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Project Report EE5003

Multi-agent Assisted Indoor Environmental Quality for Smart Buildings

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Declaration

This report is submitted for the degree of Master of Science in the Department of Electrical and Computer Engineering, **National University of Singapore**, under the supervision of Associate Professor **Dr. Sanjib Kumar Panda**. No part of this report has been submitted for any degree at any other University or Institution.

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Abstract

In urbanized area humans spend their time indoors and with the advent of closed and completely sealed buildings and centralized air-conditioning systems, the indoor environment has become more susceptible to diseases and discomfort of the occupants. This is due to the fact that the the air-conditioning systems have been used primarily for cooling the rooms, but pay less or no attention to the comfort of the occupants. On top of compromising user comfort, buildings amount to nearly 40% of total energy consumption, it is time that the building sector plays a key role in climate policy. With limited access to renewable energy resources, it is a challenge for Singapore to reduce the energy consumption of building and provide comfort to its occupants. It is noted that the HVAC systems accounts for 40% of the total energy consumed by the buildings. Since improvising the HVAC system can reduce the energy cost considerably it is becoming more attractive . While energy cost reduction is important, the indoor environmental quality (IEQ) is equally important to improve the productivity of the occupants. IEQ collectively refers to the Indoor Air Quality, Lighting Quality, Acoustic quality, Thermal Quality and Comfort of Human Beings in the building space. Since IEQ is an ensemble of features, which is the result of interplay of many subsystems in buildings, this project focuses on IEQ monitoring and integrated subsystem operations. The project also looks into the scope of multi-agent assisted feedback to the system to improvise the comfort of the occupants and reduce the energy consumption.

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Chapter 1

Introduction

1.1 Background and Motivation

Buildings amount to nearly 40% of total energy consumption, it is time that the building sector plays a key role in climate policy. With limited access to renewable energy resources, it is a challenge for Singapore to reduce the energy consumption of building and provide comfort to its occupants [13]. It is noted that the HVAC systems account for 40% of the total energy consumed by the buildings. Since improvising the HVAC system can reduce the energy cost considerably it is becoming more attractive [34]. While energy cost reduction is important, the indoor environmental quality(IEQ) is equally important to improve the productivity of the occupants. IEQ collectively refers to the Indoor Air Quality, Lighting Quality, Acoustic quality, Thermal Quality and Comfort of Human Beings in the building space. In today's scenario where people most of the time reside indoors, IEQ becomes important for the health and throughput of work of the people.

IEQ can be affected by a variety of factors such as temperature, relative humidity, particle concentration, gaseous and biological pollutants, acoustic comfort, lighting intensity and colour and number of occupants. The most important part of IEQ remains to be Thermal comfort and Air Quality. Thermal Comfort has some major standard like the ASHRAE 55-2017 based on the field studies of different countries across the world and EN-15251, which is European standard for Indoor environment parameters. These standards have a measurement for the thermal comfort based on the air speed, temperature and relative humidity in the form of a psychrometric chart. These charts give a relation between Dry Bulb Temperature and Humidity ratio and range of comfort zone for the air speed, metabolic rate and clothing level of individuals. Like the Thermal comfort, Air quality has also great impact on the IEQ.

In the past few decades, rapid industrialization in the Asian countries and large-scale usage of closed environments for workspace has resulted in interests towards study of Indoor Air Pollutants. These closed sealed environments could lead to wide variety of diseases and hence has become a point of research to reduce these pollutants. Most common indoor pollutants include Carbon-di-oxide CO2, Carbon-monoxide CO, Volatile organic compounds (VOC's), Dust (PM 2.5 and PM 10) which impact the Indoor Air quality. These components of air can cause sensory irritation even if they fall below a specified level. But if they go beyond a threshold level over a long period of time can cause major harm to health leading to variety of disease. Hence, the IAQ is much more complex in the form of controlling the pollutants as there is no direct way of controlling the level of pollutants. All the factors of thermal comfort and IAQ are to be controlled by the Air conditioning and mechanical ventilation system (ACMV) and hence this form the major part of the IEQ. The other parameters that fall into the scope of IEQ include lighting and acoustics. The lighting comfort can be controlled linearly with colour temperature and intensity of light varying linearly. The acoustic comfort is the one that depends on the noise levels within the room. As the general preference of occupants is less noisy environment, the unwanted noise arising due to equipment present in the room is to be reduced. The flooring and ceiling of the indoor environment must be surfaced with an absorbent material to reduce the noise further arising due to other factors like walking around or speech.

Figure 1.1: Branches of Indoor Environemntal Quality

IEQ has direct effect on the occupants involved and the occupants have individual preferences of the components of IEQ. The occupants themselves form the active agents of the system and the control and office equipment form the passive agents. The active agents have individual feedback about the about the environment that the passive agents learn from and have control on the environmental variables. The multi-agent feedback is essential for the goal of IEQ to be established as the comfort of the occupants are essential part of the IEQ.

1.2 Aim

The goal of this project is to integrate the multi-agent capability into the controlling of Indoor Environmental Quality and take coordinated decisions based on the sensor values. As the project had more focus into building theoretical models of the room FEC2, National University of Singapore, the mathematical model was constructed for that specific room and its physical properties where considered to model it mathematically. The indoor air quality, the thermal comfort as well as lighting were all modelled for the room which was a fully controlled environment. This was done as it is difficult to develop a universal control strategy for all residential and commercial buildings and rooms. This project involves development of computational models and experiments for a closed computer lab like environment. The project also involves in development of sensor arrays consisting of a variety of IEQ sensors that involve in the multi-agent aspect of the project. The sensors sense the constituents of air, thermal properties, lighting and sound and help in taking coordinated decisions for achieving a better IEQ index. IEQ indexes were also modelled based on the Singapore's Building and Construction Authority standards. For Indoor Air Quality in Commercial and Residential Buildings and Environmental Authority, USA standards that where modelled earlier.

To achieve the aim, the following challenges where tackled during the course of the project:

1. Development of mathematical model for the wall: The basic element of the system that can be assumed to be independent.

2. Development of mathematical model for the room: This involved multiple parameters that must be taken for the system to be as close as the real one. Various level of approximations are taken due to monetary and time restriction in the project so to be modelled and approximated to the experimental room.

3. Development of sensors array: The development of libraries for sensor array consisting of sensors that have different communication protocols with the edge processor that communicates with a central server present in the room.

4. Model fitting by approximations: The ACMV system present in the room couldn't be controlled so the system needs to be approximated. The room is not a completely sealed environment as hence the leakage of air from the external environment into the room must be approximated.

5. A GUI environment was developed for the occupants of the room to have their preferred settings of their environment.

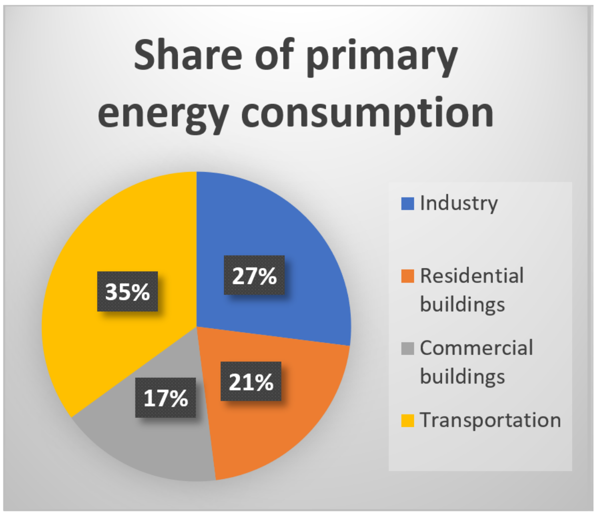
1.3 Report Organization

The report is organized as follows. Section 2 gives in detail Literature review of various standards and limits of the components of IEQ. Section 3 describes about the modelling of the system of different subsystems in detail. Section 4 gives a overview of the indices used in judgment of the quality of environment. Section 5 discusses about the simulations and results whereas section 6 gives the conclusion and related future work of the project.

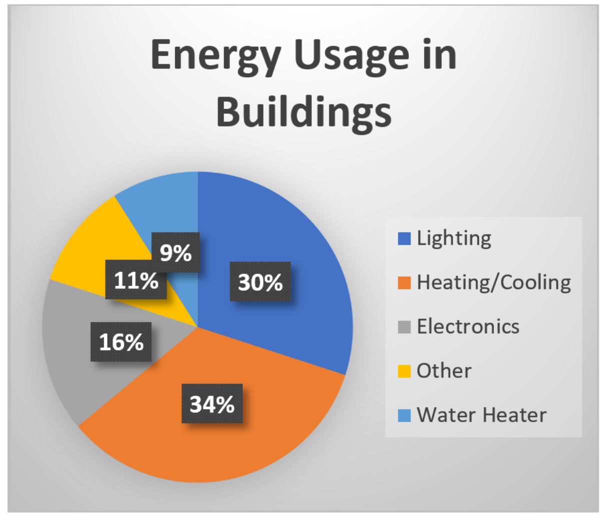
Chapter 2

Literature Review

Recent research has shown that buildings amount to 40% of the total energy consumed out of which 35% amount to the cooling and heating systems used in the buildings to maintain the temperature [2][1]. Researches over the past decade have shown that majority of the people spend 80% of their time indoors which leads to increase standard of living but also demands the other requests to be satisfied [29]. The future focuses on the occupant comfort and energy consumption aspect of the building. This implies the primary problem for the building operators are the indoor environmental quality and energy consumption of the building. The indoor environmental quality which is directly affected by factors like Indoor Air Quality, Thermal comfort, Lighting comfort and acoustic comfort. Indoor Air quality and thermal comfort are affected by building material, construction material, level of air-conditioning which influence the health of occupants directly and influence their productivity. To improvise the comfort level of occupants it is essential that its occupants also form part of the feedback loop. The sensors help in taking coordinated decisions and improvise the IEQ index. Energy consumption of buildings depend significantly on controlling the Indoor air quality, temperature, humidity and lighting and it also depends on the building design and operation. Reducing energy consumption and improvising IEQ index is the ideal goal of futuristic buildings. According to [21], the studies have shown that the cost of poor indoor environment is higher than the energy consumption in the same building as poor IEQ results in poor productivity of the occupants. Thereby improvising IEQ is the approach for energy minimization and better comfort for the occupants.



(a) Share of primary consumption [31]



(b) Energy usage in buildings

Figure 2.1: Energy usage comparison

The following sections show the influence of different IEQ properties that affect the occupants comfort thereby influencing the Indoor environmental quality.

2.1 Thermal comfort

Thermal comfort includes three main parameters viz. temperature of the room, relative-humidity and air-velocity. It is the most influential parameter that influences the occupants immediately. Most of the energy used in the system is used for the thermal comfort of the occupants.

Thermal comfort is the term defined by number of sensations and is bounded by the factors influencing the thermal conditions the occupant experiences. Thereby it is cannot be defined by a universal concept that can be applied to all places, environment and individuals.

The occupants comfort is such that he/she does not prefer a different environment than the one present [26]. ASHRAE [5] explains it to be related to physiological and physical well-being in agreement with the environment. Thermal comfort constitutes of environmental factors like temperature, velocity of air, humidity and pressure, clothing factors like thermal resistance of cloth, density of material, structure of cloth and number of layers of clothing and factors connected with that of human beings like age, sex, height, weight, metabolic rate, type of work done etc. Of the above factors only, the factors relating to the environment can be controlled i.e. temperature of air, velocity of air and humidity. As comfort of one individual cannot be same as the other occupants of the room, it is considered that if 80% of the occupants are comfortable for the environment present in the room then the room is said to thermally comfortable [10].

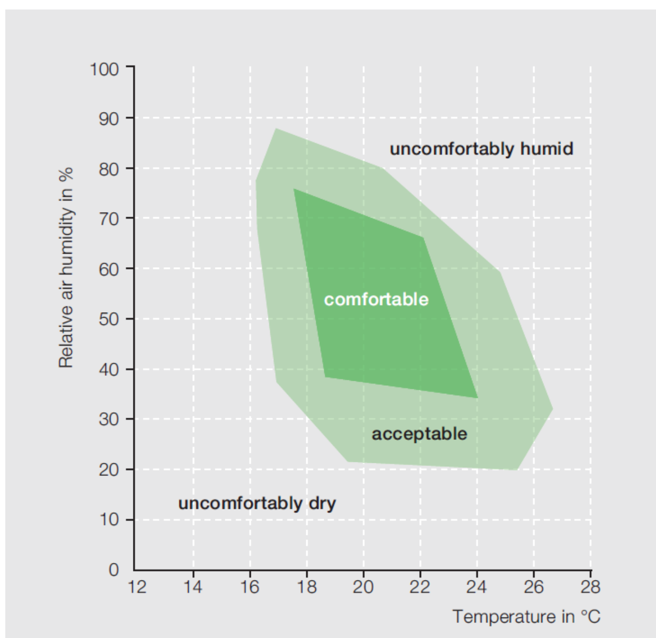


Figure 2.2: Comfortable room climate in dependence on the temperature and humidity[2]

According to [16], the human thermo-regulatory model is very complex highly non-linear system consisting of multiple level of sensors and has a complex control mechanism than any other thermal system control system ever modelled. The control variable is the internal temperatures of the body and temperature and the surface of the skin. The sensors include the external thermo-receptors in the skin. This enables the system to regulate the temperature even before the changes occurs in the body core. The thermo-receptors are so effective that they react not only to the temperature but also to the rate of change of temperature. The main control system includes the hypothalamus that gives instantaneous reactions to protect the human being from any dangerous thermal conditions present nearby. There are different automatic control actions that include: heat production by shivering, external thermal resistance by controlling the respiratory dry heat loss, water secretion and evaporation by sweat loss. The temperature at which these action takes place need not be at the same temperature nor constant. Besides these there is also thermal regulation by use of different clothing by the occupants in-order to get the feeling of comfort.

In the practical world, the ACMV system plays the key role in maintaining the thermal comfort of the occupants. Lack of variables of thermal comfort for the settings of the ACMV could lead to poor and below-par performance of the ACMV system leading to lower efficiency and energy loss [17]. The occupants could continuously give their feedback about their desired temperature to the Building Management system (BMS) which in turn could operate the ACMV system at its peak efficiency by reducing the unnecessary cooling and heating of the system and thereby reducing energy cost and the providing better thermal comfort.

Recommended levels of thermal properties of the room environment by Institute of Environmental Epidemiology, Ministry of the Environment, Singapore [11]:

Temperature	**Relative Humidty**	**Air Velocity**
22.5 – 25.5 °C	$<$ 70 %	$<$ 0.25 m/sec

Table 2.1: Recommended level of thermal properties

2.2 Indoor Air Quality

With the increase in importance to air conditioning systems, the problems persisting to the indoor air quality has been on the rise lately. The modern architecture of completely sealed buildings has made the building thermally efficient by sacrificing the indoor air quality. Considering the fact that the indoor air quality is air influencing the occupant's health and comfort level. The ACMV system has also lead to increase of energy consumption in the building. IAQ is similar to thermal comfort in terms of clarity of definition, wherein which it cannot be defined universally since it is measured by occupant's health and comfort. Use of synthetic building materials and chemically formulated pesticides and cleaning solutions in a sealed environment has led to indoor air quality being worsened.

The main types of indoor air pollutants include CO_2 , CO, Formaldehyde(HCHO), Dust particles, Ozone (O_3), Volatile organic compounds(VOCs) etc. This causes a range of symptoms which includes dryness of eyes, tiredness, headache, vomiting and prolonged exposure may lead to lifelong ailments. Another major impact is that it leads to decrease in productivity, mental distraction of the occupants [7]. Poor air quality results in variety of health problems, the following table shows some of the most common symptoms observed in the respective surveys conducted in different countries [33]:

European Countries	**USA**	**London, UK**
Dry Skin (32%)	Tired or Strained Eyes (33%)	Headache (44%)
Lethargy (31%)	Dry, itching, irritated eyes (30%)	Cough (36%)
Stuffy nose (31%)	Tiredness (27%)	Dry, itching, irritated eyes (33%)
Dry eyes (26%)	Headache (25%)	Blocked, running nose (27%)
Headache (19%)	Tension, irritability (23%)	Tired for no reason (25%)
Flu-like symptoms (14%)	Pain or stiffness of back (22%)	Rashes or itches (20%)
Chest Tightness (10%)	Stuffy or running nose (22%)	Cold, flu (19%)
Runny nose (11%)	Sneezing (18%)	Dry throat (18%)
Watering eyes (7%)	Sore or dry throat (16%)	Sore throat (17%)

Table 2.2: Symptoms with % of occupants feeling it in different countries

Regulatory level of indoor air constituents by Institute of Environmental Epidemiology, Ministry of the Environment, Singapore [11]:

Parameter	Averaging time	Limit of Acceptability	Unit
Carbon dioxide	8 hours	1000	ppm
Carbon monoxide	8 hours	9	ppm
Formaldehyde	8 hours	0.1	ppm
Ozone	8 hours	0.05	ppm
Suspended Particles	-	150	µg/m3
Volatile Organic Compounds	-	3	ppm

When these constituents are present in concentration higher than the prescribed level, there are many side effects noticed in the occupants behaviour. ASHRAE 62.1: 2013 gives a detailed report of the ill effects of constituents at different concentration level.

2.2.1 Effects of Carbon dioxide CO_2

The most important source of CO_2 in indoors is respiration of occupants. In outdoor conditions the CO_2 is generated mostly by burning of fossil fuels and industries. Outdoor CO_2 generally varies between 320 ppm to 400 ppm which is a standard for most cities. While indoor CO_2 in the range of 600 ppm to 800 ppm is usual and no complaints of discomfort. When number of people increase in the room the concentration of CO_2 may go from 2000 to 5000ppm. This range of CO_2 is quite normal for large auditoriums seating many people in the range of 500 to 1000. Some complaints may be there when CO_2 concentration exceeds 1000 ppm. The difference between indoor and outdoor CO_2 should be less than 600 ppm in order to reduce the number of complaints received. CO2 is considered to be minimally toxic by inhalation. The primary health effects caused by CO2 are the result of its behavior as a simple asphyxiant. Symptoms of mild CO2 exposure may include headache and drowsiness. At higher levels,rapid breathing, confusion, increased cardiac output, elevated blood pressure and increased arrhythmias may occur. Breathing oxygen depleted air caused by extreme CO2 concentrations can lead to death by suffocation. Singapore has a prescribed standard off 1000ppm of CO_2 concentration as recognised limit.

CO2 concentration	**Effect on Health**
5,000 ppm (0.5%)	OSHA Permissible Exposure Limit (PEL) for 8-hour exposure
10,000 ppm (1.0%)	Typically no effects, possible drowsiness
15,000 ppm (1.5%)	Mild respiratory stimulation for some people
30,000 ppm (3.0%)	Moderate respiratory stimulation, increased heart rate and blood pressure
40,000 ppm (4.0%)	Immediately Dangerous to Life or Health (IDLH)
50,000 ppm (5.0%)	Strong respiratory stimulation, dizziness, confusion, headache
80,000 ppm (8.0%)	Dimmed sight, sweating, tremor, unconsciousness, and possible death

Table 2.3: Effect of CO_2 exposure to higher concentration [25]

2.2.2 Effect of Carbon monoxide (CO)

The most important gas that has a toxic effect on the occupants is Carbon monoxide (CO). It is odourless and colorless and thereby occupants cannot directly sense it, implies it is more harmful for the occupants. It forms as a byproduct of combustion of fossil fuels. Common sources of carbon monoxide are tobacco smoke, space heaters using fossil fuels, defective central heating furnaces and automobile exhaust. Indoor air space is also polluted by Carbon monoxide by Leaking vented combustion appliances, unvented combustion appliances, parking garages and outdoor air.

