DYNAMIC MODELING AND FUZZY LOGIC CONTROL OF A LARGE BUILDING HVAC SYSTEM

PhD Oral Defence

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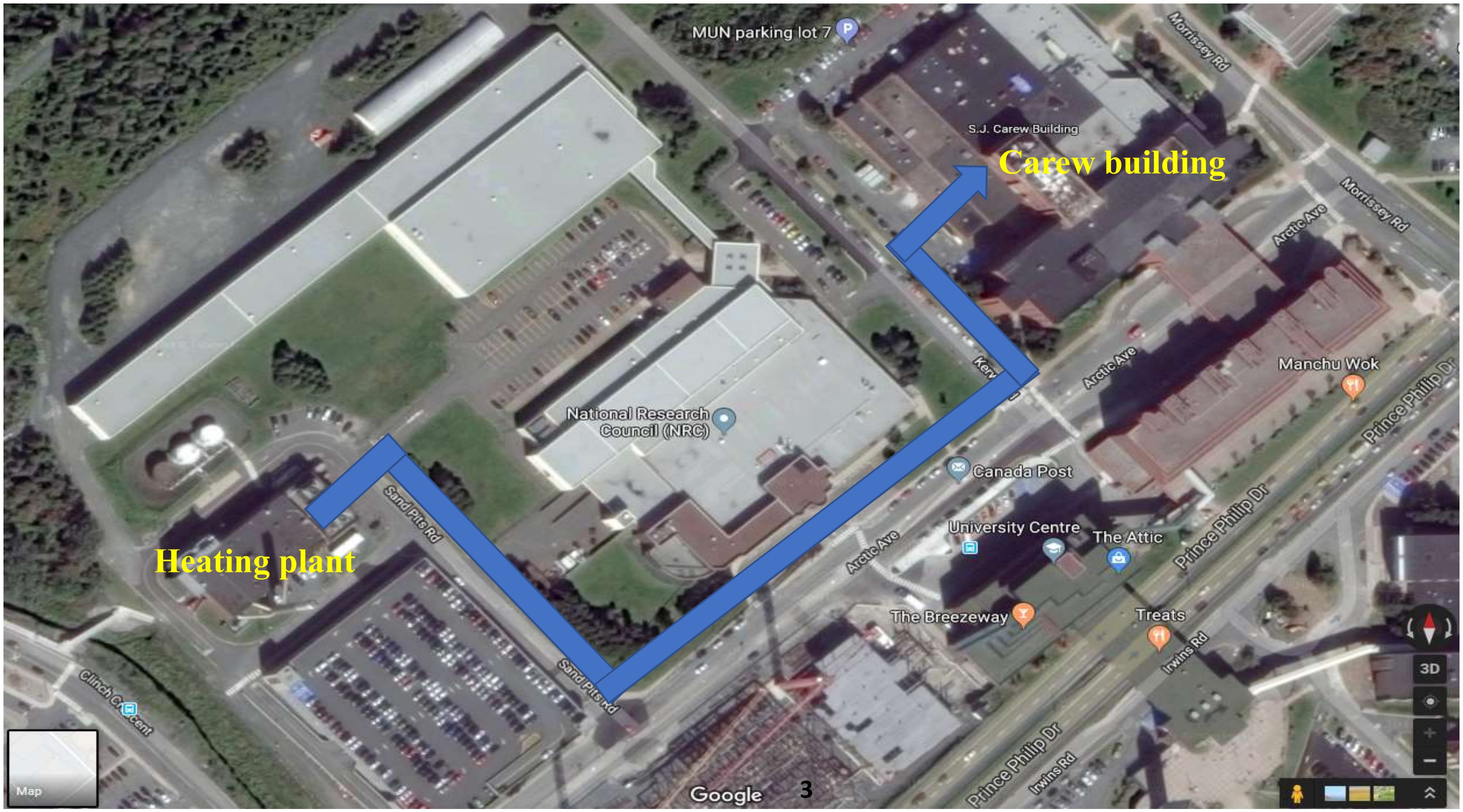
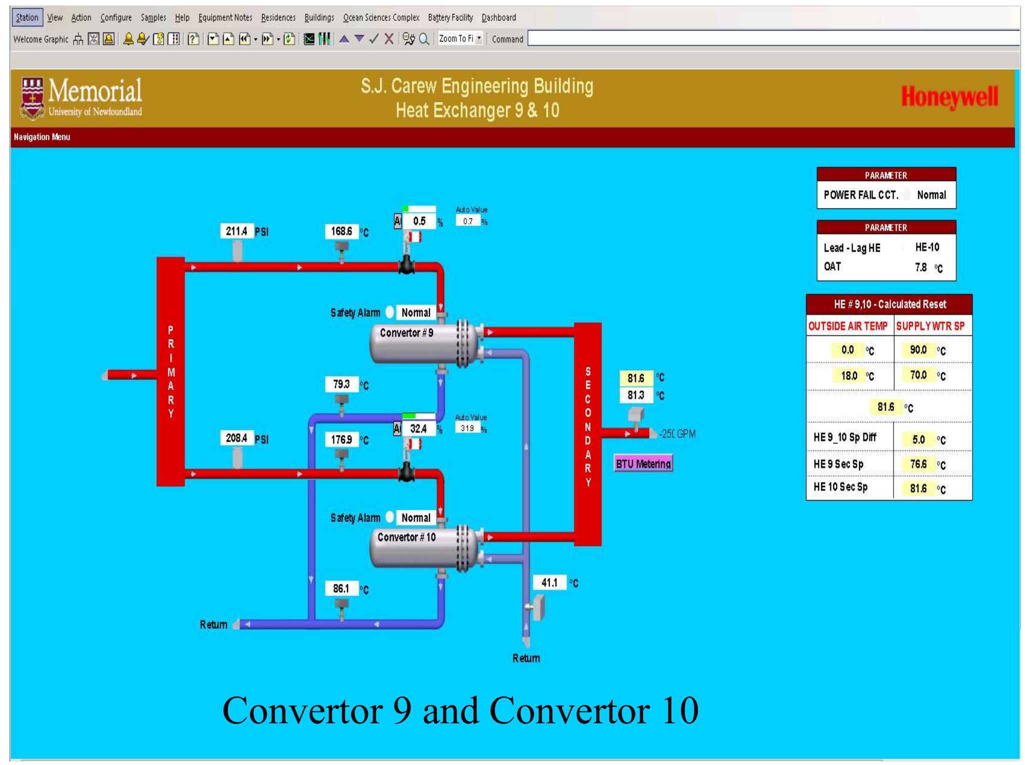
INTRODUCTION

Google map shows the location of Carew building on the campus of Memorial University and the Main room which the hot water coming from.



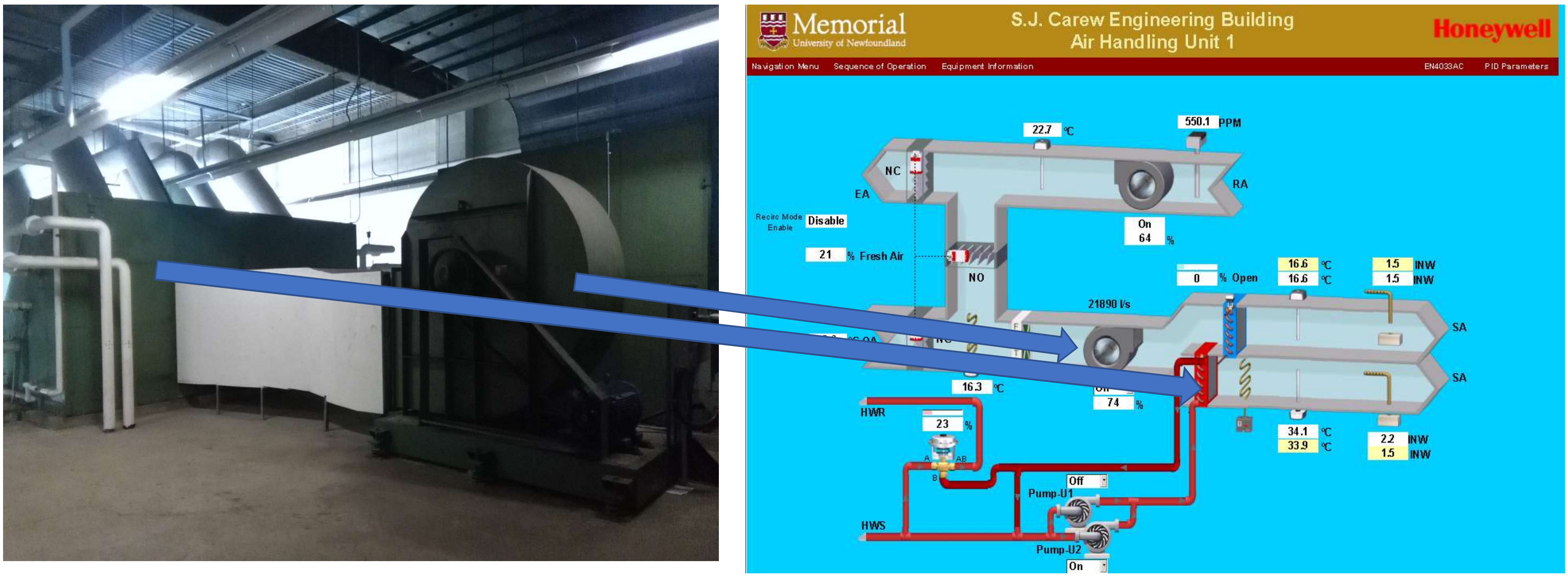
The building contains two main heat exchangers (Convertor 9 and Convertor 10) to reduce the temperature of hot water coming from the main campus heating plant. This process of the convertors which approximately reduce the temperature from 168 °C to 81 °C.

Heating plant



Convertor 9 and Convertor 10

There are four individual air-handling units (AHUs) in the building each floor has one. The figures show the supply fan and the heat exchanger of the AHU_1. From Honeywell program all data is live we can collect any data and save it.



LITERATURE REVIEW

1. A wide range of research over the past few decades supports the suitability of applying the system identification approach in energy simulation as grey box and black box. Some options used in modeling HVAC systems include linear parametric models, such as OE, BJ, ARMAX, and ARX:

   - Jacob et al. 2010. They compared a Single-input single-output system (SISO) ARMAX model.
   - Mustafaraj et al. 2010. Investigated humidity and temperature models to be applied in an office environment.
   - Mustafaraj et al. 2011. They estimated humidity and temperature, and compared the performance of these models with linear ARX models.
   - Braun et al. 2002. Using gray-box model for transient building load prediction
   - Inard et al. 2007. Using Grey-box identification of air-handling unit elements.
   - Simbarashe. 2013 Development gray-box model for heat pump
   - Afram et al. 2015 Gray-box modeling and validation of residential HVAC system for control system design.

2. The HVAC simulation can be either carried out in the existing building performance analysis tools such as:

- Peippo et al. 1991 and Henze et al. 2005 using simulation software TRNSYS.
- Ma J et al. 2011 and Candanedo et al. 2011 using Energy-Plus.
- Mendes et al. 2003 and Morosan et al. 2007 and Karlsson et al. 2011 using Matlab Simulink.
- Mateo et al. 2011 and Soleimani et al.2016. using IDA ICE program.

3. The control system is used to bring the non-linear system into a stable state, while achieving the control targets, we will start by state feedback controller:

- Hodgson in his PhD thesis 2010 feedback linearization technique have been applied for one AHU unit system design.
- Moradi et al. 2011 The control of the cross-water heat exchanger.
- Pasgianos et al. 2013 Feedback controller achieves global input/output linearization of greenhouse environments.

4. Practical applications employing fuzzy and neural control in HVAC systems are also being used, with the overall aim of lowering energy consumption and costs.

- Pal et al. 2008 "Self-tuning fuzzy PI controller and its applications to HVAC systems".
- Soyguder et al. 2009 "An expert system for the humidity and temperature control in HVAC systems using optimization with Fuzzy modeling approach".
- Navale et al. 2010. Use of genetic algorithms to develop an adaptive fuzzy logic controller for a cooling coil.
- Gacto et al. 2012."A multi-objective evolutionary algorithm for an effective tuning of fuzzy logic controllers in heating, ventilating and air conditioning systems."
- Homod et al. 2012. "RLF and TS fuzzy model identification of indoor thermal comfort based on PMV/PPD."
- Khan et al. 2013. "Multivariable adaptive Fuzzy logic controller design based on genetic algorithm applied to HVAC systems“
- Marvuglia et al. 2014. "Coupling a neural network temperature predictor and a fuzzy logic controller to perform thermal comfort regulation in an office building."(2014).

5. Over the past thirty years, numerous HVAC experts have developed operational and control methods for specific applications. During the same timeframe, numerous research studies, textbooks and journal articles have also investigated various issues of HVAC operation and control, including the supervisor control technique (e.g., Honeywell ; Levenhagen and Spethmann 1993; Wang and Jin 2000; Zaheer-Uddin and Zheng 2000; Hordeski 2001; Haines and Hittle 2003; Nassif et al. 2005; Wang 2006; etc.). They classify the primary supervisory control approaches that are employed in HVAC systems into four different types of supervisory control methods: 1) model-based, 2) model-free, 3) performance map-based, and 4) hybrid 2008.

- Shepherd and Batty 2003, conducted experiments that employed a high-level fuzzy supervisor for control decisions. They aimed to obtain the optimal quality for indoor environments by using a modified fuzzy supervisor.
- Lianzhong and Zaheeruddin 2007, built a non-linear dynamic model for water heating HWDH systems. Their work also included intelligent fuzzy logic-based hybrid control methods.

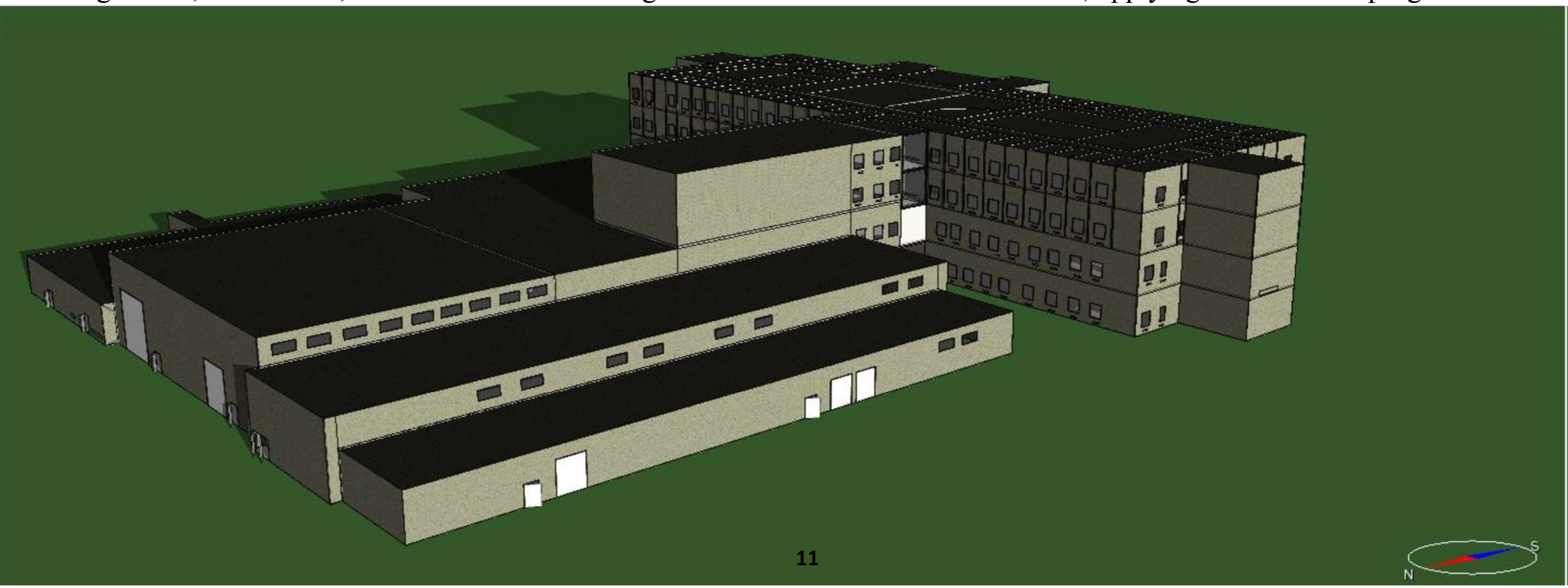
RESEARCH OBJECTIVES

- Develops a simulation for a whole building, using IDA Indoor Climate and Energy 4.7 as a simulation program
- Compare this data with actual data.
- Test system identification viability as a means for shortening the calculation times needed to simulate more complicated structures in Air Handling Unit One (AHU_1).
- Designing a state feedback controller and then apply it toward optimal functionality of a control system.
- Designing fuzzy logic controller structures that feature 6 inputs and 3 outputs and use this to develop a controller in an AHU_1 state space model.
- Develop supervisor fuzzy logic controller that feature 24 inputs and 12 outputs for all building. Also, by adding additional rules between the entry steps, the SFLC can control energy-saving features and results in an improved performance in the heating and cooling of buildings.

MODELING, ENERGY CONSUMPTION ANALYSIS OF A LARGE BUILDING AT MEMORIAL UNIVERSITY

BUILDING STRUCTURE

The structure is the S. J. Carew Building, which accommodates Memorial's Faculty of Engineering and Applied Science. There are more than 300 zones in the S. J. Carew building, which measures approximately 25,142 m^2 and comprises a cafeteria, teaching rooms, staff rooms, and research labs. The figure show 3D model for the structure, applying the IDA-ICE program



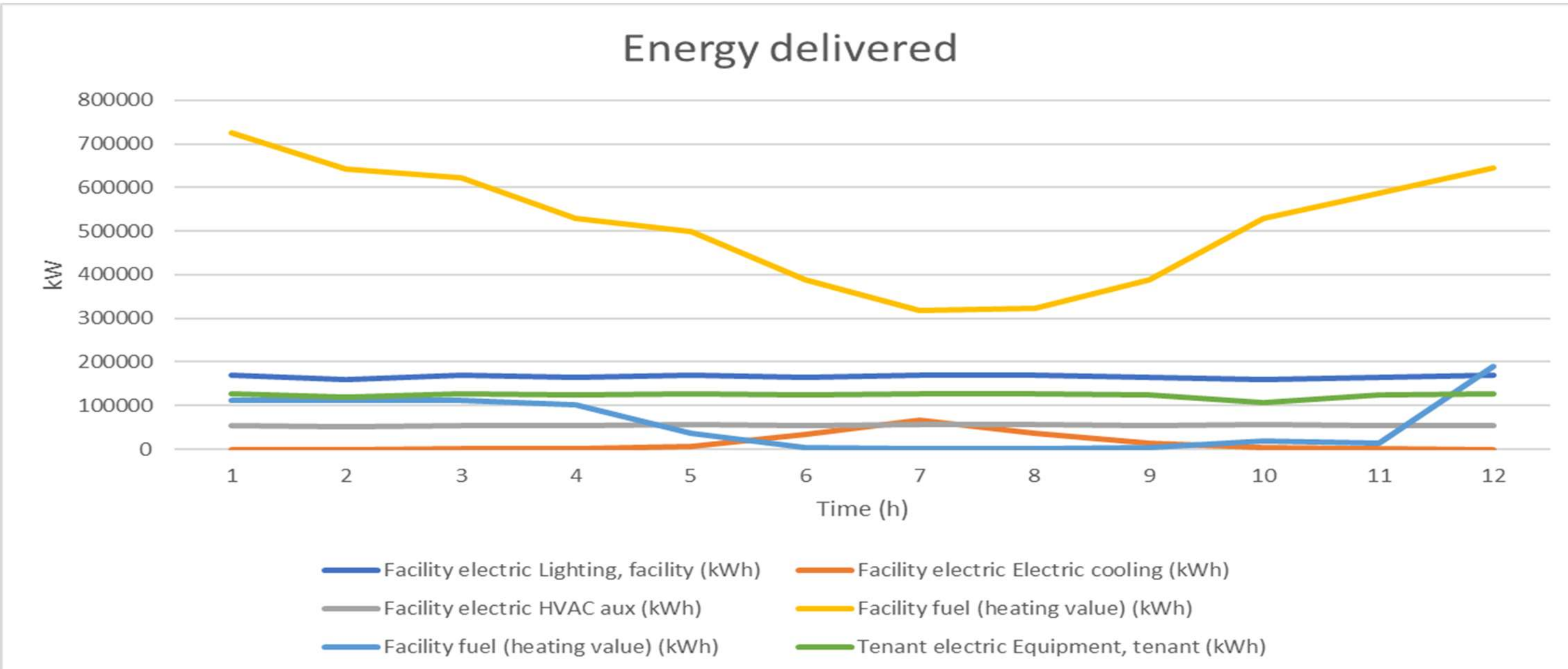
The present study develops a simulation for a whole building, using IDA Indoor Climate and Energy 4.7 as a simulation program. The IDA ICE program's calculations offered for most types of buildings:

- The thermal balance of the area, including solar radiation, light, occupants, furniture, air leaks, heating, and cooling.
- Solar radiation from windows considering shading devices and surrounding elements.
- Air and surface temperatures.
- Operating temperatures.
- Level of daylight.
- Humidity and CO_2 levels. This provides information about the air flow system.
- Airflow, CO_2 levels, pressure, and humidity in different areas of handling and distribution systems.
- Heating power: heating and cooling units, equipment, occupants, light, solar radiation.
- Total cost of energy using prices as a function of time.

