An Energy-Efficient Climate Control Solution for Smart Buildings Based on Predicted-Mean-Vote Criteria

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ABSTRACT
In this paper, the climate control solution “ClimaCon” is proposed. ClimaCon is an external extension to any HVAC system. It aims to reach the best thermal comfort for individuals in several zones with the least possible energy consumption. The Solution basically consists of a closed-loop controller, using Raspberry PI (RPI), to control the HVAC actuators and the VAV unit [1] while getting the feedback signals through wireless sensing nodes present across different places in the controlled zone. The performance of the controller is tested through extensive simulation using the MATLAB based Hambase module [2]. The controller proves the ability to maintain the thermal comfort of individuals in the zone during energy saving profiles with excellent performance over twelve different use cases.

Keywords
Ubiquitous computing, Climate Control, Building Automation, Internet of Things.

1. INTRODUCTION
It has been known for a long time that the thermal comfort of a human being is not dependent only on air temperature but it is a function of several parameters [2]; mean radiant temperature, relative air velocity, activity level, and clothing. We take this facts into consideration and by installing a control unit into the central air conditioner of any building, we try to achieve the best combination of these parameters to reach the best thermal comfort of individuals in several zones with the least possible energy consumption, the data is collected from the zone using several nodes [3][4][5][6] put in different places inside each zone and then sent to the controller. The data is processed by the controller to analyze the situation inside each zone and then predict the new values of the outputs to reach the set points of the temperature and humidity. The controller offers to the user three modes of comfort to choose from beginning with energy saving mode which cares more about saving energy then moderate mode which tries to reach more thermal comfort to the individuals and the last mode which is the high comfort mode which offers the best thermal comfort for the individuals.

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In the following parts of the paper we proceed by explaining briefly our solution, and then we describe the controller used, sensing nodes, inputs and outputs modules, the different modes offered by the controller reaching the simulation results when the controller is put into test.

2. THE CLIMACON SYSTEM

2.1 System Overview
ClimaCon System mainly consists of three parts; sensors nodes, coordinator and controller.

The sensors nodes collect the data through the temperature, humidity and air quality sensors; they communicate with the system through Zigbee [3].

The coordinator is the interface between the Zigbee domain (nodes side) and the Ethernet domain (controller side).

The controller runs the program which collects the data from all different nodes and/or zones; applies the control and fault detection algorithms; calculates outputs and sends them to the specific node.

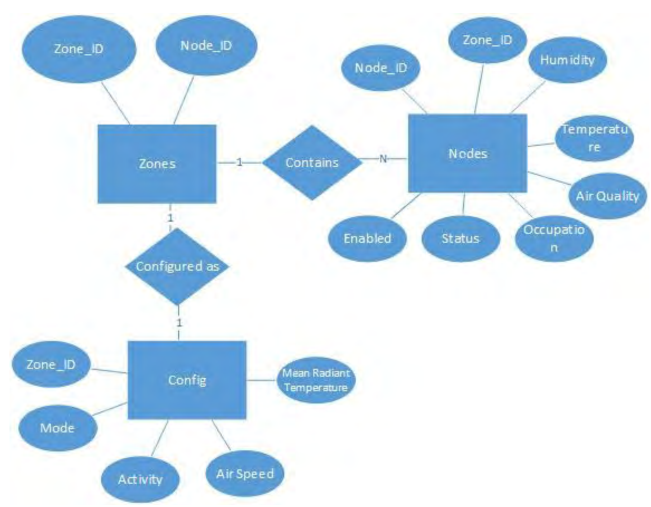

Figure 1. Entity relationship diagram

The three main entities are shown in the entity relation diagram are (Figure 1):

Zones: identify the different zones with the nodes connected to each.

Nodes: contains the attributes read by the sensor's nodes (temperature, humidity, air quality in addition to some attributes that identify the status of the node)

Configuration: contains some parameters needed by the control algorithm. These parameters need to be configured by the user for each zone; such as the expected level of activity and the air speed.

2.2 PMV and PPD

Our solution is concerned in keeping track of the thermal comfort on the individuals inside the controlled zone, to do that we must keep track of some parameters affecting the thermal comfort of human beings. These parameters are introduced in the comfort equation by Prof. P.O. Fanger [7] and then to quantify the degree of discomfort an index is devised [7] which gives the Predicted Mean Vote (PMV) from tables given in [2] page 7 or from the equation taking into account the following parameters:

- **Metabolism**, W/m^2 (1 met = 58.15 W/m^2)
- **External work**, met. Zero for most metabolisms.
- **Thermal resistance of clothing**, clo (1 clo = 0.155 m^2 K/W), the ratio of the surface area of the clothed body to the area of the nude body.
- **Air temperature**, °C
- **Relative air velocity**, m/s
- **Water vapor** pressure, Pa
- **Convective heat transfer coefficient**, W/m^{2}K and surface temperature of clothing.

