EE5003: Project Presentation on 15.November.2018

Multi agent Assisted Indoor Environmental Quality (IEQ) for Smart Buildings

Guided by
Assoc. Prof. Dr. Sanjib Kumar Panda
Electrical and Computer Engineering Department

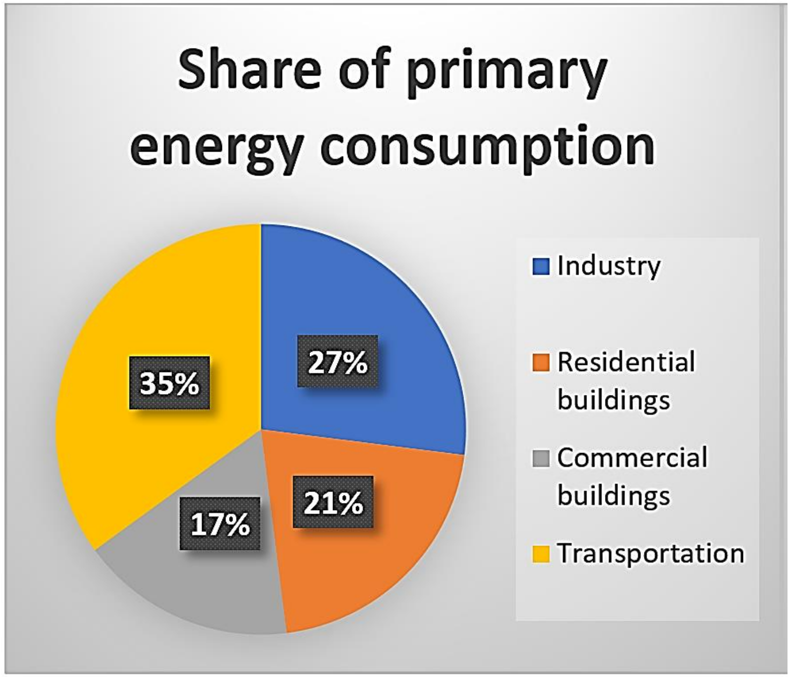
Presented by
Aravind Madan Mohan
e0154145@u.nus.edu

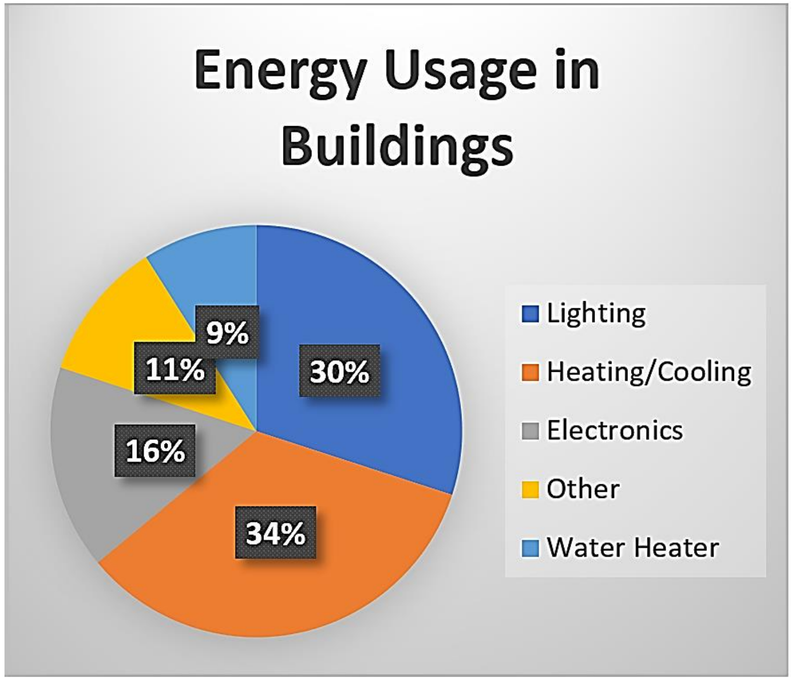
National University of Singapore

Contents

Background and Motivation

- In urbanized areas most humans spend majority of their time indoors.
- Buildings consume 39% of energy and HVAC systems and Lighting account for 64% of it.





https://www.seas.ucla.edu/~pilon/PCMIntro.html ; Ioan Susnea, Emilia Pecheanu, Adina Cocu, and Goran Hudec. Improved occupancybased solutions for energy saving in buildings. In Electrical and Electronics Engineering (IEEE), 2017 5th International Symposium on, pages 1–5. IEEE, 2017.

Background and Motivation

- Closed environments – more prone to pollution and reduced quality of environment.
- Three problems – Reduced quality of Environment, High Energy cost and less comfort
- One Solution – Multi-agent assisted Indoor Environmental Quality

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Indoor Environmental Quality (IEQ) : A Brief Overview

World Health Organization Estimates (March 25th, 2014)

"... air pollution is now the world's largest single environmental health risk. Reducing air pollution could save millions of lives."

"... a total of 3.3 million deaths linked to indoor air pollution and 2.6 million deaths related to outdoor air pollution" (in South-East Asia and Western Pacific Regions)

Quartz India (November 6th, 2018)

"On Nov. 05, Delhi residents woke up to a haze of smog after the city's pollution level reportedly hit 20 times the World Health Organization's recommended limit."

"Even before Diwali fireworks, Delhi's air is already deadly"

http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/ (based on WHO mortality data from 2012)
http://aqicn.org/city/italy/capo-granitola/cnr-isac/
https://qz.com/india/1451841/even-before-diwali-fireworks-delhis-air-is-already-deadly/

INDOOR ENVIRONMENTAL QUALITY (IEQ) : A BRIEF OVERVIEW

Four components of IEQ:

- Thermal Quality – Temperature, Relative Humidity and Air Velocity.
- Indoor Air Quality – concentration of gases - CO_2, CO, O_3, HCHO and VOC's.
- Lighting Quality – Better illuminance, colour temperature and less glare.
- Acoustics Comfort – Very less noise, no echo and ease of communication.

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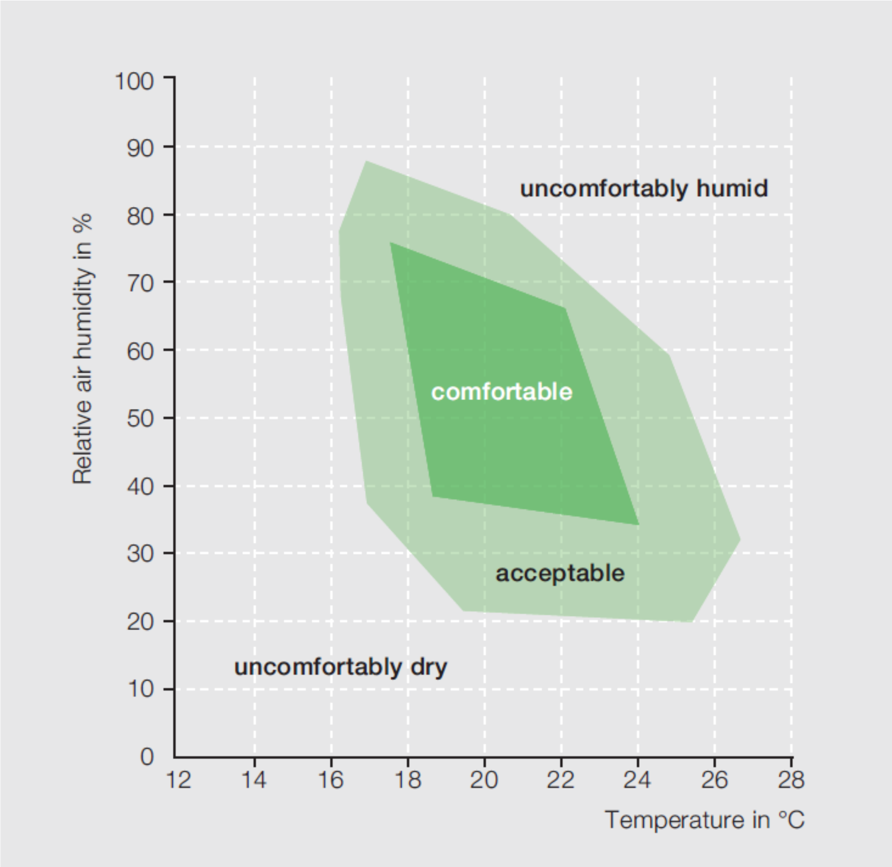
INDOOR ENVIRONMENTAL QUALITY (IEQ) : A BRIEF OVERVIEW

Thermal Quality:

- Three parameters: Temperature, Relative Humidity and Air Velocity.
- Standard range:
  - Temperature: 22.5 – 25 ºC
  - Relative Humidity: < 70 %
  - Air Velocity: < 0.25 m/sec
- Comfort varies from each individual



Temperature vs Relative Humidity and Comfort Zone

Singapore B.C.A. BCA BUILDING ENERGY BENCHMARKING REPORT 2017,

INDOOR ENVIRONMENTAL QUALITY (IEQ) : A BRIEF OVERVIEW

Indoor Air Quality:

- Increase in closed spaces, reduction in fresh ventilation – result is reduction of air quality.

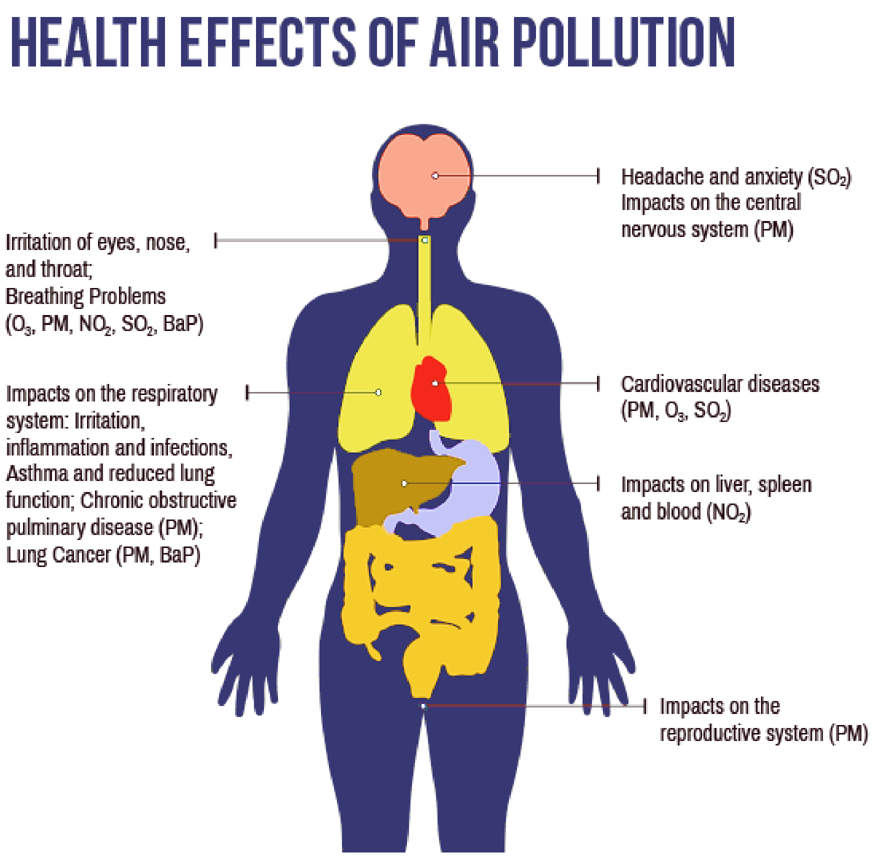
- Gases of main interest – CO_2, CO, O_3, Formaldehyde (HCHO) and Volatile Organic Compounds (VOC's) and Dust particles (PM 2.5 and PM 10).

Indoor Air Quality: Common Pollutants

https://catalysts.basf.com/products-and-industries/indoor-air-quality

Indoor Environmental Quality (IEQ) : A Brief Overview

Air Quality:



Health Effects of Air Pollution (Outdoor and Indoor)

http://mccog.net/cleanairdare/air-quality-explained.html

Indoor Environmental Quality (IEQ) : A Brief Overview

Indoor Air Quality:

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%)

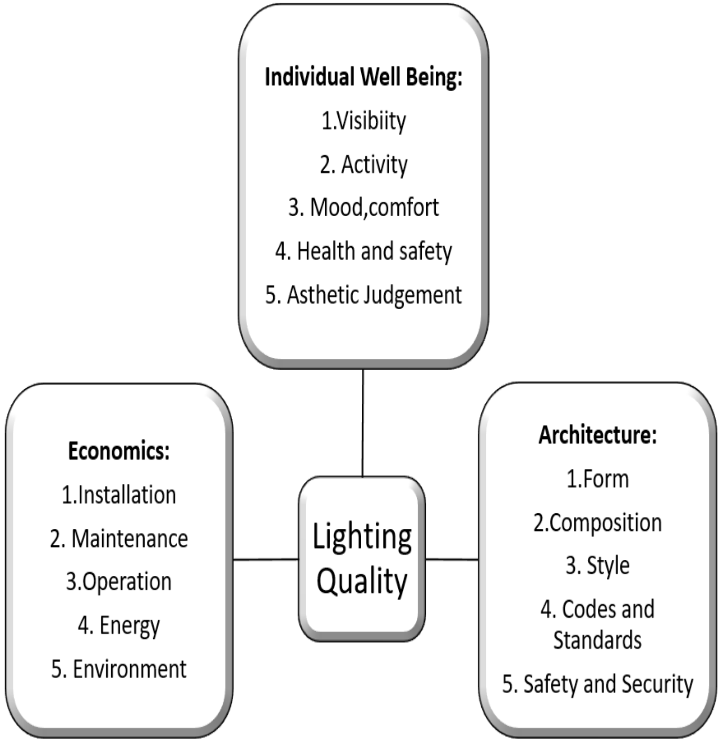
Reduced Indoor Air Quality: Symptoms with % of occupants feeling it in different countries

Peder Wolkoff. Indoor air pollutants in office environments: assessment of comfort, health, and performance. International journal of hygiene and environmental health, 216(4):371–394, 2013.

INDOOR ENVIRONMENTAL QUALITY (IEQ) : A BRIEF OVERVIEW

Lighting Quality:

- Key parameters: Illuminance, Electrical and Day-light, Glare and Personal Comfort based control.
- Least concerned - health and looked as a architectural aspect.
- No immediate health effect but may lead to eye strain, headache, dizziness and lack of concentration.
- Recommended level - Illuminating Engineering Society of North America (IESNA) is 500 lux at work place and 100 less surrounding it.



Components of Lighting Quality

INDOOR ENVIRONMENTAL QUALITY (IEQ) : A BRIEF OVERVIEW

Acoustic Quality:

- Minimizing intruding noise and maintaining satisfaction among the occupants.
- Reduction in noise – improved productivity and concentration.
- Use of sound absorbents, carpets to reduce noise in indoor spaces.

Adjacency combinations		Sound level (dB)
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

Sound level recommended by USGBC

Indoor Environmental Quality (IEQ) : A Brief Overview

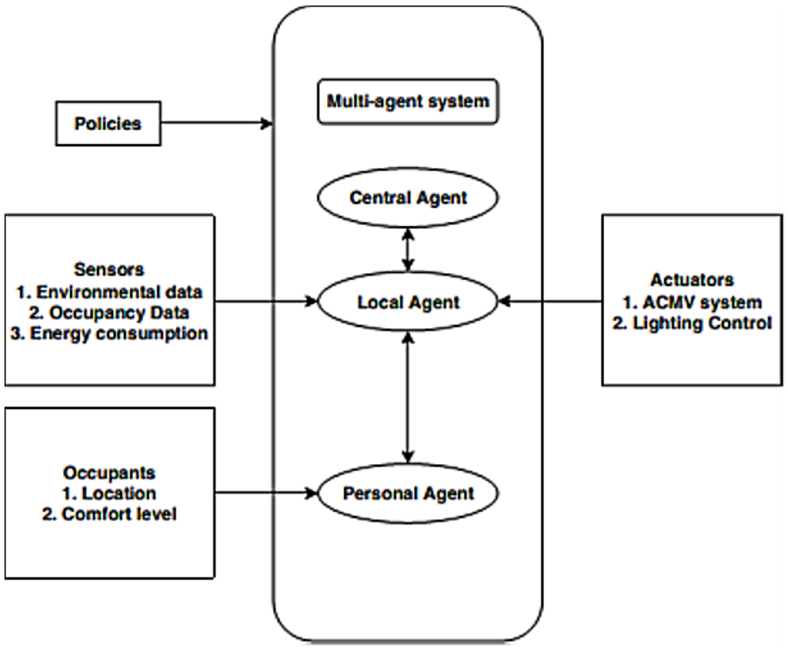
Agent behaviour:

- Characteristics:
  - Reacts to change in environment.
  - Goal oriented behavior.
  - Communicate with other agents to necessitate change.
  - Partially independent and autonomous.
  - Agents have a local view of the system except the central agent.
  - Decentralized control.

INDOOR ENVIRONMENTAL QUALITY (IEQ) : A BRIEF OVERVIEW

Multi-Agent System:

- Building Management system (BMS)– controls ACMV systems, Lighting and Indoor Air constituents.
- Multi-agent behavior can enhance the energy efficiency of BMS considering user feedback.
- Decentralized control of environment.
- Policies based on standards and comfort level.



Multi-agent System for IEQ

MODELLING OF THE SYSTEM

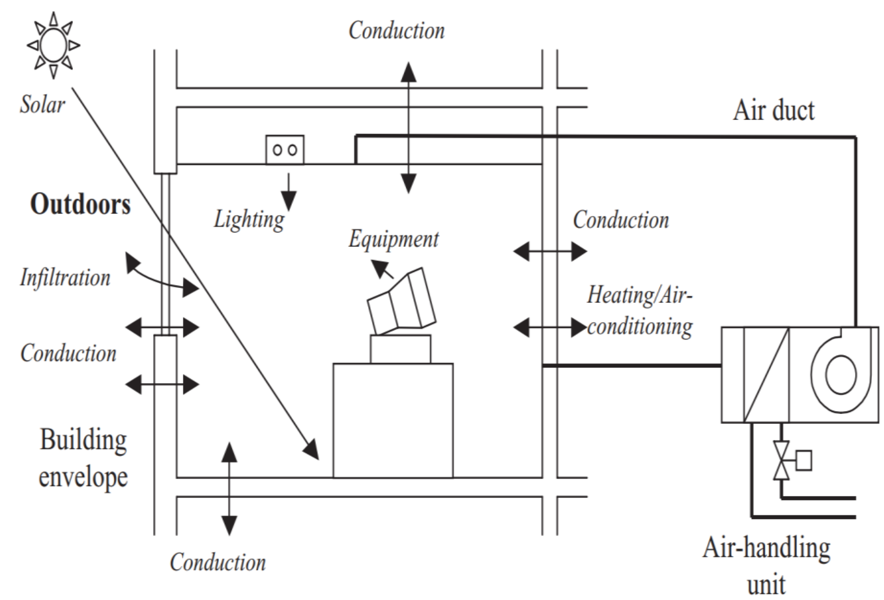
Modelling of Building:

- Many subsystems involved - Difficult in modelling of system by understanding the physical relationship between variables.
- Requires precise relationship between variables for modelling.
- Computationally inefficient and time consuming.
- Complexity increases with increase in sub-systems.