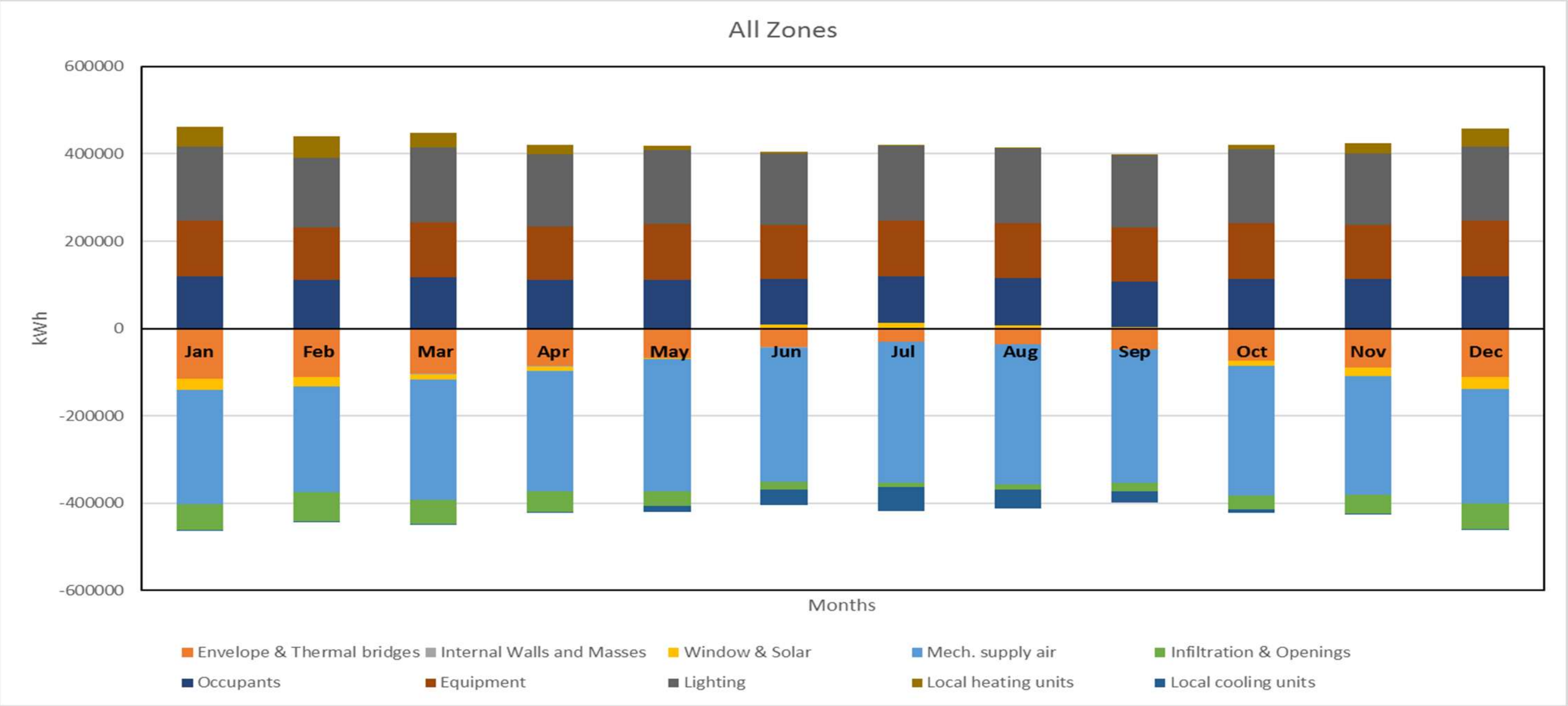
The table provides an energy report. All the details of the structure of the building which use for the simulation such as the area, walls, roof, position of the doors and windows.

EQUA SIMULATION TECHNOLOGY GROUP		Input data Report		Building envelope					Windows					
Project		Building		Building	Area [m²]	U [W/(m² K)]	U*A [W/K]	% of total	Side	Area [m²]	U Glass [W/(m² K)]	U Frame [W/(m² K)]	U Total [W/(m² K)]	U*A [W/K]
Customer		Model floor area	25141.7 m²	Walls above ground	7450.19	0.54	4002.24	44.85	N	174.36	2.86	2	2.77	483.51
Created by	Almahdi Abdo-Allah	Model volume	128952.9 m³	Roof	10529.8	0.17	1811.13	20.3	E	131.08	2.86	2	2.77	363.49
Location	Newfoundland (St. John's Airport)_718010	Model ground area	10544.5 m²	Windows	713.73	2.77	1979.24	22.18	S	213.24	2.86	2	2.77	591.35
Climate file	CAN_NF_St.Johns.718010_CWEC	Model envelope area	29440.0 m²	Doors	201.72	0.59	118.38	1.33	W	195.05	2.86	2	2.77	540.89
Case	building2017_AHU8	Average U-value	0.3031 W/(m² K)	Walls below ground	0	0	0	0	Total	713.73	2.86	2	2.77	1979.24
Simulated	1/19/2017 22:04	Envelope area per Volume	0.2283 m²/m³	Floor towards ground	10544.5	0.09	991.82	11.11						
				Total	18567.2	0.41	7689.82	100						

The report on the energy delivered provides a general overview of the total energy purchased or generated in the S. J. Carew building, The reported items are matched to the energy meters.



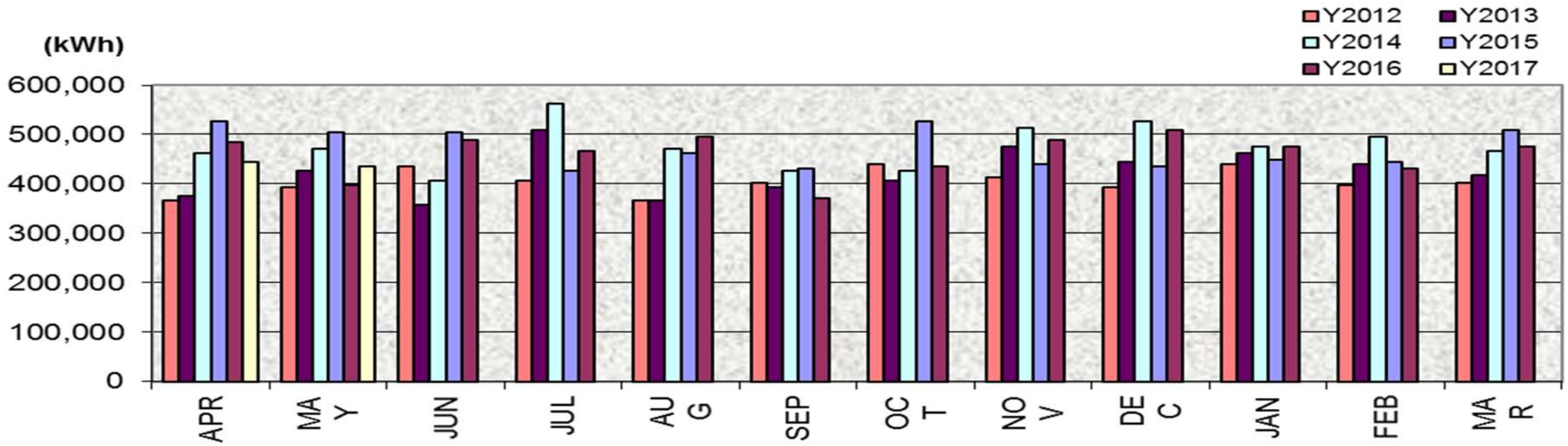
Heat balance contributions can be allocated as follows: Equipment heat, Floor and wall heat, Daylight heat, Heating/cooling room heat, Window heat and Airflow heat.



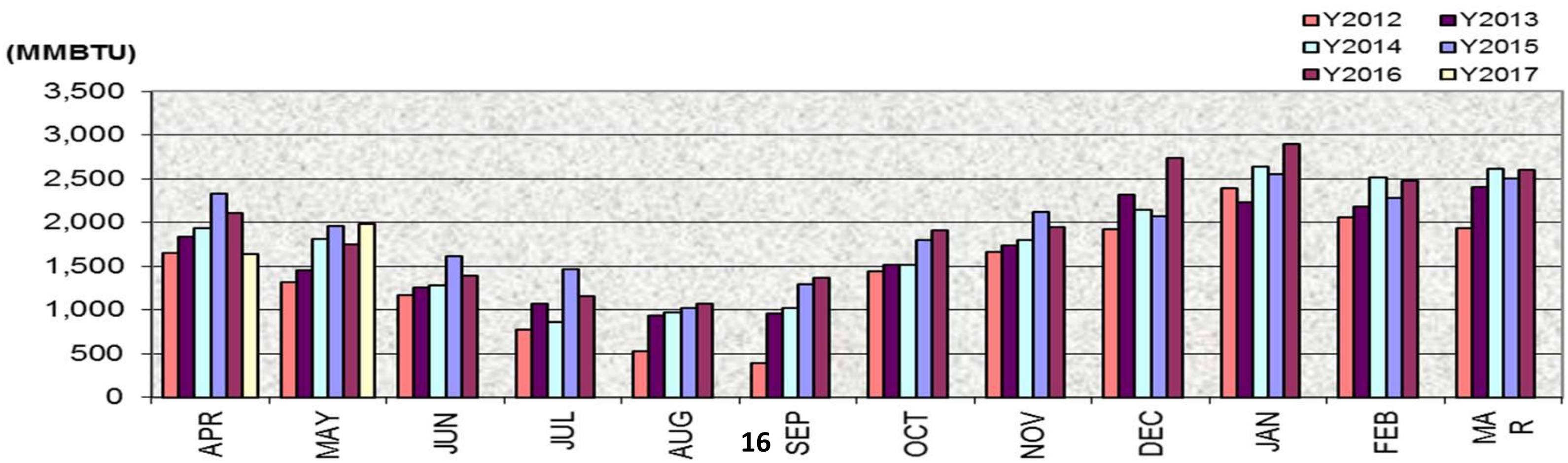
Building data for validation

The building data used was provided by Memorial University's Department of Facilities Management and the Honeywell Office. The data provided energy and hot water consumption for the S. J. Carew building were collected between April 2012 to May 2017

Power usage

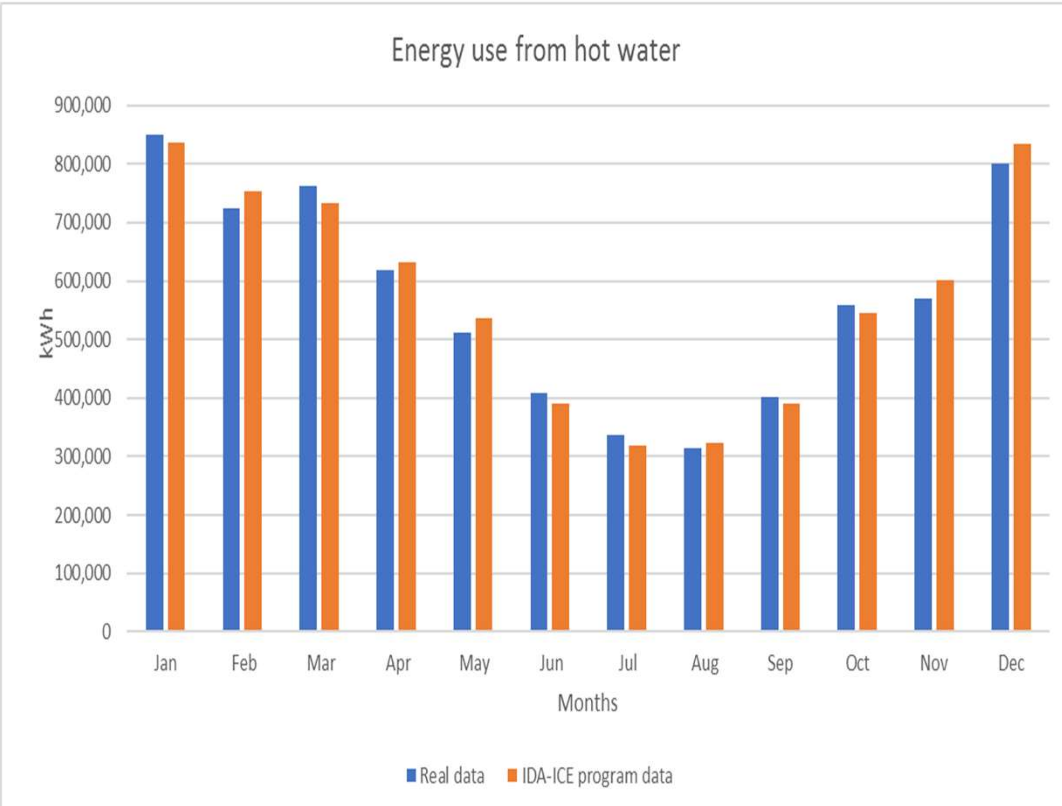


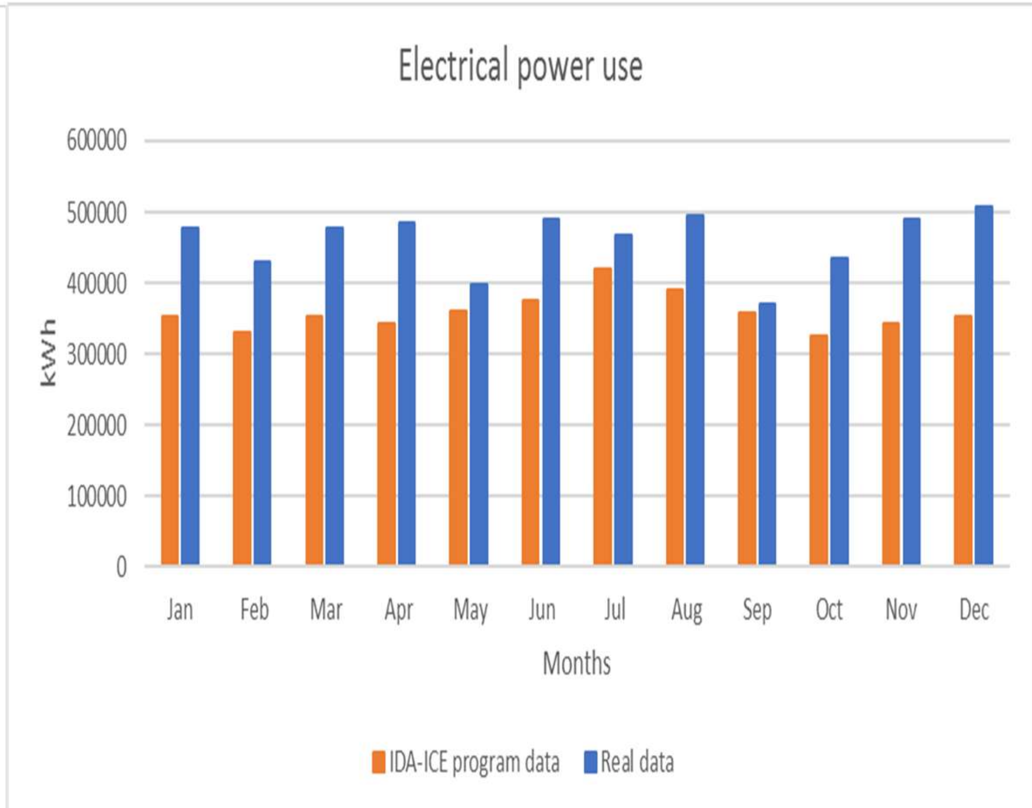
Hot water usage



IDA ICE simulation validation

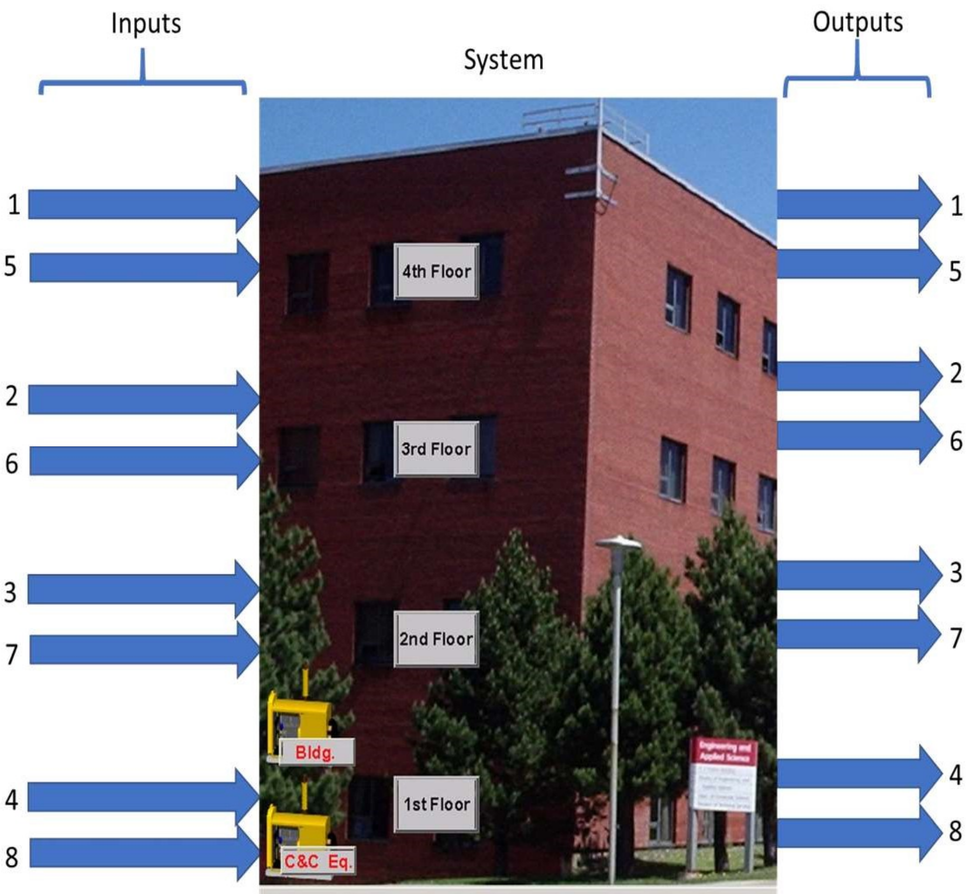
Figures show the IDA-ICE model of hot water usage and electrical power usage from January to December 2016. The actual data of hot water usage measured slightly low in some months and slightly high in others, it compared well to the IDA simulated data. The actual (measured) data of electrical power usage as moderately higher than the simulation data, but these slight differences could be due to discrepancies in the lab readings due to mis calibrated equipment

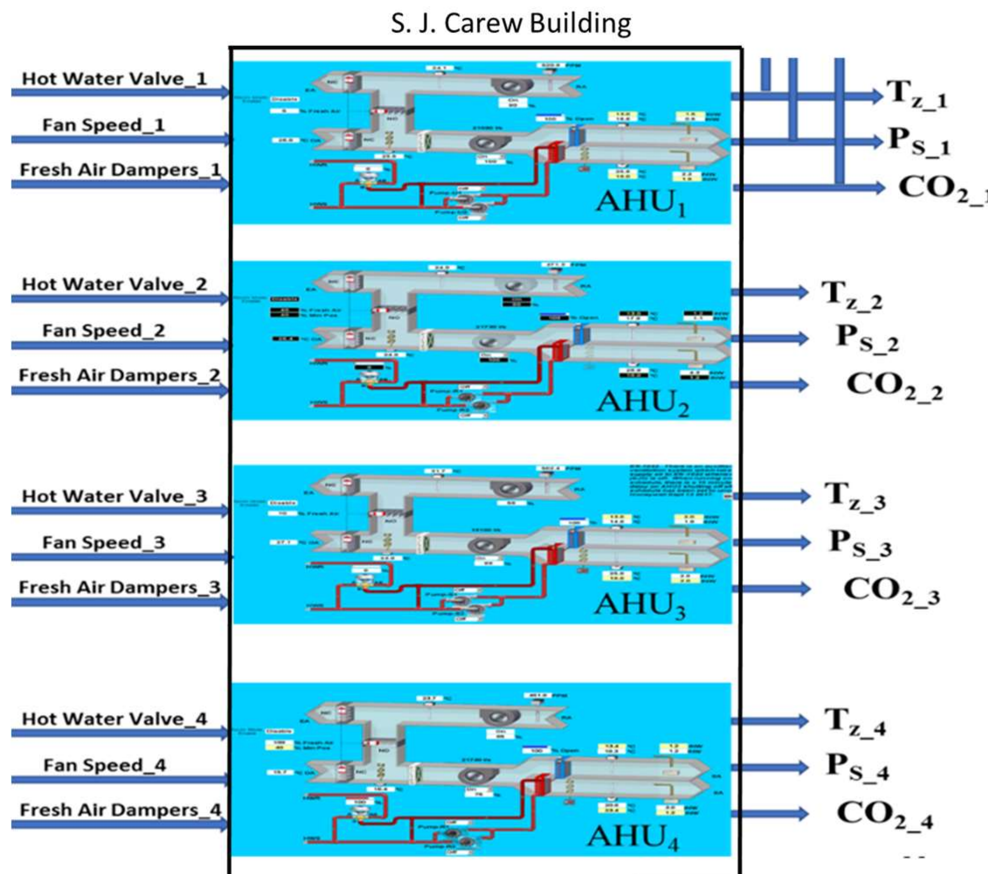




The building has eight main input data hot water and the energy usage for each AHU, while the eight main outputs returned airflow temperature and CO_2 levels for AHUs.

