperature to the sensor. This would make it difficult to understand whether the observed temperature is the air temperature or the radiative temperature. Hence it is important to make a set up for the temperature sensor such that it is not affected by the radiative temperature of the surrounding elements in the façade. This was ensured by the placement of a casing around the sensors, wrapped with aluminium foil, in order to get the specific air temperature and relative humidity

To test the performance of the measurement method, the measurements taken on the 19th of April 2019 were compared to a computational model. A basic model was made through DesignBuilder. The model contains the cavities of the three different modules, and its corresponding indoor zones in one floor.

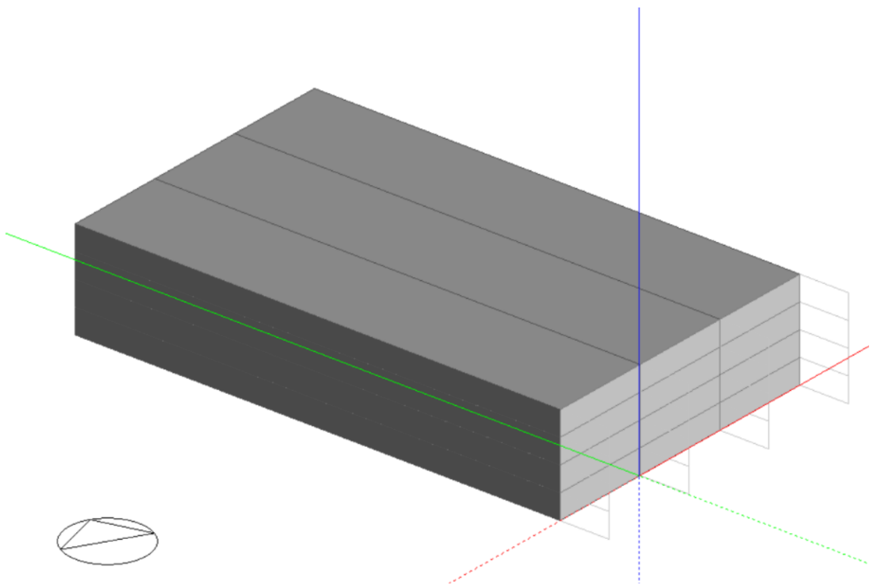


Figure 37 Basic DesignBuilder model for one floor

The model was made as multiple blocks based on zones and height. The cavities were made as four different blocks stacked on top of each other, with a height of 0.5 m, totally making the height of the cavity as 2 m. The corresponding zones were also modelled the same way. The mechanically ventilated cavity was modelled such that the zone receives a constant ventilation rate of 50 m^3/h. The container doors were modelled as partial shading, which is placed perpendicular to the façade as shown in the figure below.

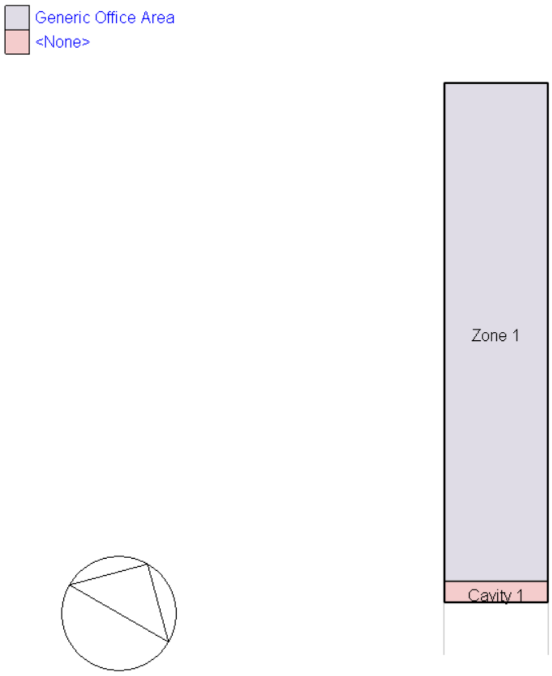


Figure 38 Zone division of cavity and indoor space in one module

The model was made such that it is south east facing as shown in figure 38. Each zone in the cavity was modelled such that the sides of the cavity in one module is adiabatic .i.e. there is no heat exchange from one module to the other. This was done to ensure clear values for each module during simulation.

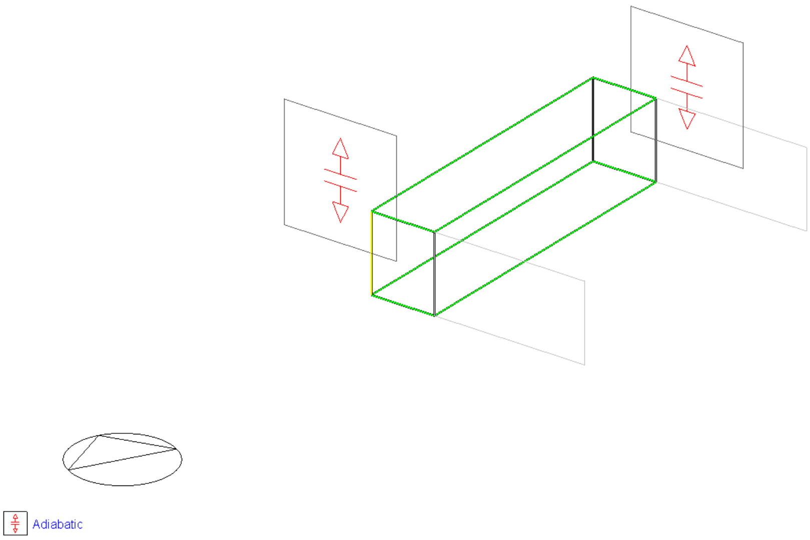


Figure 39 A zone representing the cavity of the middle facade module

The figure above shows the zone in the cavity from 1 m to 1.5 m in height. This was the region chosen for simulation as the sensors were planned to be placed at a height in between that range. The simulation was done for a period of 2 days, from 19th of April to 21st of April, corresponding to the period of measurement. The simulation was performed and based on the results, the specific air temperatures from the measurements in cavity A and C were compared to those obtained in the model. This is represented in figure 40 below

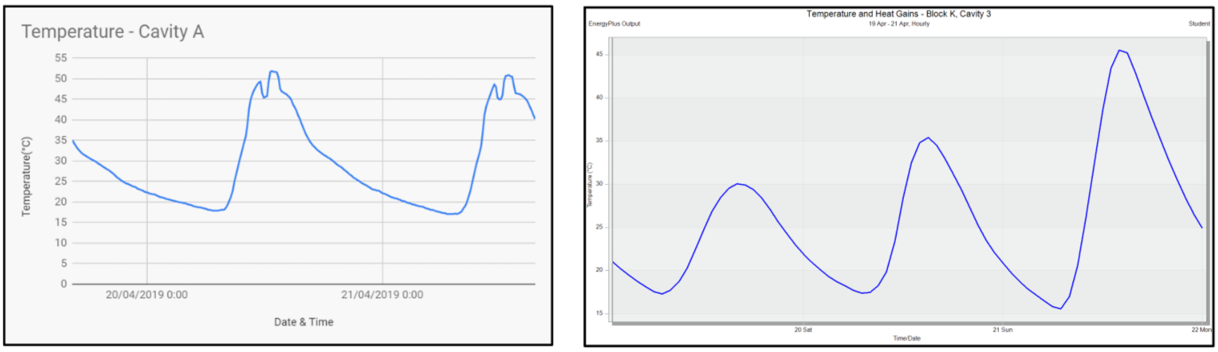


Figure 40 a) Comparison of air temperature obtained from measurements (left) to that of the computational model (right) in Cavity A

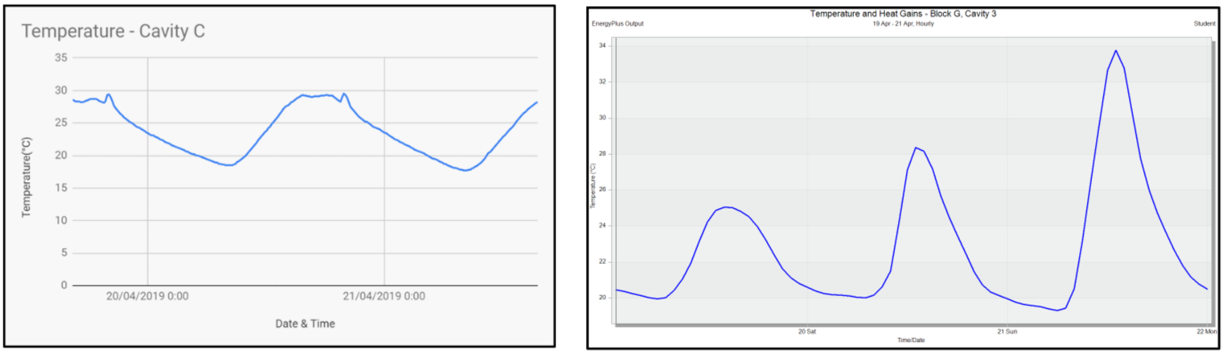


Figure 40 b) Comparison of air temperature obtained from measurements (left) to that of the computational model (right) in Cavity C

It is seen that the temperature trend in obtained from the measurements is similar to that of the computational model. The obtained temperature in the afternoon at 12:00 on the 20th and 21st of April is 10 to 15°C higher than that of the computational model in cavity A. However, in cavity C the temperature on the 20th at 12:00 is similar to the predicted value shown in the model. It should be noted that the simulation was done based on a standard hourly weather data, whereas the measurements were done real-time, pertaining to the actual climatic conditions of that region. This may be the reason for the differences shown in the temperature.

5.5 IRRIGATION SYSTEM

As discussed in section 3.3, the plants in each module are watered with the help of a drip irrigation system. However, in order to install the irrigation system in each module, it was necessary to have an understanding of the amount of water needed by each plant for the maintenance of its growth. The required weekly consumption was taken into account for each plant in litres. This was converted into an irrigation rate in drops per second. This is elaborated in the following section.

5.4.1 Required irrigation rate

On the 11th of March 2019, an interview was conducted in the PITLAB where (Gardner, 2019), the provider of the pepper pants for the façade, suggested that the Bahamian goat and the CGN21566 requires up to 3 litres of water per week whereas each of the smaller plants requires up to 1 litre of water per week. The plants were placed on the 10th of May, 2019. During the initial phase, the plants were manually watered such that each the small plants receive 0.5 ml of water per 2 to 3 days, whereas the Bahamian Goat and the CGN21566 receive 1.5 litres of water per 2 to 3 days.

Based on the idea of equal watering rate on the top floor and different watering rates in the bottom floor, cavities A,B,C and E were set to have the same watering rate. Cavity D was set to have a higher irrigation rate whereas cavity F was set to have a lower irrigation rate. The irrigation rate for each plant in cavity A,B,C and E was calculated based in the required amount of water per week. The calculated irrigation rate for modules A,B,C and E are given in table 3 below.

Table 3 Required drip irrigation rate for the top floor and module E

Type of Plant	Water Requirement per week (l)	Water Requirement per second (µl)	Volume of one drop (µl)	Drop interval (s)
Snack Pepper Orange	1	1,65	50	30
Yellow Pointy	1	1,65	50	30
Hot Chilli Red	1	1,65	50	30
CGN21566	3	4,96	50	10
Bahamian Goat	3	4,96	50	10

As the required irrigation rate was determined, it was essential to make sure whether the irrigation system can be installed such that the irrigation rate given by each dripper matches the watering requirements of the plants.

5.4.2 Drip Irrigation Experiment

Once the watering system was set up in each module, a test was done to figure the frequency of irrigation from each dripper for the plants. The test involved the placement of 800 ml bottles instead of the plants in the cavity, where two drippers each were installed such that the bottles can be filled.

The test was carried out for one hour, mainly to check how much water is given by each dripper from the watering system of the six modules. The amount of water given from the drippers were recorded and compared to each other. The amount of water given by the watering system from cavity A is given below

Figure 41 a) Amount of water in samples A1 to A5 in one hour

Figure 41 b) Amount of water in samples A6 to A9 in one hour

In figure 41 a) and b), the label in each of the bottles represents the number assigned for the drippers associated with each plant in the cavity. In the figure above, it can be observed that A1 to A5 have a similar amount of water accumulated in one hour, whereas A6 to A9 have quite a lot of differences. For example, A6 has less water accumulated whereas A7 is completely full. This may be due to faults in installation of the drippers. This similar test was done for cavities B,C,D,E and F. The amount of water from the watering system was quantified, and is represented in table 4 below

Table 4 Quantified amount of water entering each plant in one hour

Plant No.	Amount of water (ml)					
	A	B	C	D	E	F
1	100	110	10	10	250	240
2	80	80	110	120	40	20
3	80	40	90	20	20	100
4	50	150	80	30	50	100
5	10	90	160	50	610	20
6	30	310	540	130	250	800
7	800	350	800	10	120	10
8	590	620	330	10	100	20
9	120	800	620	120	100	10

It is observed that the distribution of water for each plant is irregular to a certain extent. For example, in cavity A, the amount of water being supplied to A5 in one hour is 10 ml whereas in A7, it is 800 ml. This indicates a massive difference in the irrigation rate on the two plants respectively. This difference is due to the irregular rate of dripping for each plant set by the dripper. Some were not adjusted according to the desired irrigation rate. Furthermore, the samples which showed a higher collection of water had a set of faulty drippers, which were unable to regulate the irrigation rate.

To overcome this irregularity, the required irrigation rate for each plant was calculated based on the amount of water required by the plants, and the surface area of the soil, where the plant is placed. After obtaining the required rate of irrigation for each plant in the six modules, the drippers were regulated accordingly. Moreover, the faulty drippers were replaced. The irrigation test was carried out in bottles once again to check if the rate of dripping for the modules have been regulated. The amount of water collected in cavity A after the second test is given below.

Figure 42 a) Amount of water in samples A1 to A5 in one hour after regulation

Figure 42 b) Amount of water in sample A6 to A9 in one hour after regulation

After regulating the rate of irrigation, it is observed in figure 42 a) and b) that the differences in the amount of water in each bottle is considerably less than the initial test. The quantified amount of water entering each bottle after regulation is given in table 5 below.

Table 5 Quantified amount of water in each plant in one hour after regulation

	Amount of water (ml)					
Plant No.	A	B	C	D	E	F
1	10	60	10	30	30	10
2	20	30	30	20	20	20
3	80	20	10	20	10	10
4	10	50	30	20	20	30
5	10	40	40	40	10	10
6	30	20	10	40	40	10
7	10	30	10	20	30	10
8	50	110	30	50	100	40
9	40	80	100	100	90	40

From the table above, it can be seen that the frequency of irrigation for each plant was regulated, and the differences in the amount of water entering each plant in one hour is less than the values shown in table 4. A graphical representation of the comparison of the two tests is shown in below in Figure 43.

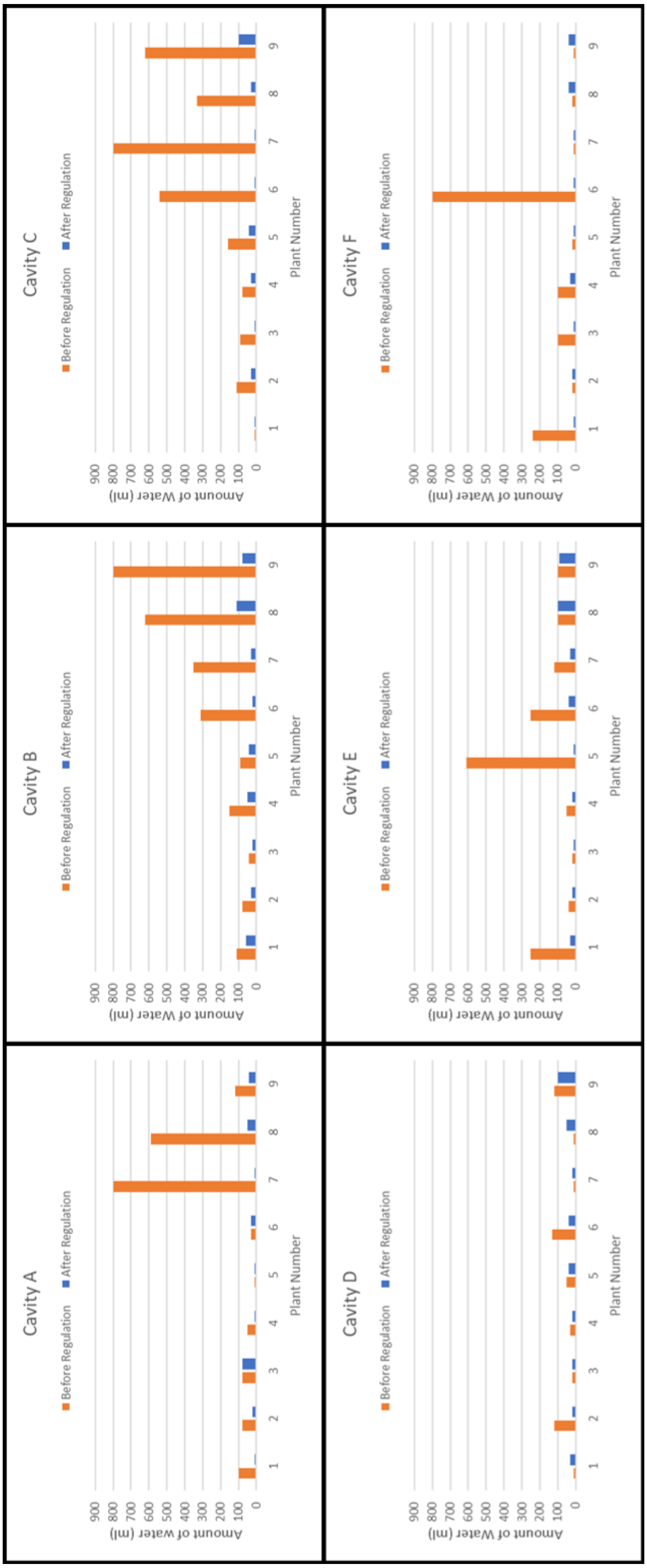


Figure 43 Comparison between the unregulated and regulated values in each plant

Although the irrigation system was regulated, the drippers were calibrated further it was observed that the lowest irrigation rate which could be set by the system was one drop in 15 seconds. This rate is higher than the required rate for the smaller plants. Hence, based on the performance of the watering system, a new set of irrigation frequency was developed. This is mentioned below in table 6.

Table 6 Irrigation rates for different plants in each cavity

Cavity	Type of Plant	Drop interval (s)
A,B,C,E	Snack Pepper Orange	12
	Yellow Pointy	12
	Hot Chilli Red	12
	CGN21566	5
	Bahamian Goat	5
D	Snack Pepper Orange	11
	Yellow Pointy	11
	Hot Chilli Red	11
	CGN21566	4
	Bahamian Goat	4
F	Snack Pepper Orange	13
	Yellow Pointy	13
	Hot Chilli Red	13
	CGN21566	6
	Bahamian Goat	6

5.4.3 Conclusion

Due to the performance of the installation of the drip irrigation system, the rate set for the plants were higher than the required amount of water for the plants. Moreover, the accuracy of the rate can be improved for each plant. Hence it can be concluded that the current drip irrigation method is not the most accurate method of watering the plants. It must be improved in terms of consistency and accuracy with respect to the required amount of water for the plants.

5.6 CONCLUSION

The preliminary measurements were performed over different time periods, to check the functioning of the measurement tools and the behaviour of the double skin façade without the adoption of the planned strategies. The plants have been placed according to the configuration explained in chapter three. The temperature and relative humidity sensors were checked for their accuracy. The initial climate chamber was performed to evaluate the performance of each sensor with respect to its absolute value. The second test was done with a three batches of five sensors each, to check the trend shown by the sensors over change in the climatic conditions of the climate chamber. Based on the results, all the sensors except sensor 6, 11 and 12 were considered for the experiment as they were relatively more accurate.

The values obtained from the preliminary measurements were also compared to a computational model made in DesignBuilder. The measurements taken from the 19th of April to the 21st of April was compared to a simulation made for the same interval. The comparison was made for the minimally ventilated module (Cavity A) and the mechanically ventilated module (Cavity C). From the comparison, it was observed that the temperature in cavity A obtained through measurements were 10°C to 15°C less than that obtained through simulation during 20th and 21st noon. For cavity C, the temperature obtained through measurement was similar to that obtained through simulation on 20th noon, with a value ranging between 28°C to 30°C.

Several factors should be taken into account as far as the simulation model is concerned. First of all, the simulation was based on a standard weather data file for the location of Schiphol, Amsterdam through energy Plus. The data obtained from the file may vary from the actual climatic conditions during the preliminary measurement. This difference influences the difference in temperature as observed in figure 40 a).

Moreover, a constant ventilation rate was set for the simulation of the performance in cavity C, with a standard value of 50 m^3/h. This case is different from the actual scenario, where the mechanical ventilation is activated only when the cavity temperature reaches a value of 24°C. This is a factor that influences the differences in values shown in figure 40 b).

The watering system was installed in each cavity in the form of a drip irrigation system. An estimation was made on the required amount of water for each plant. This was converted into an irrigation rate. The dripping system was calibrated such that it comes closest to the required amount of water for the plants. In order to do this, the irrigation rate from each dripper was checked and adjusted accordingly. The next chapter involves the experimental analysis on the performance of the modules.

The irrigation strategy was adopted such that the short plants and tall plants in cavity A,B,C and E receive drops at intervals of 12 seconds and 5 seconds respectively. Cavity D receives drops with intervals of 11 and 4 drops per second for the short and tall growing plants respectively. Cavity F receives drops with intervals of 13 and 6 drops per second for the short and tall growing plants respectively. Although the irrigation rate was set at particular values, the calibration experiments showed that the accuracy of the drippers in the watering system is not completely reliable.

CHAPTER 6 -EXPERIMENTAL ANALYSIS

6.1 OVERVIEW

The sensors for each cavity were set up and placed as per the configuration for the experiment. Moreover, the plants were placed as per the configuration assigned to each module and the design strategies were adopted to the modules as per their definition. The data was logged for a span of three days, based on the irrigation capacity of the water tank installed in each module. The data was logged bi-weekly such that the data for each module was collected for a span of 2 to 3 days. Based on the data logged per cycle, the performance of the modules were evaluated with respect to the climatic conditions during the cycle of logging. The shading strategy adopted with respect to container doors were the same for all the modules. A temperature and relative humidity sensor was kept outside the building throughout the period of the experiment, to have the outdoor climatic conditions as a reference. The hourly weather data from Schiphol from (KNMI, 2019) was used as a reference for the expected amount of solar radiation entering the building. The correlation between the illuminance and the solar radiation was made with the following set of equations, obtained from (Treado & Kusuda, 1981).

$$E_t = 105 I_t \text{ - Clear Sky}$$

$$E_t = 119 I_t \text{ - Cloudy Sky}$$

Where,

E_t = Total illuminance in lumen/m^2 (lux)

I_t = Total solar irradiation in W/m^2

The expected illuminance based on the weather data was estimated in order to compare the values from the sensors. The logging from two cycles in a week were combined and the performance was evaluated per week. Each of the modules were identified and based on the position and the design strategy used.

Since the measurement of temperature and relative humidity is done in the case of the air in the cavity, it was important to make sure that the air temperature is measured and not the operative temperature. It was important that the radiative temperature in the cavity does not affect the measurement value. Hence each sensor was wrapped in a cylindrical casing, coated with aluminium foil on the outside, such that the radiative temperature of the glass does not affect the measurement value. This is shown below in Figure 44

Figure 44 Placement of an aluminium casing around the sensor

6.2 FIRST WEEK

The experiment began on the 20th of June at 18:50, when the data from the sensors started logging for the six modules. This data was logged till the 24th of June at 11:10. The sensors were programmed such that they log the readings once in 10 minutes. All the side windows were closed during the beginning of the data logging. The container doors for all the modules were almost completely closed during the start of the experiment. The data was stopped from logging on the 24th of June at 11:10 as the water tanks in the façade modules had to be refilled, and the functioning of the sensor configuration had to be checked. The logging was resumed the same day at 18:25. All the windows were closed and the container doors remained closed. However, during the experiment, the right side windows on the top and bottom floor, and the left side windows on the bottom floor were opened and closed on the 25th and 26th of June from 8:45 to 18:00. One of the container doors of all the modules were opened on the 26th of June at 8:10. The logging was done till the 27th of June and the results were formulated. The weather data of the climatic conditions during week 1 is given below

WEATHER
week 01

		21/06/2019	22/06/2019	23/06/2019	24/06/2019	25/06/2019	26/06/2019	27/06/2019
°C	Max.	20.6	22.1	28.9	33.7	34.7	23.0	29.7
	Min.	14.0	12.7	16.4	21.2	23.3	16.9	14.1
	Average	17.0	17.5	22.3	27.1	28.0	19.7	17.1
%	Max.	89.0	82.7	76.9	58.2	74.7	85.9	77.4
	Min.	43.2	48.2	42.6	33.3	40.8	59.5	38.0
	Average	68.1	64.4	61.2	49.4	57.1	75.0	68.3

Figure 45 Weather Data Week 1

6.2.1 Module A

This Module refers to the left zone on the top floor of the building, in which there is no ventilation strategy applied for the cavity. Both the sliding doors in the façade module were closed, thus limiting the possibility of ventilation towards the cavity from outside. The plants in each cavity were watered as per the irrigation requirements of the plants and the watering strategy adopted for this module. This module contains two temperature and relative humidity sensors, one inside the cavity and one inside the building, corresponding to the cavity. It also has one air quality sensor inside the cavity and one light sensor inside the building corresponding to the cavity. The results from the temperature and relative humidity logged during the first cycle is represented in Figure 46 below

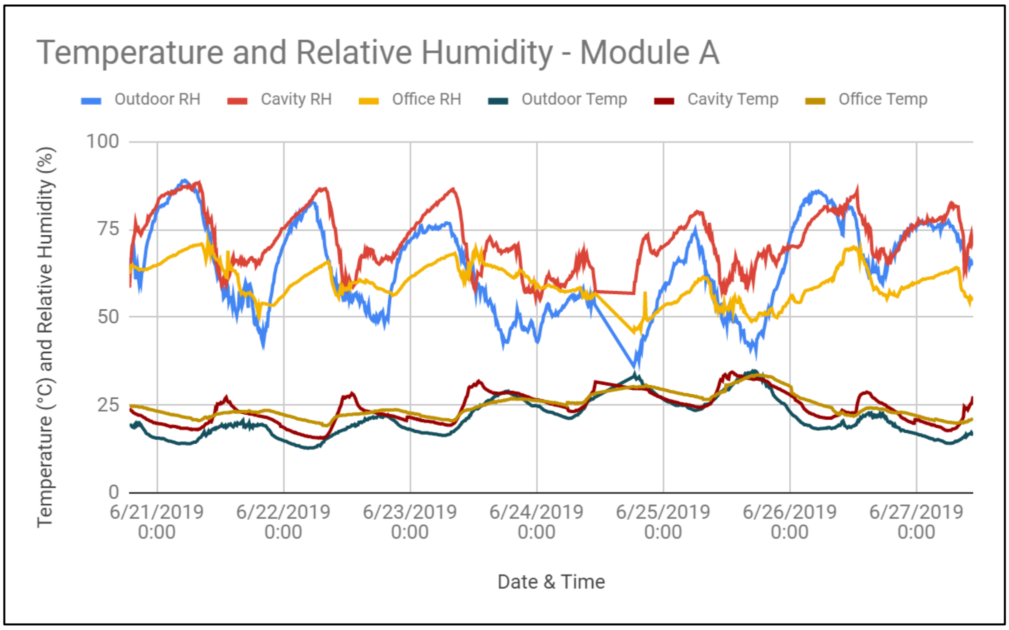


Figure 46 Temperature and relative humidity in module A - Week 1

The figure above shows the temperature and relative humidity inside the cavity and the office corresponding to module A. These readings are compared to the outdoor temperature and relative humidity. The relative humidity and temperature inside the cavity is represented as 'Cavity RH' and 'Cavity Temp' respectively. Similarly, the relative humidity inside the office is represented by 'Office RH' and 'Office Temp'. The outdoor relative humidity and temperature is represented as 'Outdoor RH' and 'Outdoor Temp' respectively. It can be noted in the graph that the data was not logged on the 24th of June between 11:10 and 18:25, as the trend in the variables remain constant during this period.

The humidity levels for both the regions follow a trend of increasing during the night and decreasing during the day as shown by the outdoor conditions. The outdoor relative humidity appears to be at its maximum during the mornings between 6:00 to 8:00, and minimum during the evenings between 18:00 and 19:00. Subsequently, the outdoor temperature is relatively higher in the evenings and the lower in the mornings.

The relative humidity in the cavity is higher than the humidity in the office almost throughout the cycle. In the afternoons, the relative humidity in the cavity is higher than that of the office, in spite of having a higher temperature. This may be due to the effect of plants in the cavity.

The rate of increase in relative humidity in the cavity is significantly higher as compared to that of the office. For example, the relative humidity inside the cavity on the 22nd of June at 8:10 is 20% higher than the relative humidity in the office.

Subsequently, the temperature in the cavity is 3°C lower than the temperature in the office. This may be due to the evaporative cooling from the plants. The process of evapotranspiration from the plants in a non-ventilated cavity can lead to the increase of water vapour in the air present in the cavity and thus, increasing the relative humidity. This may be the reason that the relative humidity in the cavity is higher than the outdoor relative humidity. The fluctuation of temperature in the cavity is higher than that of the office, with the peak temperatures reaching during the afternoon between 12:00 and 14:00.

It is seen that the temperatures inside the office and the cavity are higher than the outside temperature, when the outside temperature is below 24°C. However, the temperature in the office does not increase as the outdoor temperature increases. As a result, the outdoor temperature exceeds the office temperature when it crosses 25°C. This may be due to the effect of shading from the façade. On the 23rd of June at 18:40, the outdoor temperature is observed to be 0.4°C higher than the temperature in the cavity and 2.3°C higher than the temperature in the office. This may be due to the effect of the relative humidity at that time, as the relative humidity in the cavity was recorded to be 15% higher than the outdoor relative humidity.

The air quality in the cavity was evaluated based on the CO_2 and Total Volatile Organic Compound (TVOC) levels in parts per million (ppm) and parts per billion (ppb) respectively. The illuminance was measured inside the office with the help of a lux meter and the values were recorded in lux. The air quality and illuminance of module A is represented graphically in Appendix A.

6.2.2 Module B

This module is the middle region of the façade, corresponding to the top floor of the building. The internal sliding door of the double skin façade is open while the external sliding door remains closed. The irrigation rate for the red and yellow pepper plants is 1 drop in 12 seconds, and the rate for the Bahamian goat and the CGN21566 is 1 drop in 5 seconds. This irrigation rate remains constant for all the modules in the top floor. This module has a similar configuration of sensors as compared to module A, however, an extra light sensor is present in the cavity, close to the outer glazing of the double façade. This is mainly placed to get an idea of the illuminance entering the façade from the outside. The temperature and relative humidity in module B is graphically represented in Figure 47 below

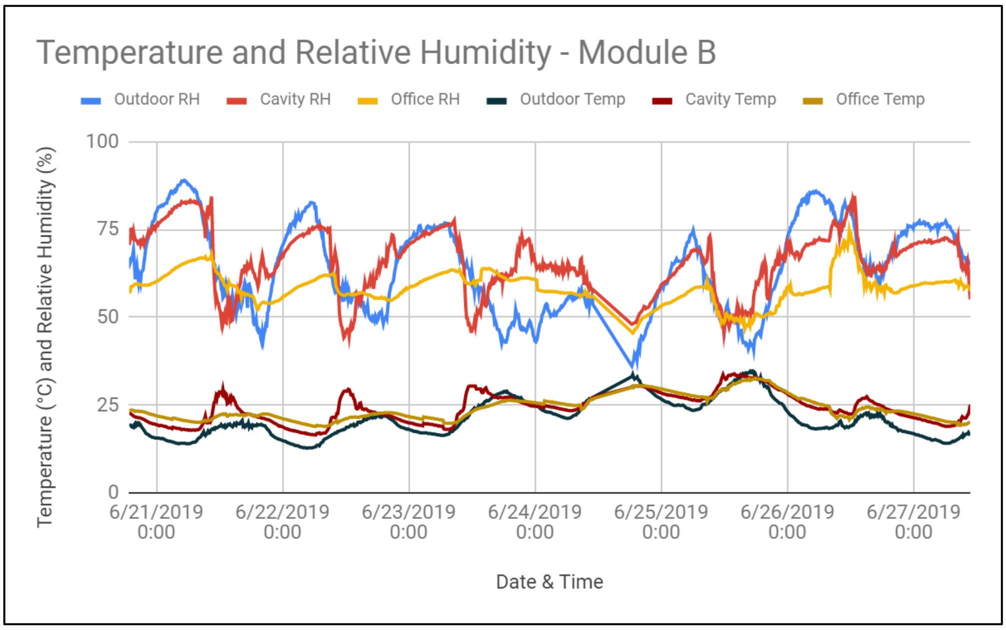


Figure 47 Temperature and Relative Humidity in Module B - Week 1

The figure above shows the trend of temperature and relative humidity in module B during the first cycle. The variables 'Cavity RH' and 'Cavity Temp' represent the relative humidity and temperature in the cavity whereas 'Office RH' and 'Office Temp' represent the relative humidity and temperature in the office. The outdoor relative humidity and temperature is represented as 'Outdoor RH' and 'Outdoor Temp' respectively. Similar to module A, the rate of change in relative humidity and temperature in the cavity is higher than that of the office. A steep decrease in the relative humidity is noticed in the cavity, where it reduces by 30% in a span of four hours. This is noticed on the 21st,22nd, 23rd and 25th of June. Subsequently, the temperature of the cavity reaches its peak in the afternoons. The trend of the change in temperature and relative humidity in the office is subtle compared to the temperature and relative humidity in the cavity.

On the afternoon of 25th of June at 12:00, the temperature of the cavity is higher than that of the office and the outdoor temperature. Subsequently, the relative humidity in the cavity is lower than that of the office and the outdoor relative humidity. This is unlike the case observed in module A, where the relative humidity in the cavity was higher than the relative humidity in the office. The temperature in the office is relatively higher in the mornings. For example, on the 27th of June at 6:15, the outdoor temperature was recorded to be 14.1°C, whereas the temperature in the office was 20.3°C.

The illuminance in the cavity and in the office was recorded in lux. The light sensor in the cavity gave an idea of how much shading effect is provided by the external container doors, as they were closed for all the modules throughout the first cycle of the experiment. The air quality sensor inside the cavity was placed in a similar manner to the one placed in module A. The illuminance reaching the cavity and the office, and the air quality in module B are graphically represented in Appendix A.

6.2.3 Module C

The right side module on the top floor consists of a mechanically ventilated double skin façade. Hence the ventilation strategy adopted in this module is the circulation of air in the cavity with the help of mechanically operated fans. The fans are installed such that they begin to operate when the temperature inside the cavity exceeds 24°C. Hence the fans are not functional continuously. This method not only helps the prevention of overheating in the cavity, but also consumes less energy compared to continuously running fans. The irrigation rate from the watering system in the module is the same as module A and B. The configuration of sensors in this module is similar to module A. The temperature and relative humidity recorded in module C for the first cycle is represented in Figure 48 below

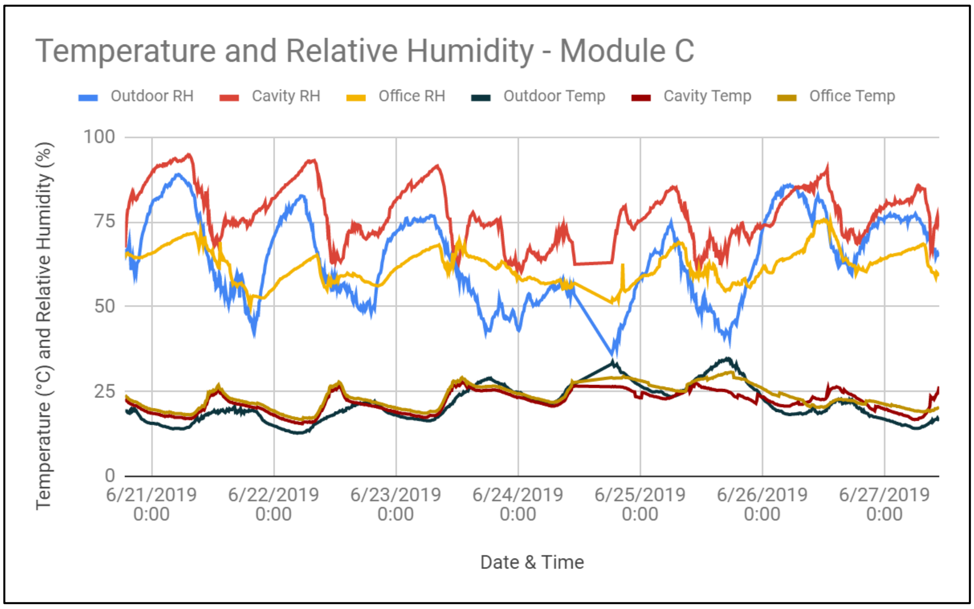


Figure 48 Temperature and Relative Humidity in Module C - Week 1

The figure above shows the trend in the relative humidity and temperature in module C during the first cycle. The relative humidity and temperature in the cavity is represented as 'Cavity RH' and 'Cavity Temp', similarly the relative humidity and temperature in the office is represented as 'Office RH' and 'Office Temp'. The outdoor relative humidity and temperature is represented as 'Outdoor RH' and 'Outdoor Temp' respectively. The relative humidity in the cavity and the office is similar to what was experienced in module A, with the highest differences of relative humidity on the 22nd of June at 8:10. However, the temperature in the cavity and the office followed a similar trend between 20th of June and 24th of June, with the temperature in the office being slightly higher than that of the cavity.

In this case, air was circulated in the cavity when the temperature exceeded 24°C. This brings an effect in the relative humidity in the cavity. This effect can be noted while observing the difference in the temperature and relative humidity in the cavity during 22nd of June at 20:30 and 23rd of June at 20:30. On the 22nd at 20:30, the temperature of the cavity was below 24°C, hence the fans were not functional. Consequently, the relative humidity increased and reached its peak during the morning of 23rd of June at 8:40, as a result of evapotranspiration from the plants, thus increasing the relative humidity in the cavity. However, on the 23rd of June at 20:30, the temperature inside the cavity was higher than 24°C, thus the fans were functional. This caused a decrease in the relative humidity inside the cavity unlike the case of what happened on the 22nd of June. This may be due to the fact that the humid air inside the cavity caused by the evapotranspiration of plants, was circulated and replaced with dry air from inside the building with the help of mechanical ventilation. This can be observed in the graph as the humidity in the cavity decreases such that it matches the humidity in the office on the 23rd of June at 21:30.

It can be seen that the mechanical ventilation has an effect in the temperature of the cavity as well as the temperature in the building. On the 25th of June at 17:35, the outdoor temperature was 33.4°C whereas the temperature in the cavity was 24.8°C. However, the temperature in the office was higher than that of the cavity. This may be the effect of cooling in the cavity due to mechanical ventilation.

The light sensor was placed in the office and the air quality sensor was placed inside the cavity of module C. The configuration of these two sensors were similar to that of module A. The illuminance, CO_2 and TVOC levels were recorded accordingly. The values from the light sensor and the air quality sensor is graphically represented in Appendix

6.2.4 Module D

This module is has a similar configuration to module A as there is no ventilation strategy adopted in the cavity. This module corresponds to the left zone of the bottom floor of the building. Unlike the cavities of the rest of the modules, this module has two Bahamian Goat pepper plants in the bottom row of the cavity instead of one Bahamian Goat and one CGN21566. The watering system is installed such that the irrigation rate for the red and yellow pepper plants is 1 drop in 11 seconds, whereas the irrigation rate for the Bahamian goat is 1 drop in 4 seconds. The configuration of the sensors is similar to that of module A. The temperature and relative humidity of module D is given in Figure 49 below

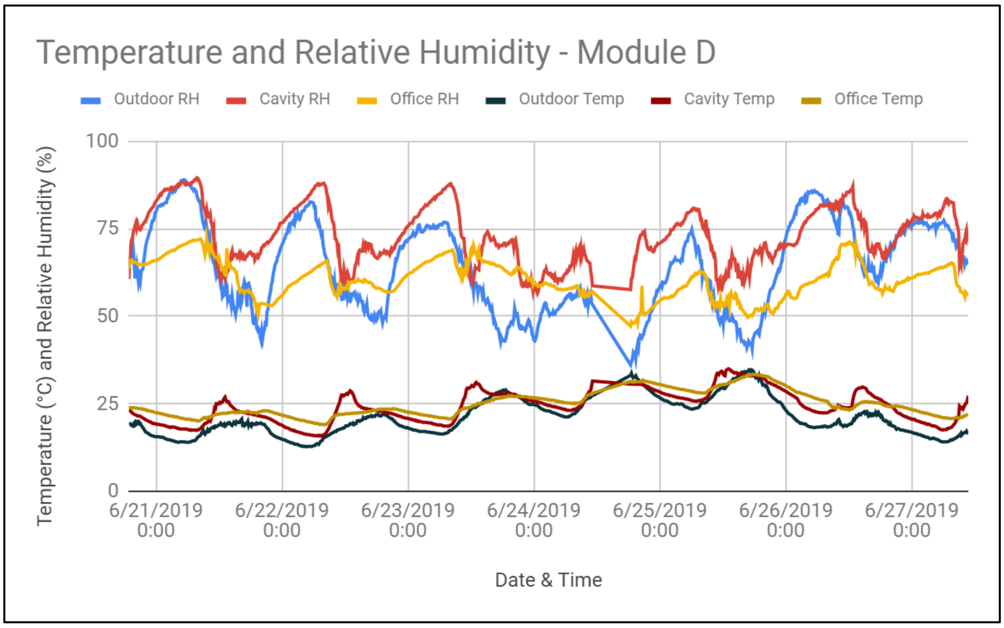


Figure 49 Temperature and Relative Humidity in Module D - Week 1

The figure above shows the trend of the temperature and relative humidity in module D. The trend in the relative humidity is similar to that of module A and module C. The relative humidity in the cavity and the office is represented by 'Cavity RH' and 'Office RH' respectively. Similarly, the temperature in the cavity and the office is represented by 'Cavity Temp' and 'Office Temp'. The outdoor relative humidity and temperature is represented as 'Outdoor RH' and 'Outdoor Temp' respectively. There is a significant difference between the peaks of the relative humidity in the cavity and in the office. In the afternoons, as the temperature reaches its peak, the relative humidity decreases. On the 21st of June and 23rd of June, the relative humidity in the cavity decreased such that it is less than the relative humidity in the office. Over the course of the first cycle, the temperature inside the office appears to fluctuate within the range of 1.5 to 2°C. The temperature in the cavity reaches its peak in the afternoons around 12:00 to 14:00. The low temperature of the cavity in the mornings correspond to the high relative humidity in the cavities at the same time.

On the 25th of June at 17:25, the outdoor temperature was observed to be 34.7°C however, the temperature in the cavity was 33°C. This may be due to the shading effect provided by the container doors as well as the high humidity present in the cavity due to the placement of the plants.

One air quality sensor was placed inside the cavity whereas one light sensor was placed inside the office. The CO_2, VOC levels and illuminance were recorded and the values are mentioned in Appendix

6.2.5 Module E

The ventilation strategy adopted in this module is natural ventilation with the help of the sliding doors in the double skin façade. The inner sliding door is kept open whereas the outer sliding door is closed. The set up of module E is similar to that of module B, including the rate of irrigation from the watering system. The dripping rate for the red and yellow pepper plants are set to be 1 drop in 12 seconds, whereas it is set to be 1 drop in 5 seconds for the Bahamian Goat and the CGN21566. The temperature and relative humidity is graphically represented below in Figure 50.

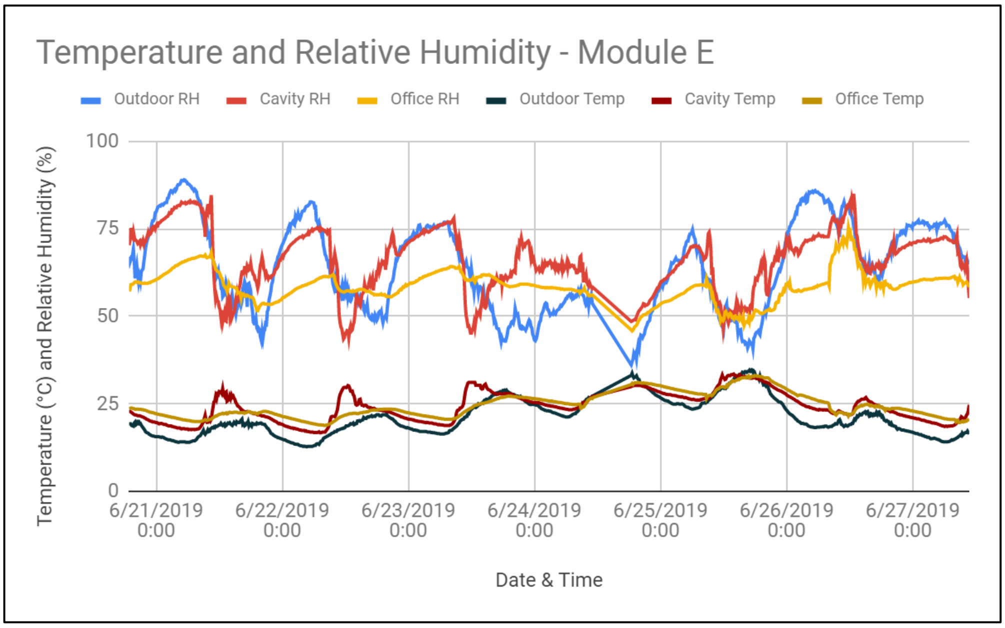


Figure 50 Temperature and Relative Humidity in Module E - Week 1

The figure above shows the trend of the relative humidity and temperature for the cavity and office region for module E. The variables 'Cavity Temp', 'Office Temp', 'Cavity RH' and 'Office RH' represent the temperature and relative humidity in the cavity and the office respectively. The outdoor relative humidity and temperature is represented as 'Outdoor RH' and 'Outdoor Temp' respectively. The change in relative humidity in the office over the period of the first week is less compared to the fluctuation of the relative humidity in the cavity. It is seen that the relative humidity in the cavity reaches its peak in the mornings at around 7:00 to 9:00. The maximum relative humidity during the morning of 21st , 22nd and 23rd of June is in a similar range, however, the maximum relative humidity on the 24th of June is lower. This may be due to a higher outside temperature on the 24th of June. In the afternoons, the relative humidity of the cavity is less than that of the office by a range of 12 to 15%. Subsequently, the temperature in the cavity is 6°C higher than that of the office.

The outdoor temperature was observed to be less than the temperature in the office and cavity throughout most of the cycle. However, the temperature of the cavity and office was observed to be less than the outdoor temperature on the 24th of June at 18:25 and on the 25th of June at 17:25.

Two light sensors were placed in this module. One was placed close to the outer glazing in the cavity, in order to determine the amount of sunlight entering the cavity. The light sensor inside the office was placed to determine the shading effect provided by the façade. An air quality sensor was placed inside the cavity of the module. The values obtained from the two light sensors and the air quality sensor are mentioned in the appendix.

6.2.6 Module F

This module has a similar set up to module C, with respect to the ventilation strategy and the type of plants placed. However, watering system in this case is set up such that the irrigation rate is lower as compared to module C. The red and yellow pepper plants have an irrigation rate of 1 drop in 13 seconds whereas the Bahamian goat and the CGN21566 are provided with an irrigation rate of 1 drop in 6 seconds. The temperature and relative humidity for this module is given below in Figure 51.

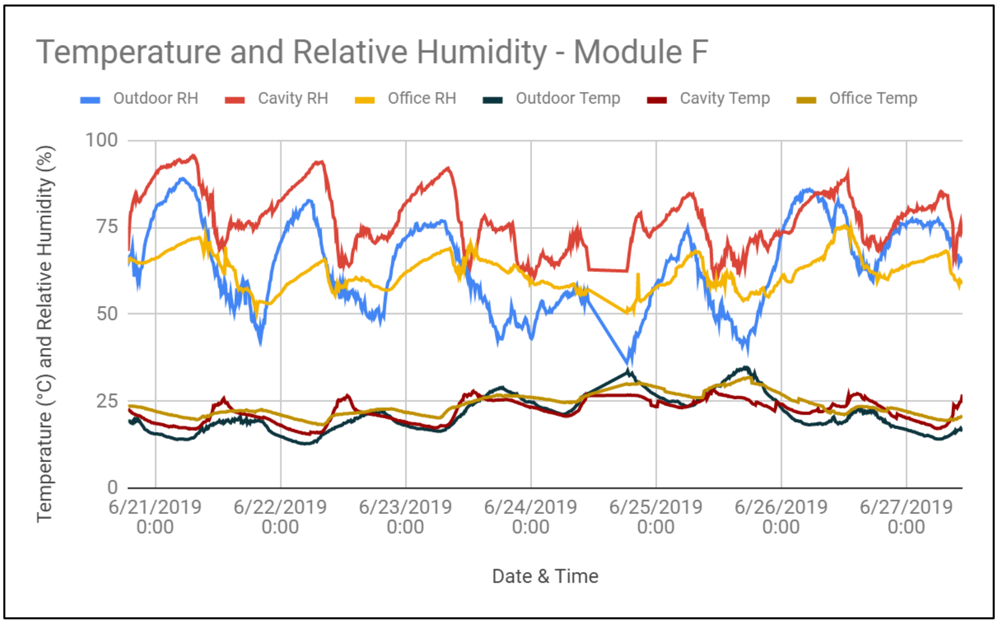


Figure 51 Temperature and Relative Humidity in Module F - Week 1

In the figure above, 'Cavity RH' and 'Office RH' represent the relative humidity in the cavity and in the office respectively. The variables 'Cavity Temp' and 'Office Temp' represent the temperature in the cavity and in the office. The outdoor relative humidity and temperature is represented as 'Outdoor RH' and 'Outdoor Temp' respectively. It can be observed that the trend of relative humidity in the cavity is similar to that of the trend in the cavity of module C. This may be due to the similar ventilation strategy adopted on both the modules. However, there is not much fluctuation in the temperature of the office as compared to the temperature of the office in module C. The temperature in the cavity does not exceed 26°C in the afternoon. This may be due to the application of the mechanical ventilation combined with the placement of the container doors.

The relative humidity in the cavity is higher than the office throughout the week. However, the temperature in the cavity was observed to be higher than the office during 26th of June in the afternoon. This may be due to the effect of the opening of the container door in the module.

The air quality sensor was placed inside the cavity and the light sensor was placed in the office. The values obtained from the light and air quality sensor is graphically represented in the appendix.

6.2.7 Combined Evaluation: Temperature and Relative humidity - Cavity

The relative humidity and the temperature inside the cavity of each module were collected and graphically compared to each other and the outdoor relative humidity and temperature. In other words, the variables 'Cavity RH' and 'Office RH' from each module were collected and compared. This is graphically represented in Figure 52 a) and b) below.