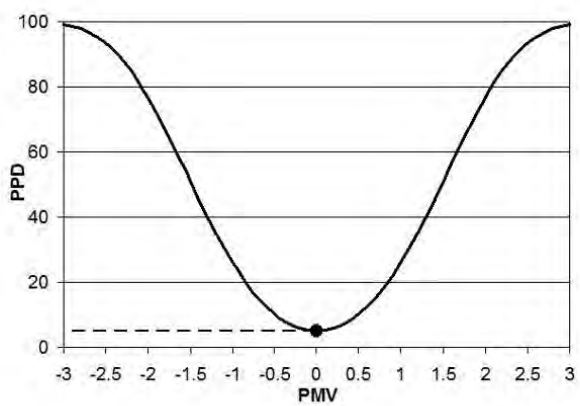

Figure 2. The relation between PPD (Predicted Percentage of Dissatisfied) and PMV (Predicted Mean Value)

The Predicted Percentage of Dissatisfied (PPD), may then be estimated from Fig.1 and when the PMV reaches zero the least percentage of dissatisfied (PPD) is located (5%)

2.3 Temperature and Relative Humidity Set Points

According to the (PMV) and (PPD) equations a study is made to find the perfect temperature and humidity for each activity and clothing values, the relative humidity in the study is set with constant value (45%) and the temperature set point will differ according to different combinations of activity and clothing. The study is shown in table 1

Table 1. Temperature Set Point study for different combinations of activity and clothing

Activity description	Clothing description	Temperature Set Point	Corresponding PPD
Lying down	summer clothing	28.7	5
Lying down	working suits	27.4	5
Lying down	Winter	26.6	5
Lying down	European Winter	24.5	5
Sitting quietly	summer clothing	26.5	5
Sitting quietly	working suits	25	5
Sitting quietly	Winter	24	5.1
Sitting quietly	European Winter	21	5
Sitting sedentary	summer clothing	25	5.1
Sitting sedentary	working suits	23	5.1
Sitting sedentary	Winter	22	5
Sitting sedentary	European Winter	19	5
Moving Light Activity	summer clothing	22.5	5
Moving Light Activity	working suits	20	5
Moving Light Activity	Winter	18.7	5
Moving Light Activity	European Winter	15	5
Moving Medium Activity	summer clothing	20	5
Moving Medium Activity	working suits	17	5
Moving	Winter	16	5.1

Medium Activity			
Moving Medium Activity	European Winter	11	5
Moving High Activity	summer clothing	13.5	5
Moving High Activity	working suits	10	5
Moving High Activity	Winter	7.2	5
Moving High Activity	European Winter	1	5

According to the predefined value of activity and clothing set by the user, the controller will work to reach the corresponding set point temperature to obtain the best PPD in all different cases.

2.4 Raspberry Pi Controller and Its Different Modes

We used a raspberry pi controller (RPI); it is one example of Plug Computers operating on Linux with 700 MHz low power ARM1176JZ-F applications processor, 512 MB of RAM and a 100MB Ethernet port.

The RPI runs the controller program which continuously read/write data from/to the router which in turn reads/writes from/to the Nodes as necessary. It also holds the Database where the collected data is stored.

Now we will list all the control input and output signals to introduce the reader to the parameters that affect the decision making of the controller and the controlled actuators; the inputs are measured and sent to the controller through several nodes installed in different places in each zone and here are the inputs and outputs of the controller:

Table 2. Inputs and outputs of the controller

Inputs	Outputs
- Zone Sensed Temperature [Tz] - Zone Sensed Relative Humidity [RHz] - Zone Sensed PIR Occupancy [Oz] - Zone Sensed Air Quality [AQz]	- Zone VAV Damper Position [DP_z] - Zone Humidifier Status [HF_z] - Zone Heater Status [HT_z] - Zone Blower Speed Fan [SF_z] - Zone Evacuation Blower [EB_z] - Zone Alarm Beeper Alarm - Zone Status LEDs (Green, Orange Yellow, Red)

On the controller two different algorithms run concurrently so we can assume the presence of two different controllers; “Air quality controller” and “Energy saving and Comfort controller”.

The first controller (air quality controller) has the higher priority. It is responsible for calculating the optimal HVAC output values (DPz, SFz, EBz, Beeper) it checks the air quality of the room and gives the output values to achieve the most healthy air quality and this controller is activated if and only if the air quality sensor gives the indication that the air inside the zone is highly polluted or severely polluted at this case the output values are taken from this controller as it has the highest priority.