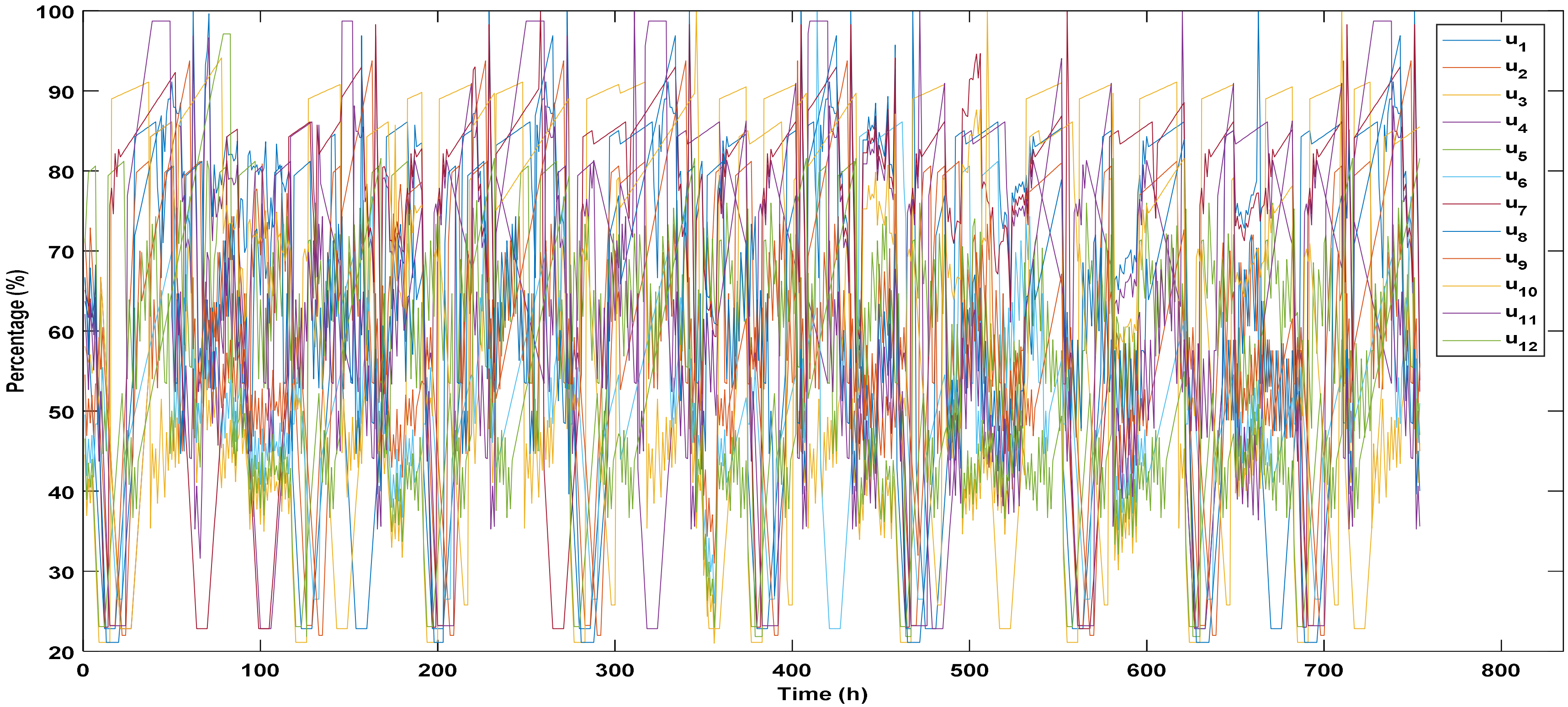
The S. J. Carew building has four floors, the system features twelve inputs and twelve outputs overall, calculated from three inputs (U) and three outputs (Y) per floor.





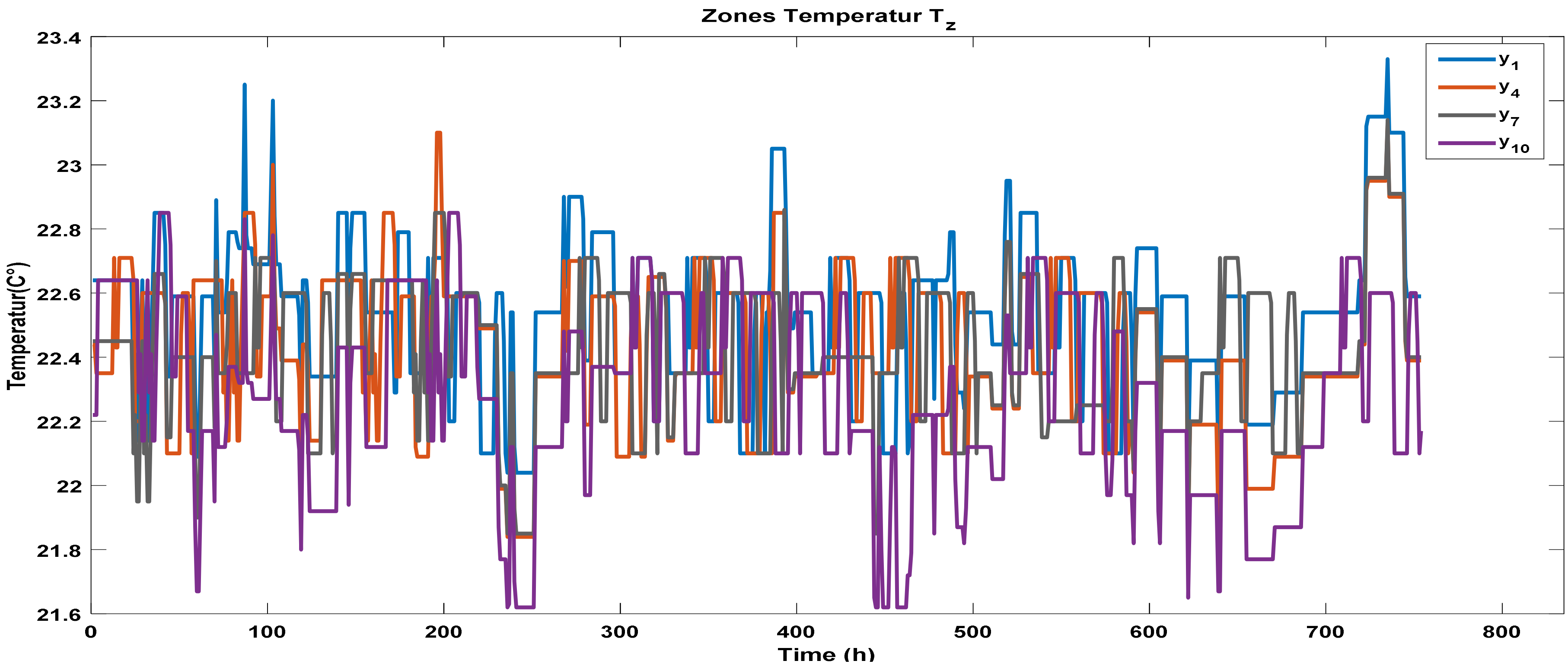
1. Input signals

- (u_1, u_4, u_7, u_{10}) the percentage of opening and closing operation of the hot water valves.
- $(u_2, u_5, u_8, u_{11})$the percentage of speed of supply fan speed.
- (u_3, u_6, u_9, u_{12}) the percentage of opening and closing operation of fresh air dampers.

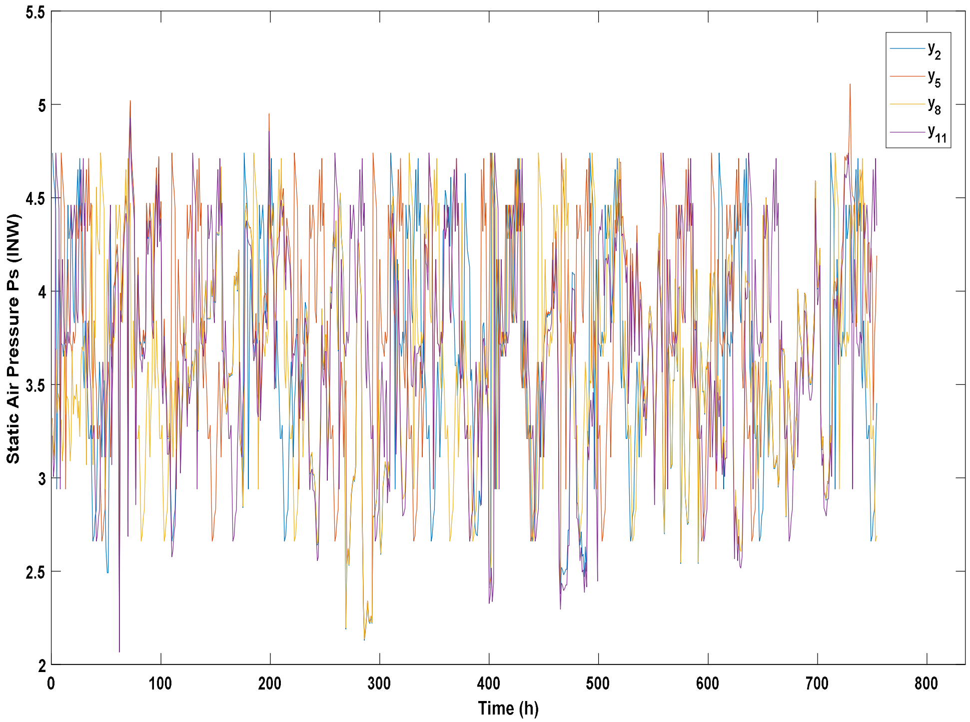


2. Output signals

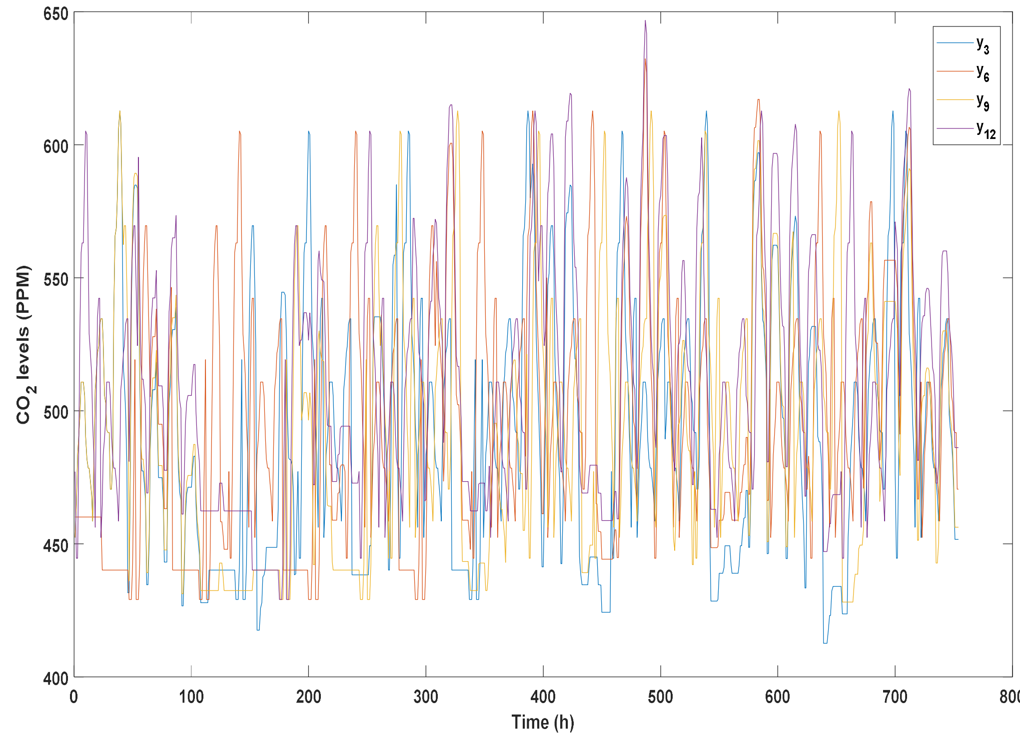
- ➢ Zonal Temperature (T_z) (y_1, y_4, y_7, y_{10}): These data are derived from the IDA-ICE software. Although the actual system features sensors in every room, the temperature on each floor still needs to be measured.



Static Air Pressure (P_s) (y_2, y_5, y_8, y_{11}): This data comes from two sensors – one for hot ducts and one for cold ducts. These outputs can be applied to the control of supply fan speed.

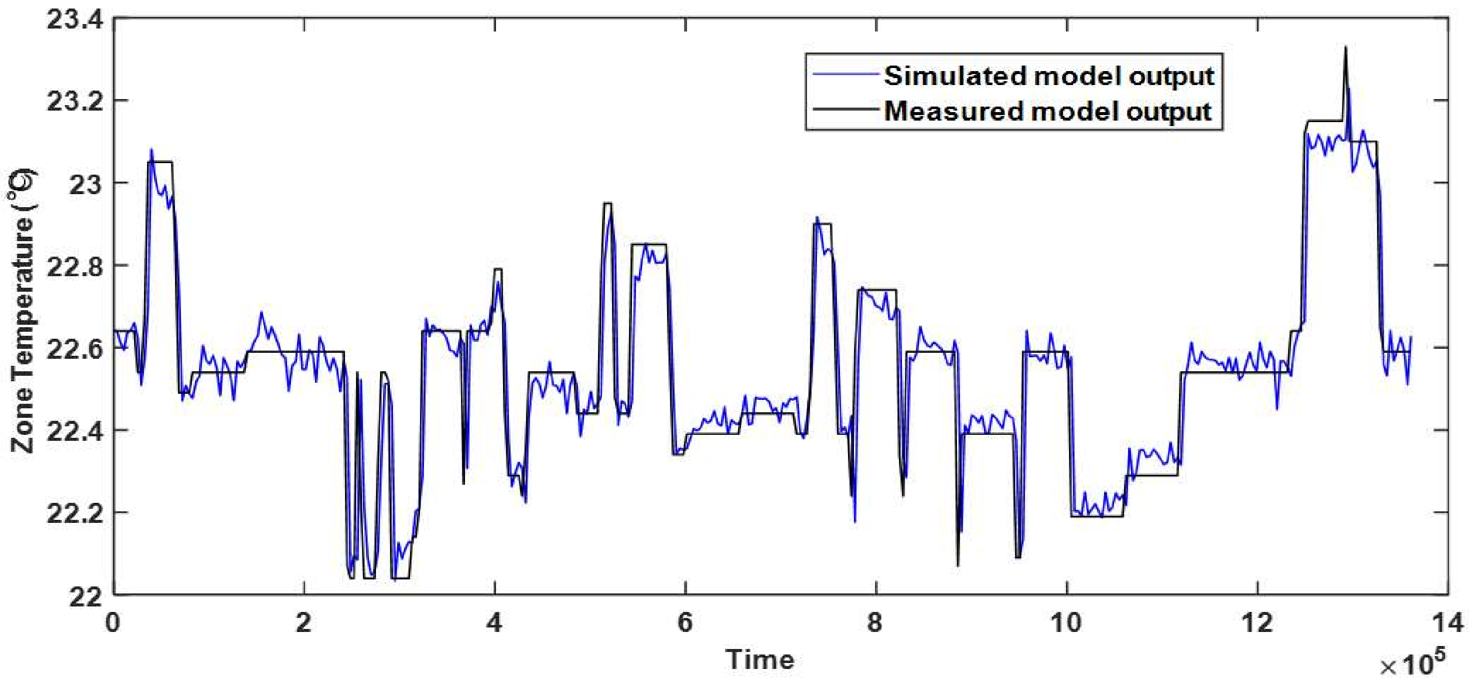


CO_2 Levels (CO_2) (y_3, y_6, y_9, y_{12}): This data is obtained from the sensors for return air flow ducts for individual AHUs. These outputs can be applied in moderating fresh air dampers.

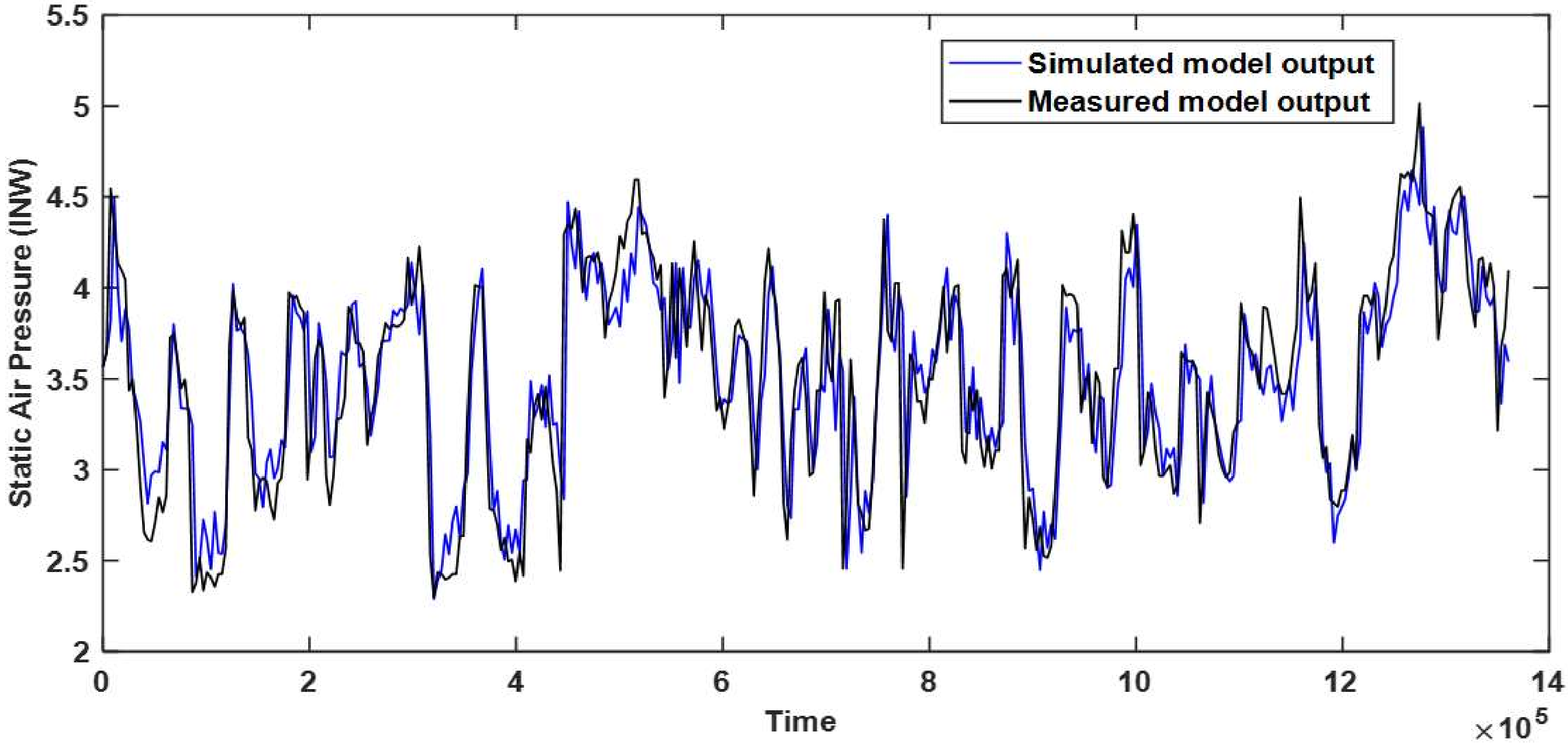


3. Every individual data set is cut in two: one half represents estimation data, while the other half represents validation data. The output of the model that follows the temperature of a zone in AHU1 with the same output as the real system. The agreement between these graphs can be seen as a percentage of the error.