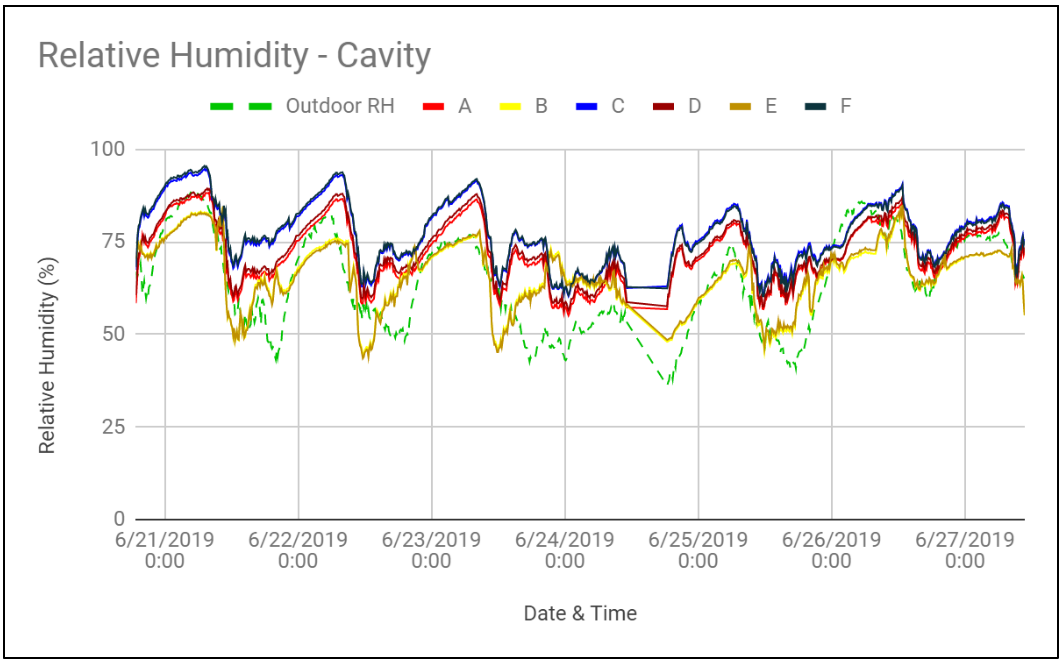


Figure 52 a) Relative Humidity in all the cavities -Week 1

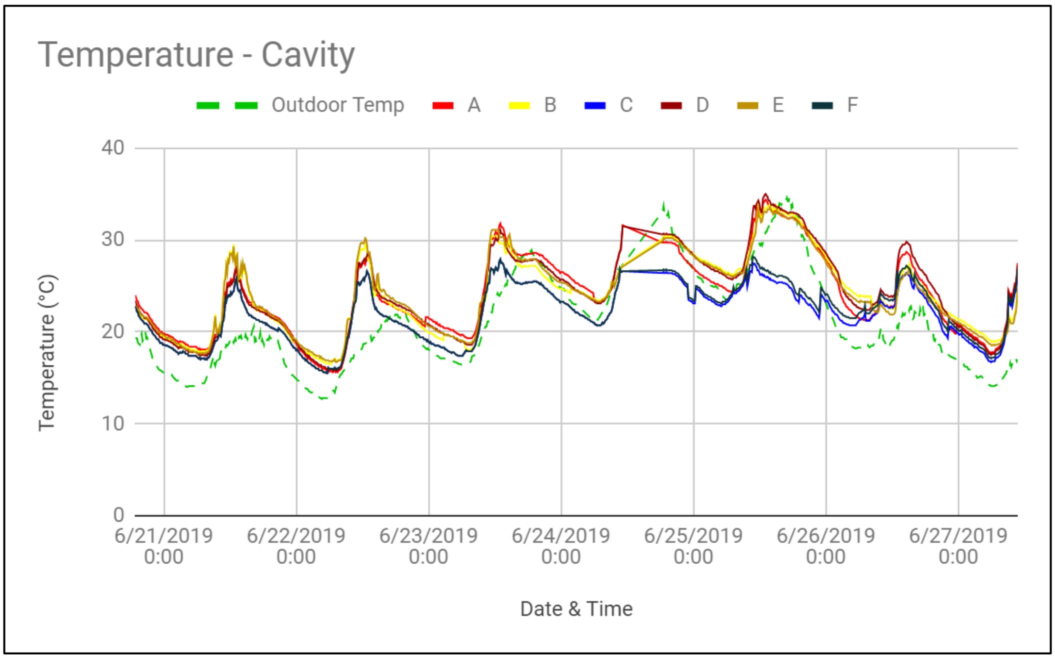


Figure 52 b) Temperature in all the cavities - Week 1

The figure above shows the trend of relative humidity and temperature in the cavity of all the six modules. It is seen that all the modules followed a similar trend over the course of the first week. The modules with the same ventilation strategies appear to show similar values. For example, cavities C and F (mechanically ventilated modules) tend to follow a similar trend with close values. It is observed that the mechanically ventilated modules have the highest relative humidity, with the values being significantly higher than that of the naturally ventilated modules. As a consequence, the temperatures in the mechanically ventilated cavities are relatively lower The average relative humidity and temperature cavity C and F were noted to be 77.4% & 21.7°C and 77.5% & 22°C respectively. The average relative humidity and temperature in cavity B and E were 66% & 24°C and

66.1% & 24°C respectively. Hence it can be seen that the average relative humidity in the naturally ventilated cavity is 12% less than that of the mechanically ventilated cavity on both the floors. As a result, the average temperature in the naturally ventilated cavity is 2.3°C higher than that of the mechanically ventilated cavity. Although there was no ventilation strategy adopted in cavity A and D, its average relative humidity is still higher than that of cavity B and E. This may be due to the evapotranspiration of the plants inside the cavity. The evapotranspiration of the plants increases the humidity in the air, which is not circulated in the case of the non-ventilated cavity. However, in the case of the naturally ventilated cavity, the humid air from the evapotranspiration by the plants is circulated and mixed with the dry air inside the office, thus reducing the humidity levels an subsequently increasing the temperature of the cavity.

In this case, one might expect the humidity levels in the mechanically ventilated cavity to be low. However, the temperature and relative humidity of the air is also a function of its velocity. Hence it is possible that higher rate of air flow from the mechanically ventilated modules decreased the overall temperature in the cavity, and thus increased the relative humidity.

On the afternoon of 23rd of June, a decline in the outdoor relative humidity was observed, whereas there an increase in the relative humidity was seen in all the cavities. The lowest outdoor relative humidity was recorded on the 24th of June at 18:25, with a value of 36.1%. The temperature at that time was recorded to be 33.1°C. Significantly lower temperatures were recorded at that time in the mechanically ventilated cavities with values of 26.7°C and 26.4°C. As a result, the mechanically ventilated cavities C and F had a relative humidity of 63% and 62.4% respectively, while the outdoor relative humidity was considerably low. Similarly, the 25th of June at 17:25, the outdoor temperature was recorded to be 34.7°C whereas the temperatures in cavities C and F were 24.8°C and 25.5°C respectively. This may be due to the ventilation strategy adopted, along with the shading provided from the container doors.

6.2.8 Combined Evaluation: Temperature and Relative humidity - Office

The temperature and relative humidity in the office for all the modules were combined into one graphical representation, and compared with respect to the outdoor temperature and relative humidity. This was done to evaluate the influence of the façade of each module inside the building with respect to temperature and relative humidity. The temperature and relative humidity of the modules are given in figure 53 a) and b) below.

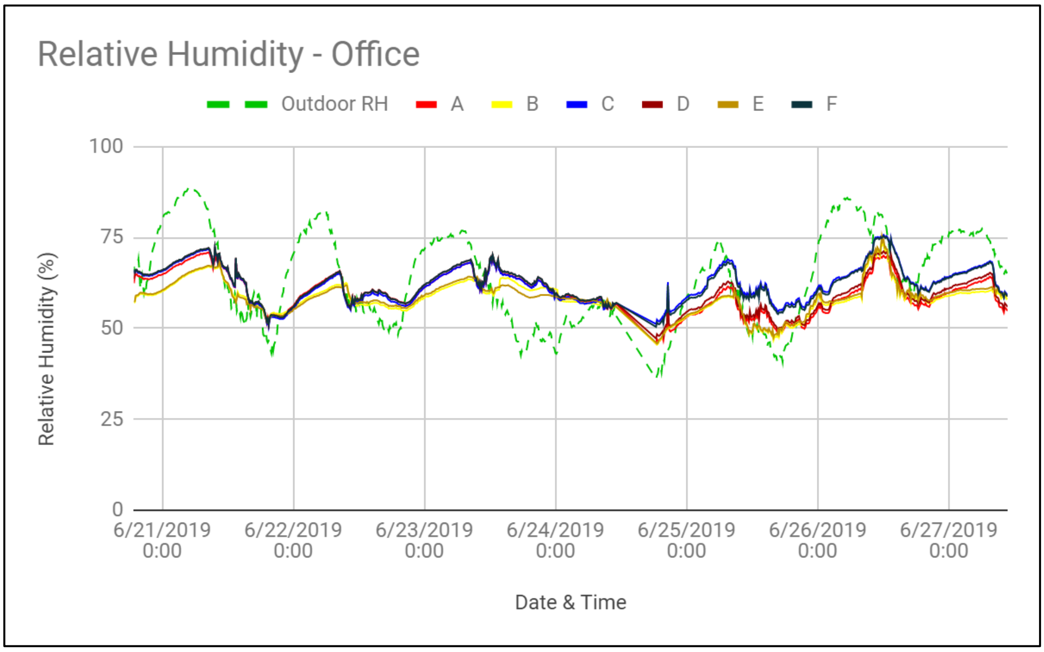


Figure 53 a) Relative Humidity in all the office spaces - Week 1

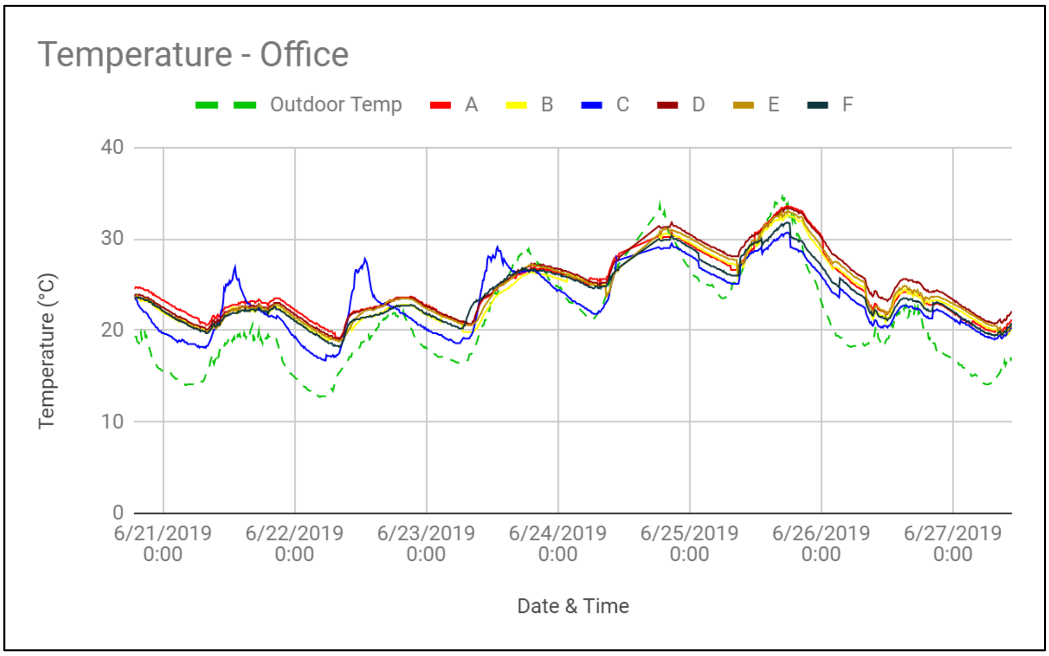


Figure 53 b) Temperature and Relative Humidity in all the office spaces - Week 1

The figure above shows the trend of relative humidity and temperature in the cavity of all the six modules. Modules B and E tend to show the lowest relative humidity with the average being 58.3% and 58.6% respectively. The modules C and F have higher values of relative humidity with the average values being 62.1%and 62.2% respectively. It is seen that the difference in relative humidity in the modules are less significant in the offices as compared to the cavities. However, the magnitude of the change in relative humidity in the modules over the week is less compared to that of the outdoor conditions. When the lowest outdoor relative humidity was recorded, the relative humidity of the modules were 10-15% higher than the outdoor relative humidity.

All the modules except module C followed a similar trend in the temperature. Although the time of increase and decrease of temperature in module C was similar to the others, the rate of increase varied. In the afternoons of 21st, 22nd and 23rd of June, the temperature in modules A,B,D,E and F ranged between 23°C to 25°C. whereas, for module C it ranged between 26.9°C to 29°C. Similarly in the mornings of 21st, 22nd and 23rd of June, the temperature in module C was 2°C lower than the rest of the modules. The average temperature in modules A and D were 23.3°C and 23.1°C respectively. Due to the high difference in relative humidity between the modules and the outdoor conditions, the outdoor temperature during its lowest relative humidity was recorded to be 2 to 2.5°C higher than the temperatures in the modules.

The maximum outdoor temperature was recorded on the 25th of June at 17:25 with a value of 34.7°C. Module C showed the minimum temperature out of all the modules with a value of 30.6°C and a relative humidity of 55.2%. On the 22nd of June at 4:40, the minimum outdoor temperature was recorded to be 12.7°C. During that time, the module with the highest temperature was module A, with a temperature of 20.9°C. The relative humidity for module A at this point was recorded to be 62.2%. Cavities C and F had a lower relative humidity at this point, however, the temperature was lower.

6.2.9 Combined Evaluation: Illuminance

The illuminance of the modules were compared to the amount of sunlight entering the cavity. Since one light sensor was placed in the cavities of module B and E, the evaluation was done separately for both the floors. The illuminances in the cavities B and E were taken as the illuminances entering the building on both the floors respectively. The light sensors in kept in the zones inside the office for each module per floor was then compared with respect to the outside illuminance. The illuminance amount of light entering the modules for both the floors is represented in figure 54 a) and b) below

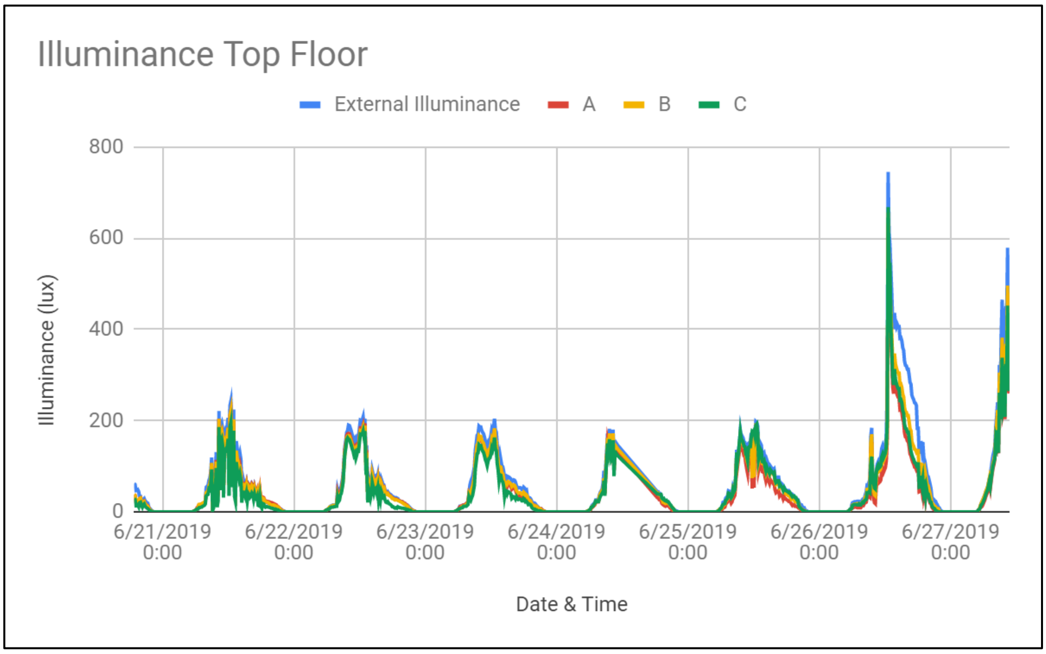


Figure 54 a) Illuminance in the top floor - Week 1

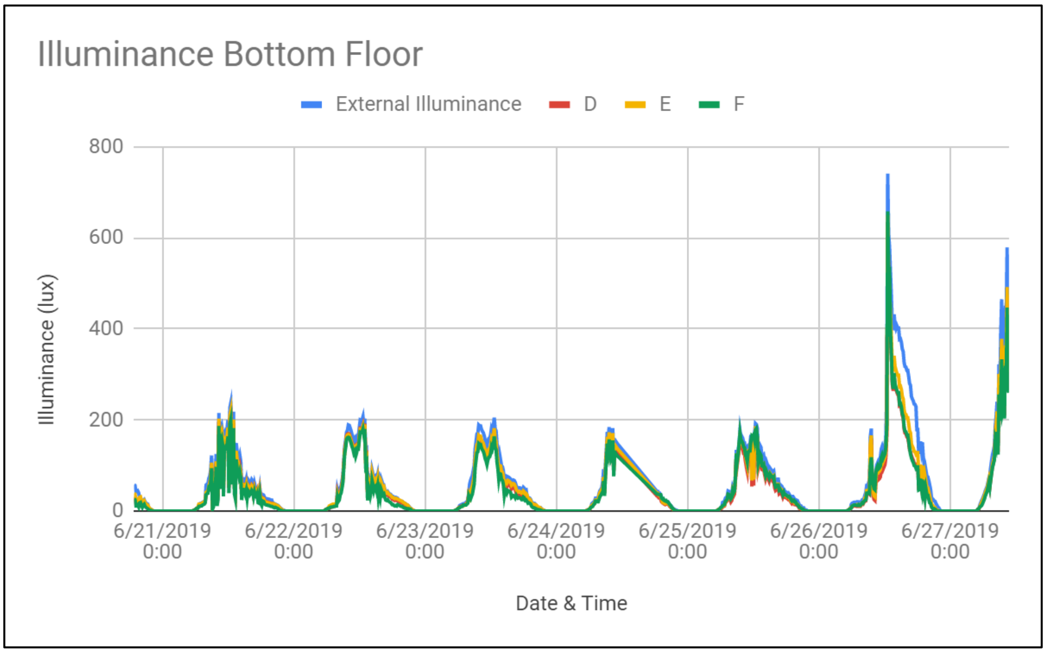


Figure 54 b) Illuminance in the bottom floor - Week 1

The figure above shows the comparison of the illuminance in each module to each other with respect to the illuminance reaching the building for both the top and bottom floors respectively. The variables Top Cavity and Bottom Cavity refer to the illuminance entering the building. The illuminances for all the modules are represented by their names (A to F).

Since the container doors were closed from the 20th of June to the 26th of June, the maximum illuminance in the building did not reach beyond 250 lux. The maximum illuminance was recorded as 242 lux in the top floor and 236 lux in the bottom floor during the afternoon of 21st June at 12:30.

Modules A,B,D, and E seem to have similar illuminance values. The difference is not significant as compared to the outdoor illuminance as the container doors were closed. However, modules C and F were relatively lower than the outdoor illuminance for both the floors, with the maximum values of illuminance reaching 196 lux and 200 lux respectively. This may indicate that the overall density of the leaves of the plants in cavities C and F are relatively higher.

One of the container doors for each module were open on the 26th of June at 8:10. The illuminance was then observed to increase drastically on both the floors. On the 26th of June at 12:45, the illuminance in the top and bottom floors were recorded to be 745 lux and 741 lux respectively. At that time, module A showed the highest effect of shading in the top floor as the illuminance in the office was the lowest, with a value of 629 lux. In the bottom floor, module D showed the highest effect of shading, with a value of 634 lux. The effect of shading in all the modules started increasing later on the day with an average difference of 150 lux. Modules A and D showed the highest effect of shading on both the floors respectively. This difference is due to a combination of the effect of one closed container door and the placement of plants.

6.2.10 Combined Evaluation: Air Quality

The air quality of all the modules were measured in terms of CO_2 levels in parts per million (ppm) and the number of Total Volatile Organic Compounds (TVOC) in parts per billion (ppb). These two quantities were recorded from the cavities for all the six modules and were combined to be compared to each other. The graphical representation for the CO_2 content in all the modules is given in figure 55 a) below.

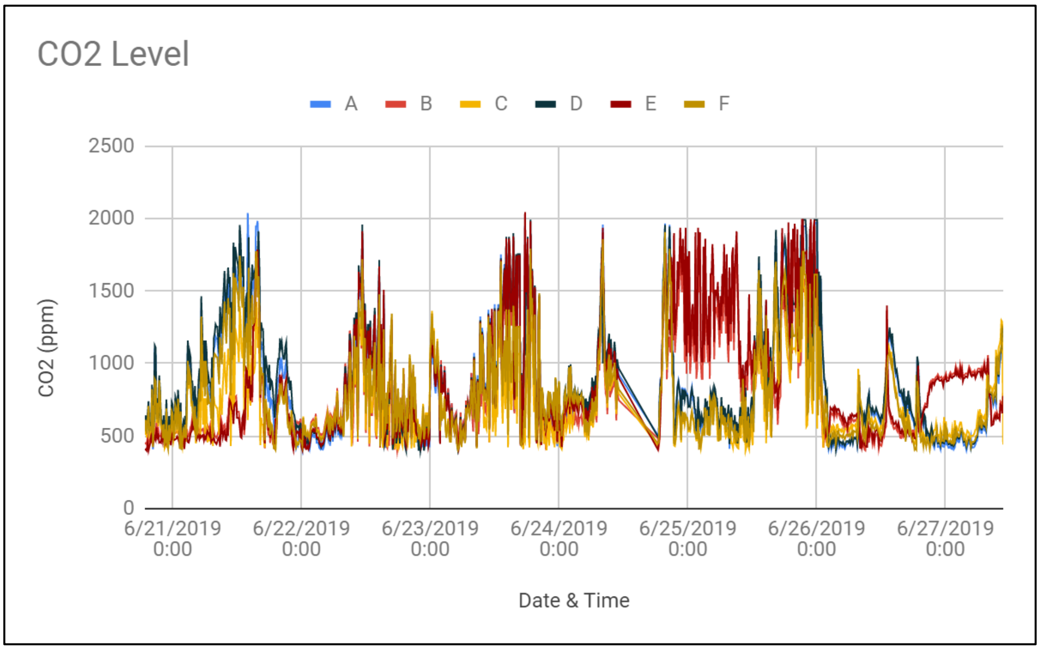


Figure 55 a) CO2 Level in the cavities - Week 1

The figure above shows the concentration of CO_2 in the air in each of the cavities in parts per million. Cavities A,B and C represent the modules in the top floor which are not ventilated, naturally ventilated and mechanically ventilated respectively. Similarly cavities D,E and F represent the modules in the bottom floor. A lot of fluctuation is observed in each of the cavities with an irregular trend of CO_2 levels. The maximum CO_2 level was recorded to be 2044 parts per million from cavity E on the 23rd of June at 17:40. The minimum CO_2 level was recorded from cavity D with a value of 400 ppm. Cavity C had the least average value of CO_2 content with a value of 710 ppm. On the 25th and 27th of June, the CO_2 levels in cavity B and E were found to be significantly higher than the rest of the cavities. On the 27th of June at 4:55, the CO_2 levels in cavities B and E were 932 and 911 parts per million respectively whereas the CO_2 content for the rest of the cavities ranged between 400 to 500 ppm. This may be due to the fact that the air in both these cavities are influenced by the air inside the building.

The number of Total Volatile Organic Compounds were also recorded and compared in a similar manner. This is represented in figure 55 b) below

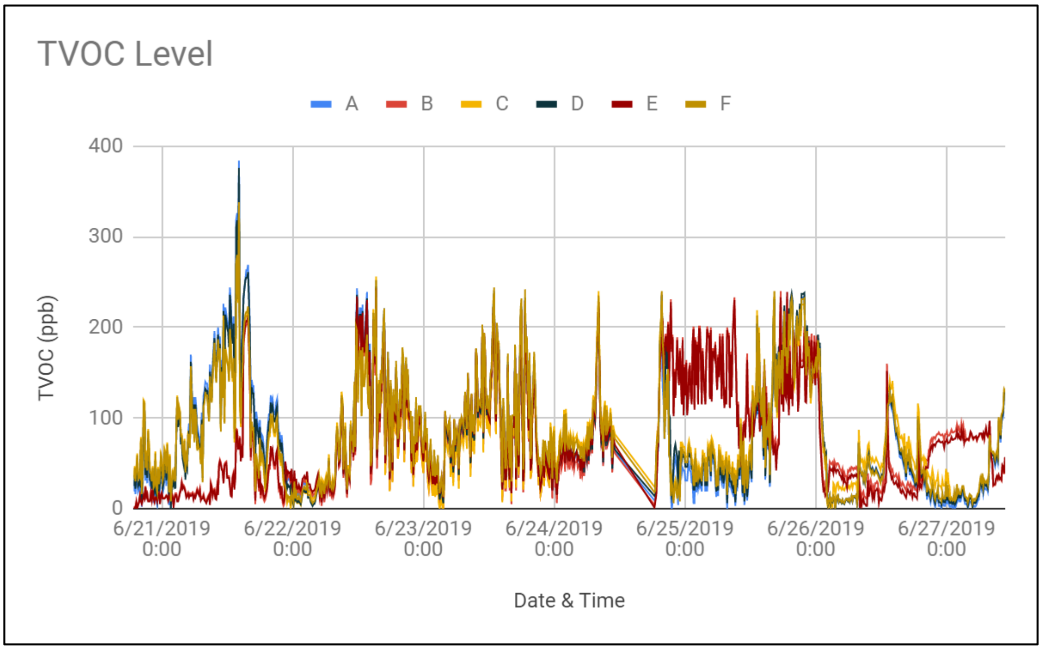


Figure 55 b) TVOC level in the cavities - Week 1

The figure above shows the number of Total Volatile Organic Compounds (TVOC) in parts per billion (ppb). It is noted that the number of TVOC's correspond to the amount of CO_2 in the air. This is observed in the figure as the maximum number of TVOC was recorded from cavity A, with 384 on the 23rd of June at 17:40. The highest average of TVOC was recorded from cavity A with a value of 90 ppb, whereas the lowest average was observed to be recorded from cavity B, with a value of 61 parts per billion. Cavities B and E tend to show higher amounts of TVOC levels based on the trend followed compared to the other modules.

6.3 SECOND WEEK

The logging of data resumed for the second week on the 27th of June at 16:55. The data was logged till the 5th of July at 11:05. The logging was paused on the 1st of July at 10:35 and resumed on the same day at 16:55. The refilling of the water tanks and the maintenance of the configuration led to the gap in the logging of data. The container doors were partially open throughout the week for all the modules, with an angle of 45°C. During the course of the logging, the window on the left side of the office in the top floor was opened on the 28th of June, between 16:28 and 18:20. The window on the right side of the office in the top floor was opened on the 27th of June between 16:00 and 17:56, and on the 28th of June between 16:58 and 18:20. The maximum outdoor temperature and relative humidity was recorded on the 29th of June at 19:45 and the 1st of July at 3:05, with values of 35.2°C and 83.8% respectively. The minimum outdoor temperature and relative humidity were recorded on the 4th of July at 5:55 and on the 29th of June at 18:35, with values of 11.4°C and 24% respectively. The weather data for week 2 is represented in the figure below. The results from the second week of data logging are elaborated in the following sections

WEATHER
week 02

		28/06/2019	29/06/2019	30/06/2019	01/07/2019	02/07/2019	03/07/2019	04/07/2019
°C	Max.	23.0	35.2	26.7	31.1	21.2	20.3	22.2
	Min.	15.1	16.0	18.4	16.9	15.1	13.9	11.4
	Average	18.3	24.9	22.6	18.8	18.1	16.7	17.0
%	Max.	75.1	81.4	73.8	83.8	80.4	75.8	75.7
	Min.	53.3	24.0	37.6	47.3	39.1	35.2	49.2
	Average	66.2	53.2	55.9	65.2	59.2	58.9	59.4

Figure 56 Weather Data Week 2

6.3.1 Module A

The behaviour of this module with respect to temperature and relative humidity is elaborated and is graphically represented in figure 57 below. The results with respect to the illuminance and air quality are mentioned in Appendix A.

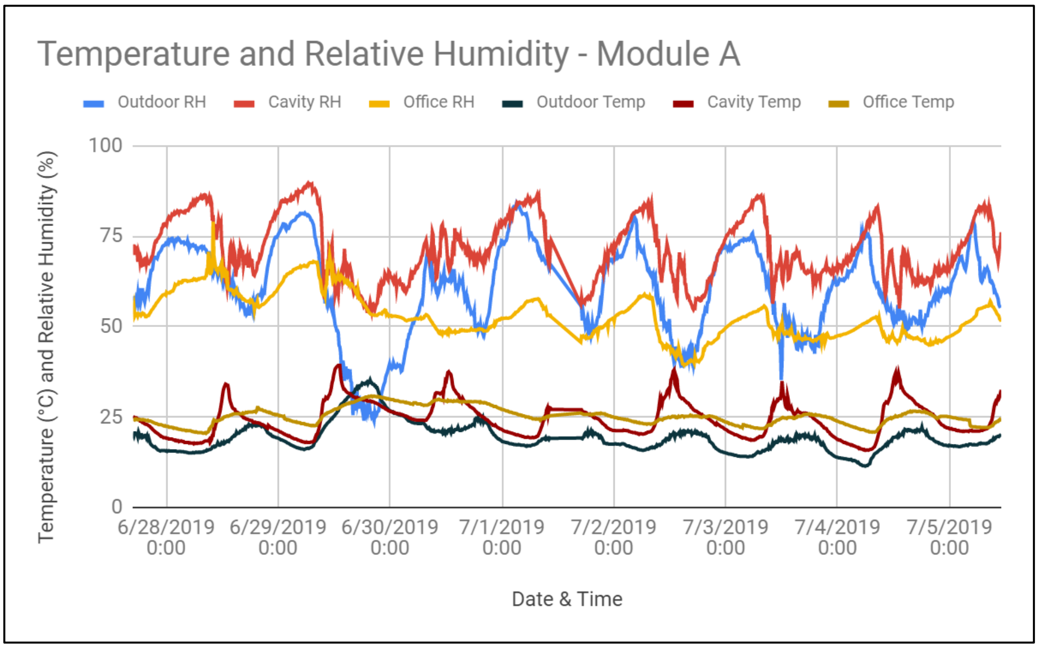


Figure 57 Temperature and Relative Humidity in Module A - Week 2

Figure 57 shows the trend in the temperature and relative humidity inside the cavity and in the office space corresponding to the cavity for the second week. The data was compared along with the outdoor temperature and relative humidity. The variables 'Outdoor RH' and 'Outdoor Temp' represent the outdoor conditions. It can be seen that the trend followed by the relative humidity in the cavity matches that of the outdoor relative humidity. The relative humidity inside the office is lower than that of the cavity throughout the week. However, the temperature in the office is not higher than the temperature in the cavity throughout the week. This shows that the outdoor conditions have a higher influence in the cavity than in the office. During the peak outdoor temperature (35.2°C) it is seen that the temperatures in the cavity and the office are lower by a value of 7°C. This may be the result of a combined effect of the shading provided by the container doors as well as the placement of the plants. It can also be seen that the relative humidity in the cavity is substantially higher than the outdoor relative humidity during the time of the maximum temperature. The temperature in the cavity is seen to reach its peak during the afternoons between 12:00 and 14:00. The temperature in the office is lower during this period.

6.3.2 Module B

The thermal behaviour of the cavity and the office in module be is represented below. In this case, the inner sliding door was open to enable natural circulation between the office and the façade. The behaviour of this module with respect to illuminance and air quality is graphically represented in Appendix A.

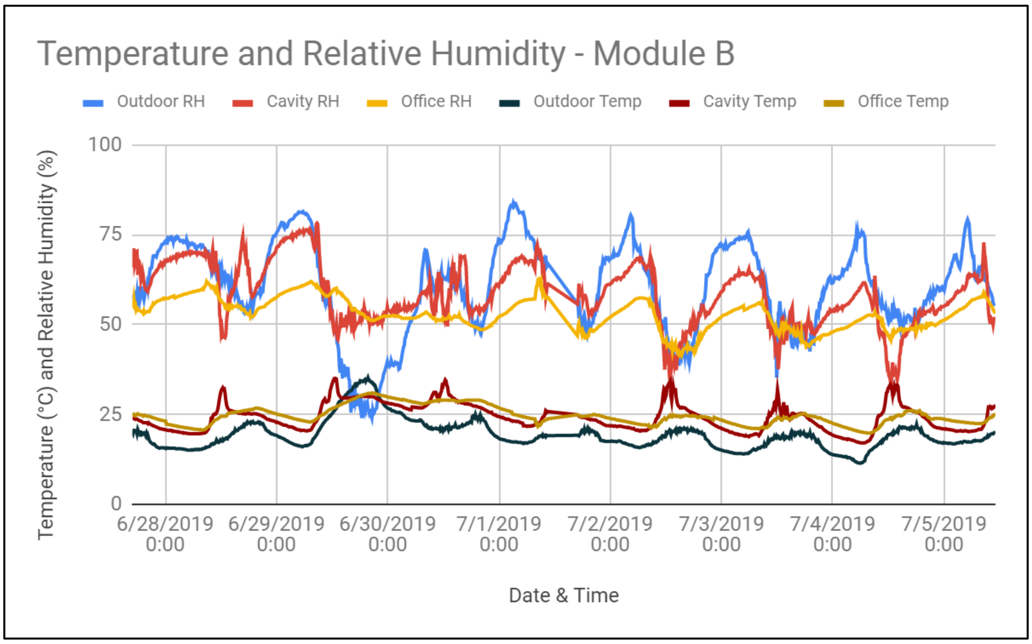


Figure 58 Temperature and Relative Humidity in Module B - Week 2

Figure 58 shows the trend of the temperature and relative humidity in module B. It is seen that the difference in temperature between the cavity and the office throughout the week is less than what is experienced in module A. Moreover, in this case the relative humidity in the cavity is not higher than that of the office throughout the week. It can be observed that the relative humidity in the cavity goes lower than that of the office during the afternoons of 3rd , 4th and 5th of July. This is observed when the temperature in the cavity is considerably higher than the office. This may be an indication that the temperature driven exchange of air between the office and the cavity is influencing the humidity in the cavity. This phenomenon is observed throughout the week except on the 1st and 2nd of July.

6.3.3 Module C

The mechanically ventilated module is installed such that it is functional when the temperature in the cavity goes beyond 24°C. The climatic performance of module C is represented below. The illuminance and the air quality in module C is shown in Appendix A.

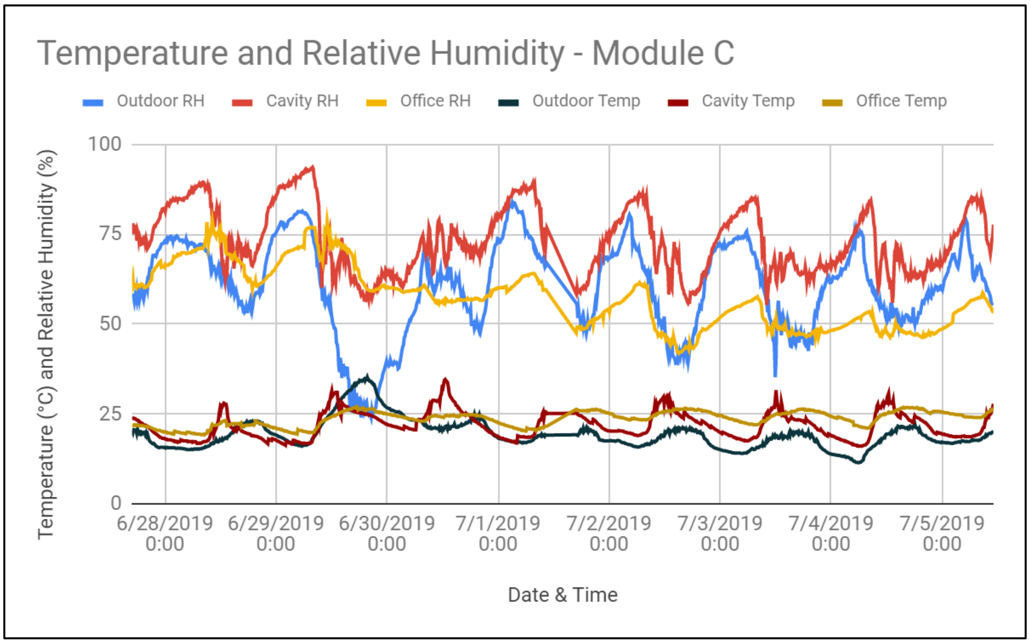


Figure 59 Temperature and Relative Humidity in Module C - Week 2

The figure above shows the trend in the temperature and relative humidity in module C throughout week 2. The trend in the temperature of the cavity and the office is similar to that of module B, however, in this case it can be seen that the relative humidity in the cavity does not decrease to an extent that it is less than the relative humidity in the office. During the highest outdoor temperature, the temperature in the cavity was observed to be 25°C, which is 10°C less than the recorded outdoor temperature. This shows the role of the mechanical ventilation inside the cavity, combined with the shading effect from the sliding doors, as well as the behaviour of the plants in the cavity.

6.3.4 Module D

The performance of module D showed similar characteristics to what was shown by module A. This may be due to the similar ventilation and shading strategy applied on both the modules. The thermal performance of module D is shown in figure 60 below. The illuminance and the air quality of module D is given in Appendix A.

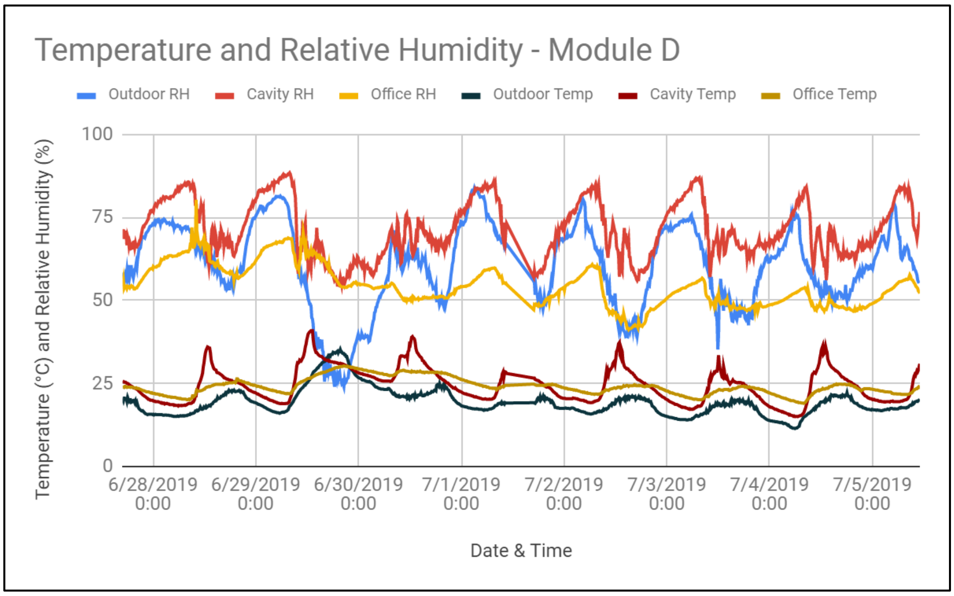


Figure 60 Temperature and Relative Humidity in Module D - Week 2

The trend in the temperature and relative humidity shown by module D seems to be similar to that shown by module A. It can be seen that the temperature in the cavity is higher than the office during high outdoor temperatures, and lower than the office during decreasing outdoor temperatures. Although the temperature in the cavity is higher than that of the office during high outdoor temperatures, the humidity in the cavity is higher than that of the office as well. The higher humidity in this case can be due to the influence of the plants.

6.3.5 Module E

The climatic behaviour shown by module E was observed to be similar to that of the module B. Primarily in terms of relative humidity in the cavity of both the modules. The trend in the temperature and relative humidity in module E is graphically represented in Figure 61 below.

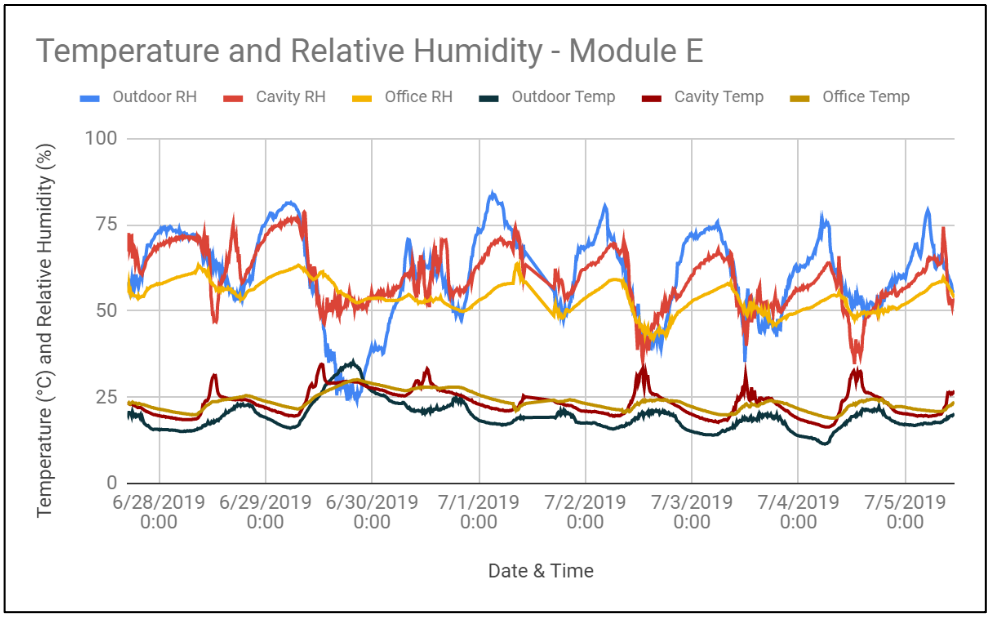


Figure 61 Temperature and Relative Humidity in Module E - Week 2

6.3.6 Module F

This module has a similar ventilation strategy to module C. This was shown by the characteristics observed in module F over the course of the week. The values in temperature in the cavity were similar to that of module C. This indicates that the mechanical ventilation was functional in module F as the temperature in the cavity went higher than 24°C. The temperature and relative humidity in module F is graphically represented below in Figure 62

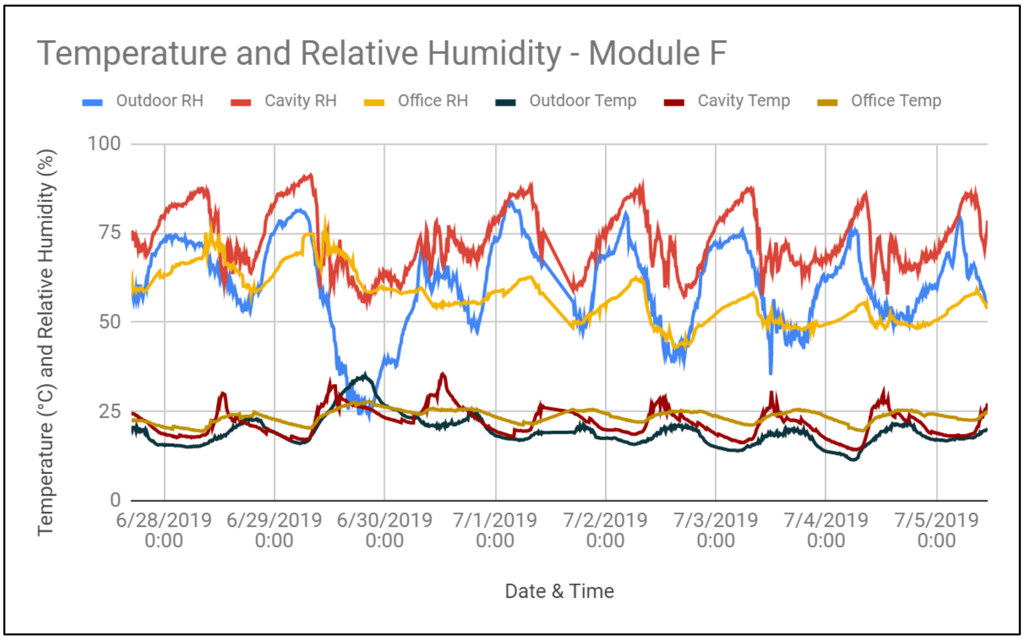


Figure 62 Temperature and Relative Humidity in Module F - Week 2

6.3.7 Combined Evaluation: Temperature and Relative Humidity - Cavity

The performance of each module with respect to temperature and relative humidity was compared by considering the trend in temperature and relative humidity in each module. This was done to see how the ventilation strategy in each module affects the climatic conditions in the cavity, with respect to the outdoor climatic conditions. This is graphically represented in Figure 63 a) and b) below.

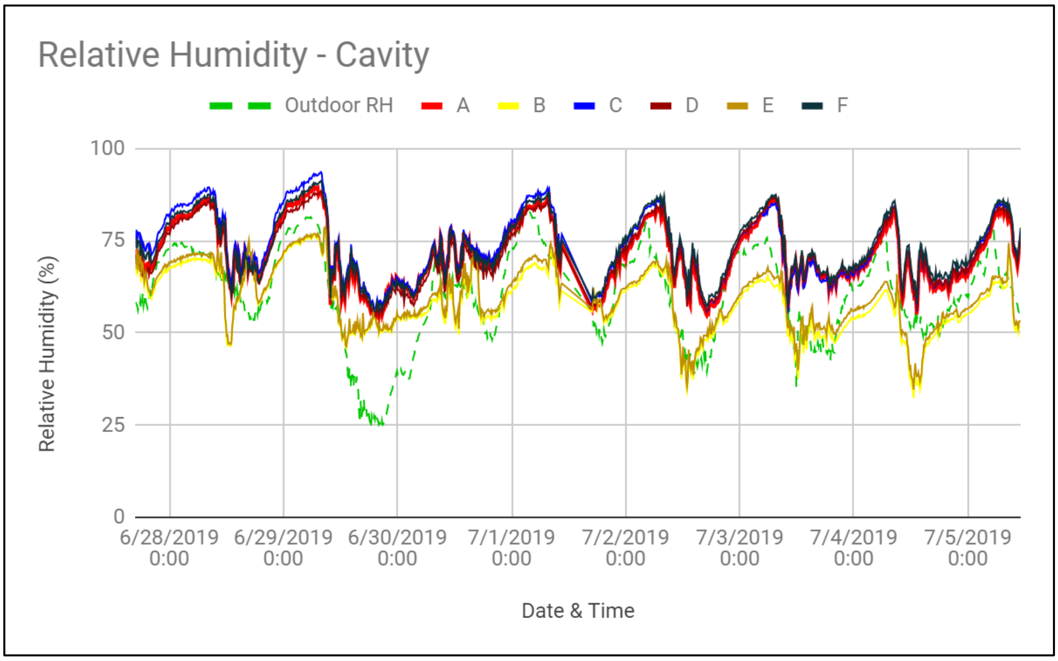


Figure 63 a) Relative Humidity in all the cavities - Week 2

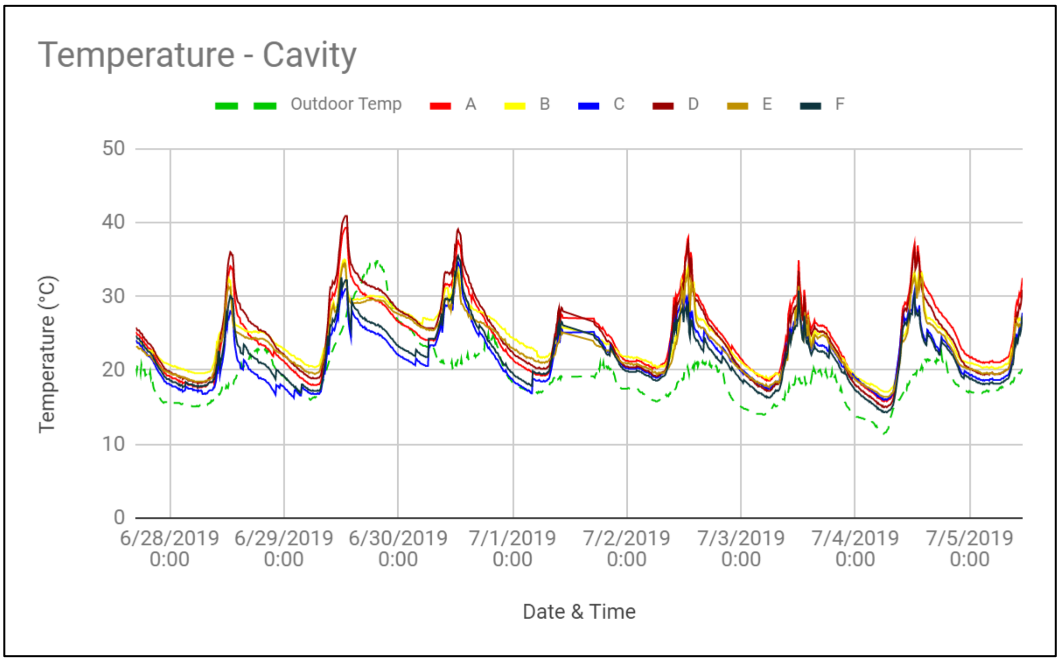


Figure 63 b) Temperature in all the cavities - Week 2

Figure 63 a) and b) show the trend in the temperature and relative humidity of each module with respect to the outdoor climatic conditions. The dashed line in both the figures represent the outdoor relative humidity and the temperature respectively. It is observed that the relative humidity in the mechanically ventilated cavities (C & F) is similar to that of the minimally ventilated modules (A & D) throughout the week. Meanwhile, the relative humidity in the naturally ventilated modules are considerably lower. This may be a result of the lower relative humidity in the office. Although the relative humidity in cavity A & D is similar to that of cavity C & F, it can be observed that the temperatures in cavity A & D are higher than that of cavity C & F. On the 29th of June at 13:05, the maximum temperature was recorded in cavity D, with a value of 40.9°C while the temperature in cavity A was 39.3°C. The temperature in cavity C & F was recorded to be 31°C and 32.2°C respectively at this time. Despite this difference in temperature, the relative humidity was similar for both cases. The cause of higher relative humidity in cavity A & D may be due to the behaviour shown by the plants. As there is no ventilation involved, the evapotranspiration from the plants make the air more humid. In the case of cavity C and F the humidity is driven by the cooling action from the high ventilation rate due to the mechanical ventilation. This explains the cooler air temperature inside the mechanically ventilated cavities.

6.3.8 Combined Evaluation: Temperature and Relative Humidity - Office

The temperature and the relative humidity in the office spaces corresponding to each module were combined and compared. This was done to get an idea of how the design strategies in each double skin façade influences the condition in the cavity. This is graphically represented below.

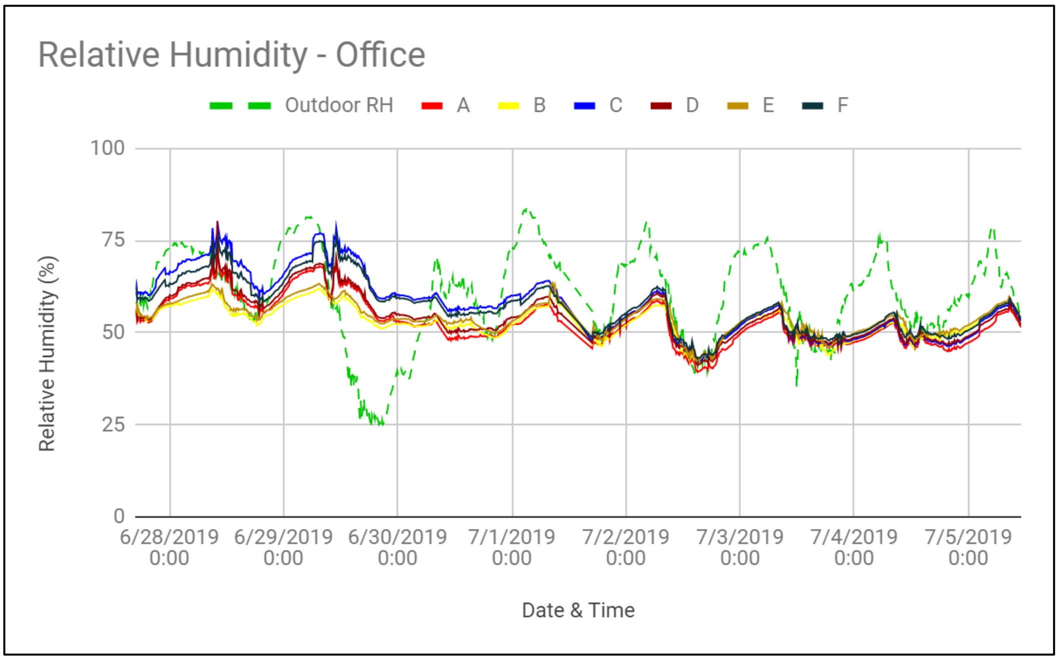


Figure 64 a) Relative humidity in all the office spaces - Week 2

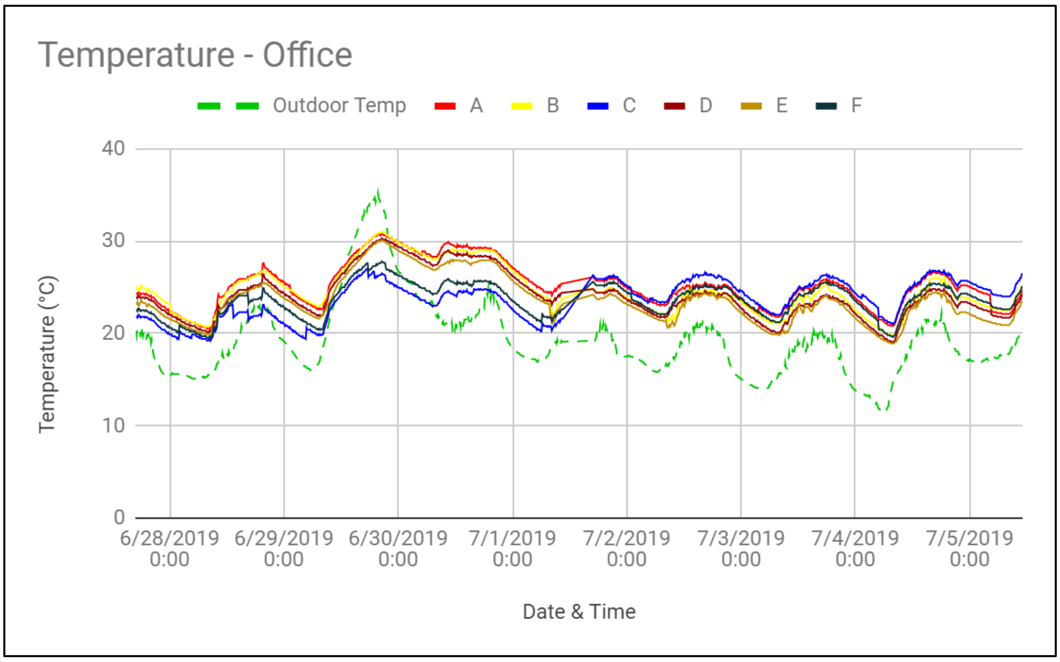


Figure 64 b) Temperature in all the office spaces - Week 2

Figure 64 a) and b) represent the temperature and relative humidity in the office spaces behind each module. They are compared with the outdoor temperature and relative humidity which is represented as 'Outdoor RH' and 'Outdoor Temp' respectively. It is observed that module A and D have similar temperature and relative humidity to that of module B and E. It can be seen that the temperature in module C & F is considerably lower than the rest of the modules during high outdoor temperatures . This indicates the role of cooling by mechanical ventilation in the cavities. Subsequently, the relative humidity in modules C & F is higher. When the outdoor temperature is below 20°C the temperatures in all the modules appear to have similar values. Modules C and F show higher temperatures than the rest of the modules from the 2nd to 5th of July. Due to the arrangement of the sensors in the offices, it can be said that the design strategies in the cavity does not solely influence the conditions in the office. The climatic conditions can also be due to external factors such as activities in the office.