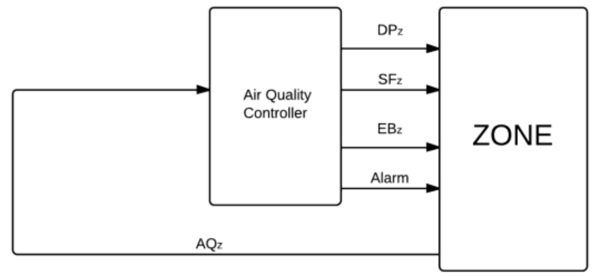

Figure 3. Air quality controller diagram

If the air quality sensor indicates that the air inside the zone is clean the air quality controller is skipped and the second controller are put into action and we take its outputs to be the new outputs of the actuator. First “The Energy saving and comfort controller” checks the occupancy in the zone if the zone is unoccupied the controller works to keep the PPD between (25% to 30%) (Energy saving sub controller) but if the room is occupied the comfort controller offers three different modes for the user to choose from them; High comfort mode (PPD value is kept between 6% to 8%), Balanced mode (PPD value is kept between 6% to 14%), Energy saving mode (PPD value is kept between 6% to 20%)

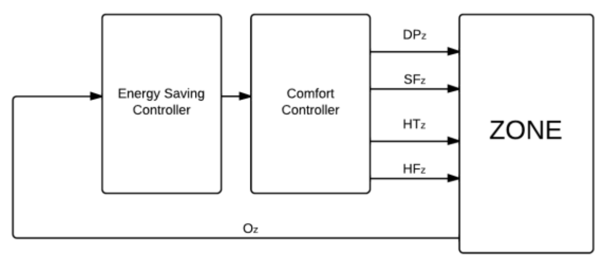

Figure 4. Comfort controller diagram

2.5 Fuzzy Logic of the Outputs

The controller updates the outputs’ values according to certain fuzzy logic for each output; we will discuss now the fuzzy logic of each output and also introduce the temperature and humidity fuzzy logic:

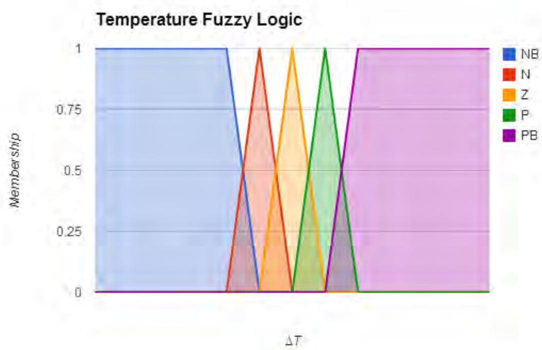

Figure 5. Temperature fuzzy logic diagram

Delta temperature = desired Temperature (according to the study) - sensed Temperature
-Less than -1.5Negative Big (NB)
-Between -3 and 0 Negative (N)
-Between -1.5 and 1.5 Zero (Z)
-Between 0 and 3 Positive (P)
-Greater than 1.5 Positive Big (PB)

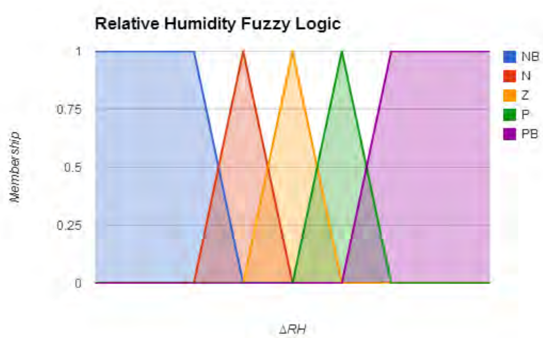

Figure 6. Relative humidity fuzzy logic diagram

Delta Relative Humidity = desired Relative Humidity (45 %) - sensed Relative Humidity
-Less than -10Negative Big (NB)
-Between -20 and 0 Negative (N)
-Between -10 and 10 Zero (Z)
-Between 0 and 20 Positive (P)
-Greater than 10 Positive Big (PB)

2.5.1 Outputs fuzzy logic:

(1) VAV Damper Position [DP_z]

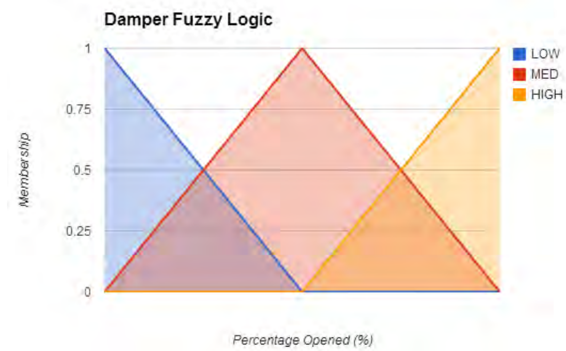

Figure 7. Damper fuzzy logic diagram

Table 3. Damper fuzzy logic values

	NB(ΔRH)	**N(ΔRH)**	**Z(ΔRH)**	**P(ΔRH)**	**PB(ΔRH)**
NB (ΔT)	HIGH	HIGH	HIGH	HIGH	HIGH
N (ΔT)	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Z (ΔT)	LOW	LOW	LOW	LOW	LOW
P (ΔT)	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM
PB (ΔT)	HIGH	HIGH	HIGH	HIGH	HIGH