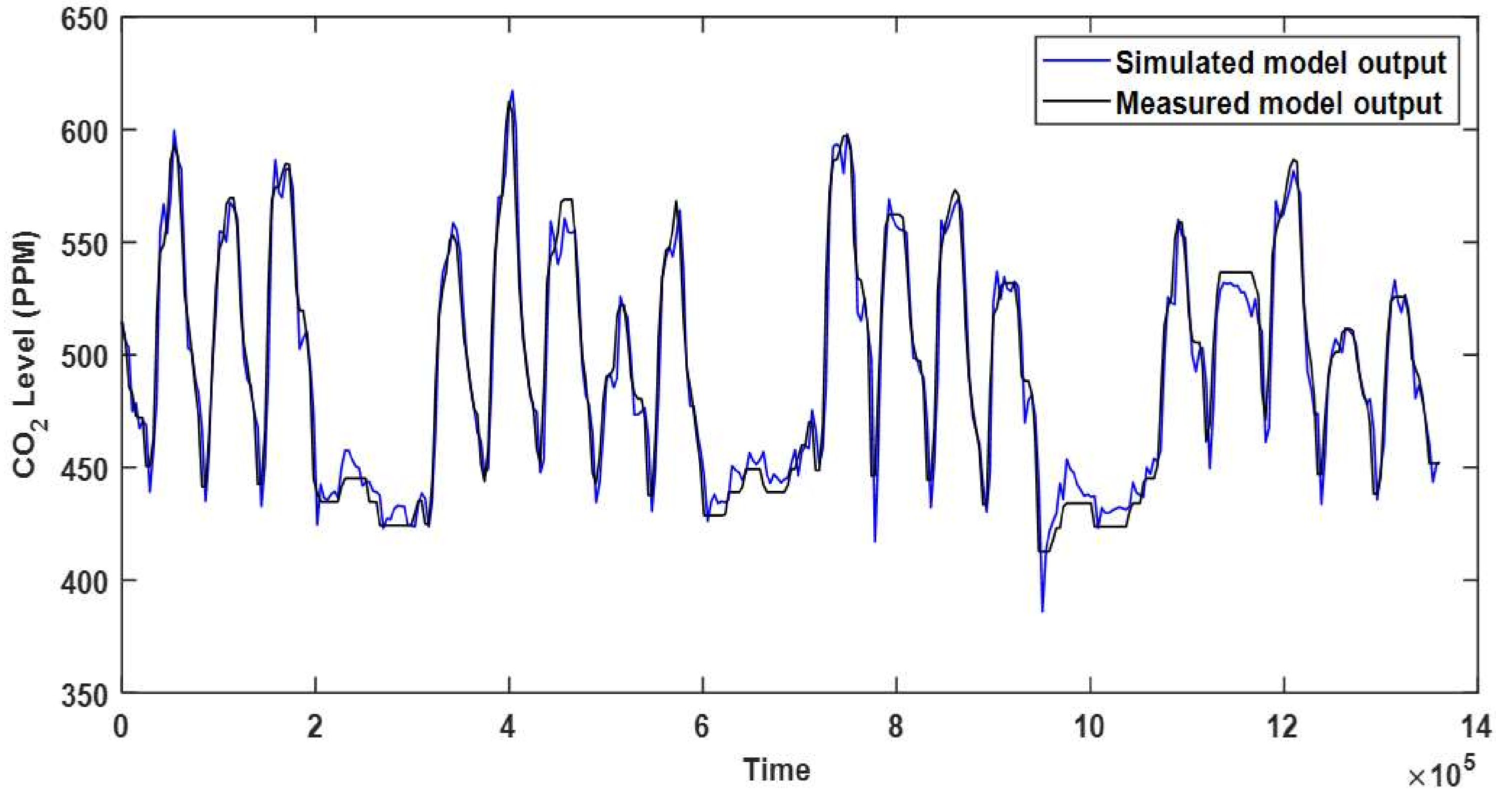
- 1. Validation of real measurements and outputs of zone temperature model fit 57%.



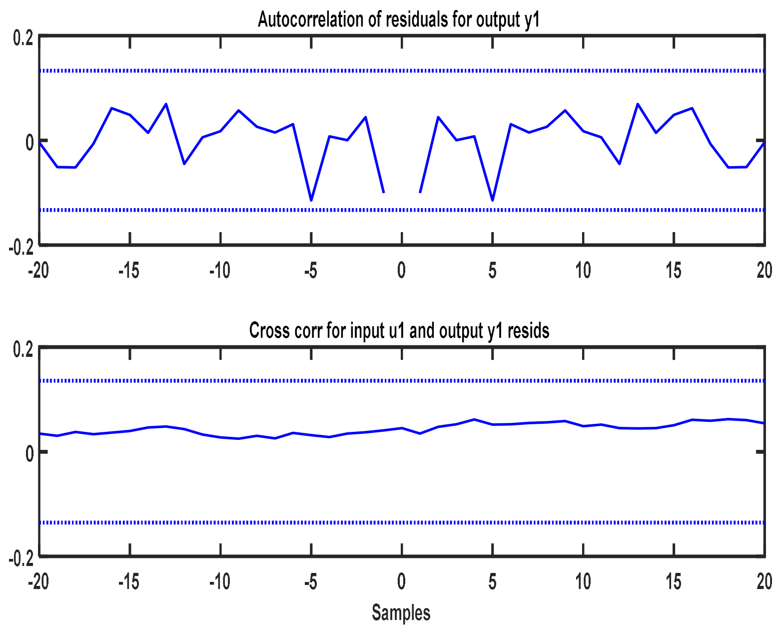
➢ Validation of real measurements and outputs of the static air pressure model fit 49%.



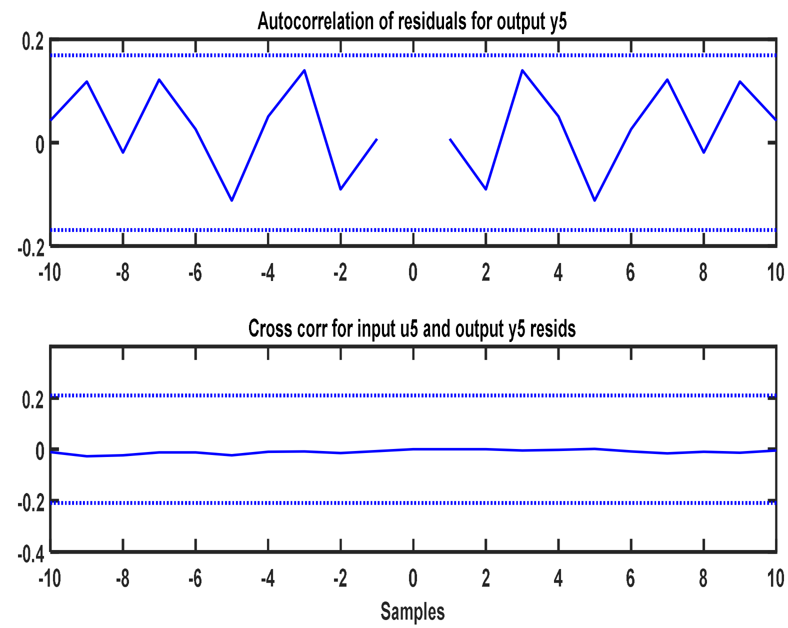
- The system performance percentage for the estimated model and the actual system of CO_2 level of zone 3 in AHU_3 was 75%.



Autocorrelation and cross-correlation of system responses to inputs. It is clear from the cross-correlation diagram of these figures that the estimated model is very similar to the responses of the system to the inputs; the correlation curves lie between the dashed lines.



Autocorrelation y1 and cross-correlation of system response u1 & y1



Autocorrelation y5 and cross-correlation of system response u5 & y5

4. State space model

$$X\ (t\ +Ts)\ =\ Ax(t)+Bu(t)+Ke(t)$$

$$Y\ (t)\ =\ Cx(t)+Du(t)+e(t)$$

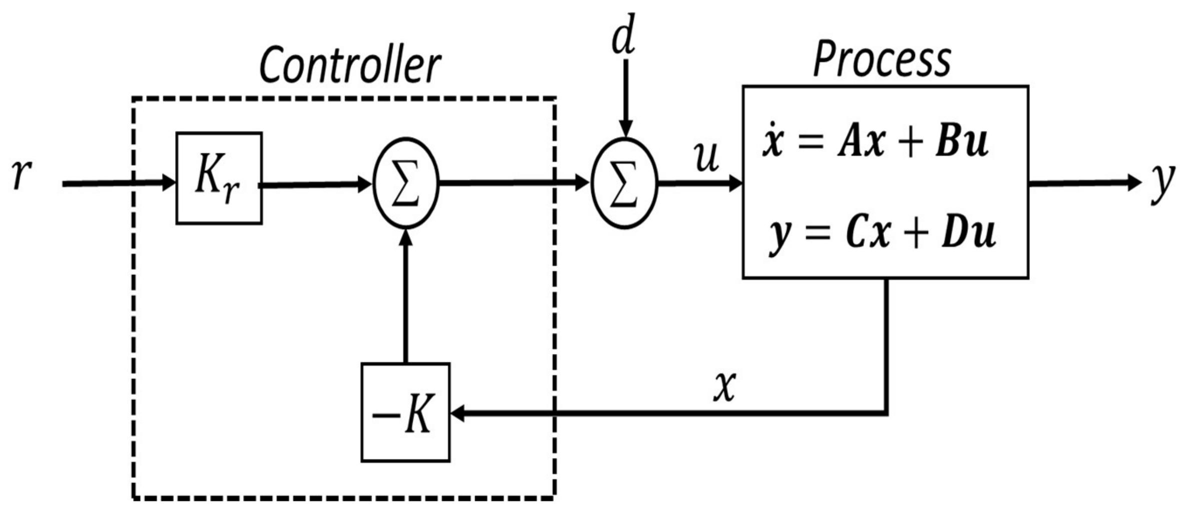
where the $x(t)$ represents the states of the system and $y(t), u(t)$ and $e(t)$ represents the output, input and error. The A, B, C, D and K matrices contains the model parameters, and Ts is the sampling time of the system.

$$\mathbf{A} = \begin{bmatrix}
1.018596 & 0.024987 & -0.09841 & -0.01809 & 0.029826 & 0.011551 & 0.122706 & -0.09652 & -0.02257 & -0.03334 & 0.021134 & 0.044136 \\
-0.04802 & 0.953931 & -0.18782 & -0.10913 & 0.017903 & 0.012705 & 0.02266 & 0.044524 & -0.00967 & -0.02612 & -0.00755 & 0.013065 \\
0.006735 & 0.161472 & 1.00175 & 0.153348 & -0.17807 & -0.0057 & -0.07445 & 0.089848 & -0.18638 & -0.04874 & -0.0658 & -0.09062 \\
0.102572 & 0.106159 & 0.015012 & 0.876272 & -0.05667 & 0.040026 & 0.034899 & 0.063895 & 0.046081 & -0.0318 & 0.058022 & 0.151734 \\
-0.01012 & 0.119388 & 0.032058 & 0.193805 & 0.875773 & 0.105007 & 0.06194 & -0.11106 & -0.27665 & 0.118682 & -0.04009 & -0.12357 \\
0.034182 & 0.001981 & 0.218893 & -0.06499 & 0.003683 & 0.698464 & -0.15637 & 0.16687 & -0.06375 & 0.068068 & -0.1383 & 0.073127 \\
-0.06088 & -0.03718 & 0.018276 & 0.026644 & 0.006168 & -0.00484 & 0.700056 & 0.134608 & 0.025221 & -0.05818 & 0.065294 & -0.06174 \\
0.128313 & -0.04206 & -0.25685 & -0.11438 & 0.260537 & -0.27507 & 0.000851 & 0.632401 & 0.220702 & -0.20081 & 0.253606 & 0.220525 \\
-0.01409 & 0.071827 & 0.152001 & -0.06185 & 0.079589 & 0.449275 & 0.220342 & 0.126901 & 0.679172 & 0.092466 & 0.145962 & 0.114791 \\
0.029159 & -0.04508 & -0.12238 & 0.073543 & 0.029797 & -0.28537 & -0.13111 & 0.07257 & -0.04701 & 0.726139 & -0.02971 & 0.136616 \\
0.147829 & -0.16104 & -0.06659 & -0.35556 & 0.222772 & -0.21727 & -0.0814 & -0.01191 & 0.091189 & 0.117558 & 0.900431 & 0.262343 \\
0.018322 & 0.124913 & 0.198312 & -0.06154 & 0.143552 & -0.17269 & 0.228241 & -0.13141 & 0.238771 & -0.21135 & -0.01898 & 0.833612
\end{bmatrix}$$

$$\mathrm{B} = \begin{bmatrix}
0.0006 & 0.0106 & -0.0019 & 0.0002 & -0.0030 & -0.0023 & 0.0037 & -0.0014 & 0.0009 & -0.0020 & -0.0027 & 0.0017 \\
0.0000 & 0.0015 & -0.0002 & 0.0002 & -0.0009 & -0.0011 & 0.0007 & 0.0000 & 0.0009 & -0.0001 & -0.0004 & 0.0002 \\
0.0019 & 0.0275 & -0.0069 & -0.0011 & -0.0059 & -0.0100 & 0.0073 & -0.0055 & 0.0060 & -0.0049 & -0.0060 & 0.0034 \\
-0.0025 & -0.0135 & 0.0021 & -0.0024 & 0.0090 & 0.0087 & -0.0045 & 0.0005 & -0.0022 & 0.0062 & 0.0043 & -0.0022 \\
0.0004 & -0.0019 & 0.0015 & 0.0023 & -0.0010 & 0.0049 & 0.0007 & 0.0013 & -0.0049 & -0.0023 & -0.0021 & -0.0019 \\
0.0012 & 0.0012 & 0.0007 & 0.0004 & -0.0001 & 0.0038 & -0.0006 & 0.0003 & -0.0058 & -0.0017 & -0.0005 & 0.0017 \\
0.0009 & 0.0002 & 0.0026 & 0.0065 & 0.0001 & 0.0128 & -0.0012 & 0.0018 & -0.0162 & -0.0059 & -0.0031 & -0.0009 \\
0.0036 & -0.0014 & -0.0010 & 0.0015 & -0.0000 & -0.0095 & -0.0055 & 0.0032 & 0.0093 & 0.0002 & -0.0006 & -0.0013 \\
-0.0015 & 0.0042 & 0.0019 & -0.0001 & -0.0055 & -0.0044 & 0.0059 & -0.0003 & 0.0047 & 0.0018 & 0.0012 & 0.0022 \\
0.0009 & -0.0123 & 0.0047 & -0.0036 & 0.0072 & 0.0098 & -0.0023 & 0.0007 & -0.0159 & -0.0005 & 0.0047 & 0.0034 \\
-0.0005 & -0.0028 & 0.0038 & 0.0015 & -0.0049 & -0.0019 & 0.0022 & 0.0013 & -0.0041 & -0.0009 & 0.0029 & 0.0044 \\
-0.0040 & -0.0142 & -0.0006 & -0.0073 & 0.0112 & 0.0019 & -0.0026 & 0.0007 & 0.0109 & 0.0116 & 0.0032 & -0.0066
\end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix}
-32.3819 & 3.032522 & 0.850361 & 1.320461 & 1.654051 & 0.228377 & -1.25475 & 0.711672 & -1.12264 & 0.011717 & -0.98978 & 0.435679 \\
-4.96281 & 4.825874 & 2.834766 & 1.076908 & 2.428522 & -0.77537 & 1.650816 & 0.829984 & 1.838859 & -1.4162 & -1.79384 & 0.42955 \\
-789.668 & 315.0027 & -248.299 & 258.1054 & 147.2952 & -161.542 & -225.011 & 100.9488 & 120.8973 & 83.13542 & -194.598 & -118.225 \\
-32.582 & 3.739006 & 1.189215 & 0.456838 & 2.628477 & -0.97674 & 0.321862 & -0.63062 & -1.01303 & 0.477141 & -0.11792 & 0.126173 \\
-7.89485 & 3.602045 & 0.534273 & 0.073331 & -0.29611 & 0.260542 & 2.093179 & 0.593547 & 0.695332 & -0.01057 & 2.583058 & -3.38128 \\
-596.62 & 338.8736 & 128.9263 & -51.9804 & -268.546 & -222.936 & -531.204 & -263.779 & 58.86106 & 194.4376 & 142.4278 & -27.9924 \\
-32.5222 & 3.375469 & 0.211781 & -0.90622 & 2.133119 & -0.3489 & -0.90599 & -0.03896 & -1.00358 & 0.530528 & -0.06908 & -0.21883 \\
-5.4587 & 1.758807 & 1.588113 & 0.661421 & 1.924165 & -2.58504 & 1.562919 & 2.286861 & 1.189903 & -0.49241 & -0.05558 & 0.912613 \\
-928.097 & 287.0009 & -266.691 & 428.3191 & 393.2388 & -234.874 & -209.795 & 90.12368 & -223.088 & -365.806 & 31.59467 & -280.605 \\
-32.443 & 3.893139 & -0.18864 & 3.345291 & 3.703252 & -0.71339 & -0.36698 & 0.15893 & 0.455992 & -0.00349 & 0.598077 & 1.910353 \\
-6.3736 & 0.362166 & 1.90677 & 3.073253 & 2.246129 & -1.03295 & 0.390075 & -1.42084 & 1.838677 & 0.77659 & -1.90933 & 1.183602 \\
-736.847 & 466.1483 & -328.719 & 73.65842 & 118.4599 & -142.761 & -464.838 & 183.0777 & -43.4737 & -86.4524 & -281.692 & -65.8117
\end{bmatrix}$$

$$\mathbf{K} = \begin{bmatrix}
-0.02247 & 0.002415 & -0.00017 & 0.006293 & -0.00173 & 0 & -0.00404 & -0.00078 & -0.00012 & 0.006362 & 0.00369 & 0.000173 \\
-0.03766 & 0.008826 & 0.000201 & 0.019432 & 0.012113 & 0 & 0.006975 & -0.00743 & 0 & 0.012768 & -0.01539 & 0.000242 \\
0.033593 & 0.016611 & 0 & 0.004704 & 0.002891 & 0.000146 & -0.01335 & -0.00477 & -0.00877 & -0.02582 & 0.004979 & -0.00043 \\
0.03453 & -0.00396 & 0.000281 & -0.01639 & 0.002948 & 0.000201 & -0.05972 & 0.003692 & 0.000146 & 0.040423 & 0.001516 & 0.003516 \\
-0.03892 & 0.023262 & -0.00018 & 0.037843 & -0.00404 & -0.00028 & 0.00469 & -0.01357 & 0 & -0.01751 & 0.014066 & 0 \\
0.051835 & 0.000717 & -0.00015 & -0.03922 & -0.00076 & -0.00837 & -0.00337 & -0.01172 & 0 & -0.00887 & 0.006588 & -0.00045 \\
-0.02582 & 0.005204 & 0.000455 & 0.030462 & 0.009431 & -0.00026 & 0.011997 & 0.002781 & 0.000145 & 0.00114 & -0.02152 & -0.0003 \\
-0.01015 & -0.01334 & 0 & -0.04976 & 0.014821 & -0.00084 & 0.001932 & 0.016727 & 0 & 0.036388 & -0.02471 & 0 \\
-0.01445 & 0.018199 & 0.000477 & -0.02753 & 0.006731 & 0.000156 & 0.001845 & -0.00527 & -0.00022 & 0.030758 & 0.010523 & 0.000299 \\
-0.03034 & -0.00941 & 0.000446 & 0.010668 & 0.006548 & 0 & 0.021502 & 0.01097 & -0.00015 & -0.01222 & -0.0214 & -0.00045 \\
-0.01857 & -0.02641 & 0 & -0.04546 & 0.014413 & -0.00011 & 0.01149 & 0.013894 & 0.000132 & 0.034855 & -0.01938 & -0.00053 \\
0.01201 & 0.001892 & -0.00049 & 0.008802 & -0.02405 & 0 & -0.06658 & 0.00417 & -0.00037 & 0.067378 & 0.02137 & 0.000465
\end{bmatrix}$$



$$u = -Kx + K_r r$$

$$\frac{dx}{dt} = (A - BK)x + BK_r r$$

To find feedback gain, *K,* to set the characteristic polynomial of the closed loop system:

$$p(s) = s^n + p_1 s^{n-1} + \cdots + p_{n-1}s + p_n$$

$$x_e = -(A - BK)^{-1} BK_r r$$

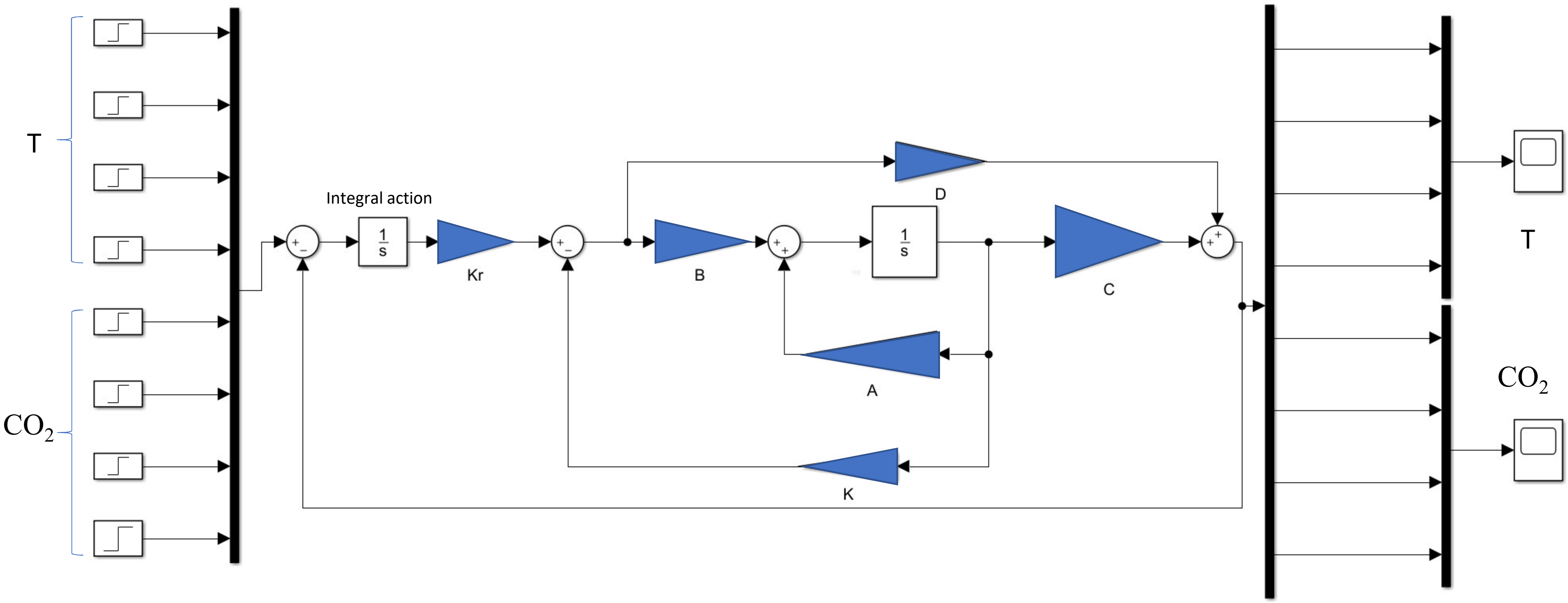
$$y_e = Cx_e$$

In this formulation, K_r is the best choice, which then gives $y_e = r$, which is the required value. Furthermore, because K_r is scalar:

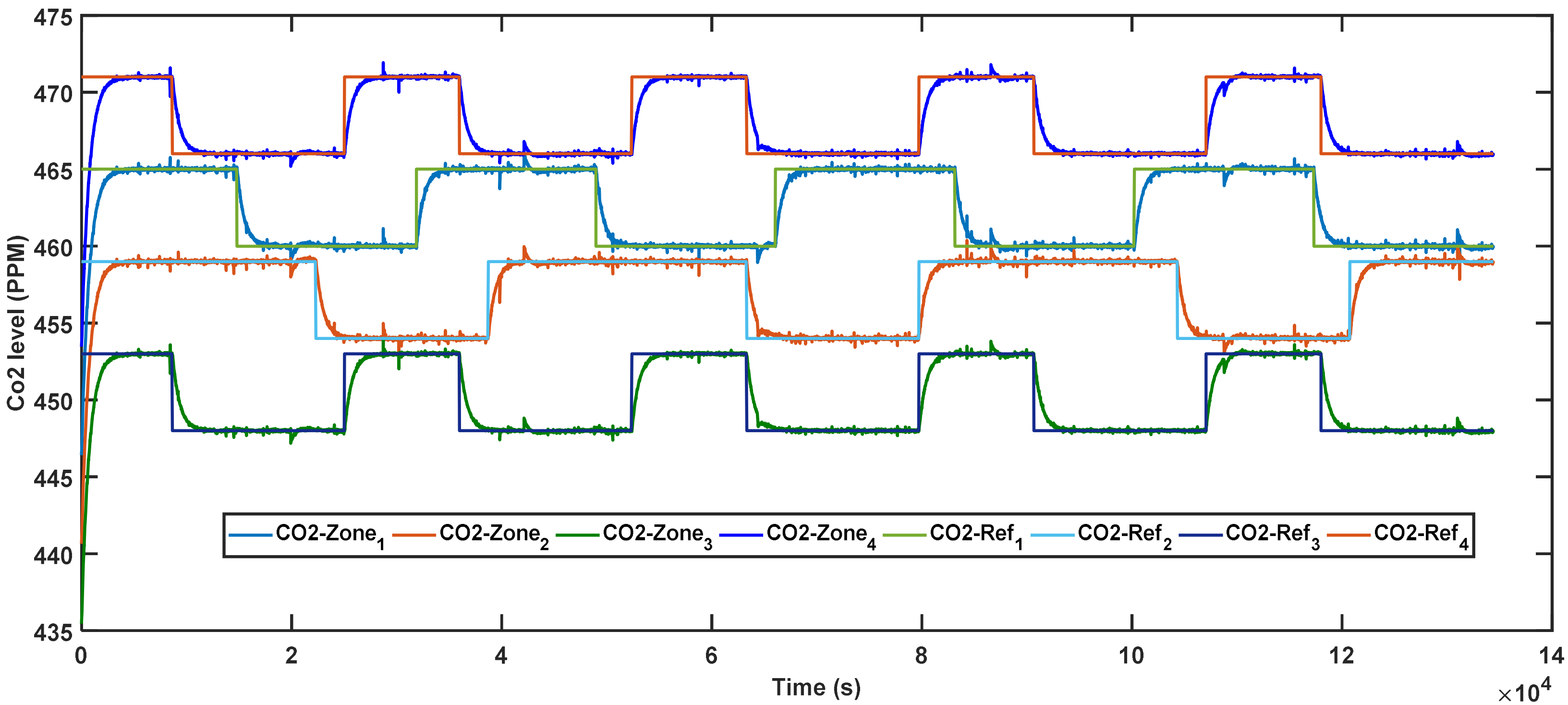
$$K_r = -1/(C(A - BK)^{-1} B)$$

The variable K_r represents the opposite of the closed looped system's zero-frequency gain. Therefore, by applying K_r input gain and K which is feedback gain matrix.

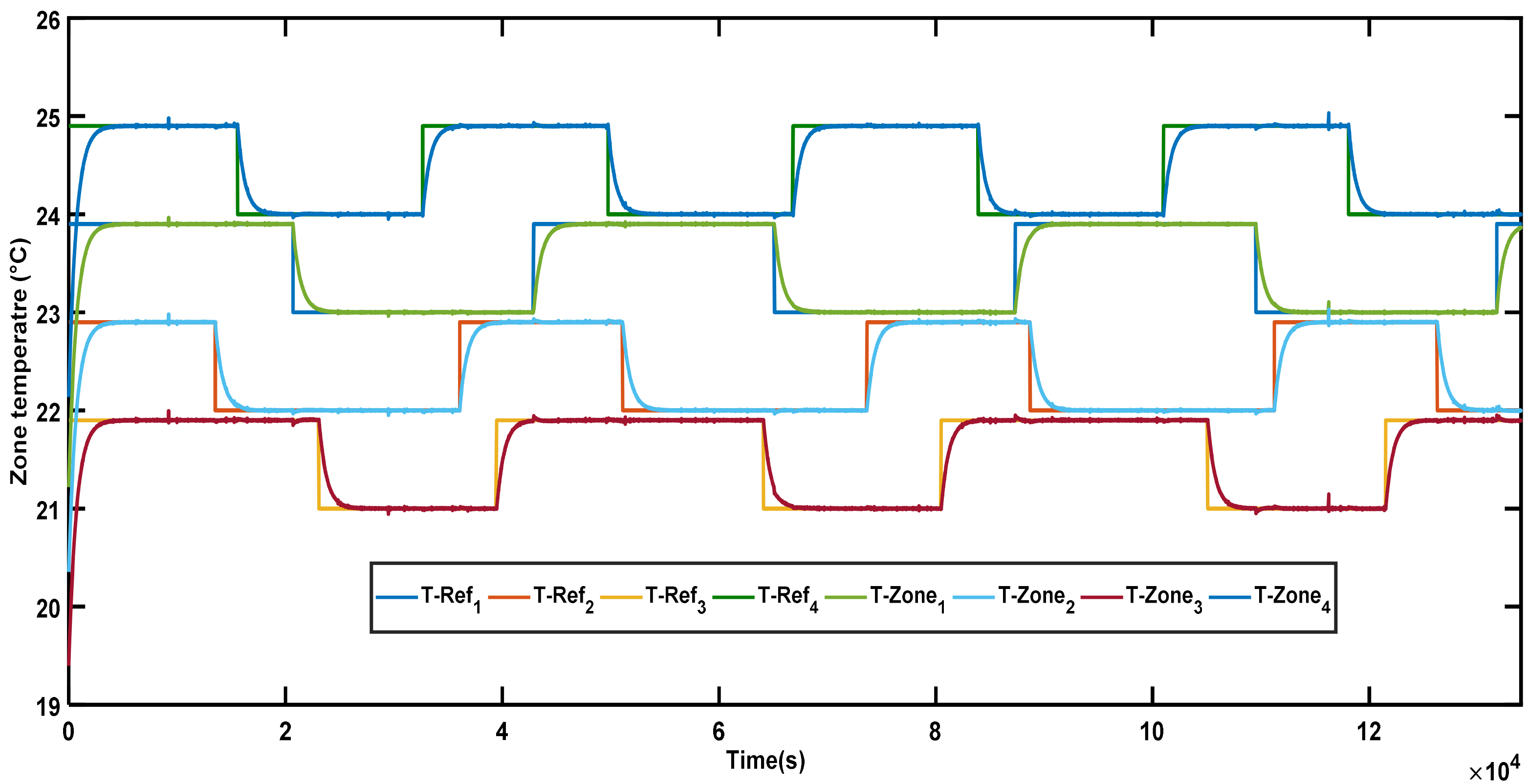
The block diagram of a system with state feedback and integral control using Matlab Simulink. Simulations are performed for a controller structure where a unit's step input is [465 459 453 471 23.9 22.9 21.9 24.9], and signals are used as the reference signal. Through simulation, mathematical modeling for the system is verified, and the performances for the controller structures are analyzed. Also, the initial state, X_0, of the system for concentrations and indoor temperatures are taken from measured data.



Simulation results of the system with a measured initial condition of CO_2 level is X_0= [446.4 440.6 435.44 453.4], and change for set points in different time investigate the system's responses with state feedback control and integral action. The responses of the CO_2 level for the zones.



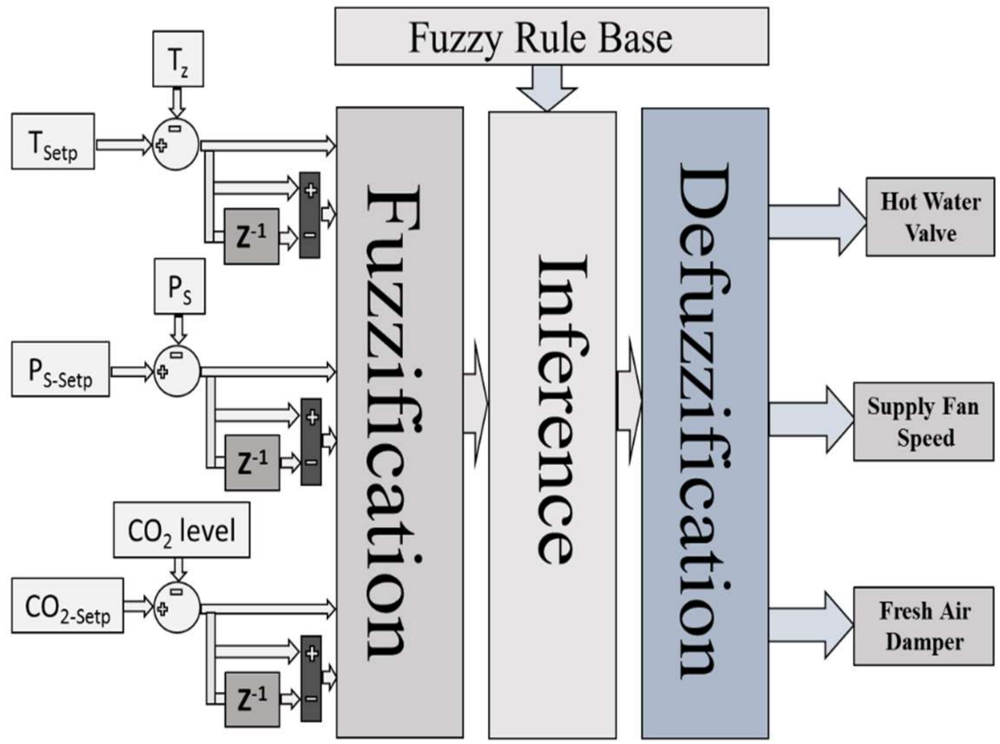
The responses of the zones temperature with measured initial condition of the zone temperatures, X_0= [21.21 20.35 19.39 22.13]. Also, change for set points in different time investigate the system's responses with state feedback control and integral action



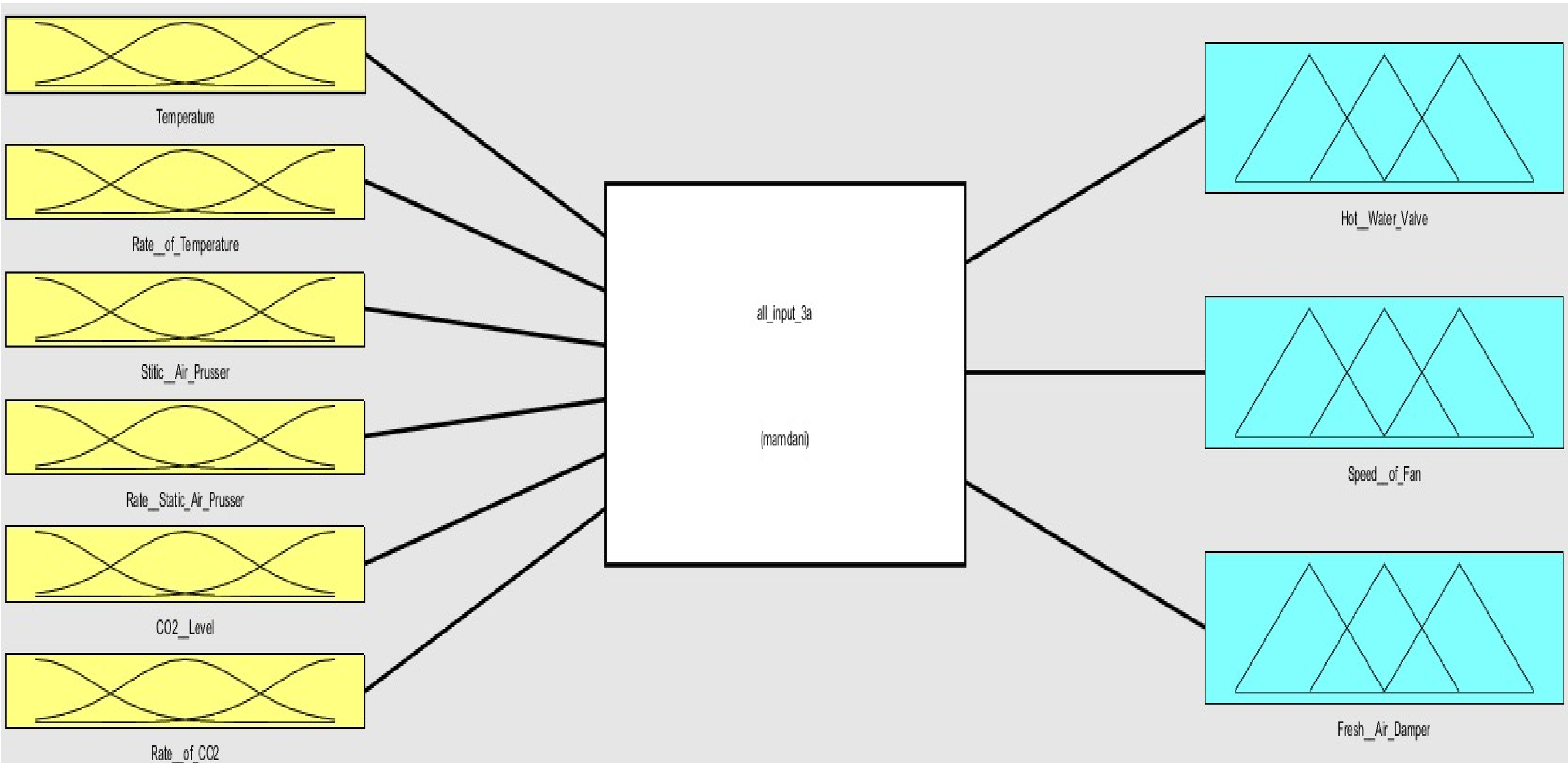
- *Step 1: Fuzzification* changes crisp/classical data into membership functions (MFs) or fuzzy data.

- *Step 2:* In the *Fuzzy Inference process*, MFs are added to control rules in order to obtain the required fuzzy output.

- *Step 3: Defuzzification* employs a variety of strategies as a means firstly to formulate every associated output, secondly to place them within a table framework, and thirdly to choose the output in a look-up table in accordance with the current input obtained for the specific application being performed. Or changes fuzzy output variables into crisp variables in order to meet control objectives. Method used was centroid method.



Fuzzy Logic Designer App of the system, with this application the FLC can be designed to add or remove input or output, fuzzy membership function, IF-Then rules, and select fuzzy inference functions.



Fuzzy membership function

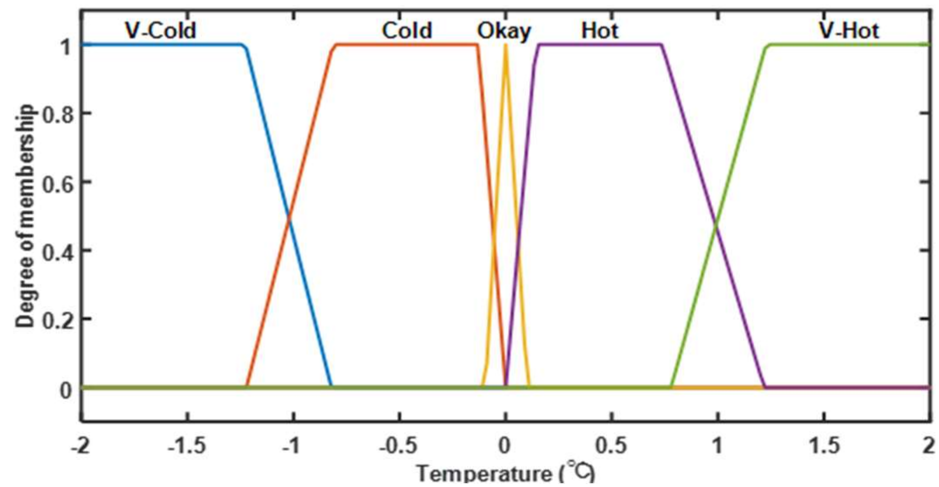
The MFs editor is used in unpacking the fuzzy tool box, which is applied in shape-defining any MFs that are related to variables in the membership. AHU_1 control system, indicating three outputs and six inputs as following:

- Input Variables

1. Temperature Differences (ΔT)

Differences between setpoint (T_{setp}) and current zone temperature (T_z) for time (k)

$$\Delta T(k) = T_{setp}(k) - T_z(k) \qquad (°C)$$

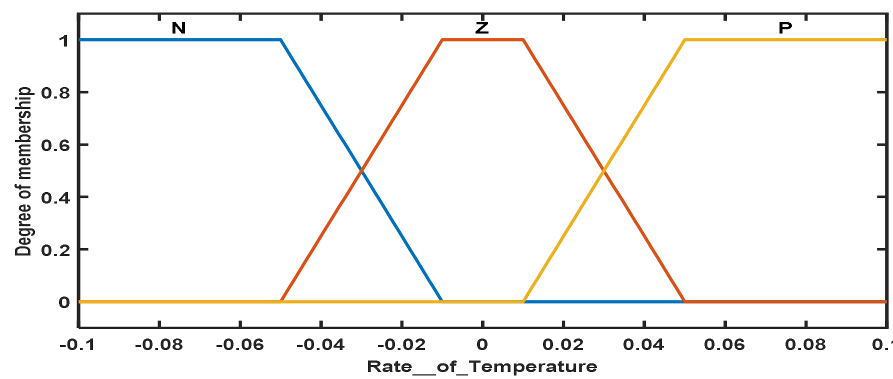


2. Change in ΔT ($d\Delta T$)

Error input variables related to changes in temperature are formulated through finding the ratio for the difference of past and present temperature error values in relation to sampling time (Δt),

$$(d\Delta T) = (\Delta T(k) - \Delta T(k-1))/\Delta t \qquad (°C/s)$$

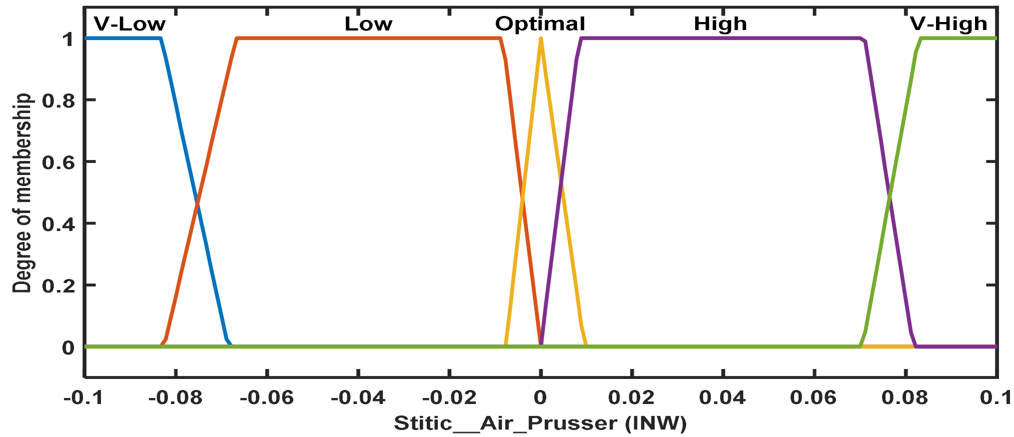
Where $\Delta t = 3$ sec



3. Static Air Pressure P_S Differences (ΔP_S)

Changes in present duct P_S; these differences were noted by sensors located in both cold- and hot-deck ducts. As can be seen, the static pressure $P_{S\text{-}setp}$ setpoints occur for time (k),