MODELLING OF THE SYSTEM

Thermal Model of the System:

- Heat storage and transmission in the room two important thermal properties.
- Influences the temperature and relative humidity in the room.
- Temperature and Relative Humidity – controlled variable.
- Controlled by quantity of heat Q removed by ACMV – manipulated variable.



Various Heat gains of a building

MODELLING OF THE SYSTEM

Thermal Model of the System:

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

Building elements and their mode of heat transfer

MODELLING OF THE SYSTEM

Thermal Capacitance and Resistance in Electrical Analogy:

- Thermal Capacitance – $$mC_t = \frac{q_x}{\dot{T}}$$
- Thermal Resistance –
  - When heat transfer by conductance:

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

  - When heat transfer is by convection:

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

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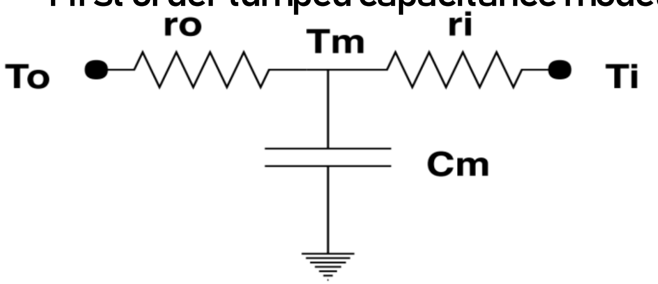
MODELLING OF THE SYSTEM

First order lumped capacitance model



Electrical model of the wall:

- First order lumped capacitance:
  - Most commonly used to represent the individual unit of wall.
  - Ease of computation .
  - Can treat all elements of the buildings as lumped capacitance and provides uniform thermal response.
  - Differential equation governing the circuit:

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

    - Tm is the voltage across capacitance C_m .
    - r_m and C_m are the thermal resistance and capacitance of the material .
    - T_i and T_o are the internal and external temperatures.

MODELLING OF THE SYSTEM

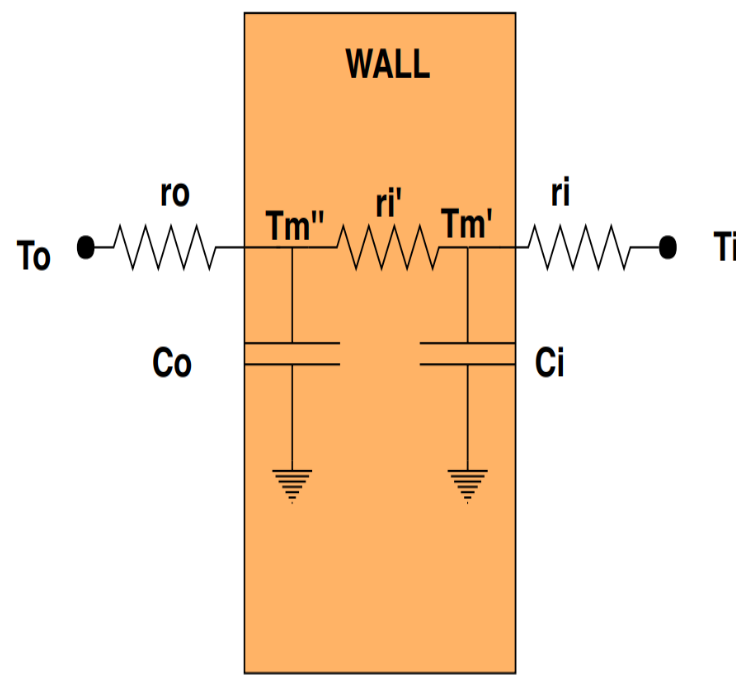
Electrical model of the wall:

- Second order lumped capacitance:
  - First order model considers the material uniform and hence inaccurate.
  - Second order considers the material internal structure that adds to the heat transmission.
  - Differential equations governing the model:

$$\frac{dT'_m}{dt} = \frac{1}{y_1 C_m}\left[q_r + \frac{(T_i - T'_m)}{x_1 r_m} - \frac{(T'_m - T''_m)}{x_2 r_m}\right]$$

$$\frac{dT''_m}{dt} = \frac{1}{y_2 C_m}\left[q_r + \frac{(T'_m - T''_m)}{x_2 r_m} - \frac{(T''_m - T_o)}{x_3 r_m}\right]$$

Second order lumped capacitance model



MODELLING OF THE SYSTEM

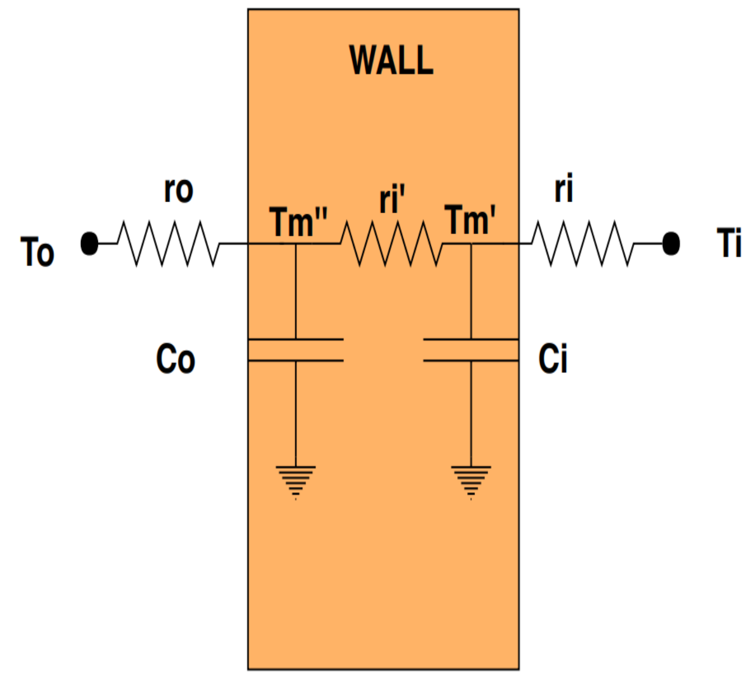
Electrical model of the wall:

The coefficients sum to 1 for the thermal resistance and capacitance when they are considered equal for all the layers.

- Second order lumped capacitance:

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

Second order lumped capacitance model



Second order lumped capacitance model coefficients where $x_1 + x_2 + x_3 = 1$ and $y_1 + y_2 = 1$

Chris Underwood and Francis Yik. Modelling methods for energy in buildings. John Wiley & Sons, 2008.

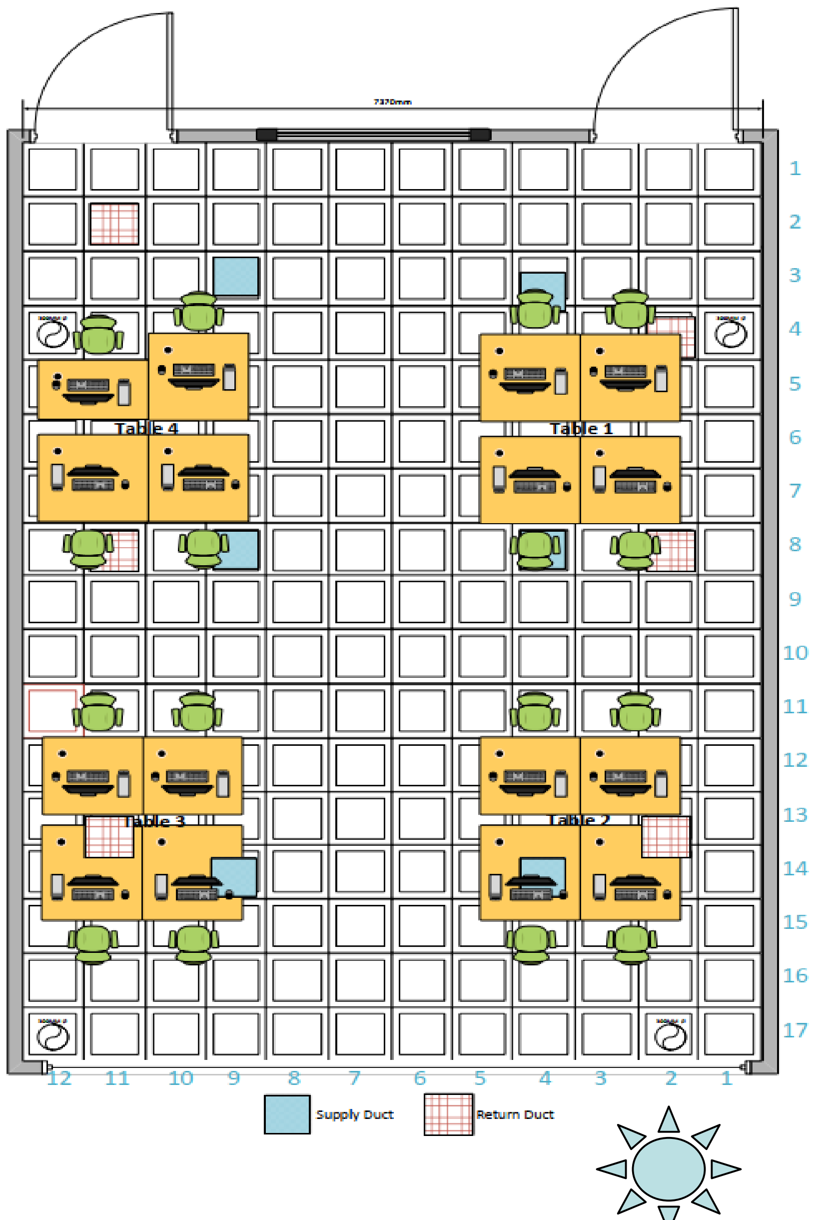
MODELLING OF THE SYSTEM

Assumptions considered for second order lumped model:

- Air inside the room is well mixed.
- Minimal variation of the temperature across the room.
- All the elements of the building fit into the lumped capacitance model.
- Heat flow is Isotropic.
- Thermo-physical properties do not change with the temperature.
- Pressure across the room is uniform so the heat flow is variant based on only temperature.
- Radiation from the sun and temperature increase follows a pattern of sin-wave input since the data for variation is not available for consideration.

MODELLING OF THE SYSTEM

Floor Plan of the room



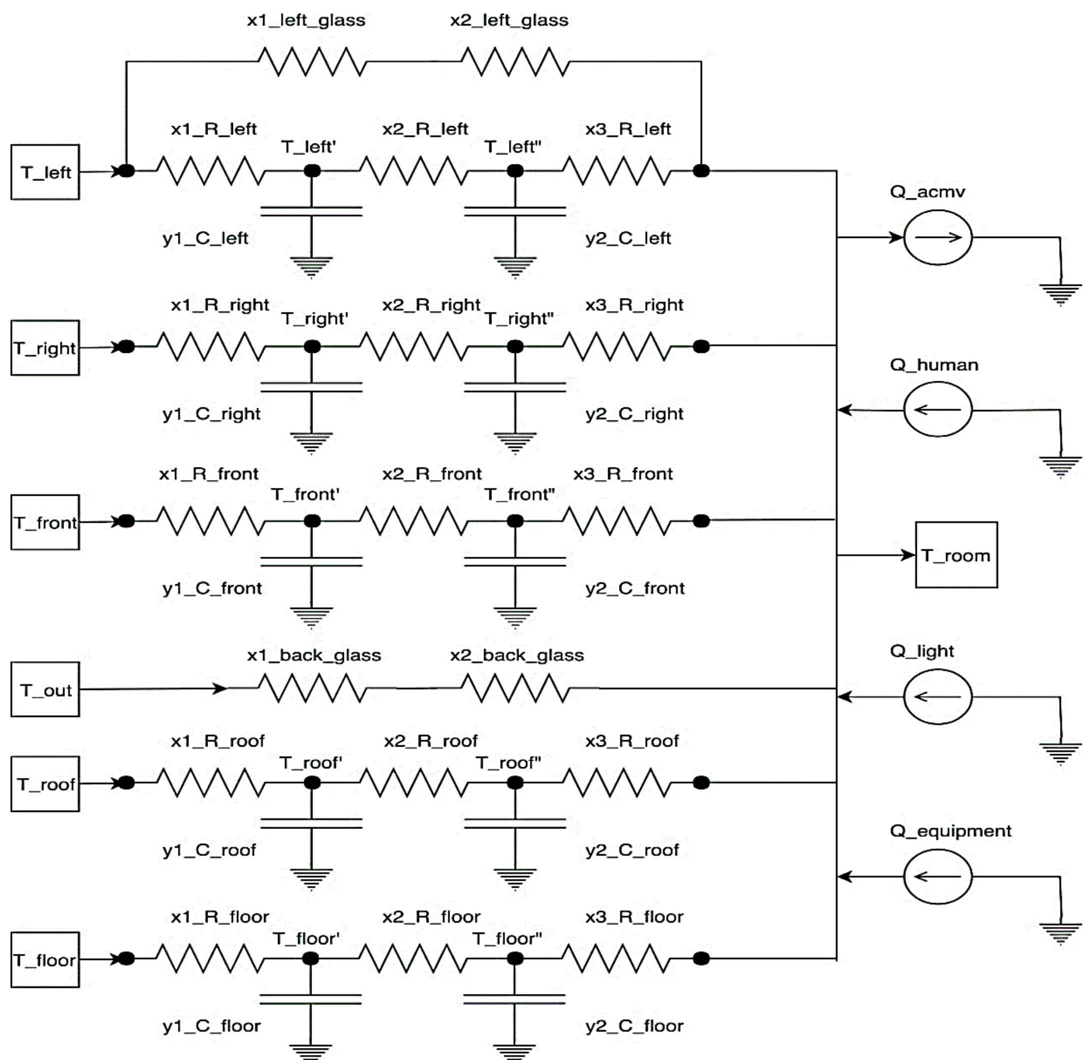
MODELLING OF THE SYSTEM

Thermal Modelling of the room:

- Based on the second order lumped capacitance of wall.
- Room under consideration FEC2 room, NUS.
- Room dimensions Length = 10.11meter, Width = 7.37 meter, Height = 2.63meter.
- Main assumptions:
  - Air is well mixed in the room
  - Floor and roof have similar properties to that of the other walls
  - Floor has no radiative effect on its temperature since it is not present in the ground floor.
  - All the constants are assumed from standard measurements.
- Subsystems – 4 walls, roof, floor, heat gains from human, ACMV system, Lighting and other equipment.

Modelling of the System

Lumped Capacitance Model of the room



MODELLING OF THE SYSTEM

Thermal Modelling of the room

Differential equation governing the system:

By heat balance equation:
Internal energy = Heat gains + work done

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

Modelling of the System

Thermal Modelling of the room:

Differential equation governing the system:

At the steady state: indoor temperature constant when ACMV working
=> Its derivative is constant.

$$Q_{acmv} = Q_{human} + Q_{light} + Q_{equipment} + \frac{A_{rw,i}(T_{rw_1'} - T_{bs})}{x_{rw,1}r_{rw}} + \frac{A_{fw,i}(T_{fw_1'} - T_{bs})}{x_{fw,1}r_{fw}}$$
$$+ \frac{A_{lw,i}(T_{lw_1'} - T_{bs})}{x_{lw,1}r_{lw}} + \frac{A_{lg,i}(T_{bs} - T_{out})}{x_{lg,1}r_{lg} + x_{lg,2}r_{lg}} + \frac{A_{bg,i}(T_{bs} - T_{out})}{x_{bg,1}r_{bg} + x_{bg,2}r_{bg}}$$
$$+ \frac{A_{roof,i}(T_{roof_1'} - T_{bs})}{x_{roof,1}r_{roof}} + \frac{A_{fl,i}(T_{fl_1'} - T_{bs})}{x_{fl,1}r_{fl}} - 0.33NV_{bs}(T_{bs} - T_{out})$$

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Modelling of the System

Air Quality of the room:

Differential equation governing the CO_2 concentration:

- CO_2 concentration depends directly on the number of persons present in the room.

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

- c_0, c are the concentration of Carbon dioxide at the outdoor and indoor. V is the volume of the room, q is the outdoor fresh air intake by ACMV system, p is the amount of CO_2 that is let in by the people in the room.

Modelling of the System

Air Quality of the room:

Differential equation governing the CO concentration:

- CO concentration depends on the outside air and not on human beings as they do not generate CO

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

- CO_{in} and CO_{out} are the concentration of Carbon monoxide at the inside and outside of the room. V is the volume of the room, q is the outdoor fresh air intake by ACMV system.

MODELLING OF THE SYSTEM

Air Quality of the room:

Differential equation governing the O_3 concentration:

- O_3 concentration depends on the outside air and not on human beings as they do not generate O_3 .

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

- O_{3in} and O_{3out} are the concentration of Ozone at the inside and outside of the room. V is the volume of the room, q is the outdoor fresh air intake by ACMV system.

Indices of the Room

Thermal Comfort Index:

Predicted Mean Value: (ASHRAE 55:2017)

- Predicts the comfort level of people theoretically.
- Uses: air temperature, radiant temperature, relative humidity, air speed, metabolic rate and clothing insulation.

