Conservation of power and energy in Data Centers by using Fuzzy Inference System

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I would like to dedicate this thesis to my supervisor and mentor Dr Mian Ilyas Ahmad, whose support in the times of COVID-19 kept me motivated.

Certificate

It is hereby declared that except where specific reference is made to the work of others, the contents of this thesis are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. The work presented in this thesis is the result of my own work.

Umair Javaid Manj

May,2021

Acknowledgement

All praise is for ALLAH Almighty Who is the complete and ultimate source of all knowledge. Allah has helped me to reach this present pedestal of knowledge with quality of doing something innovative, trailblazing and path bearing. All respects and esteems are for beloved Holy Prophet Hazrat Muhammad (PBUH) who is a fountain of knowledge and ultimate symbol of guidance.

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Abbreviations

Acronyms/Abbreviations

ScREC	Super Computing Research and Education Complex
NRDC	National Resources defense council
CRAC	Computer Room Air Conditioning
SC	Super Computer
FLC	Fuzzy Logic Control
IDC	Internet Data Centers
GLB	Geo Load Balancing
MIPS	Millions of instructions per second
CPUTIL	CPU Utilization
CSMA	Carrier Sense Multiple Access

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Abstract

With a rise in demand for centralized data processing servers and peer to peer communication application, data centers have become a key stakeholder in upkeeping of such applications. The main hinderance in the development of data centers is its operational cost. In developing countries, surge in operational is a leading factor behind unavailability of data centers. Mainly, consumption of energy within data centers is by server racks. These server racks generate tons of heat. If the heat increases from a certain limit, it can cause physical damage to the costly computing equipment within the servers, halting the ongoing operations of a data center. Server rooms are cooled with heavy duty air conditioners. These air conditioners are second in line in terms of energy consumption. In case of small and medium scale data centers no significant and cheap way for the reduction of electricity cost is introduced. Hence our research focuses on developing and validating a model for such internet data centers. In our model we reduced the power consumption by automating the on/off control mechanism of CRACs and computing nodes and through thermal aware load balancing of workload. To estimate the power consumption and for simplification of mathematical complexity we used two different techniques of fuzzy inference system. Our model was able to show significant reduction in the energy consumption of data centers.

Chapter 1

1 INTRODUCTION

1.1 Overview

The existence of internet in its current form is due to data centers. The information services, we rely upon every day, depend upon the communication, storing and processing of data in these data centers. These applications range from video streaming, online communication applications to the geo-location of places around the world. All devices utilized by data centers for providing these services use electricity. Mainly, they are categorized into servers, storage and network devices. High level processing and complex computations are done by servers in response to client's requests, storage units store the data needed to meet these requests and network devices establish the connection with internet for a sustained in and out flow of information. In accordance with the principle of conversion of energy, these devices generate heat energy after consuming electricity. Therefore, cooling equipment (which also consumes electricity) is installed to remove this heat from the premises. It is done in order to enhance the lifecycle of equipment. A Considerable amount of power is consumed by both servers and cooling equipment. Within a data center, the operational cost and the cost of electricity are directly proportional to each other. As per report from National Research and Development Center (NRDC), data center in USA consumed 91 billion kWh of electricity in 2013. For comparison, all the households in the city of New York consume the same amount of energy in two years. A calculated estimate states that this figure was increased to 140 billion kWh and around 150 billion metric ton carbon was released to air during production of this energy. According to a research done by Energy Innovations LLC, servers and cooling systems consume up to 86 percent of the total energy consumption. The distribution of power consumption in a data center is as following in figure 1:

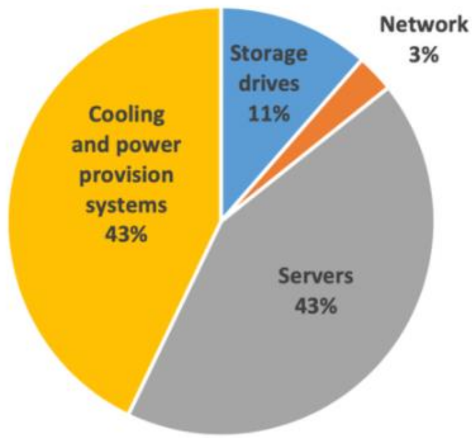

Figure 1- Distribution of Power consumption within data centers

In this thesis, our focus is to model the reduction of power consumption in a medium scale data center and its estimation through fuzzy logic and control. We will begin by a brief introduction of working of data centers and the statement of our research problem. Also, we will highlight the importance of the research problem along with an insight of our contributions.

1.2 Internet data center:

Currently, majority of the organizational and institutional data is stored and processed online through data centers. These data centers comprise of a large group of computer servers, connected in the form a network, typically used by organizations for the remote storage, processing, or distribution of large amounts of data. Physically, such data centers contain server racks and cooling equipment. Each rack accommodates a bunch of networked servers. Some of these servers are active while others are inactive. As explained in figure 2 from literature[2].

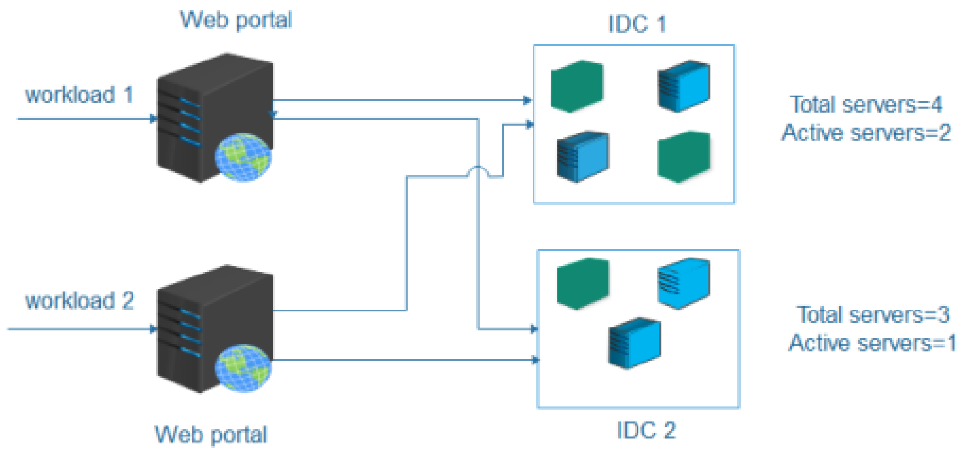

Figure 2 -Architecture of a data center

In the figure above two front end internet portals and two Internet data centers (IDC) are located at different regions. If a user sends a request to access any data from data centers in order to process or retrieve the data, the request is received by web portals. After that, web portal divides the task between IDCs. The respective IDC allocates the resources of servers for that task. The purpose of task division and parallel processing is to decrease the overall computation time. In the figure above the green state of the server shows that it is active while the others are inactive.