6.3.9 Illuminance

The illuminance for all the modules were combined in order to find the shading effect provided by the positioning of the container doors, as well as the placement of the plants in the cavity. This is provided in the figure below.

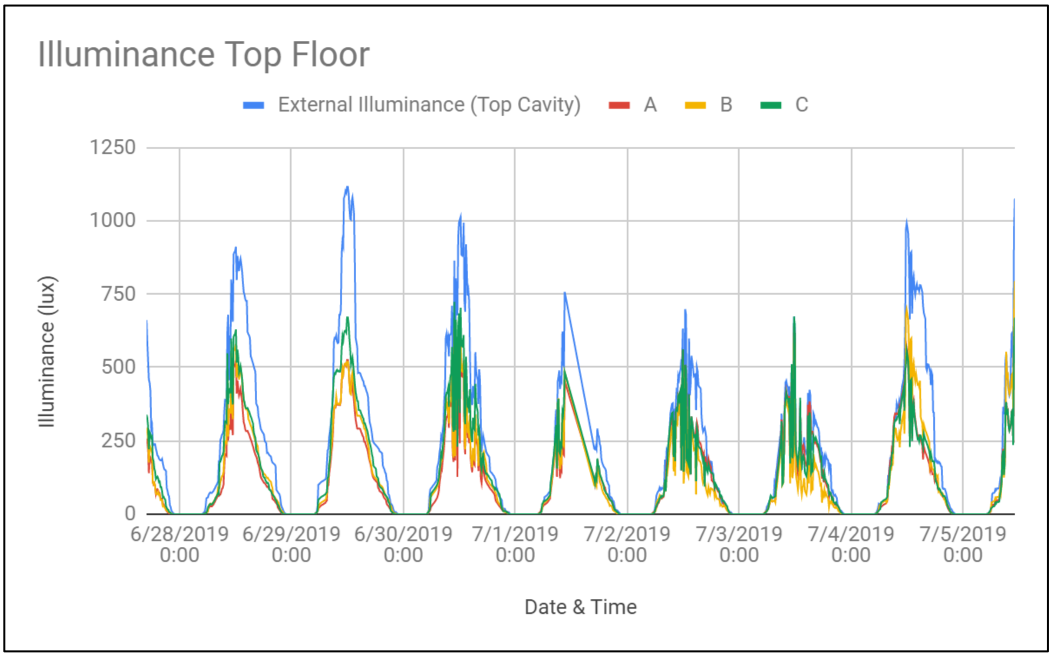


Figure 65 a) Illuminance in top floor -Week 2

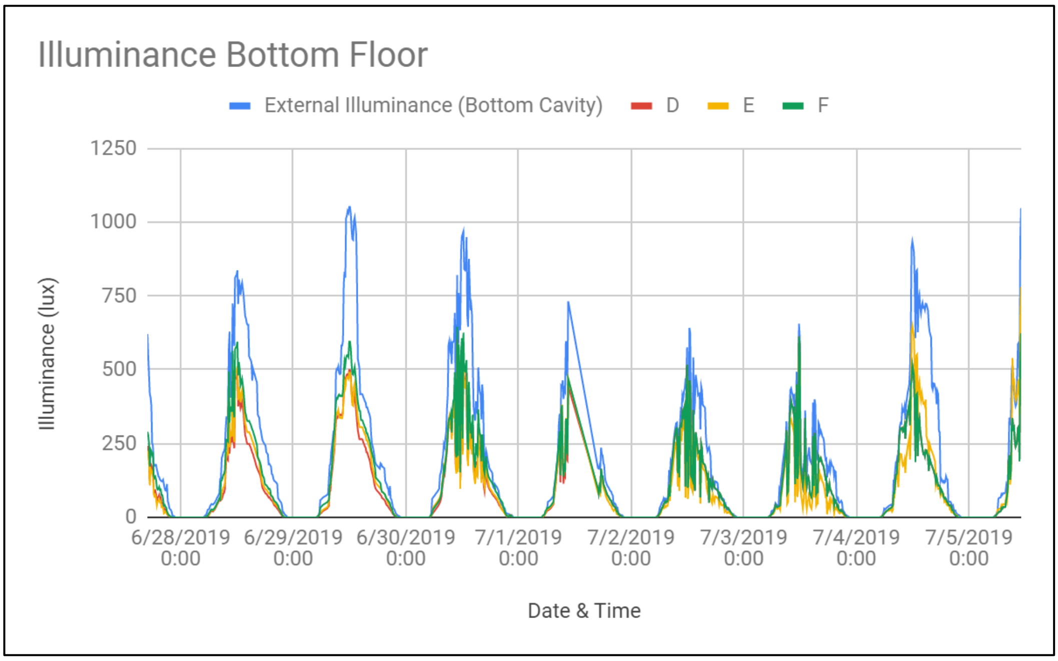


Figure 65 b) Illuminance in bottom floor – Week 2

Figure 65 a) and b) represent the illuminance of the modules on both the floors in lux, with respect to the illuminance entering the building. The variables 'External Illuminance (Top Cavity)' ad 'External Illuminance (Bottom Cavity)' represent the illuminance entering the cavities on the top and bottom floor respectively. The variables A to F represent the amount of light entering the offices. It can be seen that the maximum illuminance is recorded in the afternoons. However, it can be seen that the external illuminance is lower than expected, based on the hourly solar radiation collected in J/cm^2 from (KNMI, 2019). For example, on the 29th of June at 12:00, the solar radiation in an hour that was obtained was 313 J/cm^2 (870 W/m^2). Based on the correlation by (Treado & Kusuda, 1981), this value corresponds to a Total Illuminance of 90000 lux. However, the value shown by the sensor at that time is less than 1500 lux. This difference may be due to the limited accuracy in the sensor, as well as the positioning of the sensor during the experiment. Although the absolute value is not accurate, it can be observed that the illuminance shown in the modules are less than the external illuminance. This shows that the position of the sliding doors and the plants provide a shading effect inside the office. Hence it can be concluded that the values indicate that the shading strategy reduces the illuminance in the offices by a certain factor, compared to the external illuminance, although the absolute value does not seem to be precise.

6.3.10 Air Quality

The air quality for all the modules were recorded and observed, based on the total number of CO_2 and the Total Volatile Organic Compounds (TVOC) present in the cavities of each of the modules. The behaviour of the cavities with respect to the CO_2 and TVOC levels are given below.

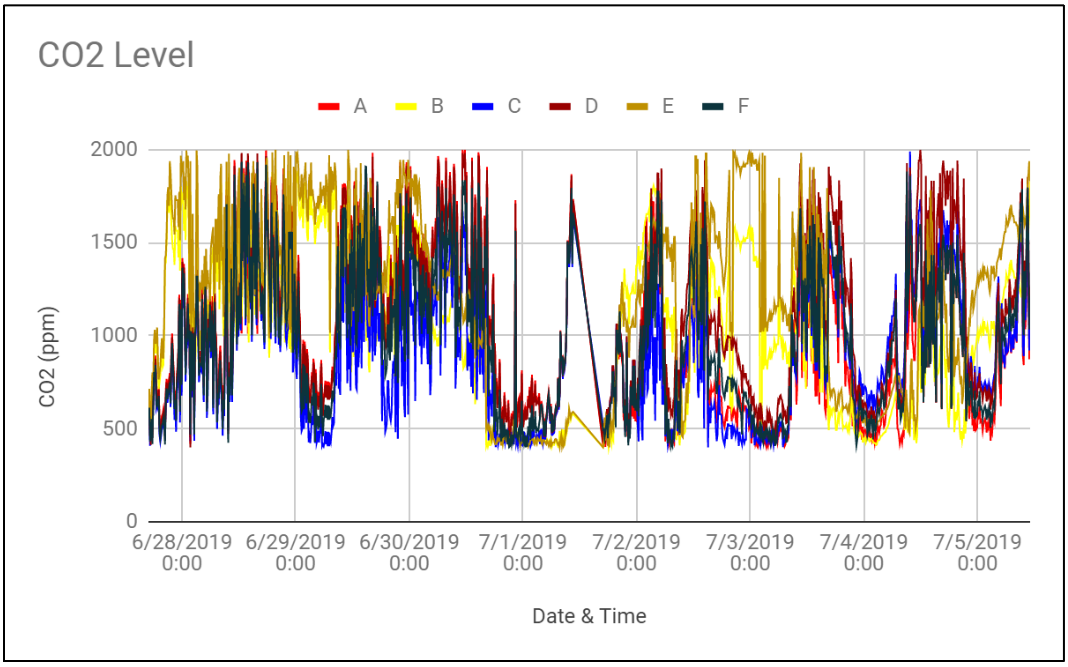


Figure 66 a) CO2 Levels in the cavities – Week 2

The CO_2 levels in the cavities are represented in Figure 66 a) above. It can be seen that there are constant fluctuations in the values for all the cavities. The maximum CO_2 level was recorded from cavity E, with a value of 1999 parts per million (ppm) on the 28th of June at 19:45. On 29th of June and on the 3rd of July, it can be observed that the naturally ventilated modules are substantially higher than the rest of the modules. This may be due to higher CO_2 levels in the office. However, this was recorded at midnight, when there was no activity going on in the office and when the occupancy was zero. The TVOC levels in each of the modules corresponded to the amount of CO_2 levels. This can be seen in the trend of the TVOC levels of each cavity. This is graphically represented in figure 66 b) below.

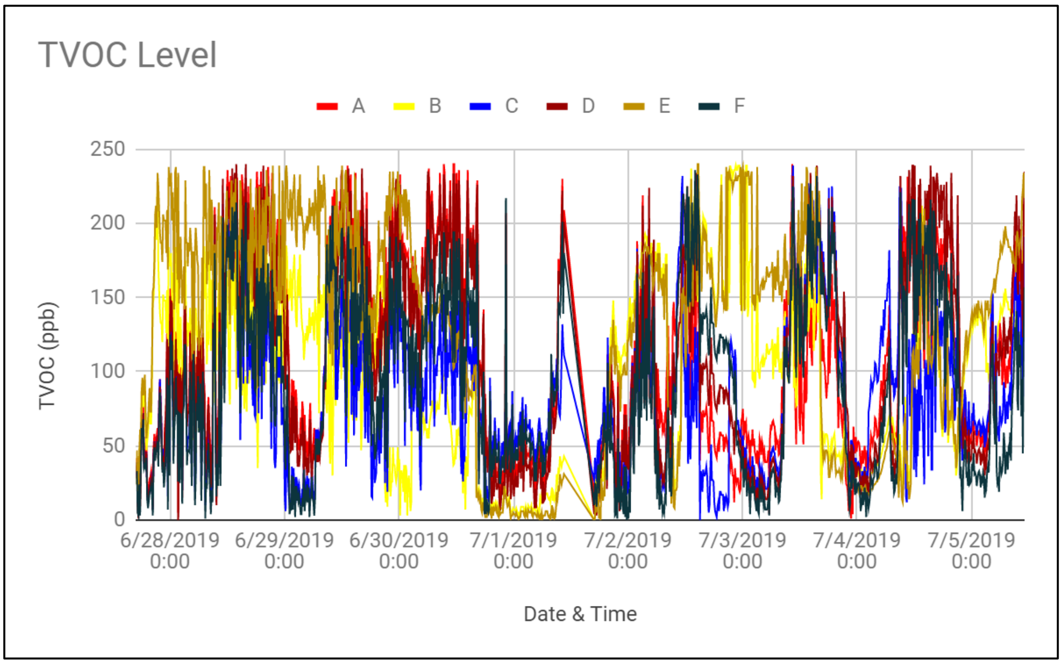
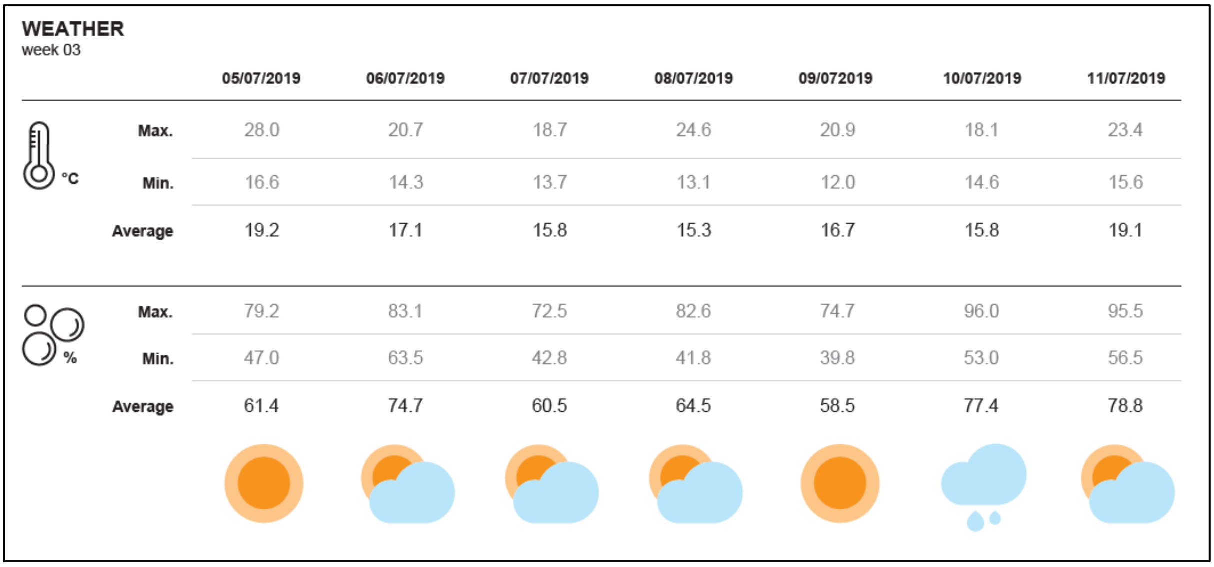


Figure 66 b) TVOC levels in the cavities - Week 2

6.4 THIRD WEEK

The data logging was resumed on the 5th of July at 13:05, after the water tanks for the irrigation system for the cavities were re-filled. The container doors were open up to an angle of 90° over the course of the logging. None of the windows in the office were opened or closed during the time of the logging. The data logging was stopped on the 8th of July at 10:35 and resumed at 13:15, due to the refilling of the water tanks for the irrigation system. However, the data in module A was not logged from the 8th due to an inconvenience in the configuration of the sensors. Hence, the performance of module A could not be analysed for the complete week. The maximum outdoor temperature in the week was recorded to be 24.6°C on the 8th of July at 13:15, and the maximum relative humidity was recorded to be 96% on the 10th of July at 23:25. The minimum temperature was recorded to be 12°C on the 9th of July at 5:25, and the minimum relative humidity was recorded to be 39.8% on the 9th of July at 15:25. The data was logged and the parameters were analysed. The weather data for the third week is given below



WEATHER
week 03

		05/07/2019	06/07/2019	07/07/2019	08/07/2019	09/072019	10/07/2019	11/07/2019
°C	Max.	28.0	20.7	18.7	24.6	20.9	18.1	23.4
	Min.	16.6	14.3	13.7	13.1	12.0	14.6	15.6
	Average	19.2	17.1	15.8	15.3	16.7	15.8	19.1
%	Max.	79.2	83.1	72.5	82.6	74.7	96.0	95.5
	Min.	47.0	63.5	42.8	41.8	39.8	53.0	56.5
	Average	61.4	74.7	60.5	64.5	58.5	77.4	78.8

Figure 67 Weather Data Week 3

6.4.1 Module A

The climatic performance of module A with respect to temperature and relative humidity in the cavity and the office is given below in figure 51. The data was only logged for three days, from the 5th of July to the 8th of July. The illuminance and air quality shown by module A is shown in appendix A.

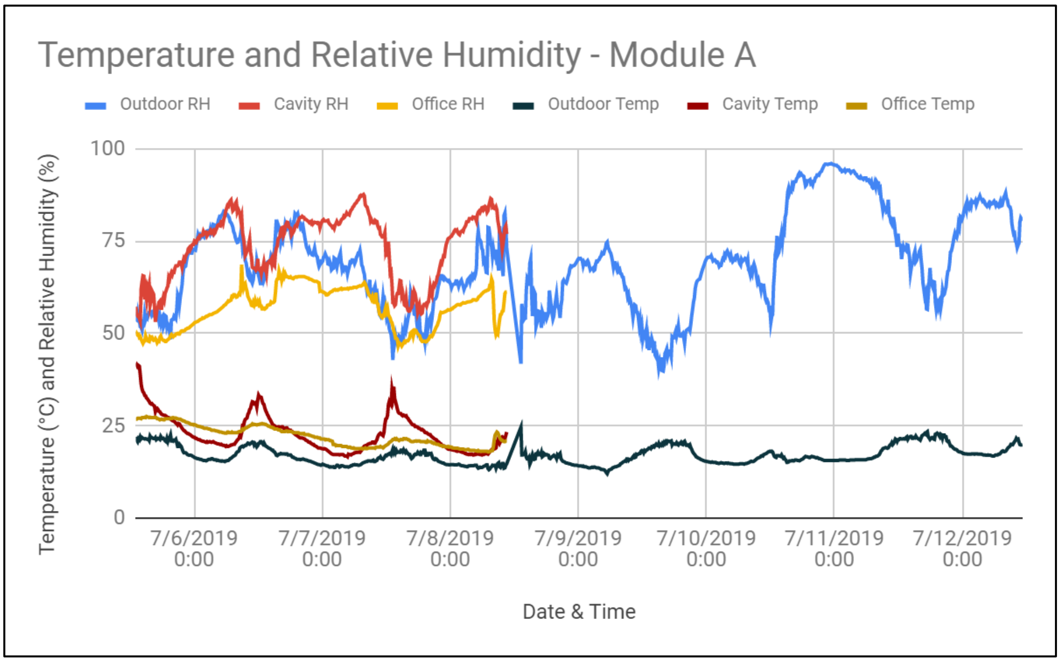


Figure 68 Temperature and Relative Humidity in Module A- Week 3

The figure above shows the trend in the temperature and the relative humidity in the cavity and office space of Module A. It is seen that the relative humidity in the cavity is higher than the office throughout the three days of logging. However, the temperature in the cavity is higher than the office in the afternoons of 5th, 6th and 7th of July, while maintaining a higher relative humidity than the office. On the 7th of July at 13:25, it is observed that the temperature in the cavity is 35.6°C, while the outdoor temperature was recorded to be 17.8°C. This difference in temperature may be due to the solar load acting on the double skin façade, as the container doors were open.

6.4.2 Module B

The temperature and relative humidity in the cavity and the office of module B was recorded throughout the week. This is graphically represented below in figure 52. The illuminance and air quality in module B is mentioned in Appendix A.

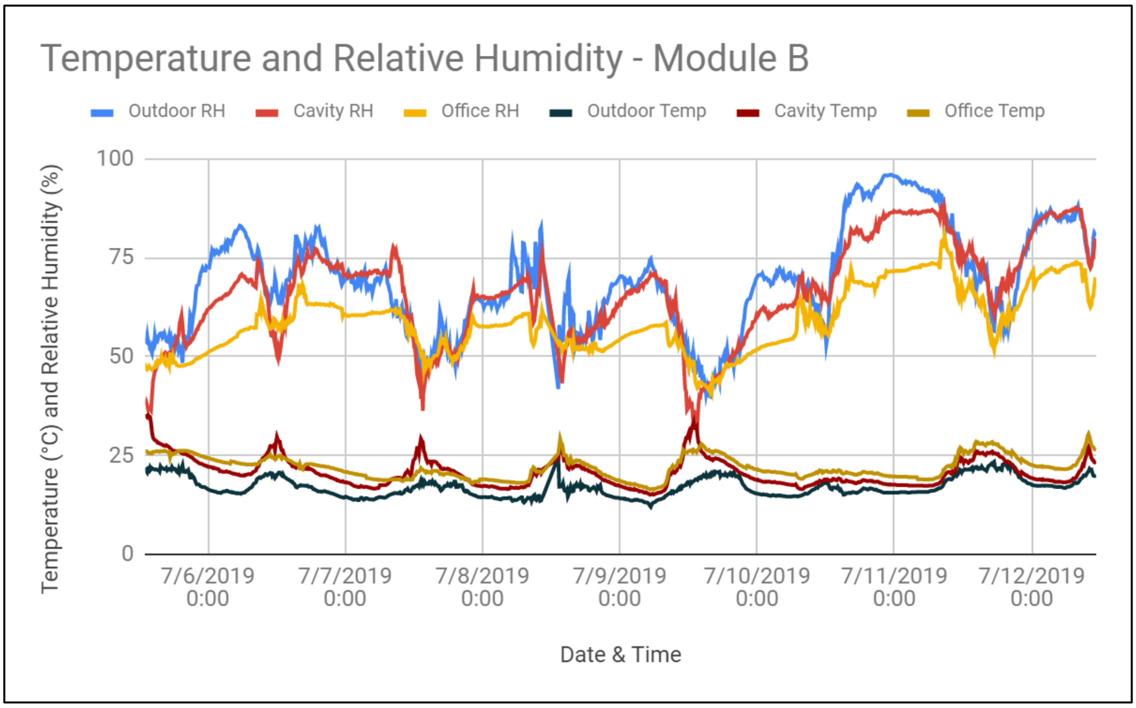


Figure 69 Temperature and Relative Humidity in Module B - Week 3

The figure above shows the trend of the temperature and relative humidity in module B. The trend shown by the cavity and the office with respect to the temperature and relative humidity follows what was recorded as the outside temperature and relative humidity. It can be seen that the relative humidity in the cavity is less than that of the office during the afternoons between 6th to 9th of July, when the temperature in the cavity is more than the office. This is unlike what was observed in module A. The temperature in the office and the cavity was observed to be higher than the outdoor temperature and relative humidity throughout the week. It is also seen that the temperature in the cavity does not increase on the days with low solar radiation. This can be correlated with the illuminance chart shown in appendix A. This shows that the solar radiation influences the temperature inside the cavity.

6.4.3 Module C

The thermal performance inside the mechanically ventilated module was recorded and is graphically represented in Figure 70 below. The illuminance and the air quality of this module is represented in the appendix A.

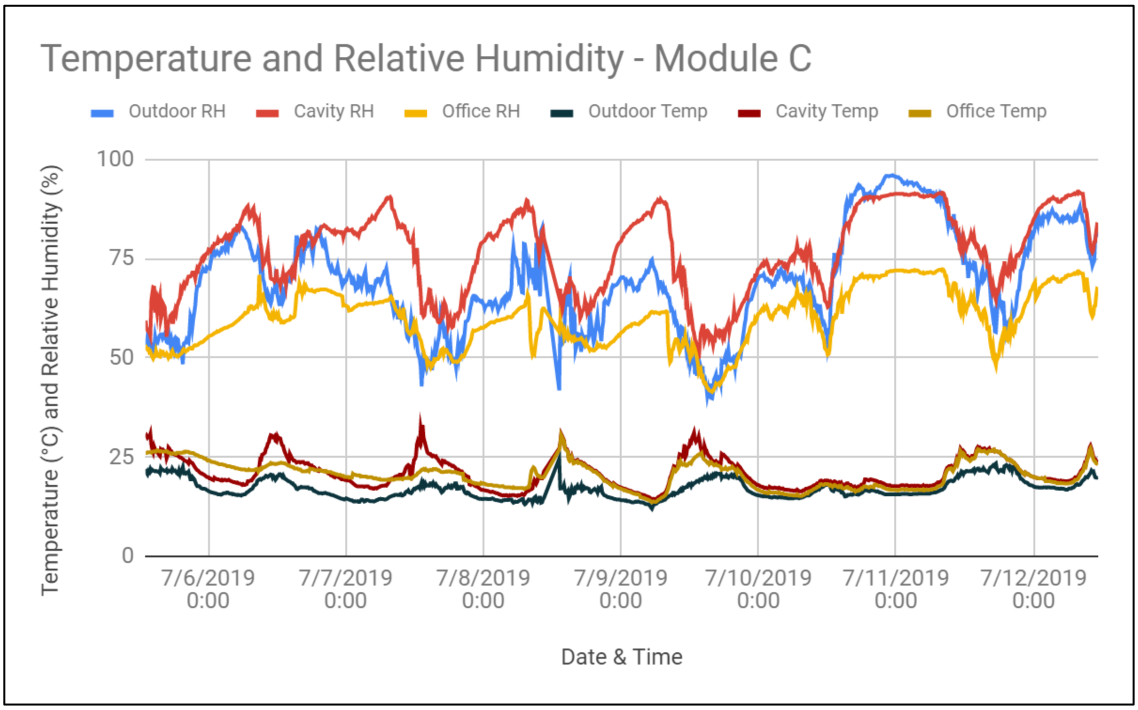


Figure 70 Temperature and Relative Humidity in module C - Week 3

Figure 70 shows the behaviour of the mechanically ventilated module C. This module shows similar behaviour to module A. This may be due to the fact that the mechanical ventilation was not functional most of the time, as the temperature inside the cavity did not reach beyond 24°C. In this case, the relative humidity in the cavity is higher than that of the office throughout the week, unlike what was seen in module B. On the days with higher outdoor relative humidity, the relative humidity in the office was observed to be considerably less than that of the cavity. The role of mechanical ventilation can be observed on the 5th , 6th and the 7th of July, as the relative humidity in the cavity is higher than the office, in spite of having a higher temperature.

6.4.4 Module D

The performance of module D was observed to be similar to module A. Hence the values shown by module D after the 8th of July gives an idea of the behaviour experienced in module A. The temperature and relative humidity in module D is given below. The illuminance and air quality in this module is given in the appendix.

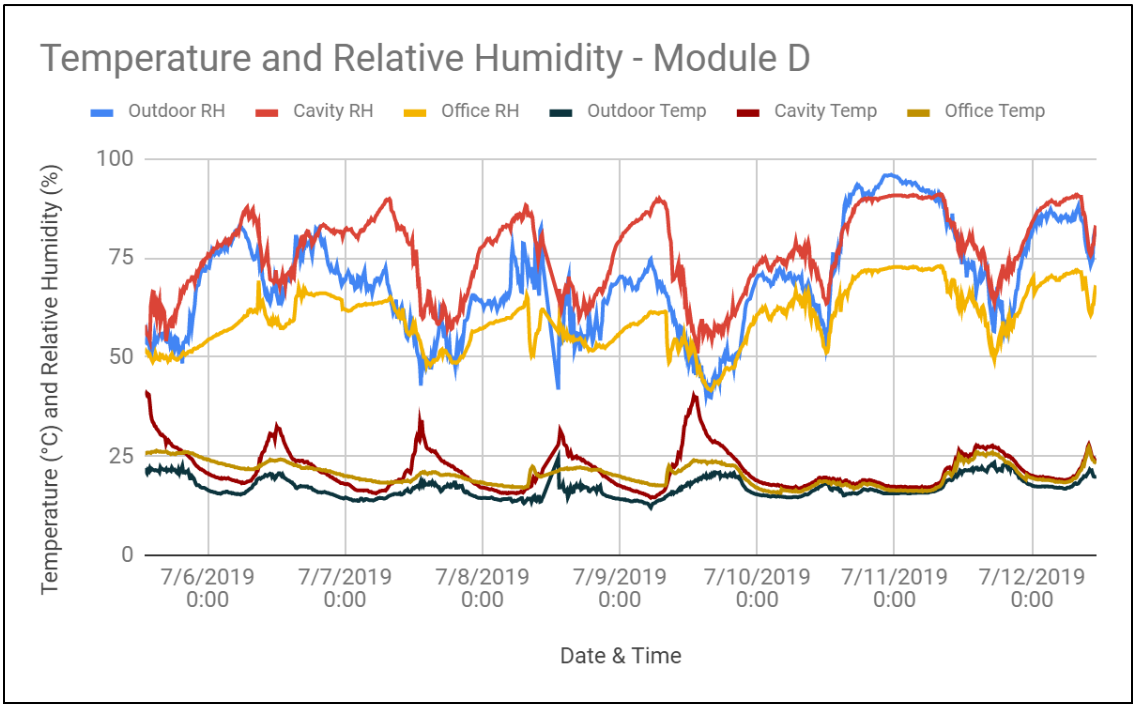


Figure 71 Temperature and Relative Humidity in Module D - Week 3

The figure above shows the trend in the temperature and relative humidity in module D. It is seen that the relative humidity in the cavity is higher than that of the office throughout the week. On the 9th of July at 12:55, the temperature in the cavity was recorded to be 40.1°C, while the outdoor temperature was recorded to be 18.5°C. This may be due to the effect of the solar radiation on the cavity, which was recorded as 922 W/m^2 (KNMI, 2019). However, the relative humidity in the cavity at this point was observed to be higher than the outdoor and the office relative humidity, with a value of 55.8%. This might be due to the role of the plants in the cavity, which humidifies the air in the cavity. This can be compared with the preliminary test that was done on the 20th of April, where a temperature sensor was kept in the cavity, and the maximum temperature was recorded to be 51.9°C, with a corresponding humidity of 13%. The results for this test are shown in Appendix A. This comparison shows the role of the plants on influencing the relative humidity in the cavity.

6.4.5 Module E

The performance of module E with respect to temperature and relative humidity was similar to that of what was observed in module B. This can be seen in the results from the data logging of module E. Figure 72 below shows the climatic performance of module E with respect to the temperature and relative humidity in the cavity and in the office.

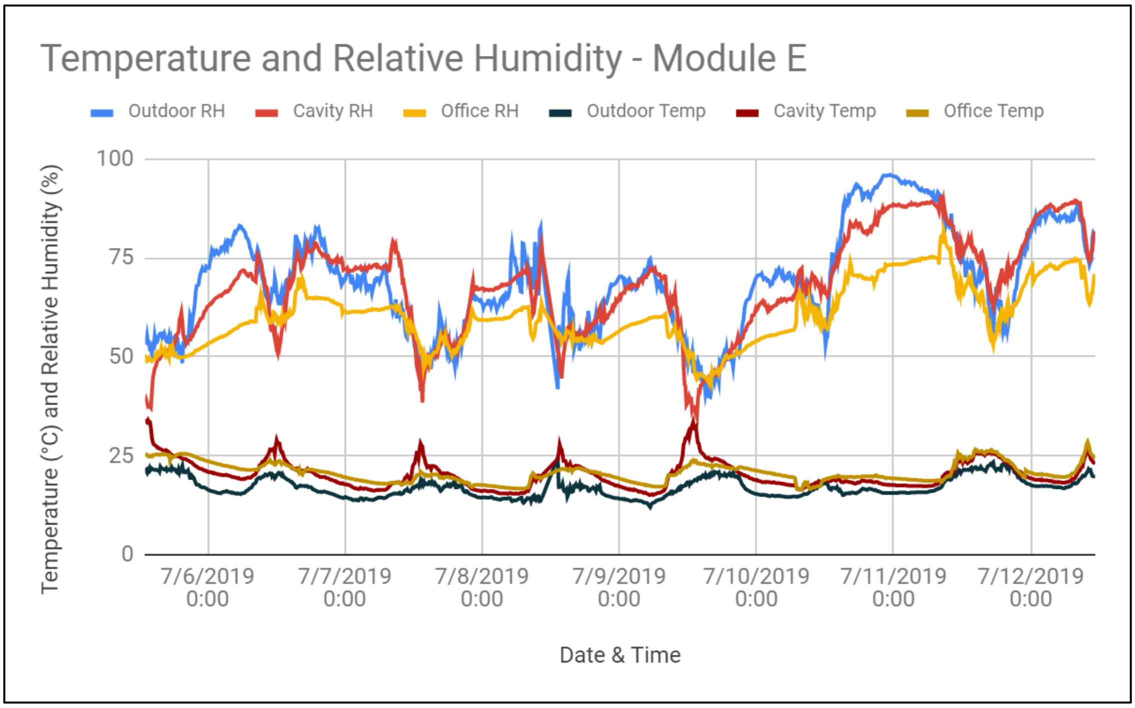


Figure 72 Temperature and Relative Humidity in Module E - Week 3

6.4.6 Module F

The mechanically ventilated module F showed similar characteristics with respect to temperature and relative humidity in the cavity and the office to module C. The humidity in the cavity corresponded to the high outdoor humidity on the 10th and 11th of July. This is represented in Figure 73 below. The illuminance and air quality is represented in the appendix.

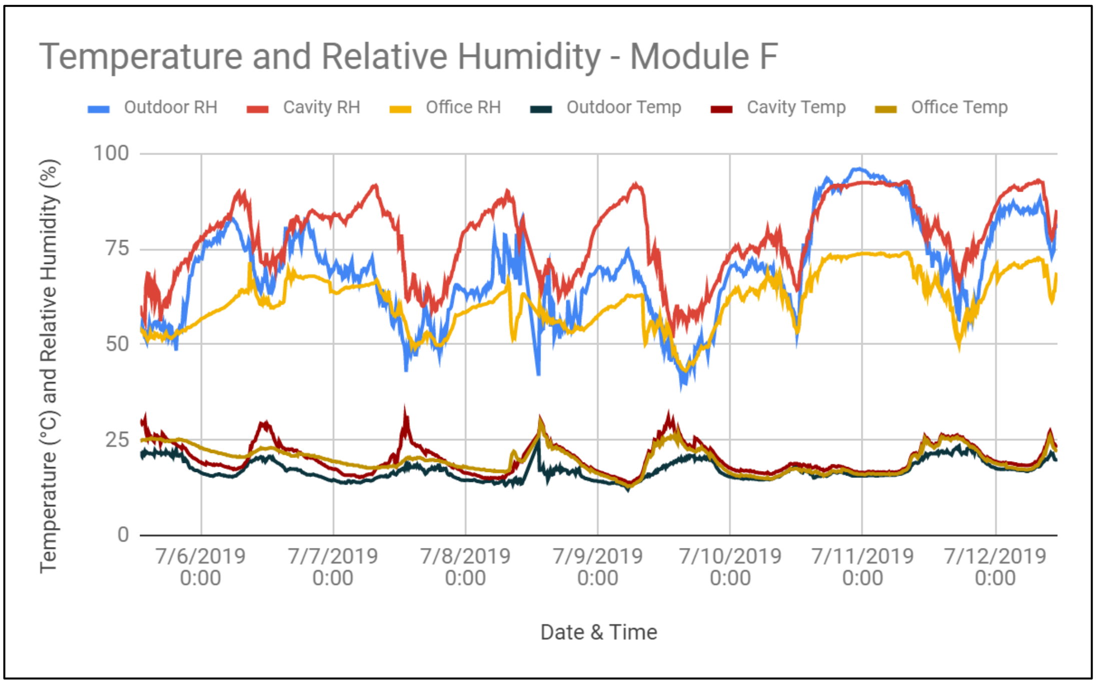


Figure 73 Temperature and Relative Humidity in Module F - Week 3

6.4.7 Combined Evaluation: Temperature and Relative Humidity - Cavity

The temperature and the relative humidity in all the cavities were compared to each other to get an idea on how the different design strategies in each cavity influenced one another. The trend in the temperature and relative humidity in the cavities is graphically represented below in Figure 74 a) and b).

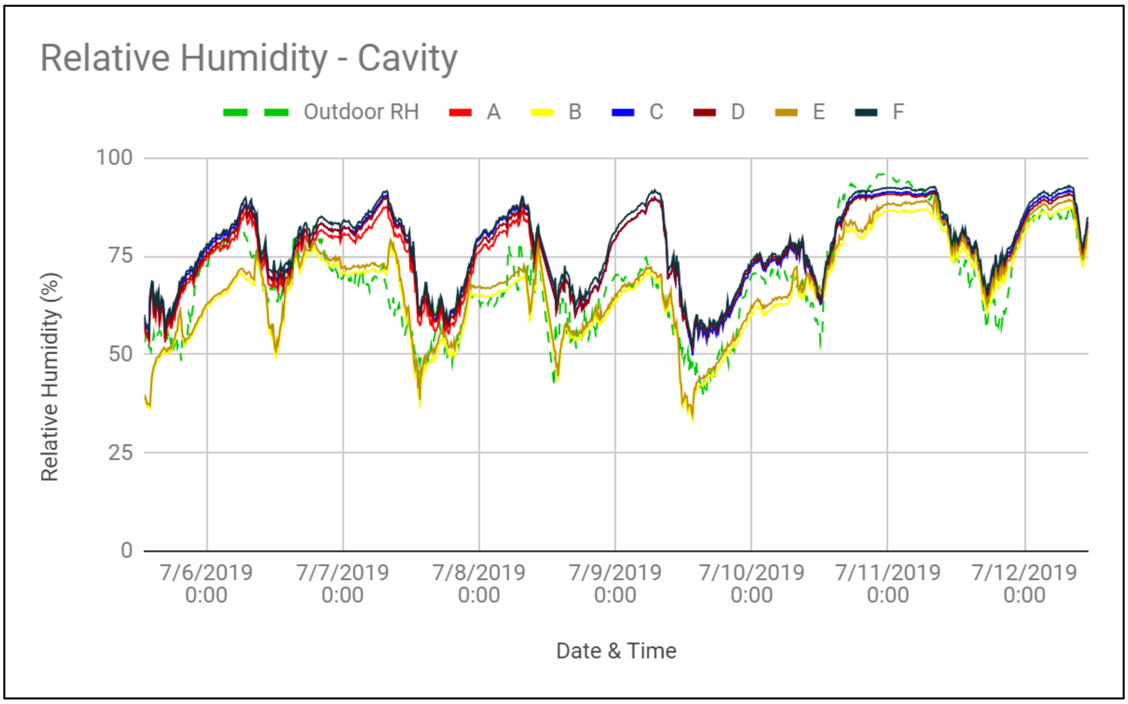


Figure 74 a) Relative Humidity in all the cavities - Week 3

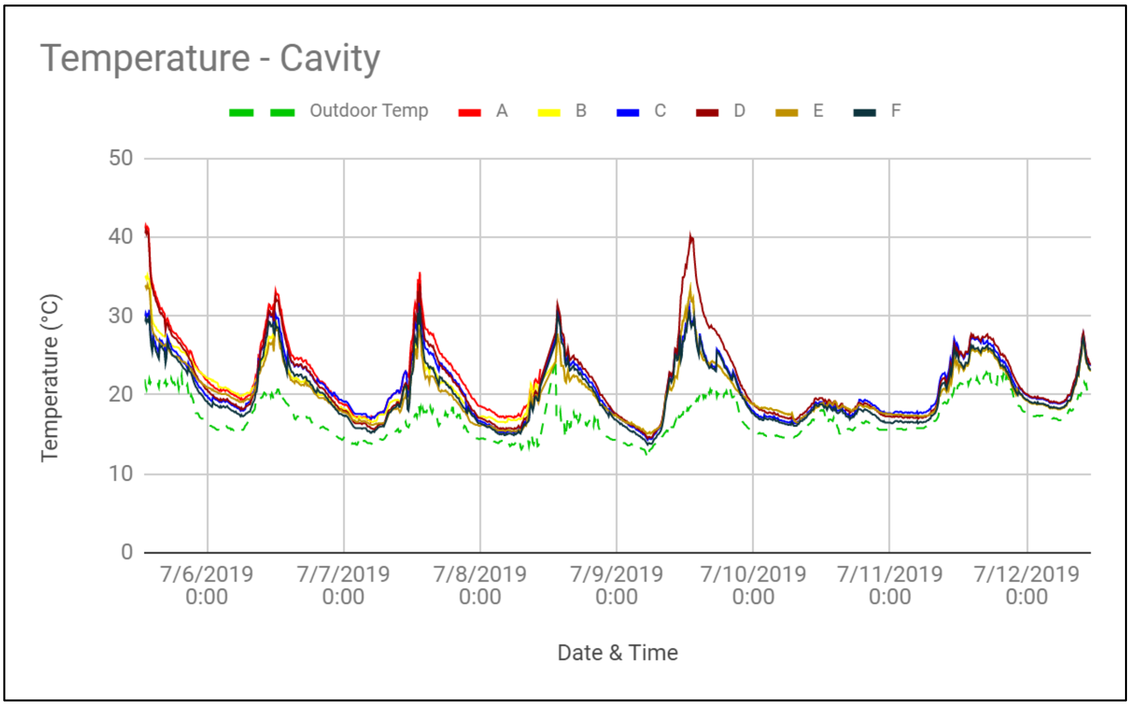


Figure 74 b) Temperature in all the cavities - Week 3

Figure 74 a) and b) shows the comparison between the relative humidity and temperature in all the modules. The dashed line represents the outdoor temperature and relative humidity. It can be observed that the relative humidity in cavity A & D is similar to the relative humidity in cavity C & F. This can in fact be observed when the temperature in the respective cavities are below 24°C. This is because cavities C & F act as cavity A & D when the temperature in the cavity is below 24°C. The maximum temperature was recorded from cavity A on the 5th of July at 13:15 with a value of 41.5°C. cavity D showed a temperature of 40.9°C. The temperatures in the naturally ventilated modules at this point were recorded to be 34.9°C and 33.7°C respectively. The mechanically ventilated modules C & F showed lower temperatures of 30°C and 29.3°C respectively. The maximum relative humidity was recorded from module F on the 12th of July at 7:55 with a value of 92.9%. The minimally ventilated module D showed values of a similar range of values at this point, however, cavity B showed a slightly lower value of 87.6%. Overall, the temperatures in all the modules were higher than the outdoor temperature throughout the week.

6.4.8 Combined Evaluation: Temperature and Relative Humidity - Office

The temperature and relative humidity in the office space corresponding to all the modules were compared to each other. This was done to check how much the design strategies adopted in each of the modules influence the condition in the office spaces. This is graphically represented in Figure 75 a) and b) below

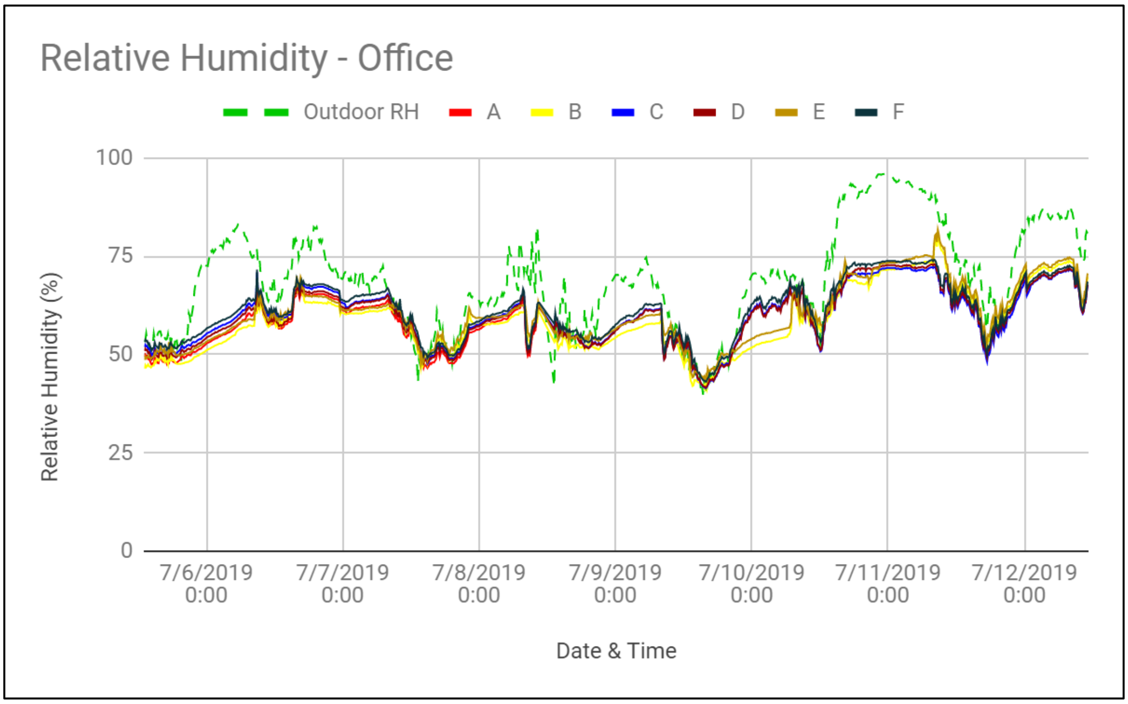


Figure 75 a) Relative humidity in all the office spaces – Week 3

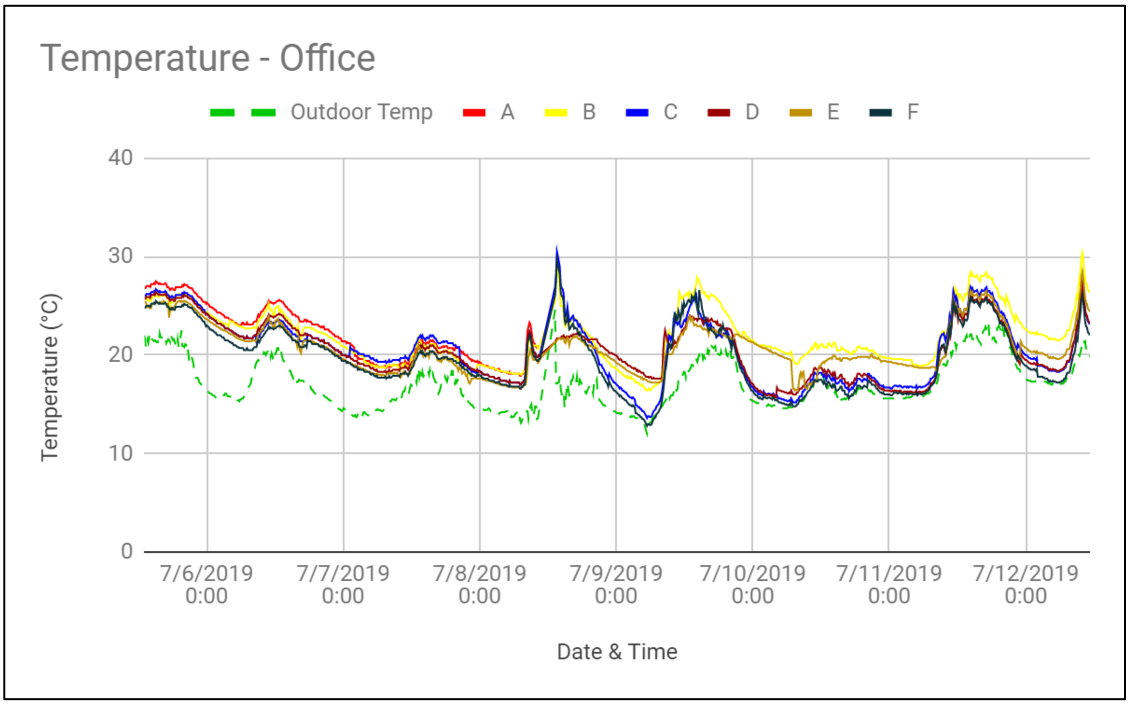


Figure 75 b) Temperature in all the office spaces - Week 3

The trend in the relative humidity and temperature in the office spaces corresponding to all modules is graphically represented above in Figure 75 a) and b). The relative humidity in all the modules seem to have a similar trend to each other. The magnitude of change in the relative humidity in all the modules are less than that of the outdoor relative humidity. On the 10th of July, it is observed that the relative humidity in module B and E is considerably less than the relative humidity in the rest of the modules. The maximum temperature was recorded from module C on the 8th of July at 13:35 with a value of 30.5°C. The maximum relative humidity was recorded from module E on the 11th of July at 8:45, with a value of 81.7%.

6.4.9 Illuminance

The illuminance in each module was recorded and compared along with the external illuminance. Figure 76 a) and b) shows the illuminance in cavity A to F throughout the week. The illuminance was not recorded in cavity A from the 8th to 12th of July.

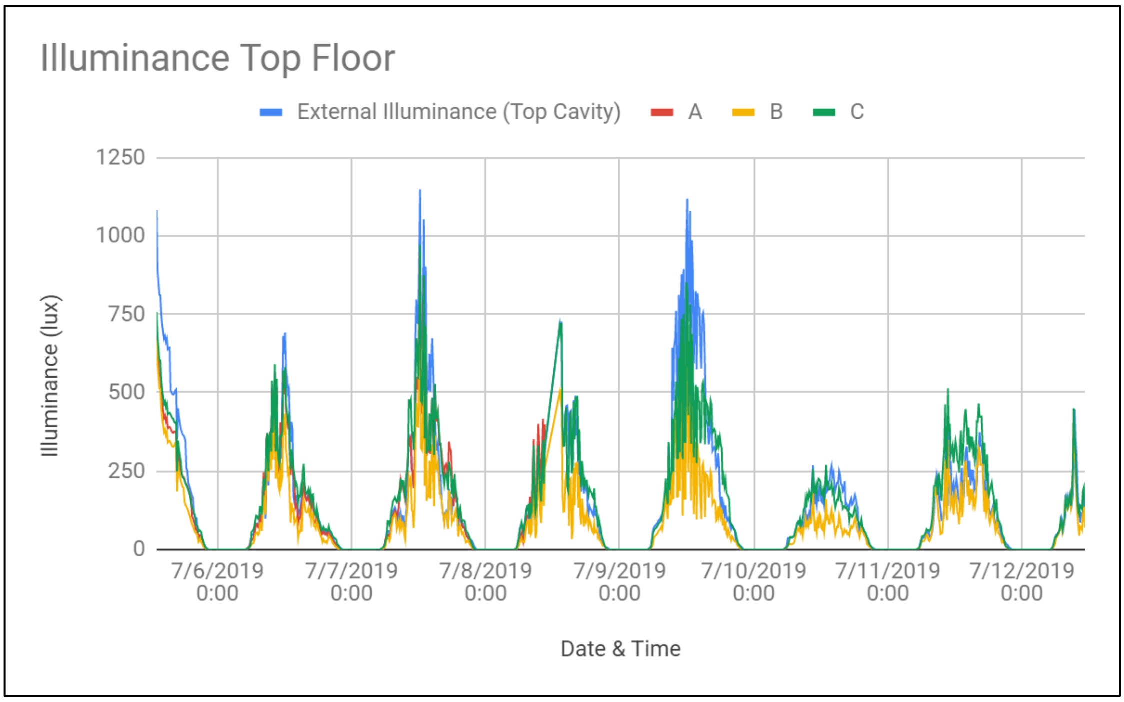


Figure 76 a) Illuminance in the top floor - Week 3

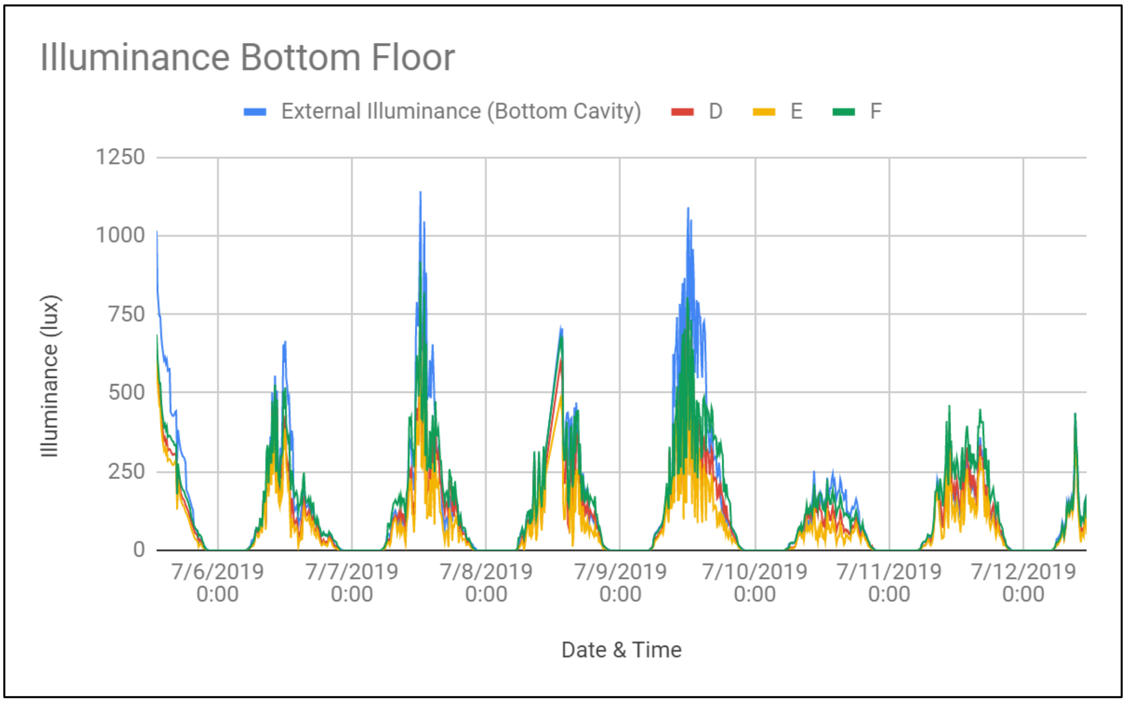


Figure 76 b) Illuminance in the bottom floor - Week 3

The figure above shows the illuminance recorded in the modules on the top and bottom floor. The variables 'External Illuminance (Top Cavity)' and 'External Illuminance (Bottom Cavity)' represent the illuminances recorded by the sensors kept in cavity B and E respectively. It is observed that the external illuminances reached above 1000 lux on the afternoons of 7th and 9th of July. The maximum solar radiation observed on these days were 644 W/m^2 and 922 W/m^2 respectively. On the 10th of July, the illuminance was recorded to be less than 250 lux. The maximum solar radiation observed at this time was 186 W/m^2. Although the absolute values of the illuminance do not correspond to the expected external illuminance, the reduction shown in the illuminance corresponds to the change in the solar radiation obtained from (KNMI, 2019). Moreover, the illuminance in the office space of all the modules seem to be less than the external illuminance on both the floors.