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

Indices of the Room

Thermal Comfort Index:

Predicted Mean Value:

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

where:

$$L = q_{met} - f_{cl}h_c(T_{cl} - T_a) - f_{cl}h_r(T_{cl} - T_r) - 156(W_{sk,req} - W_a)$$

$$-0.42(q_{met} - 18.43) - 0.00077M(93.2 - T_a) - 2.78M(0.0365 - W_a)$$

Predicted Percentage of Dissatisfaction:

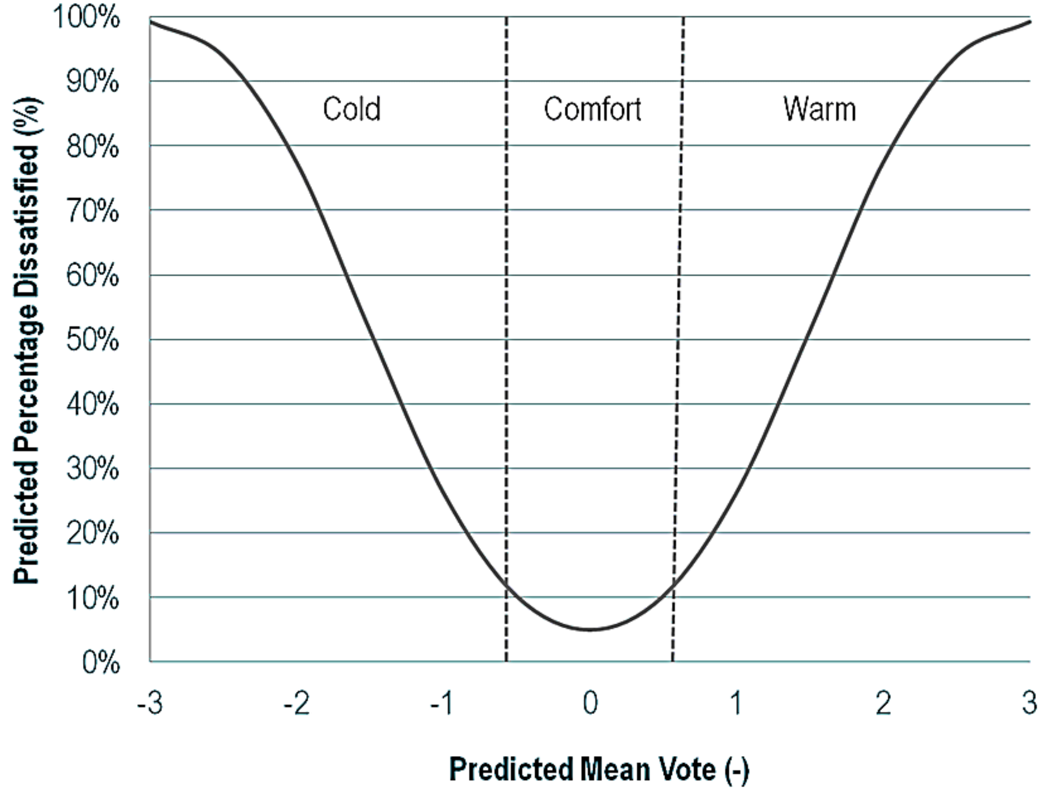
Gives the predicted value of occupants to be dissatisfied by the given conditions.

$$PPD = 100 - 95exp(-0.03353PMV^4 - 0.2179PMV^2)$$

Indices of the Room

Thermal Comfort Index:

Relation between Predicted Mean Value and Predicted Percentage of Dissatisfaction:



INDICES OF THE ROOM

Air Quality Index:

Most common index of quality and pollution measurement. Gives a number that can give the severity of the pollution present. Singapore refers to it has Pollution Standards Index (PSI)

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

Indices of the Room

Air Quality Index:

O3(ppb)(8 - hr)	*O3(ppb)(1 - hr)*	*PM2:5(µg=m3)*	*PM10(µg=m3)*	*CO(ppm)*	AQI	AQI
C_{low} - C_{high} (avg)	C_{low} - C_{high} (avg)	C_{low} - C_{high} (avg)	C_{low} - C_{high} (avg)	C_{low} - C_{high} (avg)	I_{low} - I_{high}	Category
0-54	-	0.0-12.0	0-54	0.0-4.4	0-50	Good
55-70	-	12.1-35.4	55-154	4.5-9.4	51-100	Moderate
71-85	125-164	35.5-55.4	155-254	9.5-12.4	101-150	Unhealthy
86-105	165-204	55.5-150.4	255-354	12.5-15.4	151-200	
106-200	205-404	150.5-250.4	355-424	15.5-30.4	201-300	Very Unhealthy
-	405-504	250.5-350.4	425-504	30.5-40.4	301-400	Hazardous
-	505-604	350.5-500.4	505-604	40.5-50.4	401-500	

ANSI ASHRAE. Ashrae/ies standard 55-2013, thermal environmental conditions for human occupancy. American Society of Heating, Air-Conditioning and Refrigeration Engineers, Inc, Atlanta, 2013.

Indices of the Room

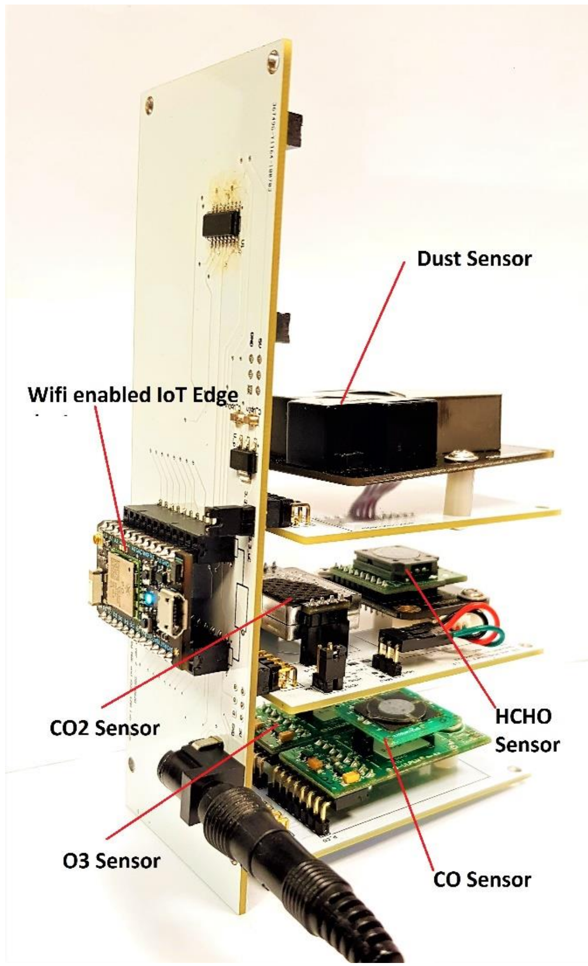
Lighting Index:

- Index based on standards of International Association of Light Designers.
- Recommended level of lighting is 500 lux at work place, 300-400 surrounding it.

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

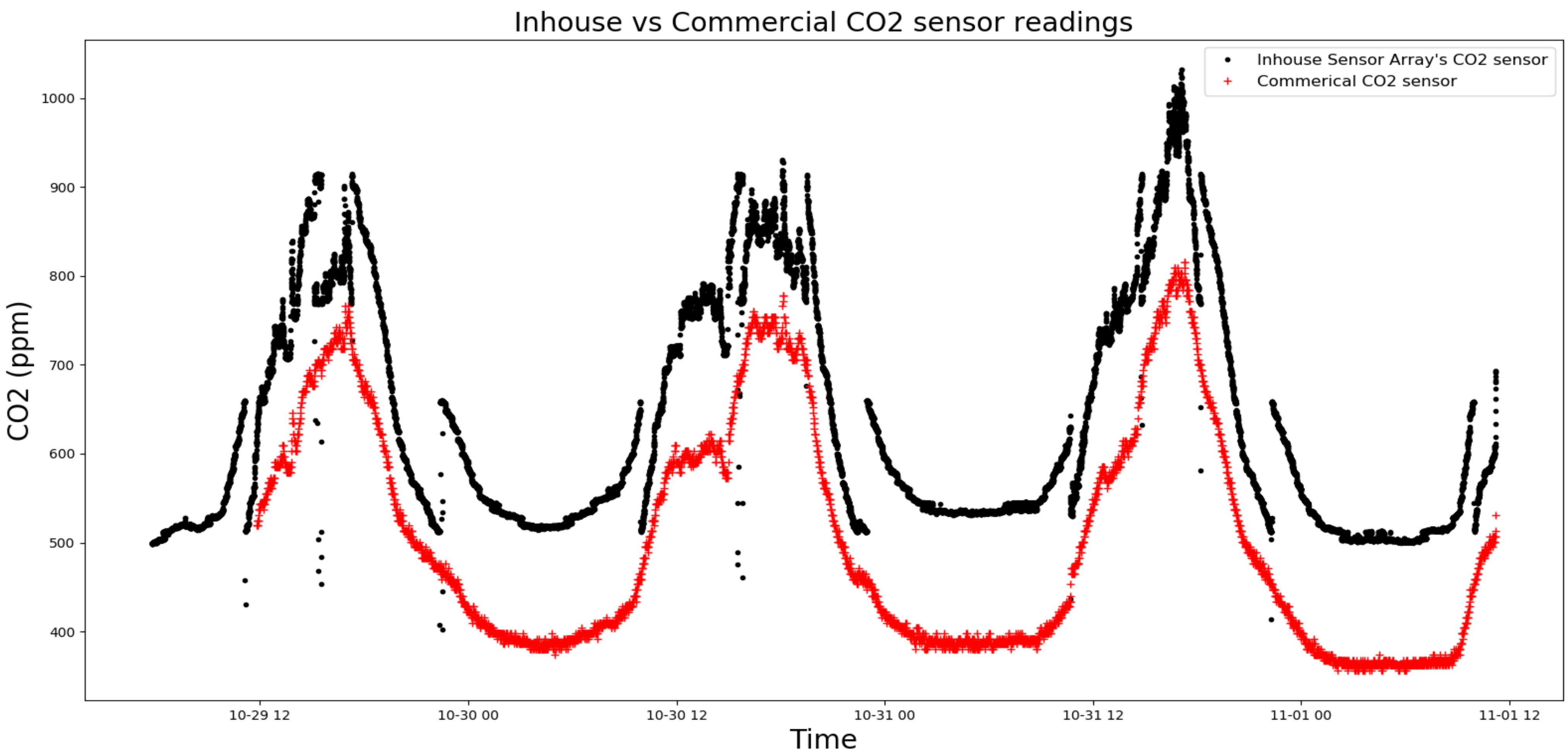
It ranges between 0 – 100 where 0 refers to compiles with the standards and 100 refers to either it is too dark or too bright.

SENSOR ARRAY AND DATA COLLECTION



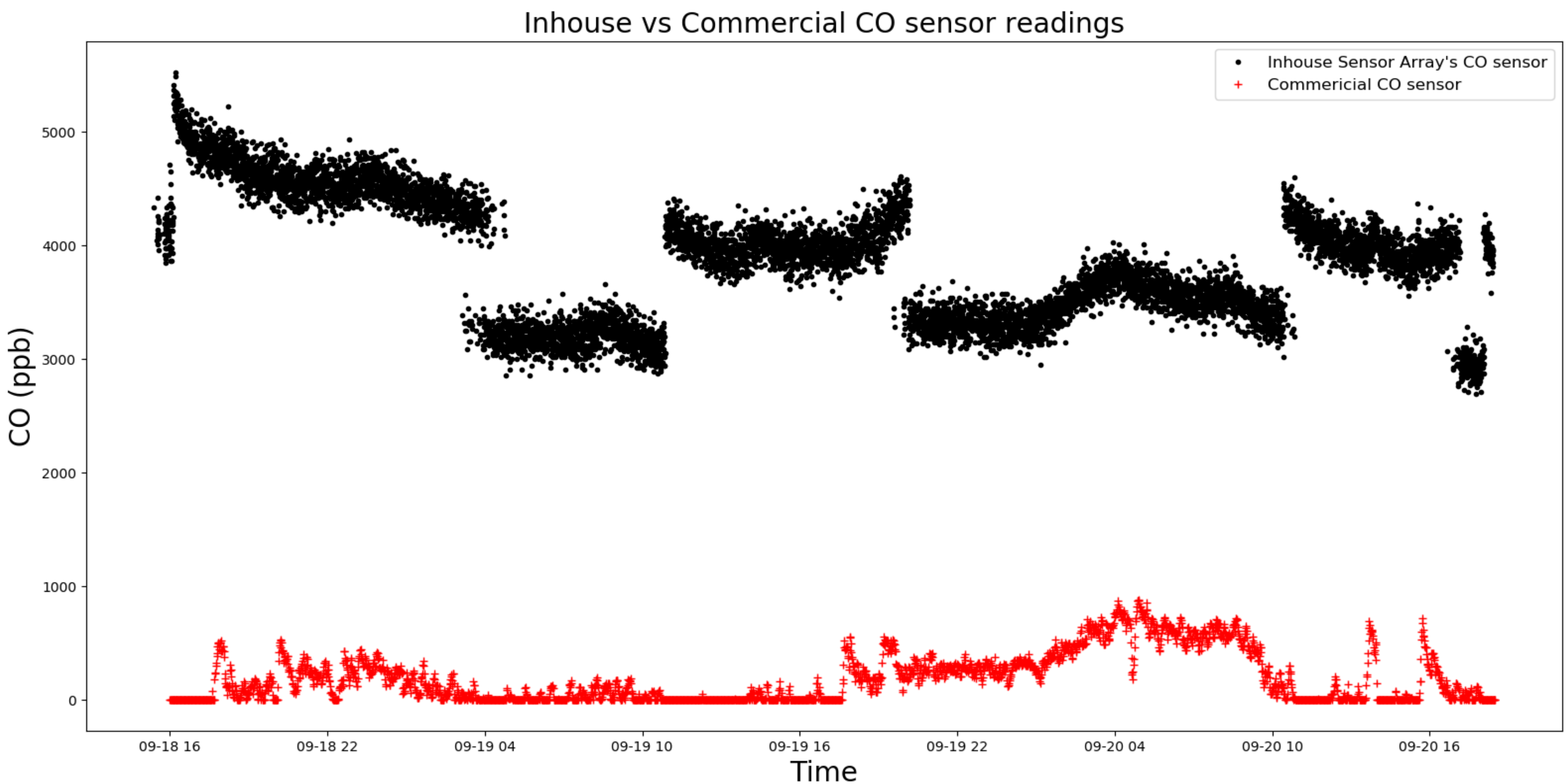
Sensor Array and Commercial Sensor used

Sensor Array and Data Collection



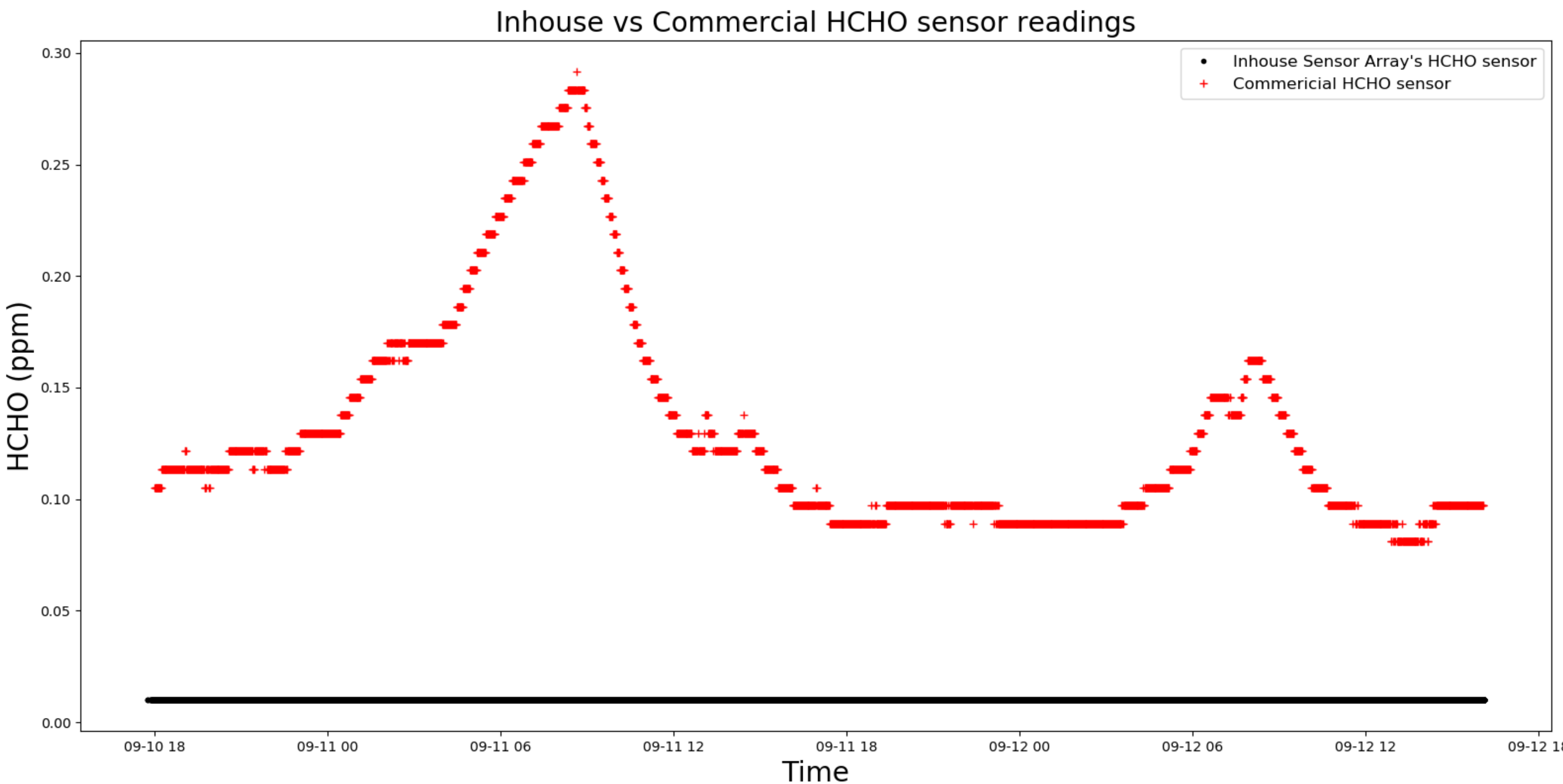
Actual CO_2 concentration – Commercial vs Inhouse sensor array