1.3 Working of cooling equipment:

Cooling equipment is necessary for maintaining a consistent adequate temperature in the data center. The computer room air conditioners (CRACs) transport the excessive heat generated by the racks of servers outside the data center. However, these CRACs consume up to 40% of the overall consumption of the data center. Hence in energy management of data centers CRACs are also counted as a crucial factor.

1.4 Problem Statement:

The small and medium datacenters in public and private enterprises does not have point-cooling mechanism for each server. The CRACs are shared by all server racks and are run at maximum capacity to keep the temperature of the server room between 15°C-25°C. We took ScREC facility as a case study. Firstly, all server nodes stayed on during service timings and even if a node is idle, the mean temperature still remained high. Secondly, workload distribution was done without accounting for nodal temperatures. The CRACs were run at maximum power to counter this temperature surge. All of these factors played a role in high consumption cost of ScREC facility. We developed a model to lower the electricity cost of the facility and also estimated the power consumption of our model through fuzzy inference system.

1.5 Research Gap:

In data centers the power consumption has always been controlled through various techniques. These techniques comprise of scheduling and workload balancing on the nodes. Along with that various research teams have also worked on the thermal aware management in data centers. Among all these some have used fuzzy logic controller to optimize and predict the scheduling on nodes. While some have balanced the power through FLC. The novelty in our work is that it will use fuzzy inference system to estimate the power consumption of CRACs using five major parameters and along with that it will also optimize the workload on the nodes.

1.6 Motivation:

Large scale private enterprises can afford higher costs of power consumption along with sophisticated server-point cooling equipment. While in case of small and medium scale enterprises (SMEs) operational costs of such data centers control a big chunk of budgetary allocation of research and development funds. Even after affording a lumpsum cost of equipment operational costs proves to be a huge road block in the way of progress. This research provides them a way for reducing the operation cost of datacenters which will be helpful in wake of decentralization under era of public-private partnership. Hence demand based power utilization in server racks and cooling system will greatly reduce the operational cost. Fuzzy logic control will not only optimize the temperature and power consumption of nodes but also of CRACs.

1.7 Objectives:

The main objectives in our research were:

- At first, develop a simple model for the reduction of power consumption in data centers.
- Dedicate, a part of this model on the technique for the estimation of the consumed power.
- The last objective was meant to validate our results of our model through the FIS based estimation technique.

1.8 Outline:

The reminder of the thesis is outlined as:

Chapter 2- Literature Review: This chapter will discuss the various techniques, ranging from work load scheduling to thermal aware power management, that have been implemented by different researchers, to minimize the energy consumption within data centers.

Chapter 3- Efficient Energy Consumption: This chapter will go through the implementation of fuzzy logic control in power management of data centers thus reducing their operational costs.

Chapter 4- Results and Discussion: This chapter will shed light on the results and findings of previously implemented techniques.

Chapter 5- Conclusion and future works: In this chapter we will conclude our thesis and present various prospects for future work.

Chapter 2

2 Literature Review

In this chapter we would look into the various techniques ranging from workload scheduling to thermal aware power management. We will observe how various researchers have implemented these techniques to reduce power consumption.

2.1 Adaptive power management of data centers:

In this technique Jianguo et al[4] focused on servers and cooling systems. Both of them are corelated to each other. In their study thermal dynamics were estimated using least square method, while the relation of thermal characteristics of CRACs and server racks with control inputs was characterized using continuous-time differential equations. Their model used a feedback based model predictive control (MPC) to dynamically control the system.

For almost all electronic devices there is a temperature maximum temperature limit. If a device works beyond its prescribed limit, it will not only shorten its life cycle but also increase its failure rate. Therefore, internet data centers should also work within their suggested temperature constraints, to provide a reliable and uninterrupted cloud services. If there is no recirculation of heat then the temperature of air in the rack can be controlled by the air with lower temperature coming out from the CRAC. However, in a practical world such a simple state cannot exist. The hot air from one server rack is recirculated toward another rack. Which can locally rise the temperature of that rack beyond the safe limit. This became the main motivation behind their study. Some significant contributions in their research were:

- The research problem they faced was to minimize the power consumption of an internet data center. For this they used thermal aware allocation of workload among the racks.
- For another problem of thermal identification, they used an adaptive estimator which is based on least square method. Once it went online, this estimator was able to capture and tackle the uncertainties of thermal dynamics.
- A model predictive control (MPC) was adopted to minimize the power by dynamically controlling it.

  Their model can be seen in figure 3 from literature[4]:

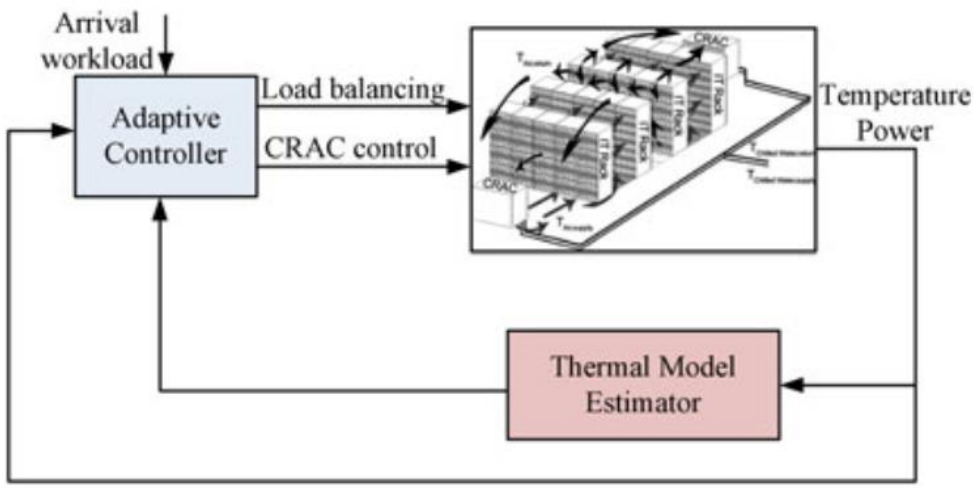

Figure 3-Model of Thermal aware work-load balancing

2.2 Using Fuzzy Logic for energy optimization:

Bissey et al[5] proposed a management system to control electrical consumption by taking user inconvenience and dynamic electricity rates into account. Main challenge for them was finding the best ratio to minimize users' constraint and to maximize the reduction in the cost of electricity. Their main contributions were:

- Efficiently predicting the daily electricity consumption in individual housing by using a fuzzy logic algorithm. This predictive model required a complete dataset of real electricity consumption from a large number of houses.

- Their algorithm for home energy management (HEM), used fuzzy logic to smooth the peak-demand and to minimize cost of electricity.

In their study all appliances are classified into night loads, inflexible and flexible on the basis of adjusting users' preference and achieving complete user-satisfaction in an optimum way. They relied on user interfaces and smart systems for such optimization and peak demand smoothing. The HEMS uses external parameters such that electricity rates and temperature sensor as well as the real consumption databases of the appliances.

Their experimental measurements require data from three temperature sensors. These sensors are placed in and outside the house at specific places. Their model is described in figure 5 from the literature[5].

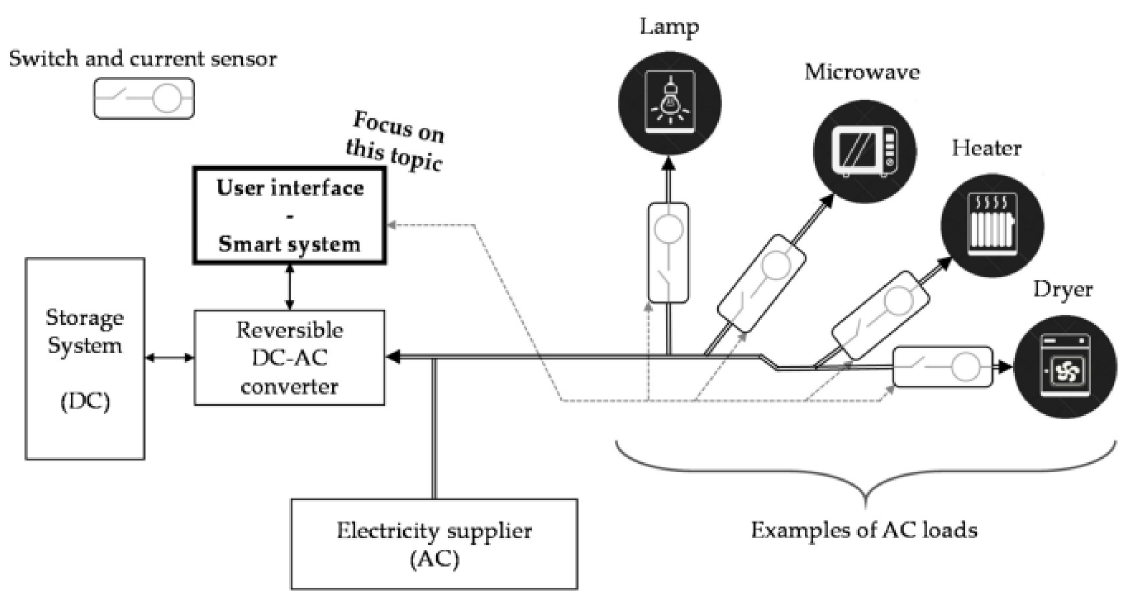

Figure 4-An illustration of suggested smart home

Their fuzzy based electricity prediction system used six inputs as such as history of electrical consumption, interior and exterior temperatures, estimated temperatures, time, day and the method to calculate load consumption. Figure 5 represents their[5] electricity prediction system:

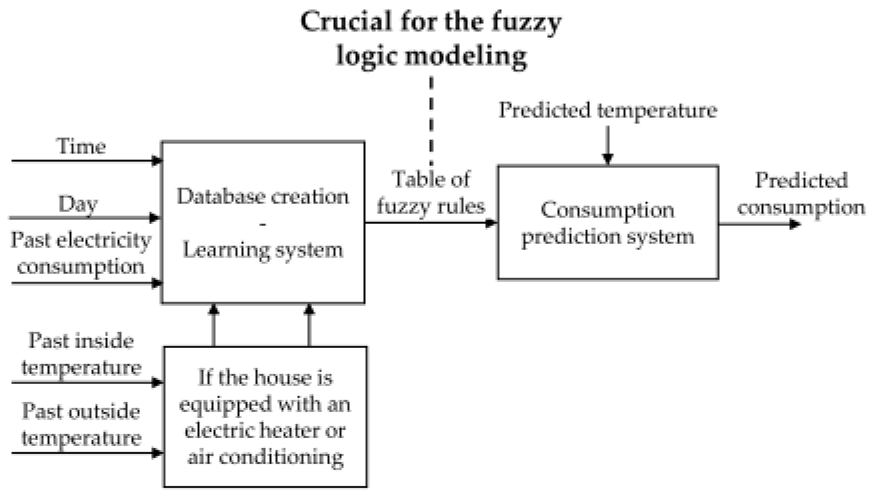

Figure 5-Fuzzy based EPS

2.3 Optimization of power through FIS:

The algorithm proposed by Seddiki et al[6] uses a Fuzzy rule base system (FRBS). They handled computing clouds which consisted of data centers. They assumed that all data centers were connected to the same cloud and are internally constituted of heterogenous machines. According to seddiki et al, after dynamically checking the processing needs, a broker (dedicated server) allocated virtual machines to data center hosts. This dedicated server also optimized the energy consumption.