6.4.10 Air Quality

The air quality in the cavities of all the modules were recorded in for the third week. However, the air quality of cavity A was only logged till the 8th of July. The CO_2 and TVOC levels were determined in the cavities of each module on both the floors. None of the side windows in the office were open or closed during this period. The trend in the CO_2 and TVOC levels for all the cavities is graphically represented in Figure 77 a) below.

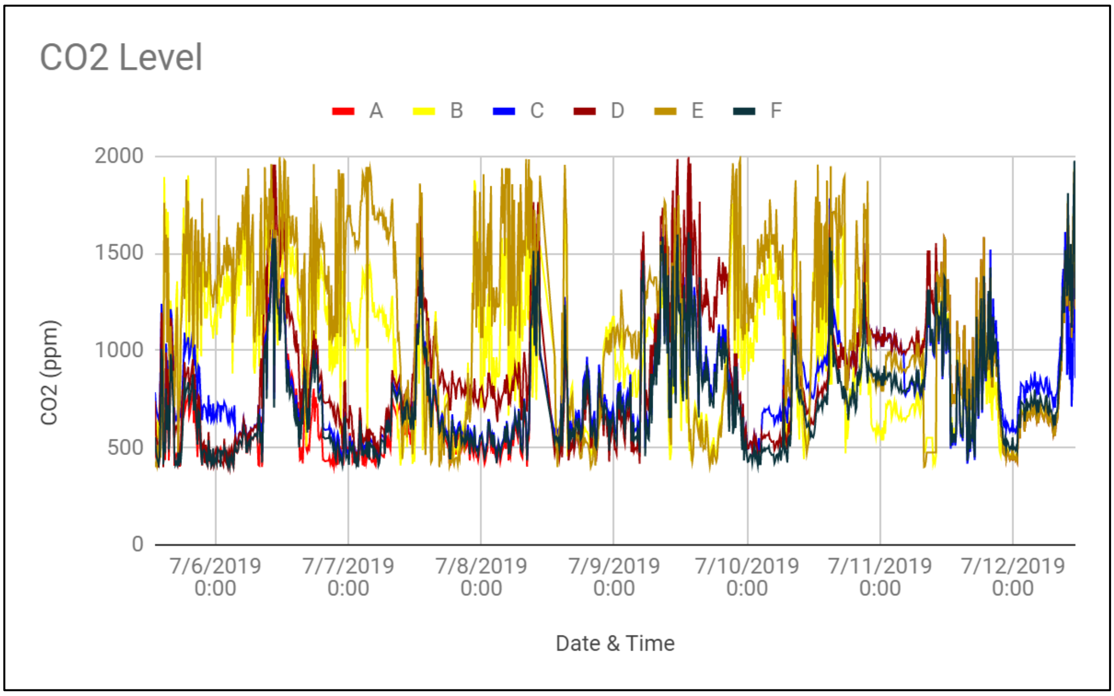


Figure 77 a) CO2 levels in the cavities - Week 3

The figure above represents the CO_2 levels in the cavities of all the modules. In spite of the continuous fluctuations observed in the values in each cavity, it is seen that cavities B and E predominantly have higher levels of CO_2 compared to the rest of the modules. This is highlighted on the 6th , 7th and the 10th of July. This may be due to the influence of higher CO_2 levels from the office. However, the maximum CO_2 level was recorded from cavity C on the 9th of July at 13:25 with a value of 1996 parts per million. The TVOC levels in the cavities corresponded to the level of CO_2 in the cavities of all the modules. The maximum TVOC level was recorded from cavity B on the 5th of July at 19:45 with a value of 240 parts per billion. The level of TVOC in the modules is graphically represented in Figure 77 b) below

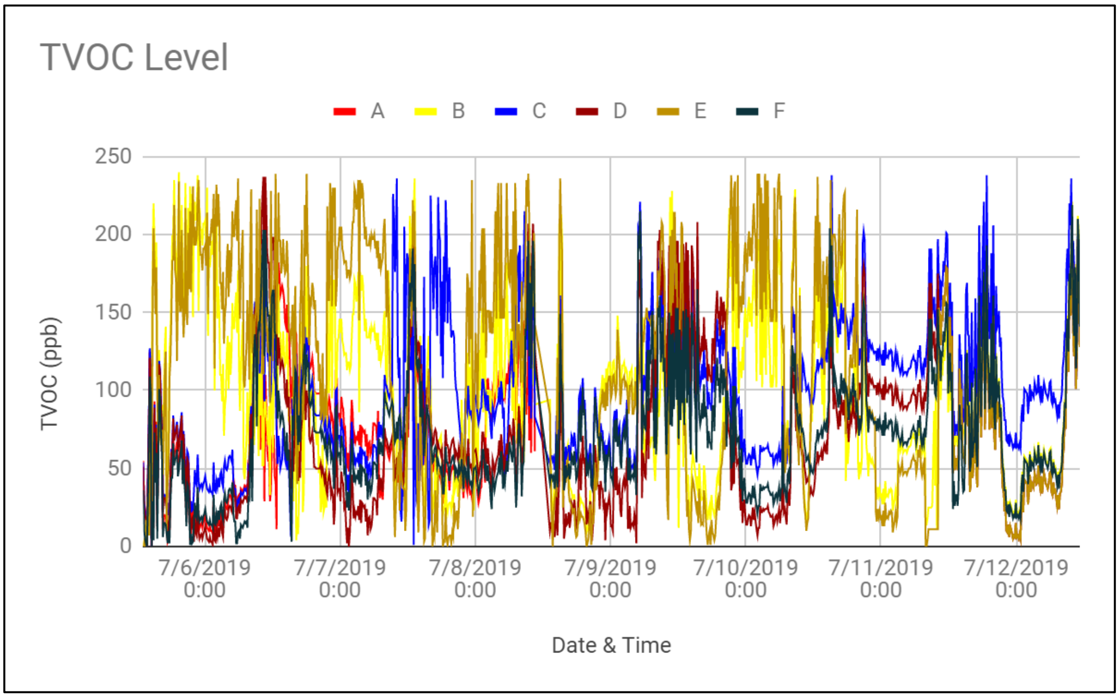


Figure 77 b) TVOC levels in the cavities -Week 3

6.5 CONCLUSION

The results have been formulated for the three weeks of data logging. The logging started from the 20th of June and ended on the 12th of July. The trends in the temperature, relative humidity, illuminance, CO_2 and TVOC levels were combined over the course of three weeks. The graphical representations of the compiled parameters are given in Appendix A. The behaviour of each module with respect to the different parameters were analysed and change in the trends were compared to each other. These values are used to evaluate the performance of the façade modules, which will be elaborated in the next chapter.

One of the highlights from the experiment is the use ventilation in controlling the air temperature in the cavity as well as in the building. This was discussed in section 3.3 in chapter 3. One of the aim from the ventilation strategy was to figure out whether the module configuration pre heats or pre cools the air during high external temperature.

From the previous section, it can be noted that the air temperature in cavity C and F at a point during week 1 is 10°C less than the outdoor temperature, whereas the office temperature is 4°C less than the outdoor temperature. This can be observed in figure 52 b) and 53 b). The office temperature is observed to be higher than the cavity temperature. This may be due to the fact that the relative humidity in the cavity is considerably higher than that of the office. This can be observed in figure 52 a) and 53 a).

Another method was used to find out the influence of ventilation on the building. The difference between the temperatures in the cavity and office of module C and F were noted for the period of the second week, in order to find out whether the office temperature was higher or lower than the temperature in the cavity.

Overall it can be concluded that the design strategy applied in this case, cools the office by reducing the temperature of up to 4°C. In the case of naturally ventilated modules, the reduction in temperature is less compared to what was observed in the mechanical ventilation. This may be a result of cooling due to a higher ventilation rate.

For both the modules, it was observed that the temperatures in the office during the nights were 3 to 6°C more than that of the cavity. During the afternoons, at times with high outdoor temperatures, the temperature in the offices were 4 to 10°C less than that of the cavity. This indicates that the air is preheated during the night and precooled during the day. This is graphically represented in section 12 in appendix A.

The absolute humidity was calculated in the cavities of each module over the course of 3 weeks. It was noticed that the minimally ventilated modules (A & D) had higher values of absolute humidity as compared to the mechanically ventilated (C & F) and naturally ventilated (B & E) modules. The least values were shown from cavity B and E. This was due to the fact that the air in the cavity interacted with the dryer air in the office, thus reducing the absolute humidity of the air. This is graphically represented in section 13 in Appendix A.

The influence of the plants in the cavity was also evaluated by the comparison of measurements obtained during the 20th of April to the measurements obtained in on the 29th of June during the first week. The air temperature and relative humidity in cavity A and the outdoor temperature and relative humidity were taken in to account for both cases and the comparison was made. The container doors on the 20th of April were open 90° and the cavity had no plants. On the 29th of June, the container doors were open up to 45° and the cavity was filled with plants. It was observed that the temperature in the cavity went up to 52°C for an outdoor temperature of 24°C and the relative humidity dropped to 12% when the outdoor relative humidity was 25% on the 20th of April. However, on the 29th of June, the temperature in the cavity was restricted to 39°C with an outdoor temperature of 25°C. Subsequently, the relative humidity in the cavity did not drop below 50% during an outdoor relative humidity of 25%.

The reason for such differences may be due to the shading strategy and the action of plants. The evapotranspiration by plants increases the moisture content in the air which in this case, is not ventilated with dryer air, thus increasing the relative humidity in the cavity. Since the container doors were partially open on the 29th of June, the modules provided shading, thus reducing the temperature in the cavity. This is graphically represented in section 11 in Appendix A.

Hence it can be concluded that shading and the action of plants have a considerable impact in reducing the temperature and increasing the relative humidity in the cavity, even in the case of the minimally ventilated modules.

CHAPTER 7 – EVALUATION

7.1 OVERVIEW

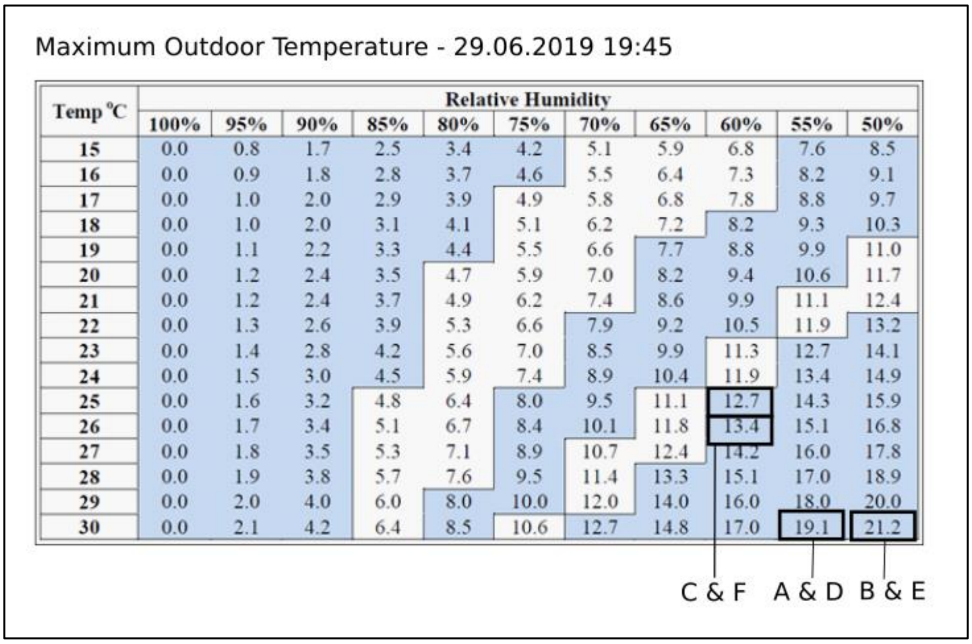
After the data logging was performed, and the climatic behaviour of each module was analysed, the data was processed to evaluate the performance of each module. This includes the conditions in the cavity for the growth of the plants (temperature, relative humidity and air quality) and the conditions in the offices (thermal and shading effect). For the condition of the plants, the temperature and relative humidity in the cavity during the time of data logging was taken into consideration, and was correlated to the required vapour transfer deficit for plants in general, as given in Figure 7 (section 2.7). The temperature and relative humidity in the office was compared to the psychrometric chart given in Figure 3 (section 2.2). The performance of each module with respect to the parameters is compared to the amount of peppers harvested from each module and the health of the plants.

7.2 THERMAL CONDITIONS – PLANTS

To evaluate the condition of the growth of the plants, the temperature and relative humidity in the each cavity was taken into account and compared to each other in accordance to four scenarios, namely maximum outdoor temperature, minimum outdoor temperature, maximum outdoor relative humidity and minimum outdoor relative humidity. The time of these conditions over the past three weeks were recorded, and the corresponding conditions of the cavities in these moments were compared to each other. The comparison for each scenario is represented in Appendix A. These values were correlated to Figure 7(section 2.7) in order to find out which module gave conditions closest to the ideal vapour transfer deficit shown in the air in the cavity.

7.2.1 Maximum Outdoor Temperature

The maximum outdoor temperature in the three weeks was recorded on the 29th of June, at 19:45. The conditions in all the cavities were noted on this time and compared to each other. The correlation with the vapour transfer deficit table is given in figure 78 below.



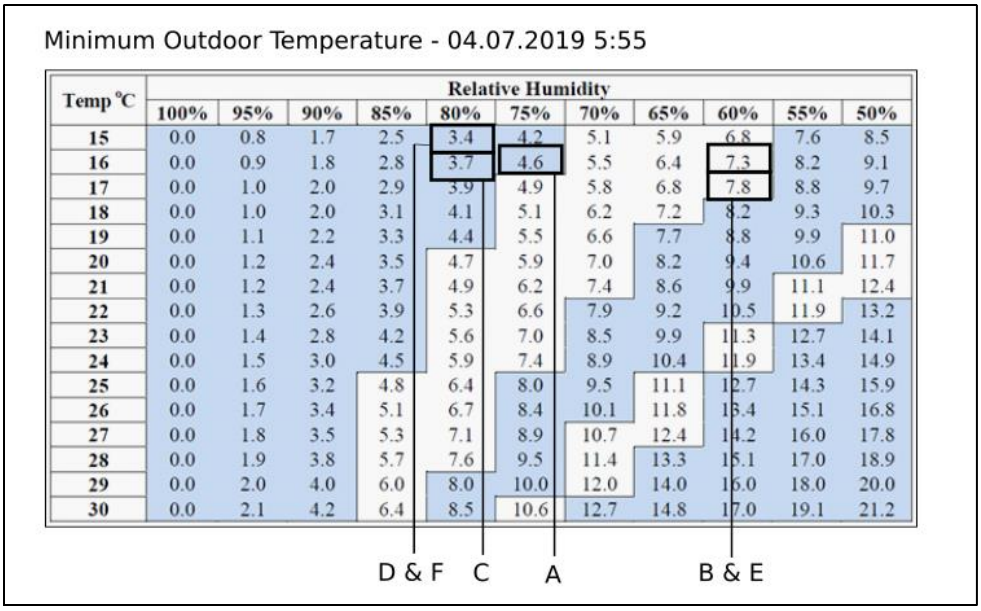
Temp °C	Relative Humidity										
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%
15	0.0	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6	8.5
16	0.0	0.9	1.8	2.8	3.7	4.6	5.5	6.4	7.3	8.2	9.1
17	0.0	1.0	2.0	2.9	3.9	4.9	5.8	6.8	7.8	8.8	9.7
18	0.0	1.0	2.0	3.1	4.1	5.1	6.2	7.2	8.2	9.3	10.3
19	0.0	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0
20	0.0	1.2	2.4	3.5	4.7	5.9	7.0	8.2	9.4	10.6	11.7
21	0.0	1.2	2.4	3.7	4.9	6.2	7.4	8.6	9.9	11.1	12.4
22	0.0	1.3	2.6	3.9	5.3	6.6	7.9	9.2	10.5	11.9	13.2
23	0.0	1.4	2.8	4.2	5.6	7.0	8.5	9.9	11.3	12.7	14.1
24	0.0	1.5	3.0	4.5	5.9	7.4	8.9	10.4	11.9	13.4	14.9
25	0.0	1.6	3.2	4.8	6.4	8.0	9.5	11.1	12.7	14.3	15.9
26	0.0	1.7	3.4	5.1	6.7	8.4	10.1	11.8	13.4	15.1	16.8
27	0.0	1.8	3.5	5.3	7.1	8.9	10.7	12.4	14.2	16.0	17.8
28	0.0	1.9	3.8	5.7	7.6	9.5	11.4	13.3	15.1	17.0	18.9
29	0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0
30	0.0	2.1	4.2	6.4	8.5	10.6	12.7	14.8	17.0	19.1	21.2

Figure 78 Vapour Transfer Deficit of Modules during maximum temperature

The figure above shows the relation between temperature, relative humidity and the vapour transfer deficit in millibar. The ideal vapour transfer deficit amount is 8 to 10 millibar (blue shaded area in the middle) (British Columbia Ministry of Agriculture, 2015). It is seen that none of the modules reach an ideal vapour transfer deficit level. Hence it can be observed that the condition of the air is dryer than it needs to be during the maximum temperature. Cavities C & F relatively performed better at this time, but still needs to be humidified.

7.2.2 Minimum Outdoor Temperature

The minimum outdoor temperature was recorded on the 4th of July at 5:55, with a value of 11.4°C. The vapour transfer deficit of the modules at this time are given below in Figure 79.



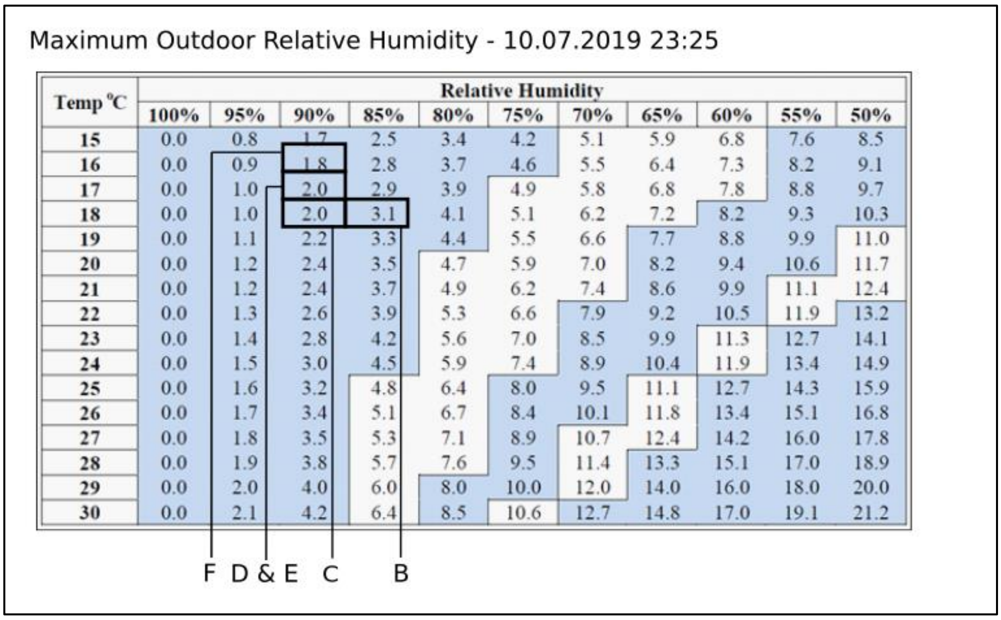
Temp °C	Relative Humidity										
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%
15	0.0	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6	8.5
16	0.0	0.9	1.8	2.8	3.7	4.6	5.5	6.4	7.3	8.2	9.1
17	0.0	1.0	2.0	2.9	3.9	4.9	5.8	6.8	7.8	8.8	9.7
18	0.0	1.0	2.0	3.1	4.1	5.1	6.2	7.2	8.2	9.3	10.3
19	0.0	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0
20	0.0	1.2	2.4	3.5	4.7	5.9	7.0	8.2	9.4	10.6	11.7
21	0.0	1.2	2.4	3.7	4.9	6.2	7.4	8.6	9.9	11.1	12.4
22	0.0	1.3	2.6	3.9	5.3	6.6	7.9	9.2	10.5	11.9	13.2
23	0.0	1.4	2.8	4.2	5.6	7.0	8.5	9.9	11.3	12.7	14.1
24	0.0	1.5	3.0	4.5	5.9	7.4	8.9	10.4	11.9	13.4	14.9
25	0.0	1.6	3.2	4.8	6.4	8.0	9.5	11.1	12.7	14.3	15.9
26	0.0	1.7	3.4	5.1	6.7	8.4	10.1	11.8	13.4	15.1	16.8
27	0.0	1.8	3.5	5.3	7.1	8.9	10.7	12.4	14.2	16.0	17.8
28	0.0	1.9	3.8	5.7	7.6	9.5	11.4	13.3	15.1	17.0	18.9
29	0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0
30	0.0	2.1	4.2	6.4	8.5	10.6	12.7	14.8	17.0	19.1	21.2

Figure 79 Vapour Transfer Deficit of modules during minimum outdoor temperature

From the figure above, it is seen that the cavities B & E perform relatively better, as the vapour transfer deficit levels are close to 8 millibar. This may be due to the lower relative humidity levels in the office at the time of the recording. The office was unoccupied at this time and there was minimal source of ventilation from outside, giving less chance for the relative humidity in the office to increase. In addition, the thermal mass of the building leads to higher temperatures inside the office. This overall has an effect on cavities B and E, as they are ventilated along with the air in the office.

7.2.3 Maximum Outdoor Relative Humidity

The maximum relative humidity was recorded on the 10th of July at 23:25. The correlation with the vapour transfer deficit table is given in Figure 80 below



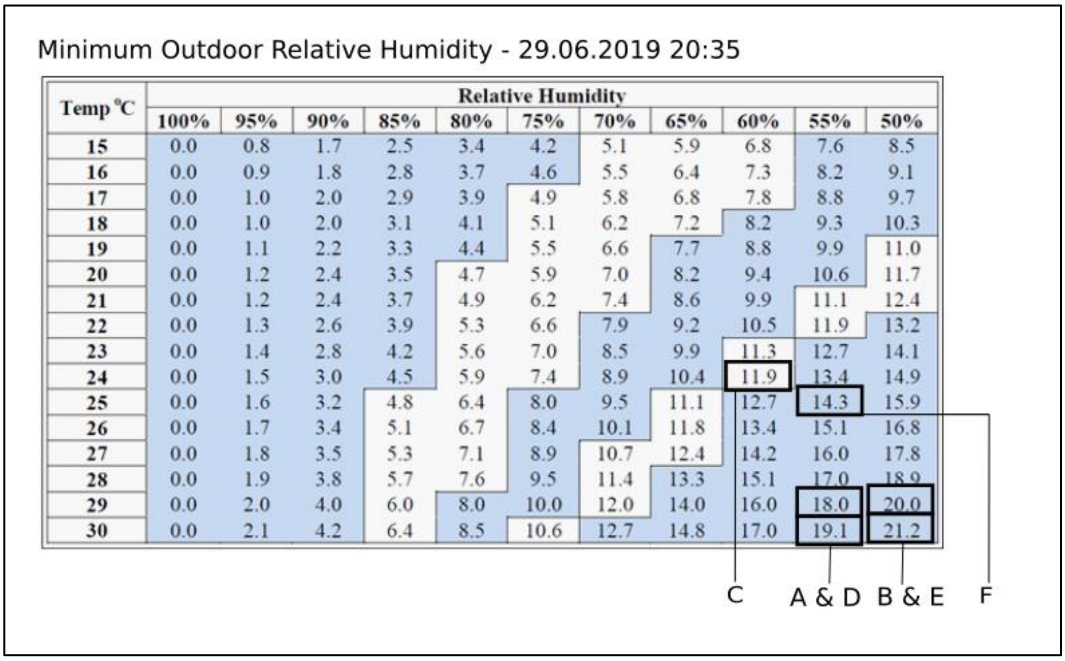
Temp °C	Relative Humidity										
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%
15	0.0	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6	8.5
16	0.0	0.9	1.8	2.8	3.7	4.6	5.5	6.4	7.3	8.2	9.1
17	0.0	1.0	2.0	2.9	3.9	4.9	5.8	6.8	7.8	8.8	9.7
18	0.0	1.0	2.0	3.1	4.1	5.1	6.2	7.2	8.2	9.3	10.3
19	0.0	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0
20	0.0	1.2	2.4	3.5	4.7	5.9	7.0	8.2	9.4	10.6	11.7
21	0.0	1.2	2.4	3.7	4.9	6.2	7.4	8.6	9.9	11.1	12.4
22	0.0	1.3	2.6	3.9	5.3	6.6	7.9	9.2	10.5	11.9	13.2
23	0.0	1.4	2.8	4.2	5.6	7.0	8.5	9.9	11.3	12.7	14.1
24	0.0	1.5	3.0	4.5	5.9	7.4	8.9	10.4	11.9	13.4	14.9
25	0.0	1.6	3.2	4.8	6.4	8.0	9.5	11.1	12.7	14.3	15.9
26	0.0	1.7	3.4	5.1	6.7	8.4	10.1	11.8	13.4	15.1	16.8
27	0.0	1.8	3.5	5.3	7.1	8.9	10.7	12.4	14.2	16.0	17.8
28	0.0	1.9	3.8	5.7	7.6	9.5	11.4	13.3	15.1	17.0	18.9
29	0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0
30	0.0	2.1	4.2	6.4	8.5	10.6	12.7	14.8	17.0	19.1	21.2

Figure 80 Vapour Transfer Deficit during maximum outdoor relative humidity

From the figure above it is observed that none of the modules have a vapour transfer deficit even close to what is considered ideal. The outdoor relative humidity at this point was recorded to be 96.0 %. All the modules seem to be too humid to obtain the ideal vapour transfer deficit. Hence dehumidification would be required.

7.2.4 Minimum Outdoor Relative humidity

The minimum outdoor relative humidity was recorded on the 29th of June at 20:35. The relative humidity was recorded to be 24% while the temperature was 34°C. The performance of the modules with respect to the vapour transfer deficit is given in figure 81 below.



Minimum Outdoor Relative Humidity - 29.06.2019 20:35

Temp °C	Relative Humidity										
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%
15	0.0	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6	8.5
16	0.0	0.9	1.8	2.8	3.7	4.6	5.5	6.4	7.3	8.2	9.1
17	0.0	1.0	2.0	2.9	3.9	4.9	5.8	6.8	7.8	8.8	9.7
18	0.0	1.0	2.0	3.1	4.1	5.1	6.2	7.2	8.2	9.3	10.3
19	0.0	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0
20	0.0	1.2	2.4	3.5	4.7	5.9	7.0	8.2	9.4	10.6	11.7
21	0.0	1.2	2.4	3.7	4.9	6.2	7.4	8.6	9.9	11.1	12.4
22	0.0	1.3	2.6	3.9	5.3	6.6	7.9	9.2	10.5	11.9	13.2
23	0.0	1.4	2.8	4.2	5.6	7.0	8.5	9.9	11.3	12.7	14.1
24	0.0	1.5	3.0	4.5	5.9	7.4	8.9	10.4	11.9	13.4	14.9
25	0.0	1.6	3.2	4.8	6.4	8.0	9.5	11.1	12.7	14.3	15.9
26	0.0	1.7	3.4	5.1	6.7	8.4	10.1	11.8	13.4	15.1	16.8
27	0.0	1.8	3.5	5.3	7.1	8.9	10.7	12.4	14.2	16.0	17.8
28	0.0	1.9	3.8	5.7	7.6	9.5	11.4	13.3	15.1	17.0	18.9
29	0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0
30	0.0	2.1	4.2	6.4	8.5	10.6	12.7	14.8	17.0	19.1	21.2

Figure 81 Vapour Transfer Deficit during minimum outdoor relative humidity

From the figure above, it is seen that the mechanically ventilated module C achieves a vapour transfer deficit of 11.9 millibar, which is the closest to the range of ideal values. The rest of the modules have high vapour transfer deficit values, and can be classified as relatively dry conditions for the plants. This may be due to the high outdoor temperature outside. Since module C is mechanically ventilated, the ventilation would humidify the air in the cavity, thus decreasing the vapour transfer deficit.

7.2.5 Conclusion

From the scenarios considered above, it is seen that the mechanically ventilated modules perform relatively better on the worst case scenarios with respect to high temperatures and low relative humidity. The naturally ventilated module perform better on colder periods, as the humidity is reduced due to the dry conditions in the office. Hence it can be concluded that the mechanically ventilated cavities have more endurance on hotter time periods whereas the naturally ventilated cavities perform better during colder and more humid periods. However, it should be taken into account that these are just the worst case scenarios. The performance of the cavities may have differed during other periods of the experiment. This will be validated by checking the yield and health of the plants in the following sections.

7.3 THERMAL CONDITIONS – OFFICES

To evaluate the thermal conditions of the office spaces in the modules, the temperature and relative humidity from each of the office spaces were taken into consideration, and were correlated to the psychrometric chart shown in Figure 3 (section 2.2). Two scenarios were taken in this case, namely the maximum outdoor temperature and the maximum outdoor relative humidity. The values obtained from the sensors were correlated with respect to these two scenarios in order to find if the conditions lie within the comfort zones.

7.3.1 Maximum Outdoor Temperature

The values from each office module was recorded during the time of the maximum outdoor temperature. The relation between temperature and relative humidity is given in Figure 82 below.

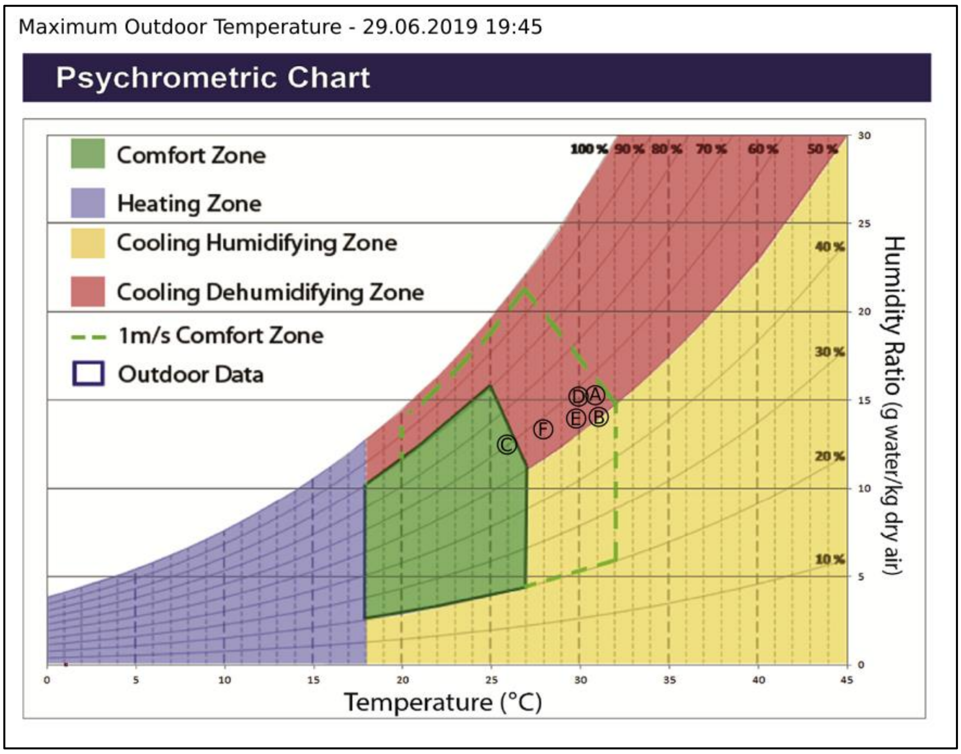


Figure 82 Position of each module during maximum outdoor temperature

From the figure above, it can be seen that all the modules lie within the comfort zone. However, module C lies in the most comfortable zone with a value of 26°C and 60%. This may be due to the mechanical air supply by the mechanical ventilation. The rest of the modules seem to show similar values. This may indicate that the conditions in the office are not directly influenced by the design of the façade. Since each zone is connected to one common office space, it is difficult to determine the effect of one single module on the conditions in the office.

7.3.2 Maximum Outdoor Relative Humidity

The maximum outdoor relative humidity was recorded to be 96% with a corresponding temperature of 15.6°C. The values in the modules were noted at this point and compared to each other. This is given in figure 83 below

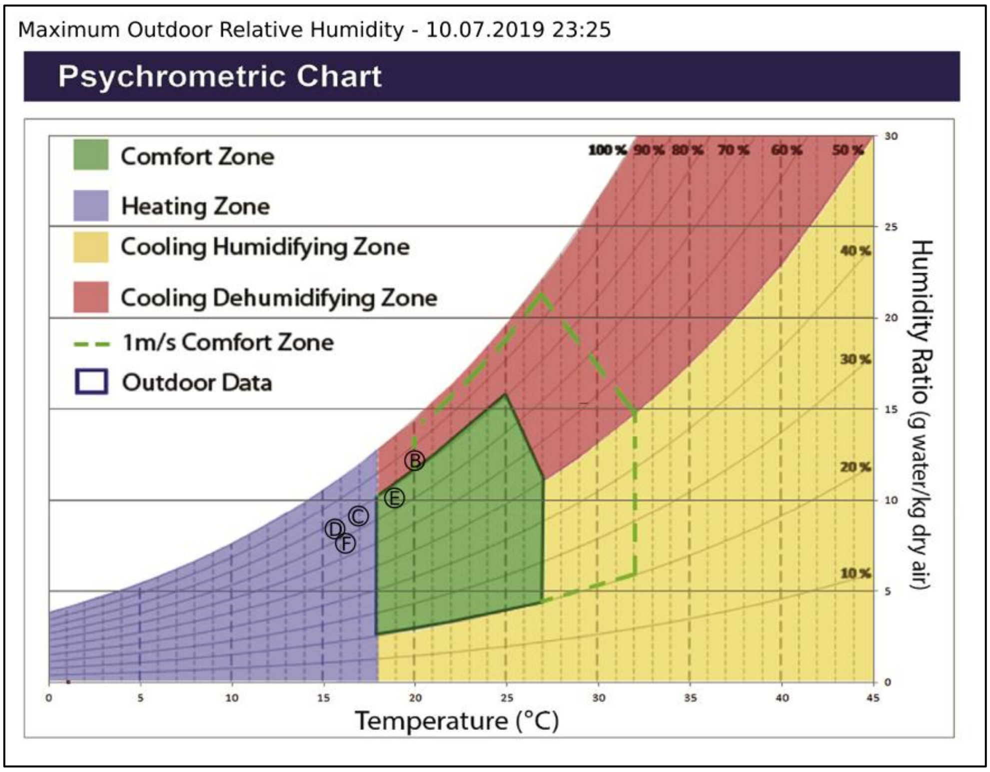


Figure 83 Position of each module during maximum outdoor relative humidity

From the figure above, it is observed that cavity B and E lie in the comfort zone. However, the rest of the cavities are in a colder zone. Hence it can be said that the naturally ventilated module perform relatively better compared to the rest of the modules on colder periods.

7.3.3 Overall comfort comparison

The comfort levels of all the modules were compared to each other with respect to the comfort zone as defined in the psychrometric chart. The daily average temperature and relative humidity for all the cavities over the course of three weeks were recorded and plotted in the psychrometric chart to evaluate whether the conditions in each module fall under the comfort zone. This is graphically represented below in figure 84.

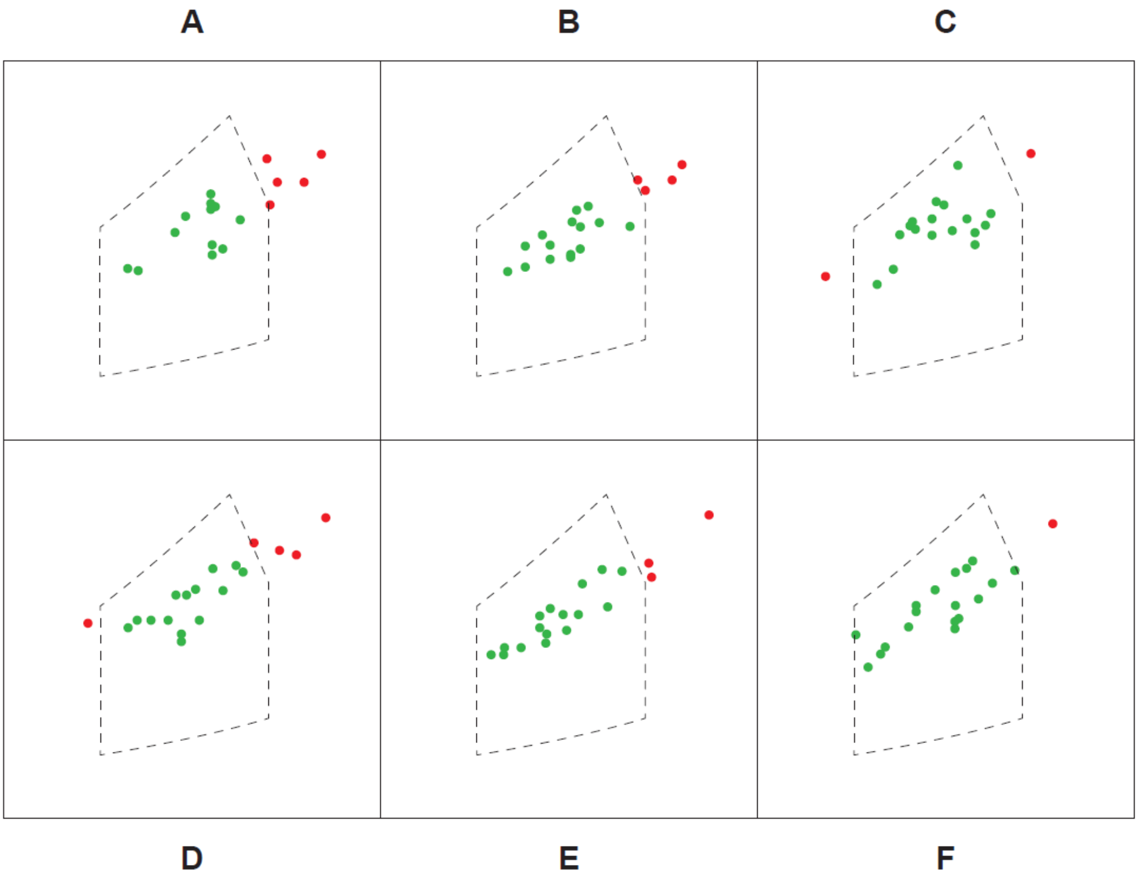


Figure 84 Comparison of all modules with respect to the comfort zone in the psychrometric chart

7.3.3 Conclusion

Two scenarios were taken to evaluate the thermal conditions in the office spaces. One with extreme high temperature (low relative humidity) and the other with high relative humidity (low temperature). For the former case, it can be concluded that module C lies in the relatively better zone compared to the rest of the modules. For the latter of the two cases, it is observed that the spaces behind the naturally ventilated cavities lie in a better zone.

Moreover, in figure 84, it can be observed that modules C and F have the least number of daily average data falling outside the comfort zone, whereas modules A and D have a considerable amount of daily averages that are outside the comfort zone. Hence with respect to comfort in the office, it can be concluded that modules C and F perform relatively better.

7.4 ILLUMINANCE

The illuminance in each module was compared per floor. The maximum external illuminance in the three weeks was recorded, and the illuminance in the offices at that time were recorded to be compared. This was done to get an idea on the shading effect provided by the design of the façade. The comparison of the illuminance in the modules are given in Figure 85 a) and b) below.

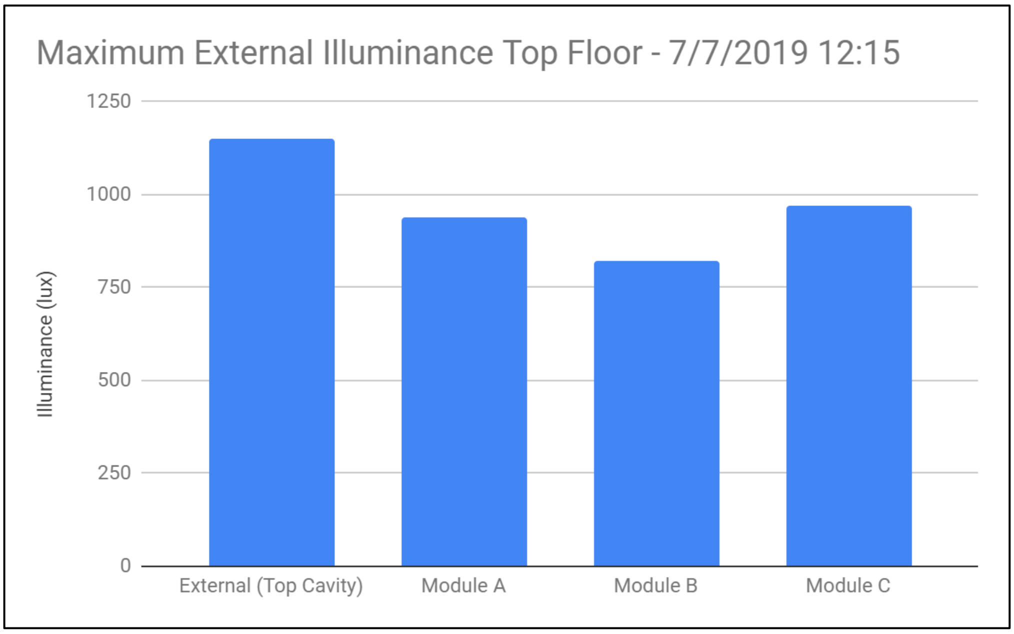


Figure 85 a) Illuminance in office spaces in the top floor during maximum illuminance

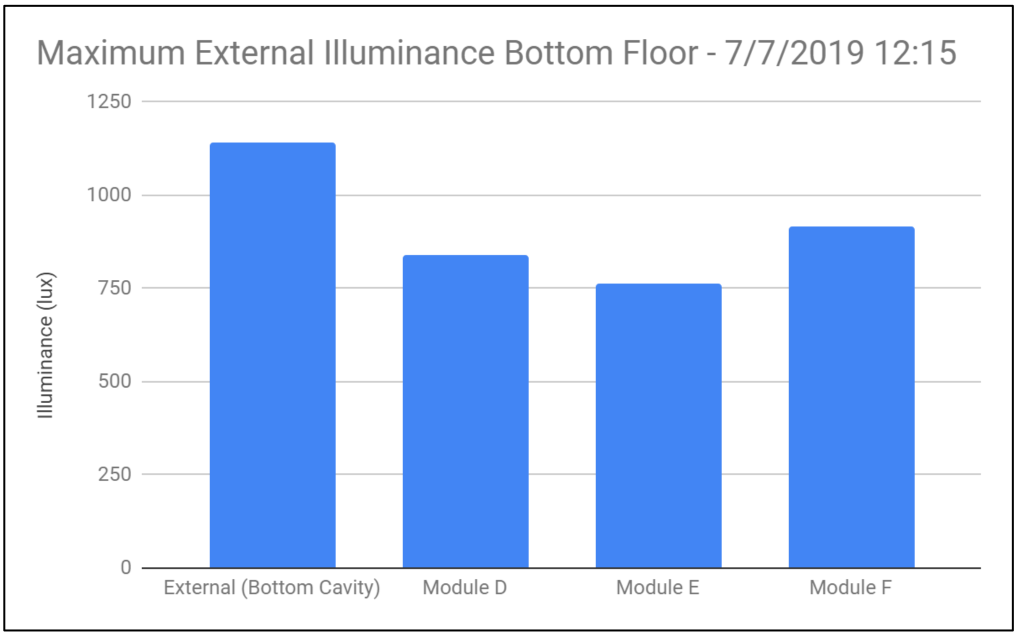


Figure 85 b) Illuminance in the office space in the bottom floor during maximum illuminance

The figure above shows the comparison of each of the modules with respect to the external illuminance on the top and bottom floor respectively. From the figure, it is clear that module B has the least illuminance (820 lux) compared to the external illuminance (1149 lux). In the bottom floor, the external illuminance was recorded to be 1142 lux and module E had an illuminance of 764 lux. Hence it can be concluded that module E had the highest shading effect during the time of the maximum illuminance, with a difference of 378 lux.

7.5 AIR QUALITY

Since the air quality of each constantly fluctuated throughout the experiment, an average of all the CO_2 and TVOC levels were taken into account and compared to each other. This is given in figure 86

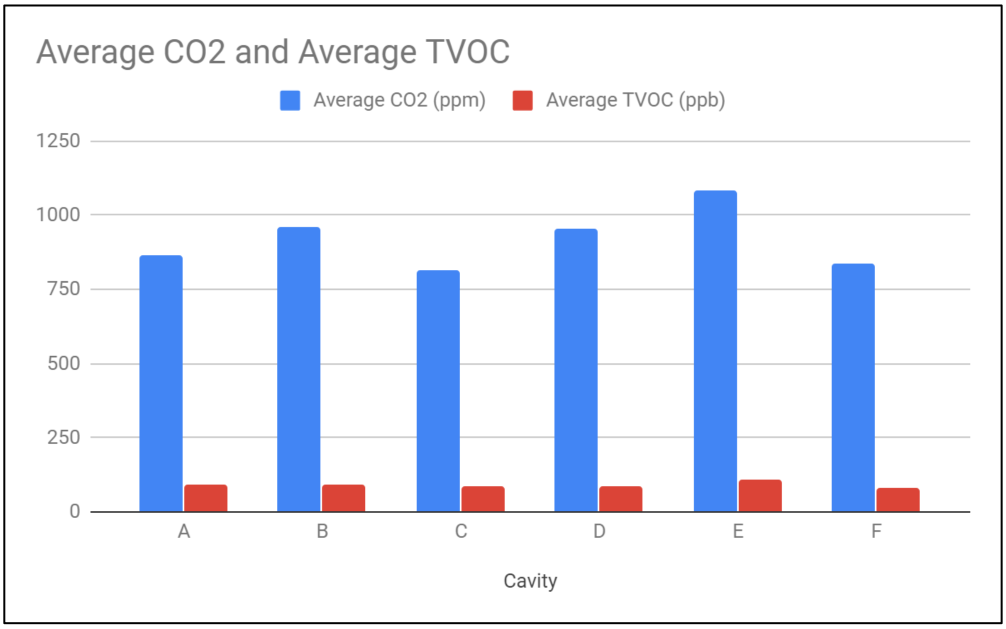


Figure 86 Average CO2 and TVOC Levels

From the figure above, it is observed that cavities B and E have relatively higher CO_2 levels compared to the others. Cavity C seems to have the most reasonable average with a CO_2 level of 815 ppm and a TVOC level of 88 ppb. Overall, it can be said that all the modules have relatively high CO_2 and TVOC levels. This may be due to the influence of the materials of the drip irrigation system installed in each cavity.

7.6 HARVEST – YIELD EVALUATION

The plants were harvested from the modules twice, over the course of the project. The first time was on the 19th of June, 2 days before the logging of the data for the experiment. The second time was on the 12th of July, during the end of the 3 weeks of logging.

7.6.1 Initial Harvest.

The peppers in all the cavities had to be harvested before the start of the logging. This was due to the presence of ripe peppers, which can potentially stop further growth of the plant. The plants were placed on the cavities on the 10th of May, as mentioned in section 3.3. Hence this period before the initial logging was spent on installing the watering system and configuring each of the sensors in the façade and in the office. The plants were maintained by manual watering. The amount of water and the frequency of watering was followed from the required irrigation rate mentioned in section 5.4. The plants were then harvested and the number of peppers were recorded along with its mass. This was compared to unit weight of each pepper plant given in Table 1. This was also compared to the number of peppers in each plant, which was calculated on the day of the placements of the plants. The table is given in appendix C. The harvested peppers from each cavity is given in Figure 87 a) and b) below

Figure 87 a) Initial harvest from the upper modules

Figure 87 b) Initial harvest from the lower modules

The figure above shows the total number of peppers harvested from each cavity. The individual weight from each plant was noted and a total weight from each cavity was also calculated. This is represented in figure 88 below

MODULE A - No ventilation in top floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
A1	Red Pepper	0	0	14
A2	Red Pepper	1	3	16
A3	Yellow Pepper	27	55	10
A4	Yellow Pepper	19	31	17
A5	Snack Pepper Orange	5	68	7
A6	Red Pepper	0	8	8
A7	Yellow Pepper	32	64	18
A8	CGN21566	0	0	27
A9	Bahamian Goat	5	16	13
Total		89	245	

Figure 88 a) Number and weight of plants harvested from cavity A

Module B - Natural ventilation in top floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
B1	Yellow Pepper	16	30	30
B2	Red Pepper	0	0	16
B3	Red Pepper	3	11	5
B4	Yellow Pepper	19	28	16
B5	Snack Pepper Orange	5	67	4
B6	Yellow Pepper	14	18	25
B7	Red Pepper	0	0	10
B8	CGN21566	0	0	7
B9	Bahamian Goat	8	21	5
Total		65	175	

Figure 88 b) Number and weight of plants harvested from cavity B

Module C - Mechanical ventilation in top floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
C1	Red Pepper	1	10	10
C2	Red Pepper	0	0	11
C3	Yellow Pepper	28	59	13
C4	Yellow Pepper	34	73	12
C5	Snack Pepper Orange	7	106	0
C6	Yellow Pepper	32	52	11
C7	Red Pepper	0	0	5
C8	CGN21566	0	0	5
C9	Bahamian Goat	4	12	10
Total		106	312	

Figure 88 c) Number and weight of plants harvested from cavity C

Module D - No ventilation in bottom floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
D1	Red Pepper	0	0	10
D2	Red Pepper	0	0	11
D3	Yellow Pepper	31	59	17
D4	Yellow Pepper	8	10	27
D5	Snack Pepper Orange	7	91	0
D6	Yellow Pepper	24	51	14
D7	Red Pepper	0	0	7
D8	Bahamian Goat	1	6	11
D9	Bahamian Goat	5	32	4
Total		76	249	

Figure 88 d) Number and weight of plants harvested from cavity D

Module E - Natural ventilation in bottom floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
E1	Red Pepper	0	0	3
E2	Red Pepper	4	18	6
E3	Yellow Pepper	31	62	5
E4	Yellow Pepper	0	0	17
E5	Snack Pepper Orange	8	106	2
E6	Yellow Pepper	19	28	6
E7	Red Pepper	0	0	8
E8	CGN21566	1	7	15
E9	Bahamian Goat	1	9	1
Total		64	230	

Figure 88 e) Number and weight of plants harvested from cavity E

Module F - Mechanical ventilation in top floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
F1	Red Pepper	0	0	3
F2	Red Pepper	3	14	6
F3	Yellow Pepper	26	54	2
F4	Yellow Pepper	40	74	4
F5	Snack Pepper Orange	5	86	3
F6	Red Pepper	0	0	7
F7	Yellow Pepper	19	40	3
F8	CGN21566	0	0	11
F9	Bahamian Goat	5	26	2
Total		98	294	

Figure 88 f) Number and weight of plants harvested from cavity F

From the first harvest, it was found that module C gave the most yield (312g). However, the maintenance method and the ventilation strategies before this harvest was the same for all the modules.

7.6.2 Second Harvest

The second harvest was performed on the 12th of July, during the end of the three weeks of data logging. The number of peppers in this case was a result of the different ventilation, shading and watering strategies for each module. The result would give an idea on which module gives the most yield of peppers. This can be correlated to the performance of the modules, with respect to the required thermal conditions for the plants. The total number of harvested peppers after the three weeks is given in figure 89 below

Figure 89 Harvest from the modules after the data logging

The figure above shows the total number of peppers harvested from each cavity after three weeks. The total weight and the number of peppers harvested were recorded to compare which cavity produced most of the yield. This is given in Figure 90 below.