Based on effects on persons with coronary artery disease, average exposure for eight hours should not exceed 9 ppm according to ASHRAE 62:2013 [4]. It reduces the ability of blood to bring oxygen to body cells and tissues. Carbon monoxide may be particularly hazardous to people who have heart or circulatory problems and people who have damaged lungs or breathing passages.

2.2.3 Effect of Ozone O_3

Major sources of Ozone in indoor environment is from outdoors, from chemical reaction of pollutants, VOCs, and NOx; indoors, from photocopiers, laser printers, ozone generators, electrostatic precipitators, and some other air cleaners.

Based on 25% increase in symptom exacerbation among adults or asthmatics (normal activity), eight-hour exposure the limit of exposure is set to be 50 ppb [4]. Ozone present at levels below the concentration of interest may contribute to the degradation of indoor air quality directly and by reacting with other contaminants in the indoor space. Ground-level ozone is the principal component of smog.

- Health effects—breathing problems, reduced lung function, asthma, irritated eyes, stuffy nose, reduced resistance to colds and other infections. May speed up aging of lung tissue.
- Property damage— Ozone damages natural and synthetic rubbers, plastics, fabrics, etc.

2.2.4 Effect of Formaldehyde (HCHO)

Major source of formaldehyde indoor include pressed-wood products, Furniture and furnishings. Concentration of Interest for Formaldehyde by ASHRAE 62:2013 [4]:

- 81.5 ppb (30 minutes) Some irritation to sensitive people.
- 27ppb (8 hour) Never to exceed guideline limit for sensitive people. It does not guarantee protection against formaldehyde's carcinogenicity.
- 45 ppb (1 hour) or 7.3 ppb (8-hour) Non-cancer proven limit for formaldehyde
- 16 ppb Limit of formaldehyde for Mobile homes

The health effects of formaldehyde include: eye, nose and throat irritation, asthma and respiratory problems. Has also shown that excess exposure to formaldehyde may also lead to cancer [4].

2.2.5 Effects of Volatile Organic Compounds (VOC)

Major sources of contamination include new building materials, furnishings, maintenance materials, deodorants, outdoor air, parking area and fueling stations nearby.

As there are number of VOC's present, each compound has specified limit of acceptability above which can cause harm to the occupants of the building. According to Institute of Environmental Epidemiology, Ministry of the Environment, Singapore [11] Toulene was considered to be a important VOC's that must be considered for evaluation. The limit of acute concentration of exposure for 1 hour period is 37000 µg/m^3. Average exposure for a lifetime should be below 300 µg/m^3. Inhalation of toluene for short periods may cause vomiting, nausea, headache, dizziness and loss of coordination. For 8 hour average the limit is less than 50 ppm [19]. Increase in weight of liver and kidney were observed in rat when exposed to higher limits. May cause delayed growth of fetal and skeletal development during pregnancy.

2.2.6 Effect of PM 2.5 and PM 10

The most common constituents of air that are associated with the index of Air quality are PM 2.5 and PM 10. Major contaminants include combustion products, outdoor air, parking garages, smoke, deteriorating materials, diesel exhaust, burning of wood, industrial effluents etc. Some indoor sources of fine particles are smoke, cooking, burning candles or oil lamps, and operating fireplaces and fuel-burning space heaters. Limit of indoor acceptability for PM2.5 and PM 10 are 15µg/m^3 and 50µg/m^3. The guideline level may prevent from exacerbation of asthma and heart disease. General exposure may lead to running nose, irritation of eyes, nose , throat, lungs, sneezing and shortness of breath.

These effects caused by the air constituents have brought the interest of research of building sciences and indoor air quality to provide a better environment and workplace for the occupants and thereby improve productivity.

2.3 Lighting Quality

The effect of lighting quality is underestimated when compared to thermal comfort and air quality as it does not have any immediate health effects. But in today's scenario where most people work in sealed environments there is no scope for outdoor lighting to come in and constrained only by the available indoor lighting. The positive of lighting are many and only been recently studied to improve the productivity of occupants. They are essential for human health, productivity and comfort. Lighting is taken for granted and value it less. But it is the parameter that makes the visual appeal to the architecture of the building and is essential at all places to work, play, shop, learn, communicate and do business. Where the above thermal quality and air quality standards vary widely over place to place, lighting quality remains uniform throughout the world. Proper installation of lighting improves productivity, satisfaction, visual appeal, improves the mood of the occupants, facilitates communication and also promotes safety and security. In the opposite, poor installation of light can cause headache, decrease productivity, glare, eye-strain and distraction and also increase of energy consumption in case of too bright lighting.

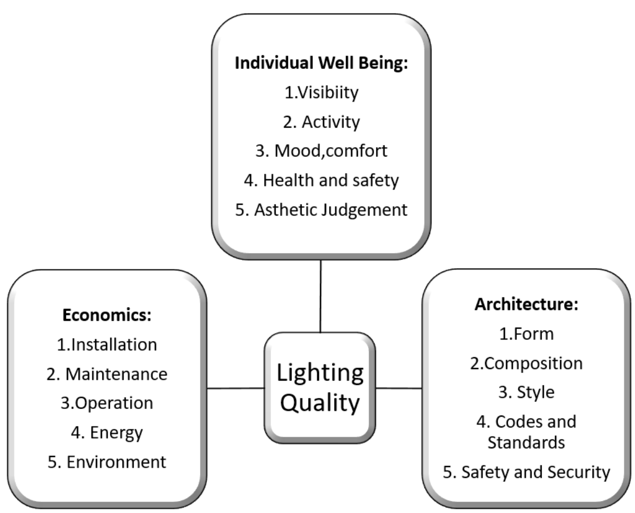


Figure 2.3: Components of Lighting quality [20]

Lighting quality consists of three broad aspects: well being, architecture and economics related to it. Well being is associated with occupants comfort, visibility, type of activity and lighting related to the activity, safety, mood of the occupant and the aesthetic judgment of the environment. The economics related to it are the installation cost, maintenance and energy consumption due to it. Architectural aspect relates to the form of lighting, composition, style and colour temperature. With regard to this project, energy consumed and intensity level of the light around the occupants are considered and other aspects fall out of scope of this project which focuses on the environmental aspect of smart buildings.

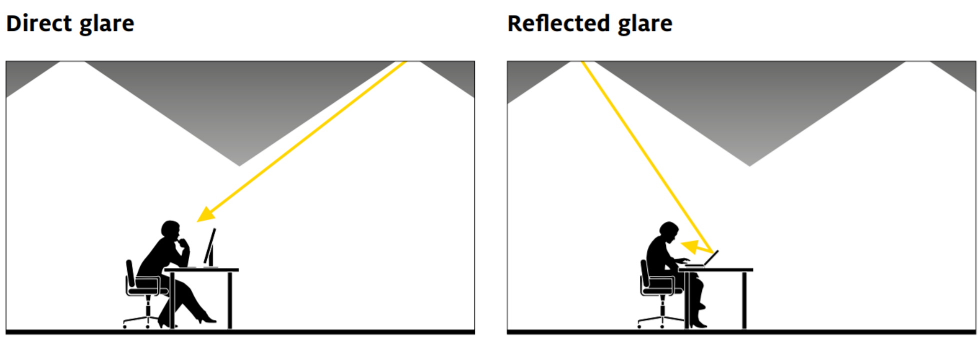


Figure 2.4: Glare: effect of poor lighting[30]

Various standards have recommended a level of 500 lux (units of light intensity) at the work place(office work) and 100 lux units lesser around the radius of 0.5 meter from the work place [20][3].

2.4 Acoustic Quality

Acoustic comfort is the well being of the occupants of the room with regard to acoustic environment. It relates to providing comfort for the occupants by minimizing intruding noise and maintaining satisfaction among the occupants.

Research has shown that well-designed sound environments in offices help to improve productivity and enable better communication. Office environment becomes more satisfying and comfortable for the occupants. In hospitals, reducing the stress and sleeplessness created by high noise levels helps patients recover faster and facilitates the work of the staff. In our own homes, protection from noises contributes to a sense of security and privacy.

Apart from damaging ears due to long term exposure to noise higher than 120dB it also leads to cardiovascular disease, high blood pressure, headaches, hormonal changes, psychosomatic illnesses, sleep disorders, decreased physical and mental performance, stress reactions, aggression, constant feelings of displeasure and a decreased sense of general well-being. It is recommended that the acoustic level of office work-space should be in the range of 45-65dB for comfort and better communication.

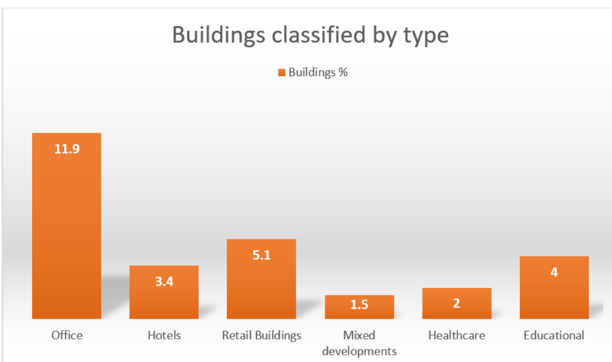
Adjacency combinations		**Sound level**
Standard office	Standard office	45
Executive office	Executive office	50
Conference room	Conference room	50
Office, conference room	Hallway, stairway	50
Mechanical equipment room	Occupied area	60

Table 2.4: Sound level recommended by USGBC [9]

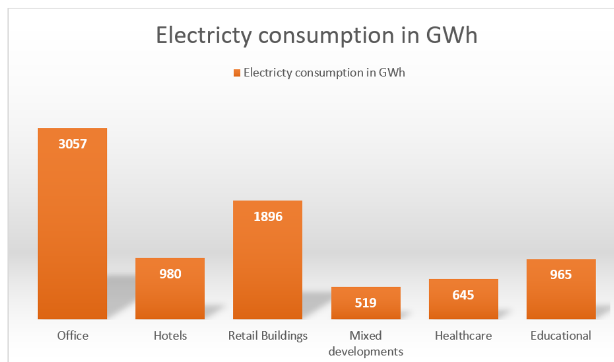
Control of noise is the most difficult thing of all other components of IEQ. Sound level cannot be directly minimized instead has to be reduced in the production itself. Architectural aspects of the building has to be modelled in such a way that there is reduction in sound travelling one corner of the room to the farthest corners of the room. Some possible solutions for reduction in noise of indoor spaces include periodic check of noise producing agents like that of the office equipment and assuring its optimum performance to reduce noise, using false ceilings with absorbent material of sound like acoustic foam and carpets for reduction of unwanted noise. External noise has to be reduced by proper sealing of windows and doors, whereas the internal noise like echo has to avoided by proper architectural planning.

2.5 Energy efficiency

Introduction of mechanical systems in the need for controlling the temperature of the room for occupants has resulted in an unfortunate phenomenon that has led to the increase of energy usage in the name of modern development. Present energy consumption that is being spent on room heating or cooling is about 40% of the total energy the buildings consume and moreover buildings themselves consume about 40% of the total energy consumed. In Singapore, the building sectors is the second highest consumer of energy[6]. According to [28], buildings consume about a third of non-renewable fuels. In developed countries, the building sector is one of the primary consumers of the total energy production. This has resulted in surge of research studies in the field of building energy efficiency. The studies have all shown that Air conditioning and mechanical ventilation systems are the primary consumers of the energy. Proper control of ACMV system and lighting will improve the energy efficiency of the building.



(a) Type of Buildings in Singapore %



(b) Energy consumption for the year 2016

Figure 2.5: Energy consumption comparison for buildings in Singapore [6]

The building management system plays a crucial role to control the necessary variables with regard to the building in terms of comfort and energy. It has to deal not only with ACMV and lighting systems but also a wide variety of other actuators for the functionality of the building. Hence, it needs a sophisticated automation system in order to improvise the energy efficiency of the building. It should also focus on the user preferences and comfort level for better optimization of energy usage. The equipment used may have to be serviced regularly in order for it work in the optimum level. As conserving energy and providing user comfort are on contrary to each other and there is need for a optimization between them there is need for the multi-agent behaviour.

2.6 Multi-agent system

Agent behaviour can be added to building energy management systems in order to control the air constituents, thermal comfort, lighting comfort and also achieve higher energy efficiency.In general agent is referred to as a software or hardware system that is present at an environment and is able to react to the changes that happens in the environment. Agent has basic characteristics that include being reactive to the change in the environment, goal oriented behaviour to change the environment towards comfort and its ability to communicate with other agents in order to necessitate change in the environment.

The design of multi-agent system with respect to the building includes system level approach where multiple agents collaborate in an environment. As there cannot be uniformity of comfort for all occupants who are all part of the multi-agent system, there cannot overall goal in the system. Hence, each agent focusses on achieving goal of comfort surrounding it rather than trying to unify the system to have one behaviour.

The agent behaviour involves decentralization of control between different level, without interfering with the goals of other agents directly. As this behaviour requires specific properties of the system, thereby a uniform multi-agent behaviour for all buildings cannot be achieved and has to be modelled individually.

The Figure 2.6 gives a overall description of the multi-agent behaviour of the system involving sensor arrays, occupants, policies and standards that the system follows and actuators required in establishing the control of the system. Sensor array are present in places of occupants interest so as to give a real time feedback of all the concentration of air constituents, temperature, humidity, lighting, sound. All these data are communicated to the local agents so as to take action according to the user's comfort and policies and standards. The user's comfort is communicated to the local agent by the personalized agents. Here the user becomes an active agent who can change the desired set-points based on his comfort. The standards and policies involve the prescribed level of concentration of gases, lighting, temperature and humidity for safe level of environment. These policies are met first and then

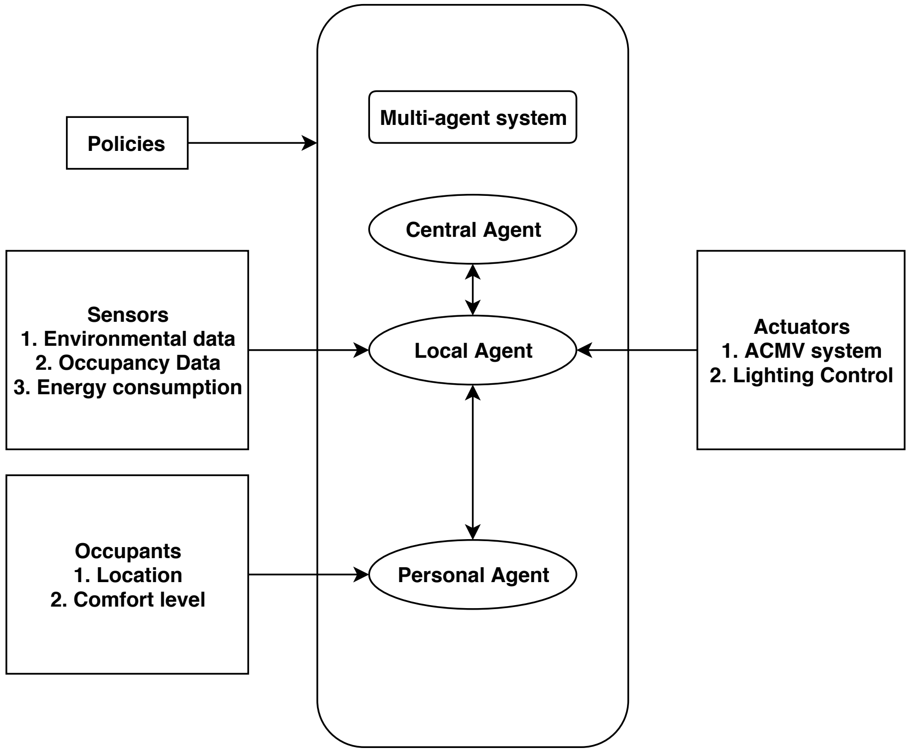


Figure 2.6: Multi-agent system for IEQ

the occupants comfort are taken into consideration for control. The air concentration is not personalized since the level of concentration cannot be sensed by the occupants and judged for safety, whereas the thermal and lighting levels associated with comfort are associated with a personalized control. The central agent is the essential component of the multi-agent system which coordinates all the decisions made by the local agents and maintains the overall policies that have to be met for a safe environment. The actuator used in the control of the environment include ACMV control system and lighting control. These are the two systems that are used in order to achieve the desired comfort level of the occupants.

Agent	**Functions**
Sensor Array	Gives the presence of Occupant, temperature, humidity, concentration of gases to the central and local agent
Human Beings	Supervise the local and central agents and provide set-points based on their comfort
Lighting Controller	Keeps the lighting level as recommended by Human beings by communicating with Central Agent. Central agent instructs the Lighting controller based on the inputs from the Sensor array and Human being's feedback
ACMV system	Keeps the temperature and humidity level as recommended by Human beings by communicating with Central Agent. Central agent instructs the ACMV system based on the inputs from the Sensor array and Human being's feedback
Central Agent	It supervises all the control actions that needs to be coordinated with the local subsystems like lighting control and ACMV system by considering the feedback from Sensor array and the occupants. The occupants have a superior level of command over the central agent when deciding the comfort level.

Table 2.5: Agents associated with IEQ and their functions

Chapter 3

Modelling of Room Space System

Building environment, energy consumed by it and user comfort are complex systems dealing with a wide variety of variables that are difficult to be modelled directly without assumption that can make these complex systems simple enough to be modelled by differential equations. The building environment system can be first broken down in to Thermal model, Lighting model and model of air constituents. The following sections will brief on these different sub-systems and their assumptions taken.

3.1 Thermal model of the System

Heat storage and transmission are part of the thermal properties of the building. Room, walls, roof, floor and windows all form part of the elements that can store or transmit heat energy from the surroundings into the room. The air that is present in the room has the capacity to store this heat and hence causes the increase in temperature of the room that is experienced by the occupants. This increase in temperature is controlled by the air conditioning and mechanical ventilation system with preference to the occupant's comfort. To build a thermal model of the system the basic components of storage and transmission of heat has to be understood and modelled.

3.1.1 Thermal Capacitance

The basic property of all materials is the specific heat capacity of the material that causes the material to store heat or thermal energy and there by causes an increase in temperature of the substance. The specific heat capacity of a substance is defined as the amount of heat required to increase the temperature of the substance by 1 Kelvin. This property of the buildings materials can be assumed to be that of capacitance of the electrical circuits. For an object of mass m and specific heat capacity of c_p, with rate of change of temperature $\dot{T}$ then the heat flow through the substance is given by

$$Q = mc_p\dot{T} \tag{3.1}$$

In terms of electrical analogy, the rate of change of temperature can be assumed to be a voltage supply, where as the heat flow can be assumed to the current flow in that direction. The specific heat capacity multiplied by mass can be assumed to be a storage element in the electrical equivalent of the thermal circuit.

3.1.2 Thermal Resistance

Resistance to flow of heat of cannot be directly measured but instead the thermal conductivity of the material is taken. Thermal conductivity is defined as the rate of steady heat flow through a unit area of material with a temperature difference of 1 kelvin across its surfaces.

Different materials have different types of transmission of heat. Three modes of transmission of heat are conduction, radiation and convection.