(2) Heater [HTz]

Table 4. Heater fuzzy logic values

	NB (ΔRH)	**N (ΔRH)**	**Z (ΔRH)**	**P (ΔRH)**	**PB (ΔRH)**
NB (ΔT)	OFF	OFF	OFF	OFF	OFF
N(ΔT)	OFF	OFF	OFF	OFF	OFF
Z(ΔT)	OFF	OFF	OFF	OFF	ON
P(ΔT)	ON	ON	ON	ON	ON
PB (ΔT)	ON	ON	ON	ON	ON

(3) Supply Fan [SFz]

Table 5. Supply fan fuzzy logic values

	NB (ΔRH)	**N(ΔRH)**	**Z(ΔRH)**	**P(ΔRH)**	**PB (ΔRH)**
NB(ΔT)	HIGH	HIGH	HIGH	HIGH	HIGH
N (ΔT)	MEDI	MEDIU	MEDIU	MEDIU	MEDI

	UM	M	M	M	UM
Z (ΔT)	LOW	LOW	LOW	LOW	LOW
P (ΔT)	MEDI UM	MEDIU M	MEDIU M	MEDIU M	MEDI UM
PB(ΔT)	HIGH	HIGH	HIGH	HIGH	HIGH

(4) Humidifier and Dehumidifier [HFz]

Table 6. Humidifier and dehumidifier fuzzy logic values [H: Humidifier ON - D: Dehumidifier ON - O: Both OFF]

	NB (ΔRH)	**N(ΔRH)**	**Z (ΔRH)**	**P (ΔRH)**	**PB (ΔRH)**
NB (ΔT)	D	D	D	O	O
N (ΔT)	D	D	D	O	H
Z (ΔT)	D	D	O	H	H
P (ΔT)	D	O	H	H	H
PB (ΔT)	O	O	H	H	H

(5) Evacuation Blower [EBz]

Table 7. Evacuation blower fuzzy logic values

	NB (ΔRH)	**N (ΔRH)**	**Z (ΔRH)**	**P (ΔRH)**	**PB (ΔRH)**
NB (ΔT)	MED	LOW	OFF	OFF	OFF
N (ΔT)	MED	LOW	OFF	OFF	OFF
Z (ΔT)	OFF	OFF	OFF	OFF	OFF
P (ΔT)	OFF	OFF	OFF	OFF	OFF
PB (ΔT)	OFF	OFF	OFF	OFF	OFF

2.6 MATLAB Simulation and Results

2.6.1 Different seasons' results:

To put our controller into test we used Simulink to run our tests. As a first phase we chose recorded data from random four days from Egypt's history, the data from each day is 24 samples from each day to the temperature and relative humidity. In other words sample every hour from that day. We meant to choose four days from the four seasons to test the ability of the controller in different seasons and different temperatures and to simulate the presence of a building with different zones we used Hambase module [8]

We ran over twelve simulation cases; three simulations for each chosen day, we chose the high comfort mode for all simulations to work on the hardest cases, we will show you now the results of sample simulation from each day:

Case (1): 2nd of August 1985 "Summer" the zone is assumed to be an office, occupied all day long, air quality clean, activity of the individuals is "Sitting sedentary" and clothing is "working suits", temperature set point from the study is 23°C and humidity set point is 45%