Sensor Array and Data Collection



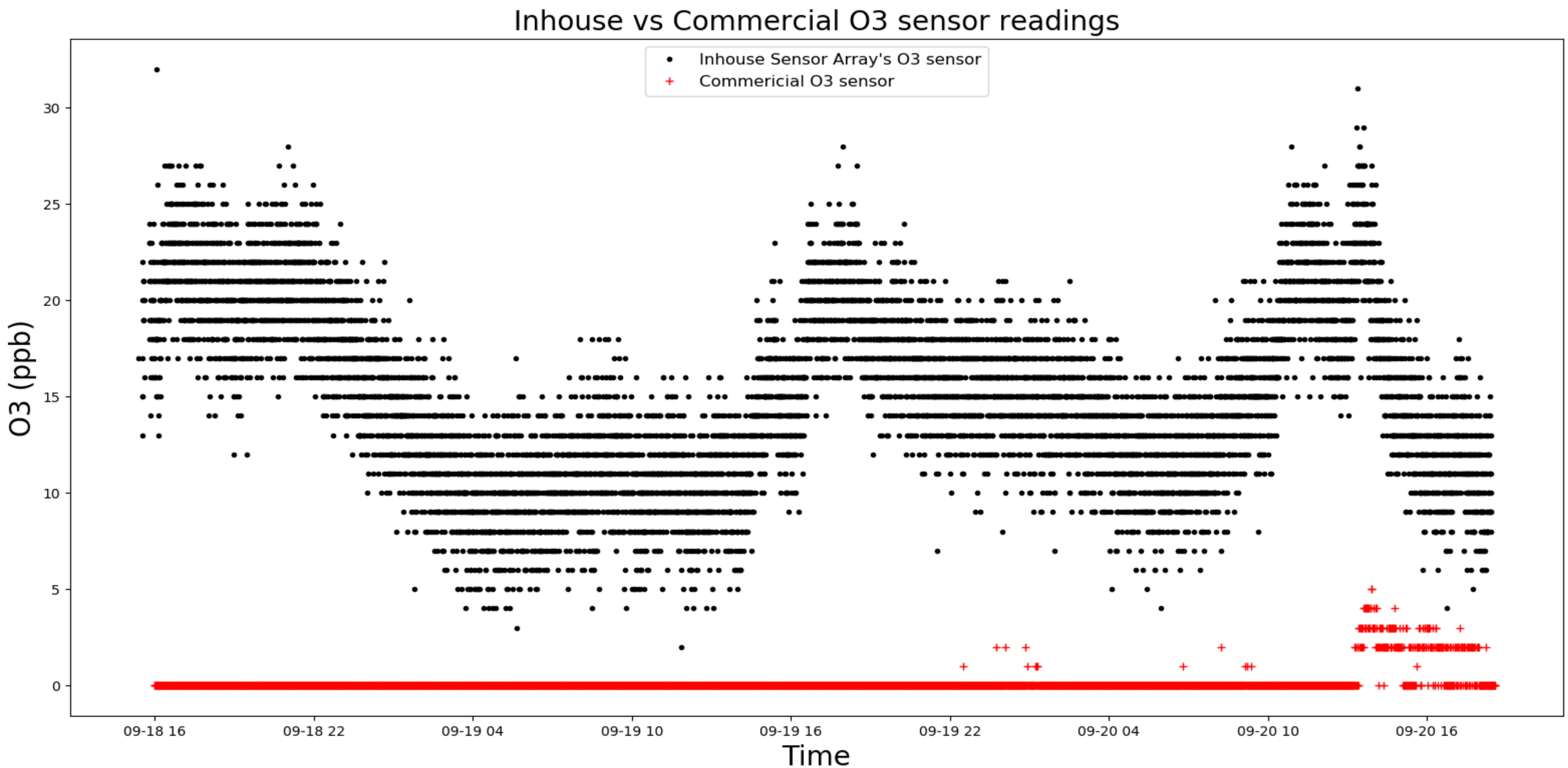
Actual CO concentration – Commercial vs Inhouse sensor array

SENSOR ARRAY AND DATA COLLECTION



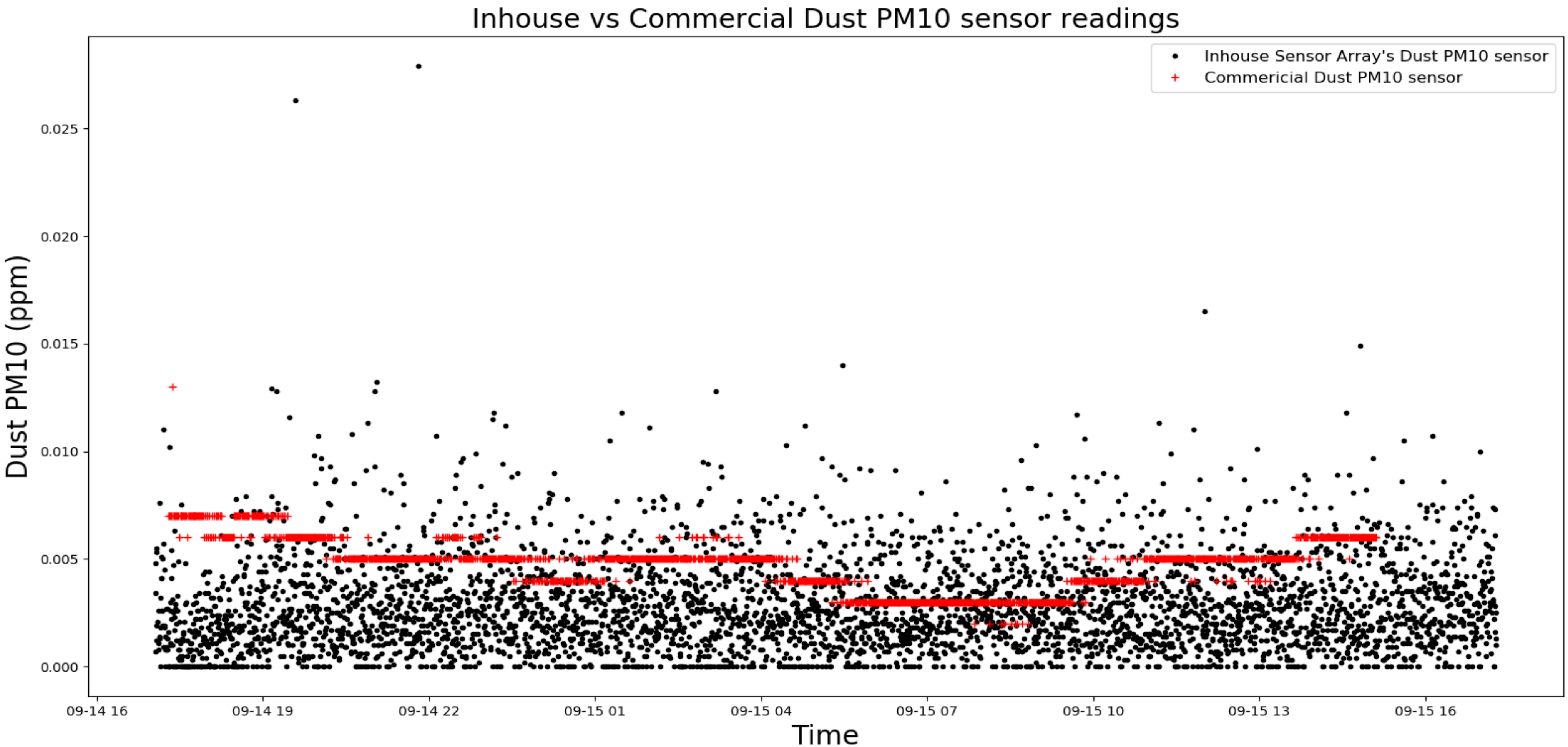
Actual HCHO concentration – Commercial vs Inhouse sensor array

SENSOR ARRAY AND DATA COLLECTION



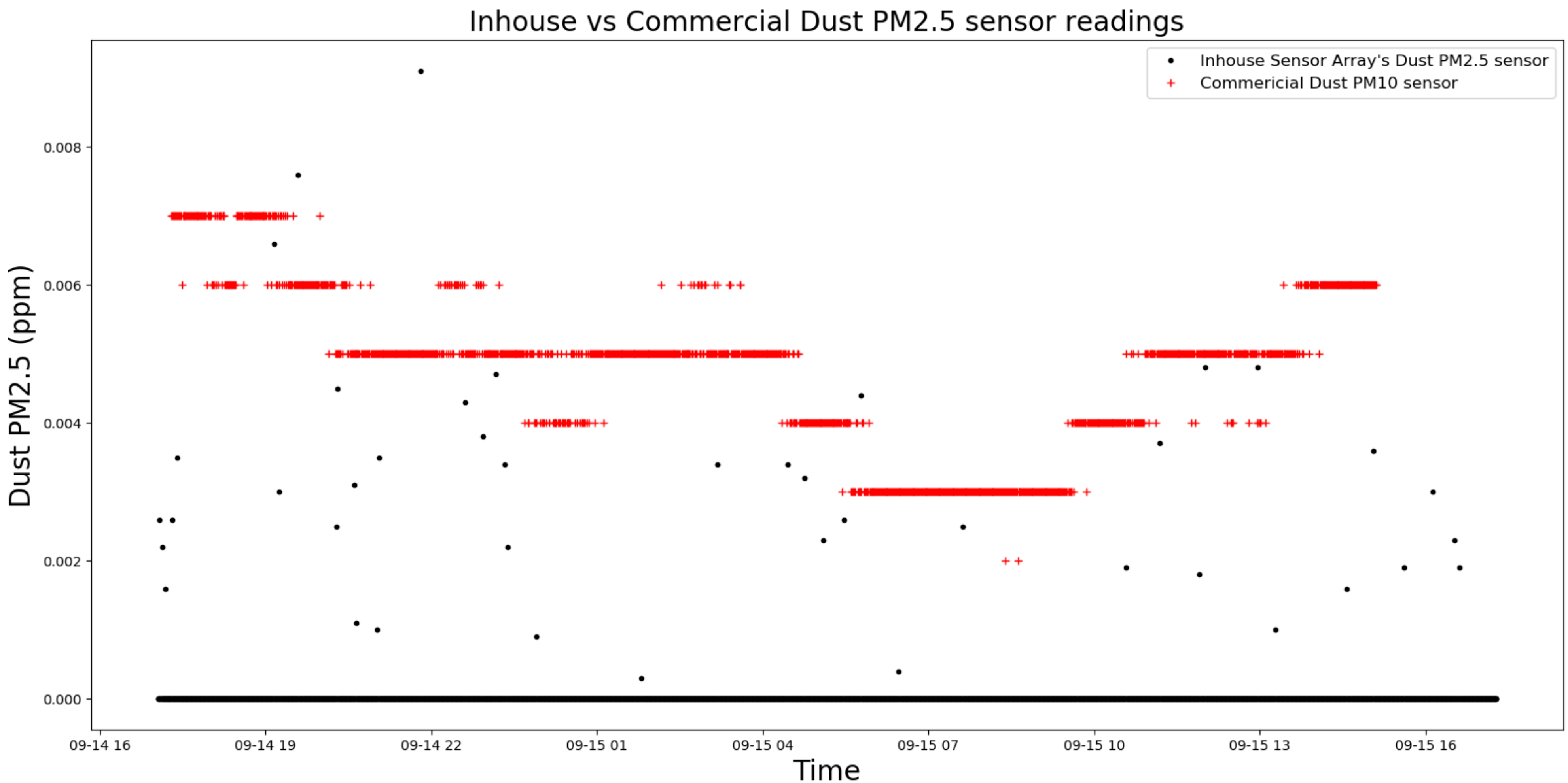
Actual O_3 concentration – Commercial vs Inhouse sensor array

SENSOR ARRAY AND DATA COLLECTION



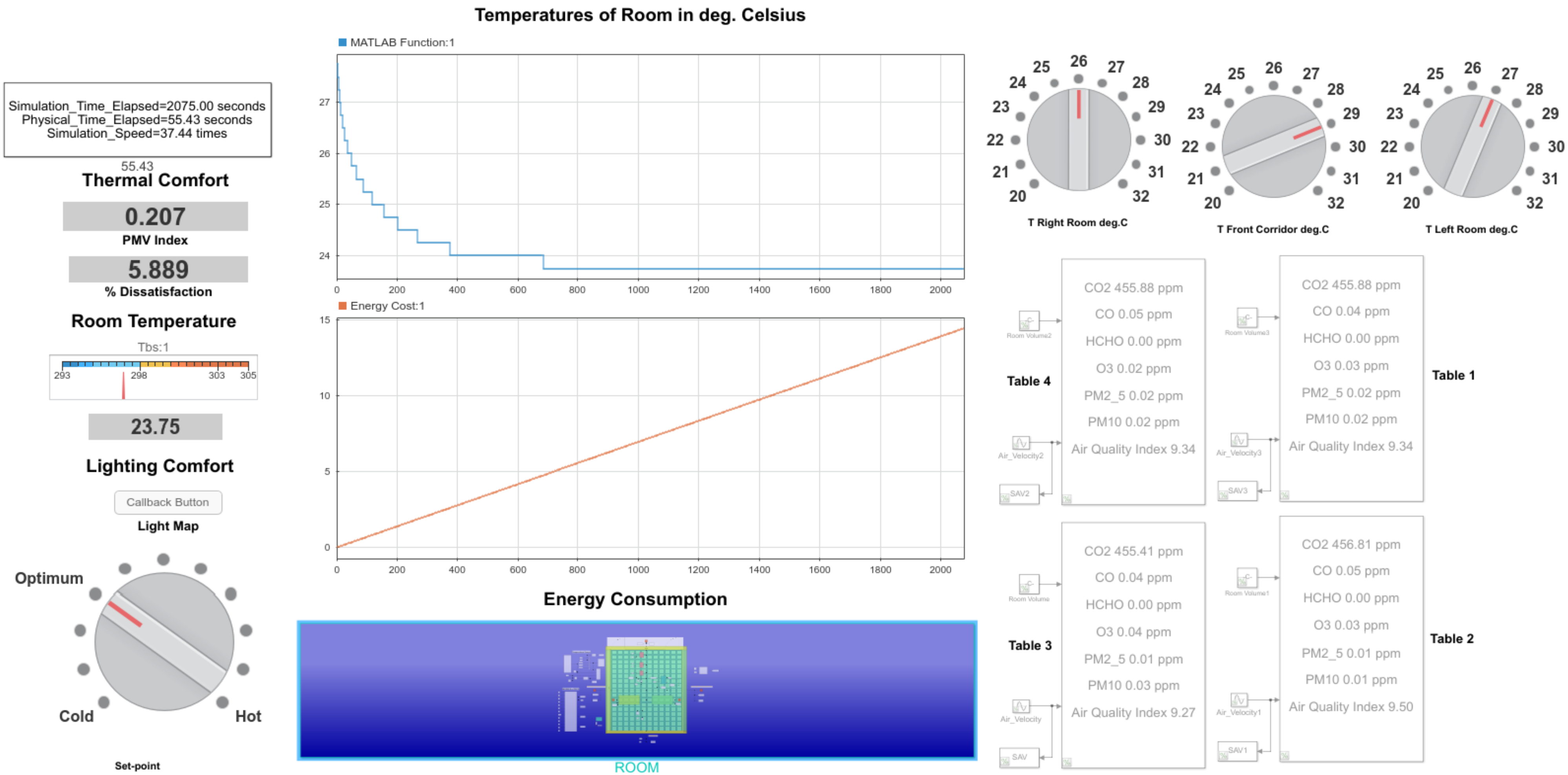
Actual PM10 concentration – Commercial vs Inhouse sensor array