Thermal Conductance: Thermal conductance is the transfer of heat energy within a body from hotter side to the cooler side by means of thermal collisions that occur within the body. Walls, floor and roof are taken to be stationary objects that has transfer of heat from the external surface to the internal surface by means of conduction. Equations governing

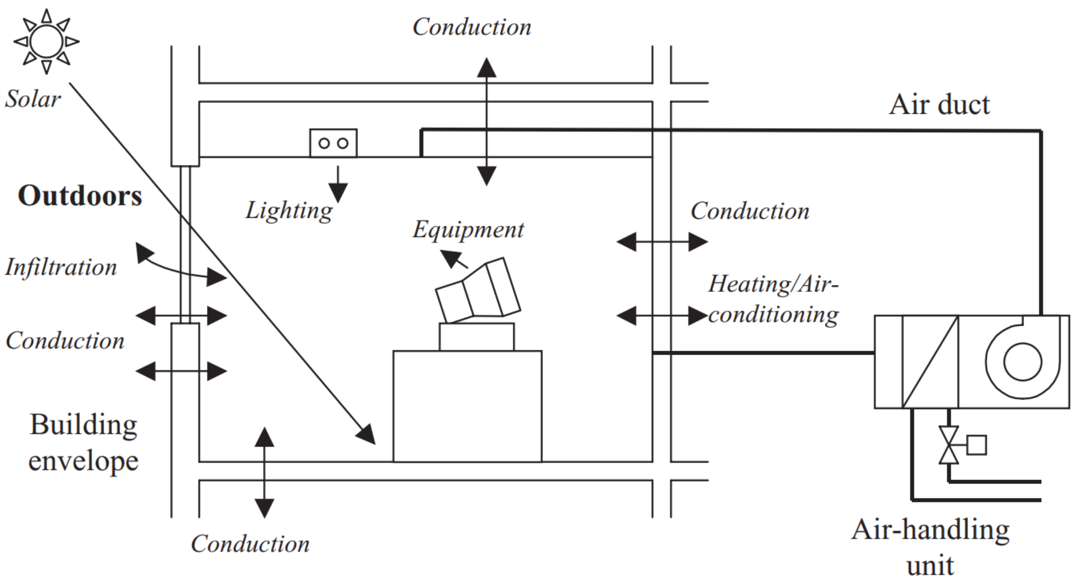


Figure 3.1: Various Heat gains of a building [32]

Heat and mass transfer processes	**Building elements**
Conduction and/or radiation heat transfer	External wall, roof,ceiling & floor slabs
Conduction heat transfer and solar radiation transmission.	Window glazing
Conduction and/or radiation heat transfer and moisture dissipation	Occupants, lights, and other equipment
Convection heat and mass transfer	Infiltration from outside and adjoin rooms/lobby

Table 3.1: Building elements and their mode of heat transfer

the conduction is based on Fourier's law. For a wall, the energy transfer rate is given by the equation

$$q_x = -kA\dot{T} \tag{3.2}$$

where $\dot{T}$ is the rate of change of temperature in the direction of heat flow and q_x is the heat transfer in direction of $x\dot{T}$he heat transfer is expressed in Watts, where as the k is the thermal conductivity expressed in $(W/m.K)$. This is expressed under steady state condition to be

$$q = kA\frac{(T_2 - T_1)}{L} \tag{3.3}$$

Here the T_2 and T_1 are the external and internal temperatures of the wall and L is the width of the wall and A is the surface are of the wall expose to external conditions.

Thermal Convection: It consists of two ways of transfer of heat energy. In addition to transfer of energy from hotter side to the colder side by thermal collisions between molecules, heat transfer also takes place by the transfer of bulk material or macroscopic motion of fluid.The equation governing is called as the Newton's law of cooling is expressed as:

$$q = hA(T_s - T_\infty) \tag{3.4}$$

where q is the convective heat transfer that is proportional to the temperature difference between the surface and the fluid (T_s and T_∞) respectively. Here h is called the convective heat transfer coefficient with units ($W/m^2.K$). Heat flow is said to be positive if surface temperature is greater than fluid temperature ($T_s > T_\infty$) or else it is negative if ($T_s < T_\infty$).

Radiation: It is the transfer of energy without the presence of any material but is transported in the form of eletromagnetic waves. The rate at which it is released is termed as emissive power (E) expressed in W/m^2 . Radiation is governed by the Stefan-Boltzmann law which is expressed as :

$$E = \alpha T_s^4 \tag{3.5}$$

T_s is the absolute surface temperature and α is the Stefan-Boltzman constant. Radiation is not used in the thermal model of the building as radiation between the surface of the walls is very low when compared to conduction. When external temperatures of the building are of importance then radiation plays a crucial role as direct radiation of sun's heat onto the external surface of the buildings.

3.1.3 Equivalent Electrical analogy of thermal properties

Analogy of Thermal Resistance to electrical circuit Thermal resistance obtained from [3.3] is analogous to the electrical resistance. Thermal resistance is the property that resists the flow of heat from hotter surface to the cooler surface in similar terms to the resistance in electrical circuit which resists the flow of charge from higher potential to the lower potential. The electrical resistance is defined as the ratio of the driving potential by the corresponding transfer of charge through the surface area. By analogy the thermal resistance due to conduction can be given by:

$$R_{t,conduction} = \frac{(T_2 - T_1)}{q_x} = \frac{L}{kA} \tag{3.6}$$

Here the difference in temperature is the potential difference of the electrical circuit where as the heat flow represents the flow of charge from higher potential to the lower potential in the direction of x which is obtained by the Ohm's law [22].

Thermal resistance due to convection, according to Newton's law of cooling is given by:

$$R_{t,convection} = \frac{T_s - T_\infty}{q} = \frac{1}{hA} \tag{3.7}$$

Analogy of Thermal Capacitance to electrical circuit Thermal capacitance obtained from [3.1] is analogous to the electrical capacitance. Thermal capacitance is property the stores the flow of heat in a substance, in similarity to electrical capacitance which stores the charge. The electrical capacitance is defined as the amount of electrical charge that will be stored when a potential difference is applied across it surface. By analogy the thermal capacitance is be given by:

$$mC_t = \frac{q_x}{\dot{T}} \tag{3.8}$$

Here the difference in temperature is the potential difference of the electrical circuit where as the heat flow represents the flow of charge from higher potential to the lower potential in the direction of x .

Thermal potential difference The difference in temperature between the two opposite surfaces of the material is analogous to the potential difference of an electrical circuit with higher temperature being higher potential and lower potential being lower potential.

3.1.4 Electrical model of the wall

The lumped capacitance model of the wall is generally followed to model the building system as it provides ease of computation and suitable for short time horizon problems like temperature control [32] by treating each building element as a lumped element of the circuit with uniform thermal response.

First order lumped model Let a building element of wall is taken for study. It can be assumed to be a first order lumped capacitance model in which it has two resistances r_i and r_o which are the internal and external thermal resistances of the wall experiencing temperatures T_i and T_o respectively. The capacitance C_m is the thermal capacitance of the material per unit area and the heat source is q .

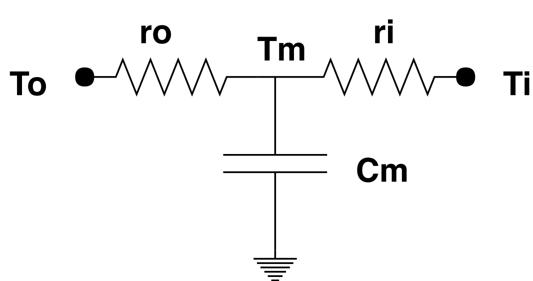


Figure 3.2: First order lumped model

As all the building elements are built up with a wide variety of layers, it can equated to a lumped model with the thermal resistance and capacitance having a relationship to the electrical equivalent. The 1980 paper of Laret [18], proposed the calculation of resistance to be:

$$r_i = a r_m \tag{3.9}$$

and outer resistance to be

$$r_o = (1 - a) r_m \tag{3.10}$$

where r_m is the resistance of the material and a is the accessibility factor given by:

$$a = 1 - \frac{1}{r_m C_m} \sum_{k=1}^{k=n} r_k^* C_k \tag{3.11}$$

where:

$$r_k^* = \sum_{j=1}^{j=n-1} r_j + r_k/2 \tag{3.12}$$

here r_m and C_m are the thermal resistance and capacitance of the material. They are expressed in m^2KW^{-1} and $Jm^{-2}K^{-1}$ respectively and n is the number of layers of the element.

Based on the above equations the heat conduction equation of the first order lumped model is:

$$\frac{dT_m}{dt} = \frac{1}{C_m}[q_r + \frac{(T_i - T_m)}{r_m} - \frac{(T_m - T_o)}{r_o}] \tag{3.13}$$

Second order lumped model The first order lumped model has two important short comings that effect the modelling of the system. They are:

- To form the heat balance equation of the building space, all the temperatures have to be known and the approximation of uniform thermal resistance T_m does not guarantee a accurate prediction of the internal surface temperature of the element.

- First order model performs well for the step change in temperature (T_i or T_o) and shows a change in heat transfer, but shows poor performance when it comes to disturbances in surface temperature due to convection or radiant sources. This is due to inaccurate model assumption of the energy that is shared among convection and conduction due to the assumption that the material is uniform throughout its structure.

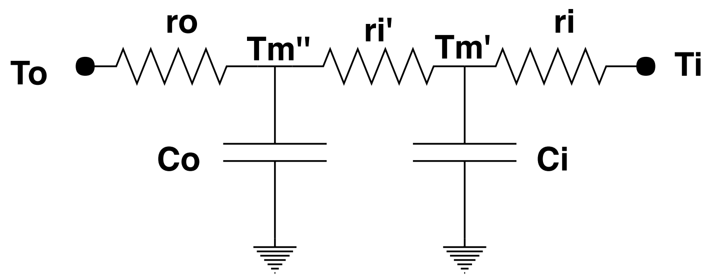


Figure 3.3: Second order lumped model

In order to overcome these short comings in modelling, second order model was proposed by Gouda[14]. The resistances and the capacitances of the lumped model can be expressed as:

$$r_i = x_1 r_m \tag{3.14}$$

$$r_i^{'} = x_2 r_m \tag{3.15}$$

$$r_o = x_2 r_m \tag{3.16}$$

$$C_i = y_1 C_m \tag{3.17}$$

$$C_o = y_2 C_m \tag{3.18}$$

all these equations are subject to the conditions that:

$$x_1 + x_2 + x_3 = 1; x_1, x_2, x_3 \geq 0; y_1 + y_2 = 1; y_1, y_2 \geq 0; \tag{3.19}$$

The second order lumped model produces the following differential equations: At node $T_m^{'}$:

$$\frac{dT_m^{'}}{dt} = \frac{1}{y_1 C_m}[q_r + \frac{(T_i - T_m^{'})}{x_1 r_m} - \frac{(T_m^{'} - T_m^{"})}{x_2 r_m}] \tag{3.20}$$

At node $T_m^{"}$:

$$\frac{dT_m^{"}}{dt} = \frac{1}{y_2 C_m}[q_r + \frac{(T_m^{'} - T_m^{"})}{x_2 r_m} - \frac{(T_m^{"} - T_o)}{x_3 r_m}] \tag{3.21}$$

Considering the room of interest where the experiment was conducted according to [32]

Type of surface	x_1	x_2	x_3	y_1	y_2
External Wall: Brick, concrete, plaster	0.111	0.506	0.383	0.186	0.814
Internal floor: Plaster board	0.1	0.482	0.418	0.211	0.789

Table 3.2: Coefficients of second order lumped model

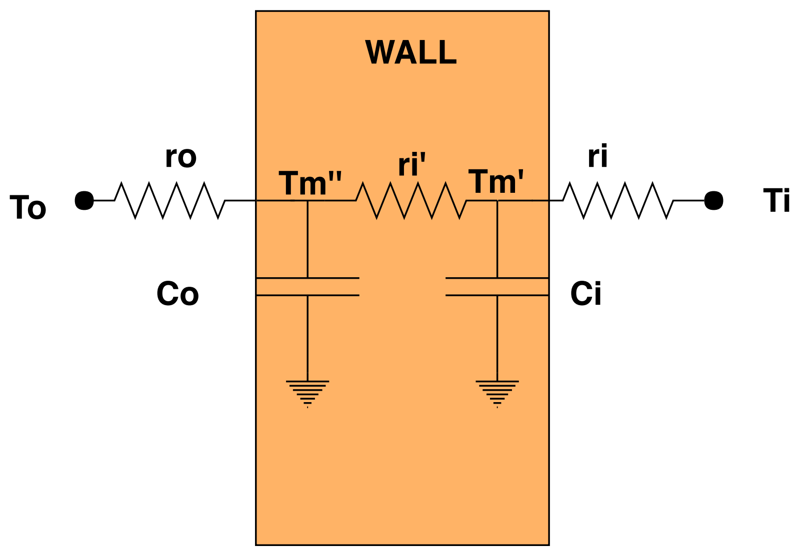


Figure 3.4: Second order lumped model of the Wall

Assumptions considered during the modelling of the wall in order to simply the complexity of the problem:

- Air inside the room is well mixed and there is very minimal variation of the temperature across the room
- All the elements of the building are considered to be fit into the lumped capacitance model.
- Heat flow within the building is considered to be Isotropic.

- Thermo-physical properties of the building material do not change with the temperature.
- Pressure across the room is considered to be uniform in order for the heat flow to be variant based on only temperature.
- Radiation from the sun and its effect is considered to be that of a sin-wave input since the data for variation is not available for consideration.

3.1.5 Equivalent electrical model of the room

In the previous section we have seen about the electrical model of the wall and its transfer function. On the basis of the second order lumped capacitance model all the elements of the building can be modelled. The room considered for the project is Field Environmental Chambers 2 (FEC2), NUS Department of Building Research. The room is controlled environment provided with an Air conditioning and mechanical ventilation system (ACMV) which is controlled by a personalized software in the control room. The following Figure:3.5 depicts about the dimensions and the element present in the room:

The dimensions of the room are 7.37 meter wide, 10.10 meter length, 2.63 meter wide. There is glass window pane on the far end of the room, on the left hand side the wall is part glass and part brickwork. The rest of the two sides are complete brickwork with layer of plastering. From the Table:3.2 the coefficients of second order model of the wall are taken. From the Figure:3.5 it can be seen that the room consists of 4 walls with two being completely brickwork and plastering and the rest containing part glasses. The floor and the roof are also considered to be similar to wall when thermal properties are compared. The flooring is made of plaster board and hence different properties are considered. The building space taken to be system for which the heat balance equation is to derived, can be expressed as sum of the Q_{heat} the amount of heat absorbed or dissipated and the W_{sys} work done by

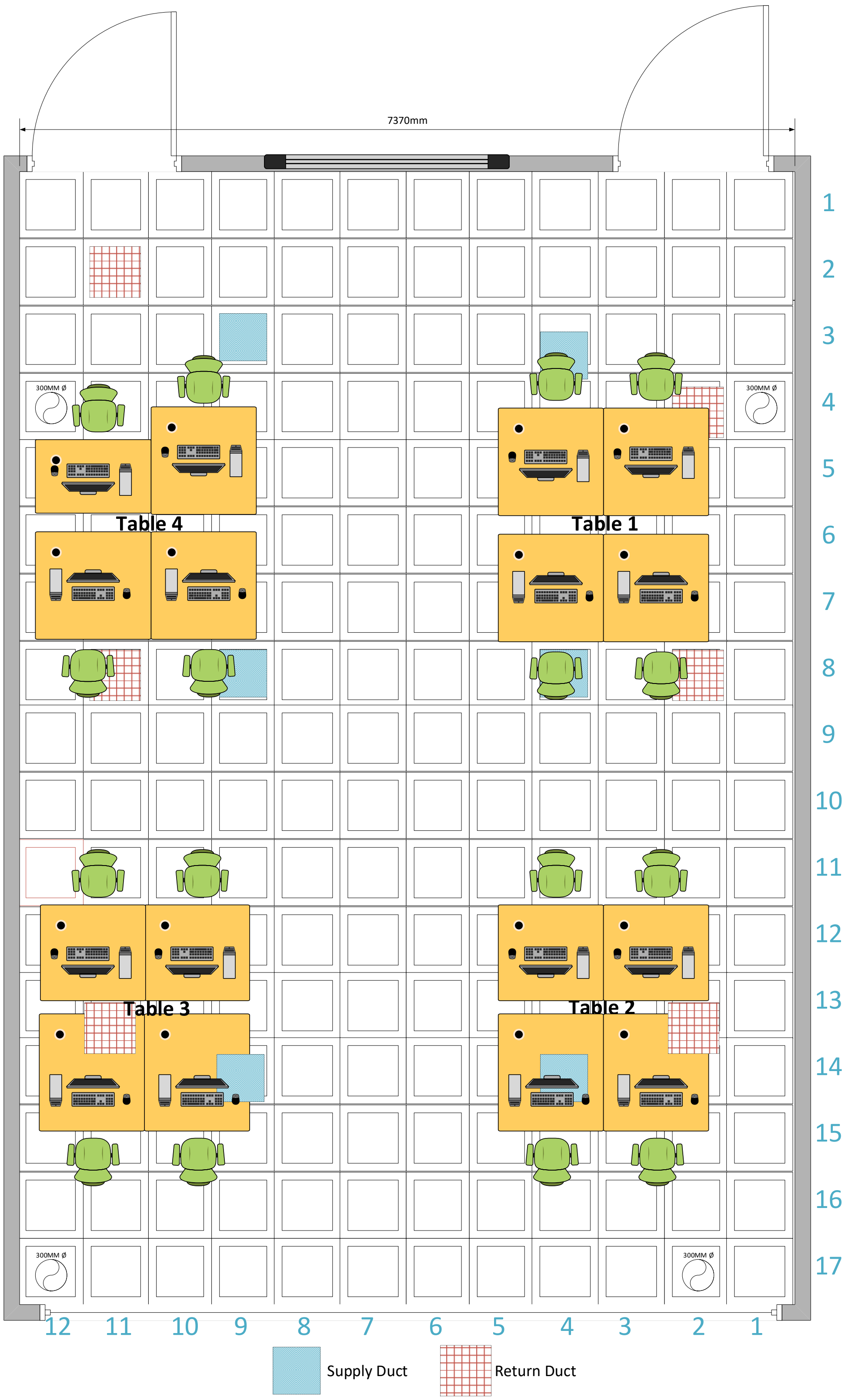


Figure 3.5: Floor plan of the room FEC2

the system is equal to the change in internal energy ΔU .

$$\Delta U = \delta Q_{heat} + \delta W_{sys} \tag{3.22}$$

By considering the building space the change in internal energy is the heat storing capacity of the air in the room multiplied by the difference in temperature between inside and outside.

$$\frac{dU(t)}{dt} = C_{th}\frac{dT_i(t)}{dt} \tag{3.23}$$

By considering the building space and its change in internal energy is equal to the Quantity of heat removed by the vent plus the work done by the system due to the temperature difference between inside and outside.

$$\frac{dU(t)}{dt} = Q_{vent} - \frac{1}{R_{th}}(T_i(t) - T_o(t)) \tag{3.24}$$

By considering the above two equation the heat balance equation of the room space can be arrived at:

$$C_{th}\frac{dT_i(t)}{dt} = Q_{vent} - \frac{1}{R_{th}}(T_i(t) - T_o(t)) \tag{3.25}$$

In the above equation C_{th} represents the thermal capacitance in $(J/^{\circ}C)$ and R_{th} represents the thermal resistance in $(^{\circ}C/W)$. Q_{vent} is the heat incoming through the ventilation. C_{th} and R_{th} are material dependant and and given by the equation:

$$R_{th} = r_{in} + r_{out} + \sum_{i=1}^{n}\frac{x_i}{k_i} \tag{3.26}$$

$$C_{th} = \sum_{i=1}^{n} x_i \rho_i C_{p_i} \tag{3.27}$$

r_{in} and r_{out} are the internal and external surface temperatures in $^{\circ}C/W$, C_p is thermal capacity in $J/kg - K$ The following are the constants in the equation considered:

		Material Used				
Property	**Units**	**concrete**	**plastering**	**gypsum**	**glass**	**soft-wood**
Density	kg/m^3	2400	850	1100	2530	550
Thermal Heat capacity	J/kgK	840	1000	700	840	1700
Thermal conductivity	W/mK	0.8	0.013	0.35	0.8	0.08
Standard Thickness	$meter$	0.01	0.005	0.015	0.01	0.015

Table 3.3: Material dependant constants from various sources

Now considering the whole room space, the balance equation is :

$$\begin{aligned}\rho_{bs}C_{ba}V_{bs}\frac{dT_{bs}}{dt} &= Q_{human} + Q_{light} + Q_{equipment} + Q_{acmv} + \frac{A_{rw,i}(T_{rw_1'} - T_{bs})}{x_{rw,1}r_{rw}} + \frac{A_{fw,i}(T_{fw_1'} - T_{bs})}{x_{fw,1}r_{fw}} \\ &+ \frac{A_{lw,i}(T_{lw_1'} - T_{bs})}{x_{lw,1}r_{lw}} + \frac{A_{lg,i}(T_{bs} - T_{out})}{x_{lg,1}r_{lg} + x_{lg,2}r_{lg}} + \frac{A_{bg,i}(T_{bs} - T_{out})}{x_{bg,1}r_{bg} + x_{bg,2}r_{bg}} \\ &+ \frac{A_{roof,i}(T_{roof_1'} - T_{bs})}{x_{roof,1}r_{roof}} + \frac{A_{fl,i}(T_{fl_1'} - T_{bs})}{x_{fl,1}r_{fl}} - 0.33NV_{bs}(T_{bs} - T_{out})\end{aligned} \tag{3.28}$$

where,

ρ_{bs} : Density of air in building space in kg/m^3

C_{ba} : Specific heat capacity of air in building space in J/kgK

V_{bs} : Volume in building space in m^3

T_{bs} : Temperature of air in building space in $^\circ C$

A : Area of the element under consideration in m^2

Q_{human} : Heat gain due to occupants in W

Q_{light} : Heat gain due to lighting in W

$Q_{equipment}$: Heat gain due to equipment in the room in W

T_{roof} : Temperature at surface of roof in $^\circ C$

T_r : Temperature at surface of right wall in $^\circ C$

T_l : Temperature at surface of left wall in $^\circ C$

T_{lg} : Temperature at surface of left glass wall in $^\circ C$

T_f : Temperature at surface of front wall in ^oC

T_{bg} : Temperature at surface of back glass wall in ^oC

T_{fl} : Temperature at surface of floor in ^oC

$x_{lw}, x_{rw}, x_{fw}, x_{roof}, x_{fl}$ are the resistance of individual models of left wall, right wall, front wall, roof, and flooring.

x_{lg}, x_{bg} are the resistance of individual models of left glass wall and back glass wall.