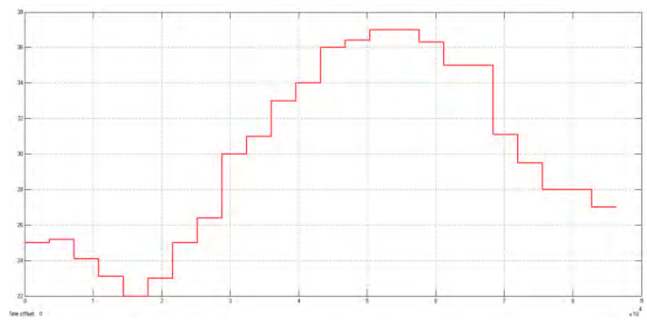

Figure 8 Case(1) outside temperature

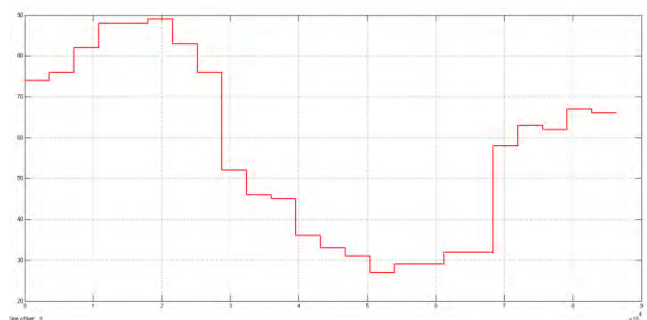

Figure 9. Case(1) outside relative humidity

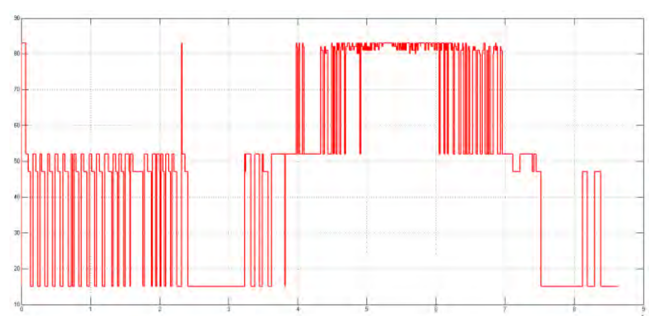

Figure 10. Case(1) VAV unit damper opening percentage

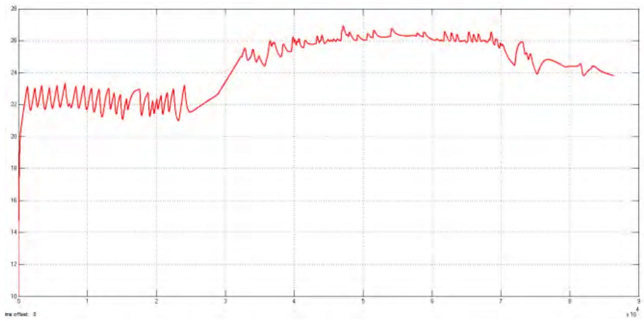

Figure 11. Case(1) zone temperature

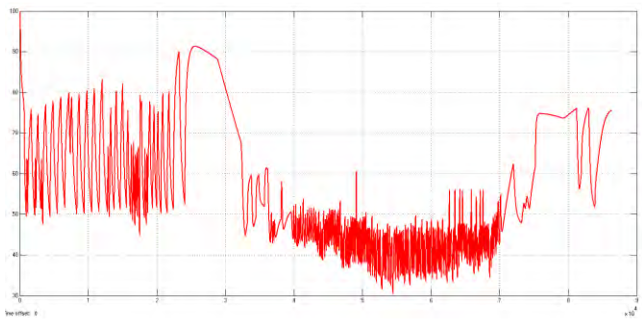

Figure 12. Case(1) zone relative humidity

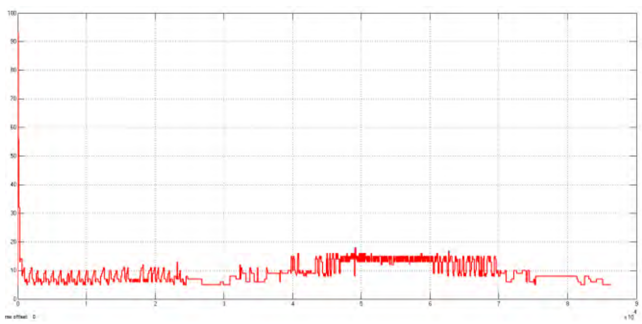

Figure 13. Case(1) individuals PPD

Case (2): 23rd of September 1993 “Autumn” the zone is assumed to be an office, occupied all day long, air quality clean, activity of the individuals is “Sitting sedentary” and clothing is “working suits”, temperature set point from the study is 23°C and humidity set point is 45%