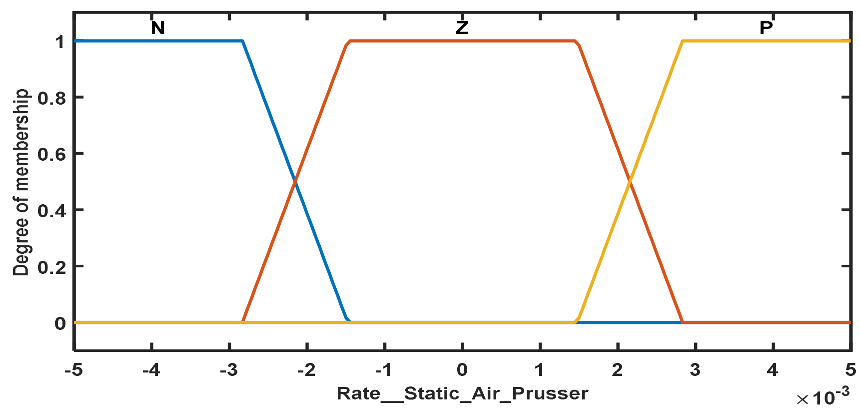
$$\Delta P_S(k) = P_{S\text{-}setp} - P_S(k) \quad \text{(INW)}$$



4. Change in ΔP_S ($d\Delta P_S$)

P_S error input variable are formulated using ratios for differences between present and past P_S error values in relation to sampling time (Δt)

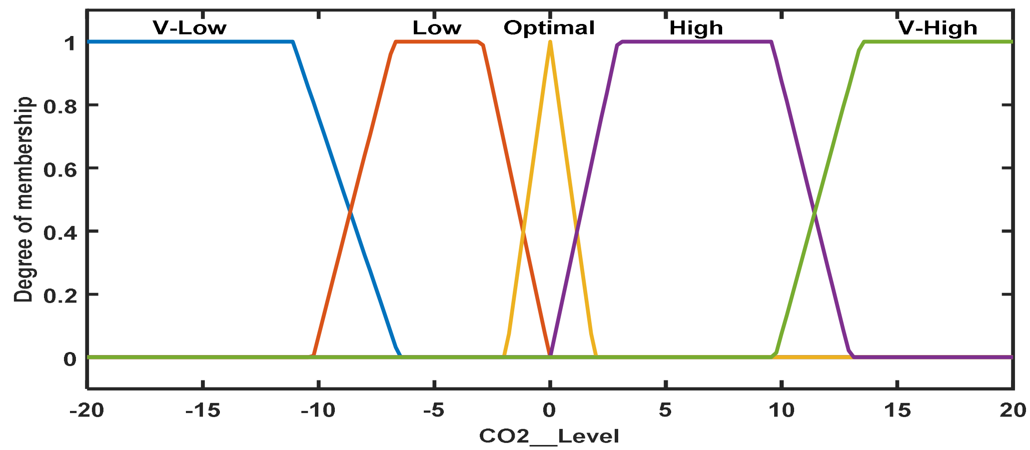
$$d\Delta Ps(k) = (\Delta Ps(k) - \Delta Ps(k-1))/\Delta t \qquad \text{(INW/s)}$$



5. Differences in CO_2 Levels (ΔCO_2)

This is the difference between the present CO_2 level in the return air from the sensor in the AHU_1 return duct and the CO_2 level $CO_{2\text{-S-setp}}$ set point, as recorded at the time (k).

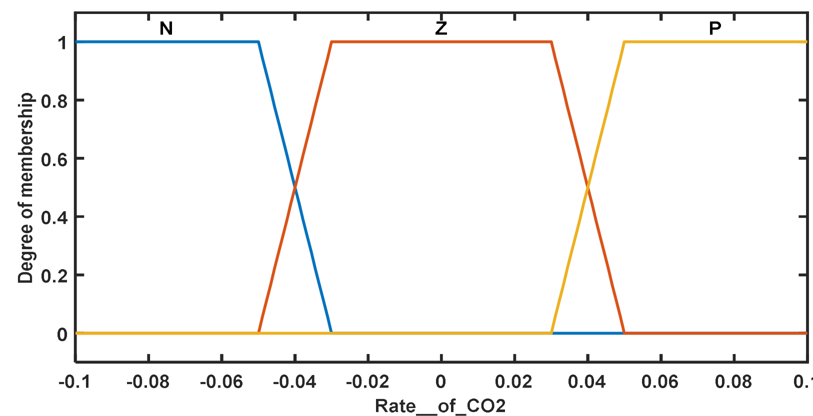
$$\Delta CO_2\,(k) = CO_{2\text{-setp}} - CO_2\,(k) \qquad (PPM)$$



6. Change in ΔCO_2 (d ΔCO_2)

CO_2 error input variable changes can be formulated through finding the ratio for the difference between the present and past CO_2 error values in relation to sampling time (Δt).

$$d\Delta CO_2\,(k) = (\Delta CO_2\,(k) - \Delta CO_2\,(k-1))/\Delta t \qquad (PPM/s)$$

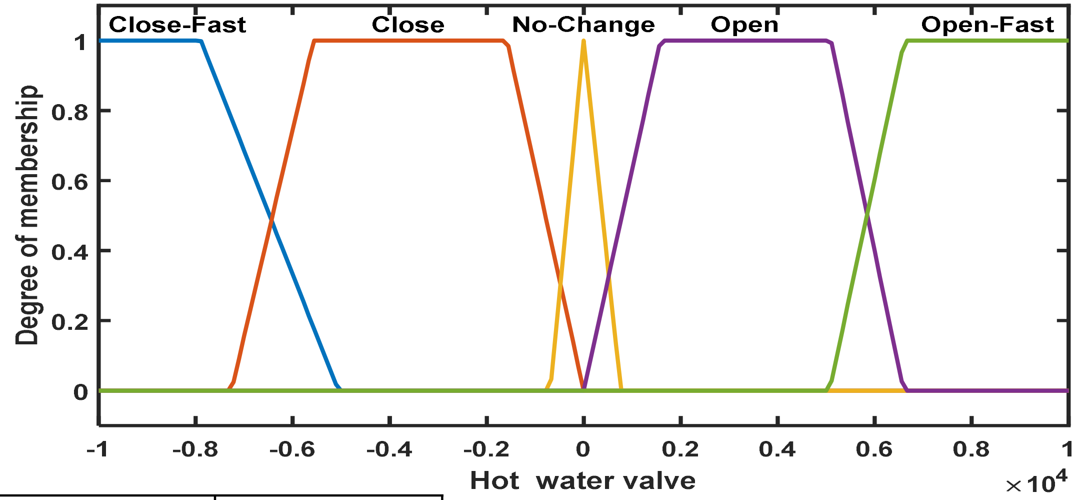


➢ Output variables

The three inputs of AHU_1 (fresh air, air flow, and hot water) serve as FLC outputs. The values are introduced as gains to the system in order to move system responses towards a stability state.

1. Aperture on hot water valve

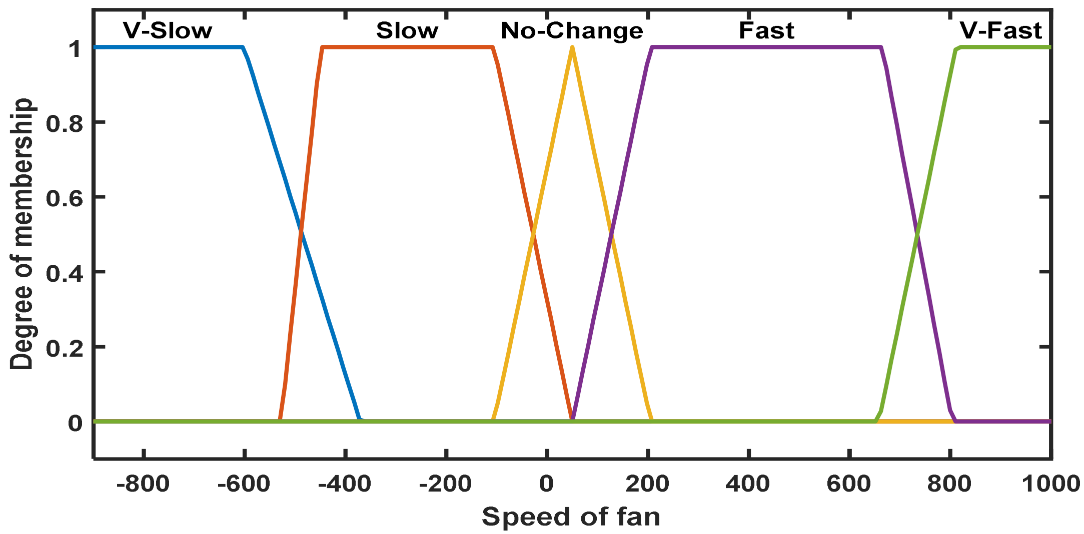
The process involving the hot water valve's opening and closing is indicated through the 5 MFs for the fuzzy controller output in order to find the zone temperature setpoint (T_{setp}).



Output field	Range	Corresponding	Fuzzy set
Hot water valve aperture	[-10320 -10000 -7894 -5060]	0%-20%	Close-Fast
	[-7894 -5060 -1580 0]	20%-40%	Close
	[-689 0 768]	40%-60%	NO-Change
	[0 1580 5100 6794]	60%-80%	Open
	[5100 6794 10220 10260]	80%-100%	Open-Fast

2. Supply fan speed

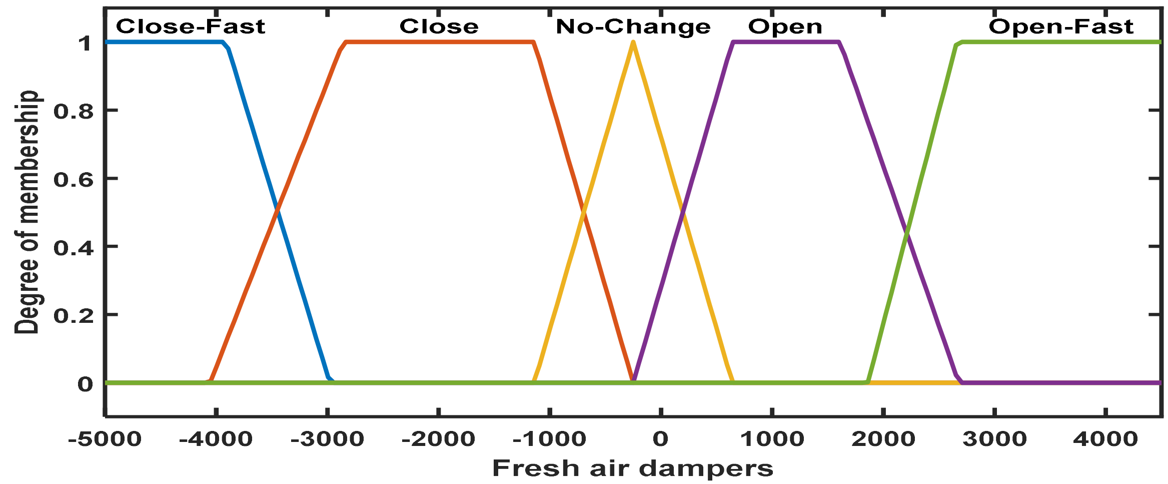
The FLC's second output serves as the speed control for the supply fan in order to reach the ducts' static air pressure set point. There are five MFs for this process.



output field	Range	Corresponding	Fuzzy set
Supply fan speed	[-1060 -913.1 -601 -371]	0%-20%	V-Slow
	[-527.9 -449 -105 50]	20%-40%	Slow
	[-105.3 50 205.4]	40%-60%	No-Change
	[46.3 201 661 800]	60%-80%	Fast
	[658 811 1002 1010]	80%-100%	V-Fast

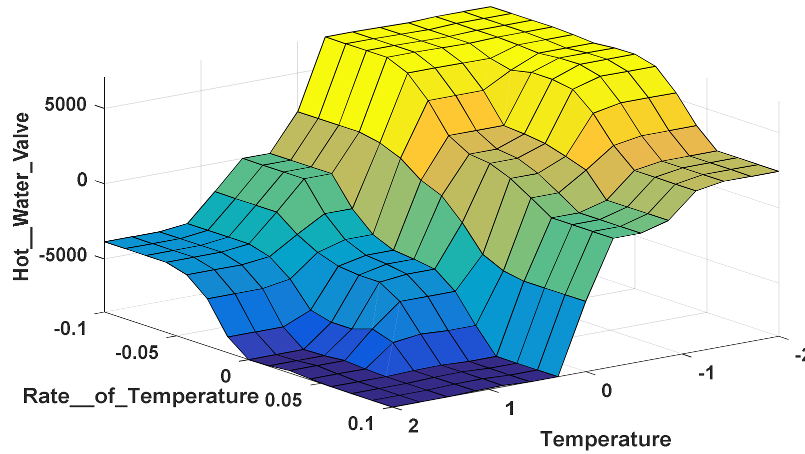
3. Fresh air dampers position

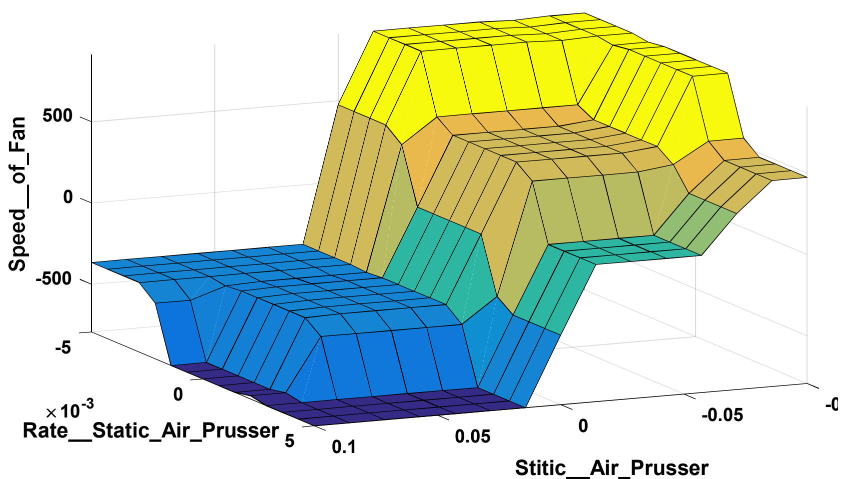
Five MFs of the fuzzy controller output for opening and closing operation of the fresh air dampers to obtain on the zone CO_2 level set point.

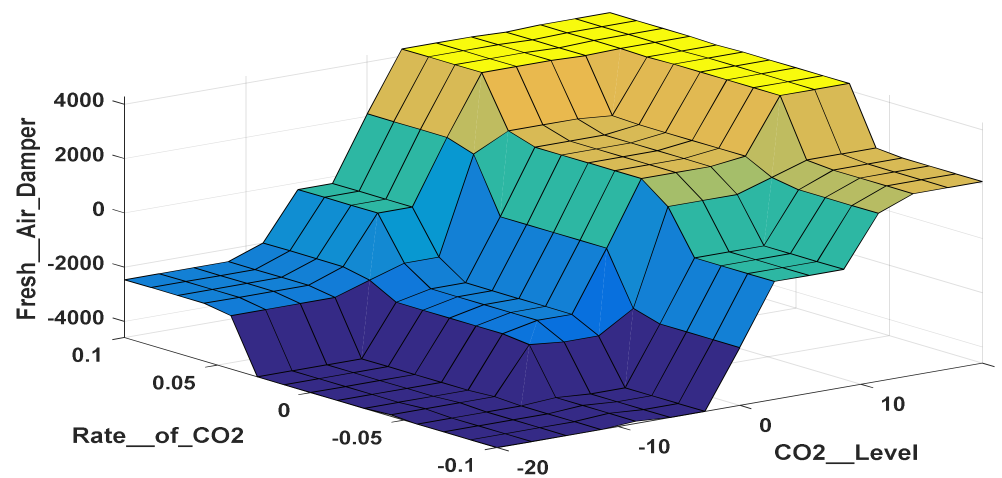


Output field	Range	Corresponding	Fuzzy set
Fresh air dampers position	[-5200 -5028 -3910 -2980]	0%-20%	Close-Fast
	[-4056 -2860 -1140 -250]	20%-40%	Close
	[-1139 -250 641.6]	40%-60%	No-Change
	[-250 642 1610 2677]	60%-80%	Open
	[1860 2660 4509 4810]	80%-100%	Open-Fast

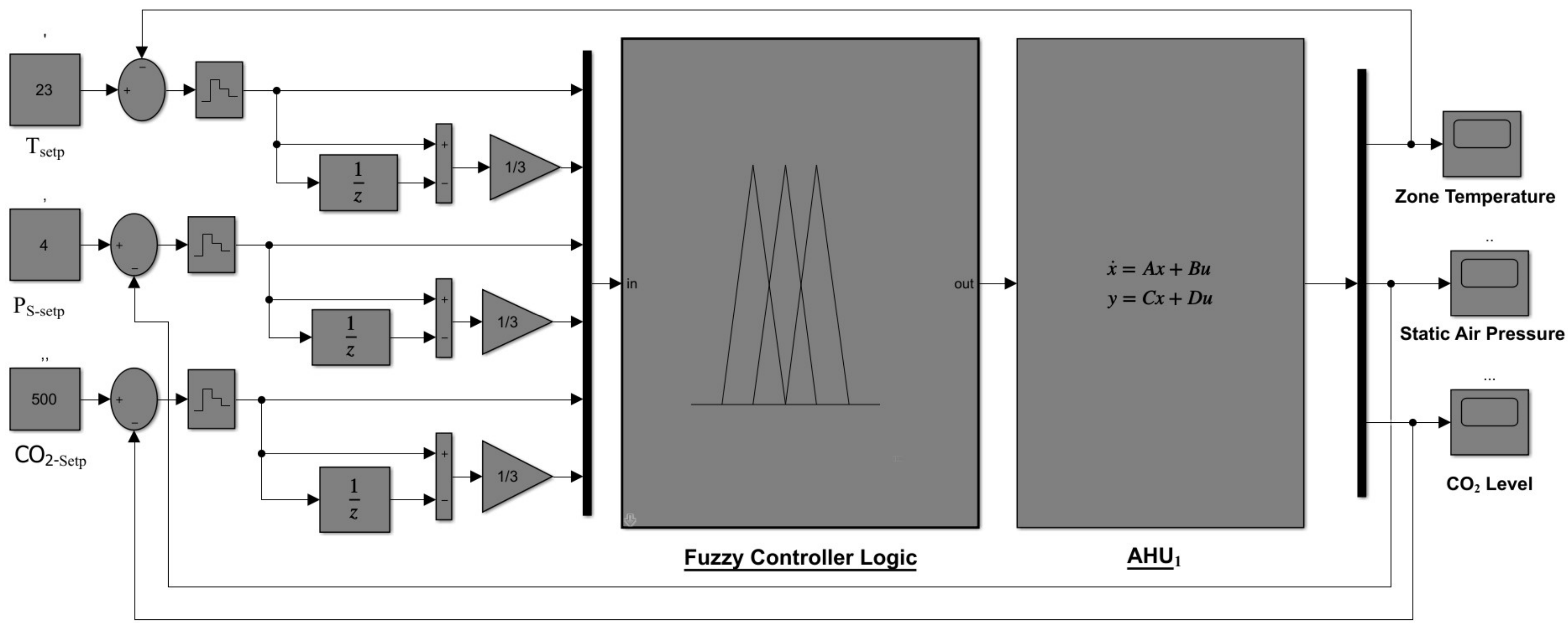
In the process of defuzzification, fuzzy set form results convert into crisp ones. This process is required for hardware applications that exchange crisp data. The present study uses the centroid approach. the control surface for implementing MFs for inputs error values as well as a fuzzy rule-implemented change of error values. The values for the control output are associated with every potential input combination for controlling the outputs in order to obtain setpoints for the system.