N : number of times the ACMV system needs to replace the air in the room space.

The subsystems present in the room include the left side wall, the left side glass wall, the right side wall, the front side wall, the back side glass wall, the roof and the floor. The temperature sources present outside the room space are generally higher than the one present inside and hence are considered to be at higher potential and the room is considered to be at lower potential. The temperature can be modelled to be a voltage sources which is either AC or DC based on the type of temperature variation throughout the day. The sources of heat gains in the room include human beings (occupants), lighting, office equipment that generate heat heat and are additive to the heat gain. When the room is to be cooled then the ACMV system removes heat from the system, it means that it is negative by sign or works in the opposite direction to that of other heat sources. The heat gain can be modelled to be a current source whose direction is into the room if the source adds to heat gain or is away from the room if the source removes the heat.

The subsystem right wall, front wall and left wall are modelled to be similar to the second order lumped capacitance model as they are of considerable thickness and are capable of storing heat in their body. The coefficients of external and internal thermal resistances are considered based on the [32] and their values are taken from standard measurements. The roof and floor are considered to be similar to that of other walls with full brickwork and hence second order lumped capacitance model is followed for modelling them. When it comes to glass wall the thickness of them is very less compared to the brick-walls and hence they possess very negligible amount of heat storage between the surfaces. Thereby the glass

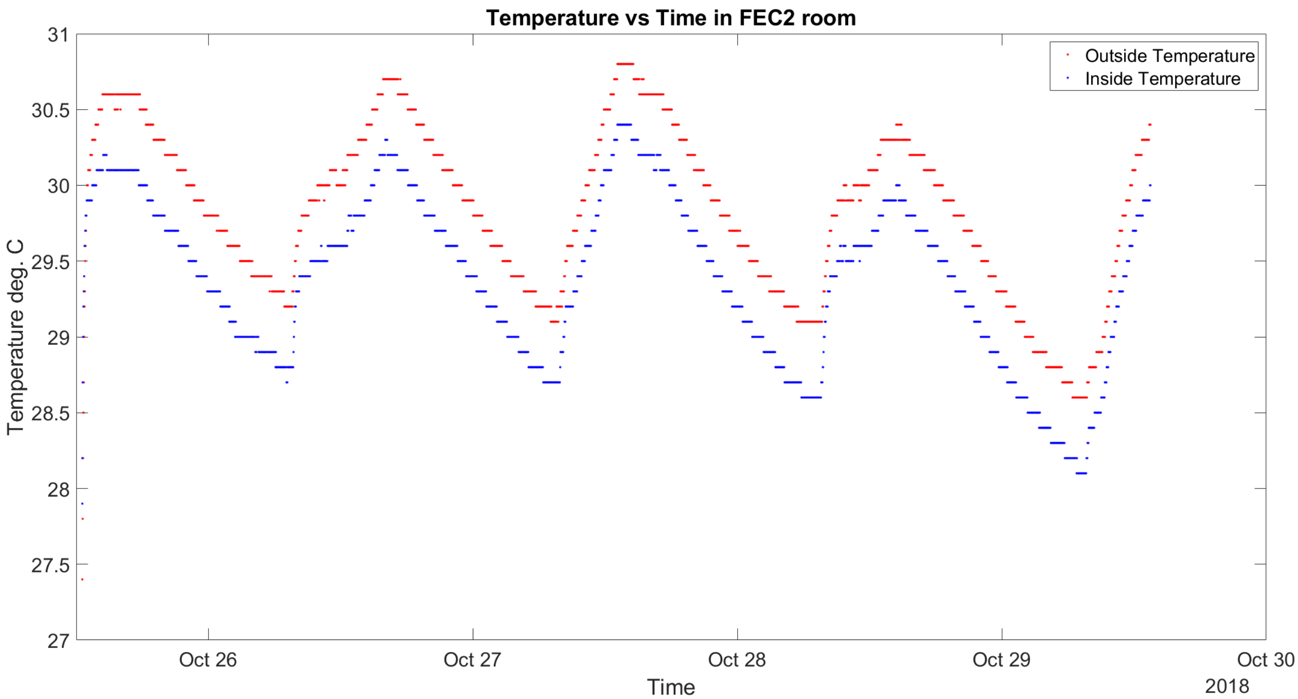


Figure 3.6: Variation of Indoor and Outdoor temperature for data collected during three days

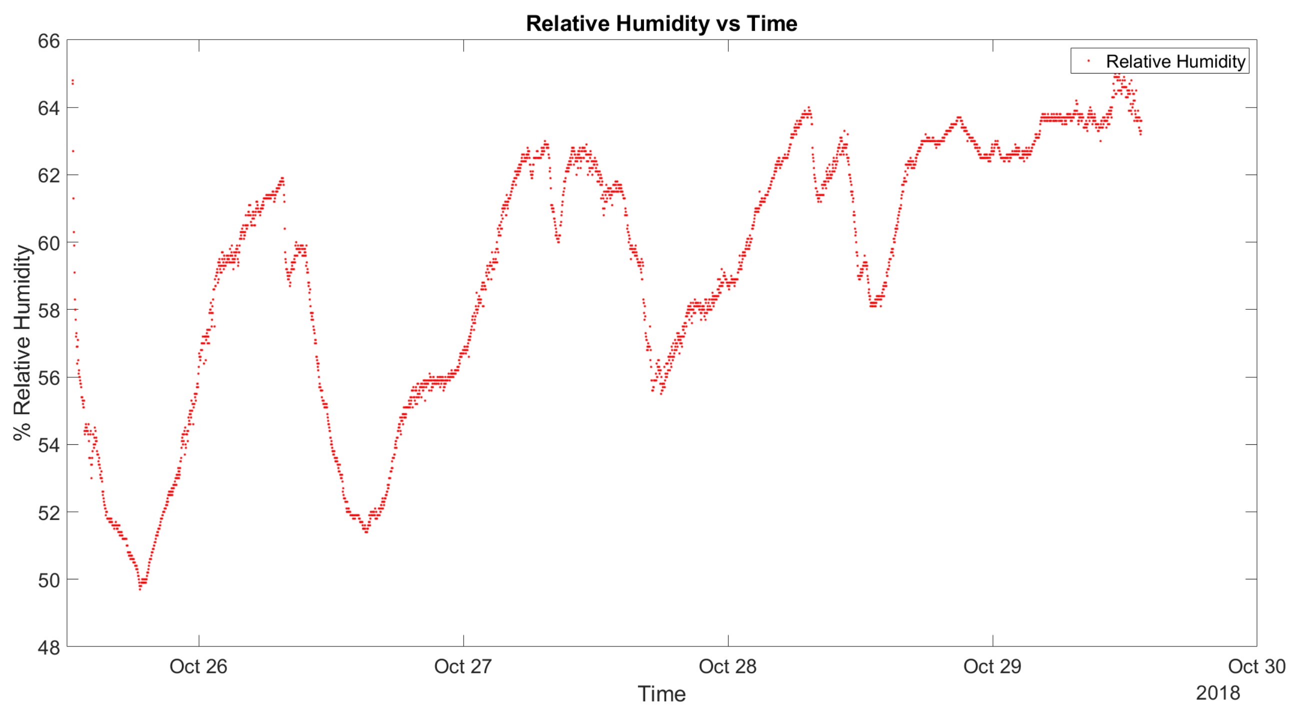


Figure 3.7: Variation of Relative Humidity for data collected during three days

surfaces are modelled by resistances connected in series which represent the internal and external temperatures connected in series.The left glass wall and back wall are based on this considerations. The voltage at the node between the capacitance and resistance network is said to be the surface temperature of the material at the outer or inner surface with respect to the node that is taken for consideration. The Figure:3.8 shows the 10th order model obtained from the combination of above subsystems:

Here the ACMV system was considered based on the cooling load calculations as the installed name plate capacity of the system was not known. The assumption that with ACMV system is in place the indoor temperature of the building space will be constant and the time derivative of indoor temperature will result in zero. The cooling of the indoor space implies the heat is removed from the system and hence Q_{acmv} is taken to be negative. The heat capacity of the volume of the air present in the room is negligible compared to other elements. By this assumption the cooling load calculation from 3.28 is as follows:

$$\begin{aligned} Q_{acmv} = Q_{human} + Q_{light} + Q_{equipment} &+ \frac{A_{rw,i}(T_{rw'_1} - T_{bs})}{x_{rw,1} r_{rw}} + \frac{A_{fw,i}(T_{fw'_1} - T_{bs})}{x_{fw,1} r_{fw}} \\ &+ \frac{A_{lw,i}(T_{lw'_1} - T_{bs})}{x_{lw,1} r_{lw}} + \frac{A_{lg,i}(T_{bs} - T_{out})}{x_{lg,1} r_{lg} + x_{lg,2} r_{lg}} + \frac{A_{bg,i}(T_{bs} - T_{out})}{x_{bg,1} r_{bg} + x_{bg,2} r_{bg}} \\ &+ \frac{A_{roof,i}(T_{roof'_1} - T_{bs})}{x_{roof,1} r_{roof}} + \frac{A_{fl,i}(T_{fl'_1} - T_{bs})}{x_{fl,1} r_{fl}} - 0.33 N V_{bs}(T_{bs} - T_{out}) \end{aligned} \tag{3.29}$$

The calculation is done based on the Heat balance equation method [23]. By substituting the constants of the system under study i.e the Area of the surface exposed to each temperature, temperature of the surface of each element derived from the lumped model and assuming the above steady state conditions the cooling load was found to be 55430 BTU/hr [15]. By conversion to watts it is equivalent to 15820 $Watts$. This is the capacity of the ACMV that must be installed to provide the necessary cooling required in the room.

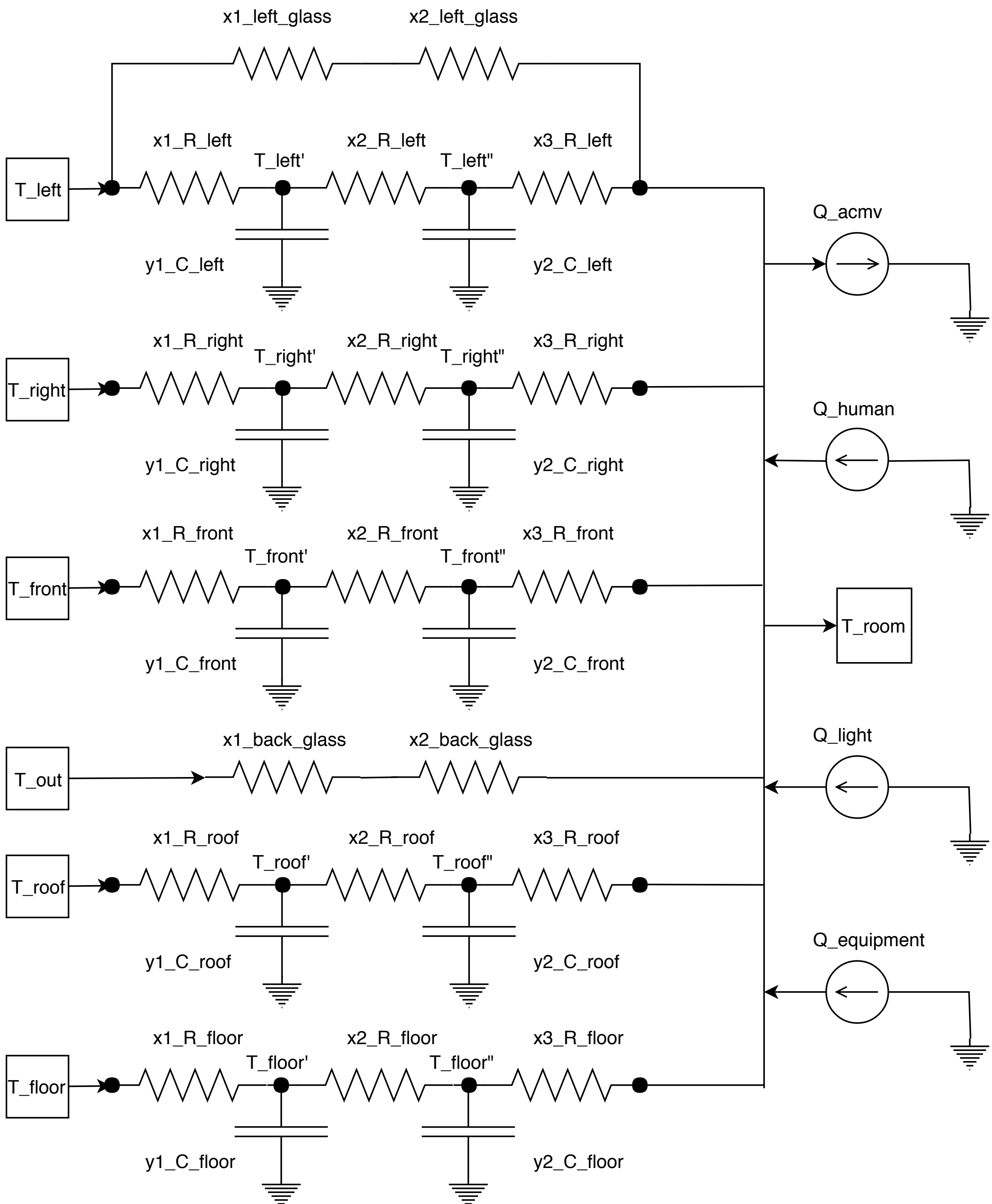


Figure 3.8: 10th order Room model based on second order lumped capacitance model

3.2 Air Quality model

In buildings with varying occupancy rate the regulation of ventilation rate is a difficult. The ventilation rates are difficult to control for momentary changes as they work like ON-OFF controller. The problem with poor ventilation is that when it is over ventilated then energy cost increases exponentially and when it is under ventilated then the occupants face a variety of health issues like headache, dizziness, sore throat, lack of concentration and decreased productivity. The under ventilated system causes a increase in the concentration of air particles in the room and this can lead to health problems when exposed to long hours. Over the period of time due to under ventilation the concentration of CO, CO_2, O_3, HCHO cause problems like eye, nose and throat irritations, lung problems, respiratory issues and cough. The following section involves the modelling of CO_2 and other gases based on steady state conditions and few other assumptions to form a transfer function model.

3.2.1 CO_2 concentration model of the room

CO_2 concentration depends directly on the number of persons present in the room. Human beings are the most important source of CO_2 in the building space and the amount of CO_2 released by them depends on the type of activity they are doing and the metabolic rate of the individual. The other source that contributes to the concentration of CO_2 is the air that is let in by the ACMV system. But it is to be noted that the ventilation system is used to remove the CO_2 by exchanging it with the external air. It is assumed that CO_2 concentration in the outdoor is constant [4]. The change in the concentration of CO_2 in the room can be given by the equation as follows [27]:

$$\frac{dc}{dt} = \frac{c_o}{V}q - \frac{1}{V}cq + \frac{1}{V}p \tag{3.30}$$

The above equation implies that the change in CO_2 concentration depends on the amount of CO_2 exhaled by the people in the room p . It also depends non-linearly on the outdoor fresh air intake q .and the outdoor concentration of CO_2 (c_o) .

This non linearlity can be represented as function:

$$\frac{dc}{dt} = f(c, q, p) \tag{3.31}$$

The function can be understood as, the concentration c is the controlled variable and the inflow q is the manipulated variable. The exhaled concentration of CO_2 cannot be measured practically and hence it is treated as a disturbance. As the process is not in equilibrium at the initial stage but in-order to design a linear controller for the system, it is necessary that the system is assumed at equilibrium. From 3.31, the non-linear form is linearized as:

$$\frac{dc}{dt} = \frac{\delta f}{\delta c}|_{(c^*,q^*)}c + \frac{\delta f}{\delta q}|_{(c^*,q^*)}q \tag{3.32}$$

where c^* and q^* are the equilibrium values of concentration of CO_2 and inflow rate of air q . At equilibrium point the function $f(c, q, p)$ will be zero as the change of concentration of CO_2 will be zero.

$$f(c, q, p)|_{(c^*,q^*)} = 0 \tag{3.33}$$

where the value of inflow rate at equilibrium is given by:

$$q^* = \frac{-p}{c_o - c^*} \tag{3.34}$$

By linearizing at equilibrium points as there are two different variables that have to attain equilibrium, by considering partial differential equations of the function:

$$\begin{aligned} \frac{\delta f}{\delta c}|_{(c^*,q^*)} &= \frac{p}{V(c_0 - c^*)} = \frac{-q^*}{V} \\ \frac{\delta f}{\delta q}|_{(c^*,q^*)} &= \frac{(c_0 - c^*)}{V} = \frac{-p}{Vq^*} \end{aligned} \tag{3.35}$$

From equation 3.30 and above it can be arrived at the following differential equation:

$$\frac{dc}{dt} = g(q^*)c + h(q^*)q \tag{3.36}$$

where $g(q^*) = \frac{-q^*}{V}$ and $h(q^*) = \frac{-p}{Vq^*}$ are constant and dependant on the inflow rate at the operating point of the system q^* , total concentration of CO_2 (p) exhaled by people. From this the final transfer function can be obtained as:

$$G_{CO_2}(s) = \frac{h(q^*)}{s + g(q^*)} \tag{3.37}$$

This transfer function can be used in predicting the amount of carbon dioxide present in the room if the number of people in the room are known and the metabolic activity they are involved in. With q^* value that can be assumed to optimum inflow rate, the concentration of carbon dioxide can be controlled by the ACMV system by the air flow intake. For the above case the carbon dioxide generated by the human being are considered by taking the type of activity done as office work and the presence of men and women in the room are assumed to equal with 8 men and 8 women. The metabolic rate is 1.4 [24]. For a age group of 21-40 years men produce average CO_2 at a rate of 0.0047 and for women 0.0037 L/sec .