MODULE A - No ventilation in top floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
A1	Red Pepper	8	56	9
A2	Red Pepper	8	57	11
A3	Yellow Pepper	8	16	2
A4	Yellow Pepper	13	10	28
A5	Snack Pepper Orange	2	39	5
A6	Red Pepper	5	29	8
A7	Yellow Pepper	18	30	7
A8	CGN21566	7	24	27
A9	Bahamian Goat	15	111	5
Total		84	372	

Figure 90 a) Number and weight of plants harvested from cavity A

Module B - Natural ventilation in top floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
B1	Yellow Pepper	17	28	18
B2	Red Pepper	10	67	6
B3	Red Pepper	4	28	1
B4	Yellow Pepper	5	10	17
B5	Snack Pepper Orange	4	74	1
B6	Yellow Pepper	20	40	7
B7	Red Pepper	7	62	4
B8	CGN21566	2	3	7
B9	Bahamian Goat	10	82	2
Total		79	394	

Figure 90 b) Number and weight of plants harvested from cavity B

Module C - Mechanical ventilation in top floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
C1	Red Pepper	6	65	6
C2	Red Pepper	8	80	4
C3	Yellow Pepper	3	5	11
C4	Yellow Pepper	5	20	9
C5	Snack Pepper Orange	0	0	5
C6	Yellow Pepper	10	11	6
C7	Red Pepper	2	31	4
C8	CGN21566	3	10	4
C9	Bahamian Goat	9	31	4
Total		46	253	

Figure 90 c) Number and weight of plants harvested from cavity C

Module D - No ventilation in bottom floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
D1	Red Pepper	9	71	6
D2	Red Pepper	9	77	2
D3	Yellow Pepper	16	29	6
D4	Yellow Pepper	7	7	37
D5	Snack Pepper Orange	0	0	3
D6	Yellow Pepper	23	33	8
D7	Red Pepper	6	41	2
D8	Bahamian Goat	12	95	11
D9	Bahamian Goat	4	36	4
Total		86	389	

Figure 90 d) Number and weight of plants harvested from cavity D

Module E - Natural ventilation in bottom floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
E1	Red Pepper	7	63	3
E2	Red Pepper	4	39	6
E3	Yellow Pepper	7	10	3
E4	Yellow Pepper	0	0	16
E5	Snack Pepper Orange	1	17	2
E6	Yellow Pepper	5	11	6
E7	Red Pepper	4	24	4
E8	CGN21566	6	27	15
E9	Bahamian Goat	10	70	0
Total		44	261	

Figure 90 e) Number and weight of plants harvested from cavity E

Module F - Mechanical ventilation in top floor

Plant number	Type	Number of ripe peppers	Weight (g)	Number of Young peppers
F1	Red Pepper	8	73	3
F2	Red Pepper	8	69	6
F3	Yellow Pepper	14	23	2
F4	Yellow Pepper	12	20	4
F5	Snack Pepper Orange	0	0	3
F6	Red Pepper	7	48	7
F7	Yellow Pepper	13	24	2
F8	CGN21566	0	0	11
F9	Bahamian Goat	6	25	2
Total		68	282	

Figure 90 f) Number and weight of plants harvested from cavity F

Based on the yield obtained in three weeks from each module, an estimate was made on the potential production rate of each plant. The yield from each plant present in each façade module was then predicted for a period of three months. The predicted yield is given in the figure below.

YIELD ESTIMATION JUN / JULY / AUG	A	B	C	D	E	F
CGN21566	56 g	16 g	16 g	-	80 g	16 g
BAHAMIAN GOAT	168 g	168 g	72 g	384 g	24 g	48 g
RED CHILI	308 g	28 g	112 g	168 g	112 g	308 g
YELLOW CHILI	372 g	156 g	96 g	468 g	36 g	84 g
ORANGE PEPPER	0 g	92 g	460 g	276 g	184 g	276 g
	904 g	460 g	756 g	1.296 g	436 g	732 g

Figure 91 a) Estimated yield for every plant from each module for the month of June July and August

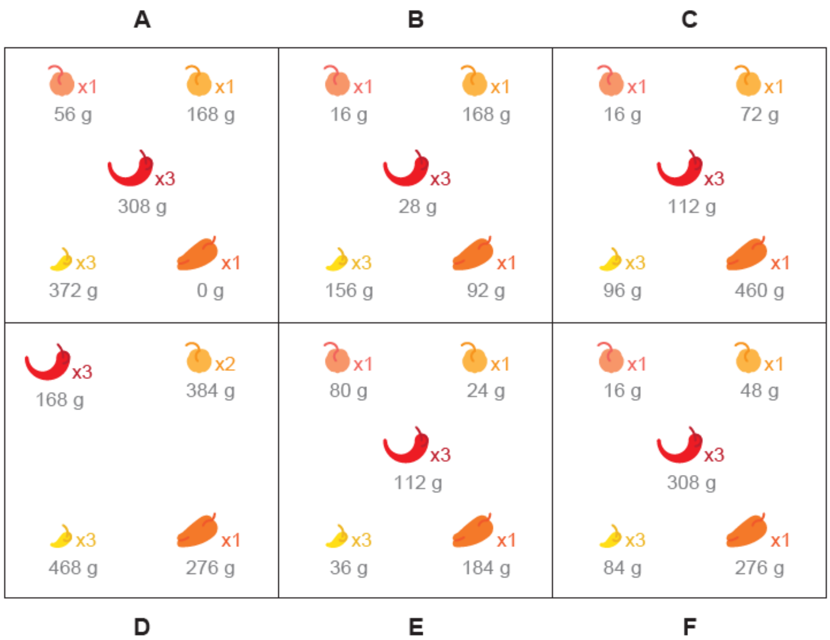


Figure 91 b) Schematic representation of estimated yield for every plant

Based on the amount of water used for all the plants in each module through the course of the experiment, a similar estimation was made on the total consumption of water for each plant for three months (June, July and August). This is represented in the figure below

WATER CONSUMPTION JUN / JULY / AUG	A	B	C	D	E	F
CGN21566	72.6 L	72.6 L	72.6 L	-	72.6 L	60.5 L
BAHAMIAN GOAT	72.6 L	72.6 L	72.6 L	181.6 L	72.6 L	60.5 L
RED CHILI	90.9 L	90.9 L	90.9 L	99 L	90.9 L	83.4 L
YELLOW CHILI	90.9 L	90.9 L	90.9 L	99 L	90.9 L	83.4 L
ORANGE PEPPER	30.3 L	30.3 L	30.3 L	33 L	30.3 L	27.8 L
	357.3 L	357.3 L	357.3 L	412.6 L	357.3 L	315.6 L

Figure 92 a) Estimated water consumption for every plant from each module for the month of June July and August

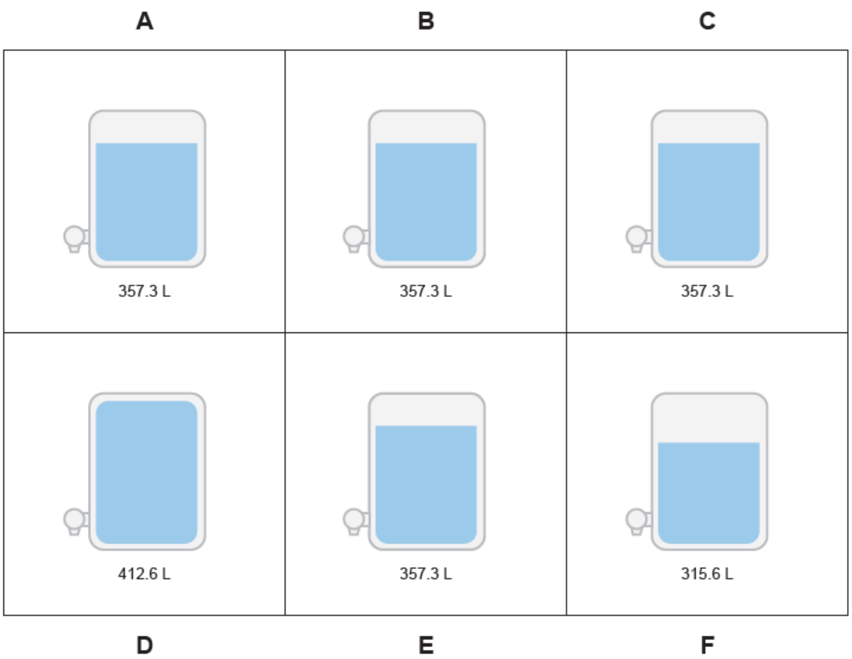


Figure 92 b) Schematic representation of estimated water consumption for every plant

The health of the plants were analysed visually by taking pictures of each cavity. The density of plants on the last day of logging (12th July 2019) was compared to the density of plants when they were kept (10th May 2019). The comparison for each module is given below in Figure 93.

Figure 93 Comparison of plants in the modules over two months

From observing the health of each plant in the façade modules, a schematic representation was made on the overall health of each plant in each module. This is represented in the figure below

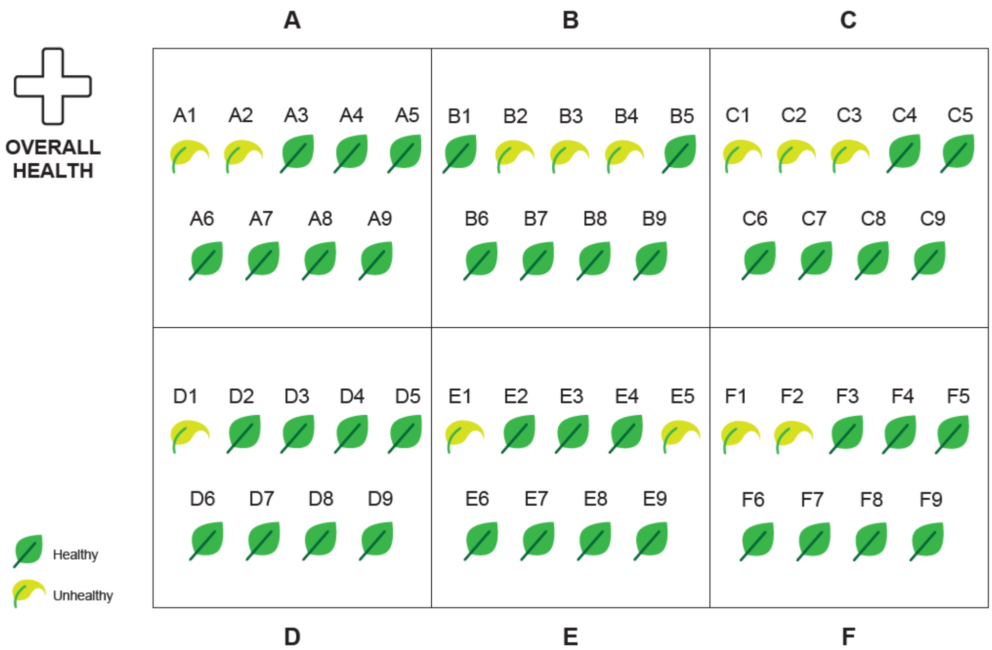


Figure 94 Schematic representation on the health of each plant in the façade modules

From figure 89 above, it is noticed that cavity B produced the highest yield of 394 g, followed by cavity D with 389 g and cavity A with 372 g. The rest of the modules have produced relatively less yield. Overall, it can be inferred that the minimally ventilated modules have produced the highest aggregate of yield (761 g). From the estimated yield for three months, it is seen that cavity A and D produce the highest yield. This result contradicts the performance of the minimally ventilated modules as per the thermal requirements with respect to the vapour transfer deficit. However it should be noted that the vapour transfer deficit was a general criteria for plants. Moreover, the analysis was done for only four scenarios. After observing the health of the plants in each module, it was noted that Cavity A, D and F had the highest success rate with respect to the health of the plant. Cavity D only had one unhealthy plant (D1). However, it should be noted that the poor health in B3 and C2 was a result of excessive watering. This was due to irregular irrigation rate from the drippers in the respective plants, thus leading to an overflow of water in the plants. Looking at the result of the yield provided and the health of the plants, it can be concluded that a minimally ventilated cavity with a specified irrigation rate and a shading strategy is enough to maintain the health of the plants, with respect to production of yield.

7.7 CONCLUSION

The performance of the modules were evaluated with respect to the discussed parameters. In the case of the plants, the condition in the cavity was analysed and the yield produced was counted. In the case of the office spaces, the values were compared to the psychrometric chart to find the comfort criteria. As mentioned before, was not possible to observe the influence of the façade on the indoor environment of the building. Hence, in order to get a clearer idea on the indoor comfort of the building, a survey was taken with the occupants in the building and the following results were observed.

- For the thermal comfort a Predicted Mean Vote was taken for the year and it was observed that on the period between July to September, 60% of the occupants rated the thermal conditions as warm (+2), 16% of the occupants found the place to be slightly warm (+1) and 16% found the place to be hot (+3). The remaining found the place to be slightly cool (-1).
- 54.6% of the occupants are satisfied with the illuminance of the building whereas 45% of the occupants find the illuminance to be unsatisfactory.
- All the occupants in the building seem to find the aesthetic appeal of the plants to be satisfactory. This was observed when a 7 scale rating system was made from satisfactory (1) to unsatisfactory (7). 50% of the occupants rated 1, 33.3% gave a rating of 2 and the rest gave a rating of 3
- 72,8% of the occupants claim that their productivity is increased up to 20%, whereas the rest claim that their productivity is decreased by up to 20%.

CHAPTER 8 – CONCLUSION

The objective of this research was to investigate the performance of a 'Do It yourself' green double skin façade such that it can accommodate the growth of edible vegetation, along with its influence on the indoor environment in an office building. Thus the research question was formulated-

How does a **'Do It Yourself'** double skin façade perform with respect to conditions for growing **edible vegetation** and for the indoor environment in an office building?

This chapter contains the conclusions formulated from all the performed experiments over the course of the project. The first part contains the experiments performed, values measured and the results obtained for the experiments conducted. The second part covers the implications of the findings and the answers to the research questions. The third part contains recommendations for further research.

8.1 RESULTS

Several experiments were performed during the project. The preliminary experiments involved checking the accuracy of the temperature and relative humidity sensors. The sensors were placed in a climate chamber and the behaviour of 15 sensors were evaluated. It was found that three sensors, namely sensor 6,11 and 12 were relatively less accurate and was hence omitted from further experiments. The sensors were not calibrated for further accuracy.

A preliminary test was done to test the performance of the measurement system. This was compared to a simulation model performed from a computational model. It was observed that the trend shown in temperature and relative humidity in the sensors matched that of the values shown in the computational model (DesignBuilder). However, there were differences in the absolute values shown by both the methods. Hence it was concluded that the behaviour of the real time measurements are similar to the one shown in the computational model.

The drip irrigation system was set for all the modules and after a series of testing after calibration, it was observed that, the rate set for the plants was higher than the required amount of water for the plants. Hence it can be concluded that the current drip irrigation method is not the most accurate method of watering the plants. It must be improved in terms of consistency and accuracy with respect to the required amount of water for the plants.

The data logging experiment was done over a course of three weeks from 19th of June 2019 to 12th of July. The cavities of each module were evaluated based on temperature, relative humidity, CO_2 and TVOC levels. The offices were evaluated based on the temperature, relative humidity and illuminance.

For the case of thermal performance of plants, it was found that the mechanically ventilated modules (module C & F) perform better during hotter days as its vapour transfer deficit is closer to the ideal range (10 to 12) millibar. On colder days, the naturally ventilated cavities (module B & E) perform better with respect to vapour transfer deficit. This is due to the influence of the higher temperature in the office.

In the case of comfort criteria in the offices, it was observed that modules C & F perform relatively better compared to the rest of the modules, as they contained the least number of daily average thermal conditions outside the comfort zone according to the psychrometric chart. This was also observed in the case of maximum outdoor temperature. In the case of maximum relative humidity, modules B & E performed relatively better.

It was found that module E provides the maximum shading effect out of the modules. This may indicate that the density of the plants are the highest in module E. Although the absolute value of the illuminance may not be accurate, it was found that the external illuminances are higher than the internal illuminances. However, it should be noted that the placement of the container doors predominantly causes an effect on the illuminance levels entering the building. This can be seen in the differences in the external illuminance as the position of the container doors are changed.

For the air quality in the cavities, the average air quality was calculated over the course of the experiment from each module. It was observed that cavities B and E have relatively higher CO_2 levels compared to the others with values ranging from 1000 to 1200 ppm. Cavity C showed a reasonable average with a CO_2 level of 815 ppm and a TVOC level of 88 ppb. The average TVOC levels were similar for all the modules. This may be due to several factors such as the material of the planters and the drip irrigation system. However, when the air quality sensor was initially checked, it was observed that the rate of change in TVOC level was proportional to the rate of change in the CO_2 levels. Hence, the difference in TVOC levels in all the modules may be a result of different CO_2 levels shown from the modules.

Based on the harvest from each module after the experiment, an estimation was done on the predicted yield and water consumption for three months. It was observed that module D produces the highest yield and also consumes maximum amount of water. The health of the plants were observed after the experiment and it was noted that module D produced a relatively higher number of healthy plants, based on leaf colour and density.

8.2 INTERPRETATION & CONCLUSION

In order to answer the research question, a few sub research questions were formulated, these were approached through literature research, experimental analysis and evaluation.

The parameters considered for evaluation in this project were **thermal parameters** (air temperature and relative humidity), **light parameters** (illuminance) and **the quality of air** (CO_2 and VOC levels). A comfort criteria was studied based on the required amount of the aforementioned parameters, to get an idea on what to expect from the results of the research.

A literature study was done on the type of plants that can be grown in a double skin façade. This involved researching on different climatic requirements for different types of plants. Since the majority of this research was to be done in summer, a conclusion was made that pepper plants shall be added. Based on consultations with plant experts and providers, five types of pepper plants were provided, namely the **Hot Chilli Red, Yellow Pointy, Snack Pepper Orange, CGN21566** and the **Bahamian Goat.**

The parameters involved in the experiment are defined by the design strategies in the façade, which were based on ventilation, placement of plants, installation & rate of irrigation and shading. The plants were placed in a similar order for all the modules. The shading strategy was applied based on the position of the container doors in the building

The presence of plants influenced the conditions in the cavity primarily in terms of humidity. This was noted especially in the behaviour of the non-ventilated modules (A & D). It was concluded that the relative humidity stays above 50% even at high outdoor temperatures (>25°C), mainly due to the evapotranspiration by the plants. The vapour transfer deficit could only be evaluated for extreme case scenarios, and not continuously during the time of logging. This was due to the unavailability to determine the leaf temperature of each plant, as suggested in section 2.7.

In the case of the ventilated modules, it was concluded that the façade with the placement of plants precools the air in the summer during high temperatures, and preheats the air in the nights. This was evaluated by calculating the difference between the temperature in the cavity and office.

From a survey conducted in the office, it was concluded that the plants provide an aesthetic appeal to all the occupants in the office, thus increasing most of the occupants productivity up to 20%

A major part of research was carried out through experimental analysis. This was done through real time measurements, with the help of sensors. These measurements were collected as data and compared with the required values for each factor, obtained from the literature. This was done to evaluate the performance of each module.

Based on the individual observations of the different experiments and evaluation of different parameters, a conclusion was made on which module has a relatively better performance. The criteria used to evaluate the performance of each module were yield production, health of plants, water consumption and indoor comfort. A weighted scoresheet was made to evaluate the performance of each module. This is shown in figure 95

	YIELD OF PEPPERS	HEALTH OF PLANTS	WATER CONSUMPTION	INDOOR COMFORT	
MODULE	25%	30%	15%	30%	OVERALL
A	8	8	8	7	7,7
B	6	6	8	7,5	6,8
C	7	6	8	8,5	7,3
D	9,5	9	7	7	**8,2**
E	6	8	8	8	7,5
F	7	8	8,5	9	8,1

Figure 95 Weighted scoresheet for all the modules

From the figure above, it was found that **module D** received the highest score, followed by module F. Although the mechanically ventilated (C & F) perform better with respect to indoor comfort, module D performed better with respect to the growth of the plants. However, it should be noted that the design of the façade modules does not solely influence the indoor environment in the office. This is a result of external factors such as activities inside the office.

The different design strategies showed different performances of a 'Do It Yourself' façade. From the experiment, it was found that the performance of the minimally ventilated modules (A & D) results in relatively better health and production of the plants, however, the indoor environment and the water consumption is compromised. Similarly, the performance of the mechanically ventilated modules (C & F) results in better indoor comfort along with lower water consumption, but the health and conditions of the plants were compromised. Moreover, it should be noted that the conditions in the office did not solely depend on the performance of the double skin façade.

It can be concluded that a 'Do It Yourself' façade, such as the case in this research, is capable of growing edible vegetation in the cavity of the double skin façade, as long as the design and maintenance strategies are applied. From the experiment, it was found that a ventilation strategy is important during high temperatures. However, it is not necessary to be adopted as long as the shading strategy is adopted, with the help of the container doors. Hence, a minimally ventilated module **(A & D)** can be used for the growth of plants in summer conditions as the evapotranspiration of the plants humidifies the air in the cavity as the temperature increases. This helps in the growth of the plant. However, an appropriate shading strategy should be used such as what was used during this experiment.

8.3 RECOMMENDATION

From the conclusions, it can be noted that a 'Do it yourself' double skin green façade can be designed to fulfil different requirements based on the users priority. For example, if a user in a dwelling wishes to adopt this idea for a façade, and aims to maximise vertical farming, then he or she shall prioritise the well being and production of plants. In this case, a minimally ventilated double skin façade module can be suggested, based on the conclusions made on the research. However, if a user wants to use a double skin green façade in order to improve the comfort in the building and thinks of vertical farming as a bonus feature, then a design such as the mechanically ventilated module can be considered.

As far as the individual plants are concerned, it was found that the Bahamian Goat had a reasonably good yield, and also provided the maximum leaf density compared to all the other plants. From the short growing peppers, the yellow pointy had the maximum production of yield. Hence for the users who prioritise yield, these two plants can be considered.

The experiment was done during summer time, and the façade design was specific to the case of PITLAB. Hence, this research provides opportunities for continuing this project for different conditions and requirements. For example, the performance of the façade in winter can be evaluated with different design strategies and different plants. This can be carried forward based on the users requirements and preferences.

Due to limitations in this research, the influence of the design of the façade itself on the overall indoor environment of the office could not be determined. Hence further research can be made in order to isolate indoor environmental conditions, such that it is easier to determine the influence of the façade in the indoor environment of the building.

One method to check the influence of the double skin façade on the indoor environment is the evaluation of air quality in the building. The air quality was not measured in the office spaces due to availability constraints. This method can be used to evaluate if the plants in the cavity play a role in purifying the air in the building.

The computational model was made based on the façade modules without the placement of plants. Hence, this project provides the opportunity of developing computational models of green double skin facades, with the consideration of the action provided by plants in the cavity.

Moreover, it was mentioned before that a continuous vapour transfer deficit could not be formulated due to the limitation based on finding the leaf temperature. Hence, this experiment can be improved by finding a method to determine the leaf temperature of the plants, in order to find the vapour transfer deficit. This would give a clearer answer to the performance of cavities with respect to the health of the plants.

In order to get more accurate results from sensors, they can be wither calibrated or sensors with higher accuracies can be adopted.

Overall, a measurement system has been made such that the thermal, light and the air quality parameters are measured in order to evaluate the performance of the façade. The data was logged continuously over a period of three weeks, and will continue to be used to measure the performance of the façade. This method of analysis of the conditions in the façade for the growth of the plants will further be used on the proposed **greenhouse** on the roof of the PITLAB, where edible plants will be grown, and design strategies will be adopted on the greenhouse based on this research.

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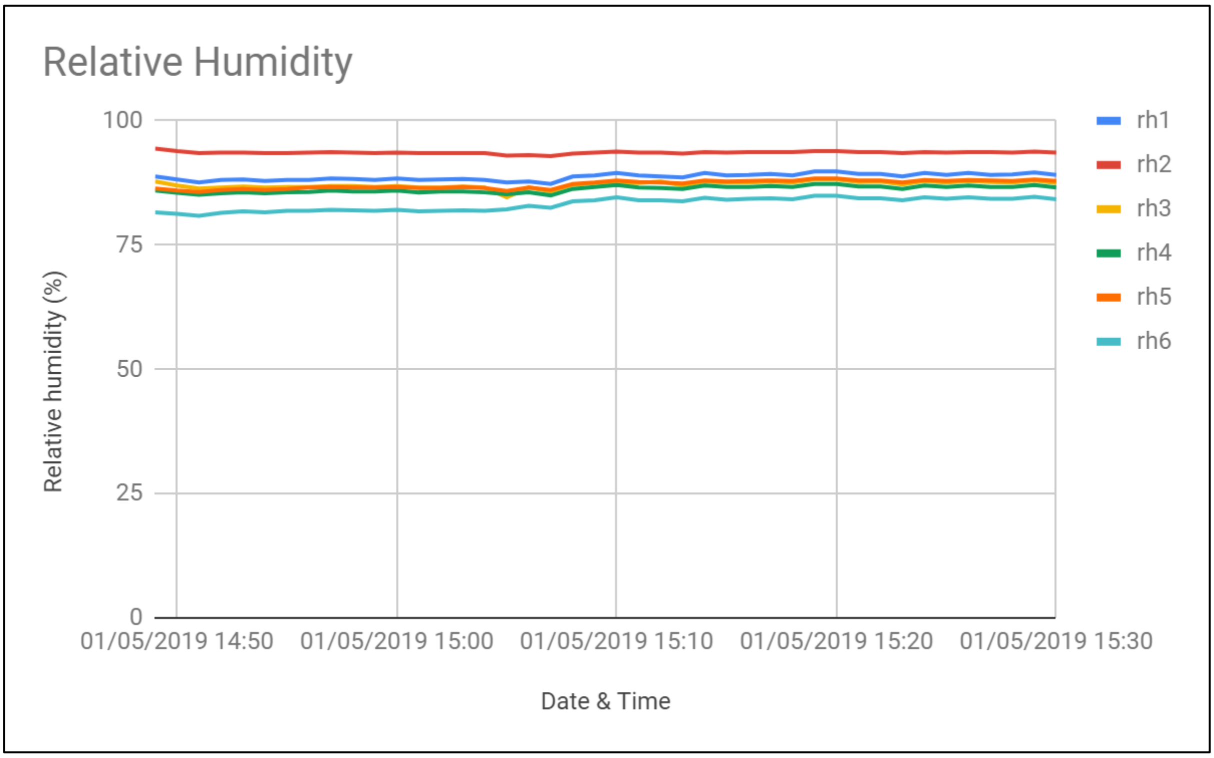
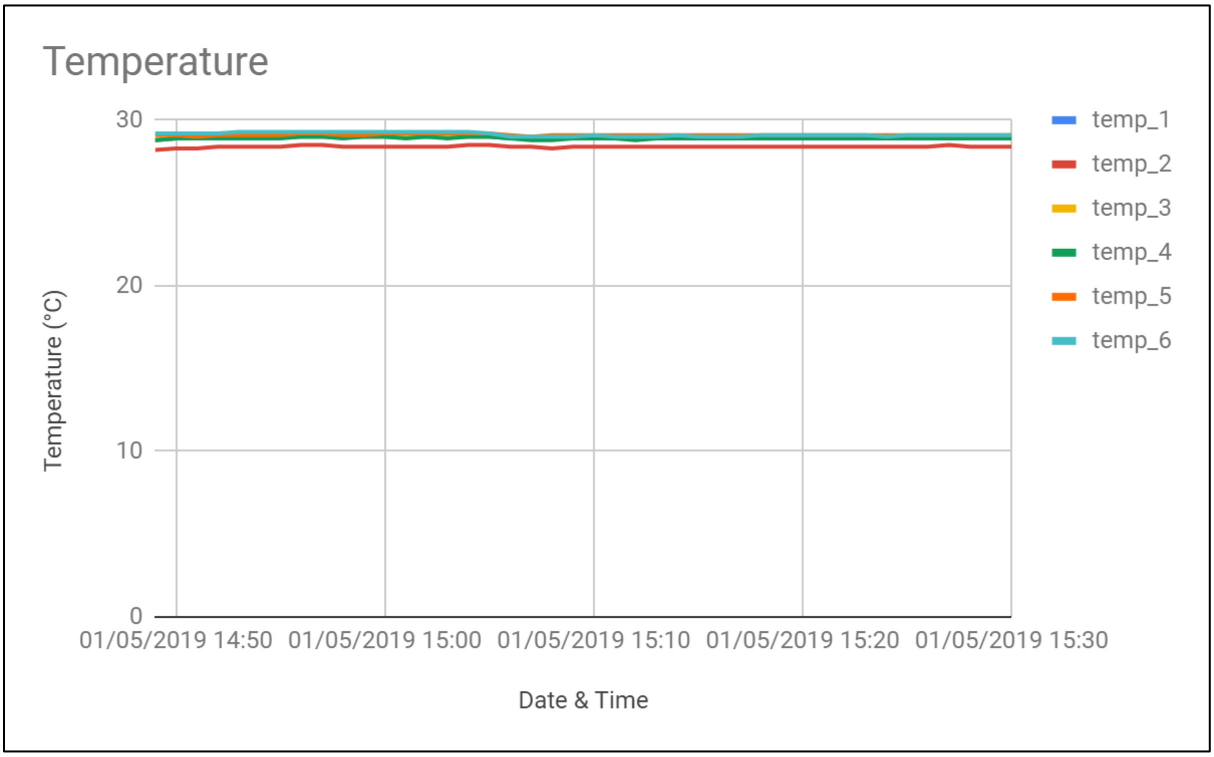
APPENDIX

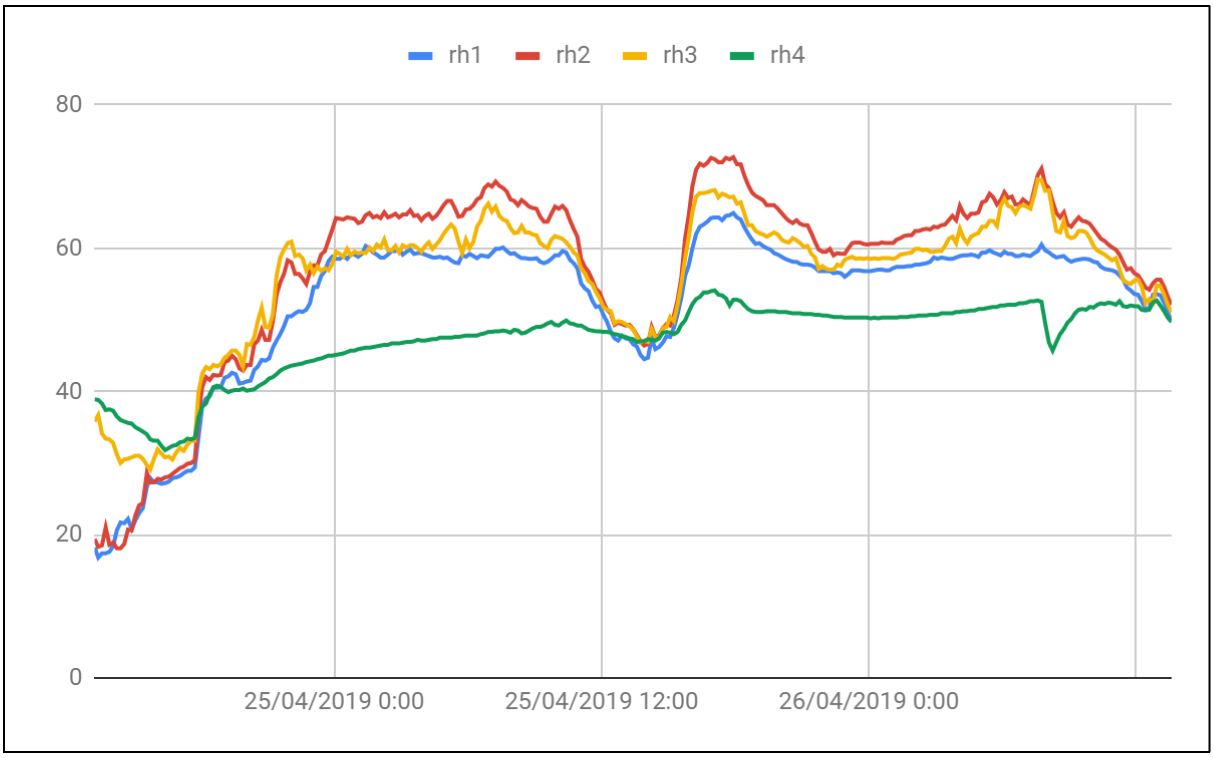
APPENDIX A – DATALOGGING RESULTS

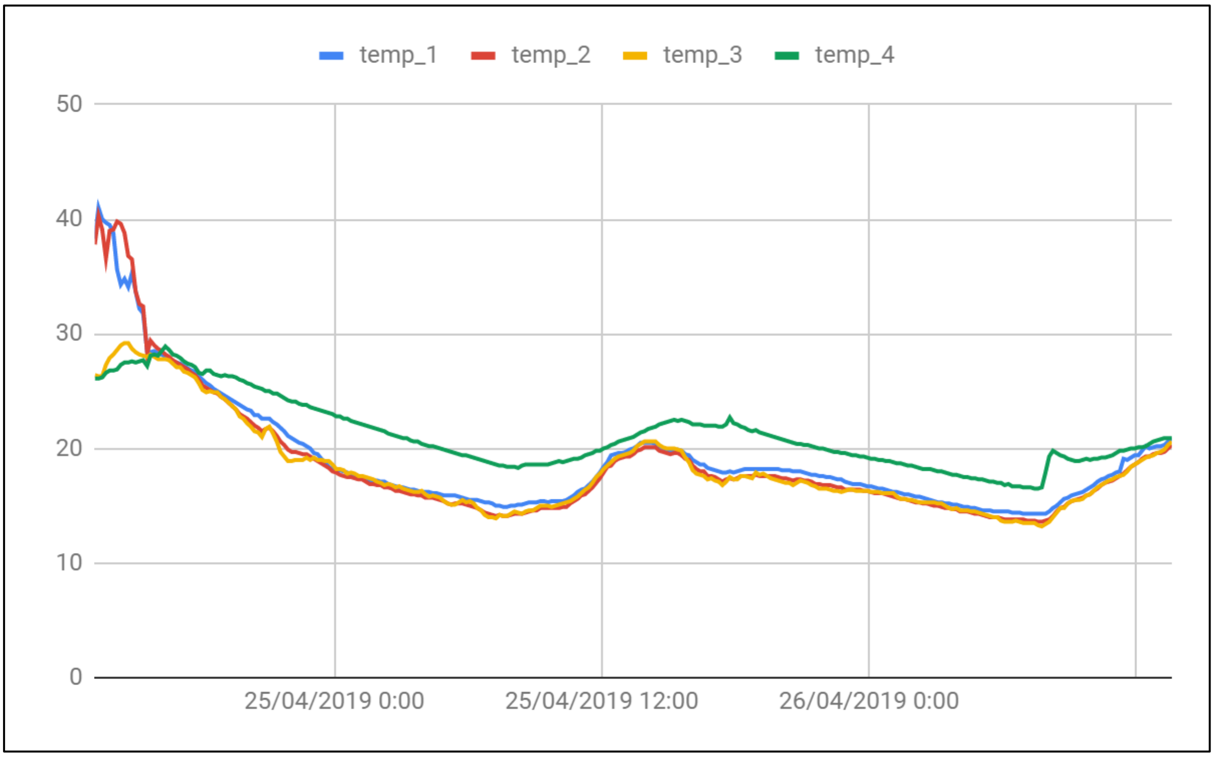
1. Climate chamber test





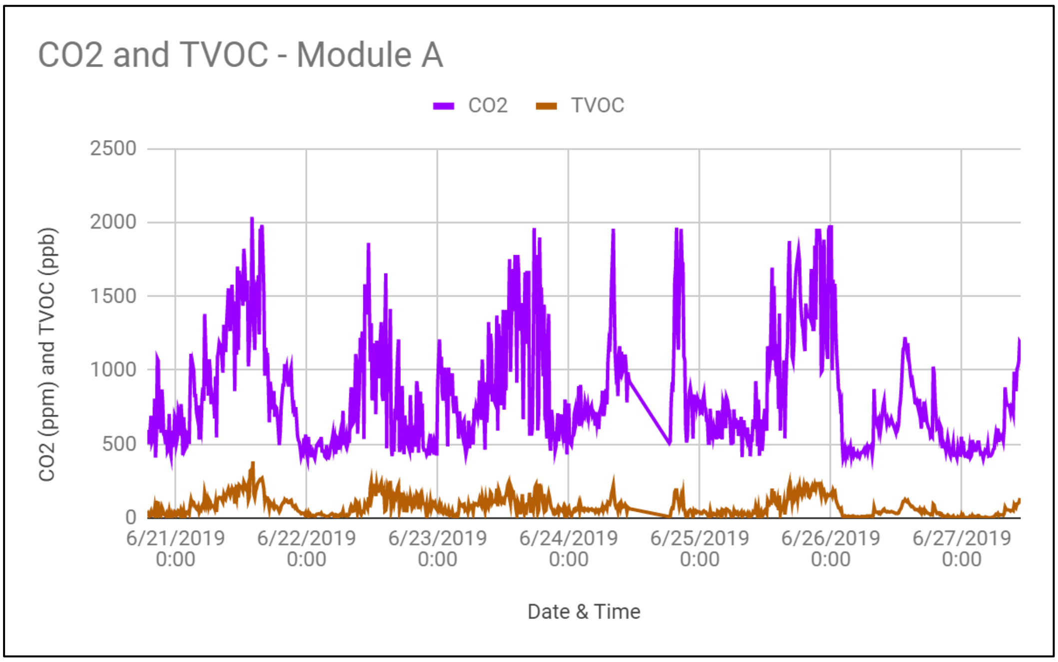
2. Datalogger test – Temperature and relative humidity – 24/04/2019 to 27/04/2019

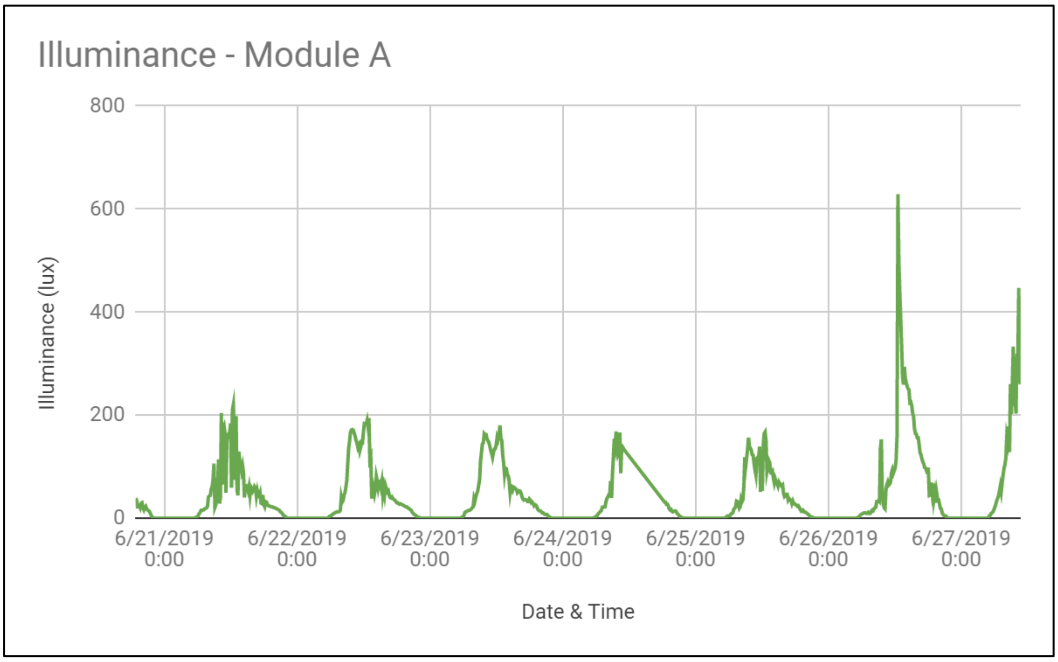




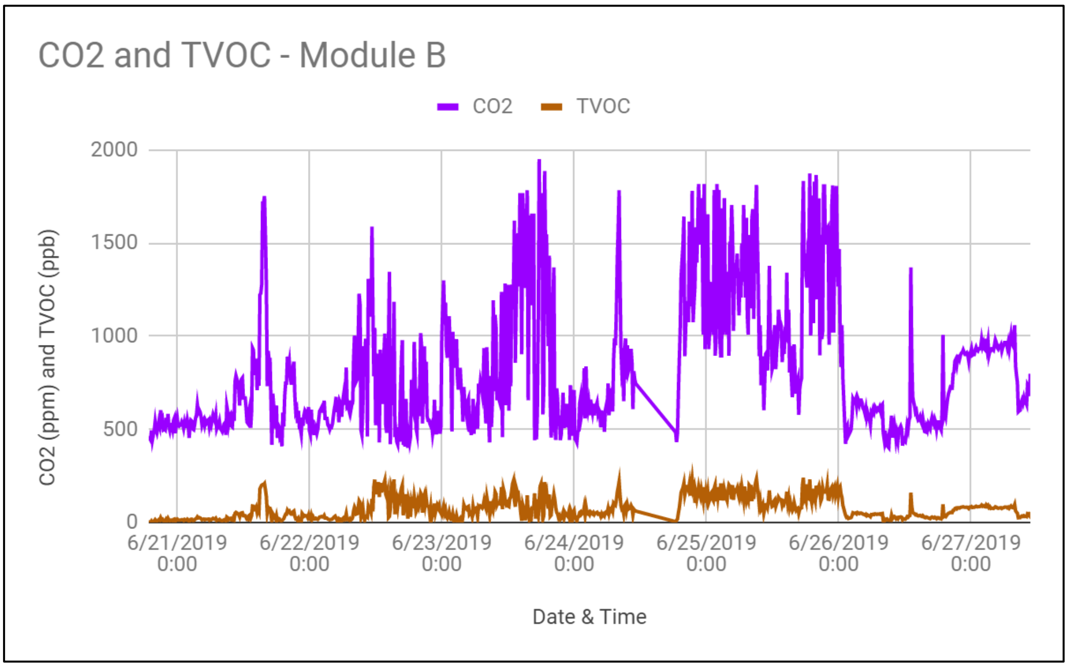
3. Module Performance – Illuminance and Air quality – Week 1

Module A

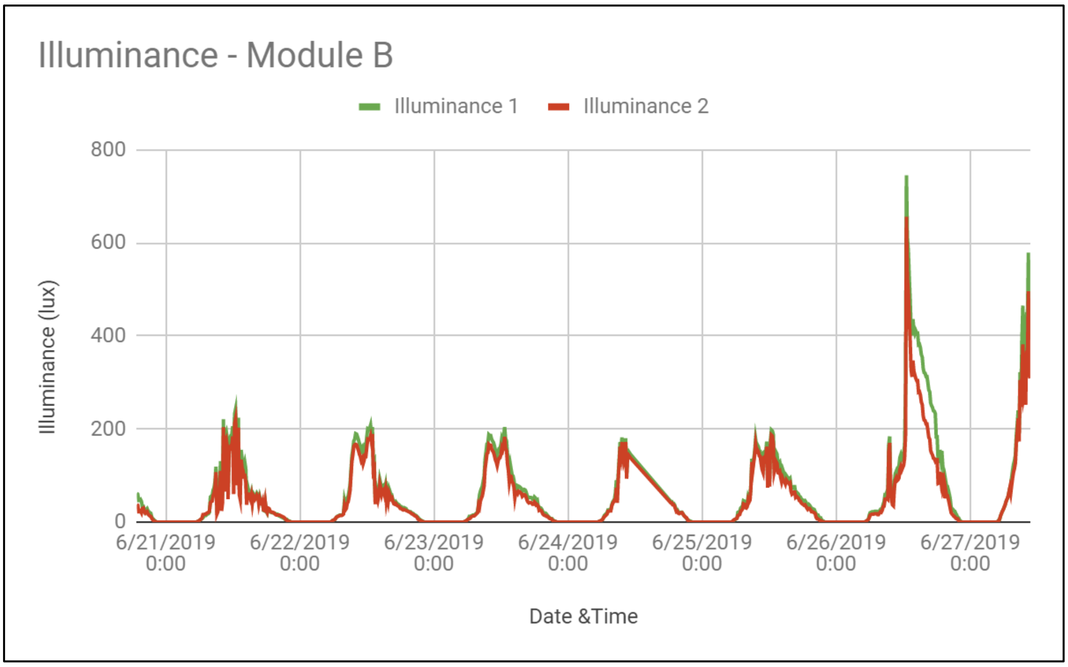




Module B

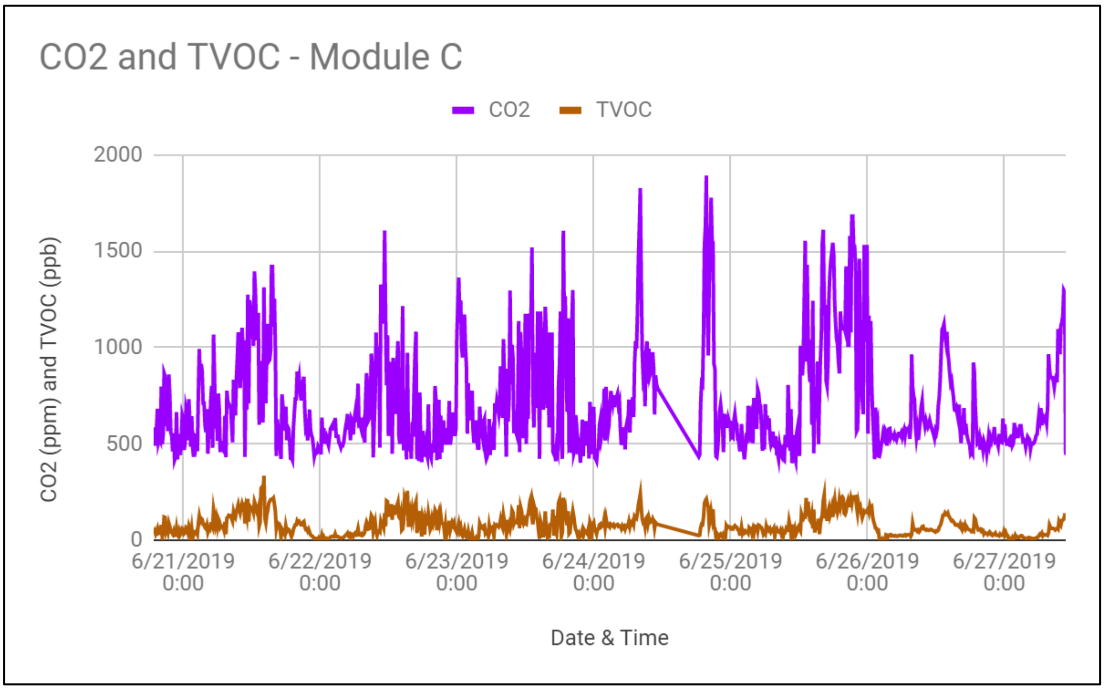


CO2 and TVOC - Module B
CO2
TVOC
CO2 (ppm) and TVOC (ppb)
2000
1500
1000
500
0
6/21/2019 0:00
6/22/2019 0:00
6/23/2019 0:00
6/24/2019 0:00
6/25/2019 0:00
6/26/2019 0:00
6/27/2019 0:00
Date & Time



Illuminance - Module B
Illuminance 1
Illuminance 2
Illuminance (lux)
800
600
400
200
0
6/21/2019 0:00
6/22/2019 0:00
6/23/2019 0:00
6/24/2019 0:00
6/25/2019 0:00
6/26/2019 0:00
6/27/2019 0:00
Date &Time

Module C


CO2 and TVOC - Module C
CO2
TVOC
2000
1500
1000
500
0
CO2 (ppm) and TVOC (ppb)
6/21/2019 0:00
6/22/2019 0:00
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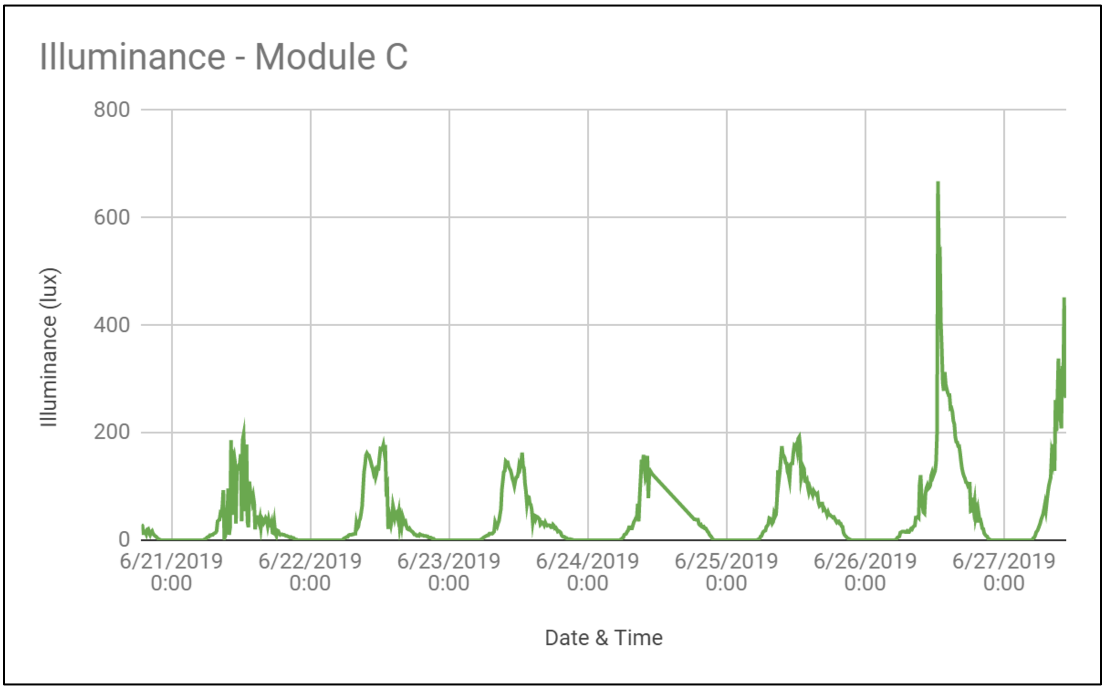
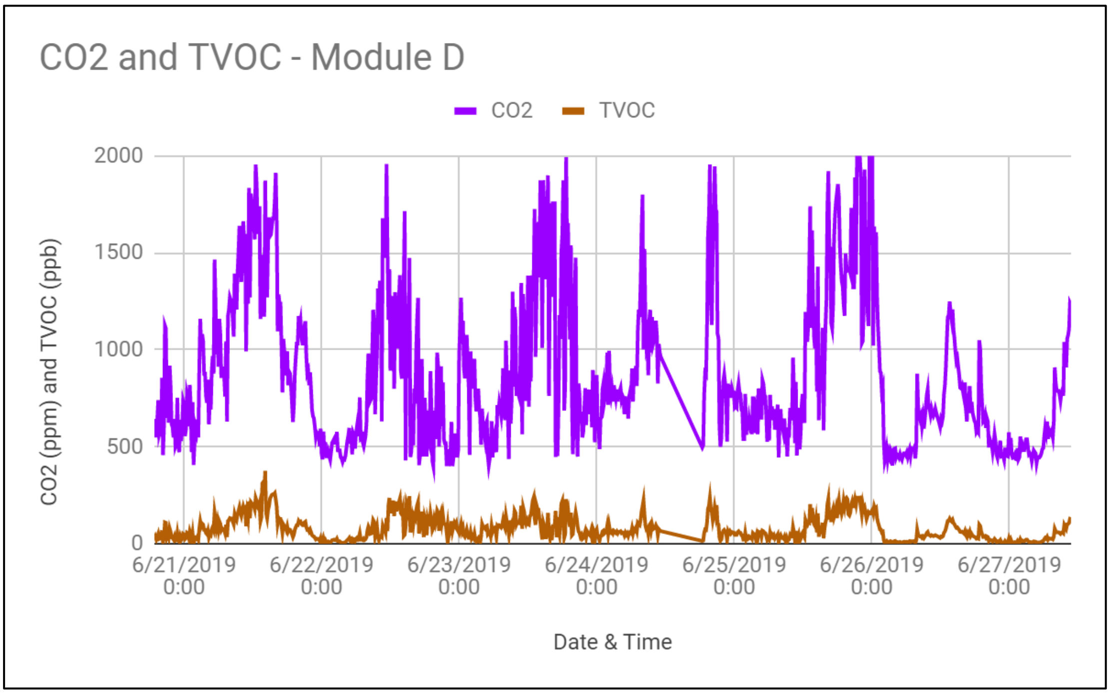
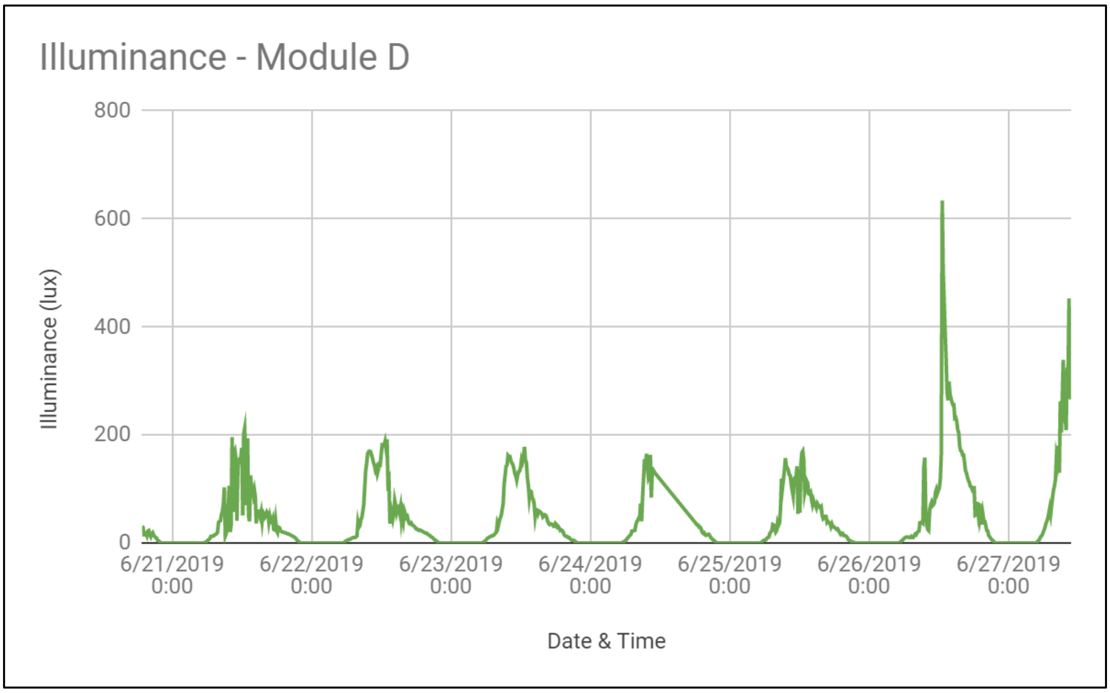
6/27/2019 0:00
Date & Time