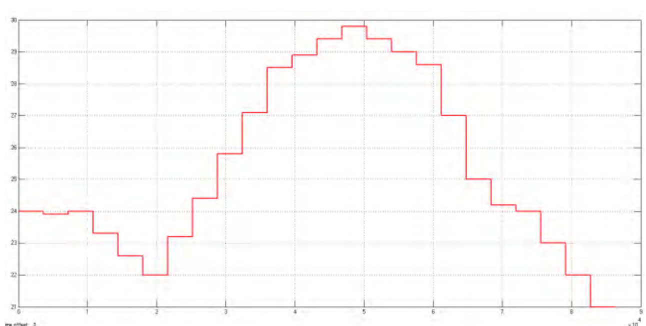

Figure 14. Case(2) outside temperature

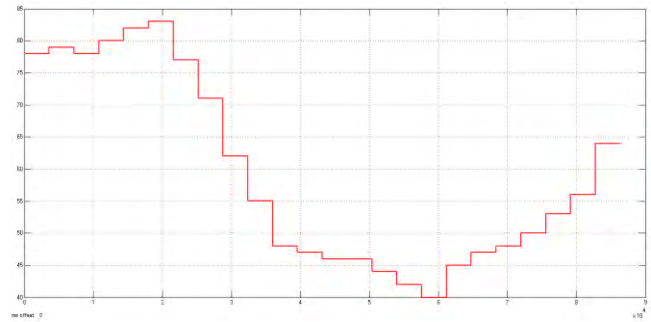

Figure 15. Case(2) outside relative humidity

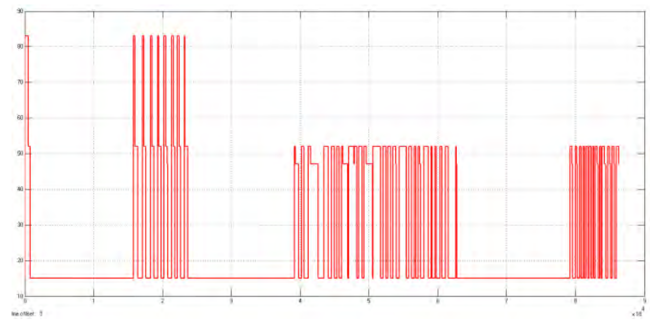

Figure 16. Case(2) VAV unit damper opening percentage

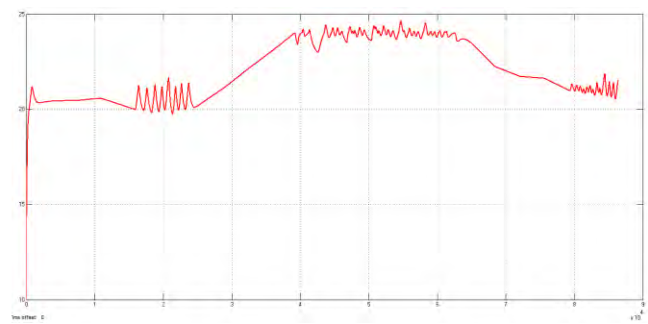

Figure 17. Case(2) zone temperature

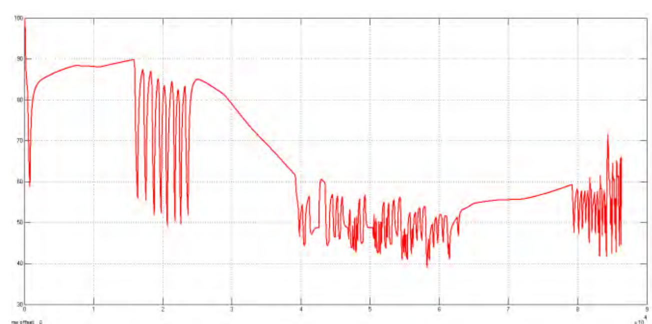

Figure 18. Case(2) zone relative humidity

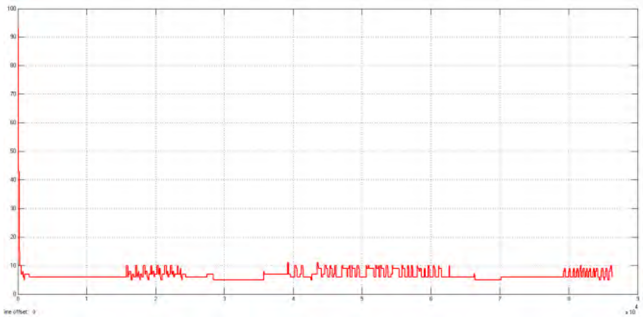

Figure 19. Case(2) individuals PPD

Case (3): 1st of January 1988 “Winter” the zone is assumed to be an office, occupied all day long, air quality clean, activity of the individuals is “Sitting sedentary” and clothing is “European Winter”, temperature set point from the study is 19°C and humidity set point is 45%