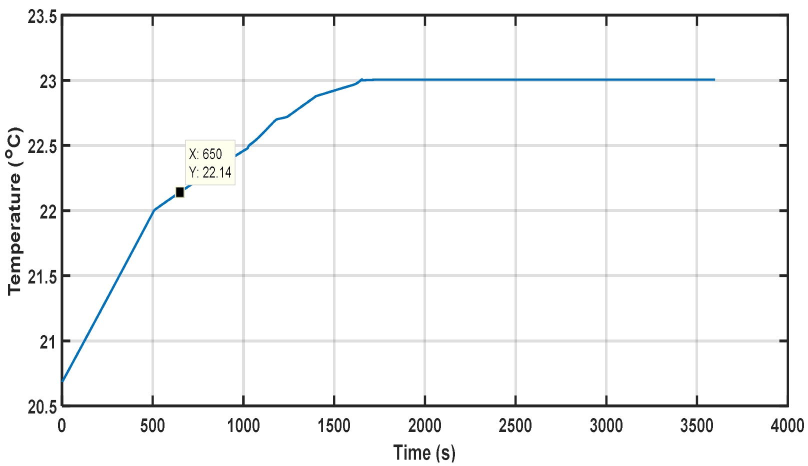


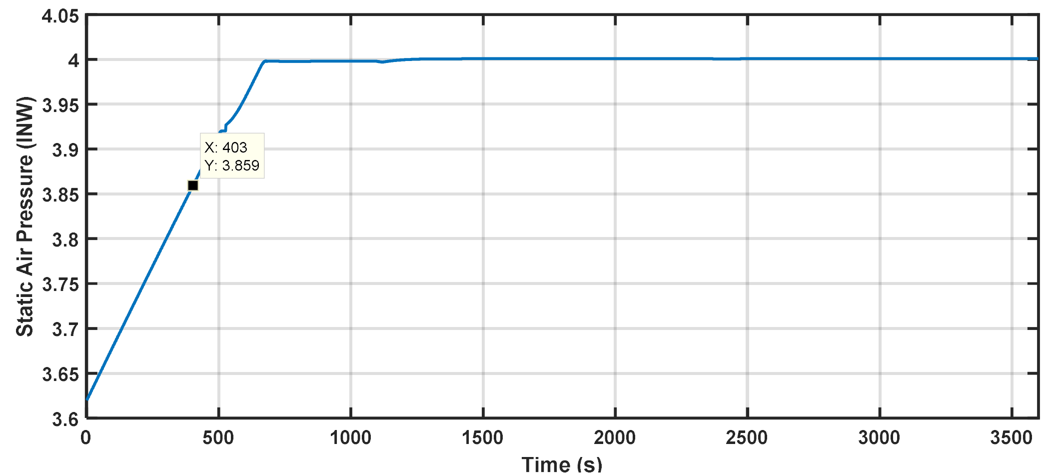


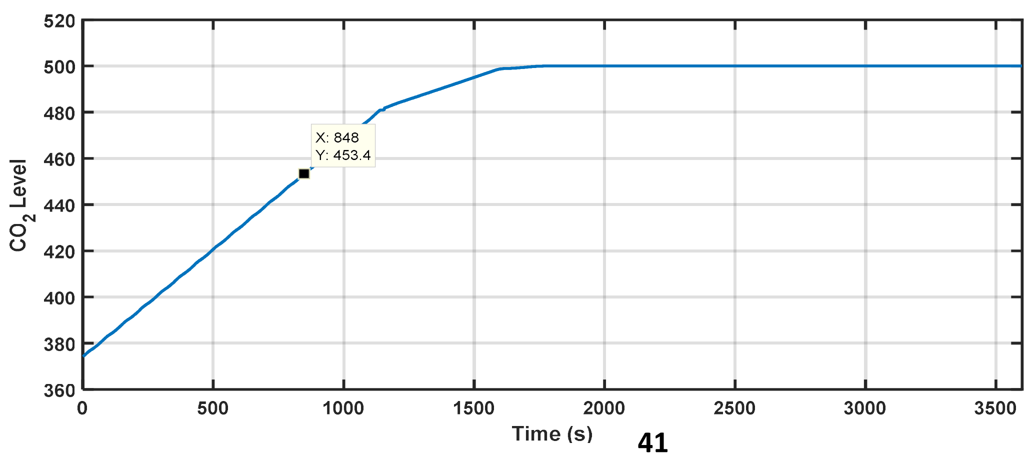
Block diagram for the AHU_1 state space model for a fuzzy controller with MATLAB / Simulink. The initial conditions selected for temperature, air pressure, and CO_2 levels are 20.7 ^{o}C, 3.62 INW, and 374.2 MMP, respectively. The sampling time is three seconds for the control action, which is the same as for the real system.



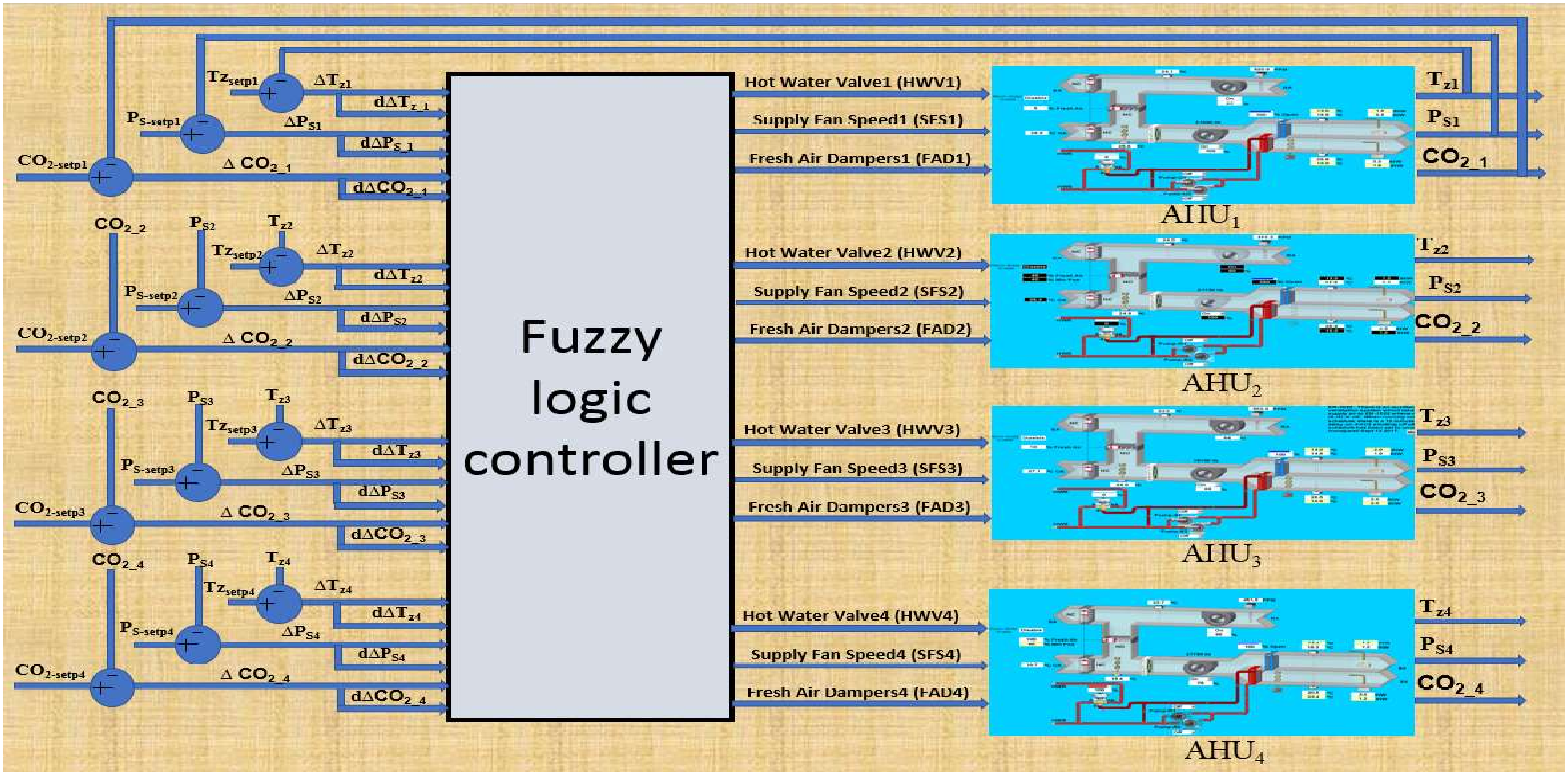
Three of the system's output responses that demonstrate the system's stability. Zone temperature T_z achieves the set point of 23 ^{o}C at a rise time of only 10.83 minutes and no overshoot. The response of static pressure, with a rise time of 6.71 minutes and no overshoot. CO_2 level response, achieving the set point, again with no overshoot, at a rise time of 14.13 minutes.







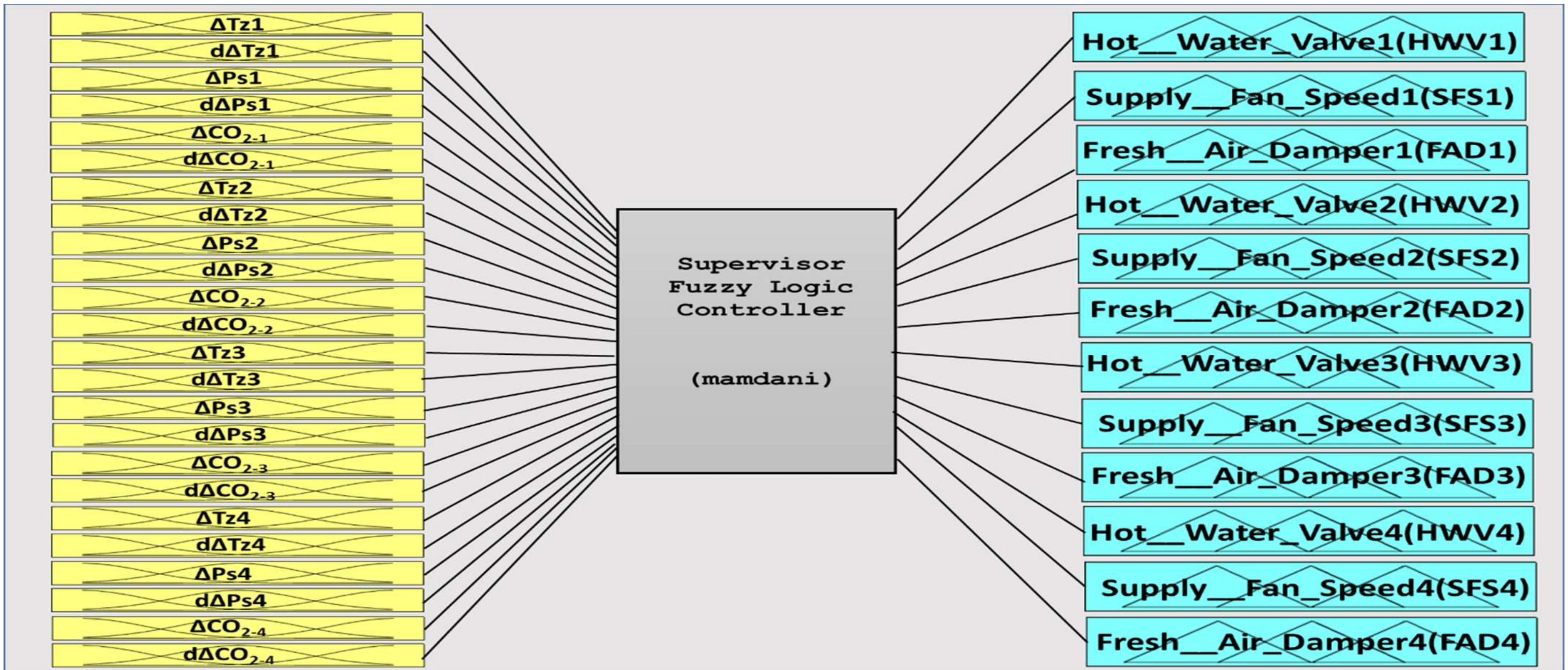
SUPERVISOR FUZZY LOGIC CONTROLLER OF WHOLE BUILDING



Application designer of SFLC

SFLC of the system has 24 inputs and 12 outputs as following:

- 8 inputs are temperature differences (ΔT) and the ratio for the difference ($d\Delta T$) of AHUs.
- 8 inputs are static air pressure P_S differences (ΔP_S) and the ratio for the difference ($d\Delta P_S$).
- 8 inputs are differences in CO_2 Levels (ΔCO_2) and the ratio for the difference ($d\,\Delta CO_2$).
- 12 outputs of the SFLC; each AHU has three (fresh air dampers, fan speed of air flow, and valve of hot water).



1. Inputs variables

The control system has 6 inputs from each AHU. Three for the difference between setpoints and current values, there are five MFs of (V-High, High, Optimal, Low, and V-Low). Table illustrate the details of all MFs.

Range / Inputs	V-Low	Low	Optimal	High	V-High
ΔT_{z1}	[-5.26 -4.24 -0.611 -0.5]	[-0.611 -0.5 -0.134 0]	[-0.134 0 0.1357]	[0 0.134 0.51 0.7817]	[0.5797 0.7323 1.774 9.13]
ΔP_{S1}	[-7 -0.15 -0.083- 0.068]	[-0.08 -0.06 -0.008 0]	[-0.007 0 0.0095]	[0 0.008 0.071 0.081]	[0.07052 0.08278 0.1399 9]
$\Delta CO_{2\text{-}1}$	[-62.73 -5.04 -4.1 -3.55]	[-4.117 -3.5 -0.73 0]	[-0.28 0 0.28]	[0 0.73 2.21 3.082]	[2.098 3.025 30 119.5]
ΔT_{z2}	[-8.76 -4.24 -0.611 -0.5]	[-0.611 -0.5 -0.134 0]	[-0.134 0 0.1357]	[0 0.134 0.51 0.7815]	[0.5795 0.7325 1.774 9.63]
ΔP_{S2}	[-5.6 -0.126 -0.06 -0.05]	[-0.07 -0.05 -0.007 0]	[-0.0061 0 0.007]	[0 0.006 0.056 0.065]	[0.05642 0.0662 0.1119 7.2]
$\Delta CO_{2\text{-}2}$	[-56.4 -5.04 -4.107 -3.5]	[-4.11 -3.507 -0.73 0]	[-0.18 0 0.18]	[0 0.73 2.21 3.082]	[2.098 3.025 30 119.5]
ΔT_{z3}	[-5.26 -4.24 -0.611 -0.5]	[-0.611 -0.5 -0.134 0]	[-0.134 0 0.1357]	[0 0.134 0.51 0.7815]	[0.5795 0.7325 1.774 9.63]
ΔP_{S3}	[-6.4 -0.12 -0.066 -0.05]	[-0.06 -0.05 -0.006 0]	[-0.0061 0 0.007]	[0 0.0067 0.057 0.06]	[0.05642 0.0662 0.1119 7.2]
$\Delta CO_{2\text{-}3}$	[-56.48 -5.048 -4.1 -3.5]	[-4.117 -3.51 -0.73 0]	[-0.28 0 0.28]	[0 0.73 2.21 3.082]	[2.098 3.025 30 119.5]
ΔT_{z4}	[-5.26 -4.24 -0.611 -0.5]	[-0.611 -0.5 -0.134 0]	[-0.134 0 0.1357]	[0 0.134 0.51 0.7815]	[0.5795 0.7325 1.774 9.63]
ΔP_{S4}	[-4.9 -0.12 -0.06 -0.048]	[-0.06 -0.04 -0.005 0]	[-0.005 0 0.0067]	[0 0.006 0.049 0.058]	[0.05 0.05795 0.09793 6.3]
$\Delta CO_{2\text{-}4}$	[-56.5 -5.04 -4.11 -3.55]	[-4.12 -3.507 -0.73 0]	[-0.288 0 0.288]	[0 0.73 2.21 3.082]	[2.098 3.025 30 119.5]

The another inputs are the ratio for response differences. There are three MFs used to define error variable changes: Positive (P), Negative (N), and Zero (Z). Table illustrate the details of all MFs.

Range / Inputs	P	Z	N
$d\Delta T_{z1}$	[-0.1062 -0.09279 -0.045 -0.009]	[-0.04601 -0.009 0.01 0.04499]	[0.0109 0.0395 0.1381 0.175]
$d\Delta P_{S1}$	[-0.005533 -0.005 -0.003 -0.001469]	[-0.002833 -0.0014 0.001478 0.002833]	[0.00158 0.00293 0.00595 0.0065]
$d\Delta CO_{2\text{-}1}$	[-2.1 -1 -0.5 -0.3]	[-0.499 -0.3002 0.2993 0.5]	[0.3 0.5 1 1.091]
$d\Delta T_{z2}$	[-0.1062 -0.09279 -0.045 -0.009]	[-0.045 -0.009 0.009 0.045]	[0.009 0.045 0.1381 0.1615]
$d\Delta P_{S2}$	[-0.0053 -0.005 -0.0028 -0.00149]	[-0.002833 -0.0014 0.001478 0.002833]	[0.00148 0.003 0.00635 0.00635]
$d\Delta CO_{2\text{-}2}$	[-2.21 -1.1 -0.53 -0.323]	[-0.5 -0.3 0.3 0.5002]	[0.3005 0.501 1 1.1001]
$d\Delta T_{z3}$	[-0.1064 -0.09279 -0.045 -0.01]	[-0.045 -0.019 0.0101 0.045]	[0.009002 0.04502 0.139 0.162]
$d\Delta P_{S3}$	[-0.005433 -0.005 -0.00288 -0.00147]	[-0.002833 -0.0014 0.001478 0.002833]	[0.00148 0.00283 0.00585 0.0055]
$d\Delta CO_{2\text{-}3}$	[-2.21 -1.4 -0.555 -0.343]	[-0.5 -0.289 0.3 0.499]	[0.3 0.5005 1 1.0891]
$d\Delta T_{z4}$	[-0.1072 -0.09379 -0.04501 -0.01]	[-0.045 -0.009 0.009 0.045]	[0.01 0.045001 0.138 0.161501]
$d\Delta P_{S4}$	[-0.005433 -0.005 -0.0028 -0.001478]	[-0.002833 -0.0014 0.001478 0.002833]	[0.0025 0.00298 0.00585 0.0075]
$d\Delta CO_{2\text{-}4}$	[-2.103 -1 -0.501 -0.312]	[-0.5 -0.3 0.3 0.5]	[0.299 0.50035 1 1.1]

2. Outputs variables MFs

The inlet of all ventilation units (hot water, fan speed, and fresh air) acts as an SFLC output. This means that SFLC has twelve output. Values are entered as a gain in the system to introduce system reactions into a steady state. Table illustrate all the details of MFs (Close-Fast, Close, No-Change, Open, and Open-Fast) and the related operation percentages of hot water valve's, fan speed and fresh air dampers of the whole system.

Corresponding	0% - 20%	20% - 40%	40% - 60%	60% - 80%	80% -100%
Range / Outputs	Close-Fast	Close	No-Change	Open	Open-Fast
HWV_1	[-17160 -13000 -10270 -6578]	[-9447 -7241 -2054 0]	[-895 0 998]	[0 2054 6630 8576]	[6588 8590 13280 13340]
SFS_1	[-14020 -12170 -8227 -5319]	[-7296 -6307 -1958 0]	[-1963 0 1963]	[0 1911 7723 9475]	[7680 9612 12020 12130]
FAD_1	[-7823 -7545 -5779 -4310]	[-6010 -4121 -1405 0]	[-1404 0 1407]	[0 1408 2936 4622]	[3332 4595 7515 7988]
HWV_2	[-15840 -12000 -9473 -6072]	[-8717 -6684 -1896 0]	[-826 0 921]	[0 1896 6120 7913]	[6081 7929 12260 12310]
SFS_2	[-8768 -7605 -5138 -3323]	[-4563 -3938 -1223 0]	[-1227 0 1227]	[0 1195 4827 5925]	[4800 6008 7515 7583]
FAD_2	[-11460 -11060 -8476 -6322]	[-8814 -6044 -2062 0]	[-2059 0 2065]	[0 2066 4307 6778]	[4886 6738 11020 11720]
HWV_3	[-11090 -8400 -6631 -4249]	[-6102 -4679 -1327 0]	[-578 0 645]	[0 1327 4284 5539]	[4257 5549 8585 8617]
SFS_3	[-7010 -6083 -4110 -2659]	[-3652 -3150 -979 0]	[-981 0 981]	[0 955.8 3862 4735]	[3840 4805 6014 6065]
FAD_3	[-9379 -9053 -6935 -5173]	[-7211 -4945 -1686 0]	[-1684 0 1689]	[0 1690 3524 5546]	[3998 5514 9017 9587]
HWV_4	[-11220 -8500 -6707 -4301]	[-6172 -4735 -1343 0]	[-585 0 652]	[0 1343 4335 5604]	[4307 5616 8686 8720]
SFS_4	[-31540 -27410 -18520 -11960]	[-16450 -14180 -4406 0]	[-2614 0 2614]	[0 4298 17360 21330]	[17280 21620 27050 27290]
FAD_4	[-17600 -17010 -13020 -9709]	[-13550 -9287 -3166 0]	[-1456 0 1469]	[0 3177 6616 10400]	[7505 10330 16930 18020]

3. Fuzzy rules

Table illustrate just the rules between first and second input (ΔTz_1 *and* $d\Delta Tz_1$) of the controller as the fuzzy default rule, there are three inputs in each AHU and four AHUs for the system, that mean the SFL controller has ($15 \times 3 \times 4$) 180 rules.