SENSOR ARRAY AND DATA COLLECTION



Actual PM2.5 concentration – Commercial vs Inhouse sensor array

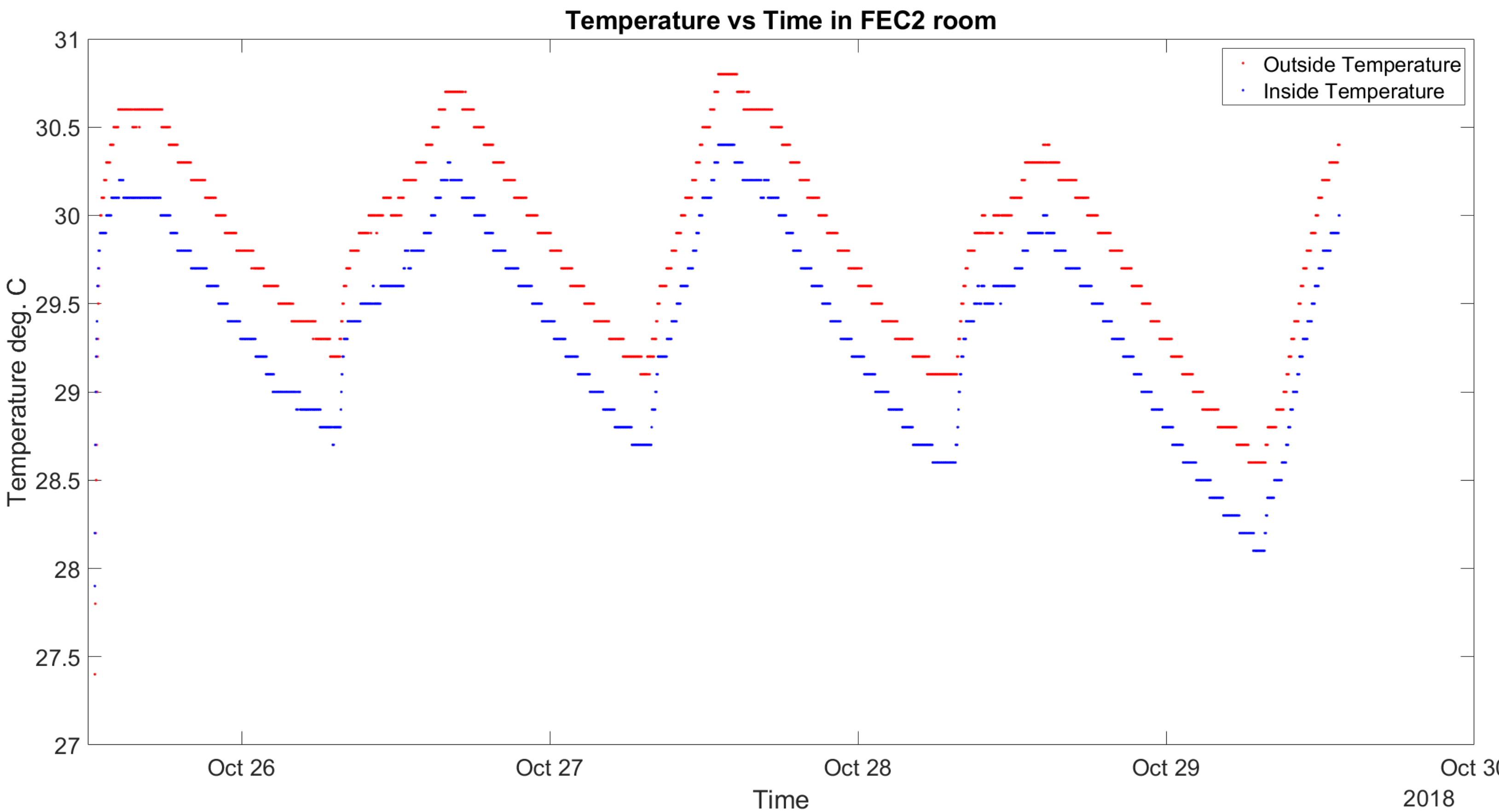
DISCUSSION OF RESULTS



GUI in Simulink for the IEQ system

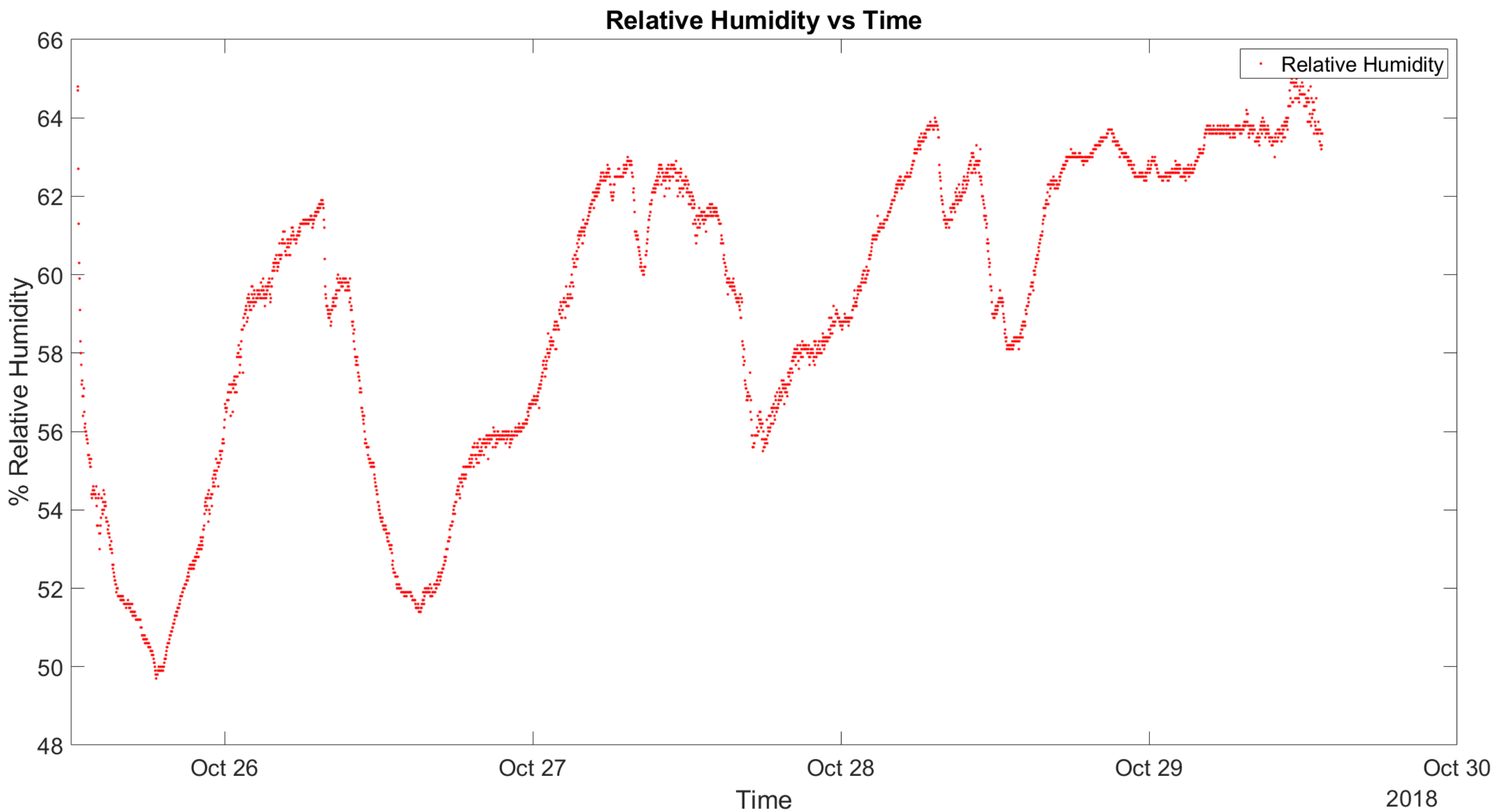
Discussion of Results

Thermal Comfort



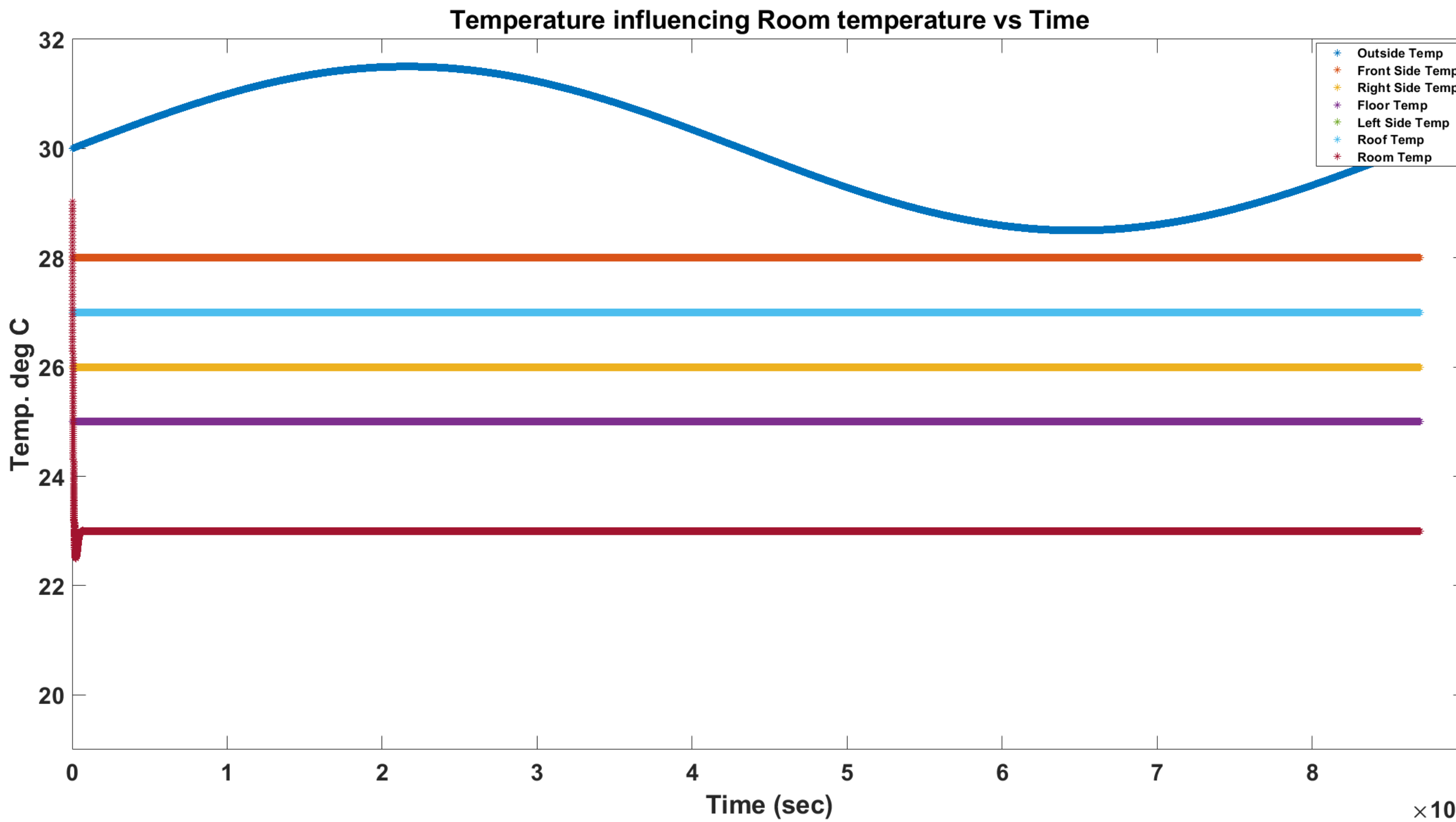
Actual Temperature variation between Indoor and Outdoor in deg. C in FEC2 room

Discussion of Results



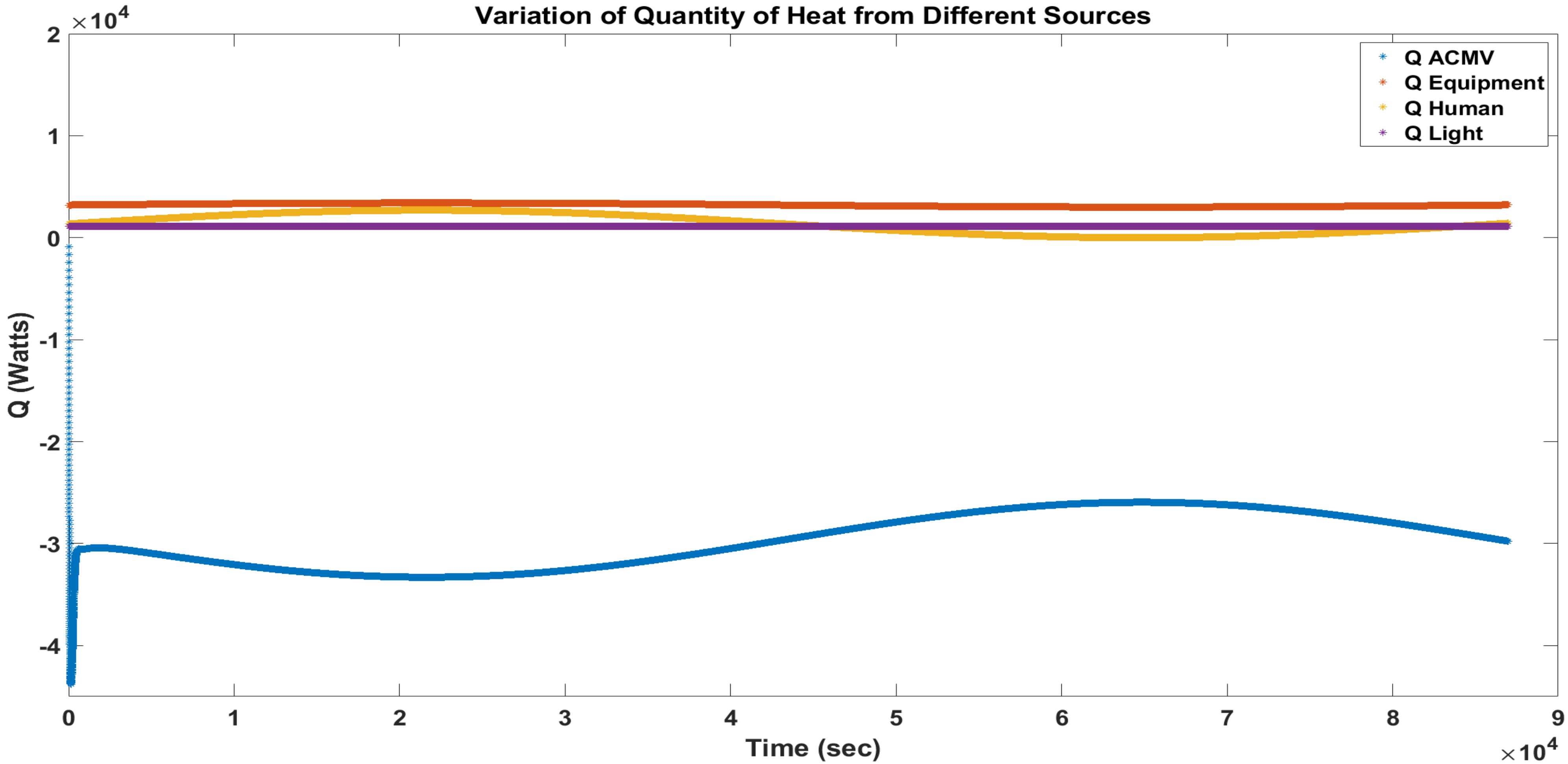
Actual Humidity variation in the FEC2 room

Discussion of Results



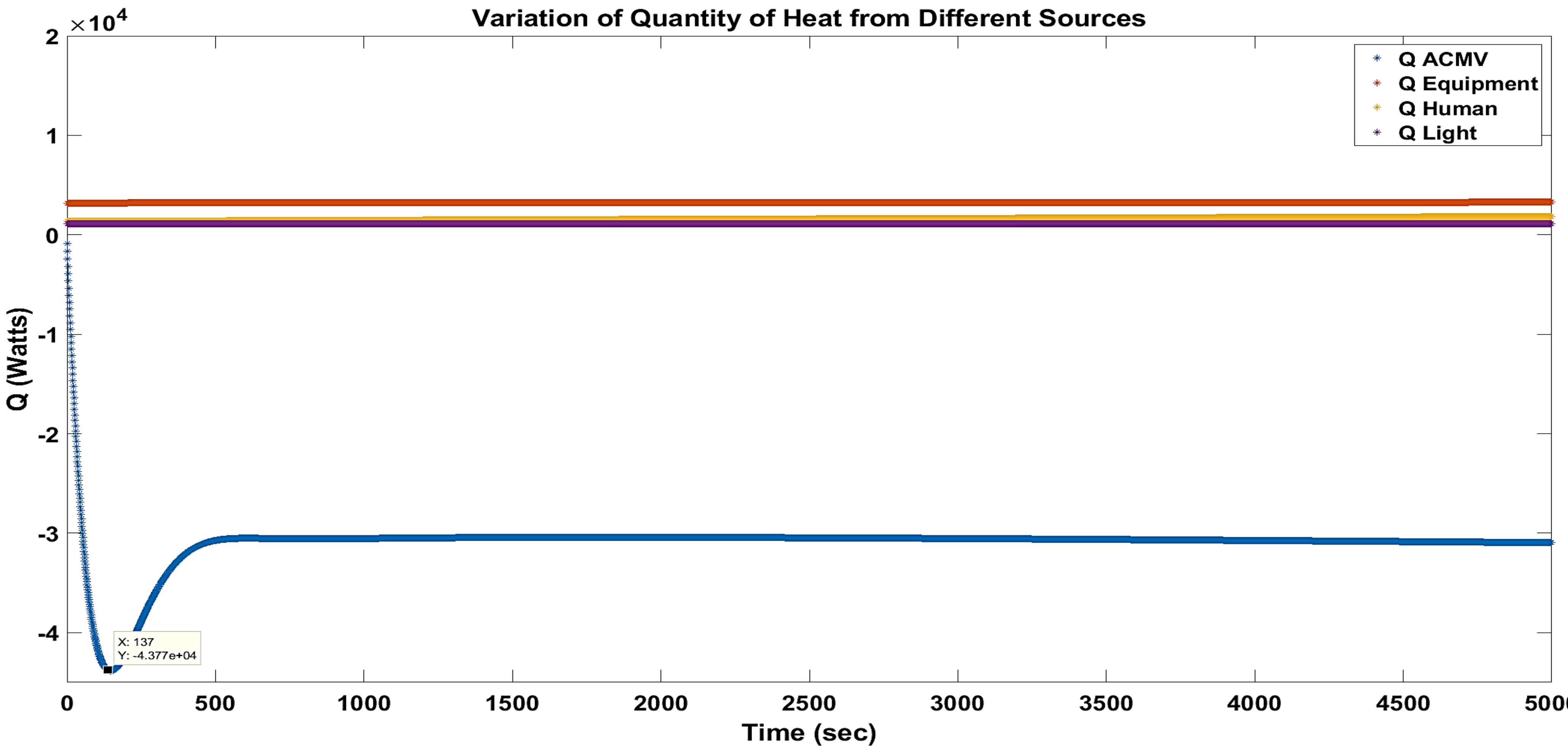
Simulated Temperature variation in the room

Discussion of Results



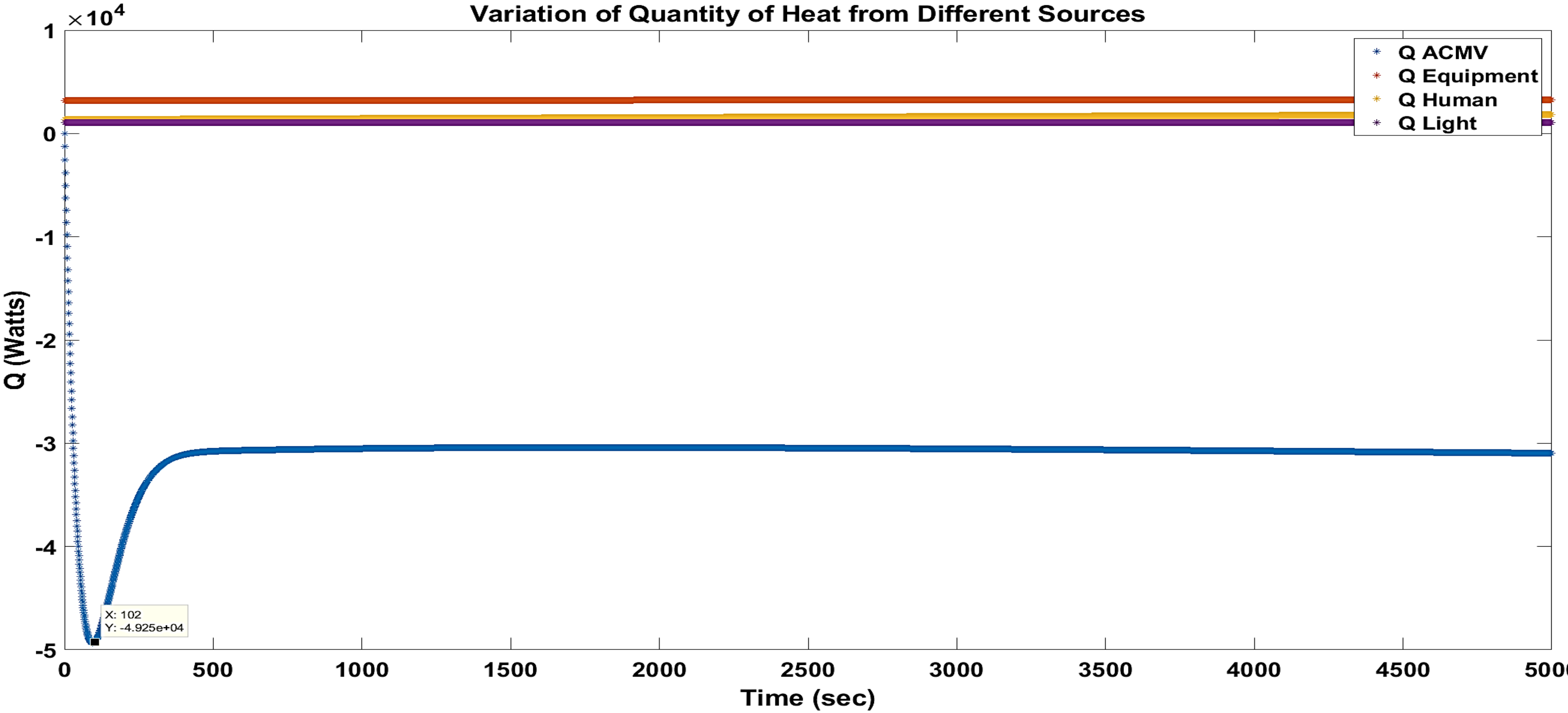
Simulated Heat Gains in the room
Qacmv is calculated based on the cooling load calculation