3.2.2 Modelling of Air constituents concentration based on a process model

Other constituents of air are modelled similar to carbon dioxide but the difference is that they are not generated by human being and hence that factor is not considered and instead they are dependant on the other sources present in the room or there is increase in concentration due to the intake of outdoor air.

Differential equation governing Carbon monoxide :

CO is not generated by human being and hence they are not part of the function. Only the room volume, the air intake and CO present outside are taken into consideration. The differential equation governing the relation is:

$$\frac{dCO_{in}}{dt} = \frac{CO_{out}q}{V} - \frac{CO_{in}q}{V} \tag{3.38}$$

Differential equation governing Ozone :

O_3 is not generated by human being and hence they are not part of the function. Only the room volume, the air intake and CO present outside are taken into consideration. The differential equation governing the relation is:

$$\frac{dO_{3_in}}{dt} = \frac{O_{3_out}q}{V} - \frac{O_{3_in}q}{V} \tag{3.39}$$

Differential equation governing Formaldehyde :

Formaldehyde $HCHO$ is not generated by human being and hence they are not part of the function. Only the room volume, the air intake and HCHO present outside are taken into consideration. The differential equation governing the relation is:

$$\frac{dHCHO_{in}}{dt} = \frac{HCHO_{out}q}{V} - \frac{HCHO_{in}q}{V} \tag{3.40}$$

The other constituents like VOC and dust cannot be modelled in a similar way, as they are complex elements consisting of wide variety of factors that influence their presence in air. They can assumed to be less in concentration from the outside air and more amount of fresh air intake can brought in to control the concentration so that they do not reach hazardous level for the occupants. One more possibility is to use air-purifiers indoor to reduce the dust and VOC concentration in indoor air [8].

Chapter 4

Indices of the Room

Indices includes thermal comfort index, Air quality index and index based on lighting quality. Indices on a whole for IEQ is not formulated as it doesn't fall into the scope of the project. The following sections brief overview about each index and provides a range of the index that is recommended by ASHRAE 55:2013 [5].

4.1 Thermal comfort index

The thermal comfort can be predicted by a variety of methods and one of the popular one is the PMV/PPD model that was developed by P.O. Fanger [12] using heat-balance equations and empirical studies about skin temperature to define comfort. Survey about the thermal sensation on a seven-point scale from cold (-3) to hot (+3) is conducted on occupants and they are used to get the information about user's comfort. The properties that influence the thermal comfort index include air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation.PMV is used to calculate the comfortable range from -3 to 3 based on a set of equations. PMV is recommended to be in the range between -0.5 to 0.5, which is calculated based on the six parameters mentioned above. Although predicting the temperature at which occupants are comfortable it is also essential to determine the number of dissatisfied occupants present in the room. This is calculated by Predicted percentage of Dissatisfaction, which can be useful to find if the people will be satisfied or not.

PMV value						
-3	-2	-1	0	1	2	3
Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

Table 4.1: PMV range and their comfort level

This method assumes all occupants the same. It does not consider the location and adaptation of the occupant to the temperature. It states that the room temperature should be the same irrespective of the season prevailing. This method simplifies the computation by assuming that humans do not have to adapt to different temperatures prevailing outside as the indoor temperatures are constant in which they stay most of the time.

The Predicted Mean value is given by:

$$PMV = 3.155(0.303e^{-0.114M} + 0.028)L \tag{4.1}$$

where:

M : metabolic rate per unit area in $BTU/hrft^2$

L : evaporative losses influenced by skin temperature in $BTU/hrft^2$

The evaporative loss is given by [5]:

$$\begin{aligned} L = q_{met} - f_{cl}h_c(T_{cl} - T_a) - f_{cl}h_r(T_{cl} - T_r) - 156(W_{sk,req} - W_a) \\ -0.42(q_{met} - 18.43) - 0.00077M(93.2 - T_a) - 2.78M(0.0365 - W_a) \end{aligned} \tag{4.2}$$

where:

T_{cl} : average surface temperature of the body in $^{\circ}F$

f_{cl} : ratio of clothed surface area to DuBois surface area

R_cl : effective thermal resistance (R-value) of clothing $ft^{2\circ}Fhr/BTU$

T_a : Temperature of the room in $^{\circ}F$

h_c :convection heat transfer coefficient in $BTU/hrft^{2o}F$

T_r : Mean radiant Temperature of the room in ^oF

h_r :radiative heat transfer coefficient in $BTU/hrft^{2o}F$

W_a : Humidity ratio

W_{sk} : saturated Humidity ratio at skin temperature predicted The DuBois surface area is given by:

$$Surfacearea_{DuBois} = 0.20247(height)^{0.725}(weight)^{0.425} \tag{4.3}$$

The following are the approximations to be taken:

$$f_{cl} = \begin{cases} 1.0 + 0.2I_{cl} I_{cl} < 0.5clo \\ 1.05 + 0.1I_{cl} I_{cl} > 0.5clo \end{cases} \tag{4.4}$$

$$h_c = max \begin{cases} 0.361(T_{cl} - T_a)^{0.25} \\ 0.151\sqrt{V} \end{cases} \tag{4.5}$$

$$h_r = 0.7BTU/hrft^{2o}F \tag{4.6}$$

The predicted percentage of dissatisfaction is given by:

$$PPD = 100 - 95exp(-0.03353PMV^4 - 0.2179PMV^2) \tag{4.7}$$

The PMV/PPD is theoretical method of prediction of the thermal comfort value rather than continuously adapting to the user's response. But this method has been widely accepted to understand the thermal comfort of the occupants.The relationship between PMV and PPD is given by the graph with a inverted Gaussian structure:

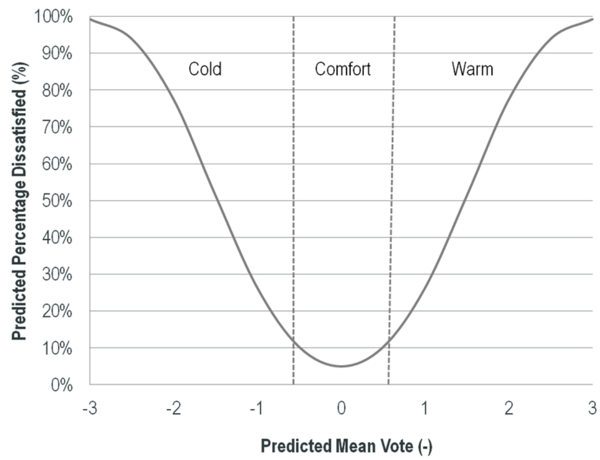


Figure 4.1: Relationship between PMV and PPD [5]

4.2 Air Quality Index

It is the most common index used in the predicting the pollution in outdoor air. Singapore uses it by the name Pollutant Standards Index(PSI). It is unit-less number that gives a scope of the pollution prevalent in the area for the people to decide if it is safe to continue to be in that area or any other precaution is necessary for stay. The Air quality Index is given by:

$$AQI = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}(C - C_{low}) + I_{low} \tag{4.8}$$

where:

AQI :The Air Quality Index

C :Pollutant Concentration

C_{low} :Concentration break-point that is $\leq$ C

C_{high} :Concentration break-point that is $\geq$ C

I_{high} :Index break-point corresponding to C_{high}

I_{low} :Index break-point corresponding to C_{low}

C_{low} - C_{high} (avg)		AQI	AQI
$O3(ppb)(8-hr)$	$O3(ppb)(1-hr)$	$I_{low}-I_{high}$	Category
0-54	-	0-50	Good
55-70	-	51-100	Moderate
71-85	125-164	101-150	Unhealthy
86-105	165-204	151-200	
106-200	205-404	201-300	Very Unhealthy
-	405-504	301-400	Hazardous
-	505-604	401-500	

Table 4.2: Ozone range of concentrations versus AQI [5]

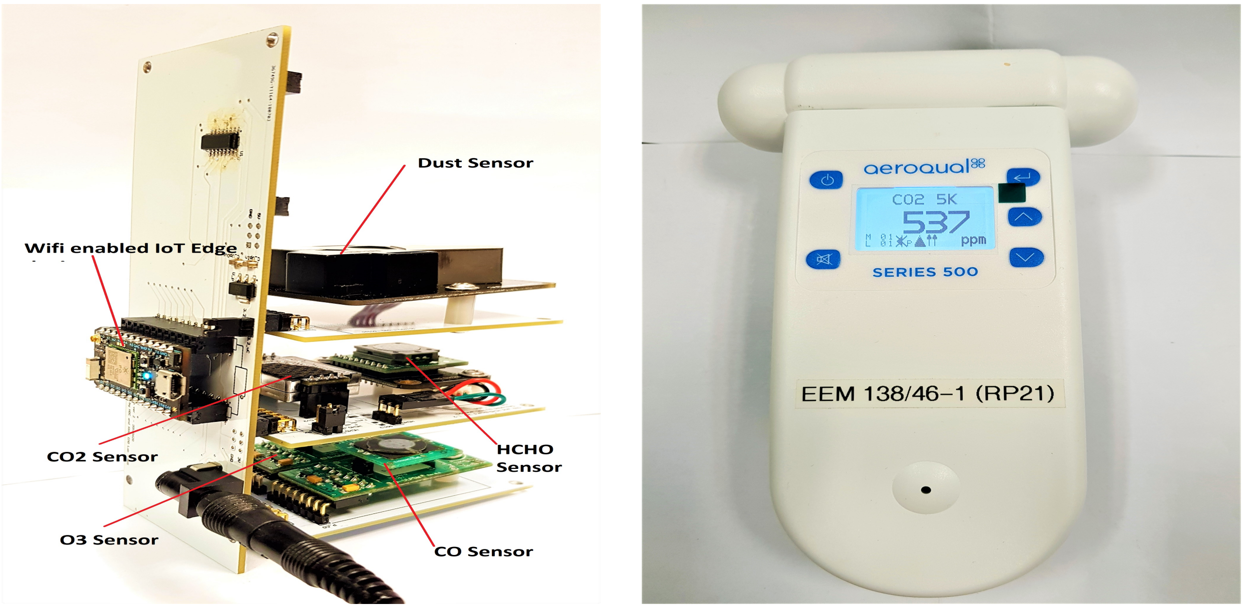
C_{low} - C_{high} (avg)			AQI	AQI
$PM2.5(\mu g/m3)$	$PM10(\mu g/m3)$	$CO(ppm)$	$I_{low}-I_{high}$	Category
0.0-12.0	0-54	0.0-4.4	0-50	Good
12.1-35.4	55-154	4.5-9.4	51-100	Moderate
35.5-55.4	155-254	9.5-12.4	101-150	Unhealthy
55.5-150.4	255-354	12.5-15.4	151-200	
150.5-250.4	355-424	15.5-30.4	201-300	Very Unhealthy
250.5-350.4	425-504	30.5-40.4	301-400	Hazardous
350.5-500.4	505-604	40.5-50.4	401-500	

Table 4.3: Carbon monoxide and Dust range of concentrations versus AQI [5]

4.2.1 Sensor Array

In order to find the concentration of gases in the FEC2 room, sensor-array with CO_2 , CO , O_3 , $HCHO$, VOC and $Dust$ sensors where used to find the concentration of these gases. The sensor-arrays was made in-house and it was first compared to a Aero-qual commercial grade sensor for testing the performance of the in-house sensors. The data was collected for a few days before comparison of the two datasets.

CO_2 data collection Sensor used for measuring the concentration of CO_2 was SenseAir-S8 CO_2 sensor. This sensor is a low cost sensor that can measure CO_2 in the range 0-20000 ppm. But below 400ppm erroneous readings are a possibility. The graph 4.3 shows a comparison between the SenseAir S8 CO_2 sensor and Aeroqual CO_2 sensor.



(a) Sensory Array (b) Aero-qual commercial grade sensor

Figure 4.2: Sensors used in data collection

CO **data collection** Sensor used for measuring the concentration of CO was SPEC CO sensor. This sensor is a low cost sensor that can measure CO in the range 0-1000 ppm. Aeroqual CO sensor was used during the same period for the comparison with a range of 0-100 ppm. The Figure4.4 shows a comparison between the SPEC CO sensor and Aeroqual CO sensor.

O_3 **data collection** Sensor used for measuring the concentration of O_3 was SPEC O_3 sensor. This sensor is a low cost sensor that can measure O_3 in the range 0-5 ppm. Aeroqual O_3 sensor was used during the same period for the comparison with a range of 0-0.5ppm. The graph 4.5 shows a comparison between the SPEC O_3 sensor and Aeroqual O_3 sensor.

$HCHO$ **data collection** Sensor used for measuring the concentration of $HCHO$ was DF-Robot $HCHO$ sensor. This sensor is a low cost sensor that can measure $HCHO$ in the range 0-5 ppm. Aeroqual $HCHO$ sensor was used during the same period for the comparison with a range of 0-10 ppm. The graph 4.6 shows a comparison between the DF-Robot $HCHO$ sensor and Aeroqual $HCHO$ sensor.

$PM10$ and $PM2.5$ data collection Sensor used for measuring the concentration of $PM10$ was SW-PWM-01C *Dust* sensor. This sensor is a low cost sensor that can measure $PM10$ and $PM2.5$ in the range 0-3000 $\mu g/m^3\dot{A}$eroqual *Dust* sensor was used during the same period for the comparison with a range of 0-ppm. The graph 4.7 and 4.8 shows a comparison between the SW-PWM-01C *Dust* sensor and Aeroqual *Dust* sensor.