According to their assumption a data center would consist of distributed and heterogenous hosts, they formulated their problem through the allocation of a set V of virtual machines {Vm1, Vm2, . . ., Vmn} to these hosts by following a scheduling criterion. They optimized the energy consumption through these scheduling strategies. The features used by them as an input to their Fuzzy Inference Controller (FIS) for the classification of scheduling conditions are:

- Available million instruction per second (MIPS).

- Power of the host (POW).
- CPU utilization (cputil). It can be found through equation 1:

$$\text{Utilization of CPU} = 1 - \frac{host.getAvailiableMips()}{host.getTotalMips()} \qquad (1)$$

- Maximum Utilization of power after allocation (ualloc).
- Power of host after allocation (palloc).

The scheduler for fuzzy rule base by seddiki et al can be seen in figure 6 from literature[6]:

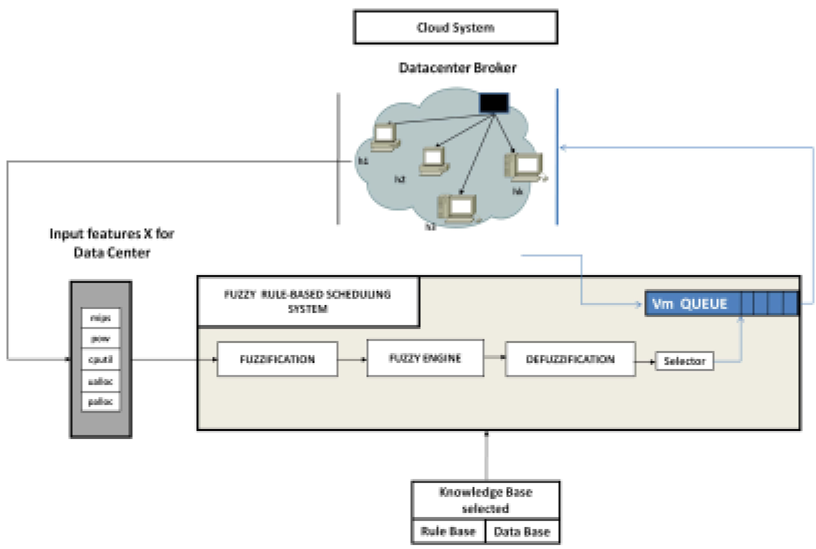

Figure 6-Fuzzy rule-based scheduler

They defined different conditions for medium and large data centers therefore, their output varied with respect to the size of data center. The categorization of output for medium and large data centers was limited to five and three respectively.

2.4 Load balancing within geo-distributed data centers:

Adel et al [7] showed that load balancing through optimal strategy is computationally prohibitive due to growth in number of data centers and the number of requests. They characterized a load balancing algorithm, which works offline and in which future knowledge of energy consumption and workload of each data center are assumed to be known beforehand. But it is an undeniable fact that even with the availability of exact future knowledge, it is considerably difficult to optimally balance the load. Their main contributions were:

- By assuming the exact future demand and showing that the optimal strategy is computationally intractable. They characterized the optimal offline (Geographical Load Balancing) GLB.
- They proposed a load balancing algorithm based on fuzzy logic that saves the cost significantly without requiring any knowledge about future demands beforehand.
- They used simulation of a case study which was focused on real world statistics of electricity prices and meteorological data with respect to real workloads in data center, to evaluate their proposed algorithm.

The model of the system[7] proposed by them can be seen in figure 7:

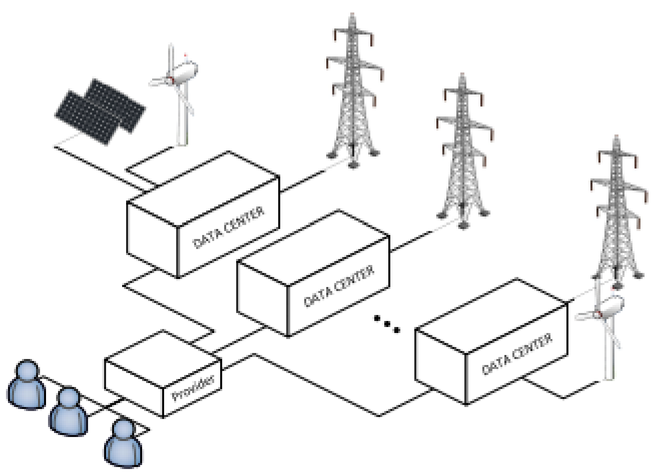

Figure 7-System model[7]

The pseudo-code for optimal geographical Load balancing algorithm used by Adel et al[7] is shown in figure 8. This algorithm is a recursive function to calculate the minimum cost upon electrical prices and the availability of renewable energy at a certain time. The cost of request r_j placed in data center d_i is computed in lines from eight to eleven, whereas the external loop in line six checks placement options for request r_j and through a recursive call at line twelve it finds the minimum cost for the remaining requests.

```
Input: j, e
Output: mincost
1: function GLB-OPT(j, e)
2:     if j > T then
3:         return 0
4:     end if
5:     mincost ← +∞
6:     for i ← 1 to n do
7:         e′ ← e
8:         for t ← a_j to min(T, a_j + l_j − 1) do
9:             c(r_j, d_i) ← (q_j − e′_{i,t})^+ × p_{i,t}
10:            e′_{i,t} ← (e′_{i,t} − q_j)^+
11:        end for
12:        cost ← c(r_j, d_i) + GLB-OPT(j + 1, e′)
13:        if cost < mincost then
14:            mincost ← cost
15:        end if
16:    end for
17:    return mincost
18: end function
```

Figure 8-Geographical load balancing algorithm

2.5 FIS and neural-network based energy management:

The study by Haririan et al [8] inspired both the current and future prospects of our study in terms of predicting the power consumption relatively accurate to FIS. It was consisted of two phases. In the first phase they obtained the energy consumption of computing resources by designing a fuzzy controller in accordance to their inputs. In the second phase they used neural networks for the estimation done by fuzzy in order to get a relatively more accurate prediction. For this they used auto regression and neural networks. Their fuzzy inference system had three inputs and an output as per figure 9.