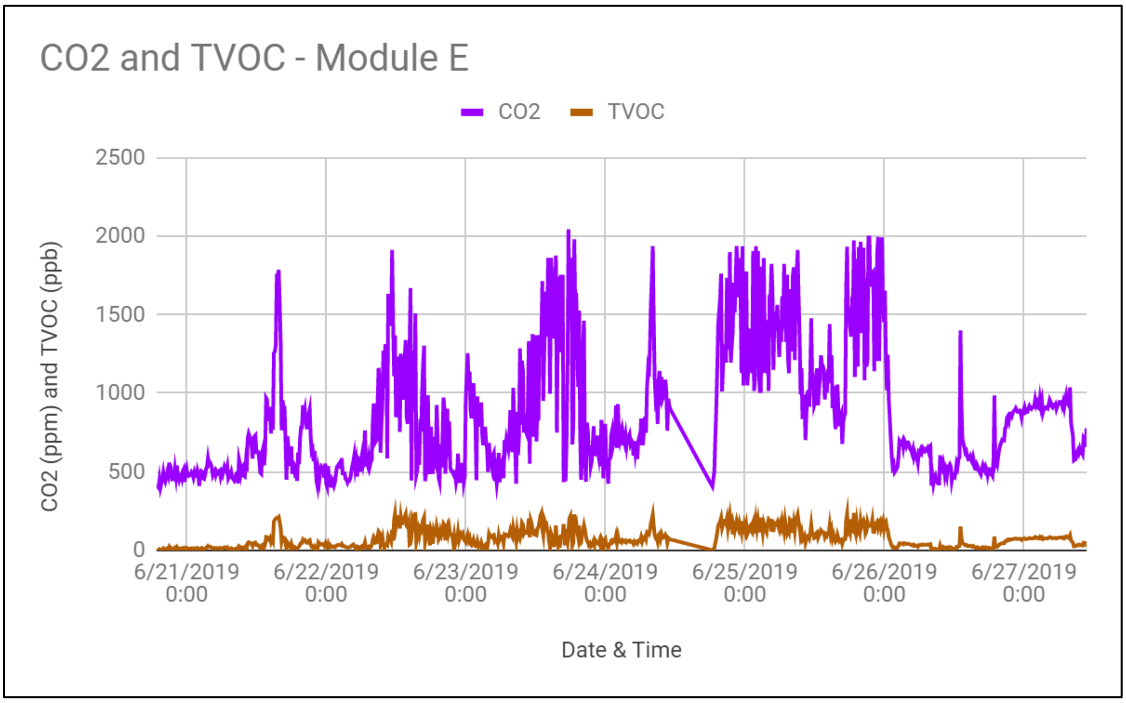

Illuminance - Module C
800
600
400
200
0
Illuminance (lux)
6/21/2019 0:00
6/22/2019 0:00
6/23/2019 0:00
6/24/2019 0:00
6/25/2019 0:00
6/26/2019 0:00
6/27/2019 0:00
Date & Time

Module D

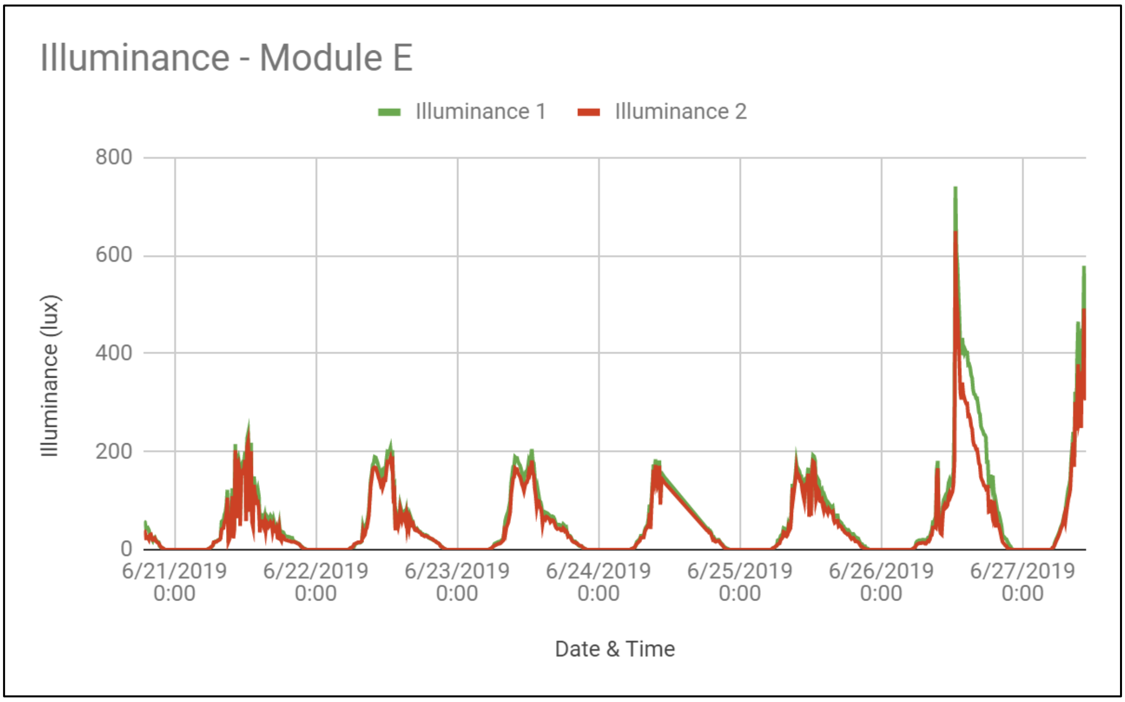

CO2 and TVOC - Module D
CO2
TVOC
2000
1500
1000
500
0
CO2 (ppm) and TVOC (ppb)
6/21/2019 0:00
6/22/2019 0:00
6/23/2019 0:00
6/24/2019 0:00
6/25/2019 0:00
6/26/2019 0:00
6/27/2019 0:00
Date & Time


Illuminance - Module D
800
600
400
200
0
Illuminance (lux)
6/21/2019 0:00
6/22/2019 0:00
6/23/2019 0:00
6/24/2019 0:00
6/25/2019 0:00
6/26/2019 0:00
6/27/2019 0:00
Date & Time

Module E

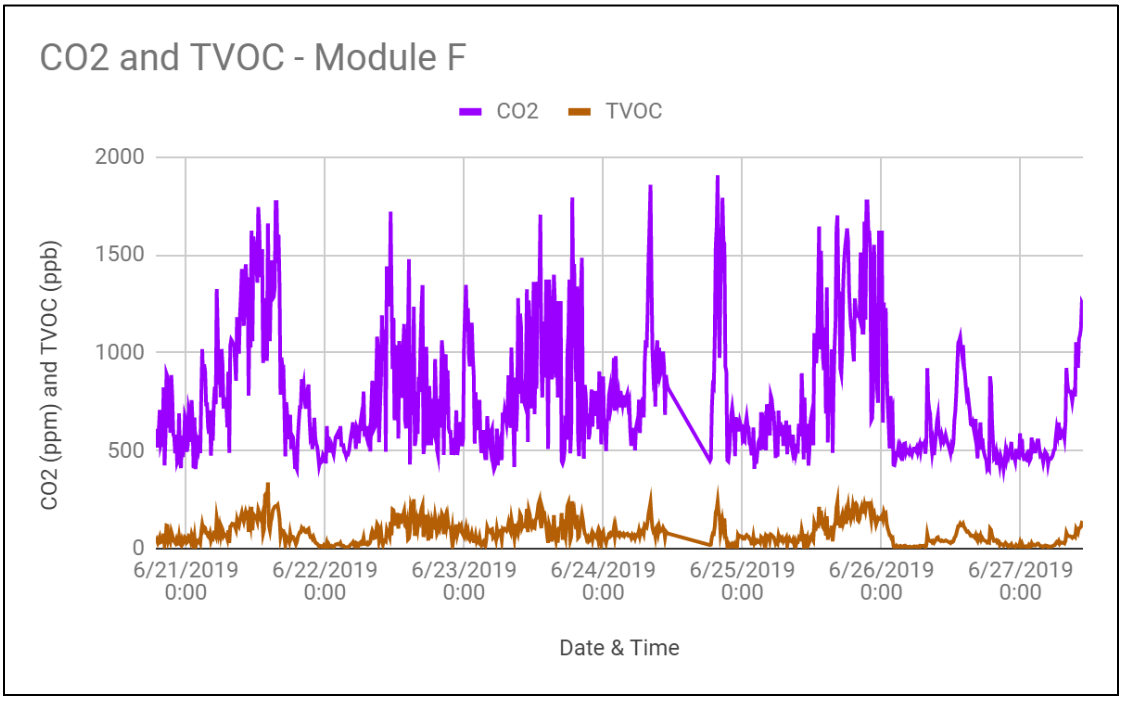


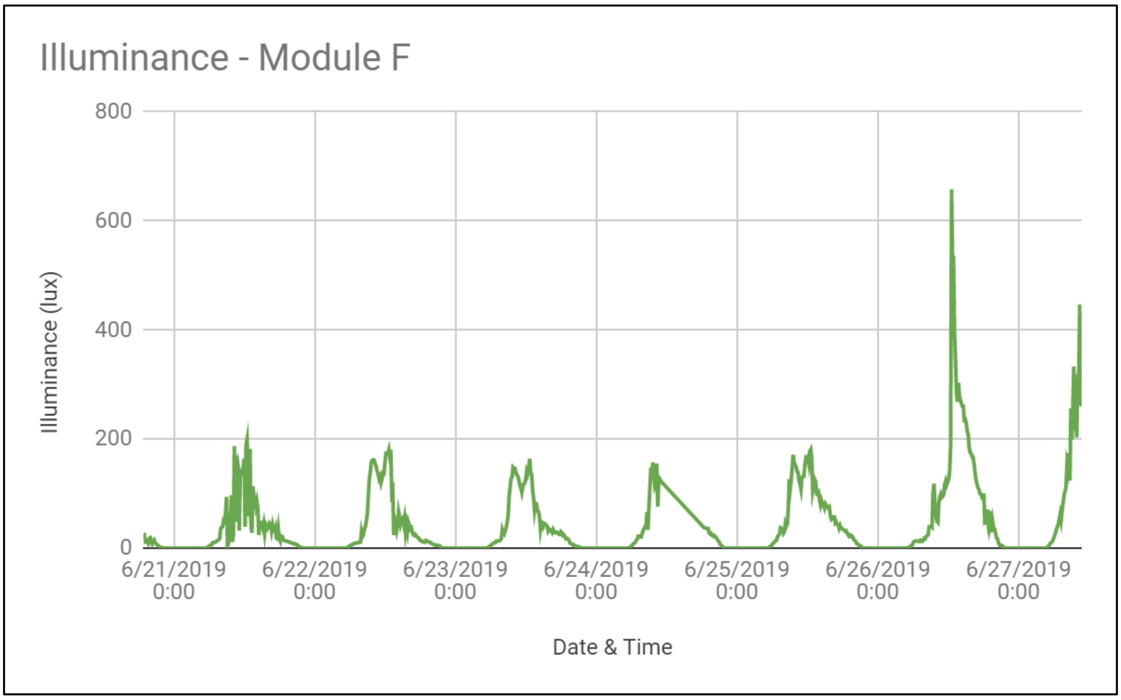
CO2 and TVOC - Module E
CO2
TVOC
2500
2000
1500
1000
500
0
CO2 (ppm) and TVOC (ppb)
6/21/2019 0:00
6/22/2019 0:00
6/23/2019 0:00
6/24/2019 0:00
6/25/2019 0:00
6/26/2019 0:00
6/27/2019 0:00
Date & Time



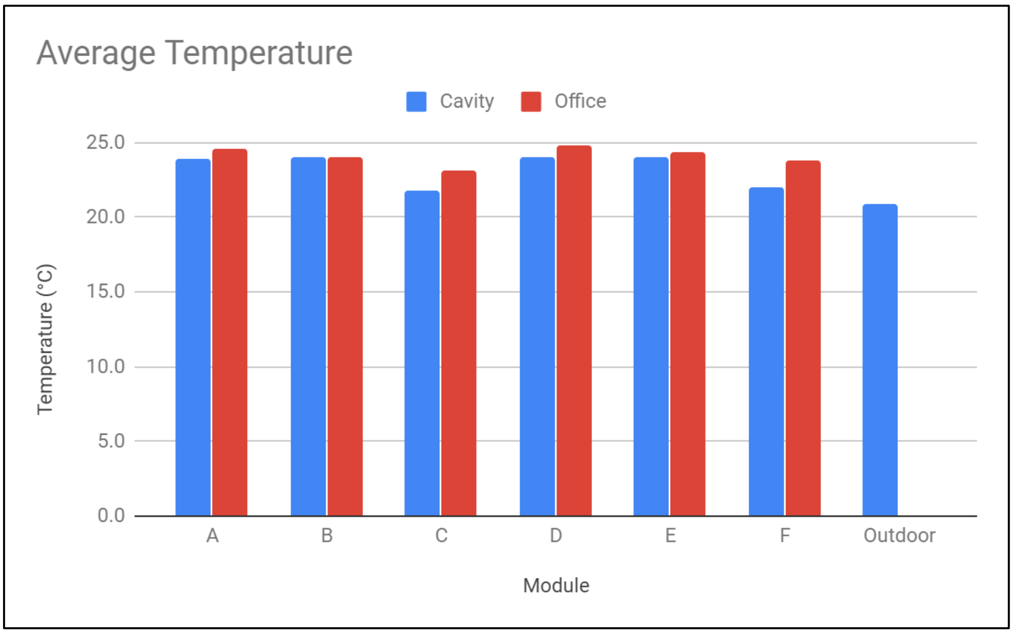
Illuminance - Module E
Illuminance 1
Illuminance 2
800
600
400
200
0
Illuminance (lux)
6/21/2019 0:00
6/22/2019 0:00
6/23/2019 0:00
6/24/2019 0:00
6/25/2019 0:00
6/26/2019 0:00
6/27/2019 0:00
Date & Time

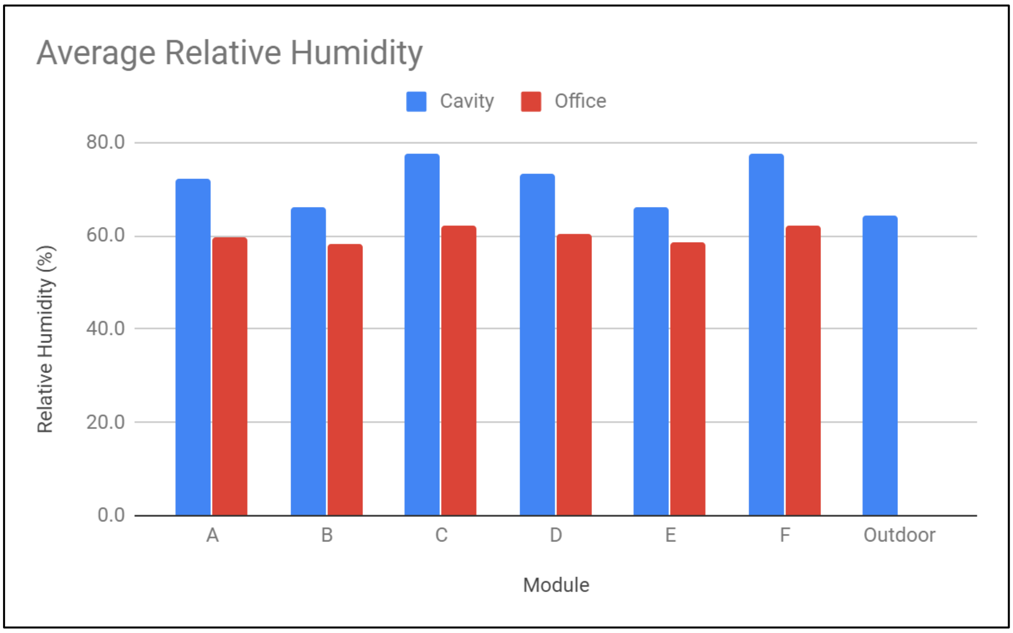
Module F


CO2 and TVOC - Module F
CO2
TVOC
CO2 (ppm) and TVOC (ppb)
2000
1500
1000
500
0
6/21/2019 0:00
6/22/2019 0:00
6/23/2019 0:00
6/24/2019 0:00
6/25/2019 0:00
6/26/2019 0:00
6/27/2019 0:00
Date & Time


Illuminance - Module F
Illuminance (lux)
800
600
400
200
0
6/21/2019 0:00
6/22/2019 0:00
6/23/2019 0:00
6/24/2019 0:00
6/25/2019 0:00
6/26/2019 0:00
6/27/2019 0:00
Date & Time

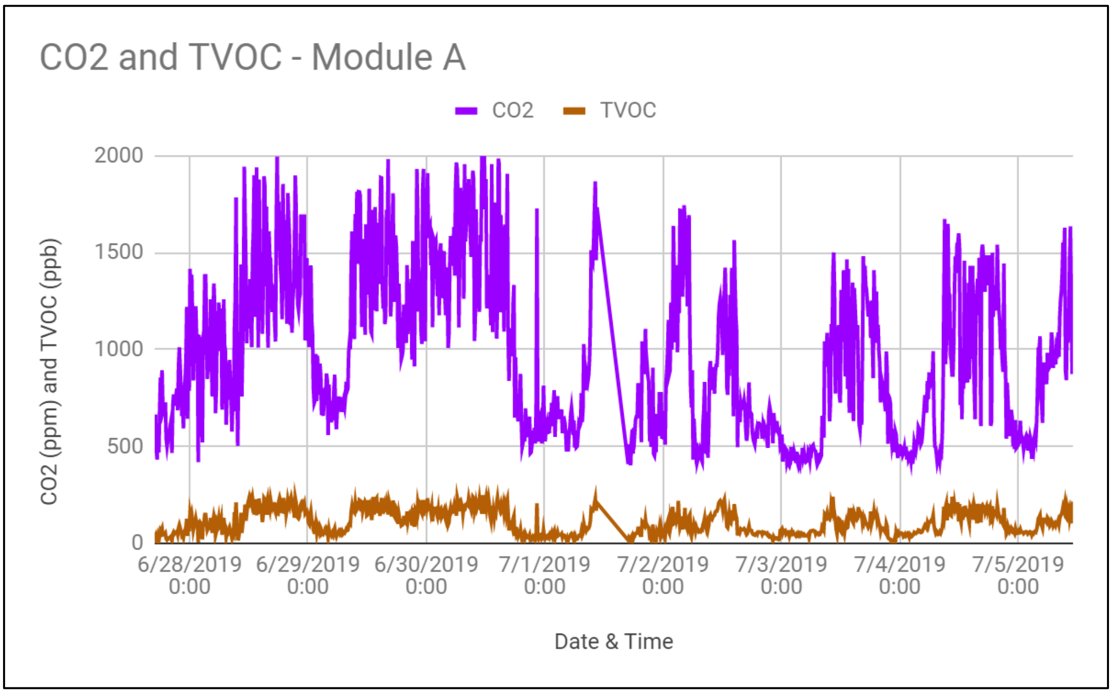
AVERAGE TEMPERATURE AND RELATIVE HUMIDITY - WEEK 1

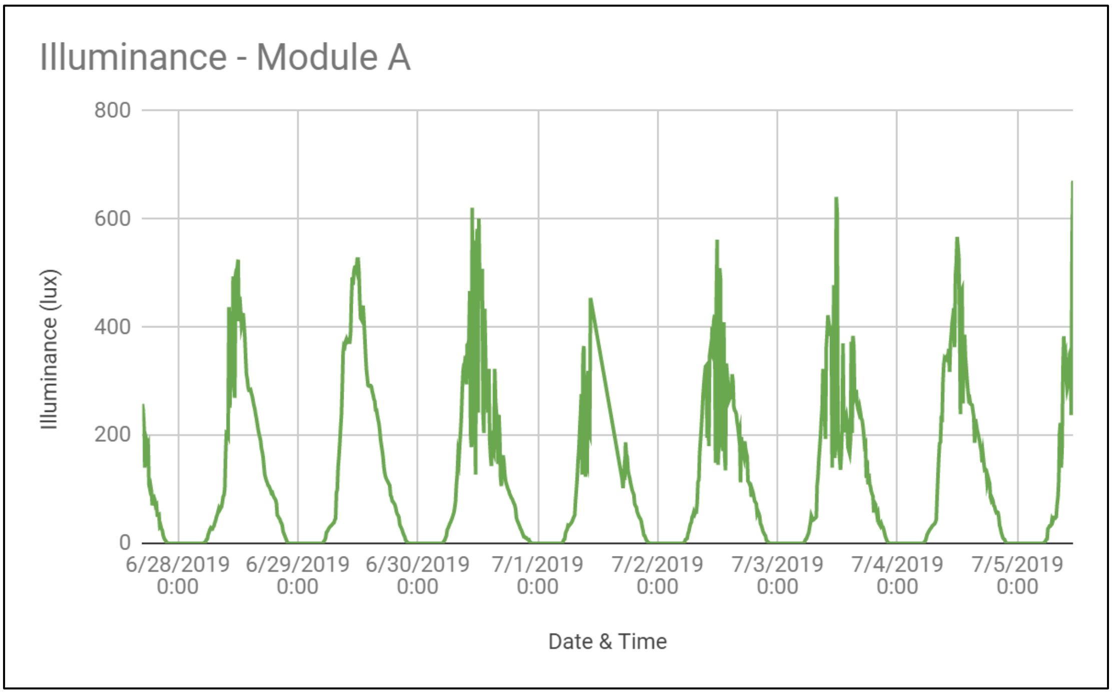




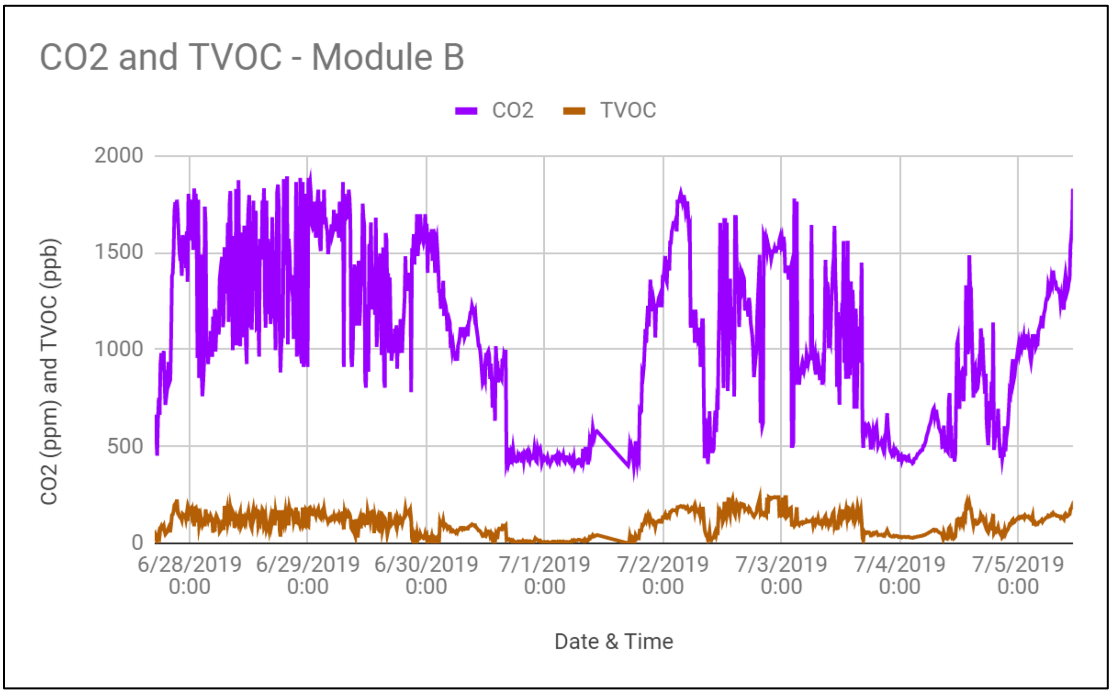
4. Module Performance – Illuminance and Air quality – Week 2

Module A

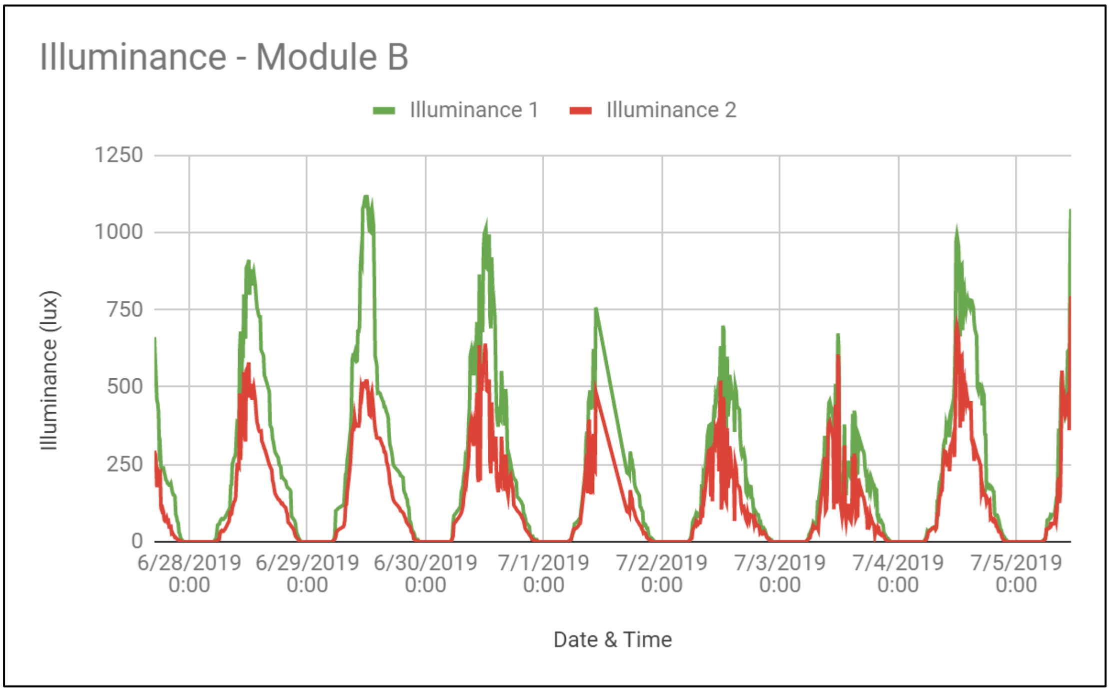




Module B

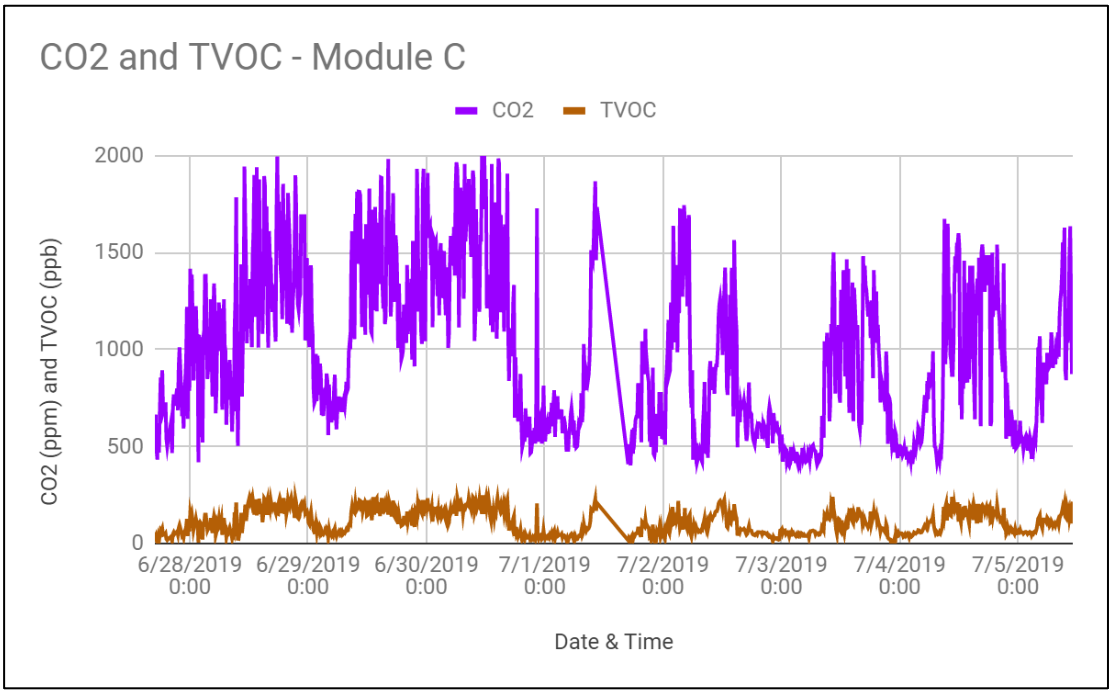


CO2 and TVOC - Module B
CO2
TVOC
CO2 (ppm) and TVOC (ppb)
2000
1500
1000
500
0
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time

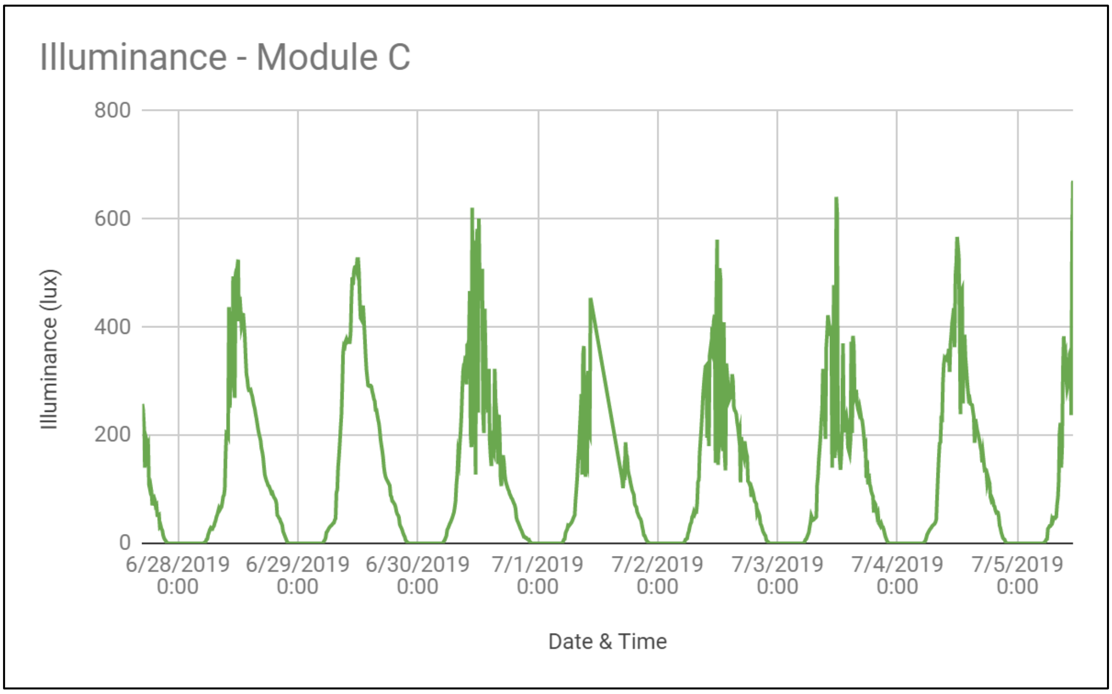


Illuminance - Module B
Illuminance 1
Illuminance 2
Illuminance (lux)
1250
1000
750
500
250
0
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time

Module C

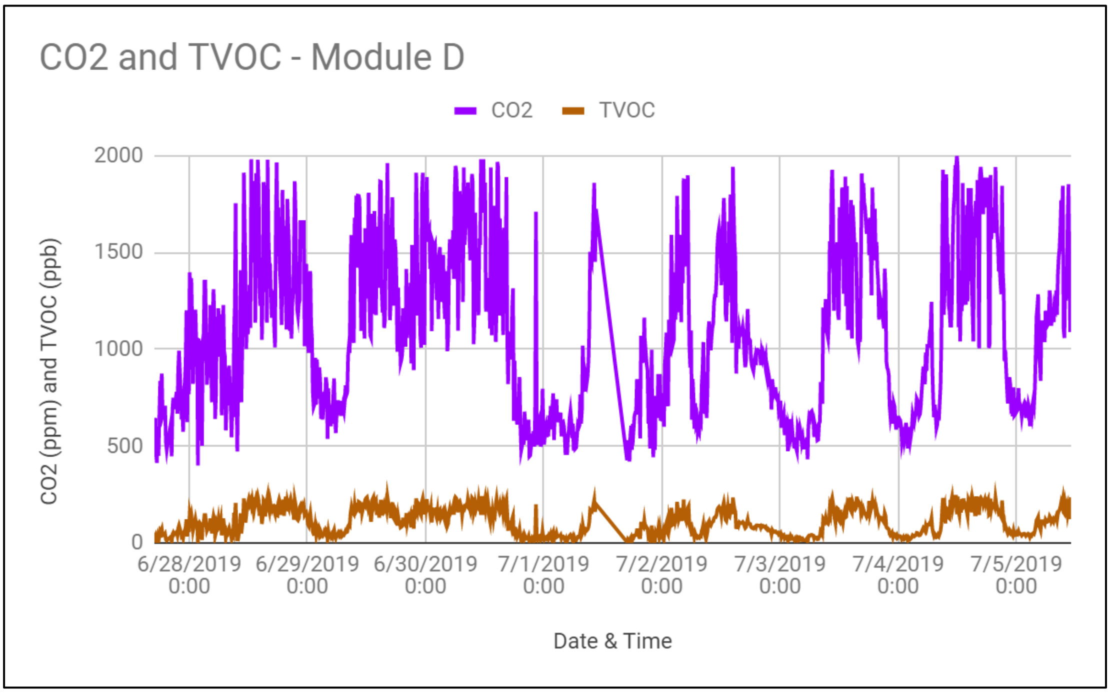


CO2 and TVOC - Module C
CO2
TVOC
2000
1500
1000
500
0
CO2 (ppm) and TVOC (ppb)
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time

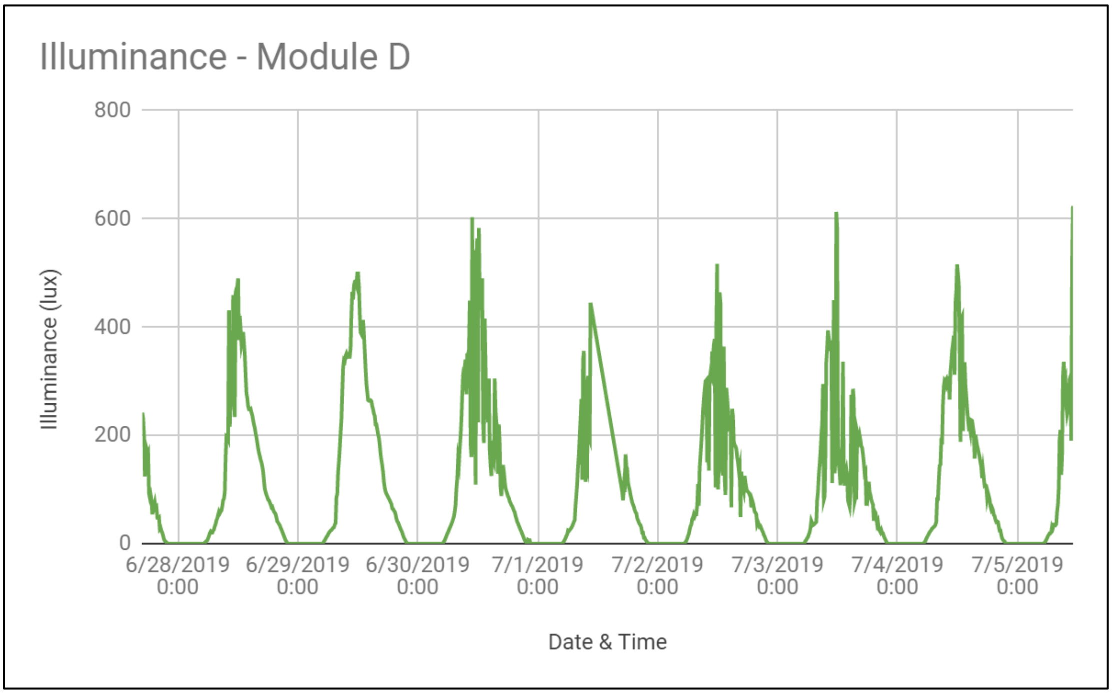


Illuminance - Module C
800
600
400
200
0
Illuminance (lux)
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time

Module D

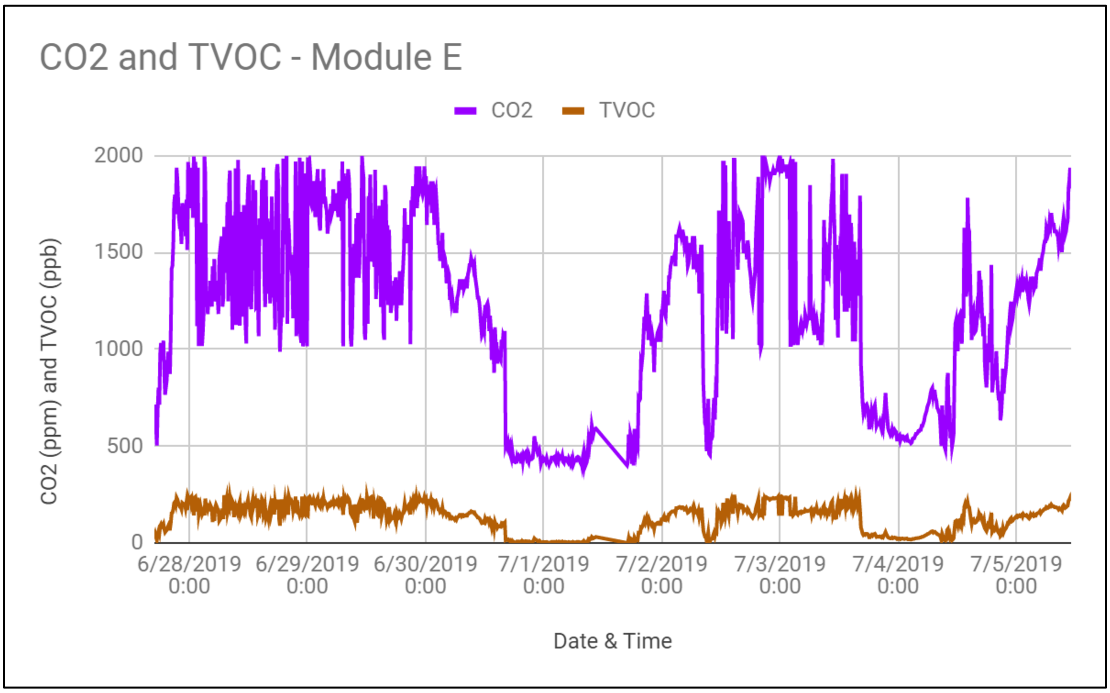


CO2 and TVOC - Module D
CO2
TVOC
2000
1500
1000
500
0
CO2 (ppm) and TVOC (ppb)
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time

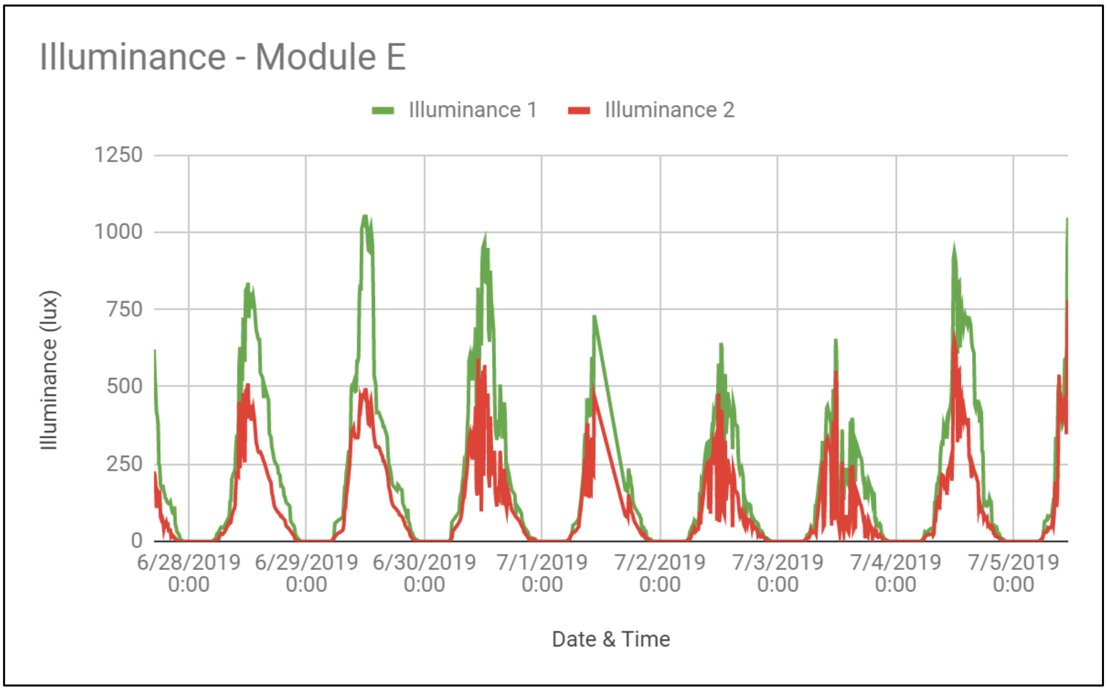


Illuminance - Module D
800
600
400
200
0
Illuminance (lux)
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time

Module E

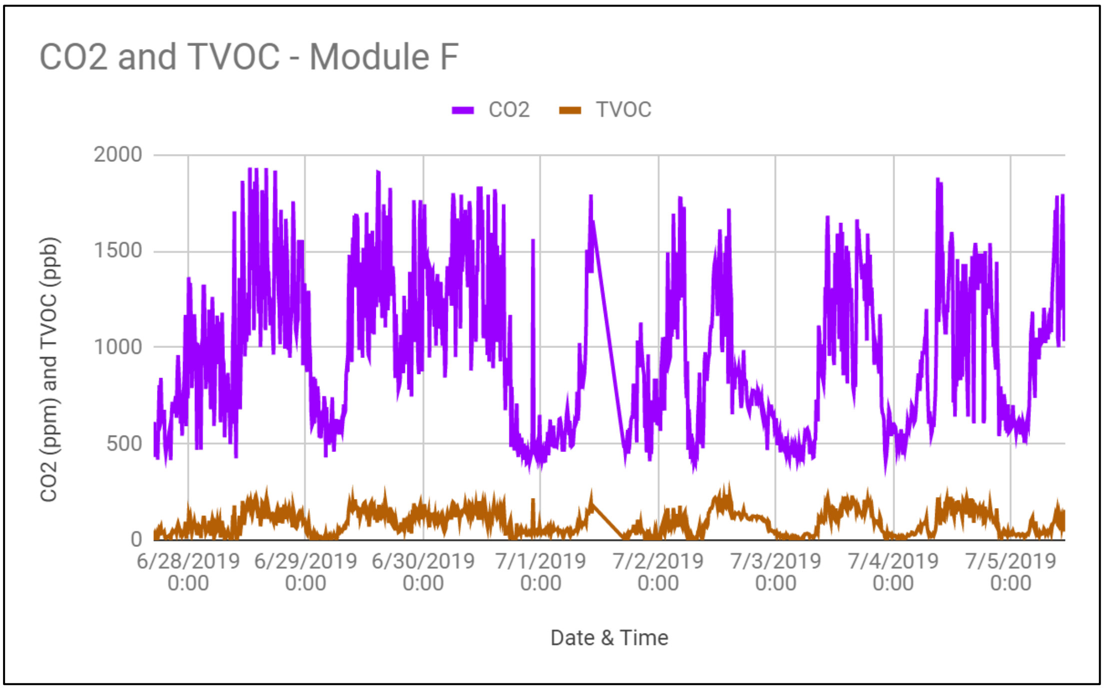


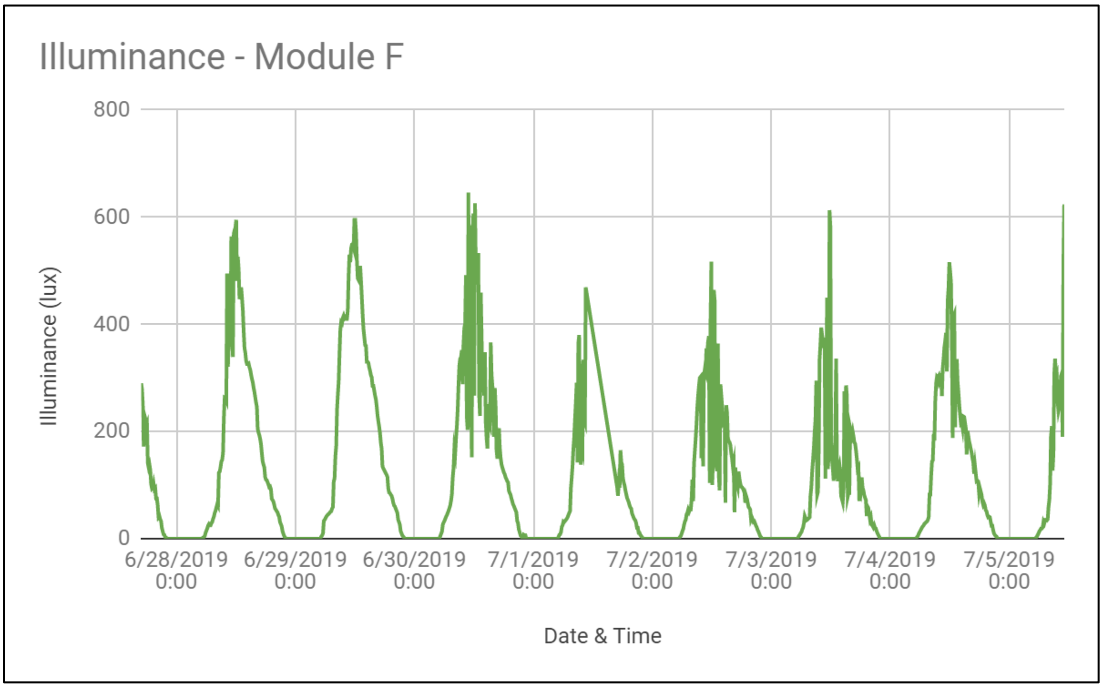
CO2 and TVOC - Module E
CO2
TVOC
CO2 (ppm) and TVOC (ppb)
2000
1500
1000
500
0
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time



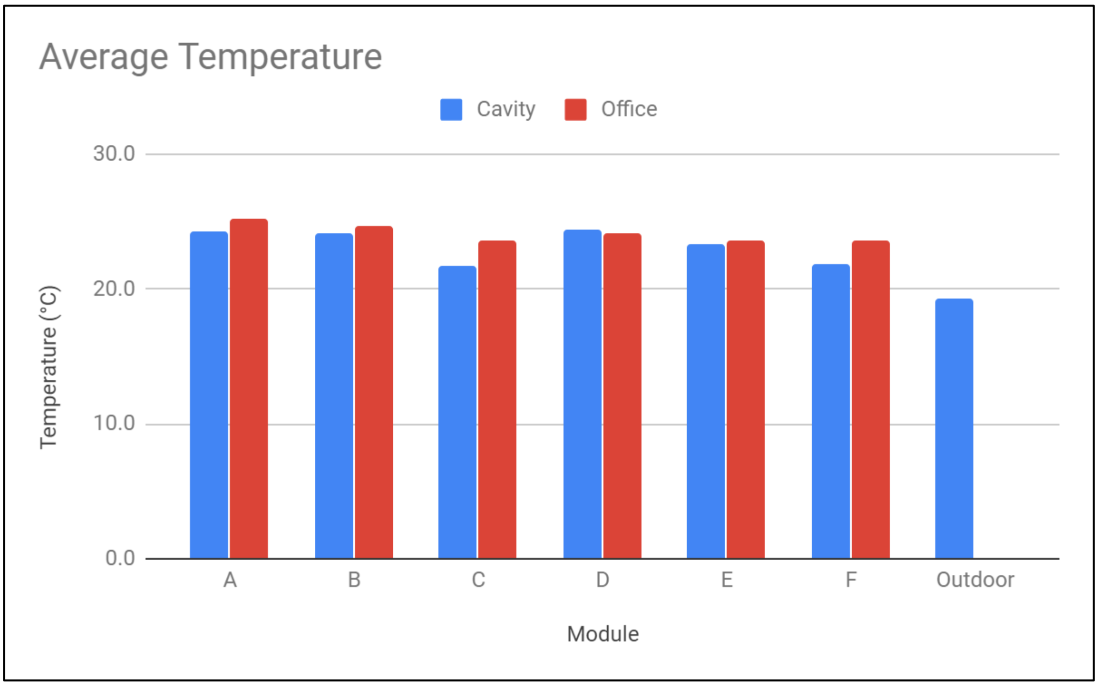
Illuminance - Module E
Illuminance 1
Illuminance 2
Illuminance (lux)
1250
1000
750
500
250
0
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time

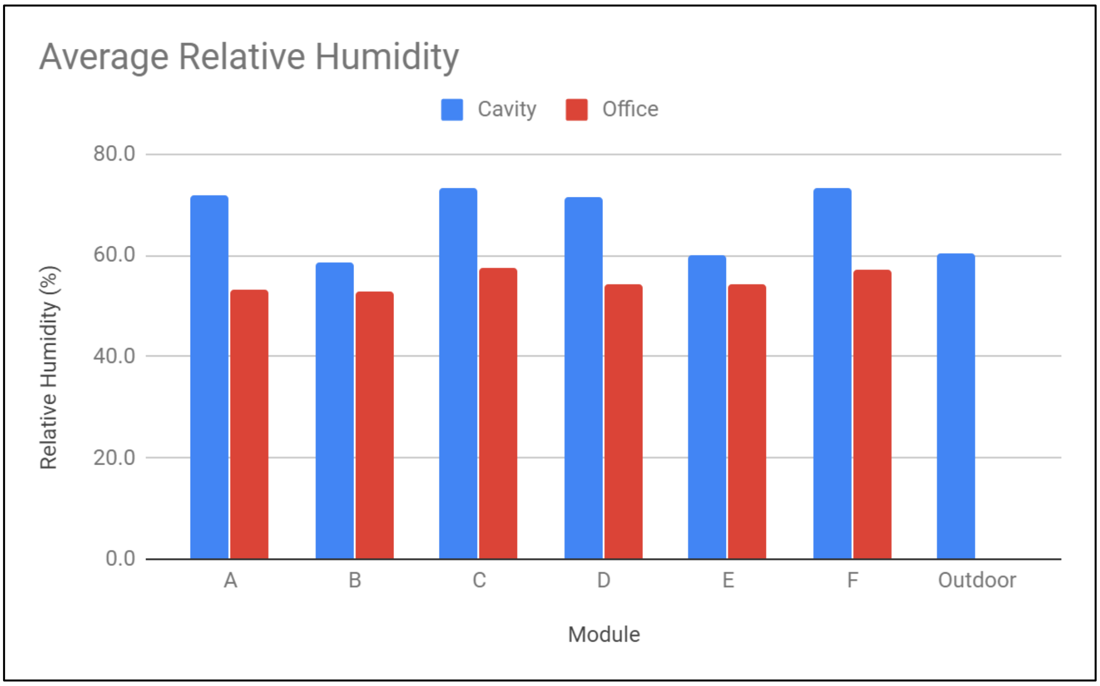
Module F


CO2 and TVOC - Module F
CO2
TVOC
2000
1500
1000
500
0
CO2 (ppm) and TVOC (ppb)
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time


Illuminance - Module F
800
600
400
200
0
Illuminance (lux)
6/28/2019 0:00
6/29/2019 0:00
6/30/2019 0:00
7/1/2019 0:00
7/2/2019 0:00
7/3/2019 0:00
7/4/2019 0:00
7/5/2019 0:00
Date & Time