Discussion of Results



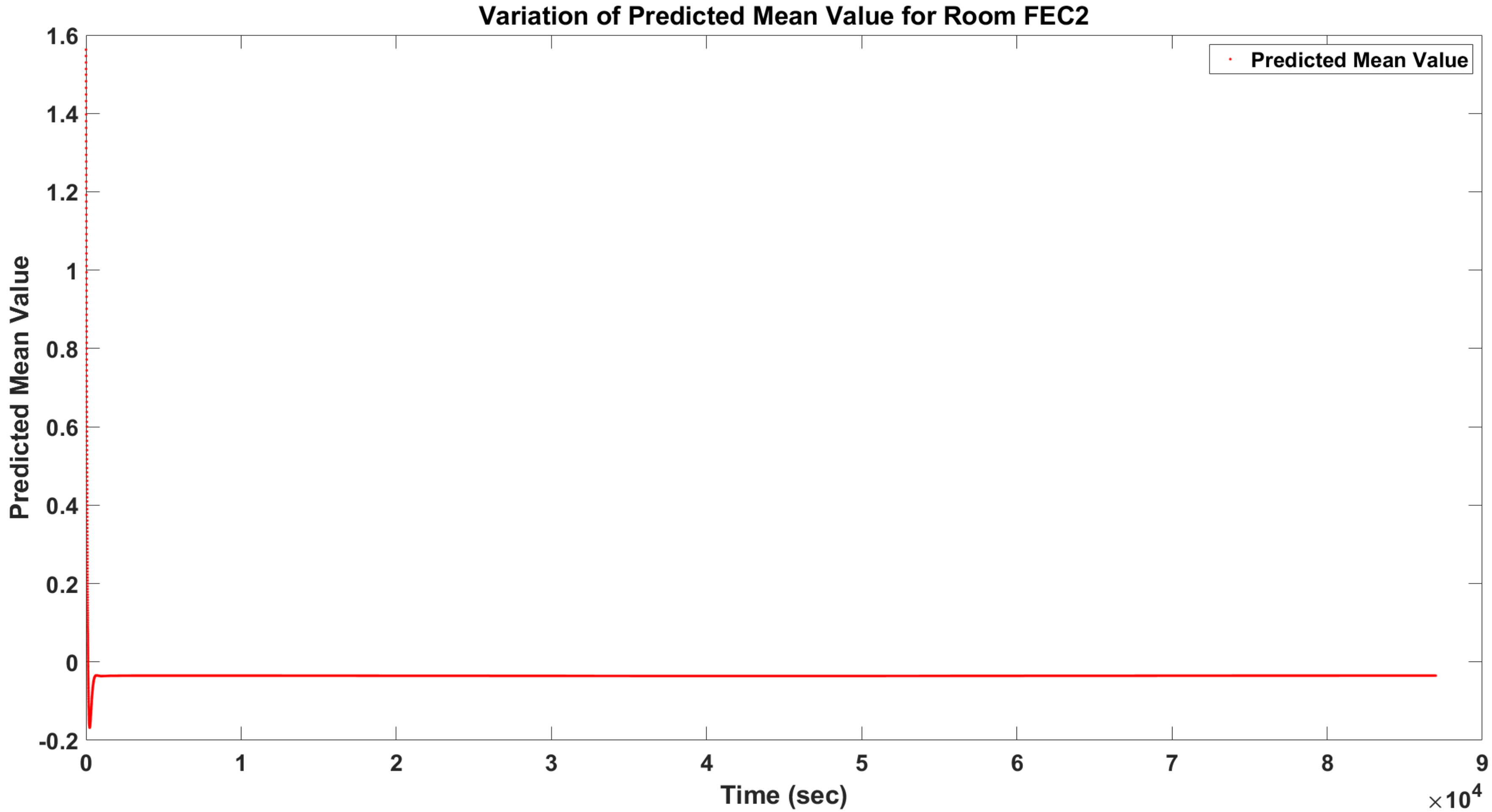
Simulated Heat Gains in the room
Qacmv with policies

DISCUSSION OF RESULTS



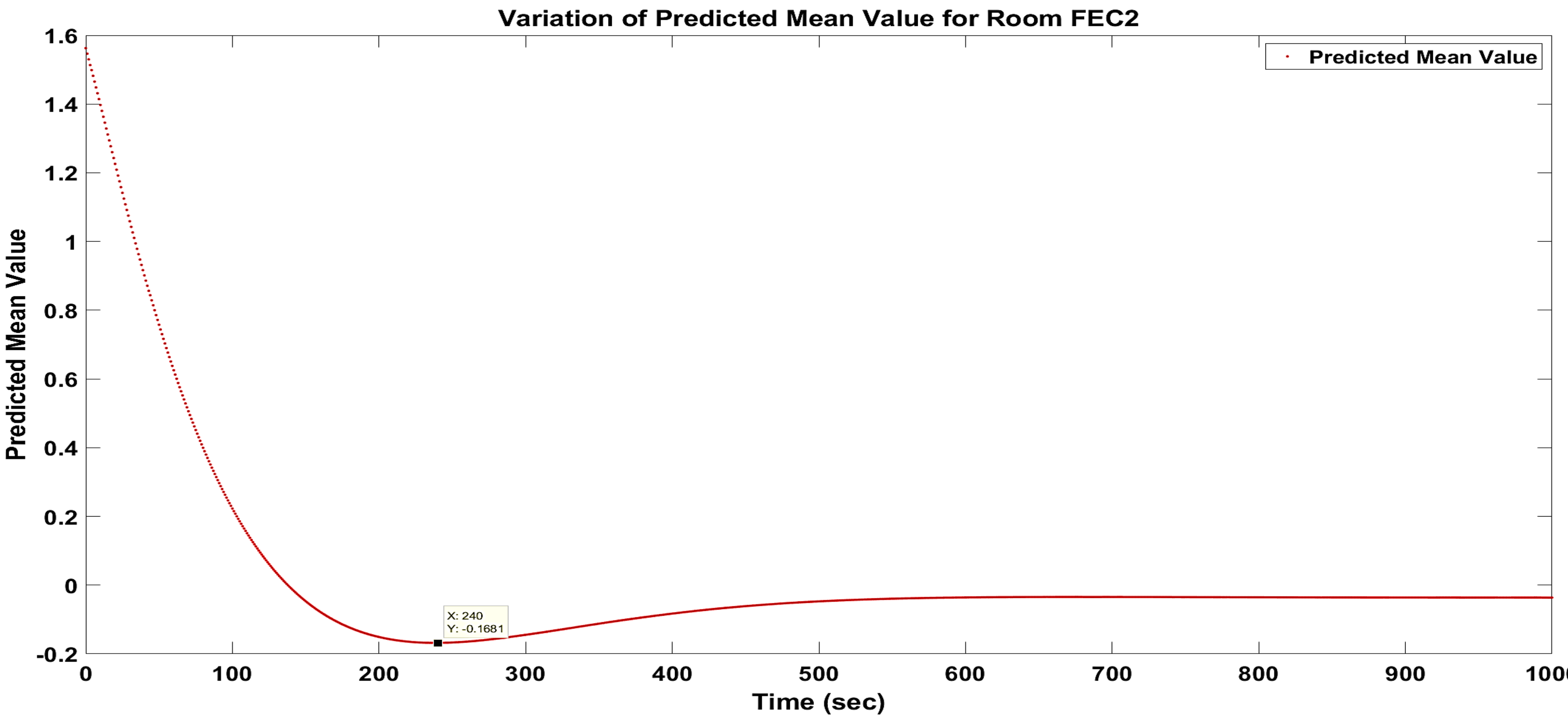
Simulated Heat Gains in the room
Qacmv without policies

Discussion of Results



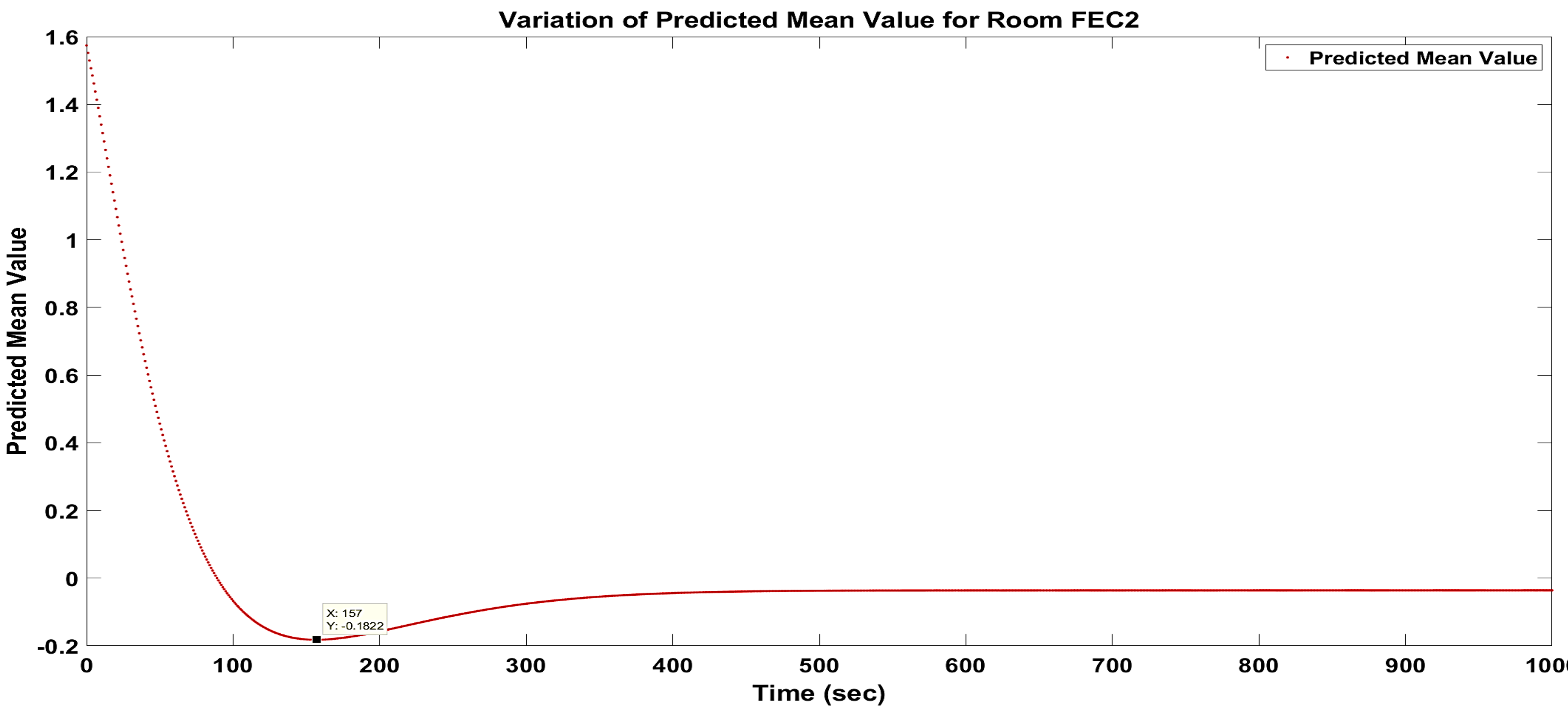
Predicted Mean Value of Thermal Comfort based on simulated temperature variations

Discussion of Results



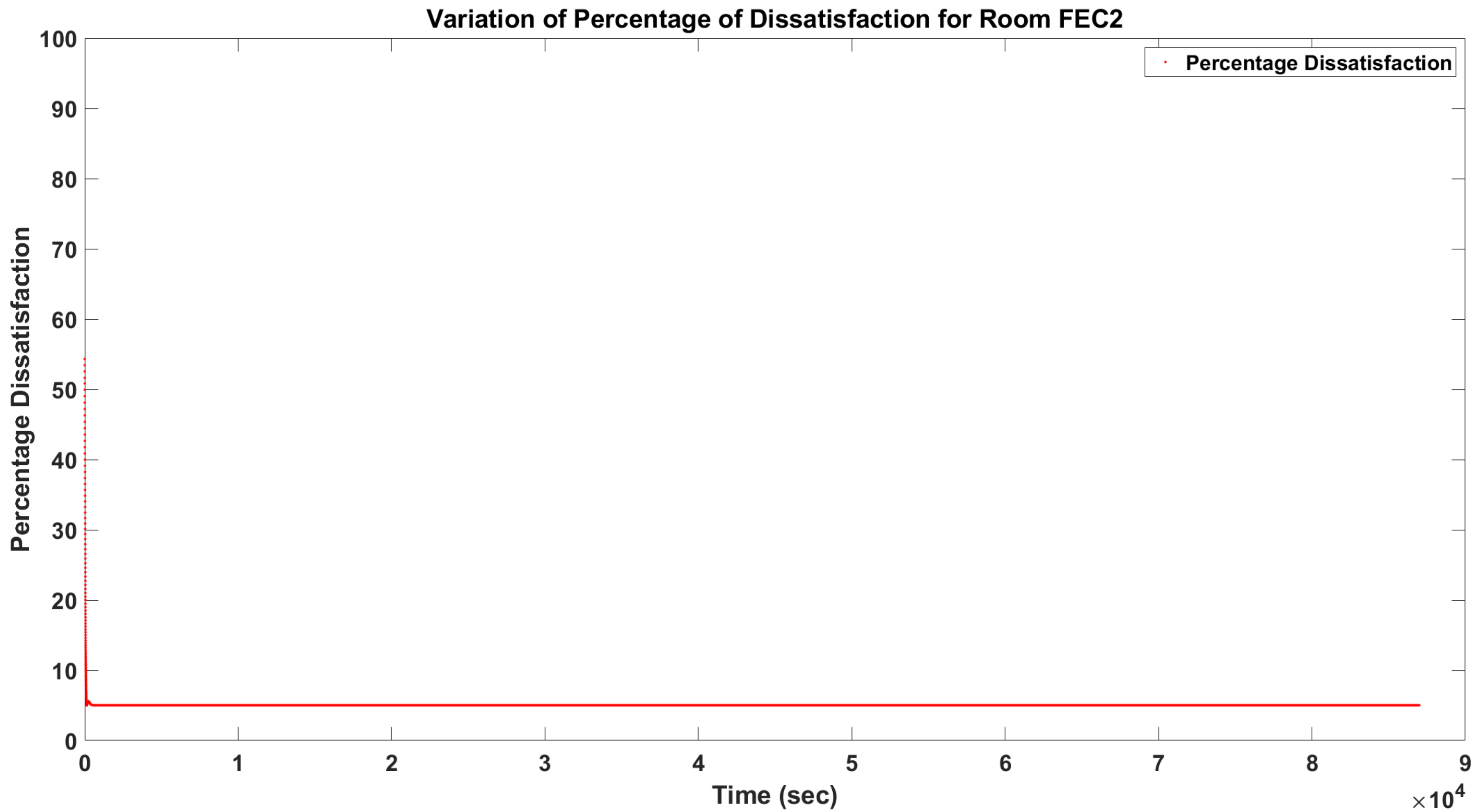
Predicted Mean Value of Thermal Comfort with policies

DISCUSSION OF RESULTS



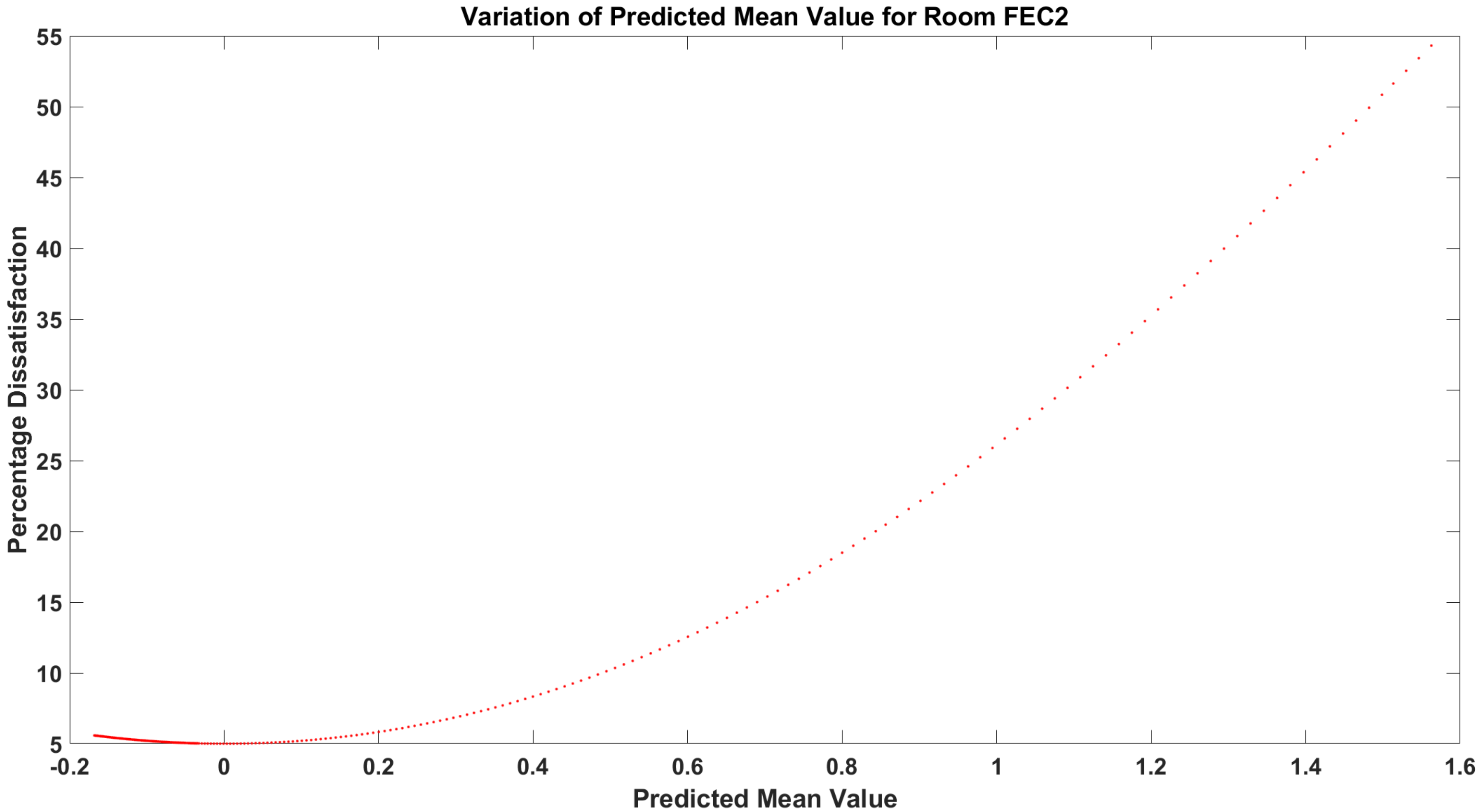
Predicted Mean Value of Thermal Comfort without policies