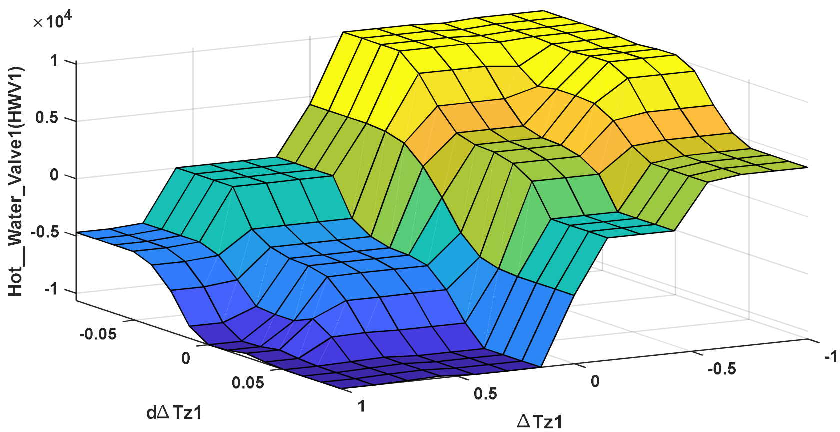
Δ inputs / dΔ inputs	V-Low	Low	Optimal	High	V-High
N	Open-Fast	Open-Fast	Open	No-Change	Close
Z	Open-Fast	Open	No-Change	Close	Close-Fast
P	Open	No-Change	Close	Close-Fast	Close-Fast

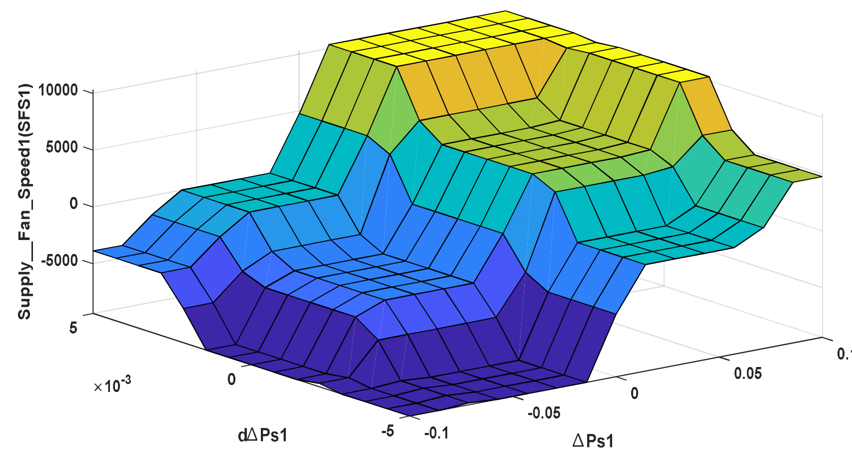
4. Defuzzification

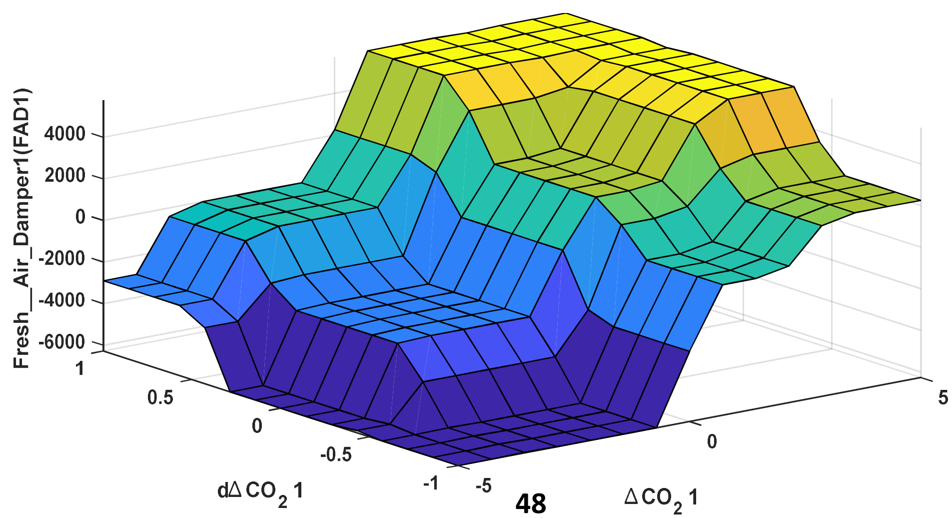
Defuzzification changes fuzzy output variables into crisp variables in order to meet control objectives.

Method used was centroid method.

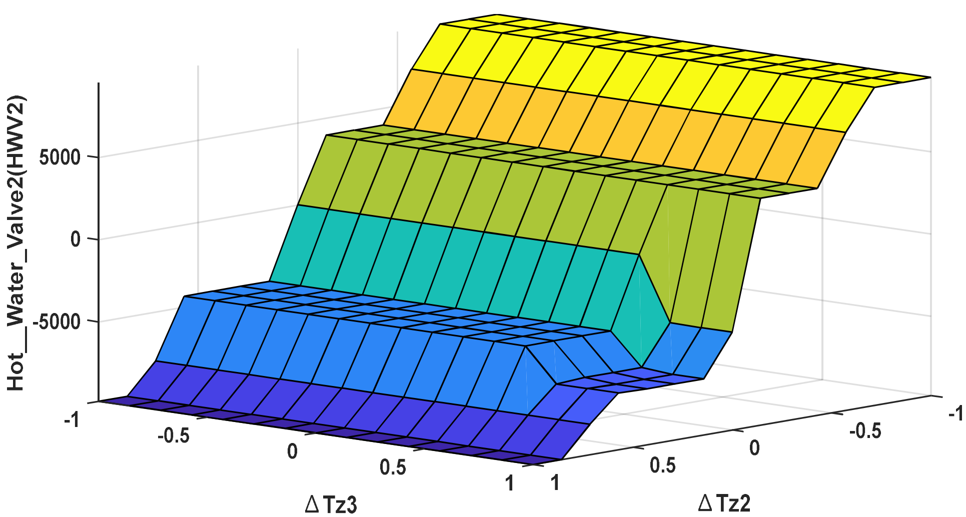
The control surface with the applied MFs. (Δ) and (dΔ) based on fuzzy rules have been used. The control output values derive from a range of input combinations in hot water valve, speed of fan and fresh air dampers functions.



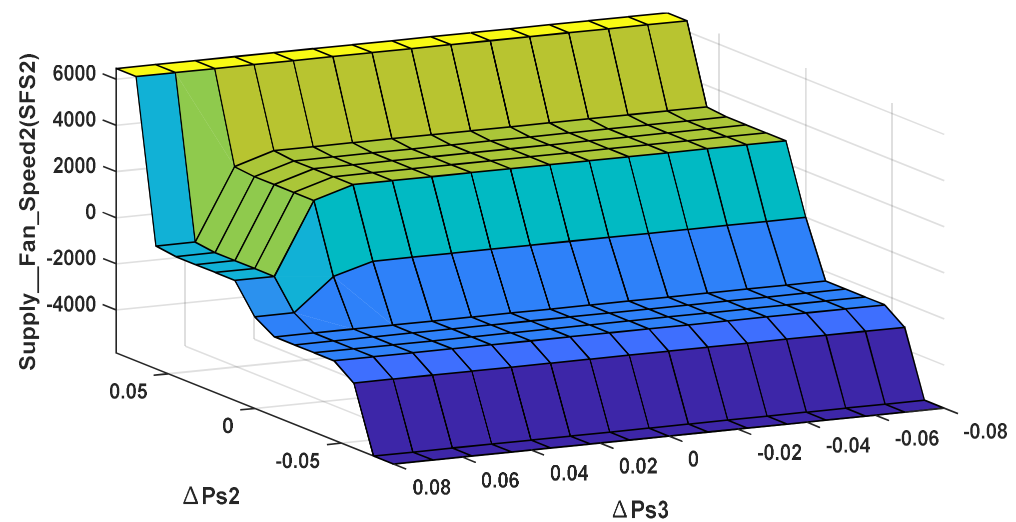




For the extra rules between floors, the control surface between second and third-floor temperature differences for saving energy and better the performance of the hot water valve of AHU_2 (*HWV2*).

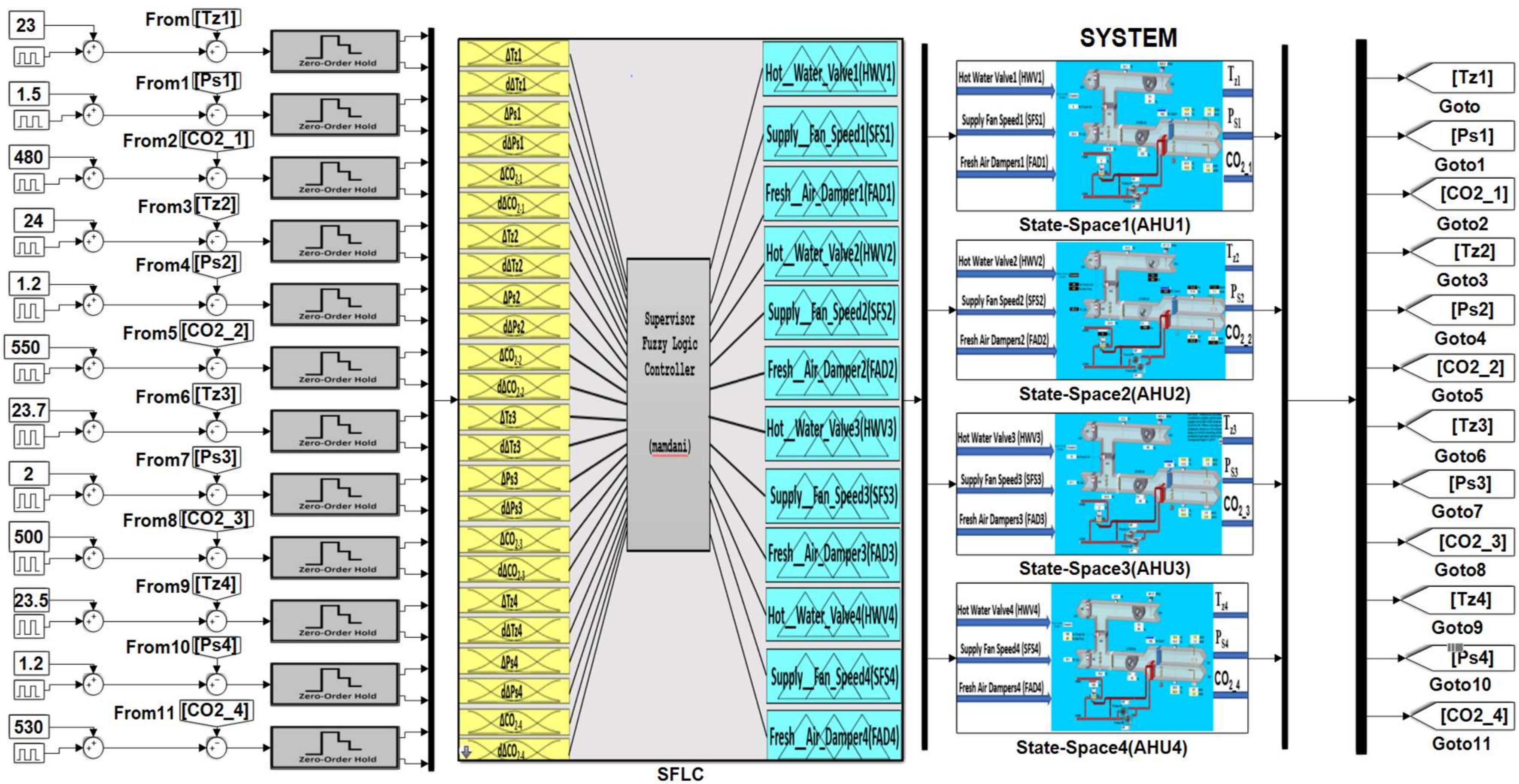


The control surface between the second and third floor Static Air Pressure Differences for saving energy and better the performance of supply fan speed of AHU_2 (*SFS2*).

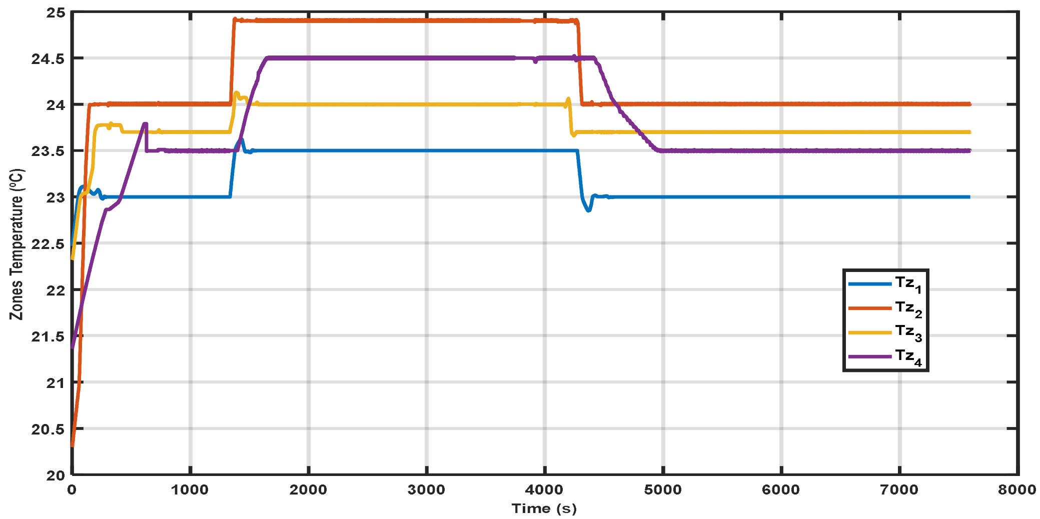


Main control block diagram

block diagram for state space models of a whole building (four AHUs), supervisor fuzzy logic controller and all setpoints using MATLAB / Simulink. There are four state space models; each AHU has one with three inputs and three outputs;

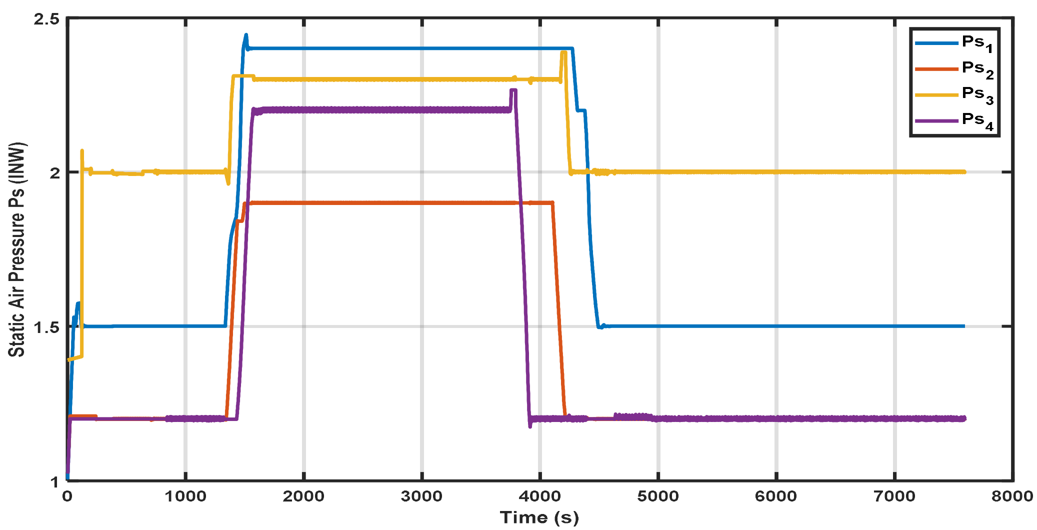


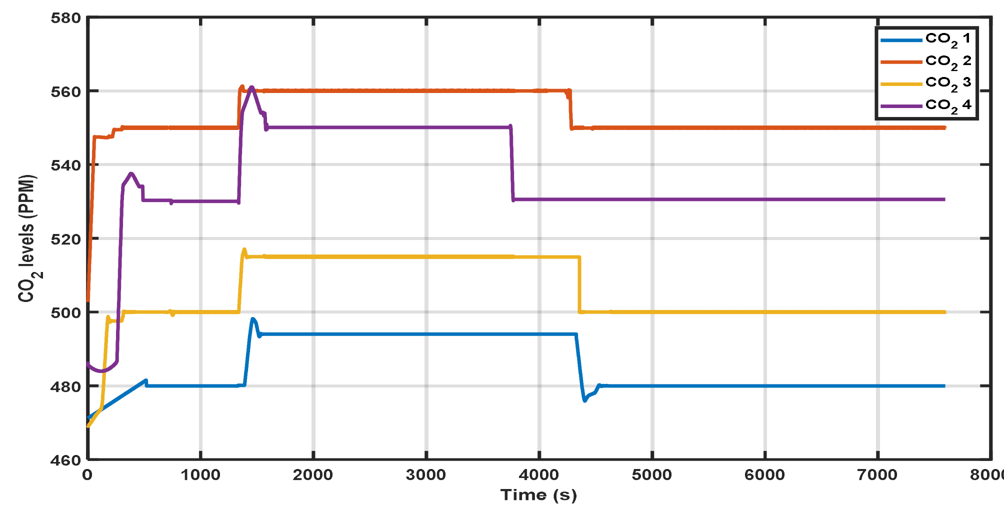
Simulation results



First of the system's output responses of each AHU that demonstrate the system's stability.

- Zones temperature (T_{z1}, T_{z2}, $T_{z3,}$ and T_{z4}) achieves setpoints at good rise time and there is a small overshoot of some responses.
- Responses of static air pressure of AHUs (Ps_1, Ps_2, $Ps_{3,}$ and Ps_4), with perfect rise time and some small overshoots of the responses
- CO_2 level responses of AHUs ($CO_{2\text{-}1}$, $CO_{2\text{-}2}$, $CO_{2\text{-}3,}$ and $CO_{2\text{-}4}$), achieving the setpoints of CO_2 level with good rise time and small overshoot of some responses





CONCLUSION

- The S.J. Carew building was modeled using the IDA-ICE program using all details of HVAC system and instructions of the building. This model provides good approximations comparing the consumption of hot water and electricity with the real data for a full year (2016). It also compares the average of the outside temperature of the weather file of IDA-ICE program and the actual data.
- The system identification toolbox was used to obtain the state space model of the multi-input and multi-output system
- Input-output feedback linearization method to linearize the HVAC system, one type of linear controller, pole placement controller with input gain and integral action were able to regulate the linearized HVAC system at the desired set point without steady state error.
- Fuzzy logic controller modulated the three AHU_1 inputs (fresh air, air flow and hot water). The FLC algorithm gave a stable response and could deal better with a number of different parameters, including steadying errors, response time, and overshoot.

- The simulation results indicated that the novel HVAC model was able to provide the desired level of environmental comfort throughout the structure by employing a supervisor FLC to control the targeted AHUs. Specifically, every floor of the Building was considered a fully single block, thus giving four models. The advantage of this separation approach was a reduction in the number of supervisor controller rules to 180. With the addition of a few rules in the entry steps, the SFLC was able to regulate the power-saving and provide enhanced performance of the Building's heating and cooling system.

Contributions

- Modeling of a large building HVAC system
- Identification of building dynamic model
- Model simulation and verification
- Design of system controller and simulation (state feedback controller)
- Design fuzzy logic controller and simulation for just AHU one
- Design of novel supervisor fuzzy logic controller for whole building

FUTURE WORK

There are various directions to extend this work, which can be briefly outlined as follows:

- Modeling part of the HVAC system, in system identification can add more variables such lighting system and disturbances such as occupants the building, solar and the wind direction.
- Cost estimate for implementation could be done.
- The software can be found to estimate the cost of the heating process.
- Switching to another heating source could be studied.
- System simulation can include measured disturbance variable.
- For the FLC each floor model was determined and used in this study. A whole building model can also be used although that will need many more fuzzy rules.

PUBLICATIONS

1. Abdo-Allah, Almahdi, Tariq Iqbal, and Kevin Pope. "Modeling, Analysis, and State Feedback Control Design of a Multizone HVAC System." Journal of Energy 2018 (2018).

2. Abdo-Allah, Almahdi, Tariq Iqbal, and Kevin Pope. "Modeling, Analysis, and Design of a Fuzzy Logic Controller for an AHU in the SJ Carew Building at Memorial University." Journal of Energy 2018 (2018).

3. Almahdi Abdo-Allah, M. Tariq Iqbal, and Kevin Pope, "Energy Consumption Analysis of a Large Building at Memorial University," Journal of Energy, vol. 2019, Article ID 5243737, 21 pages, 2019.

4. Abdo-Allah, A., Iqbal, M., & Pope, K. (2019). Supervisor Fuzzy Logic Controller for HVAC System of S.J Carew Building at Memorial University. European Journal of Electrical Engineering and Computer Science, 3(4). https://doi.org/10.24018/ejece.2019.3.4.92

5. Abdo-Allah, Almahdi, Tariq Iqbal, and Kevin Pope. "Modeling and analysis of an HVAC system for the SJ Carew Building at Memorial University." In Electrical and Computer Engineering (CCECE), 2017 IEEE 30th Canadian Conference on, pp. 1-4. IEEE, 2017.

6. Almahdi Abdo-Allah, Tariq Iqbal, Kevin Pope, Modeling, Simulation and Control of HVAC System for a Large Building, presented at 25th IEEE NECEC conference 2016.

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THANK YOU