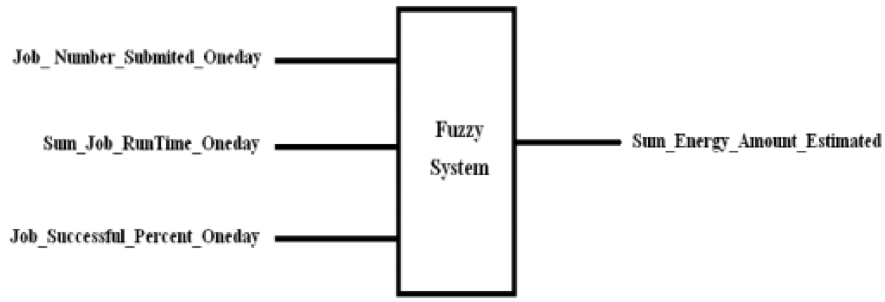

Figure 9-Designed fuzzy system

The parameters they chose to design their rule base were; number of submitted job in one day, percent of successful job in one day, sum of runtime of jobs and aggregated energy consumed in one day. The first three parameters were used as input to the FIS to predict the total consumption of energy within a day. Figure 10 shows a sample of rule base containing these parameters.

Rule number	Number of submitted job in one day	Percent of successful job in one day	Sum of runtime of jobs in one day	Sum of energy consumption in one day
1	low	low	low	low
2	low	low	high	middle
3	low	middle	high	high
4	middle	high	low	low
5	middle	high	middle	middle
6	high	low	high	high
7	high	middle	low	middle
8	high	high	low	low
9	high	middle	high	high
10	high	high	middle	middle

Figure 10-Rule-base for estimation

After obtaining an estimated output of power consumption in phase one, they used multilayer perceptron's network to predict it more accurately as compared to the fuzzy inference system. It can be seen in the figure 11:

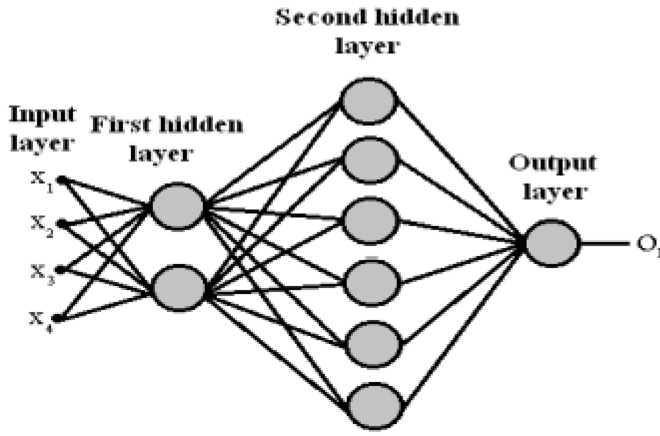

Figure 11- Designed Multilayer Neural Network

The neural networks used by Haririan et al [8] were configured in three steps:

i) At first data sets for the neural networks was prepared and divided for test and training purposes. From the data obtained by fuzzy logic 75% was given to neural network for training and 25% was given as test data. Among the four inputs of neural network (X1, X2, X3 and X4) only X1 was forwarded from FIS without any change to it. Whereas CSMA with m=1, m=2 and m=3 was applied to the remaining three inputs.

ii) At training stage "Back Propagation Algorithm" was used. In which the simulation function for each nerve was considered as weighted sum of inputs to that nerve.

iii) At test stage, to achieve the neural network error, the output of training stage compared with a portion of the data that are not logged in the system. This data is called test input data and the obtained results are known as test output.

2.6 Using FIS for user-comfort vis-a-vis energy management:

In this study, Qurat-ul-ain et[3] al focused on energy consumption in residential sector. They used fuzzy logic control to count in user comfort in automated heating and ventilation system in residential properties. Their control mechanism inspired us to intake various parameters as inputs and then use them to draw out control signals for optimal power preservation. Their model focused upon the following changes in temperature inside a room.

Here various parameters like outside temperature and room temperature help in generating a control signal to control the heater placed inside the room. Moreover, they also used parameter like occupancy of the room so that the FIS can decide on the basis of occupancy. FIS helped them to focus toward more states of occupancy. Usually, the heaters focus on binary states of occupancy that if anyone is present inside a room or not. With FIS multiple states of occupancy ranging from low to high were able to get defined. Along with occupancy they focused upon relative humidity of the room. As relative humidity inside a room also effects the user comfort level. This comfort level was categorized within cold and warm cities. Their model also focused upon the preset thermostat set point. Which gave way for a real time human input.

Their model inspired us to take various parameters into account and give them in the form of a crisp input to a fuzzy logic control system so that desired output can be achieved.

Chapter 3

3 Methodology

In this chapter we will discuss the architecture of a data center in RCMS institute at NUST, and how our technique reduced and estimated the energy consumption of this facility. We begin with the basics of fuzzy logic controller which is used in our framework.

3.1 Fuzzy Logic Controller (FLC):

FLC works like any other controller. It takes some quantity as an input and provides with an output at the opposite end. However, the magic of fuzzy lies within the controller. The beauty of fuzzy controller is simple that it takes crisp data and then deal with it in an unquantifiable manner to generate crisp output that can be easily processed. Such a technique also reduces the mathematical modeling. The process that happens inside fuzzy controller is as following:

- In the first step all membership functions related to system variables are initialized, defined and fuzzified.
- Further in the second step the rules for fuzzy rule base are defined through assignment of weights to the member functions of input variables. A suitable fuzzy value is also assigned to every rule.
- In the third step, the output is defuzzied and a crisp value is obtained for the energy consumption. The process is illustrated in figure 15 from the literature [3].