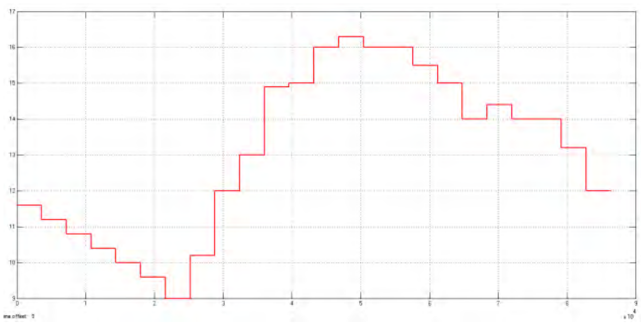

Figure 20. Case(3) Outside Temperature

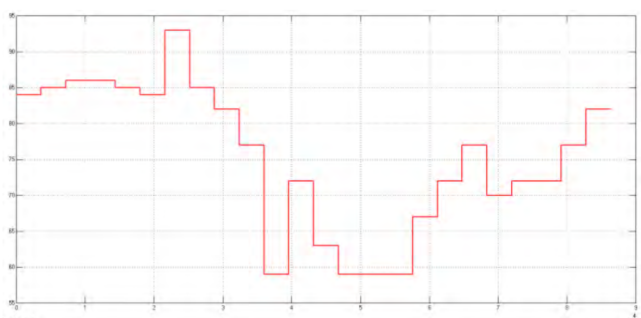

Figure 21. Case(3) outside relative humidity

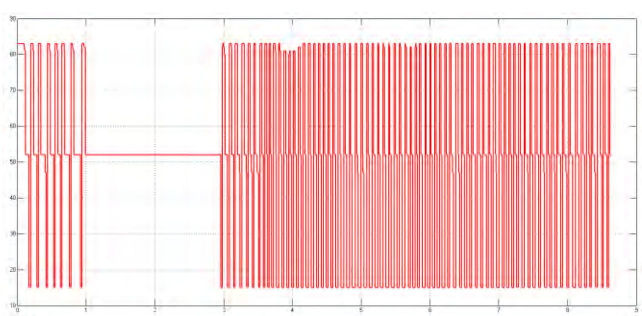

Figure 22. Case(3) VAV unit damper opening percentage

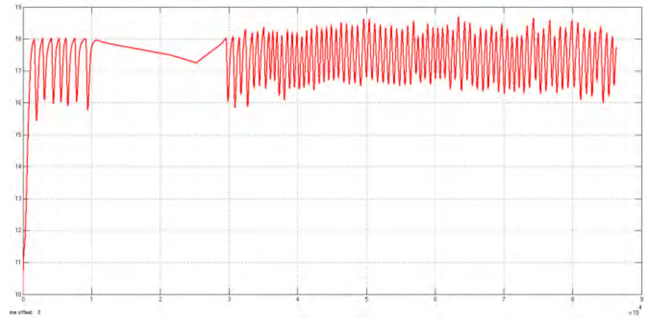

Figure 23. Case(3) zone temperature

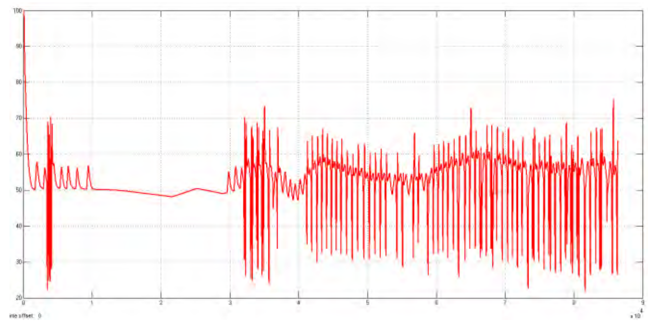

Figure 24. Case(3) zone relative humidity

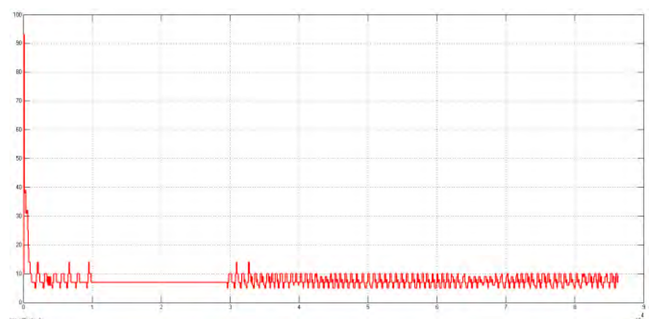

Figure 25. Case(3) individuals PPD

Case (4): 1st of April 1990 “Spring” the zone is assumed to be an office, occupied all day long, air quality clean, activity of the individuals is “Sitting sedentary” and clothing is “Working suits”, temperature set point from the study is 23°C and humidity set point is 45%