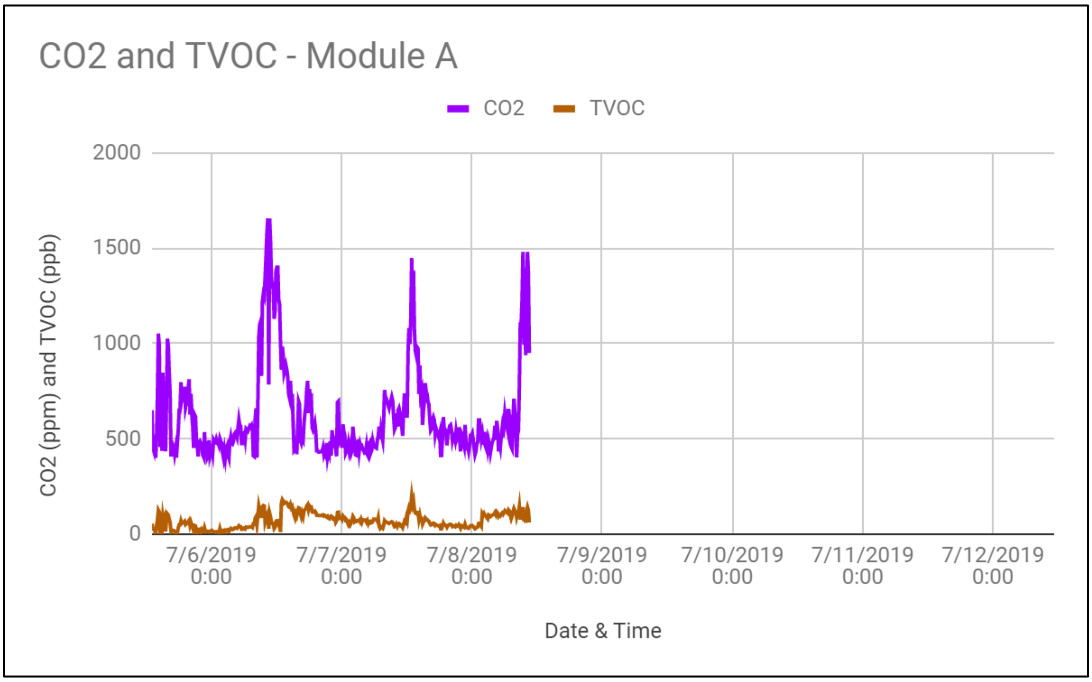
AVERAGE TEMPERATURE AND RELATIVE HUMIDITY – WEEK 2

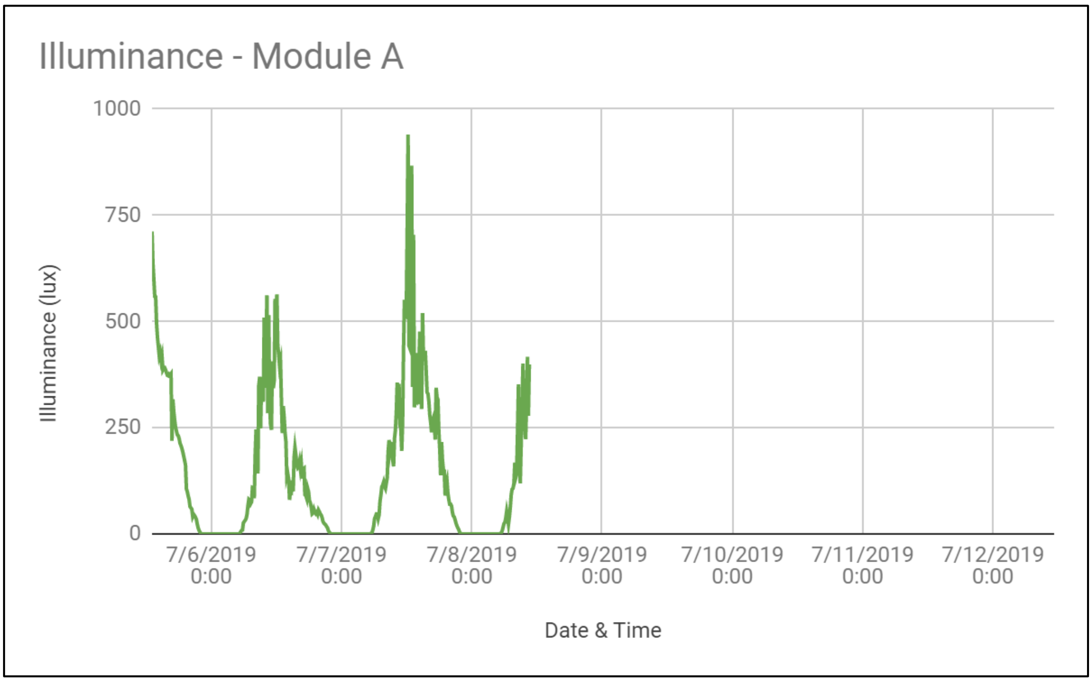




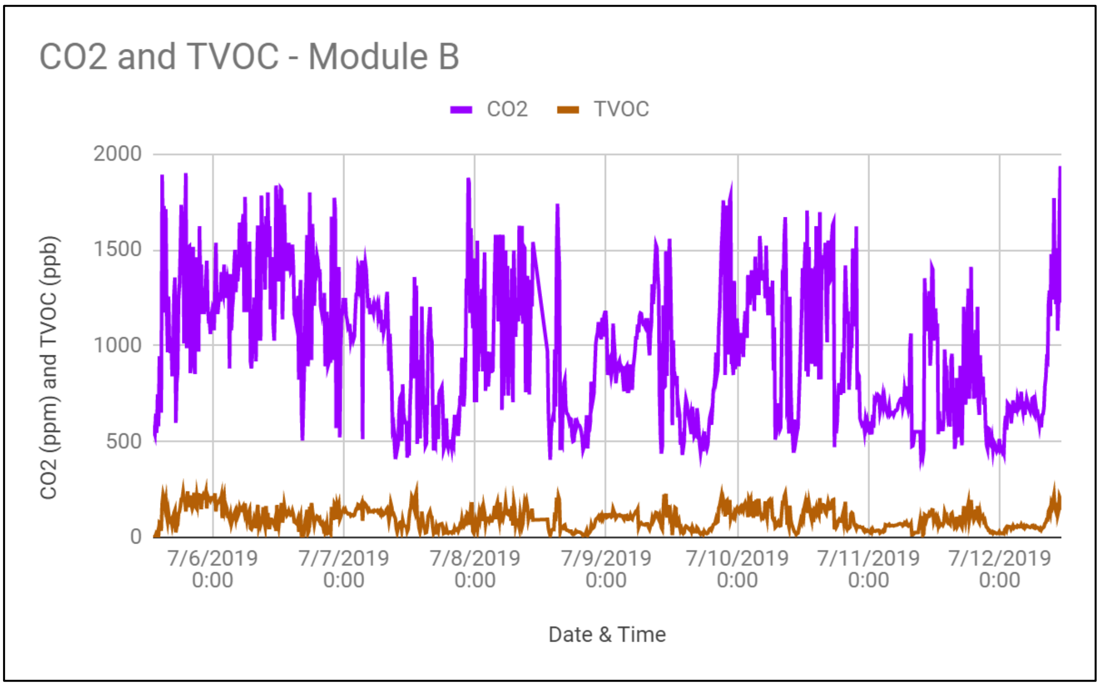
5. Module Performance – Illuminance and Air quality – Week 3

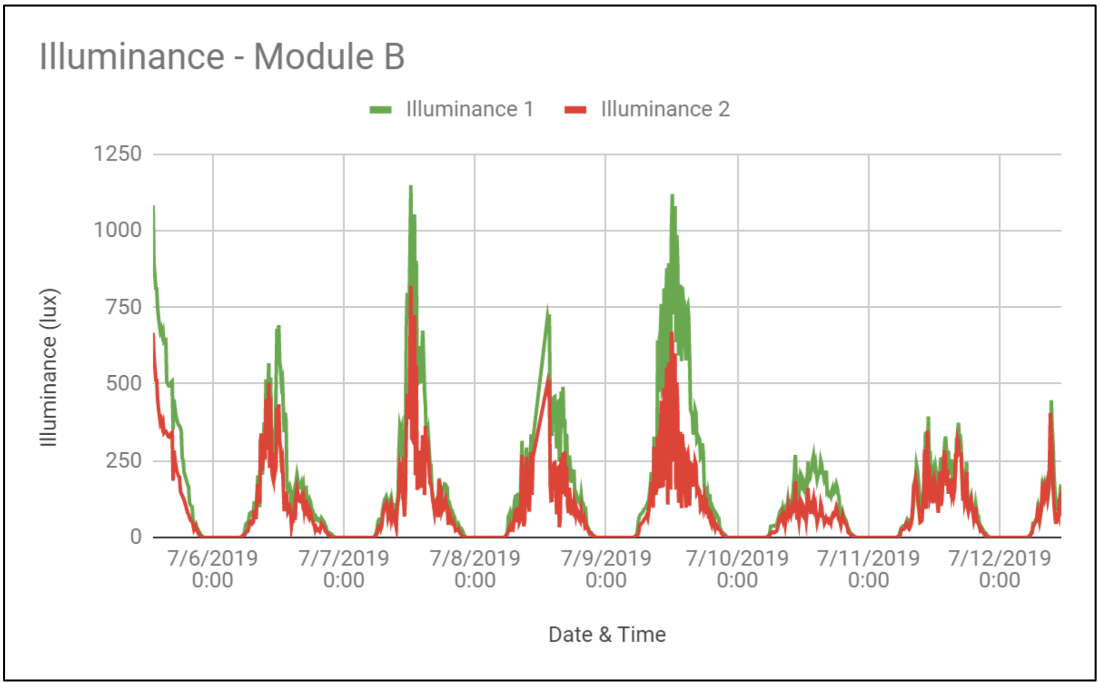
Module A



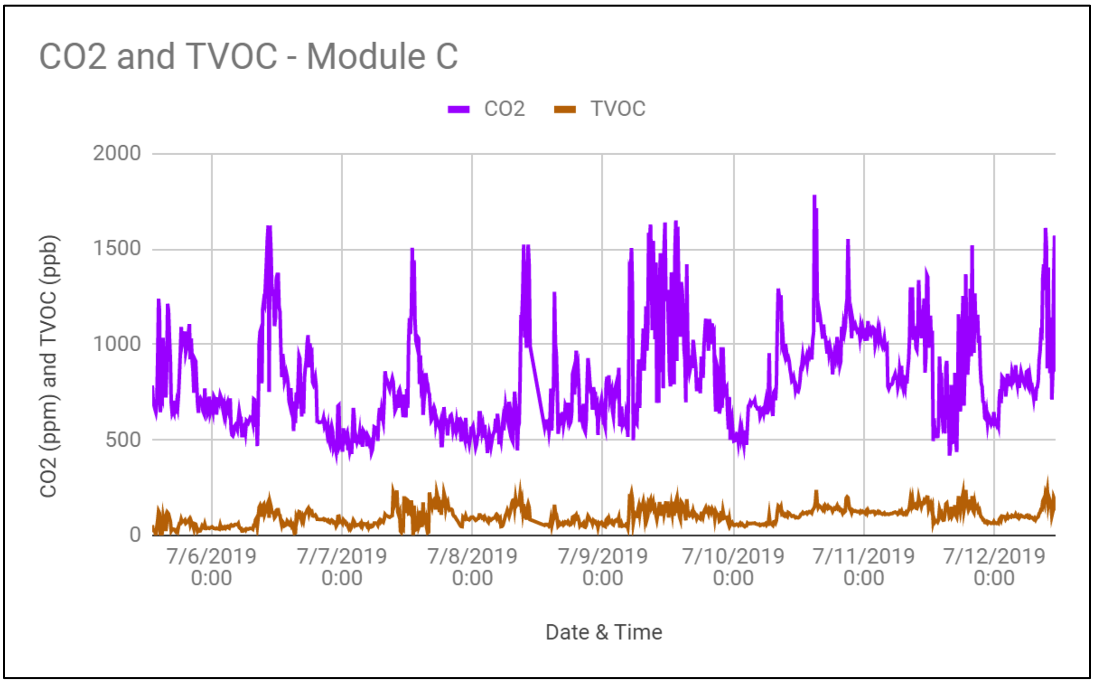


Module B

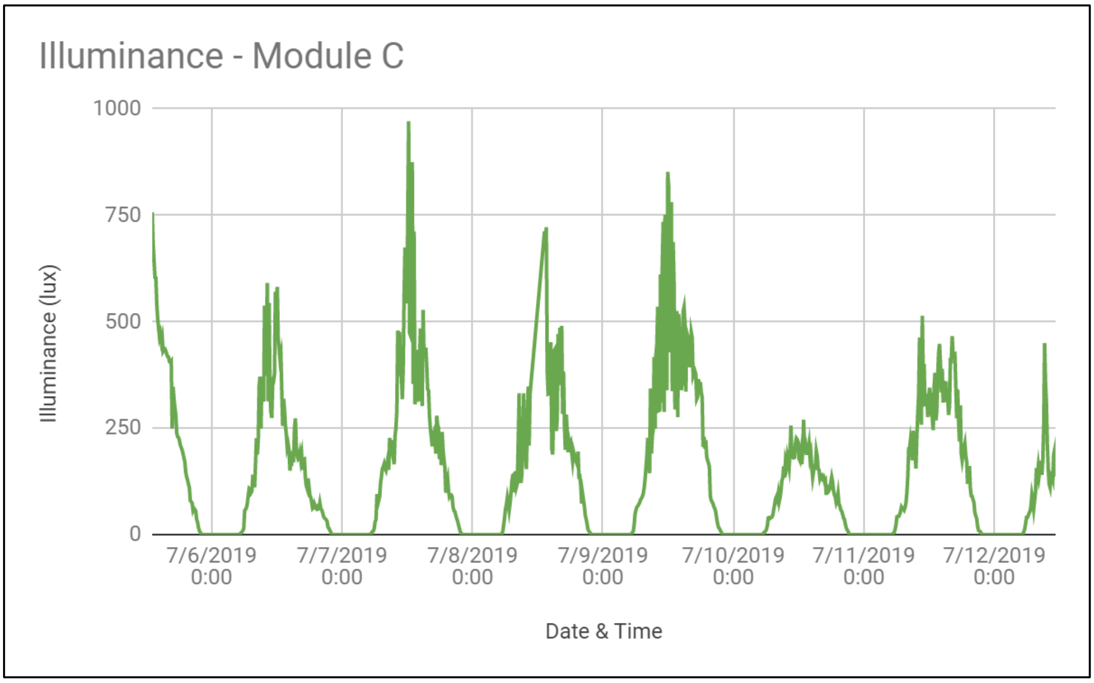

CO2 and TVOC - Module B
CO2
TVOC
CO2 (ppm) and TVOC (ppb)
2000
1500
1000
500
0
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time


Illuminance - Module B
Illuminance 1
Illuminance 2
Illuminance (lux)
1250
1000
750
500
250
0
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time

Module C

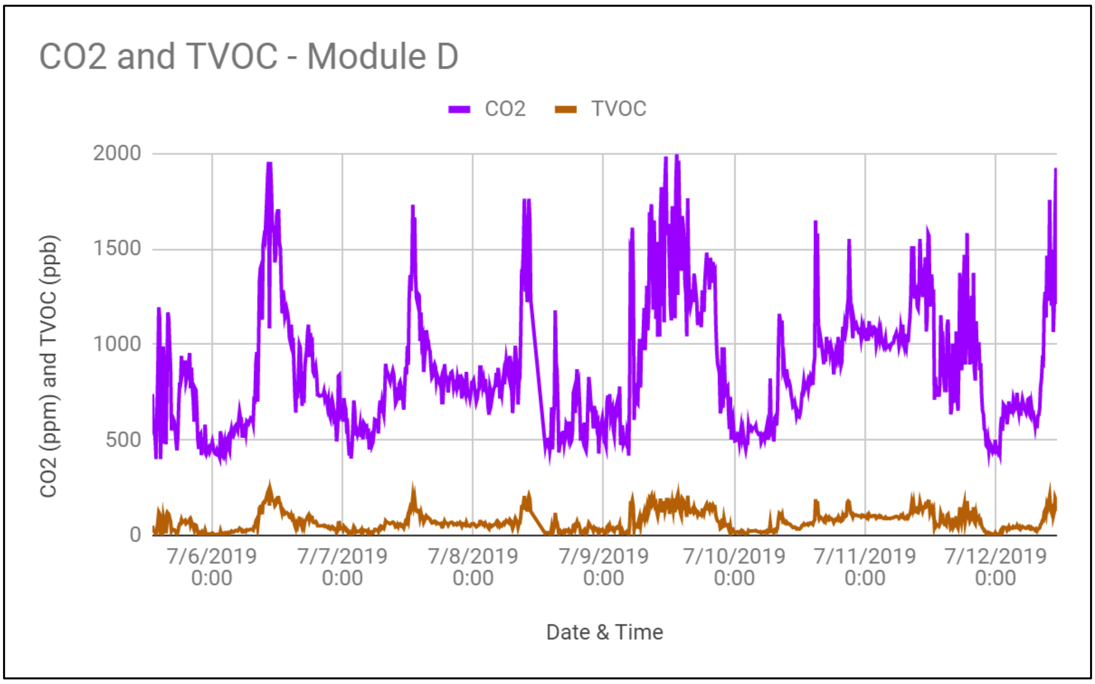


CO2 and TVOC - Module C
CO2
TVOC
CO2 (ppm) and TVOC (ppb)
2000
1500
1000
500
0
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time

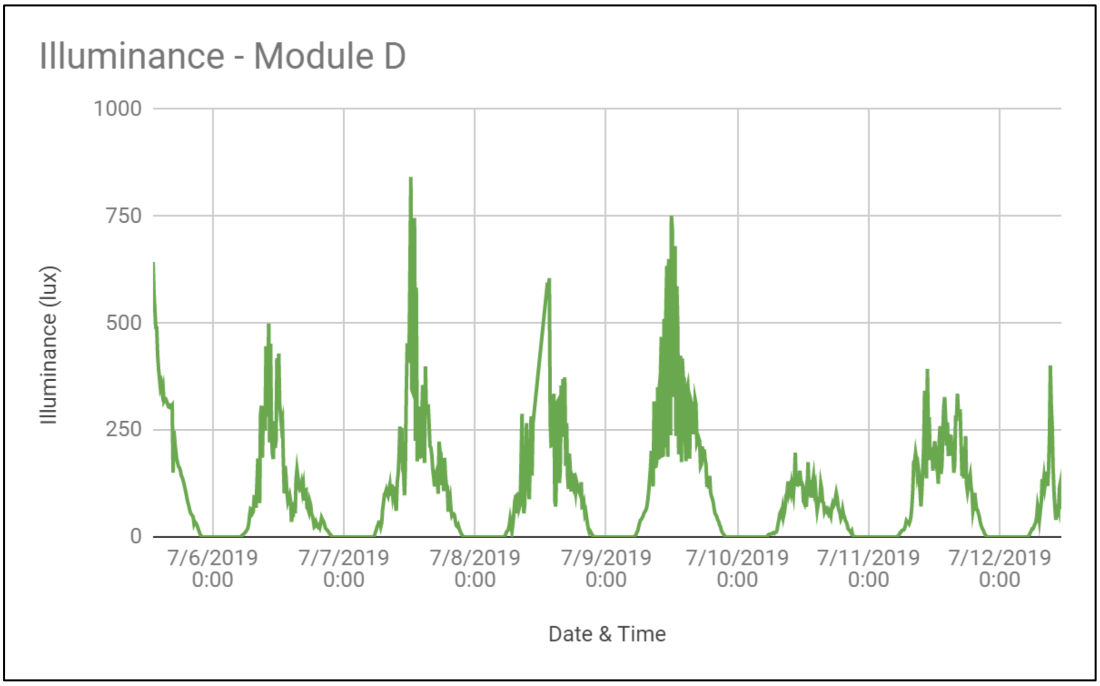


Illuminance - Module C
Illuminance (lux)
1000
750
500
250
0
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time

Module D

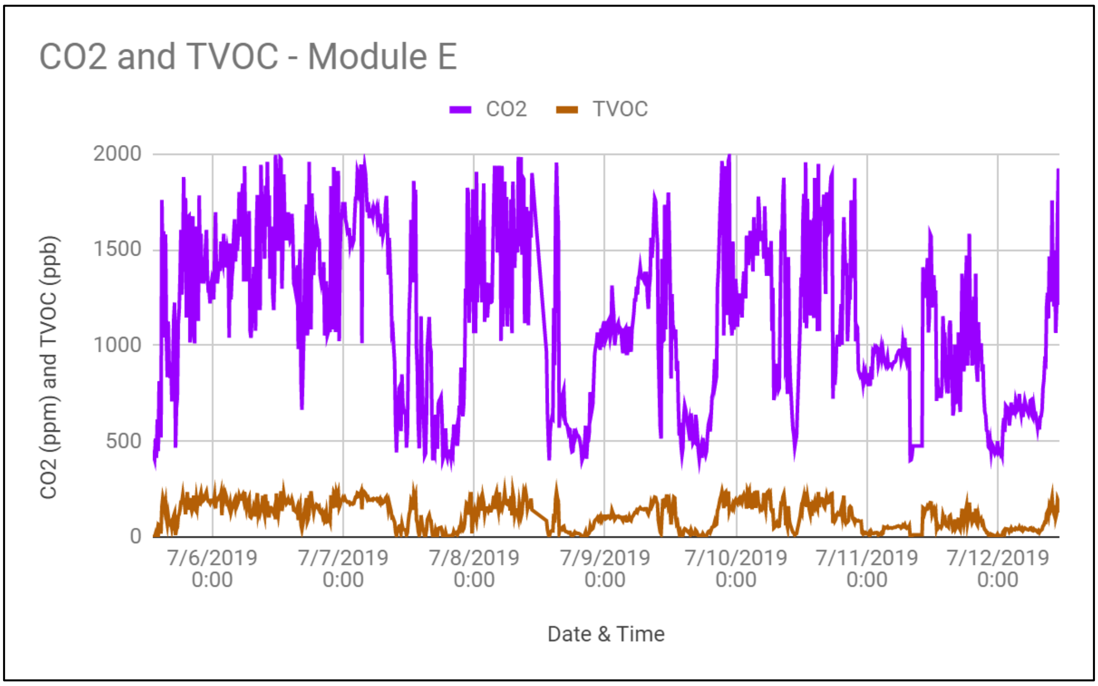


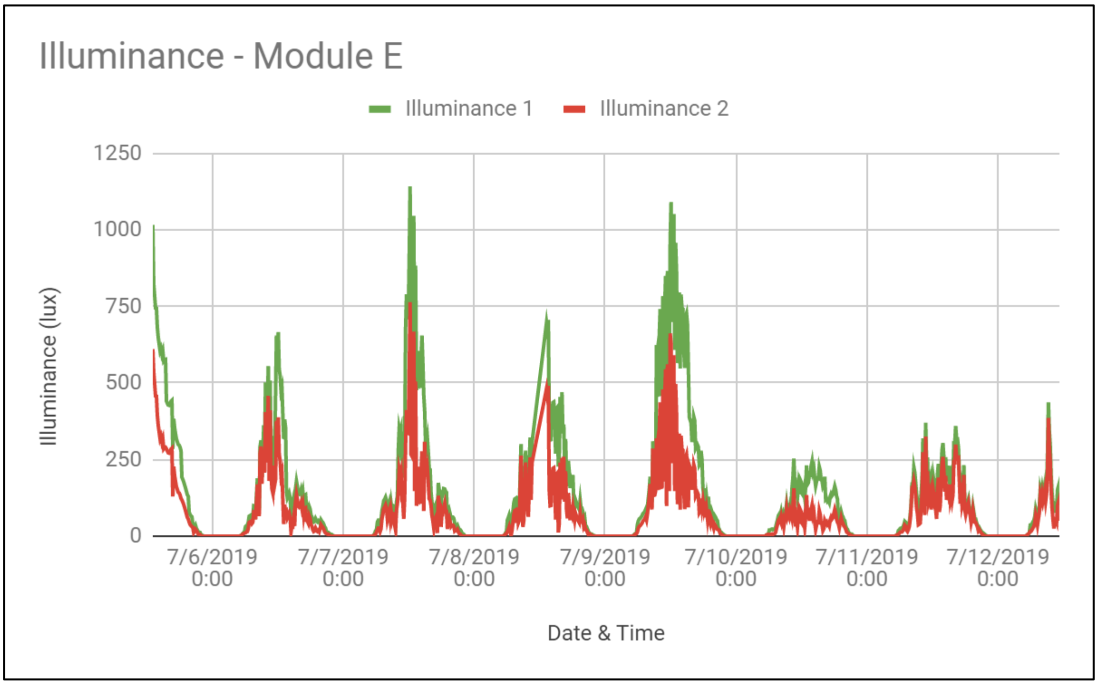
CO2 and TVOC - Module D
CO2
TVOC
2000
1500
1000
500
0
CO2 (ppm) and TVOC (ppb)
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time



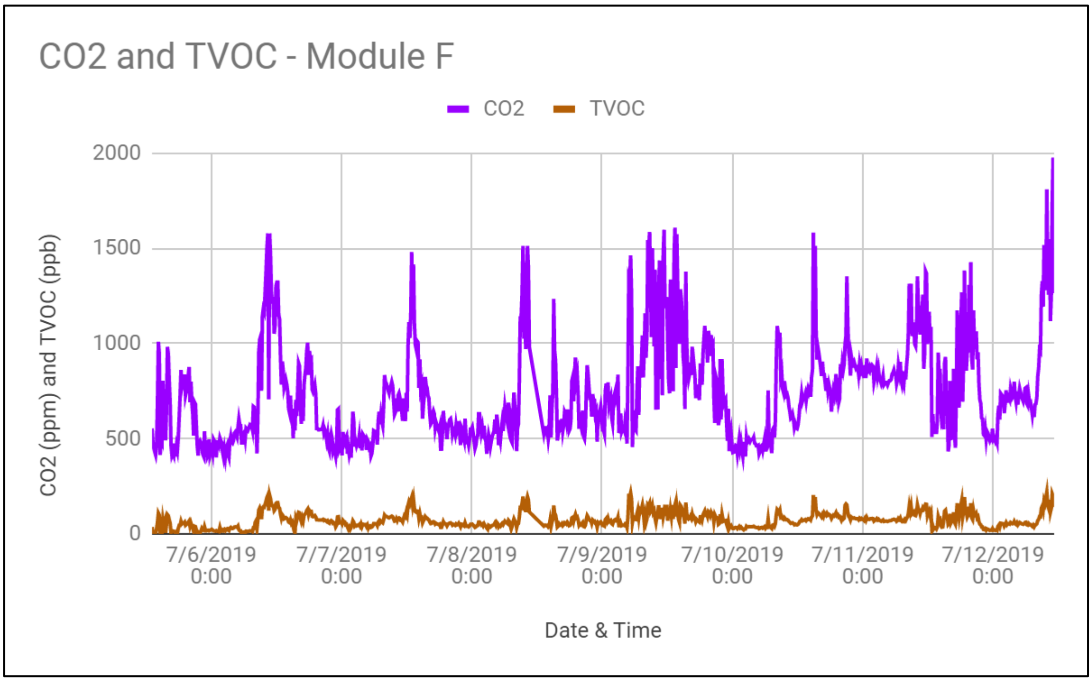
Illuminance - Module D
1000
750
500
250
0
Illuminance (lux)
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time

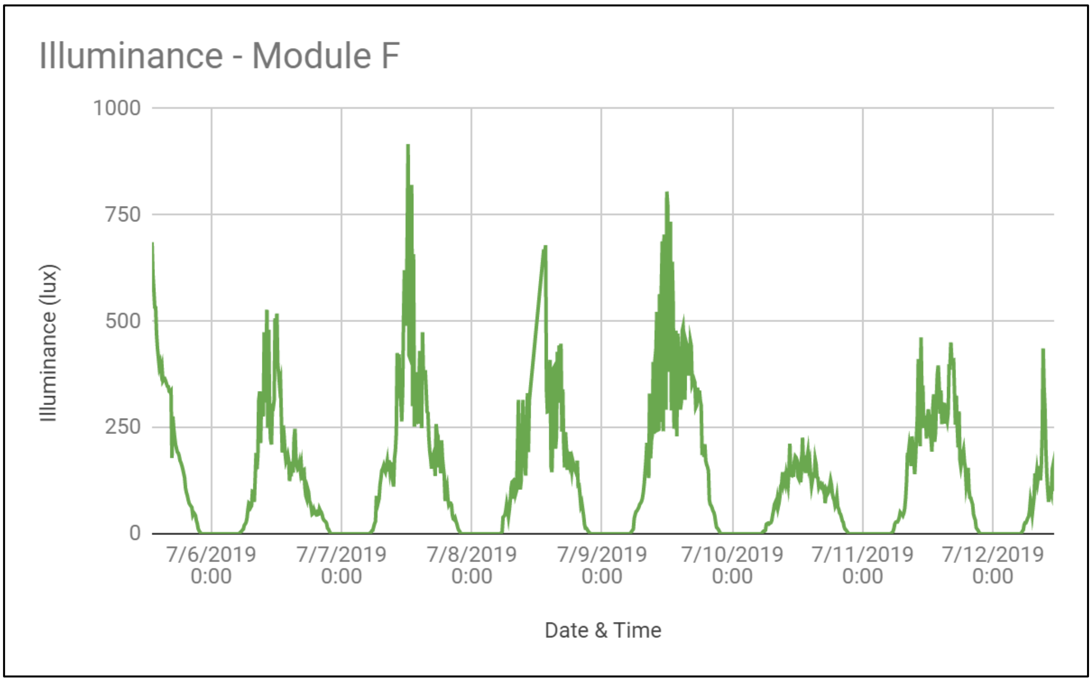
Module E


CO2 and TVOC - Module E
CO2
TVOC
2000
1500
1000
500
0
CO2 (ppm) and TVOC (ppb)
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time

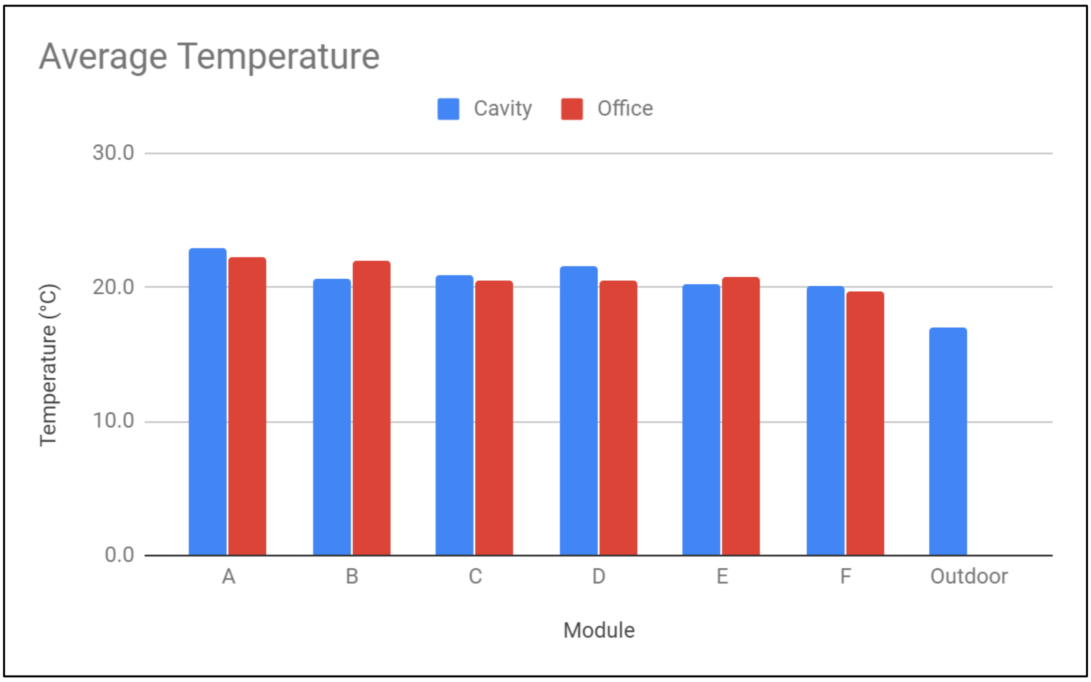

Illuminance - Module E
Illuminance 1
Illuminance 2
1250
1000
750
500
250
0
Illuminance (lux)
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time

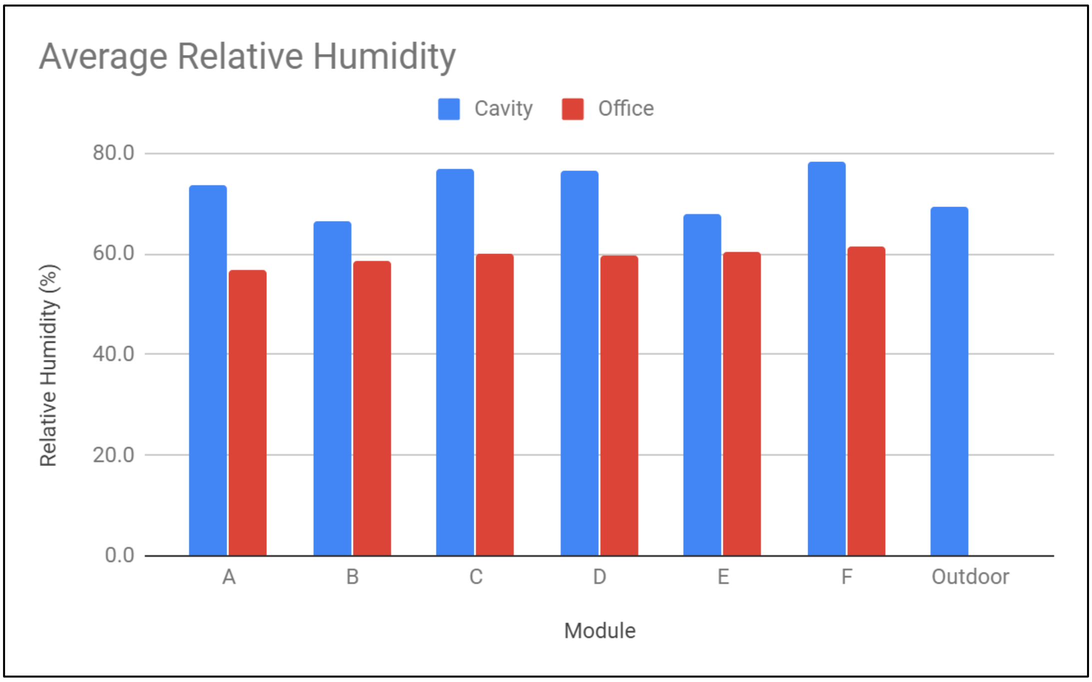
Module F


CO2 and TVOC - Module F
CO2
TVOC
CO2 (ppm) and TVOC (ppb)
2000
1500
1000
500
0
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time

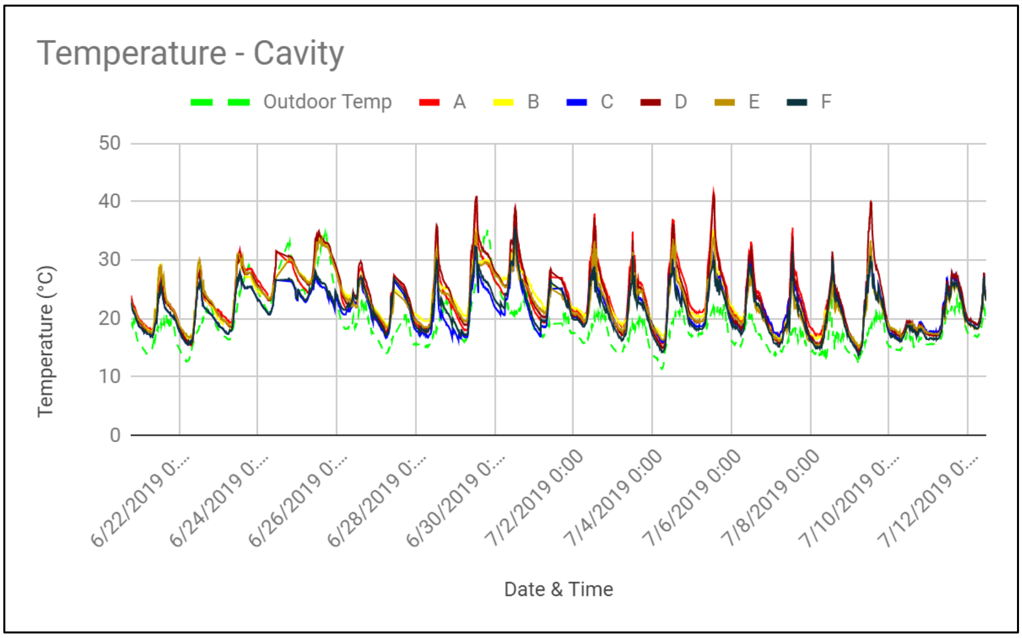

Illuminance - Module F
Illuminance (lux)
1000
750
500
250
0
7/6/2019 0:00
7/7/2019 0:00
7/8/2019 0:00
7/9/2019 0:00
7/10/2019 0:00
7/11/2019 0:00
7/12/2019 0:00
Date & Time

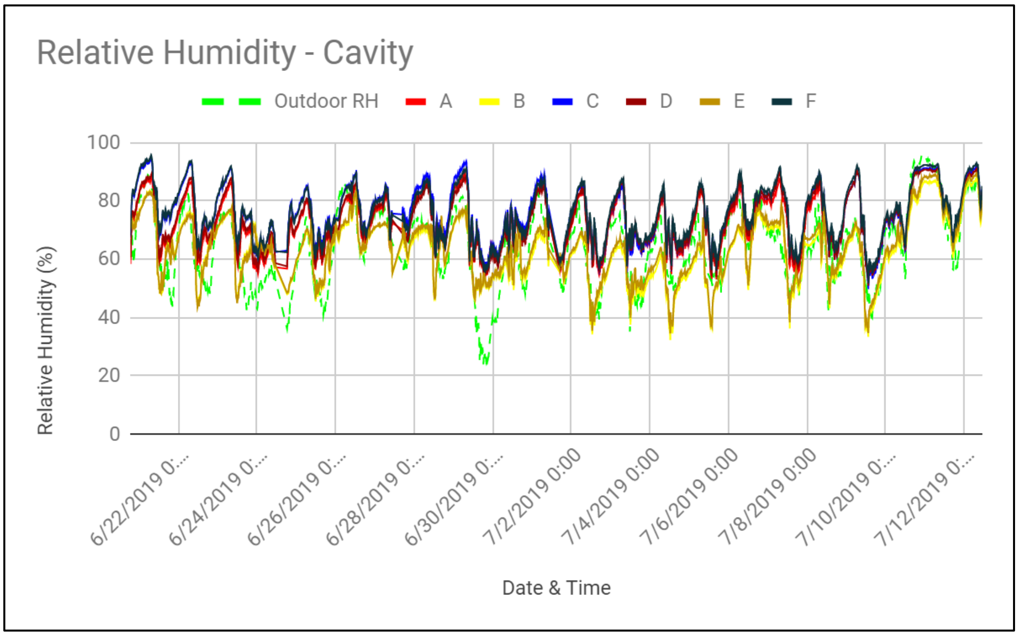
AVERAGE TEMPERATURE AND RELATIVE HUMIDITY – WEEK 3



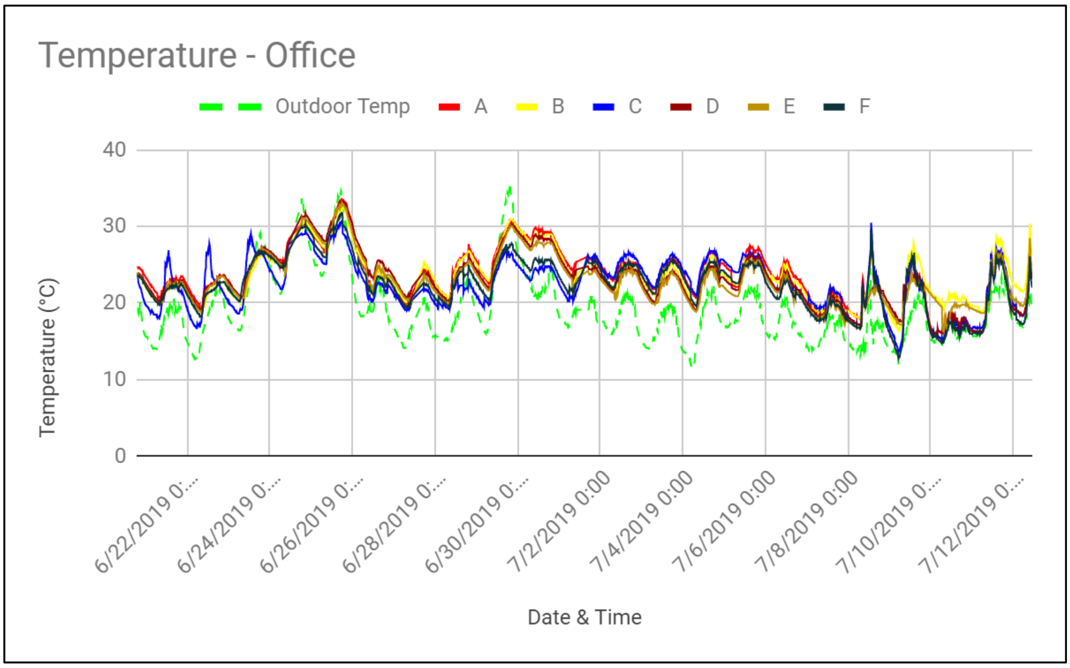


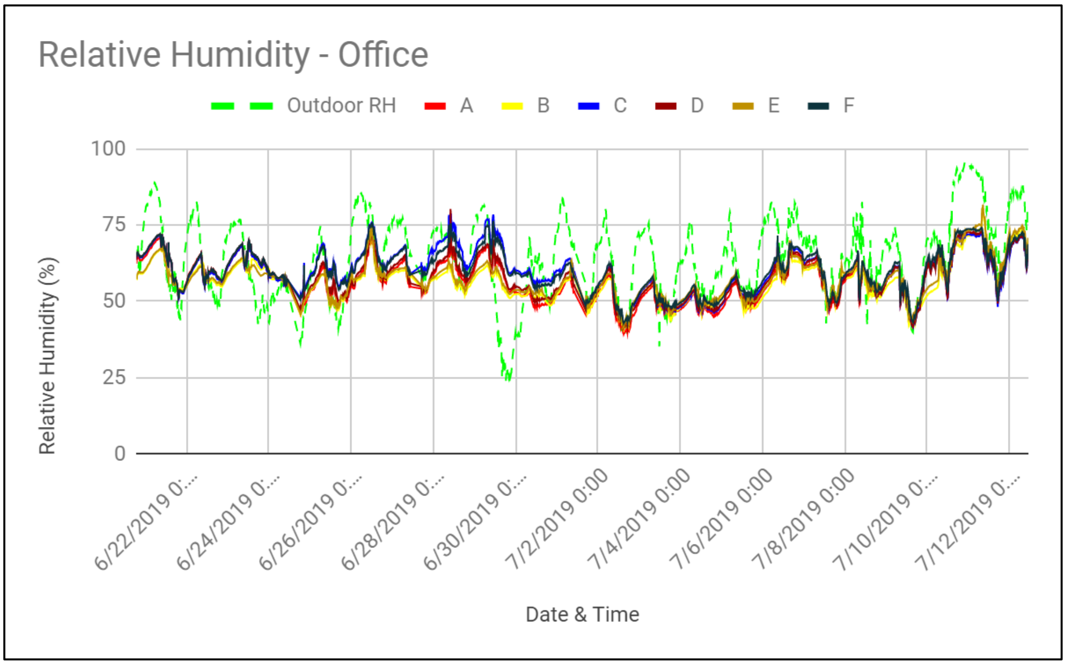
6. Overall Temperature and Relative Humidity – Cavity



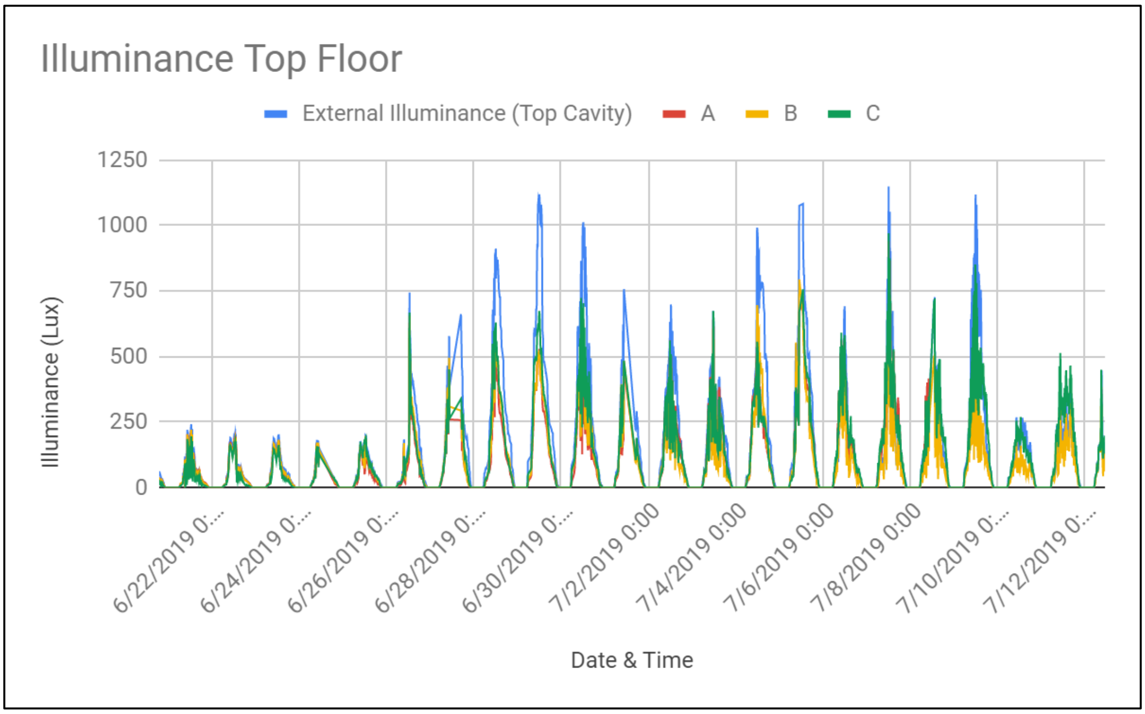


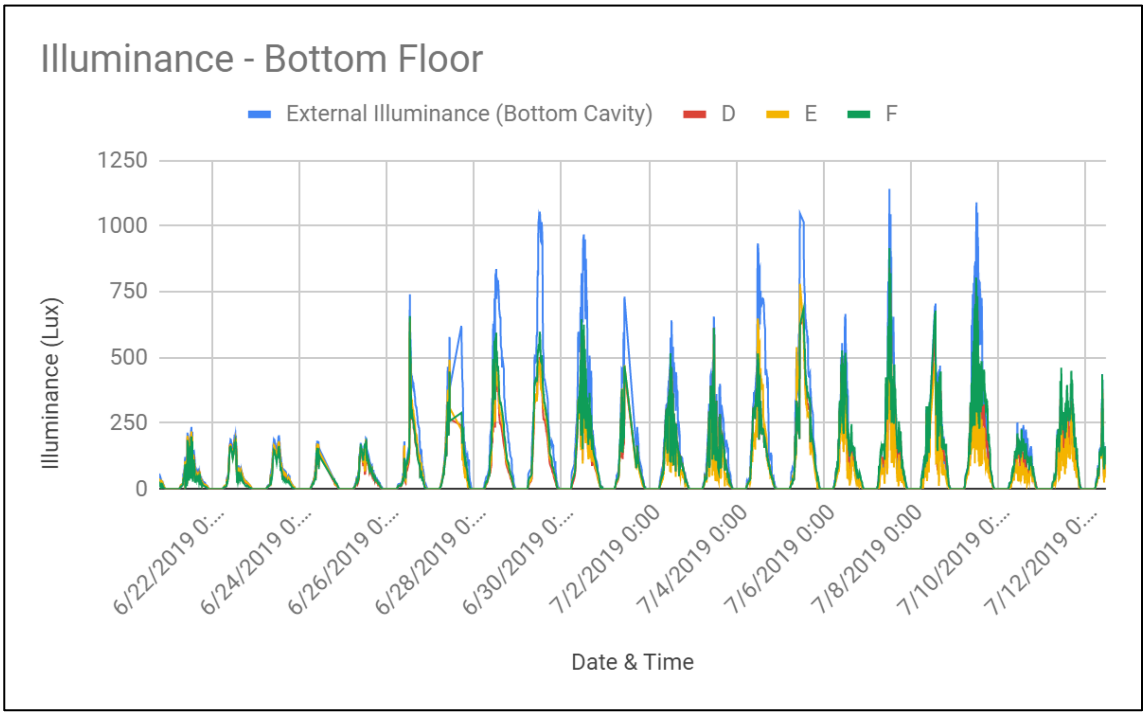
7. Overall Temperature and Relative Humidity – Office



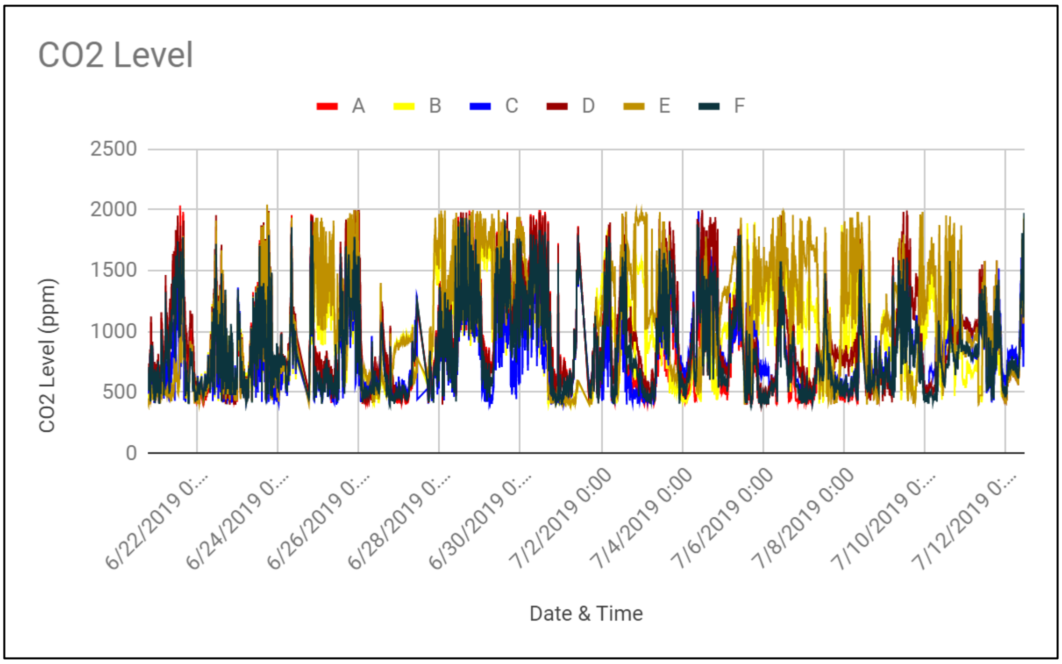


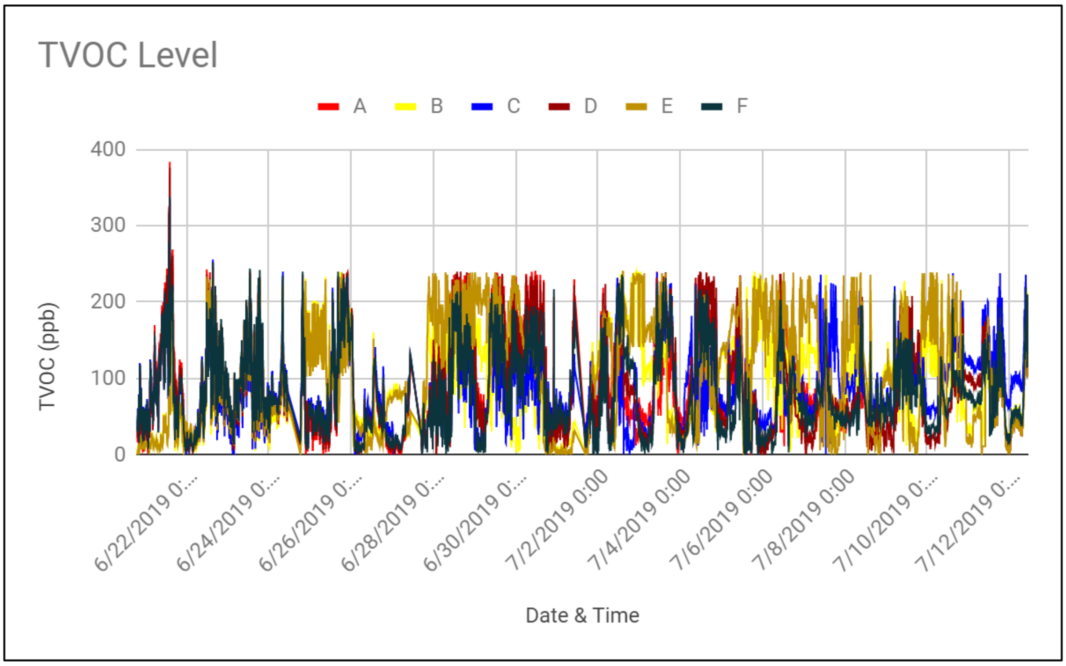
8. Overall Illuminance – Top and Bottom Floor