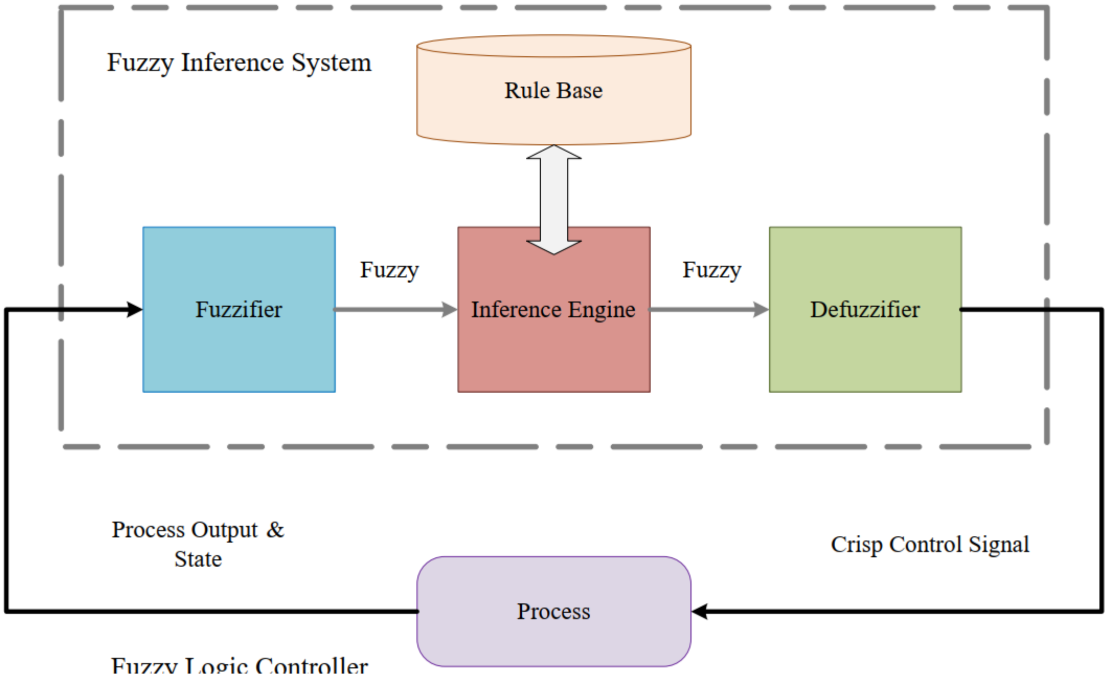

Figure 15-Fuzzy Logic Controller-conceptual illustration

The rule base of Fuzzy Inference system can be seen in figure 16.

Error→ **Change in error ↓**	**VL**	**L**	**Z**	**H**	**VH**
VL	VL	VL	VL	H	VH
L	VL	L	Z	H	VH
Z	VL	Z	Z	H	VH
H	VL	H	H	H	H
VH	VL	VH	VH	VH	VH

Figure 16-Sample of fuzzy rule base

In the figure above one can see that both error and change in error are categorized with five subsequent categories. The output will be flawless if both of them are zero. Though the occurrence of such output also depends upon the weights assigned to the parameters.

We also used two different sub-techniques of fuzzy inference system for the evaluation of output to our model. These techniques are Mamdani and Sugeno. Mamdani based fuzzy inference system used equation 3 for centroid defuzzification:

$$w = \frac{\int \mu_c(w).w\,dw}{\int \mu_c(w)\,dw} \tag{3}$$

While Sugeno based fuzzy inference system used equation 4 for the process of defuzzification:

$$w = \frac{\int \mu_c(\overline{w}).\overline{w}\,dw}{\int \mu_c(\overline{w})\,dw} \tag{4}$$

The difference between Mamdani and Sugeno FIS can be seen in the following points:

3.1.1 Difference between Mamdani and Sugeno FIS:

Mamdani FIS has output membership functions. The final crisp output is obtained by defuzzification of consequent. Output surface in Mamdani is non-continuous. It is suitable for both Multiple Input Single Output and Multiple Input Multiple Output systems. There is less flexibility in system design.

In Sugeno FIS there is no output function present. The crisp output is achieved through weighted average of rules’ consequent not through defuzzification. There is a continuous output surface. It is mostly suitable for MISO systems. There is a loss of interpretability. However, it provides more flexibility in the system design. In a nutshell it can be said that Mamdani results into a computational burden

3.2 Main Algorithm:

Now the main algorithm of our model is focused upon two main steps. In the first step a thermal aware controller will control the power consumption of both computer room air conditioner (CRAC) and of the computing nodes. While in the second step two fuzzy Inference systems will predict the reduction in operating costs of both CRAC and nodes. Now let us have a detailed outlook of the first step in figure 17.