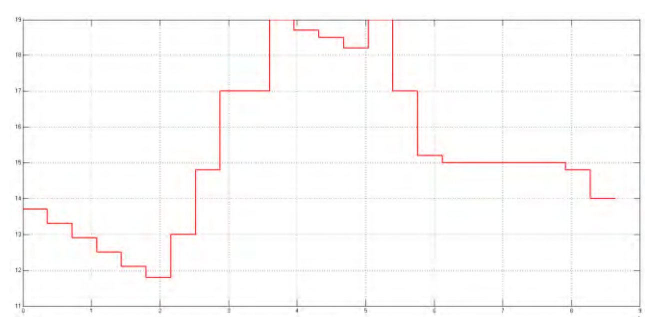

Figure 26. Case(4) outside temperature

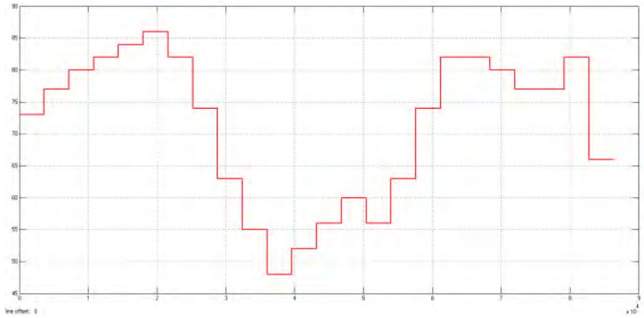

Figure 27. Case(4) outside relative humidity

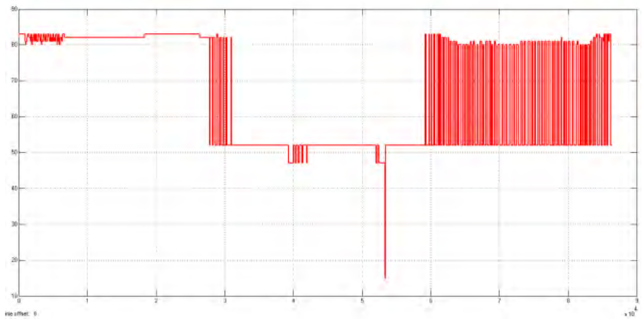

Figure 28. Case(4) VAV unit damper opening percentage

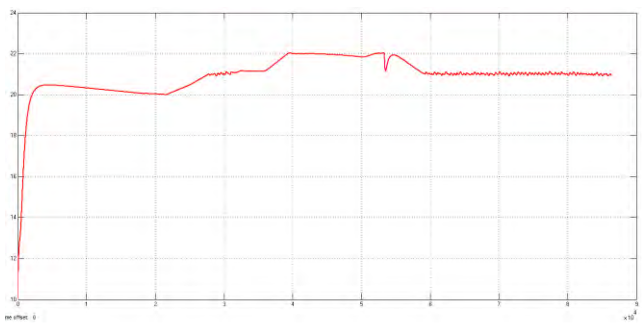

Figure 29. Case(4) zone temperature

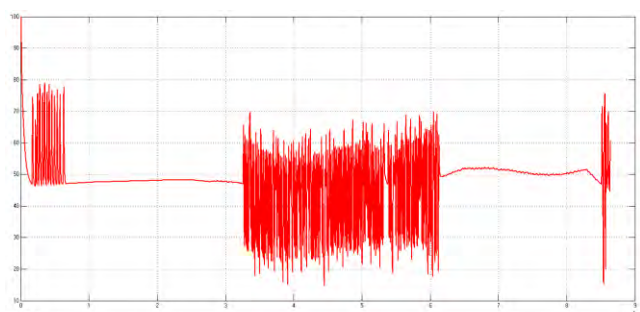

Figure 30. Case(4) zone relative humidity

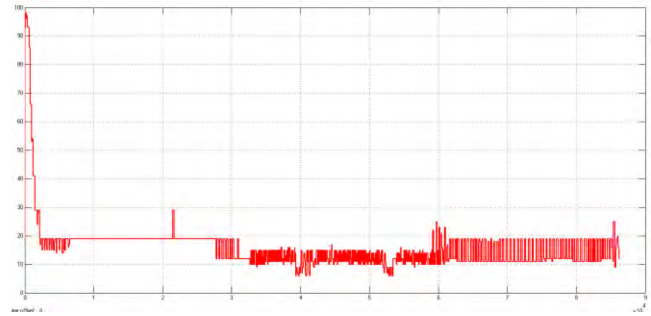

Figure 31. Case(4) individuals PPD

2.6.2 Energy saved in different modes:

After performing the previous simulation to test the response of the controller through different cases in different seasons we took the same summer and winter cases and performed simulations for all possible modes to compare the energy consumption through different modes and test the ability of the controller to save energy and here are the results:

Table 8. Energy consumption in the three modes

Case	Mode	PPD range	Energy consumption
Summer	Energy Saving	6% to 20%	14 KWH
Summer	Moderate	6% to 14%	15.5 KWH
Summer	High Comfort	6% to 8%	24 KWH
Winter	Energy Saving	6% to 20%	18 KWH
Winter	Moderate	6% to 14%	32 KWH
Winter	High Comfort	6% to 8%	49 KWH

From the above table (Table 8) we can see how the energy consumption varies from one mode to another and how the controller in the energy saving mode was able to save 10 KWH in summer case 31 KWH in winter case compared to the High Comfort mode which is highly similar to the thermostat method of control. Further simulation cases should be put into test putting different scenarios for the zone occupancy as we assumed in all cases that the zone is occupied all day long which will give more realistic results and mush more energy saving.

3. CLIMACON MOBILE APPLICATION

Another addition to our solution is a mobile application to make it simpler to connect to our nodes wirelessly through the mobile. The application accesses the database to set and get the values from the nodes.

As you enter the application, the mobile will access the database which contains all the values read from the nodes in different zones. There are two main pages, one is for users and admins and the other is for admins only. Users can only monitor the readings from different zones (Temperature, humidity, it feels like, air quality, occupancy and status) but admins can:

- Set the degree of comfort
- Monitor the energy consumption
- Set the alarms

- Detect any failures in the system
- Shutdown a certain zone if there was any error
- View the occupancy of all the zones

4. CONCLUSION

After performing several tests on Simulink we can see that the controller succeeded in keeping the PPD of individuals inside the zone in the expected ranges maintaining the thermal comfort of individuals in the zone. The ClimaCon system is now ready for real life test on real building to get more realistic results.

5. REFERENCES

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