DISCUSSION OF RESULTS



Predicted percentage of Dissatisfaction of Thermal Comfort based on simulated temperature variations

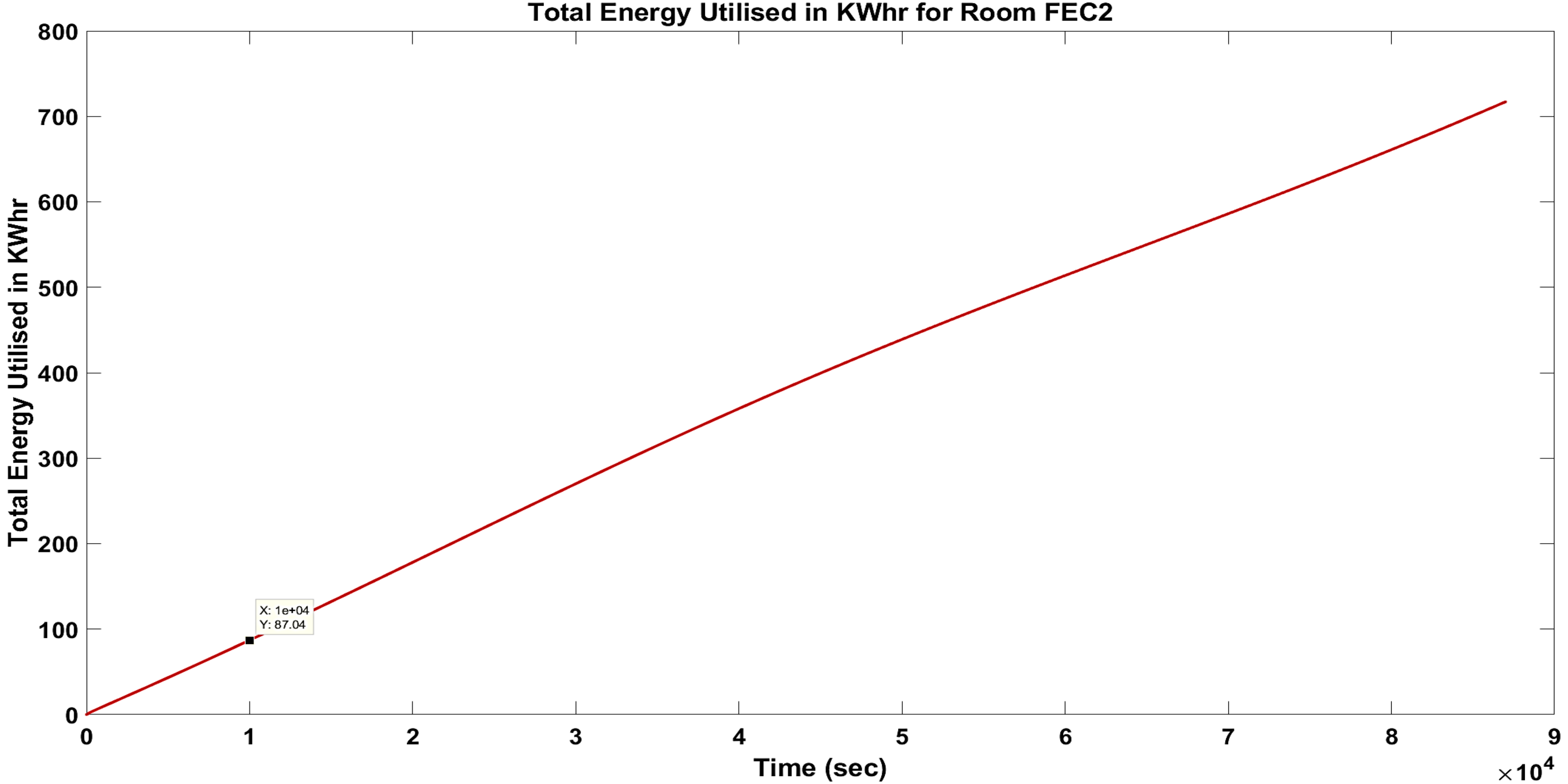
DISCUSSION OF RESULTS



Predicted Mean Value vs PPD of Thermal Comfort based on simulated temperature variations

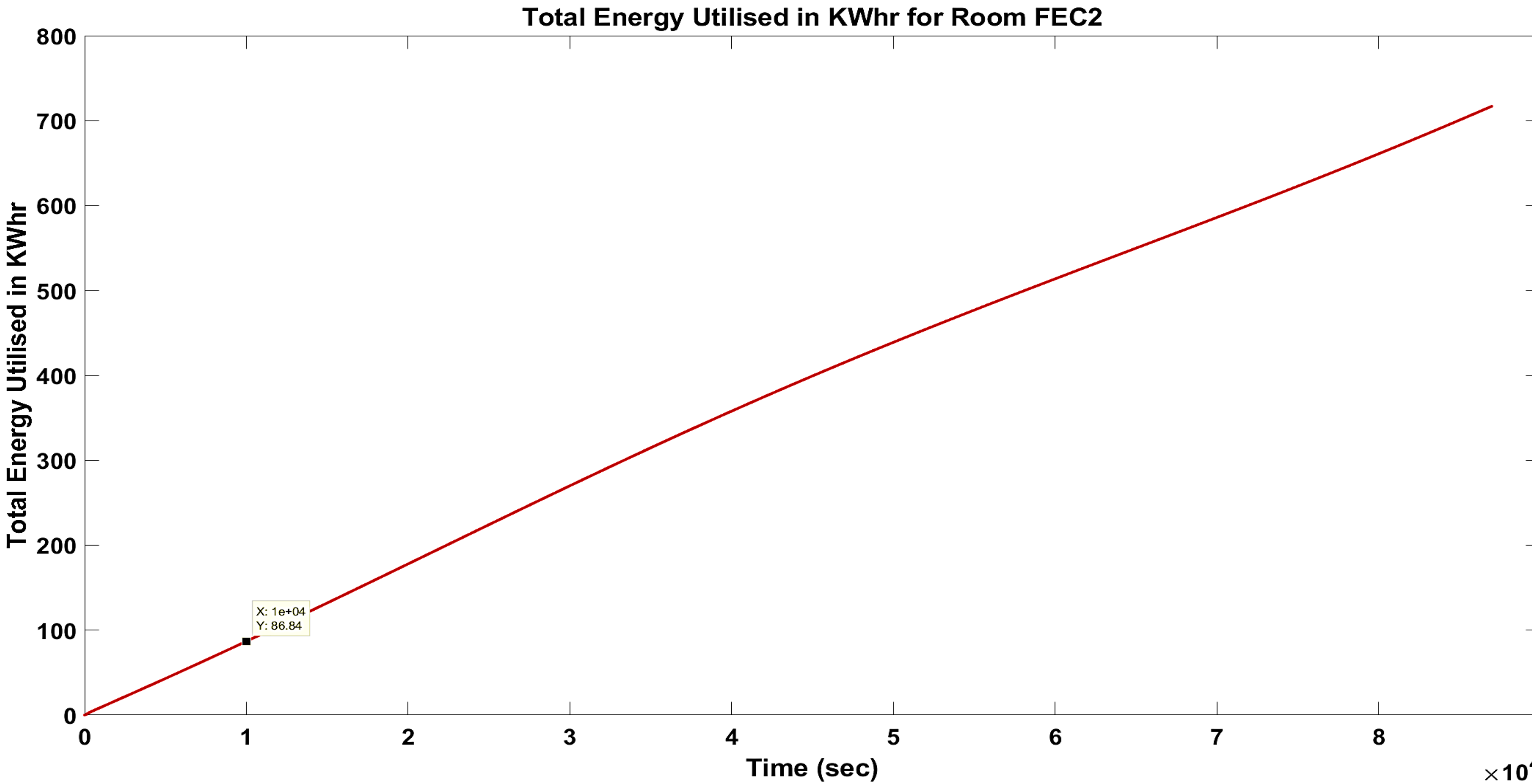
Discussion of Results

Energy cost without policies being implemented



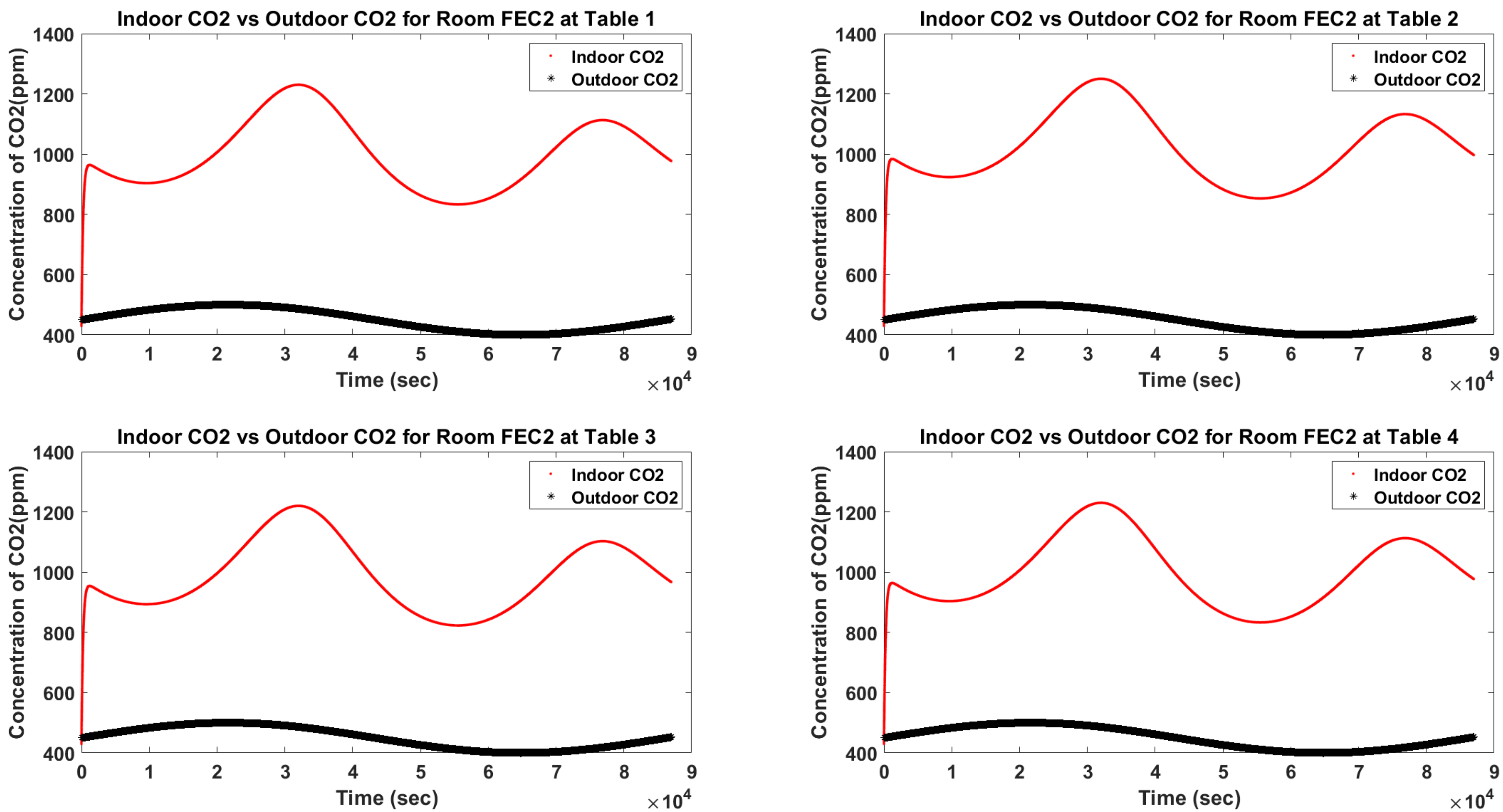
Discussion of Results

Energy cost with policies being implemented



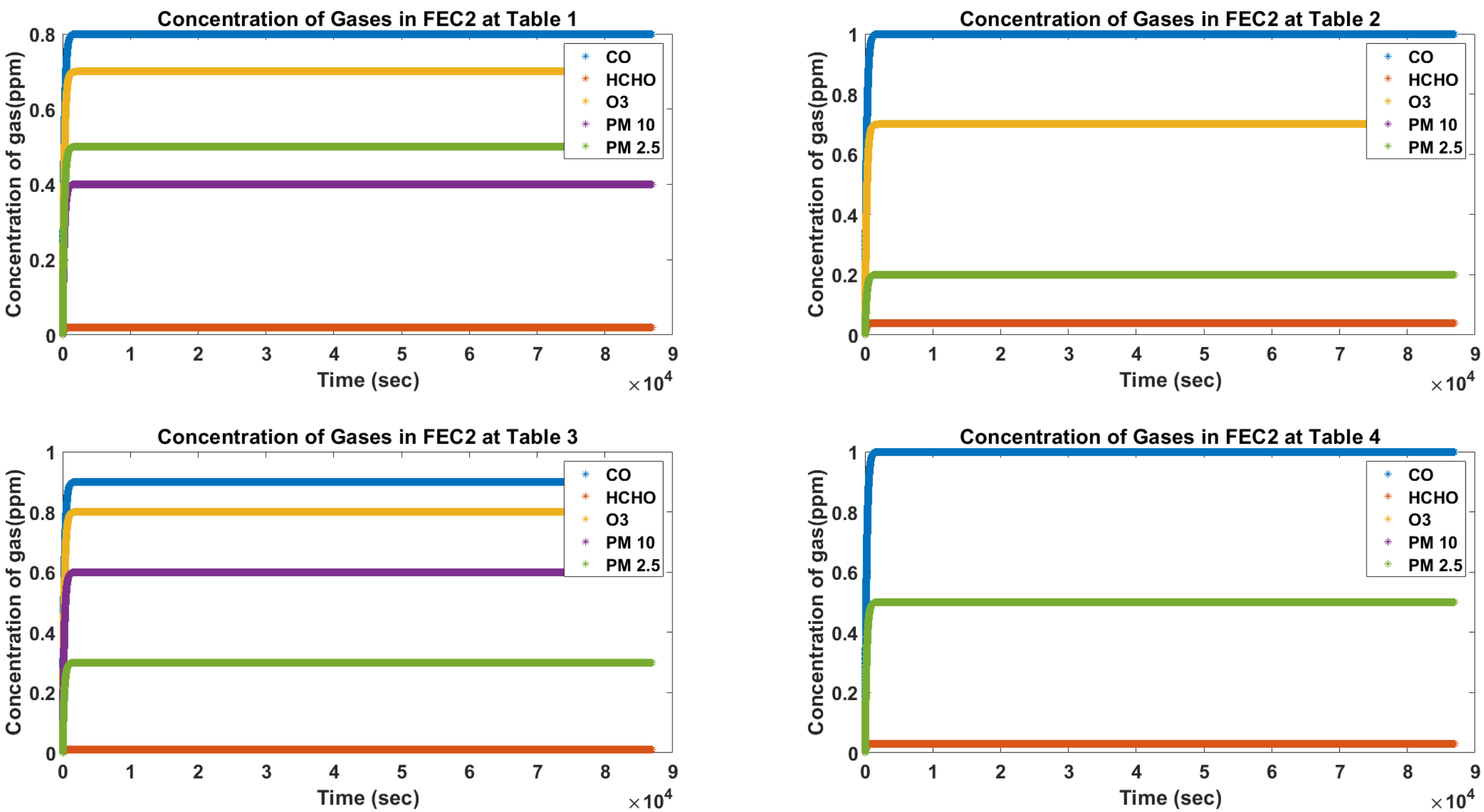
Discussion of Results

Air Quality



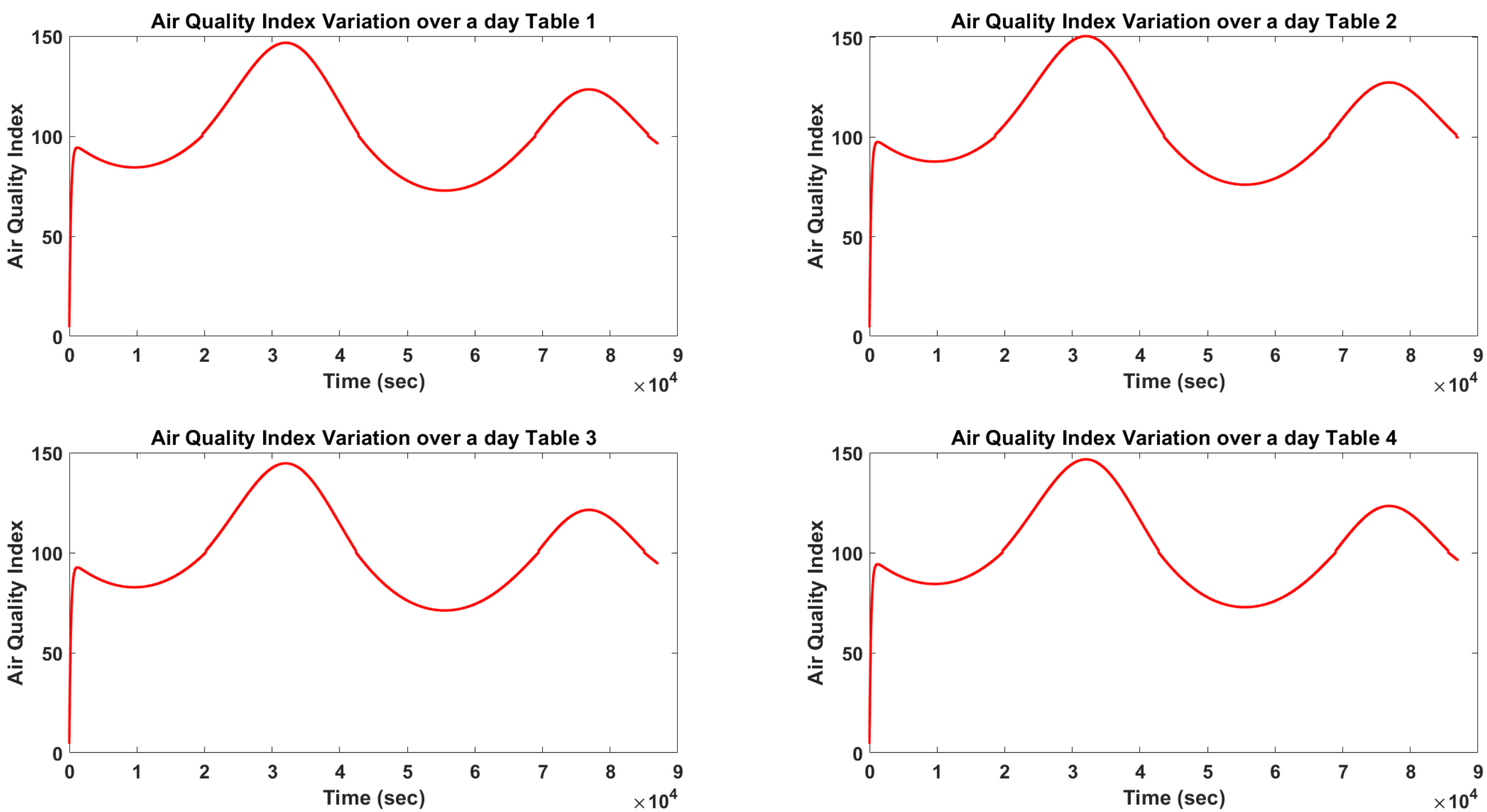
Simulated CO2 variation in the room at 4 Tables