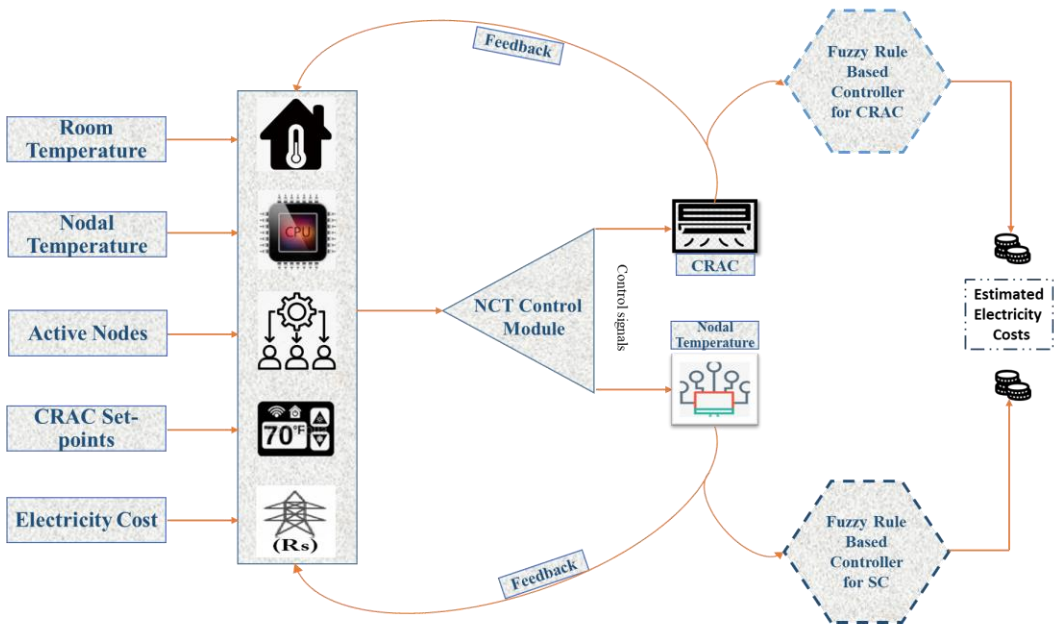

Figure 17-Control and estimation algorithm flow chart

3.2.1 TNC Control Module:

The Nodal and CRAC temperature control module accomplishes the task of reduction in consumption cost of electricity. The main factor which is taken into consideration during the development of this algorithm is the effect of higher temperatures on the cost of electricity. As per equation 5 the temperature is directly proportional to the energy consumption

$$T \propto EC \qquad (5)$$

As the nodal temperature rises the CRAC has to operate on maximum capacity in order to reduce the room temperature. In smaller data centers it is difficult to account for the temperature of a certain server among the racks of servers. To tackle that estimated value (mean) of temperature for all the working nodes is considered which is shown in equation 6.

$$E(T) = \frac{\sum_{n=1}^{p} T_n}{n} \tag{6}$$

So, the algorithm works in the following steps:

1. At the first step it initiates a record of all the nodes which are occupied and those nodes which are at an idle condition.
2. Secondly, it assigns a tri-tier status to all the nodes. The three categories of the nodes are ON, OFF and IDLE.
3. Moreover, it turns off the idle nodes. Hence the energy which was earlier being assumed by these idle nodes is saved.
4. Furthermore, it keeps a temperature record of all the nodes and as a new work load arrives it initiates a three-step safety process for the allocation of that work load.
5. It arranges the nodal index as per their temperature profile.
6. It turns on the node with the least temperature. Then, allocates the workload on that node.
7. In this way the mean temperature of nodes stays within safe limits. Which directly reduces the room temperature.

In order to reduce the energy consumed by CRAC its compressor is only turned on when the nodal mean temperature surpasses a certain limit. Otherwise, the speed of compressor of the CRAC is controlled through a control signal rather than turning it off in order to save the initial energy.

A customized function was generated in order to test the algorithm mentioned above. Which included all the maximum and minimum load time durations during the working hours from 9am – 9pm. It is shown below in figure 18:

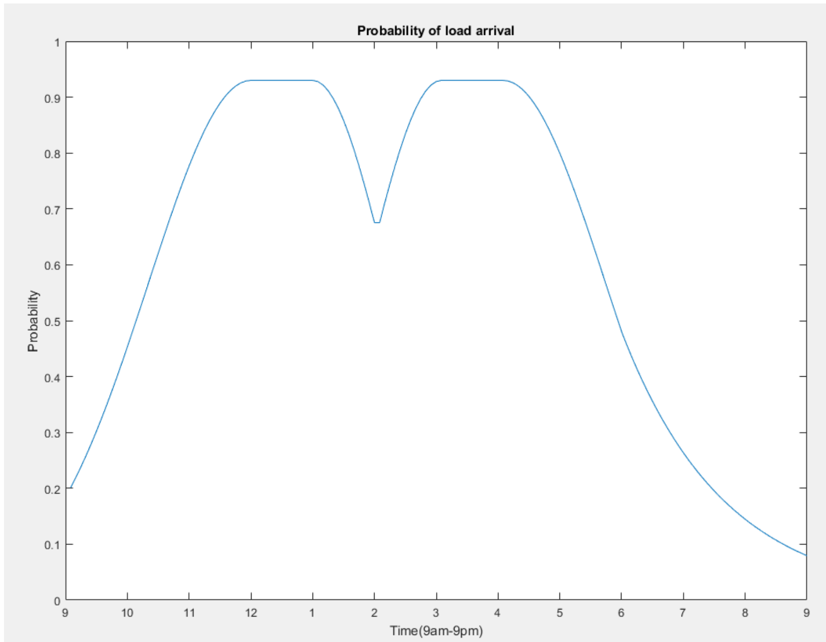

Figure 18-Probability of arrival of load

The preset threshold temperatures to turn the CRAC are also automated as per workload during the operational hours of the facility in order to reduce the human error. The nodal algorithm was also tested on a mini-server, however due to the absence of CRAC and inability to verify the temperature change it was unable to validate the model. The mini server is shown in figure 19.

Figure 19-Attempt of validation on mini-server

Hence after designing a model to reduce the energy cost of the ScREC facility, it is necessary to validate these results by getting an estimate of the costs. This estimate is obtained by using a fuzzy inference system on both the server and CRAC end.

3.2.2 Fuzzy Inference System for CRAC:

The fuzzy inference system on CRAC end uses nodal and room temperatures to generate an outlook of energy consumption. The output is evaluated by both Mamdani and Sugeno FIS. The rule base of fuzzy inference system for CRAC is evaluated by assigning weights to both the nodes and connections of that network. The formation of rule base for can be seen from the algorithm in figure 20.

Algorithm 1 Automatic Rule Generator for CRAC

```
TempNodal ← {VL,L,M,H,VH}
TempRoom ← {VL,L,M,H,VH}
EC ← {VL,L,M,H,VH}
for TempNodal ⌊1⌋ to TempNodal ⌊n⌋ do
    for TempRoom ⌊1⌋ to TempRoom⌊n⌋ do
            Compute Score
            If Score = 0 or Score = 1 then
            EC = VL
            else if Score = 2 then
            EC = L
            else if Score = 3 or Score = 4 then
            EC = M
            else if Score = 5 or Score = 6 then
            EC = H
            else
            EC = VH
            end if
        end for
    end for
```

Figure 20-Fuzzy Rule base generator for CRAC

Equation 7 was followed in the formulation of rule base:

$$\text{Score\_CRAC} = \sum_{i=1}^{3} W(vi) \qquad (7)$$

In case of CRAC FIS the vi is represented in table 1:

i	**v_i**
1	$Temp_{Nodal}$
2	$Temp_{Room}$

Table 1-Member functions SC

As per this equation a rule base is generated. Its sample is given in table 2.