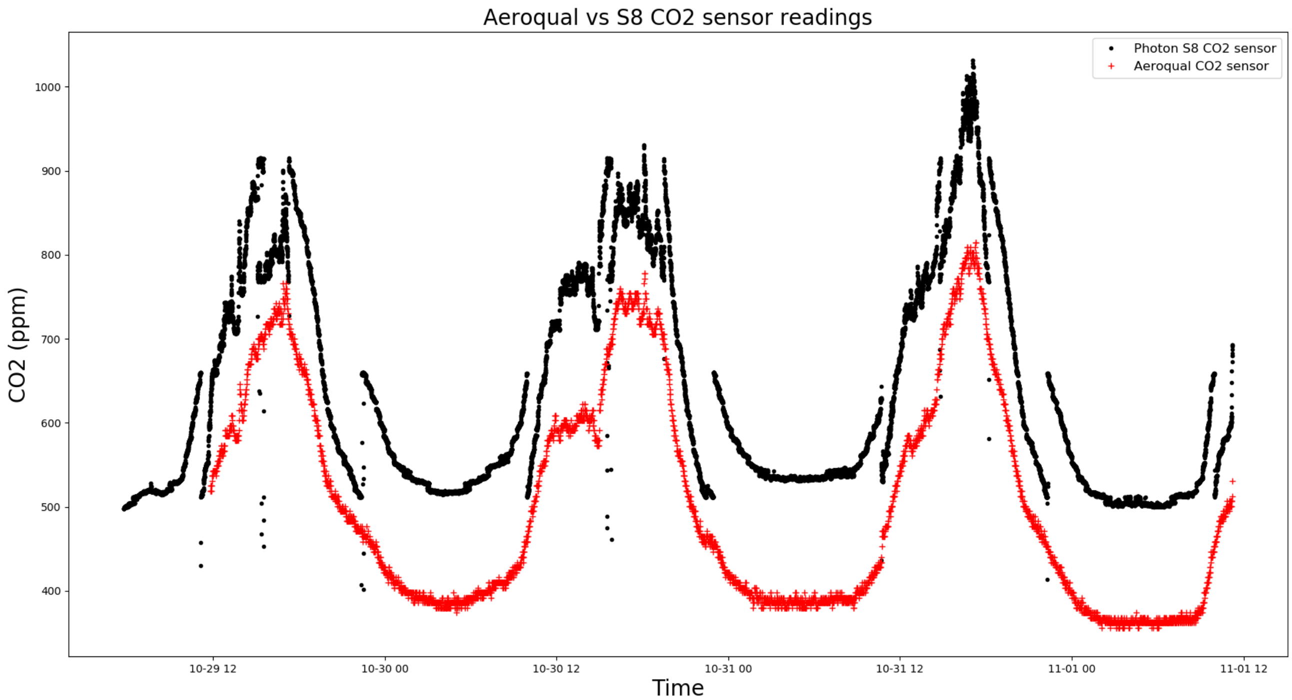


Figure 4.3: Aeroqual CO_2 versus SenseAir S8 CO_2 sensor

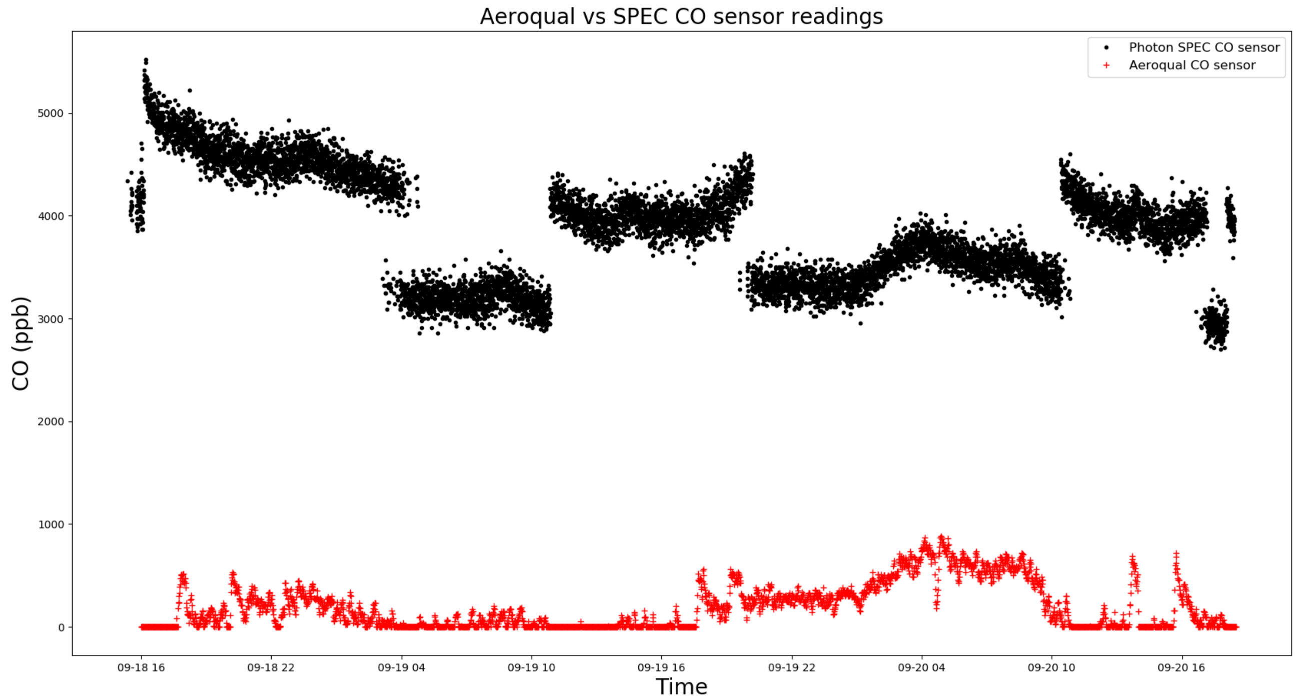


Figure 4.4: Aeroqual CO versus SPEC CO sensor

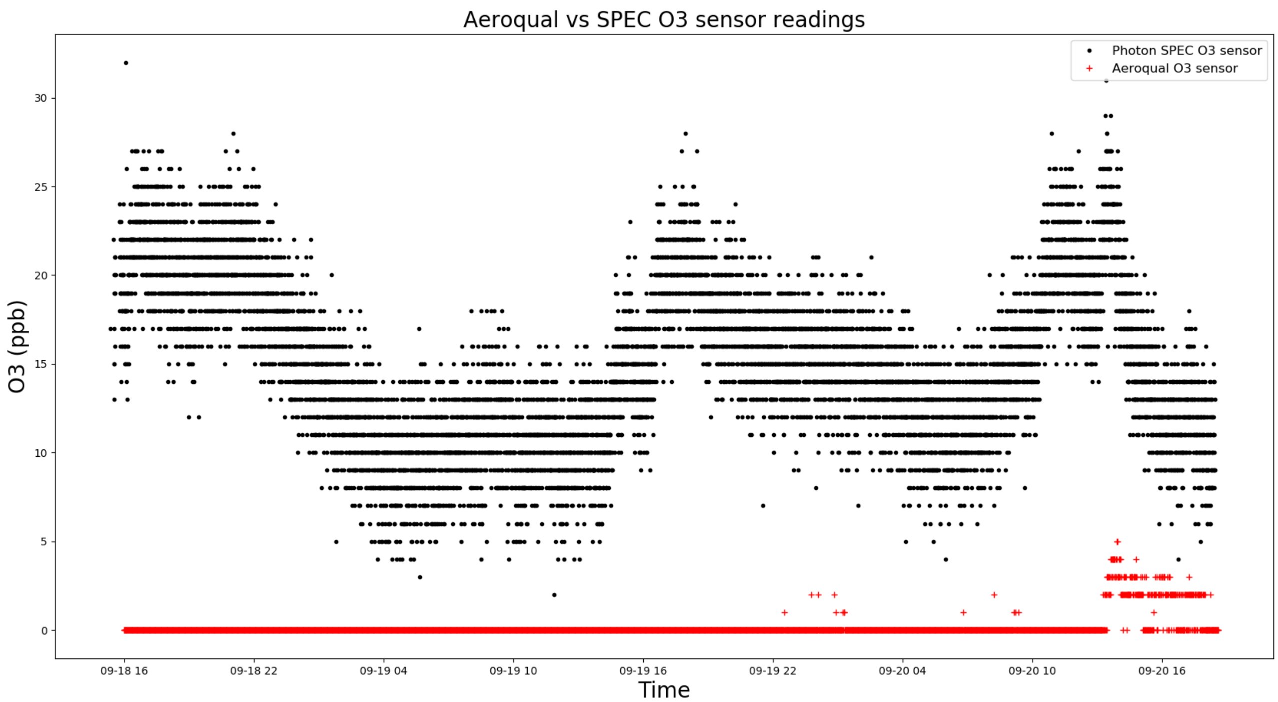


Figure 4.5: Aeroqual O_3 versus SPEC O_3 sensor

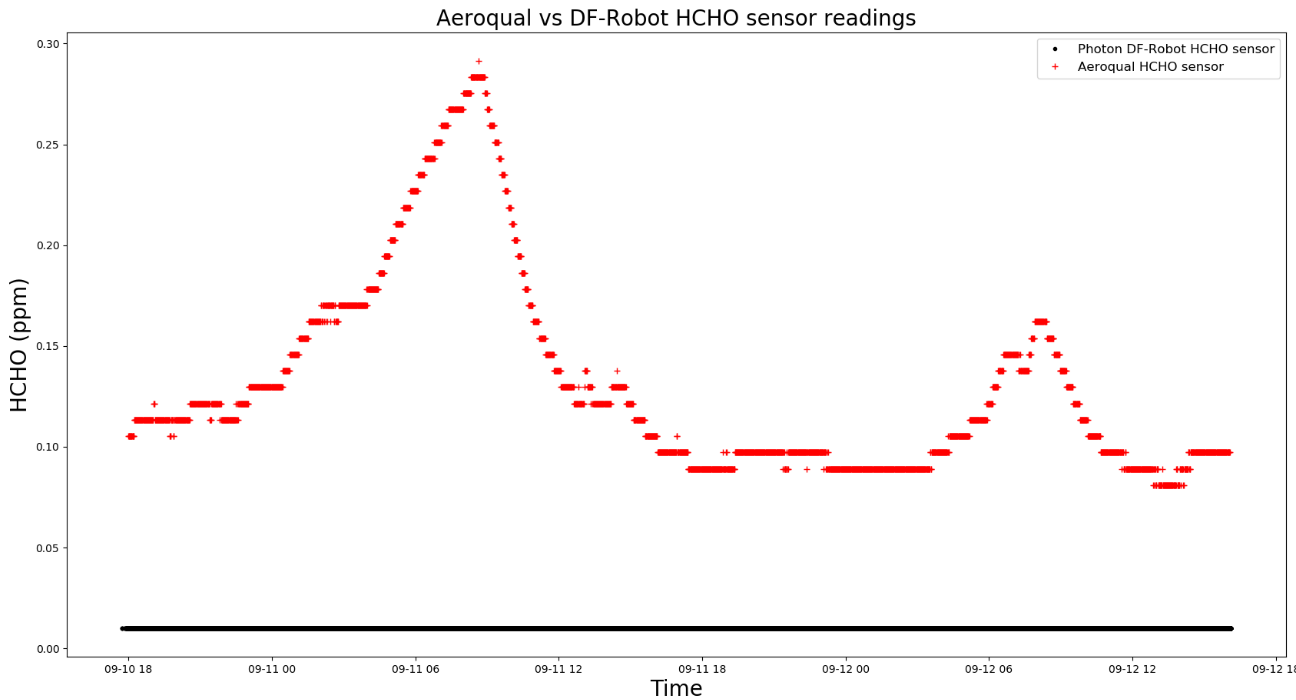


Figure 4.6: Aeroqual $HCHO$ versus DF-Robot $HCHO$ sensor

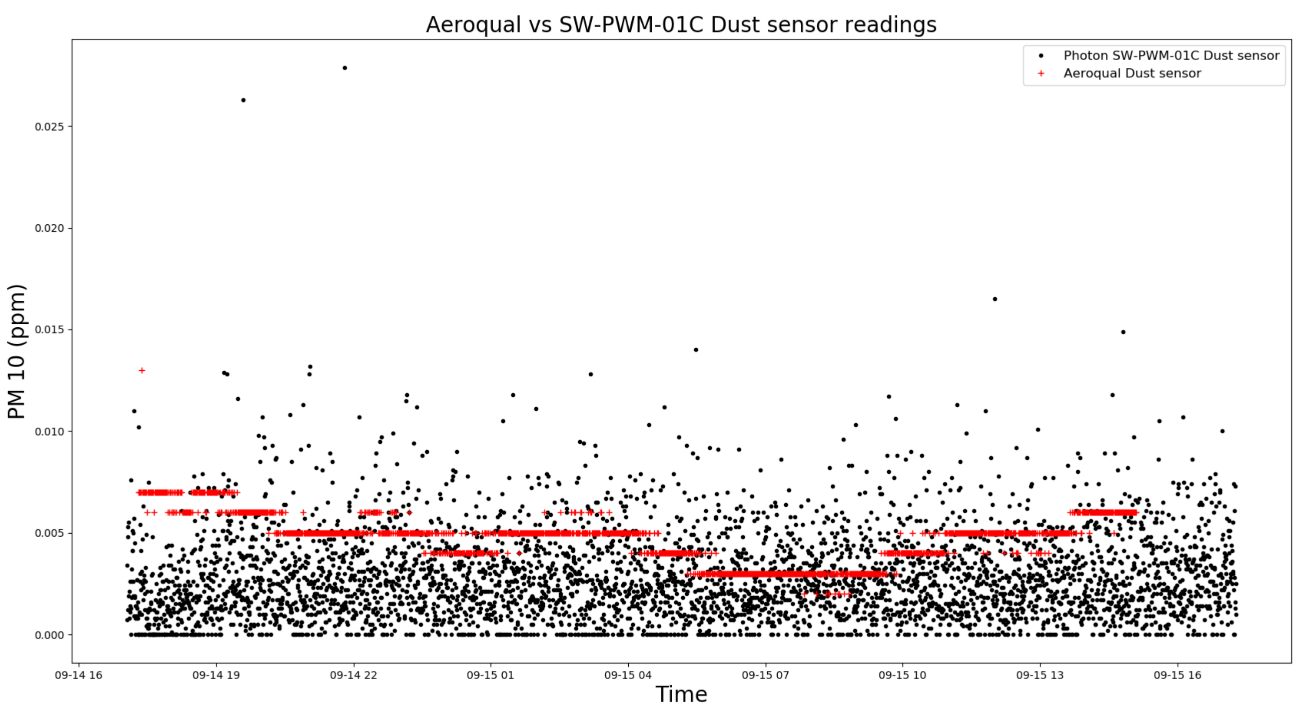


Figure 4.7: Aeroqual $PM10$ versus SW-PWM-01C $PM10$ sensor

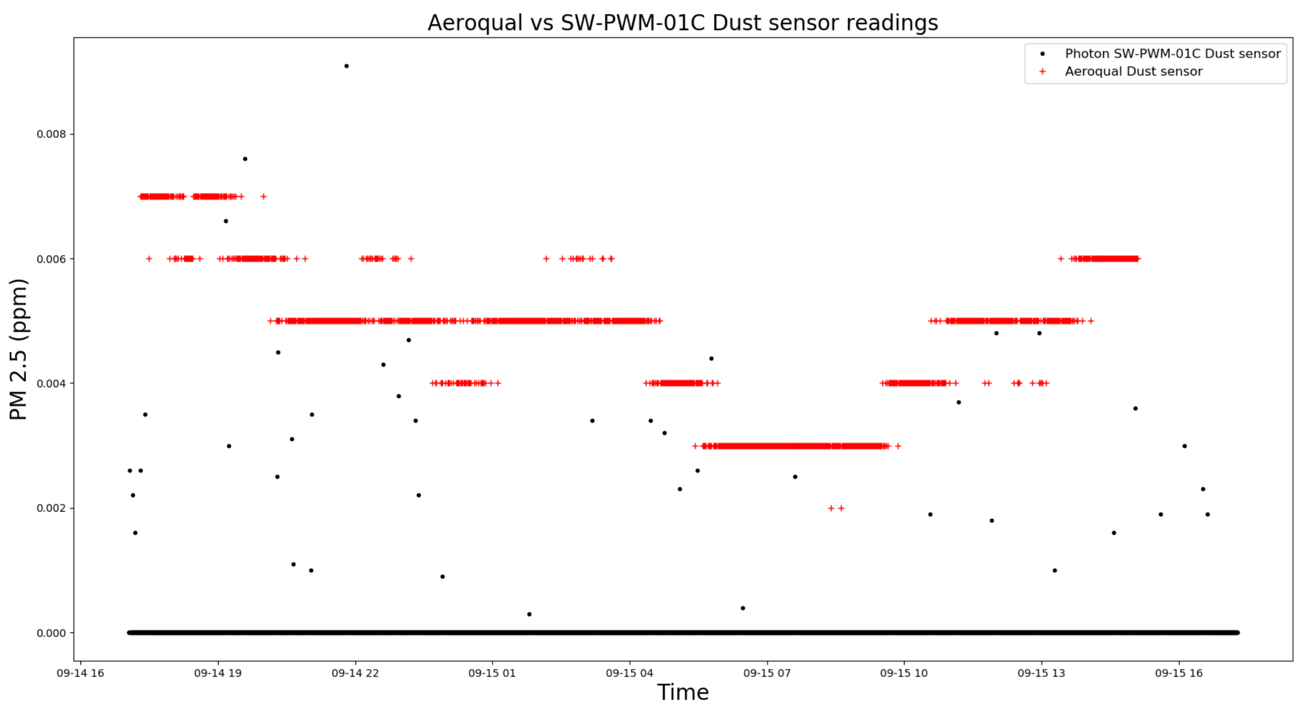


Figure 4.8: Aeroqual $PM2.5$ versus SW-PWM-01C $PM2.5$ sensor

4.3 Lighting Quality and Light Map for the room FEC2

The lighting quality prescribed by [20] International Association of Light Designers is about 500 lux. From the standards stated by [6], an index for lighting quality is defined in the range of 0 to 100 where 0 shows that the place is optimum lit and 100 shows it is either too dark or too bright. The measurement of light was taken at 204 points in the FEC2 in lux. At each point the index corresponding to the level of light is calculated and shown in Figure:4.11. The index is calculated as follows:

$$LightingIndex = \frac{I_{high} - I_{low}}{L_{high} - L_{low}}(L - L_{low}) + I_{low} \tag{4.9}$$

where:

$LightingIndex$:The Lighting Quality Index

L :Intensity of Light at the point

L_{low} :Intensity of Light break-point that is $\leq$ L

L_{high} :Intensity of Light break-point that is $\geq$ L

I_{high} :Index break-point corresponding to L_{high}

I_{low} :Index break-point corresponding to L_{low}

The higher shade of blue indicates a comfortable region of the room whereas the higher shade of red indicates that the region is not comfortable. In Figure:4.10, the bright white indicates that it is too bright and black indicates it is too dark, the optimum level of lighting is represented by red shade. Level of lighting mean value is given below:

Lighting Level Mean value				
-2	-1	0	1	2
Dark	Slightly Dark	Neutral	Slightly Bright	Bright