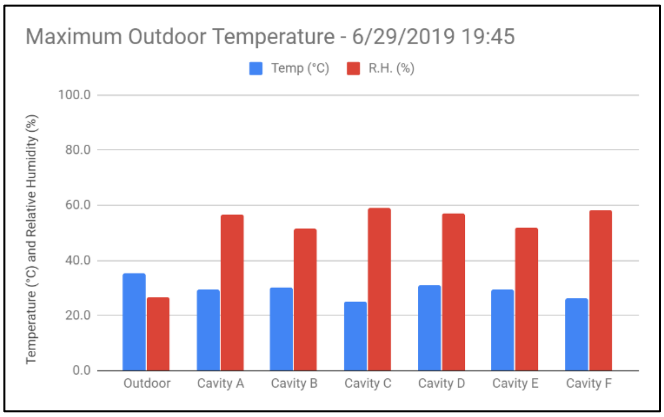


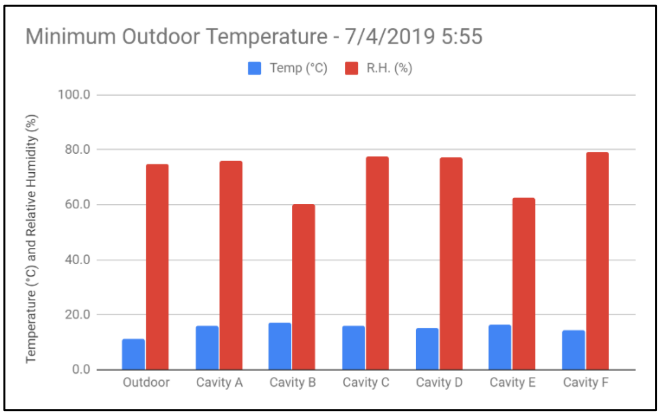
9. Overall Air Quality – CO_2 and TVOC

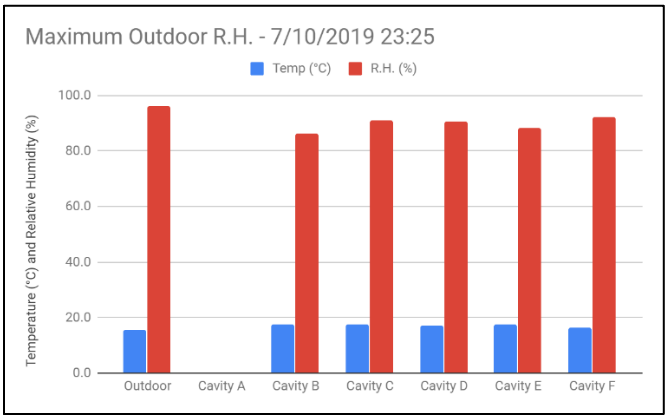


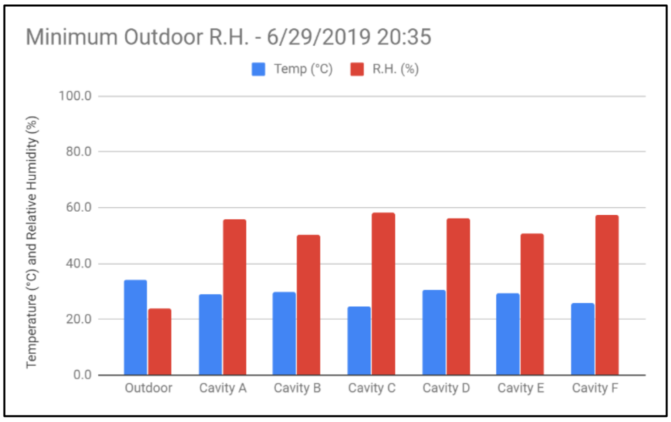


10. Comparison of cavities in extreme scenarios

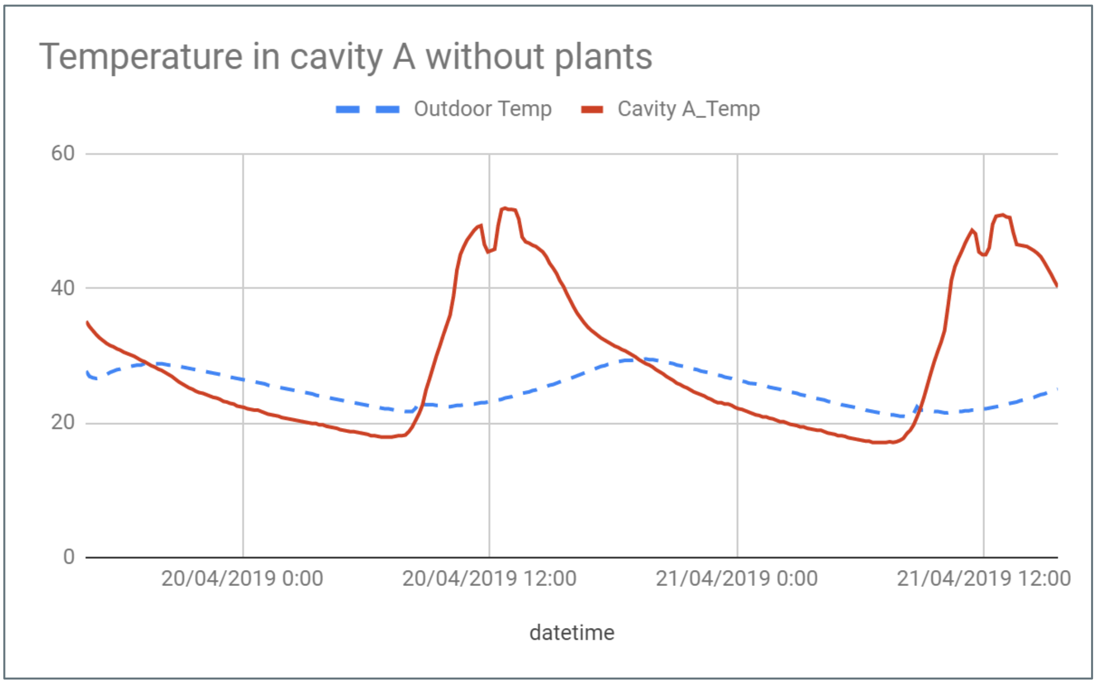




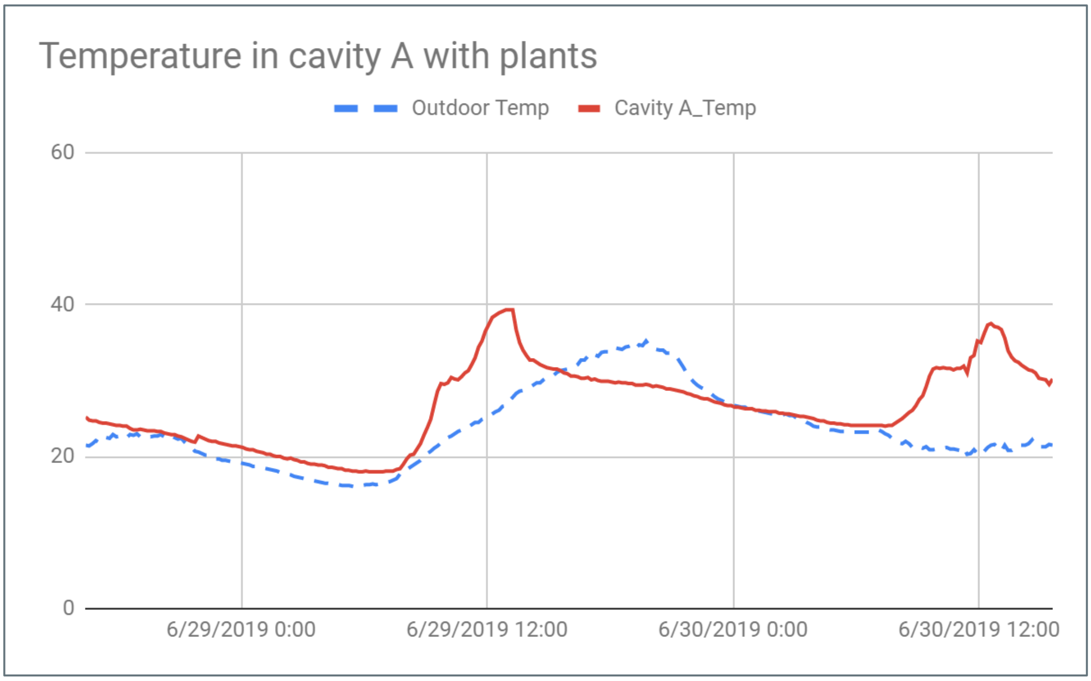




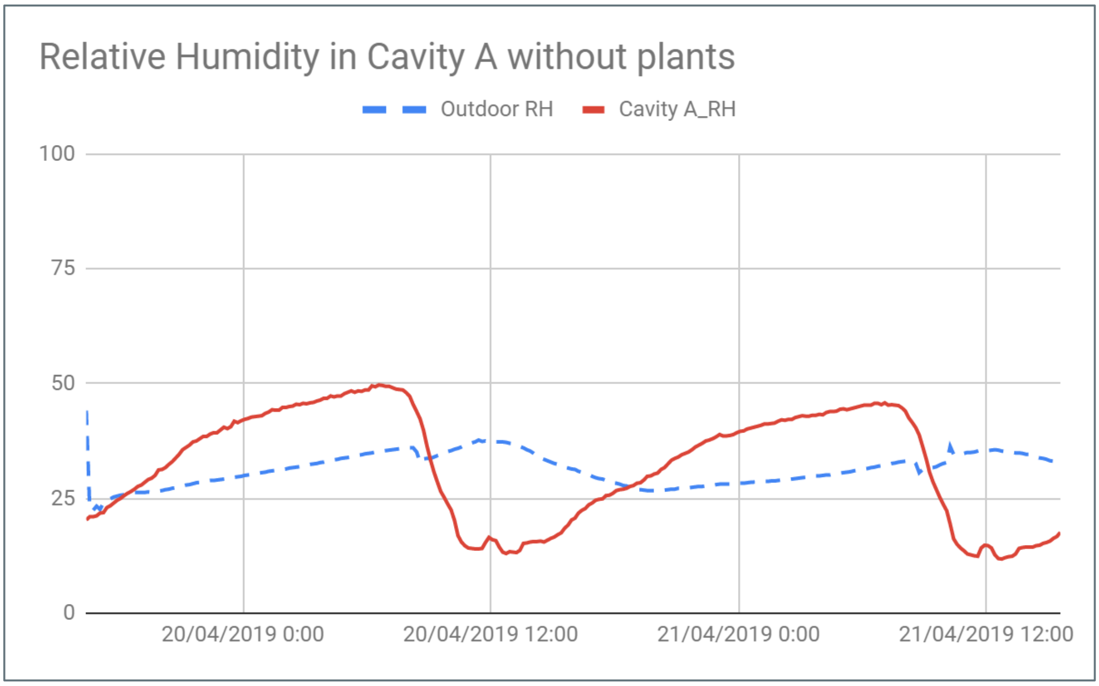
11. Comparison between measurements in cavities without plants and with plants



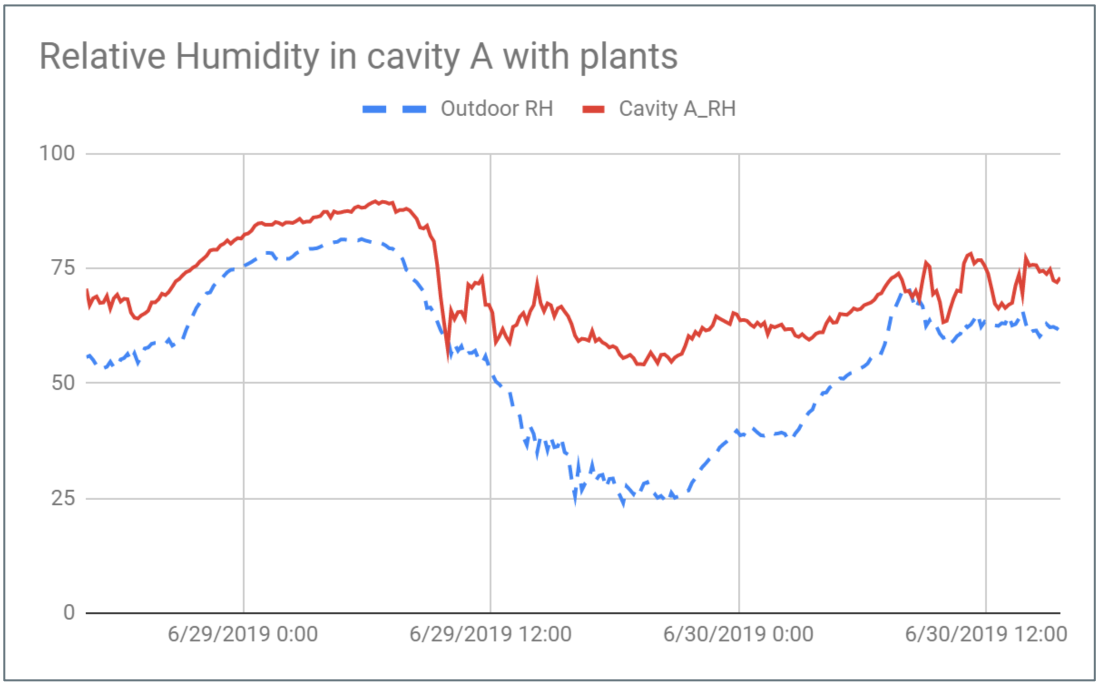
Container doors open 90°



Container doors open 45°

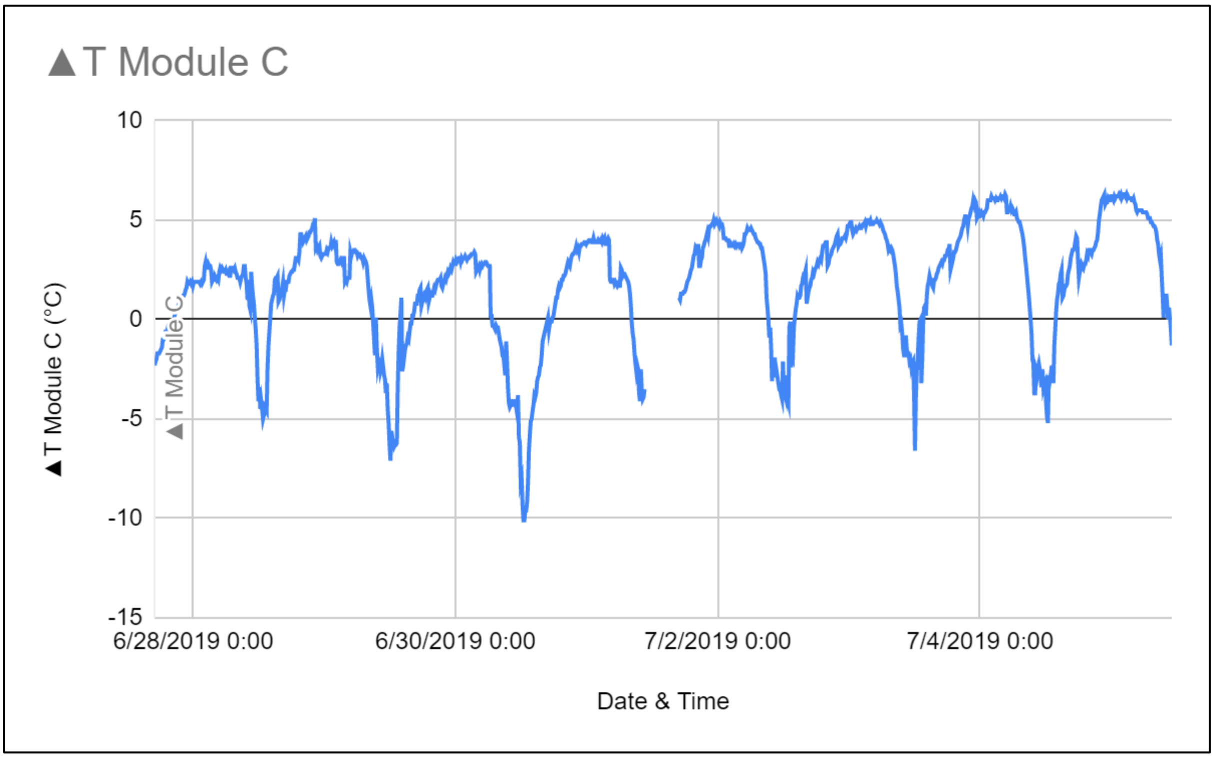


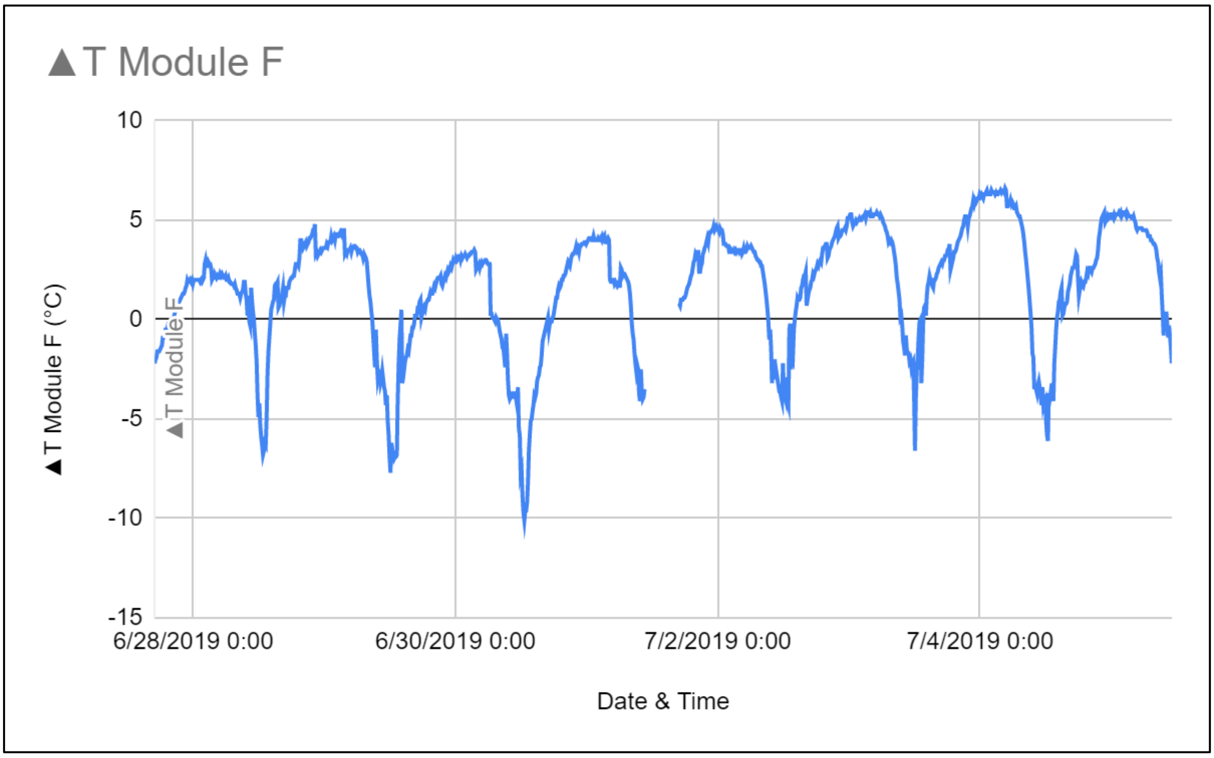
Container doors open 90°



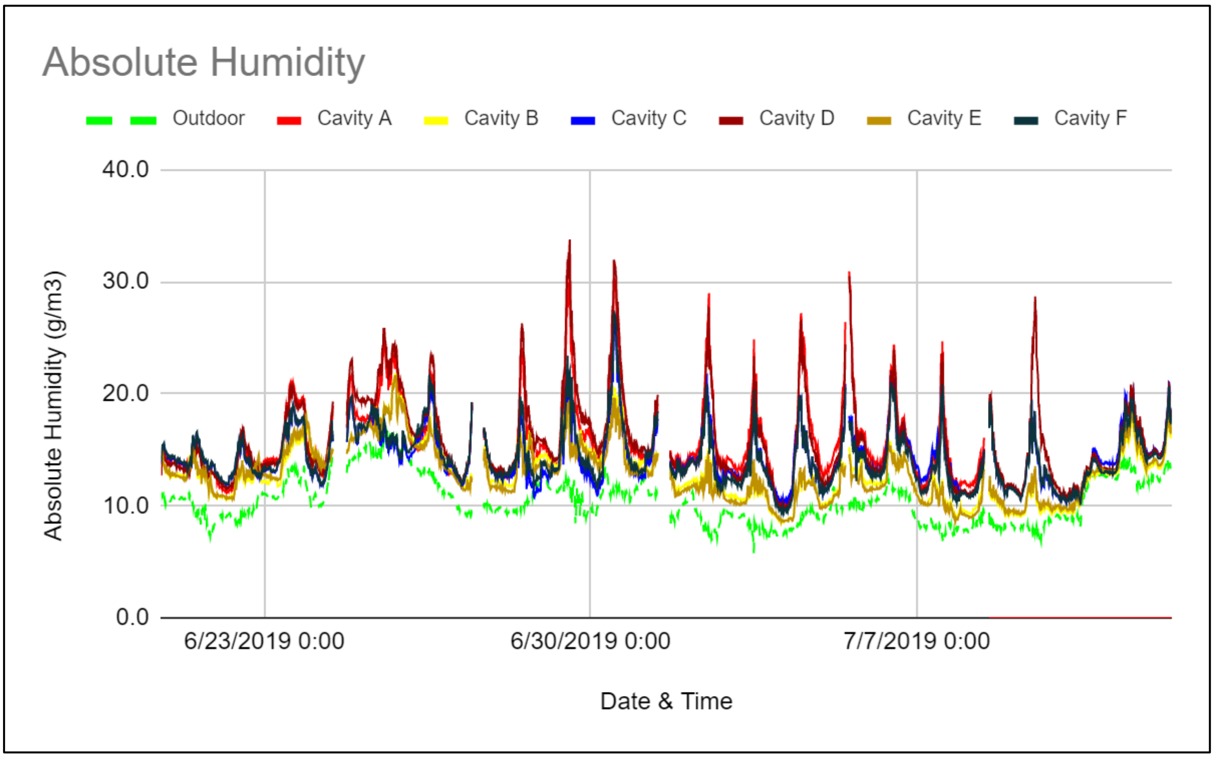
Container doors open 45°

12. Comparison between cavity and office temperature in module C and F (Week 2)





13. Absolute humidity in the cavities of all modules in g/m^3



APPENDIX B - ARDUINO CODE SCRIPTS

Many scripts and codes were used for experimental purposes. All scripts were made with Arduino IDE. Some highlighted codes are given below

1. <u>Script for DHT22 sensor</u>

```
/*  DHT11/22 code taken from - Dejan Nedelkovski
 *  www.HowToMechatronics.com
 * DHT library taken from Arduino official website
 * https://playground.arduino.cc/Main/DHTLib
 */

#include <dht.h>
#define dataPin 7 // Defines pin number to which the sensor is connected
dht DHT; // Creats a DHT object
void setup() {
  Serial.begin(9600);
}
void loop() {
  int readData = DHT.read22(dataPin); // Reads the data from the sensor
  float t = DHT.temperature; // Gets the values of the temperature
  float h = DHT.humidity; // Gets the values of the humidity
```

```
  // Printing the results on the serial monitor
  Serial.print("Temperature = ");
  Serial.print(t);
  Serial.print(" *C ");
  Serial.print("    Humidity = ");
  Serial.print(h);
  Serial.println(" % ");

  delay(1000); // Delays 2 secods, as the DHT22 sampling rate is 0.5Hz
}
```

2. <u>Script for BH1750 sensor</u>

```
/*
 * BH1750 code taken from - BH1750 library
 * https://create.arduino.cc/projecthub/afsh_ad/measure-lux-with-arduino-using-bh1750-91dad1

  Example of BH1750 library usage.

  This example initialises the BH1750 object using the default high resolution
  continuous mode and then makes a light level reading every second.

  Connection:

    VCC -> 3V3 or 5V
    GND -> GND
    SCL -> SCL (A5 on Arduino Uno, Leonardo, etc or 21 on Mega and Due, on esp8266 free selectable)
    SDA -> SDA (A4 on Arduino Uno, Leonardo, etc or 20 on Mega and Due, on esp8266 free selectable)
    ADD -> (not connected) or GND

  ADD pin is used to set sensor I2C address. If it has voltage greater or equal to
  0.7VCC voltage (e.g. you've connected it to VCC) the sensor address will be
  0x5C. In other case (if ADD voltage less than 0.7 * VCC) the sensor address will
  be 0x23 (by default).

*/

#include <Wire.h>
#include <BH1750.h>

BH1750 lightMeter;


void setup(){

  Serial.begin(9600);

  // Initialize the I2C bus (BH1750 library doesn't do this automatically)
  Wire.begin();
```

```
  // On esp8266 you can select SCL and SDA pins using Wire.begin(D4, D3);

  lightMeter.begin();

  Serial.println(F("BH1750 Test begin"));

}


void loop() {

  uint16_t lux = lightMeter.readLightLevel();
  Serial.print("Light: ");
  Serial.print(lux);
  Serial.println(" lx");
  delay(1000);

}
```

3. Script for CCS811 sensor

```
/***************************************************************************
  This is a library for the CCS811 air

  This sketch reads the sensor

  Designed specifically to work with the Adafruit CCS811 breakout
  ----> http://www.adafruit.com/products/3566

  These sensors use I2C to communicate. The device's I2C address is 0x5A

  Adafruit invests time and resources providing this open source code,
  please support Adafruit andopen-source hardware by purchasing products
  from Adafruit!

  Written by Dean Miller for Adafruit Industries.
  BSD license, all text above must be included in any redistribution
 ***************************************************************************/

#include "Adafruit_CCS811.h"

Adafruit_CCS811 ccs;

void setup() {
  Serial.begin(9600);
  ccs.begin();
  Serial.println("CCS811 test");
```

```
 //if(!ccs.begin()){
   //Serial.println("Failed to start sensor! Please check your wiring.");
   //while(1);
 //}

 //calibrate temperature sensor
 //while(!ccs.available());
 //float temp = ccs.calculateTemperature();
 //ccs.setTempOffset(temp - 25.0);
}

void loop() {
 //if(ccs.available()){
   //float temp = ccs.calculateTemperature();
   //if(!ccs.readData()){
     ccs.readData();
     int CO2 = ccs.geteCO2();
     int TVOC = ccs.getTVOC();
     Serial.print("CO2: ");
     Serial.print(CO2);
     Serial.print("ppm, TVOC: ");
     Serial.print(TVOC);
     Serial.println("ppb");
     //Serial.println(temp);
   //}
   //else{
    // Serial.println("ERROR!");
    // while(1);
 delay(1000);
}
```

4. Script for data logging 6 DHT22 and 2 BH1750

```
/*Code for DHT taken from Jeff Walker
 * https://gist.github.com/walkerjeffd/c1fe2d498476b4e6a9b0
 * Code for BH1750 taken from YoungSoo Ahn
 * https://blog.naver.com/ysahn2k/221393101823
 * Code combined and modified by Shirish Ramachandran
 */
// log DHT sensor readings to SD card
#include "DHT.h"
#include <SD.h>
#include <Wire.h>
#include <SPI.h>
//#include <BH1750.h>
#include "RTClib.h"
RTC_DS1307 RTC;
```

```
// how many milliseconds between grabbing data and logging it. 1000 ms is once a second
#define LOG_INTERVAL  60000 // mills between entries (reduce to take more/faster data)

#define ECHO_TO_SERIAL   1 // echo data to serial port

#define DHT1PIN 2     // what pin we're connected to
#define DHT2PIN 3
#define DHT3PIN 4
#define DHT4PIN 5
#define DHT5PIN 6
#define DHT6PIN 7
// Uncomment whatever type you're using!
//#define DHTTYPE DHT11   // DHT 11
#define DHT1TYPE DHT22   // DHT 22  (AM2302)
#define DHT2TYPE DHT22
#define DHT3TYPE DHT22
#define DHT4TYPE DHT22
#define DHT5TYPE DHT22
#define DHT6TYPE DHT22
//#define DHTTYPE DHT21   // DHT 21 (AM2301)

// Connect pin 1 (on the left) of the sensor to +5V
// Connect pin 2 of the sensor to whatever your DHTPIN is
// Connect pin 4 (on the right) of the sensor to GROUND
// Connect a 10K resistor from pin 2 (data) to pin 1 (power) of the sensor

#define BH1750_POWER_DOWN 0x00  // No active state
#define BH1750_POWER_ON 0x01  // Waiting for measurement command
#define BH1750_RESET 0x07  // Reset data register value - not accepted in POWER_DOWN mode

// Measurement Mode
#define CONTINUOUS_HIGH_RES_MODE 0x10  // Measurement at 1 lux resolution. Measurement
time is approx 120ms
#define CONTINUOUS_HIGH_RES_MODE_2 0x11  // Measurement at 0.5 lux resolution.
Measurement time is approx 120ms
#define CONTINUOUS_LOW_RES_MODE 0x13  // Measurement at 4 lux resolution. Measurement
time is approx 16ms
#define ONE_TIME_HIGH_RES_MODE 0x20  // Measurement at 1 lux resolution. Measurement time is
approx 120ms
#define ONE_TIME_HIGH_RES_MODE_2 0x21  // Measurement at 0.5 lux resolution. Measurement
time is approx 120ms
#define ONE_TIME_LOW_RES_MODE 0x23  // Measurement at 4 lux resolution. Measurement time is
approx 16ms

// I2C Address
#define BH1750_1_ADDRESS 0x23  // Sensor 1 connected to GND
#define BH1750_2_ADDRESS 0x5C  // Sensor 2 connected to VCC
DHT dht1(DHT1PIN, DHT1TYPE);
```

```
DHT dht2(DHT2PIN, DHT2TYPE);
DHT dht3(DHT3PIN, DHT3TYPE);
DHT dht4(DHT4PIN, DHT4TYPE);
DHT dht5(DHT5PIN, DHT5TYPE);
DHT dht6(DHT6PIN, DHT6TYPE);
int16_t RawData;
int16_t SensorValue[2];

// select 10 for adafruit shield
const int chipSelect = 53;

// create file to log to
File logfile;

void setup() {
 Serial.begin(9600);
 Serial.print("Initializing SD card...");
 // make sure that the default chip select pin is set to
 // output, even if you don't use it:
 pinMode(53, OUTPUT);
 pinMode(10, OUTPUT);

 if (!SD.begin(chipSelect)) {
  Serial.println("Card failed, or not present");
  // don't do anything more:
  return;
 }
 Serial.println("card initialized.");

 // create a new file
 char filename[] = "LOGGER00.CSV";
 for (uint8_t i = 0; i < 100; i++) {
  filename[6] = i/10 + '0';
  filename[7] = i%10 + '0';
  if (! SD.exists(filename)) {
   // only open a new file if it doesn't exist
   logfile = SD.open(filename, FILE_WRITE);
   break;  // leave the loop!
  }
 }

 if (! logfile) {
  Serial.println("could not create file");
 }

 Serial.print("Logging to: ");
 Serial.println(filename);

 // connect to RTC
```

```
  Wire.begin();
  if (!RTC.begin()) {
    logfile.println("RTC failed");
#if ECHO_TO_SERIAL
    Serial.println("RTC failed");
#endif  //ECHO_TO_SERIAL
  }


logfile.println("millis,datetime,rh1,rh2,rh3,rh4,rh5,rh6,temp_1,temp_2,temp_3,temp_4,temp_5,temp
_6,illuminance_1,illuminance_2");
#if ECHO_TO_SERIAL

Serial.println("millis,datetime,rh1,rh2,rh3,rh4,rh5,rh6,temp_1,temp_2,temp_3,temp_4,temp_5,temp
_6,illuminance_1,illuminance_2");
#endif //ECHO_TO_SERIAL
  dht1.begin();
  dht2.begin();
  dht3.begin();
  dht4.begin();
  dht5.begin();
  dht6.begin();
}

void loop() {
  DateTime now;

  delay((LOG_INTERVAL -1) - (millis() % LOG_INTERVAL));

  String dataString = "";

  // fetch the time
  now = RTC.now();
  // log time
  logfile.print(now.unixtime()); // seconds since 1/1/1970
  logfile.print(",");
  if (now.month() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.month(), DEC);
  logfile.print("/");
  if (now.day() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.day(), DEC);
  logfile.print("/");
  logfile.print(now.year(), DEC);
  logfile.print(" ");
  if (now.hour() < 10) {
```

```
    logfile.print(0, DEC);
  }
  logfile.print(now.hour(), DEC);
  logfile.print(":");
  if (now.minute() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.minute(), DEC);
  logfile.print(":");
  if (now.second() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.second(), DEC);
#if ECHO_TO_SERIAL
  Serial.print(now.unixtime()); // seconds since 1/1/1970
  Serial.print(",");
  if (now.month() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.month(), DEC);
  Serial.print("/");
  if (now.day() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.day(), DEC);
  Serial.print("/");
  Serial.print(now.year(), DEC);
  Serial.print(" ");
  if (now.hour() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.hour(), DEC);
  Serial.print(":");
  if (now.minute() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.minute(), DEC);
  Serial.print(":");
  if (now.second() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.second(), DEC);
#endif //ECHO_TO_SERIAL

  // Reading temperature or humidity takes about 250 milliseconds!
  // Sensor readings may also be up to 2 seconds 'old' (its a very slow sensor)
  float h1 = dht1.readHumidity(); // relative humidity, %
  float h2 = dht2.readHumidity();
  float h3 = dht3.readHumidity();
```

```
  float h4 = dht4.readHumidity();
  float h5 = dht5.readHumidity();
  float h6 = dht6.readHumidity();
  float t_1 = dht1.readTemperature(); // air temp, degC
  float t_2 = dht2.readTemperature();
  float t_3 = dht3.readTemperature();
  float t_4 = dht4.readTemperature();
  float t_5 = dht5.readTemperature();
  float t_6 = dht6.readTemperature();

  init_BH1750(BH1750_1_ADDRESS, CONTINUOUS_HIGH_RES_MODE);
  //delay(500);
  RawData_BH1750(BH1750_1_ADDRESS);
  SensorValue[0] = RawData / 1.2;

  init_BH1750(BH1750_2_ADDRESS, CONTINUOUS_HIGH_RES_MODE);
  //delay(500);
  RawData_BH1750(BH1750_2_ADDRESS);
  SensorValue[1] = RawData / 1.2;

  // check if returns are valid, if they are NaN (not a number) then something went wrong!
  if (isnan(t_1) || isnan(t_2) || isnan(t_3) || isnan(t_4) || isnan(t_5) || isnan(t_6) || isnan(h1) ||
isnan(h2) || isnan(h3) || isnan(h4) || isnan(h5) || isnan(h6) || isnan(SensorValue[0]) ||
isnan(SensorValue[1]))
  {
    Serial.println("Failed to read from DHT and BH1750");
  }
  else
  {
    logfile.print(",");
    logfile.print(h1, 2);
    logfile.print(",");
    logfile.print(h2, 2);
    logfile.print(",");
    logfile.print(h3, 2);
    logfile.print(",");
    logfile.print(h4, 2);
    logfile.print(",");
    logfile.print(h5, 2);
    logfile.print(",");
    logfile.print(h6, 2);
    logfile.print(",");
    logfile.print(t_1, 2);
    logfile.print(",");
    logfile.print(t_2, 2);
    logfile.print(",");
    logfile.print(t_3, 2);
    logfile.print(",");
    logfile.print(t_4, 2);
```

```
    logfile.print(",");
    logfile.print(t_5, 2);
    logfile.print(",");
    logfile.print(t_6, 2);
    logfile.print(",");
    logfile.print(SensorValue[0]);
    logfile.print(",");
    logfile.print(SensorValue[1]);

#if ECHO_TO_SERIAL
    Serial.print(",");
    Serial.print(h1, 2);
    Serial.print(",");
    Serial.print(h2, 2);
    Serial.print(",");
    Serial.print(h3, 2);
    Serial.print(",");
    Serial.print(h4, 2);
    Serial.print(",");
    Serial.print(h5, 2);
    Serial.print(",");
    Serial.print(h6, 2);
    Serial.print(",");
    Serial.print(t_1, 2);
    Serial.print(",");
    Serial.print(t_2, 2);
    Serial.print(",");
    Serial.print(t_3, 2);
    Serial.print(",");
    Serial.print(t_4, 2);
    Serial.print(",");
    Serial.print(t_5, 2);
    Serial.print(",");
    Serial.print(t_6, 2);
    Serial.print(",");
    Serial.print(SensorValue[0]);
    Serial.print(",");
    Serial.print(SensorValue[1]);
#endif //ECHO_TO_SERIAL
  }

  logfile.println();
#if ECHO_TO_SERIAL
  Serial.println();
#endif // ECHO_TO_SERIAL

  // flush to file
  logfile.flush();
}
```

```
void init_BH1750(int ADDRESS, int MODE)
{
 //BH1750 Initializing & Reset
 Wire.beginTransmission(ADDRESS);
 Wire.write(MODE);  // PWR_MGMT_1 register
 Wire.endTransmission(true);
}

void RawData_BH1750(int ADDRESS)
{
 Wire.beginTransmission(ADDRESS);
 Wire.requestFrom(ADDRESS,2,true);  // request a total of 2 registers
 RawData = Wire.read() << 8 | Wire.read();  // Read Raw Data of BH1750
 Wire.endTransmission(true);
}
```

5. <u>Script for datalogging in preliminary set up</u>

```
/*Code taken from Jeff Walker
 * https://gist.github.com/walkerjeffd/c1fe2d498476b4e6a9b0
 * Code modified by Shirish Ramachandran
 */
// log DHT sensor readings to SD card
#include "DHT.h"
#include <SD.h>
#include <Wire.h>
#include <SPI.h>
//#include <BH1750.h>
#include "RTClib.h"
RTC_DS1307 RTC;

// how many milliseconds between grabbing data and logging it. 1000 ms is once a second
#define LOG_INTERVAL  60000 // mills between entries (reduce to take more/faster data)

#define ECHO_TO_SERIAL   1 // echo data to serial port

#define DHT1PIN 2     // what pin we're connected to
#define DHT2PIN 3
#define DHT3PIN 4
#define DHT4PIN 5
// Uncomment whatever type you're using!
//#define DHTTYPE DHT11   // DHT 11
#define DHT1TYPE DHT22   // DHT 22  (AM2302)
#define DHT2TYPE DHT22
#define DHT3TYPE DHT22
#define DHT4TYPE DHT22
//#define DHTTYPE DHT21   // DHT 21 (AM2301)
```

```
// Connect pin 1 (on the left) of the sensor to +5V
// Connect pin 2 of the sensor to whatever your DHTPIN is
// Connect pin 4 (on the right) of the sensor to GROUND
// Connect a 10K resistor from pin 2 (data) to pin 1 (power) of the sensor


DHT dht1(DHT1PIN, DHT1TYPE);
DHT dht2(DHT2PIN, DHT2TYPE);
DHT dht3(DHT3PIN, DHT3TYPE);
DHT dht4(DHT4PIN, DHT4TYPE);

// select 10 for adafruit shield
const int chipSelect = 10;

// create file to log to
File logfile;

void setup() {
 Serial.begin(9600);
 Serial.print("Initializing SD card...");
 // make sure that the default chip select pin is set to
 // output, even if you don't use it:
 pinMode(10, OUTPUT);

 if (!SD.begin(chipSelect)) {
  Serial.println("Card failed, or not present");
  // don't do anything more:
  return;
 }
 Serial.println("card initialized.");

 // create a new file
 char filename[] = "LOGGER00.CSV";
 for (uint8_t i = 0; i < 100; i++) {
  filename[6] = i/10 + '0';
  filename[7] = i%10 + '0';
  if (! SD.exists(filename)) {
   // only open a new file if it doesn't exist
   logfile = SD.open(filename, FILE_WRITE);
   break;  // leave the loop!
  }
 }

 if (! logfile) {
  Serial.println("could not create file");
 }

 Serial.print("Logging to: ");
```

```
  Serial.println(filename);

  // connect to RTC
  Wire.begin();
  if (!RTC.begin()) {
    logfile.println("RTC failed");
#if ECHO_TO_SERIAL
    Serial.println("RTC failed");
#endif  //ECHO_TO_SERIAL
  }

  logfile.println("millis,datetime,rh1,rh2,rh3,rh4,temp_1,temp_2,temp_3,temp_4");
#if ECHO_TO_SERIAL
  Serial.println("millis,datetime,rh1,rh2,rh3,rh4,temp_1,temp_2,temp_3,temp_4");
#endif //ECHO_TO_SERIAL
  dht1.begin();
  dht2.begin();
  dht3.begin();
  dht4.begin();
}

void loop() {
  DateTime now;

  delay((LOG_INTERVAL -1) - (millis() % LOG_INTERVAL));

  String dataString = "";

  // fetch the time
  now = RTC.now();
  // log time
  logfile.print(now.unixtime()); // seconds since 1/1/1970
  logfile.print(",");
  if (now.month() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.month(), DEC);
  logfile.print("/");
  if (now.day() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.day(), DEC);
  logfile.print("/");
  logfile.print(now.year(), DEC);
  logfile.print(" ");
  if (now.hour() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.hour(), DEC);
```

```
  logfile.print(":");
  if (now.minute() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.minute(), DEC);
  logfile.print(":");
  if (now.second() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.second(), DEC);
#if ECHO_TO_SERIAL
  Serial.print(now.unixtime()); // seconds since 1/1/1970
  Serial.print(",");
  if (now.month() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.month(), DEC);
  Serial.print("/");
  if (now.day() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.day(), DEC);
  Serial.print("/");
  Serial.print(now.year(), DEC);
  Serial.print(" ");
  if (now.hour() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.hour(), DEC);
  Serial.print(":");
  if (now.minute() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.minute(), DEC);
  Serial.print(":");
  if (now.second() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.second(), DEC);
#endif //ECHO_TO_SERIAL

  // Reading temperature or humidity takes about 250 milliseconds!
  // Sensor readings may also be up to 2 seconds 'old' (its a very slow sensor)
  float h1 = dht1.readHumidity(); // relative humidity, %
  float h2 = dht2.readHumidity();
  float h3 = dht3.readHumidity();
  float h4 = dht4.readHumidity();
  float t_1 = dht1.readTemperature(); // air temp, degC
  float t_2 = dht2.readTemperature();
```

```
  float t_3 = dht3.readTemperature();
  float t_4 = dht4.readTemperature();


  // check if returns are valid, if they are NaN (not a number) then something went wrong!
  if (isnan(t_1) || isnan(t_2) || isnan(t_3) || isnan(t_4) || isnan(h1) || isnan(h2) || isnan(h3) ||
isnan(h4)) {
    Serial.println("Failed to read from DHT and BH1750");
  } else
  {
    logfile.print(",");
    logfile.print(h1, 2);
    logfile.print(",");
    logfile.print(h2, 2);
    logfile.print(",");
    logfile.print(h3, 2);
    logfile.print(",");
    logfile.print(h4, 2);
    logfile.print(",");
    logfile.print(t_1, 2);
    logfile.print(",");
    logfile.print(t_2, 2);
    logfile.print(",");
    logfile.print(t_3, 2);
    logfile.print(",");
    logfile.print(t_4, 2);


#if ECHO_TO_SERIAL
    Serial.print(",");
    Serial.print(h1, 2);
    Serial.print(",");
    Serial.print(h2, 2);
    Serial.print(",");
    Serial.print(h3, 2);
    Serial.print(",");
    Serial.print(h4, 2);
    Serial.print(",");
    Serial.print(t_1, 2);
    Serial.print(",");
    Serial.print(t_2 , 2);
    Serial.print(",");
    Serial.print(t_3 , 2);
    Serial.print(",");
    Serial.print(t_4 , 2);

#endif //ECHO_TO_SERIAL
  }
  logfile.println();
```

```
#if ECHO_TO_SERIAL
  Serial.println();
#endif // ECHO_TO_SERIAL

  // flush to file
  logfile.flush();
}
```

6. <u>Final script for data logging</u>

```
/*Code taken from Jeff Walker
 * https://gist.github.com/walkerjeffd/c1fe2d498476b4e6a9b0
 * Code modified by Shirish Ramachandran
 */

// log DHT sensor readings to SD card

#include "DHT.h"

#include <SD.h>

#include <Wire.h>

#include <SPI.h>

#include <BH1750.h>

#include "RTClib.h"

#include "Adafruit_CCS811.h"

RTC_DS1307 RTC;


// how many milliseconds between grabbing data and logging it. 1000 ms is once a second

#define LOG_INTERVAL  600000 // mills between entries (reduce to take more/faster data)


#define ECHO_TO_SERIAL   1 // echo data to serial port


#define DHT1PIN 3     // what pin we're connected to

#define DHT2PIN 4


// Uncomment whatever type you're using!
```

```
//#define DHTTYPE DHT11   // DHT 11

#define DHT1TYPE DHT22   // DHT 22  (AM2302)

#define DHT2TYPE DHT22

//#define DHTTYPE DHT21   // DHT 21 (AM2301)


// Connect pin 1 (on the left) of the sensor to +5V

// Connect pin 2 of the sensor to whatever your DHTPIN is

// Connect pin 4 (on the right) of the sensor to GROUND

// Connect a 10K resistor from pin 2 (data) to pin 1 (power) of the sensor


DHT dht1(DHT1PIN, DHT1TYPE);

DHT dht2(DHT2PIN, DHT2TYPE);

//BH1750 lightMeter;

BH1750 active_sensor(0x23); // We will use this adress for stating the active sensor

BH1750 inactive_sensor(0x5C); //HIGH

Adafruit_CCS811 ccs;

// select 10 for adafruit shield

//const int chipSelect = 53;

const int chipSelect = 10;


// create file to log to

File logfile;


void setup() {

 Serial.begin(9600);

 Serial.print("Initializing SD card...");

 // make sure that the default chip select pin is set to

 // output, even if you don't use it:

 //pinMode(53, OUTPUT);
```

```
  pinMode(10, OUTPUT);

// Setting the input pins for controling the addr pins of the modules

  //MEGA
  //pinMode(22, OUTPUT);
  //pinMode(23, OUTPUT);
  //digitalWrite(22, LOW);
  //digitalWrite(23, LOW);



  //UNO
  pinMode(11, OUTPUT);
  pinMode(12, OUTPUT);
  digitalWrite(11, LOW);
  digitalWrite(12, LOW);



  if (!SD.begin(chipSelect)) {
    Serial.println("Card failed, or not present");
    // don't do anything more:
    return;
  }
  Serial.println("card initialized.");

  // create a new file
  char filename[] = "LOGGER00.CSV";
  for (uint8_t i = 0; i < 100; i++) {
    filename[6] = i/10 + '0';
```

```
    filename[7] = i%10 + '0';
    if (! SD.exists(filename)) {
      // only open a new file if it doesn't exist
      logfile = SD.open(filename, FILE_WRITE);
      break;  // leave the loop!
    }
  }

  if (! logfile) {
    Serial.println("could not create file");
  }

  Serial.print("Logging to: ");
  Serial.println(filename);

  // connect to RTC
  Wire.begin();
  if (!RTC.begin()) {
    logfile.println("RTC failed");
#if ECHO_TO_SERIAL
    Serial.println("RTC failed");
#endif  //ECHO_TO_SERIAL
  }

  logfile.println("millis,datetime,rh1,rh2,temp_1,temp_2,illuminance_1,illuminance_2,CO2,TVOC");
#if ECHO_TO_SERIAL
  Serial.println("millis,datetime,rh1,rh2,temp_1,temp_2,illuminance_1,illuminance_2,CO2,TVOC");
#endif //ECHO_TO_SERIAL
  dht1.begin();
```

```
  dht2.begin();
  //lightMeter.begin();
  active_sensor.begin(BH1750::CONTINUOUS_HIGH_RES_MODE);
  ccs.begin();
}

void loop() {

  DateTime now;

  delay((LOG_INTERVAL -1) - (millis() % LOG_INTERVAL));

  String dataString = "";

  // fetch the time
  now = RTC.now();
  // log time
  logfile.print(now.unixtime()); // seconds since 1/1/1970
  logfile.print(",");
  if (now.month() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.month(), DEC);
  logfile.print("/");
  if (now.day() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.day(), DEC);
  logfile.print("/");
```

```
  logfile.print(now.year(), DEC);
  logfile.print(" ");
  if (now.hour() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.hour(), DEC);
  logfile.print(":");
  if (now.minute() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.minute(), DEC);
  logfile.print(":");
  if (now.second() < 10) {
    logfile.print(0, DEC);
  }
  logfile.print(now.second(), DEC);
#if ECHO_TO_SERIAL
  Serial.print(now.unixtime()); // seconds since 1/1/1970
  Serial.print(",");
  if (now.month() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.month(), DEC);
  Serial.print("/");
  if (now.day() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.day(), DEC);
  Serial.print("/");
```

```
  Serial.print(now.year(), DEC);
  Serial.print(" ");
  if (now.hour() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.hour(), DEC);
  Serial.print(":");
  if (now.minute() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.minute(), DEC);
  Serial.print(":");
  if (now.second() < 10) {
    Serial.print(0, DEC);
  }
  Serial.print(now.second(), DEC);
#endif //ECHO_TO_SERIAL

  // Reading temperature or humidity takes about 250 milliseconds!
  // Sensor readings may also be up to 2 seconds 'old' (its a very slow sensor)
  float h1 = dht1.readHumidity(); // relative humidity, %
  float t_1 = dht1.readTemperature(); // air temp, degC
  float h2 = dht2.readHumidity();
  float t_2 = dht2.readTemperature();
  //uint16_t lux = lightMeter.readLightLevel();
  ccs.readData();
  int CO2 = ccs.geteCO2();
  int TVOC = ccs.getTVOC();
```

```
// check if returns are valid, if they are NaN (not a number) then something went wrong!
//if (isnan(t_1) || isnan(t_2) || isnan(h1) || isnan(h2) || isnan(lux) || isnan(CO2) || isnan(TVOC)) {
  //Serial.println("Failed to read from DHT and BH1750");
//} else
//{
  logfile.print(",");
  logfile.print(h1, 2);
  logfile.print(",");
  logfile.print(h2, 2);
  logfile.print(",");
  logfile.print(t_1, 2);
  logfile.print(",");
  logfile.print(t_2, 2);
  logfile.print(",");
  for(int i = 1; i<=2;i++)
{
  //digitalWrite(i+21,LOW);
  digitalWrite(i+10,LOW); //UNO
  //delay(50);
  //int lux = 0;
  lightSensors[i] = active_sensor.readLightLevel();
  logfile.print(lightSensors[i]);
  logfile.print(",");
  //digitalWrite(i+21,HIGH);
  digitalWrite(i+10,HIGH); //UNO
  //delay(50);


}
  logfile.print(",");
```

```
  logfile.print(CO2);
  logfile.print(",");
  logfile.print(TVOC);

#if ECHO_TO_SERIAL
  Serial.print(",");
  Serial.print(h1, 2);
  Serial.print(",");
  Serial.print(h2, 2);
  Serial.print(",");
  Serial.print(t_1, 2);
  Serial.print(",");
  Serial.print(t_2, 2);
  Serial.print(",");
  for(int i = 1; i<=2;i++)
 {
  //digitalWrite(i+21,LOW);
  digitalWrite(i+10,LOW); //UNO
  //delay(50);
  //int lux = 0;
  lightSensors[i] = active_sensor.readLightLevel();
  Serial.print(lightSensors[i]);
  Serial.print(",");
  //digitalWrite(i+21,HIGH);
  digitalWrite(i+10,HIGH); //UNO
  //delay(50);

 }
  Serial.print(",");
```

```
    Serial.print(CO2);
    Serial.print(",");
    Serial.print(TVOC);
#endif //ECHO_TO_SERIAL
  //}

  logfile.println();
#if ECHO_TO_SERIAL
  Serial.println();
#endif // ECHO_TO_SERIAL

  // flush to file
  logfile.flush();
}
```

APPENDIX C – PLANT AND SURVEY DATA

1. Number and Weight of plants during initial phase of the experiment

MODULE A - No ventilation in top floor

Plant number	Type	Number of Young peppers	Number of ripe peppers
A1	Red Pepper	5	0
A2	Red Pepper	6	0
A3	Yellow Pepper	20	0
A4	Yellow Pepper	17	0
A5	Snack Pepper Orange	5	3
A6	Red Pepper	4	0
A7	Yellow Pepper	23	0
A8	CGN21566	0	0
A9	Bahamian Goat	4	0

Module B - Natural ventilation in top floor

Plant number	Type	Number of Young peppers	Number of ripe peppers
B1	Yellow Pepper	21	0
B2	Red Pepper	3	0
B3	Red Pepper	5	0
B4	Yellow Pepper	17	0
B5	Snack Pepper Orange	4	2
B6	Yellow Pepper	16	0
B7	Red Pepper	6	0
B8	CGN21566	0	0
B9	Bahamian Goat	8	0

Module C - Mechanical ventilation in top floor

Plant number	Type	Number of Young peppers	Number of ripe peppers
C1	Red Pepper	5	0
C2	Red Pepper	4	0
C3	Yellow Pepper	27	1
C4	Yellow Pepper	25	0
C5	Snack Pepper Orange	4	1
C6	Yellow Pepper	26	0
C7	Red Pepper	3	0
C8	CGN21566	0	0
C9	Bahamian Goat	7	0

Module D - No ventilation in bottom floor

Plant number	Type	Number of Young peppers	Number of ripe peppers
D1	Red Pepper	4	0
D2	Red Pepper	3	0
D3	Yellow Pepper	13	0
D4	Yellow Pepper	27	0
D5	Snack Pepper Orange	5	2
D6	Yellow Pepper	24	0
D7	Red Pepper	8	0
D8	Bahamian Goat	4	0
D9	Bahamian Goat	8	0

Module E - Natural ventilation in bottom floor

Plant number	Type	Number of Young peppers	Number of ripe peppers
E1	Red Pepper	3	0
E2	Red Pepper	6	0
E3	Yellow Pepper	19	1
E4	Yellow Pepper	0	0
E5	Snack Pepper Orange	4	3
E6	Yellow Pepper	14	0
E7	Red Pepper	4	0
E8	CGN21566	2	0
E9	Bahamian Goat	6	0

Module F - Mechanical ventilation in top floor

Plant number	Type	Number of Young peppers	Number of ripe peppers
F1	Red Pepper	4	0
F2	Red Pepper	7	0
F3	Yellow Pepper	24	1
F4	Yellow Pepper	32	0
F5	Snack Pepper Orange	4	0
F6	Red Pepper	4	0
F7	Yellow Pepper	18	0
F8	CGN21566	0	0
F9	Bahamian Goat	6	0

2. <u>Survey – Productivity of occupants in the office</u>