Discussion of Results



Simulated Gas Concentration variation in the room at 4 Tables
Constant after some time as no external variation of data available

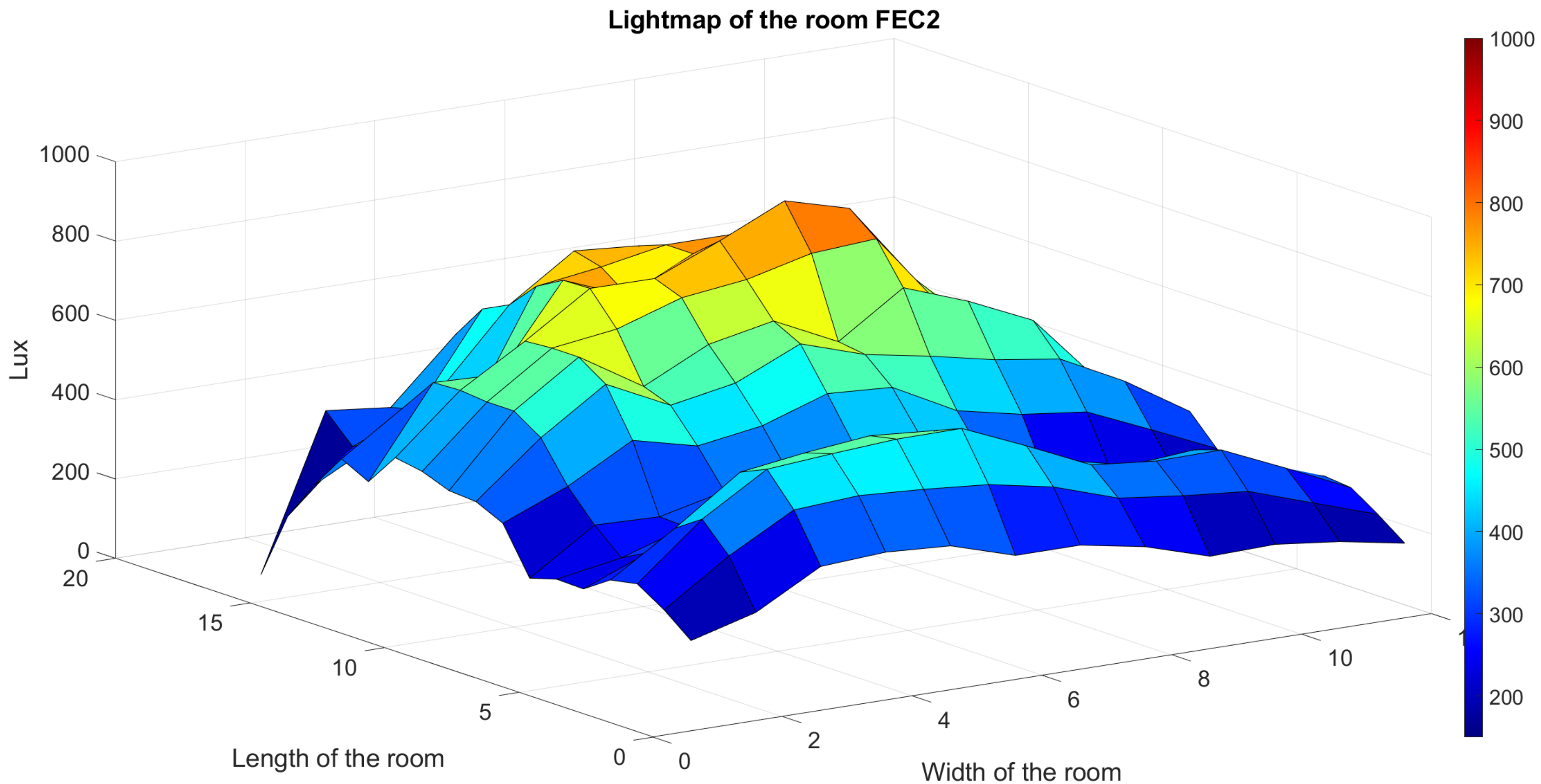
DISCUSSION OF RESULTS



Air Quality Index variation from Simulated Concentration of gases

Discussion of Results

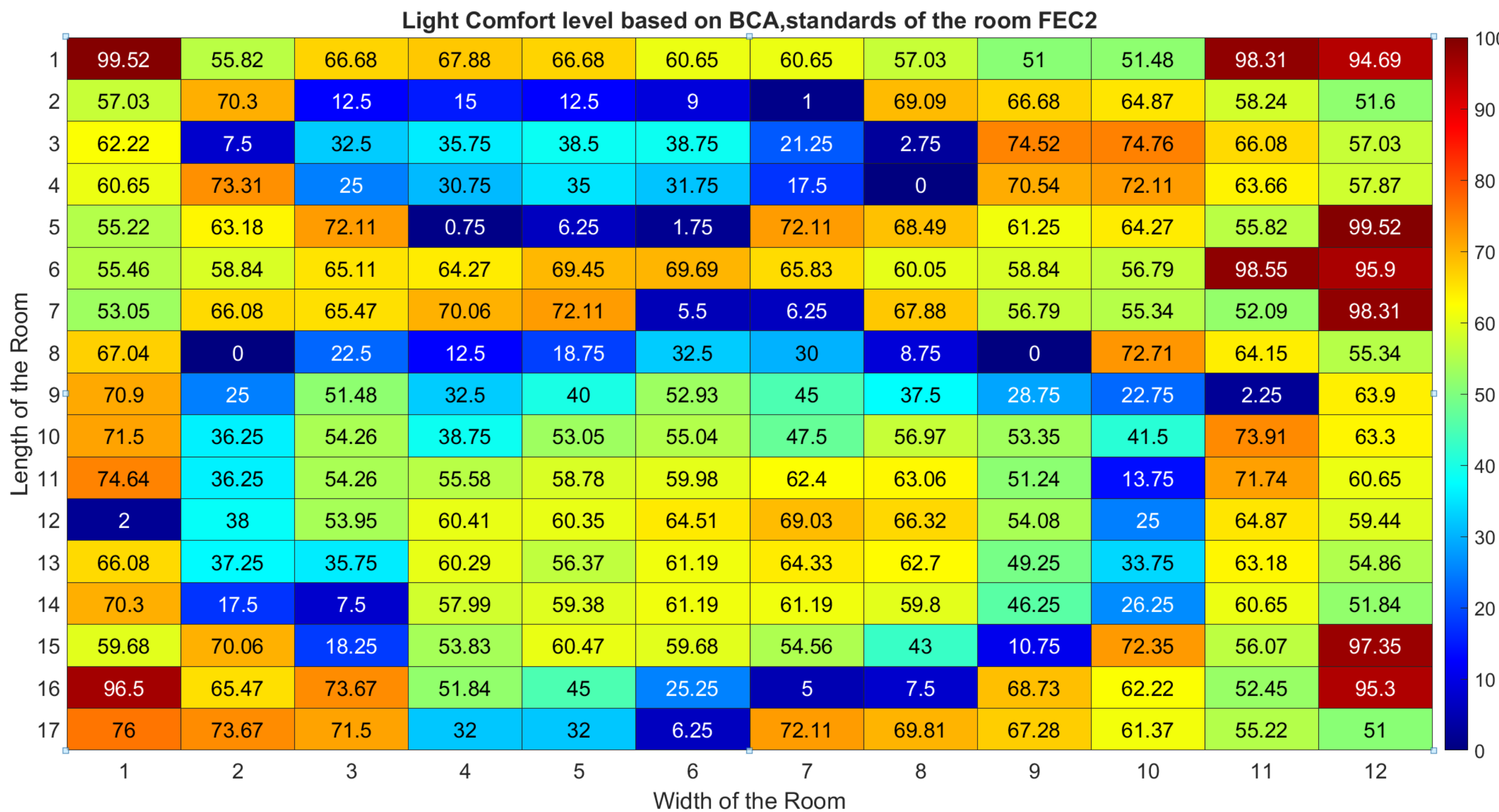
Lighting Quality



Lightmap of the room FEC2

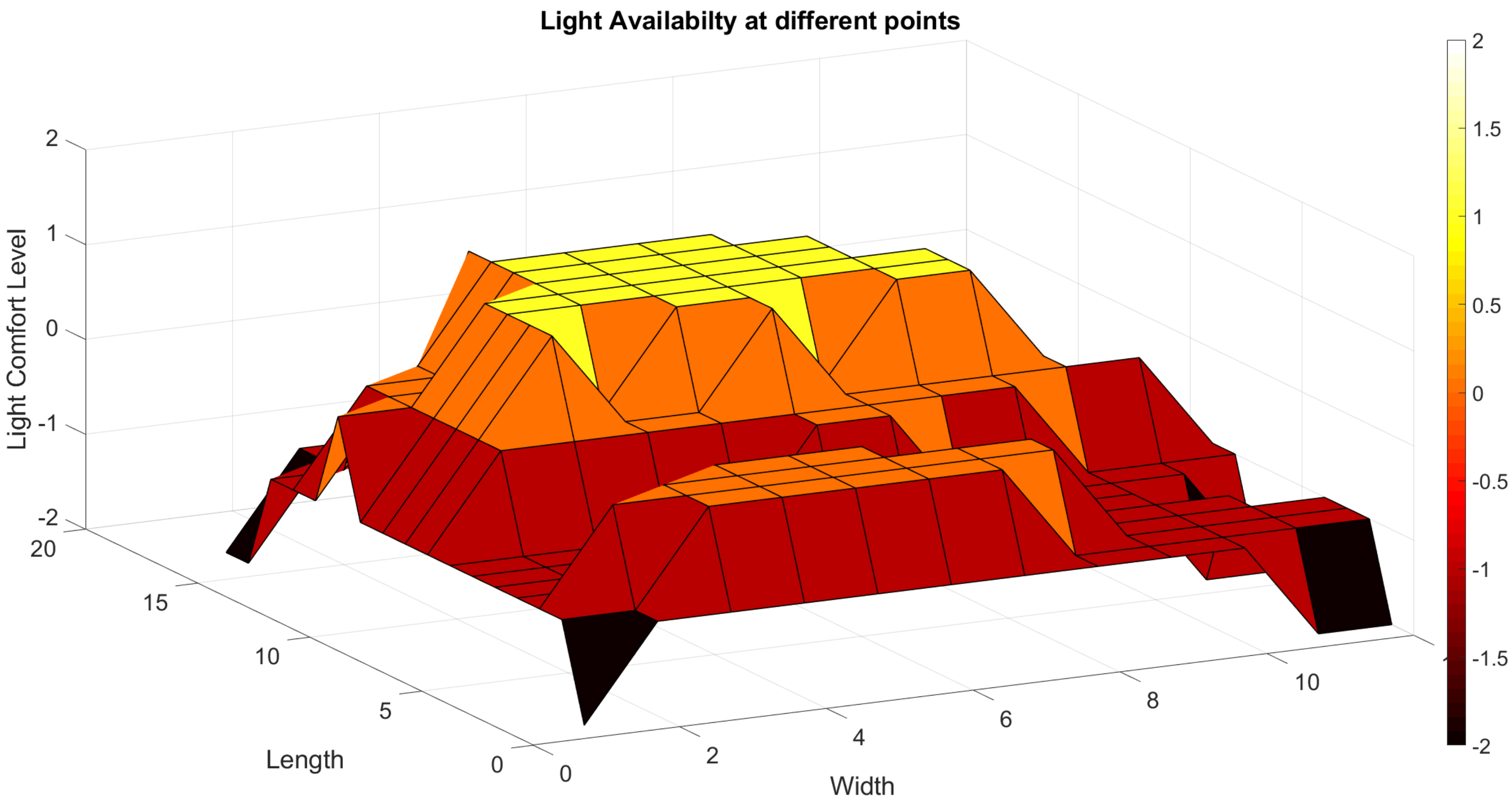
NUS National University of Singapore

Discussion of Results



Lighting Index at each point of measurement taken in room FEC2

DISCUSSION OF RESULTS



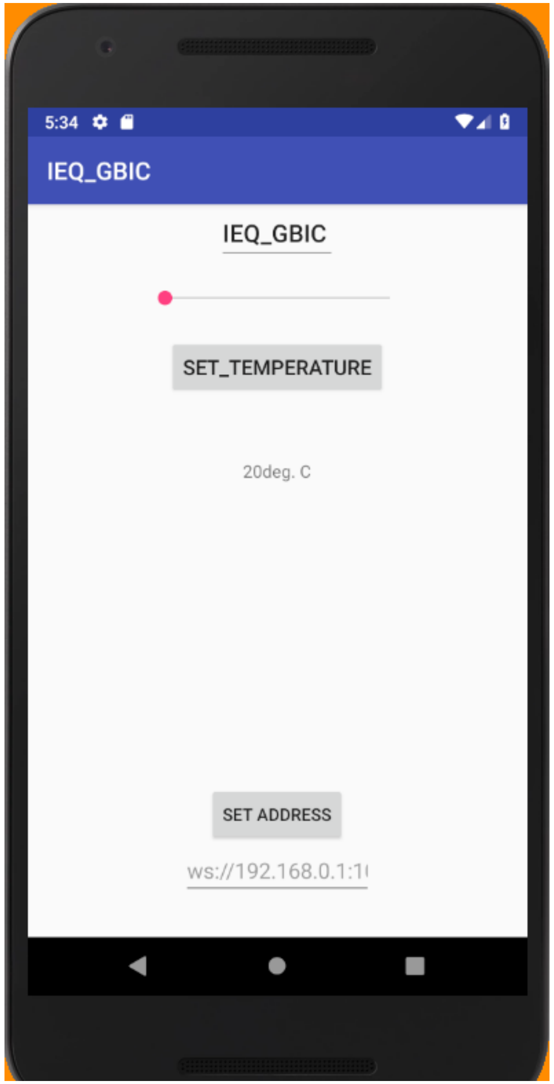
Lighting Comfort Level at each point of measurement taken in room FEC2 ranging from -2 to 2

CONCLUSION

IEQ monitoring was done by GUI in MATLAB Simulink based on simulated environment. Agent system was implemented based on policies but control of environment not taken rather indices were given for user information and thereby variation of set-point from user.

Future work may include: Development of phone application for user input and feedback.

RELATED WORK



ANDROID APP FOR USER PREFERENCE

NUS
National University of Singapore

THANK-YOU

APPENDIX

Indoor Air Quality:

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

Regulatory level of indoor air constituents by Institute of Environmental Epidemiology, Ministry of the Environment, Singapore

APPENDIX

Thermal Capacitance and Resistance in Electrical Analogy:

- Thermal Capacitance – Capacity to store heat – analogous to Capacitance in electrical circuit.
- Thermal Resistance – Resists the flow of heat - analogous to Resistance in electrical circuit.
- Flow of heat Q – Analogous to current in the circuit.
- Temperature Difference between two surfaces – Analogous to Potential difference in electrical circuit.

APPENDIX

Gas measured	Sensor	Range	Accuracy	Resolution	Communication
CO_2	SenseAir S8	0-20000ppm	± 4ppm	1 ppm	Modbus to UART
CO_2	Aeroqual	0-5000ppm	± 20ppm	1 ppm	-
CO	Spec CO sensor	0-1000ppm	± 1ppm	0.1 ppm	Digital UART interface
CO	Aeroqual	0-1000ppm	± 2ppm	1 ppm	-
O_3	Spec O3 sensor	0-5ppm	15% of reading	20 ppb	Digital UART interface
O_3	Aeroqual	0-10ppm	± 0.01ppm	0.01ppm	-
HCHO	DF Robot HCHO sensor	0-5ppm		0.01 ppm	UART or DAC
HCHO	Aeroqual	0-10ppm	± 0.05ppm	0.01ppm	
Dust PM2.5 and PM 10	SM-PWM-01C dust sensor	0.01-3000 ug/m3			Analog
Dust PM2.5	Aeroqual	0-1000 ug/m3	0.002 mg/m3	0.001 mg/m3	