Table 4.4: Lighting comfort level

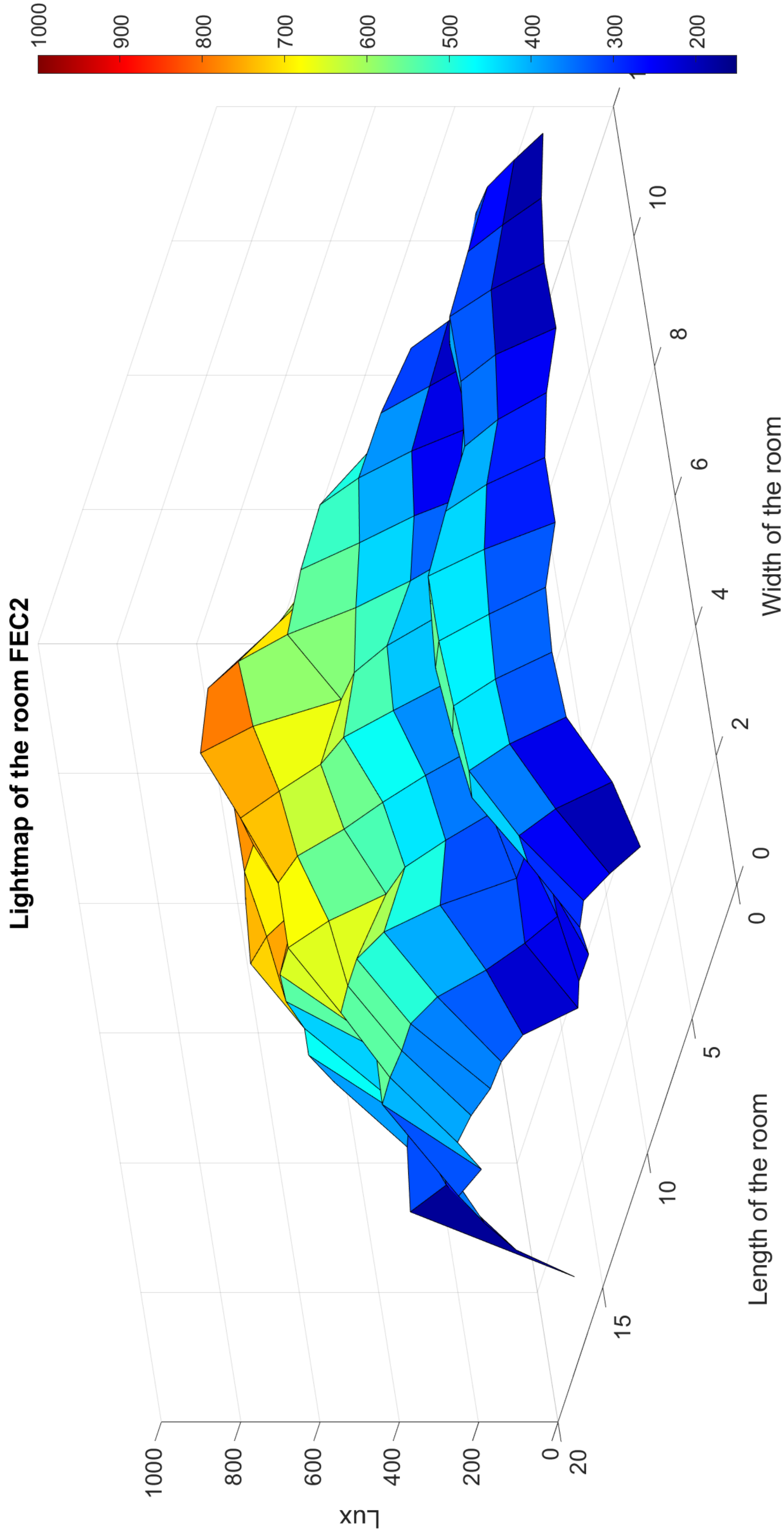


Figure 4.9: Light map of FEC2 room

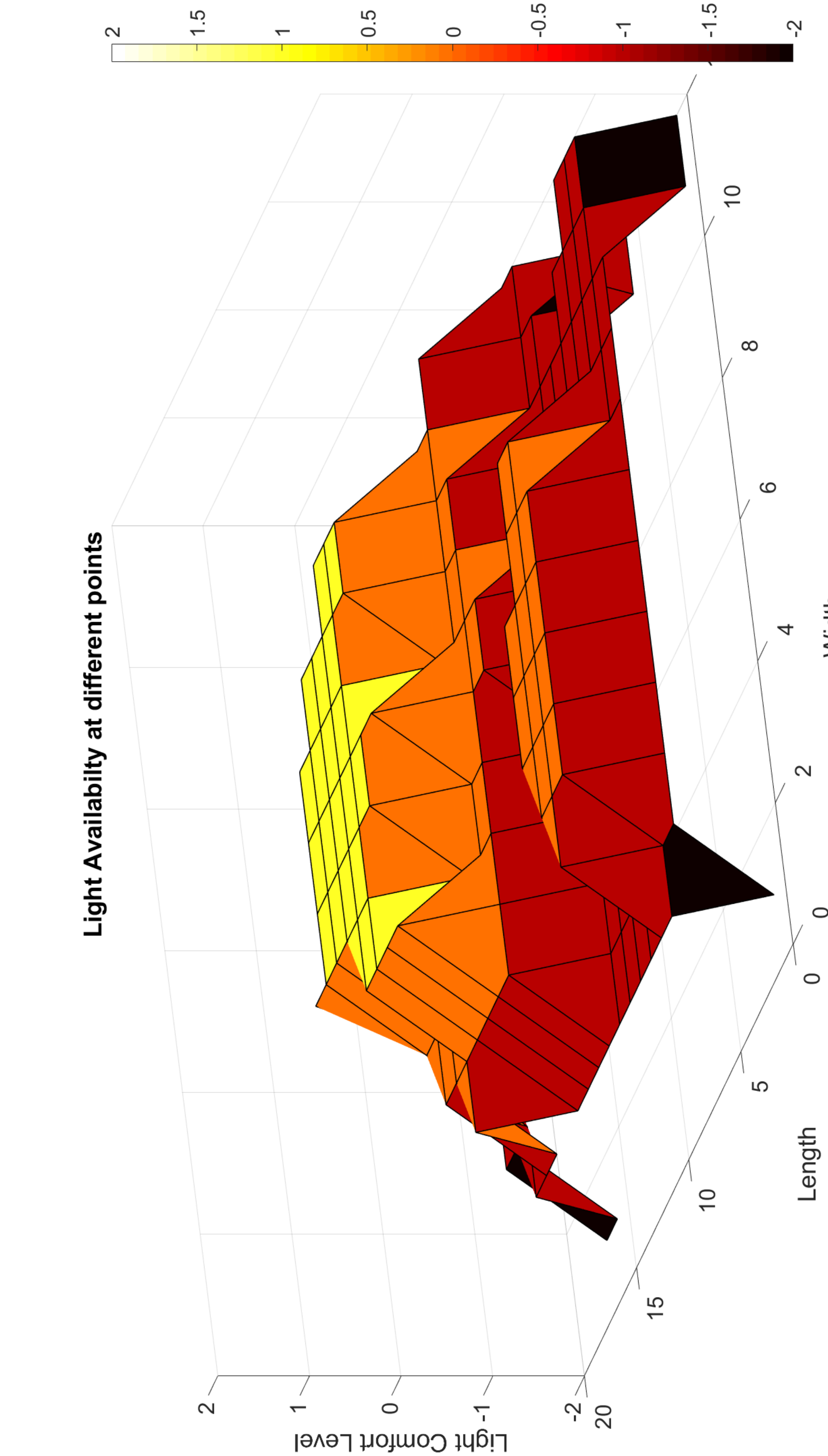


Figure 4.10: Lighting level ranked from -2 to 2

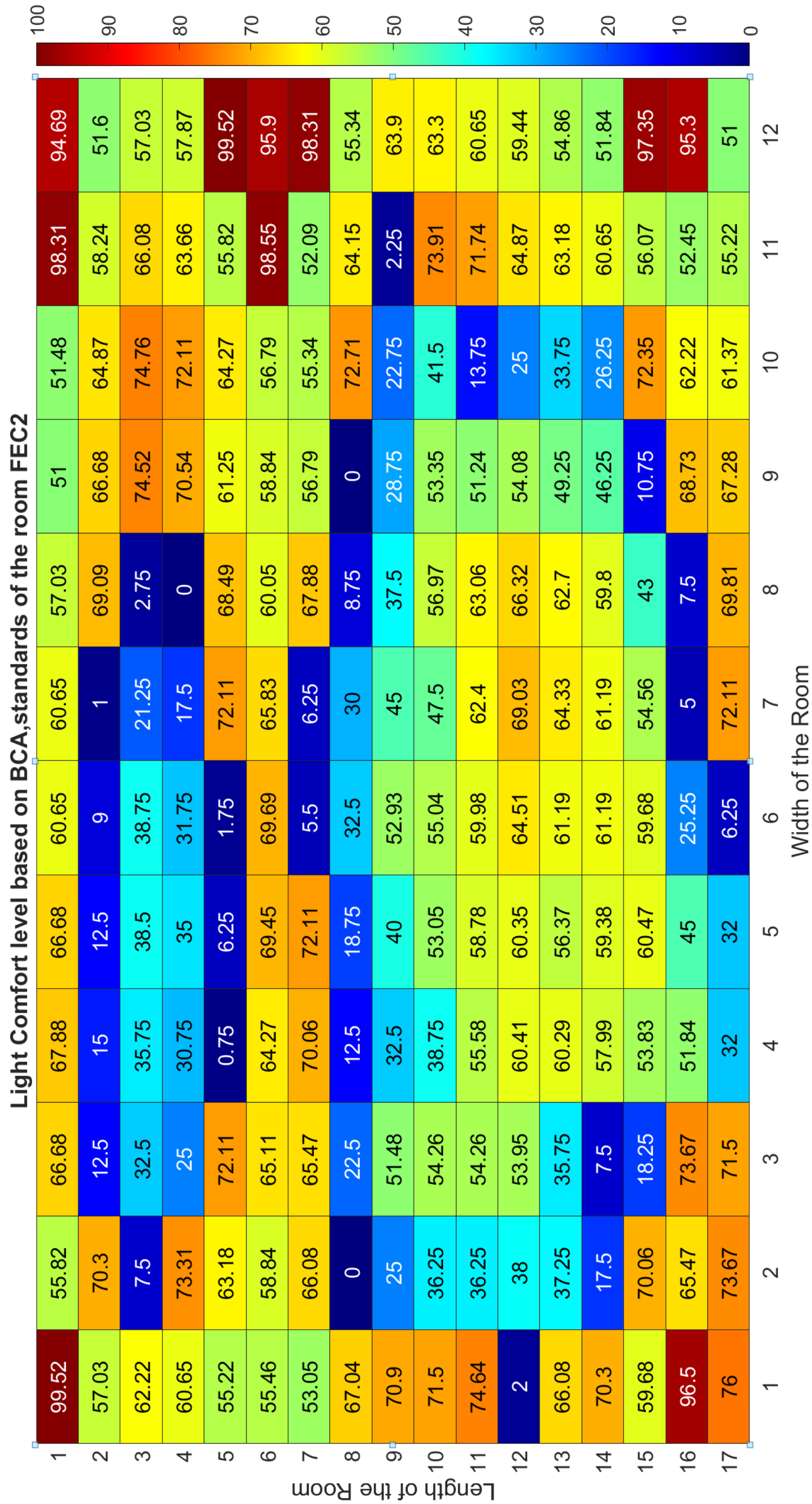


Figure 4.11: Lighting Index based on BCA standards, Singapore

Chapter 5

Simulation, Results and Discussion

The simulation was done in MATLAB Simulink environment with GUI to vary the different variables of the system. The Figure 5.1 shows the layout of the interface:

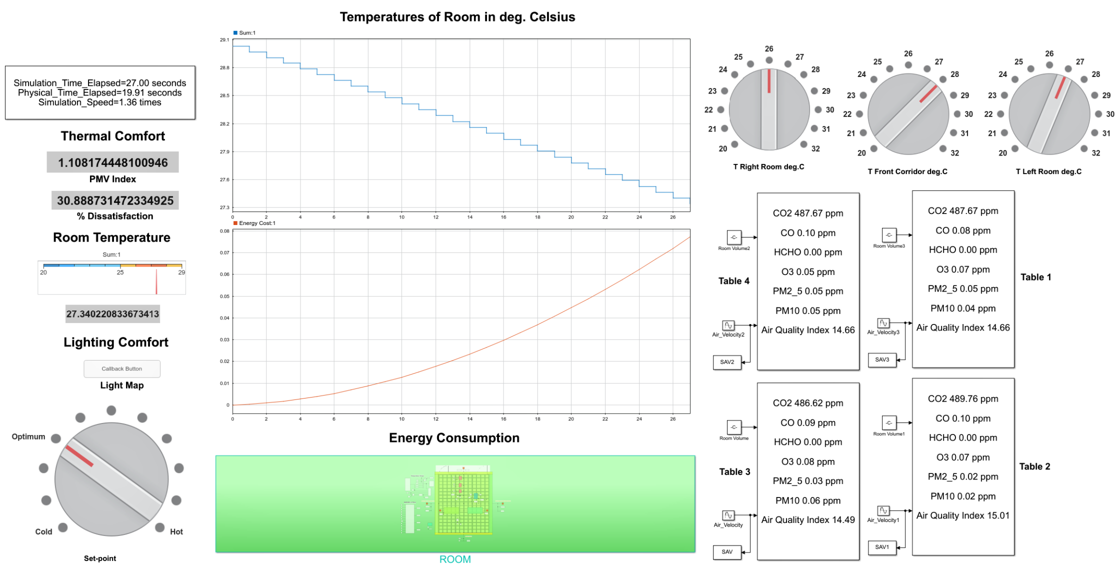


Figure 5.1: MATLAB Simulink Inerface

MATLAB model of the room under consideration is shown in Figure: 5.2. The colour of the element represents the external temperature the element is subjected to. In the simulation the external temperatures of the left side, front side, right side, the roof and the floor are kept to be constant since they are the walls in between two rooms and temperature in those rooms do not change considerably as outside. The floor temperature is taken as

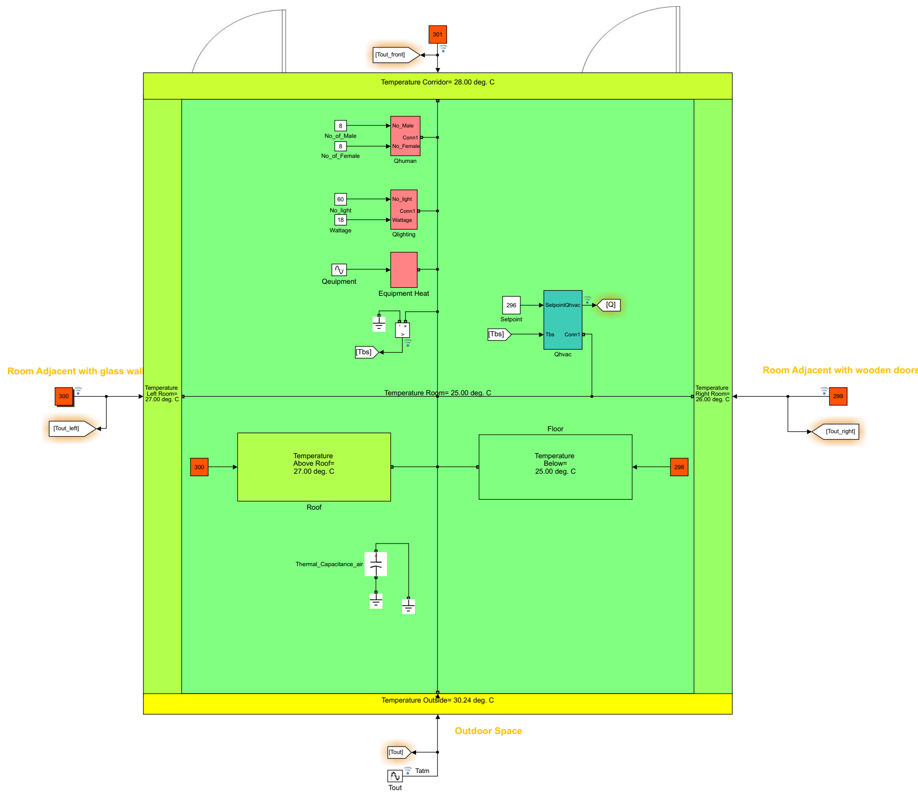


Figure 5.2: MATLAB Simulink model of the room

a constant since the room is not located at the ground level for the effect of radiation to change its temperature. The Figure: 5.3 shows the variation of temperatures affecting the room and also the room temperature for period of a day. The temperature variation prevalent outside as seen in Figure 3.6 is represented closely by the sine wave function represented in the Figure 5.3. The outside temperature variation in Singapore ranges between 29^oC to 31^oC which varies like a sine wave. The Figure: 5.4 shows the variation in the various heat gains in the room along with heat removed by the ACMV system. The heat removed by the ACMV system is based on the minimum capacity of cooling load needed to cool the room that was calculated by Cooling load calculation. Thermal comfort index prescribed by ASHRAE 55:2013 was also implemented and Predicted Mean Value and Predicted Percentage of Dissatisfaction where found out various temperature variations. This method has been the most prescribed method for Thermal comfort calculation. Air Quality index was also calculated for variations across 4 tables present in the room. The variations in the air constituents where also modelled by the differential equation governing them and not direct measurement since it involves data collection by subjecting 16 occupants to work in then room throughout the day which is out of scope for this project. The Figure 5.5 shows the concentration of gases present in the room at table 1. The Figure 5.6 shows the indoor and outdoor CO_2 variation. The remaining Figure from 5.7 to 5.10 show the various quality indices over a period of time.The Figure 5.11 gives the total energy utilzation over time.

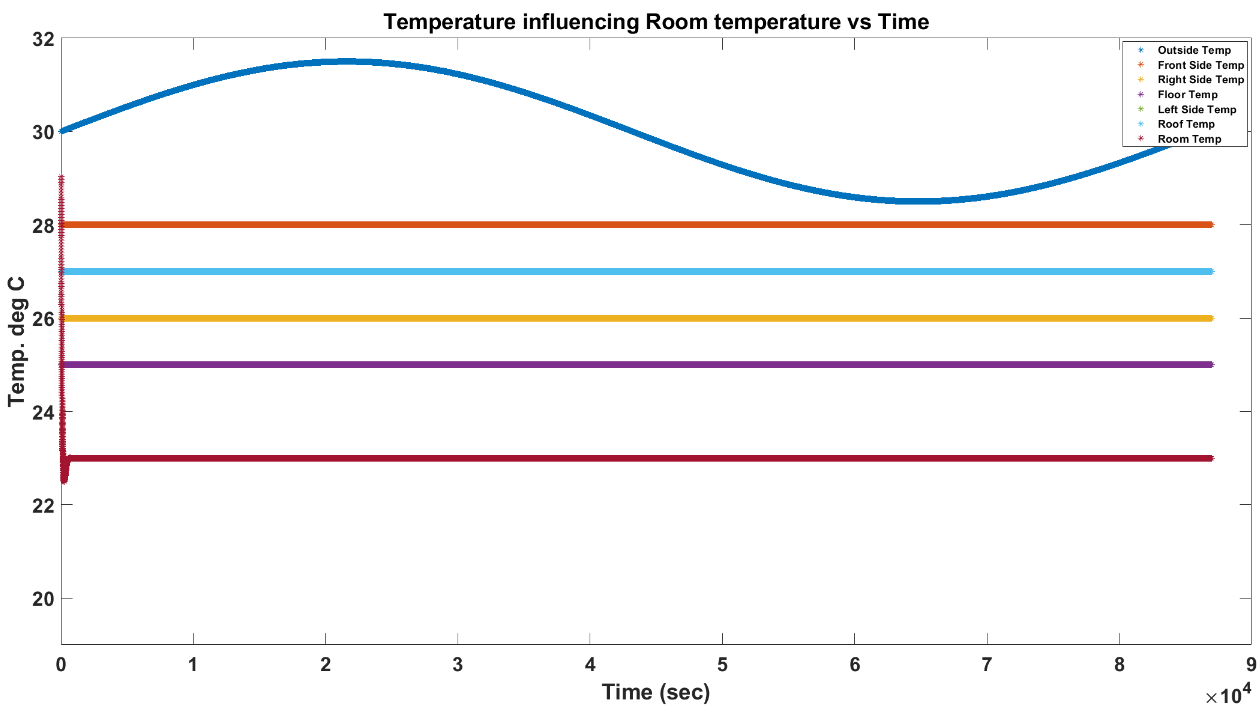


Figure 5.3: Simulated Temperature Variations in the room

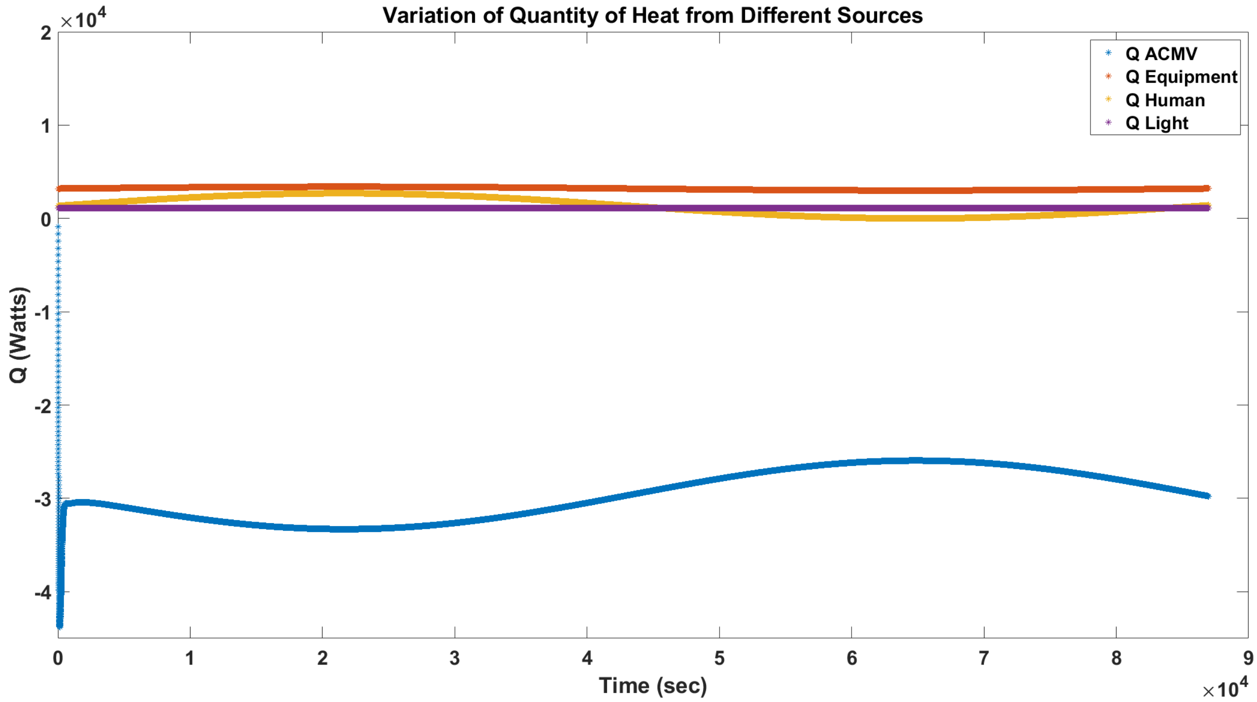


Figure 5.4: Simulated Variation of Heat gain vs time in FEC2

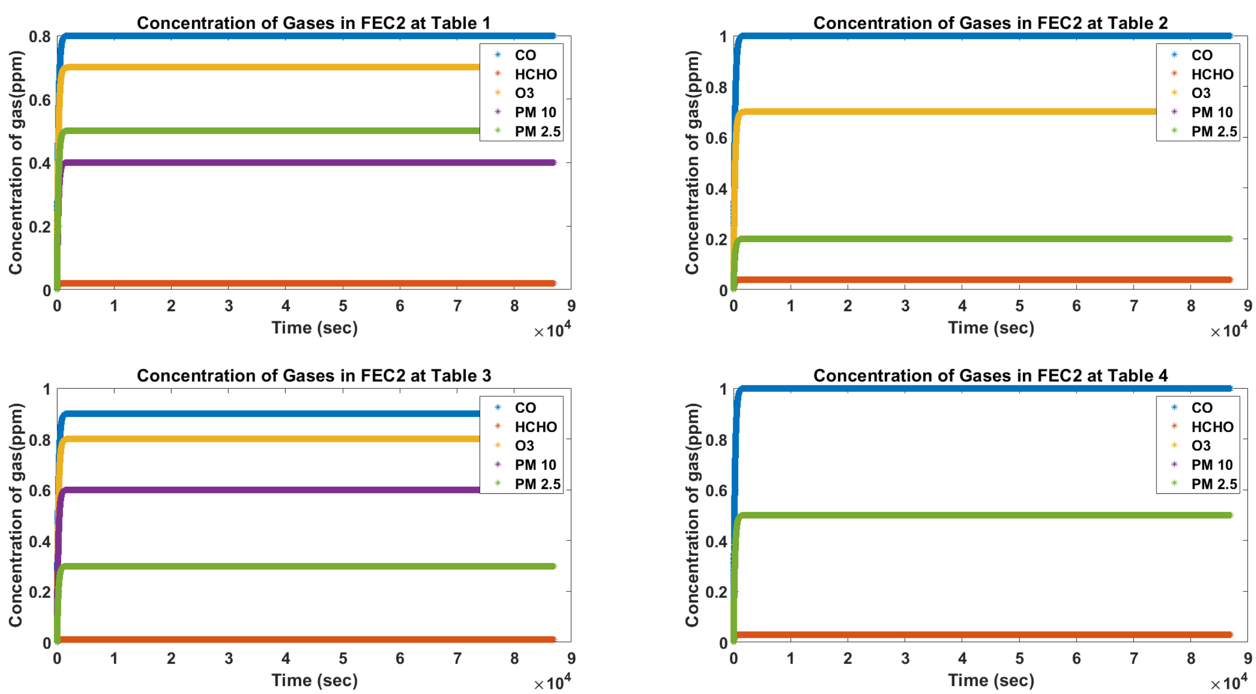


Figure 5.5: Simulated Variation of Concentration of gases in FEC2

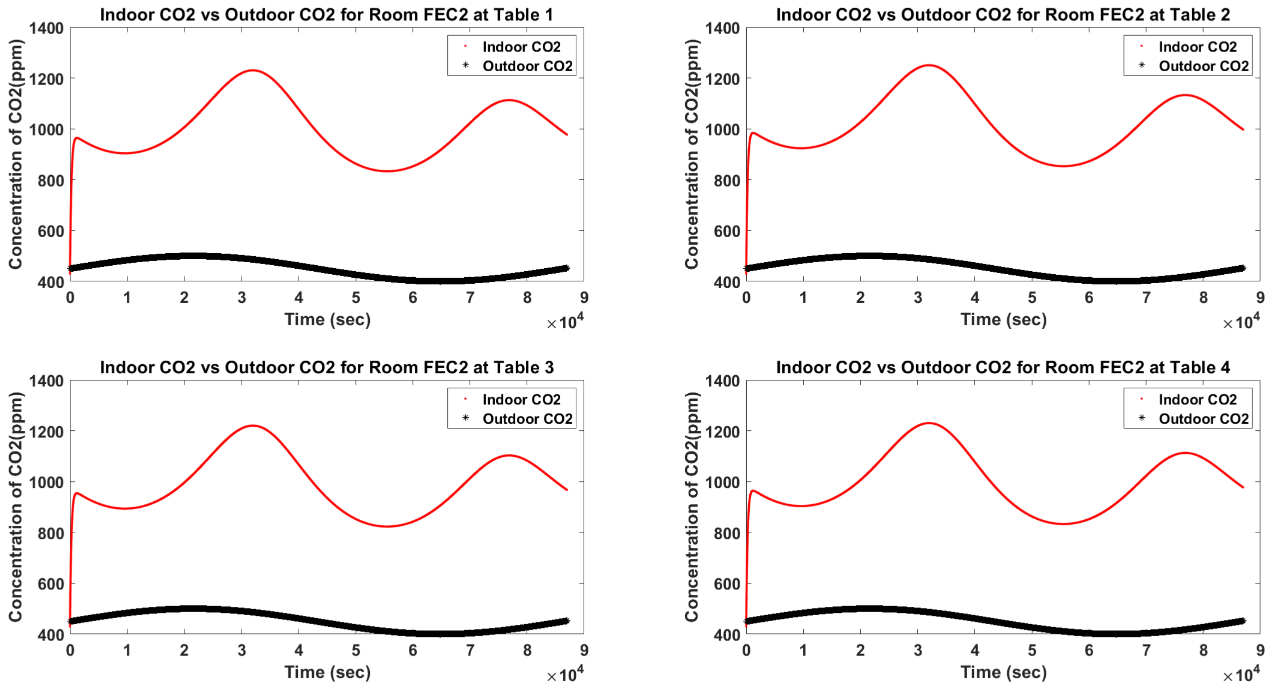


Figure 5.6: Simulated Indoor CO2 vs Outdoor CO2 in room FEC2

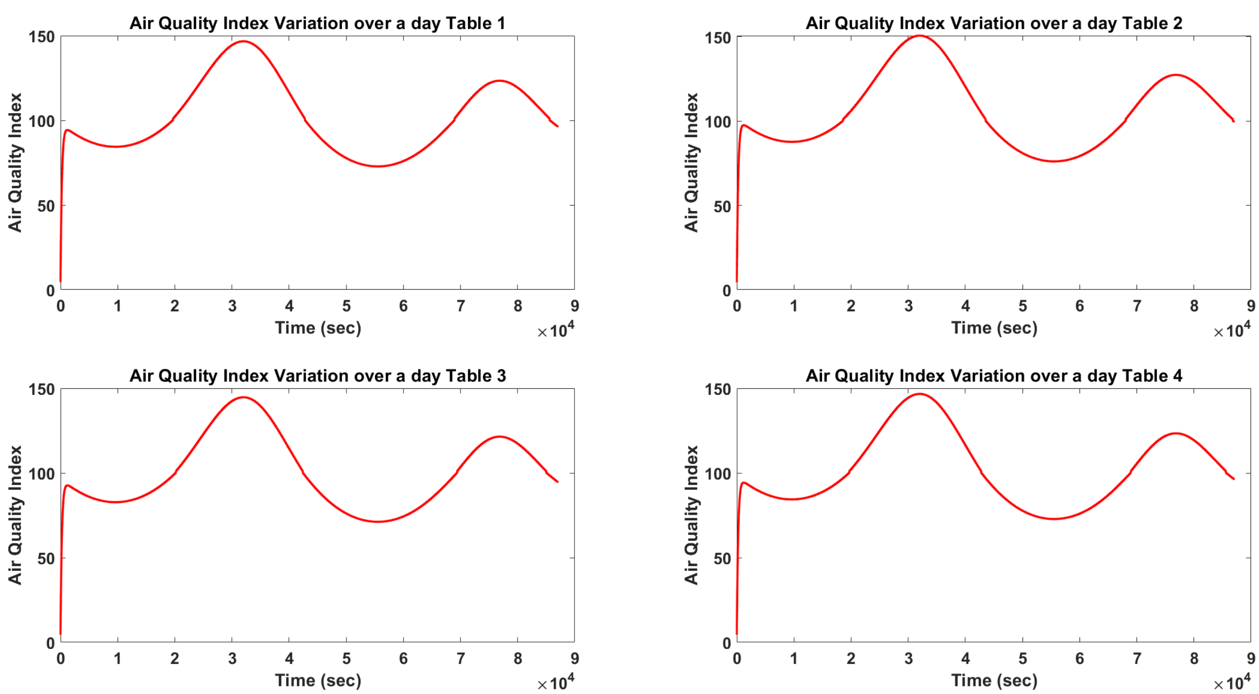


Figure 5.7: Simulated Variation of Air Quality Index in room FEC2

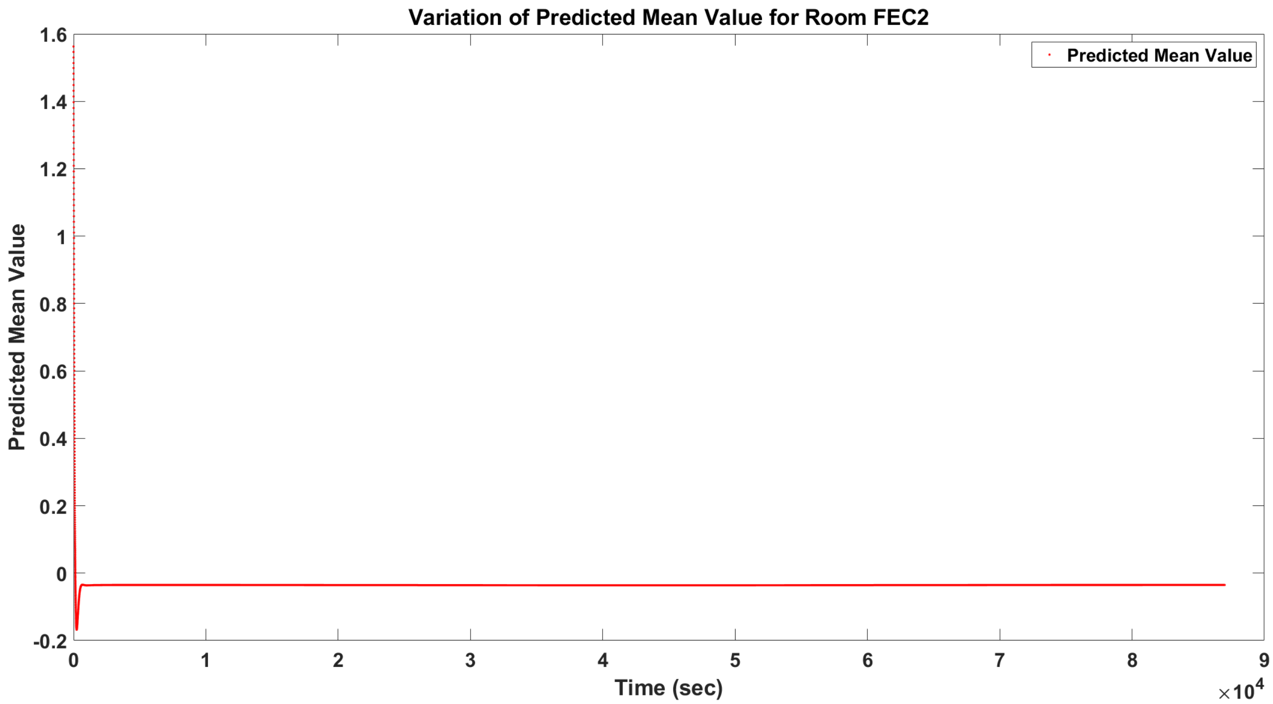


Figure 5.8: Predicted Mean Value vs Time

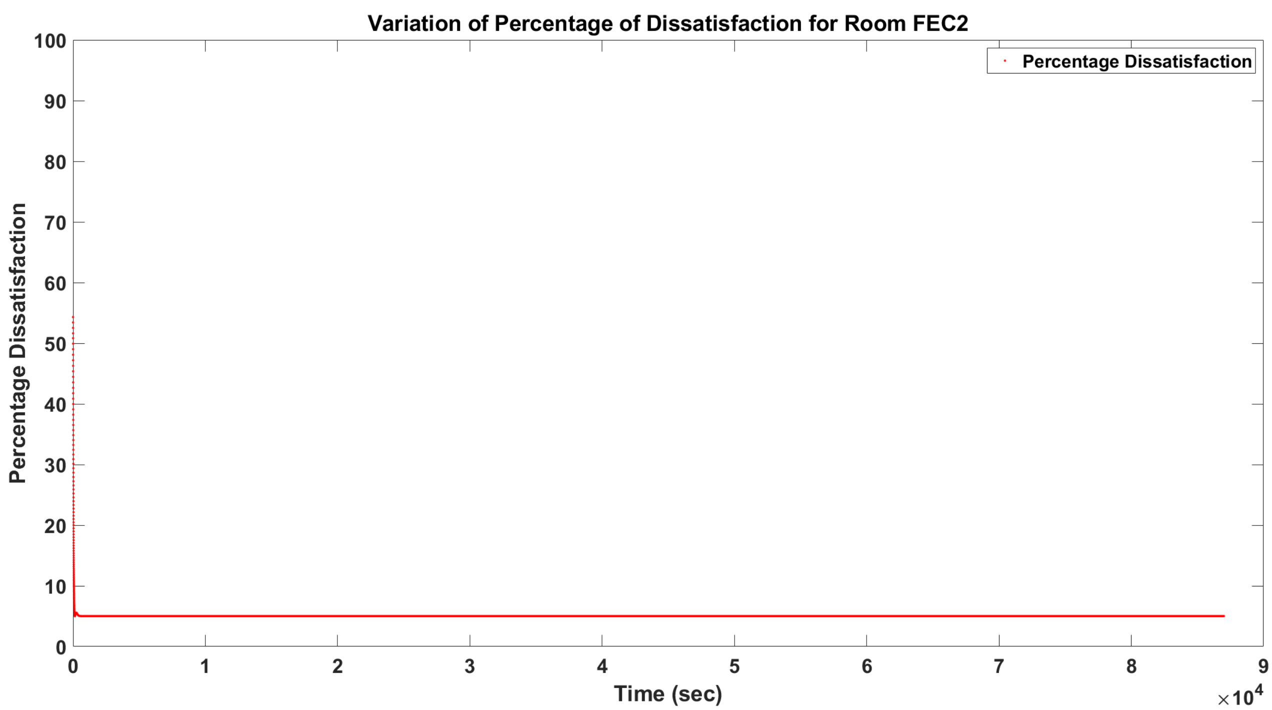


Figure 5.9: Predicted Percentage of Dissatisfaction

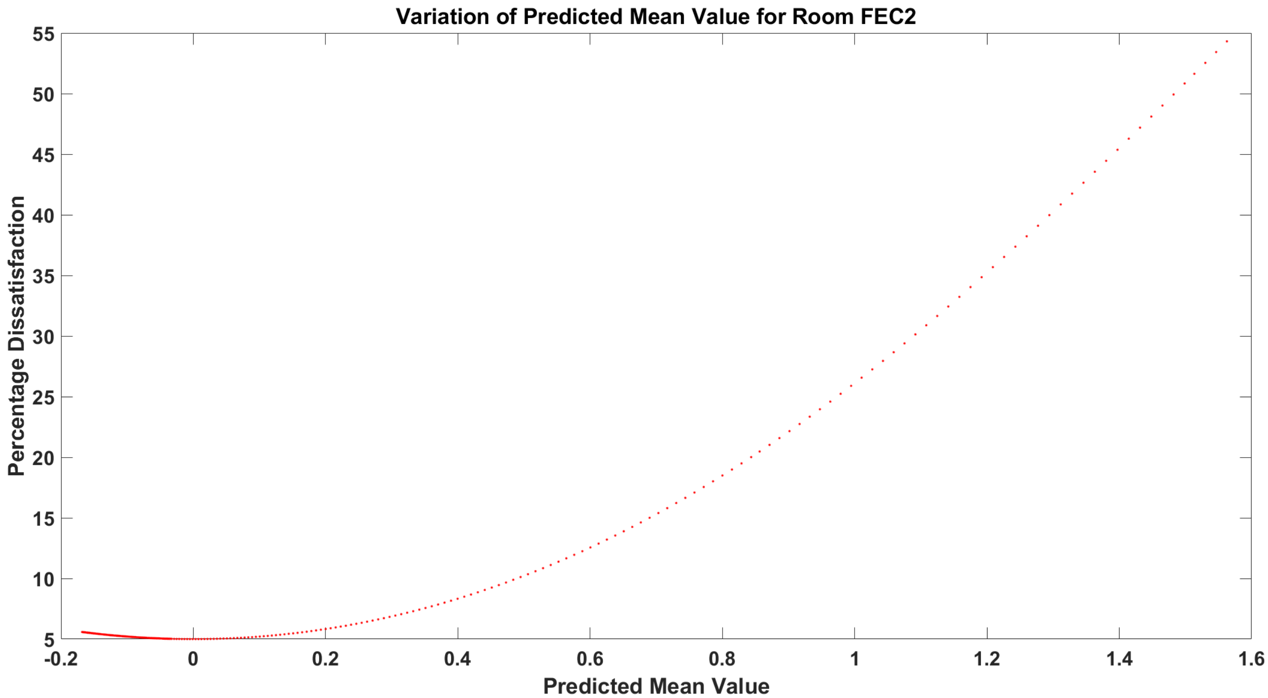


Figure 5.10: Predicted Mean Value vs Predicted Percentage of Dissatisfaction

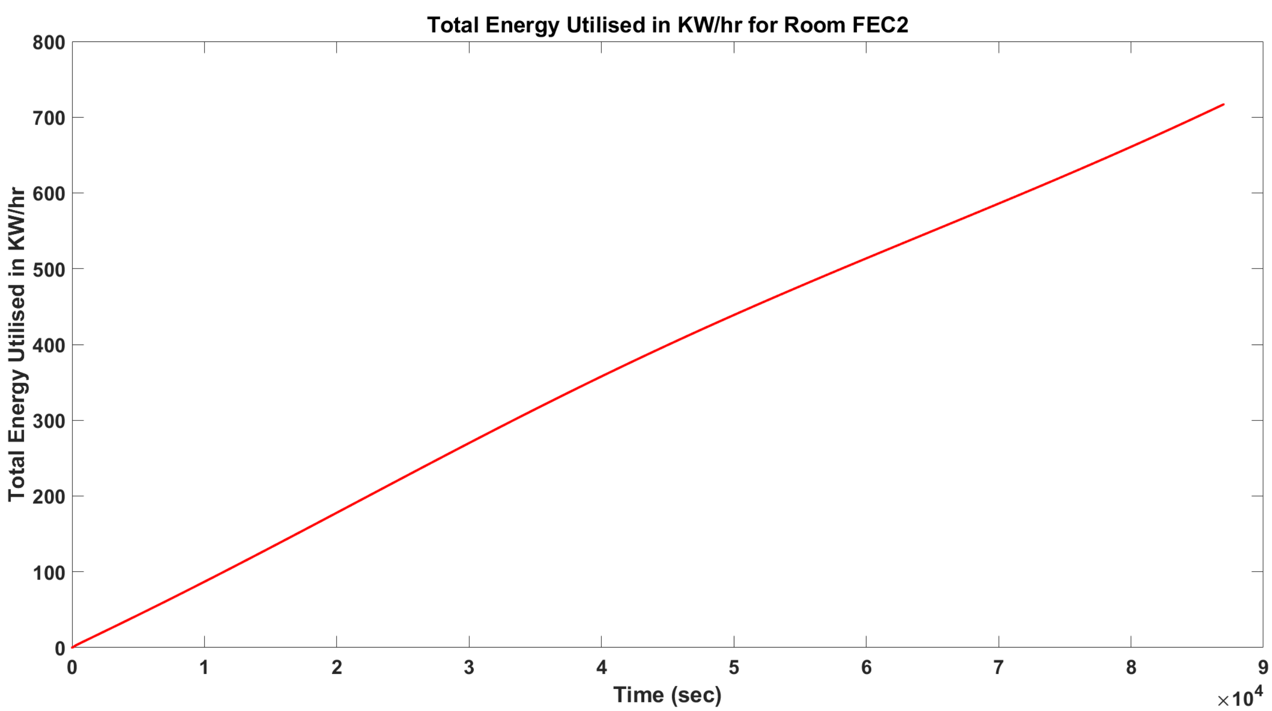


Figure 5.11: Total energy utilization in a day

Chapter 6

Conclusion

In this project, integration of several subsystems in the room were modelled and then integrated to function as a whole system. The design that was made was based on certain assumption that could simplify a very complex system like that of a room to be computationally efficient and easy to analyze. The quality index involving thermal,air quality and lighting were computed for different points of the room using the standards set by BCA, Singapore and Ministry of Environment, Singapore. As the project scope was limited to the integration of several subsystems to work as real model, the ACMV system was modelled based on the cooling load calculation and not on the derived model by testing the real ACMV system that was installed in the room. A MATLAB simulink user interface was also created for the user to give the temperature inputs and also have a glimpse of the quality indices present in the room with the energy consumption.

Future work may involve the development of a mobile application for each user to input his/her comfort level in the room and there by change the personalized conditions accordingly.

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