#Rule	$Temp_{Nodal}$	$Temp_{Room}$	EC
1	L	L	VL
2	L	L	L
3	L	L	M
4	L	M	L
5	L	M	M
6	L	M	M
7	L	H	M

Table 2-SC Rule base sample

Based upon this rule base an output in the power consumed by CRAC is generated. To assess the real time power consumption the program is iterated after the interval of every five minutes for a 12-hour operational period.

3.3 Implementation on ScREC

We would first briefly discuss the architecture of ScREC and then implementation of Fuzzy Inference System on ScREC.

3.4.1 ScREC Architecture

The logical and physical layout of equipment and resources within a data center facility is known as architecture of data center. It can also be used as a blueprint to design and deploy a data center facility and it also provides guidelines to further develop and expand a data center. It is mostly created during construction and design phase. It provides the specification to physically place racks, servers, storage devices and networking devices within the facility. The interconnection scheme of these devices and the security work flows (physical and logical) are also described through it. Normally the architecture of a data center consists of following sub-architectures.

- Network architecture
- Computing architecture
- Security architecture
- Physical architecture
- Information architecture

As case study for a small and medium scale data-center the facility of "Super Computing Research and Educational Center (ScREC)" at Research center for modeling and simulation (RCMS) can be discussed. Its physical architecture consists of two server racks. While it's logical architecture contains two storage nodes connected through SAN switches, network switches, and Computing nodes. In it total nodes are 34 where 2 nodes act as head nodes while remaining 32 act as computing nodes. The processor used per node 2 x 4-core Xeon E5520 processor (each having the power of 80w). A 12-ton CRAC is used to keep the temperature optimized. All details can also be observed in figure 12:

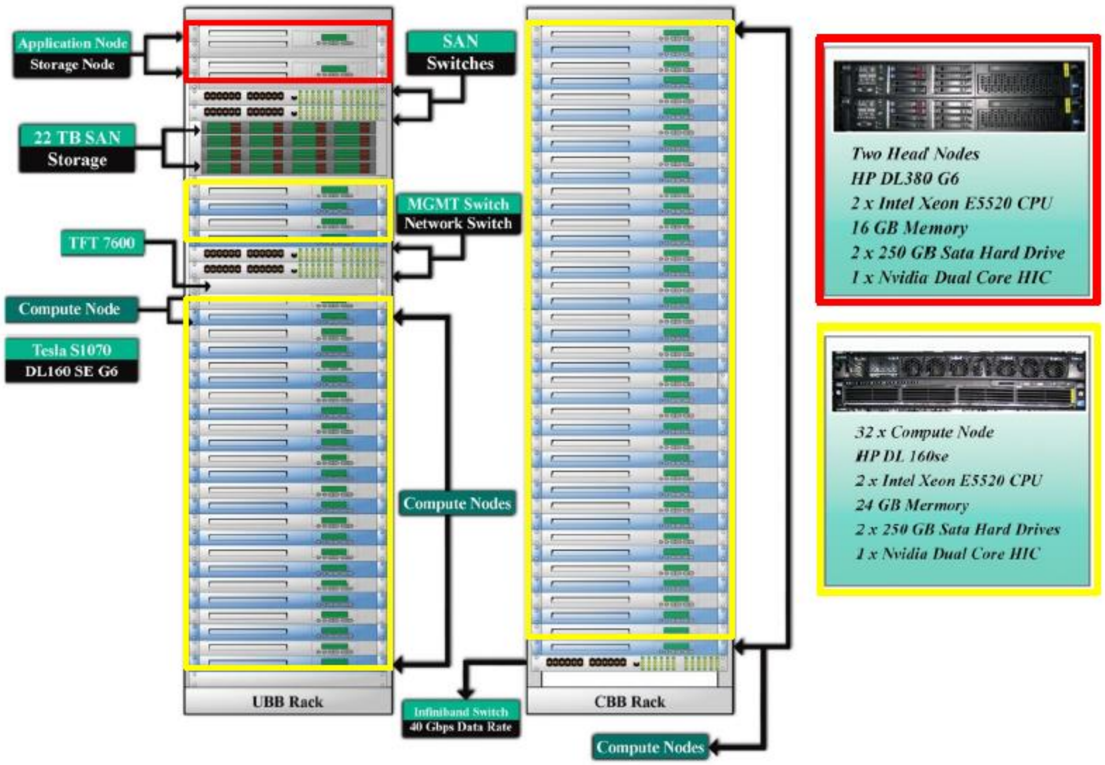

Figure 12- Architecture of ScREC

The facility's cost analysis with respect to power consumption is given in figure 13 and figure 14:

Phase Load	**Super Computer**	**CRAC**	**SC Lab**
Red	42 A	21.5 A	2 A
Blue	36 A	19 A	5 A
Yellow	34 A	21 A	4 A
Total Load	112 A	61.5 A	11 A

Figure 13-Load description of ScREC

Equation 2 is used to calculate the power output for both CRAC and Screech.

$$P\ (w) = V \times I \times Cost \times \sqrt{3} \qquad (2)$$

P (w) of SC = 65955w

P (w) of CRAC = 36216w

P (w) of SC Lab = 6478w

	Load (W)	Hours	Days	Unit Cost (Rs)	Cost (Rs)
Super Computer	65,955	12	30	18.95	449,945.01
CRAC	36,216	12	30	18.95	247,065
SC Lab	6,478	12	30	18.95	44,192
Total	108,649				741,202

Figure 14-Cost of power Vis a Vis consumption in ScREC

If the data given in the figures above is analyzed with respect to the productivity achieved during the online hours, it is pretty evident that a significant amount of power is being consumed more than the necessary amount. The reasons behind it would be the following:

- Always ON status of idle nodes.
- Work assignment without any consideration of nodal temperature.
- Manual ON/OFF control of CRACs.
- CRACs running at constant temperature without taking nodal temperature into account.

3.3.2 Fuzzy Inference System for ScREC:

In the same way as CRAC an FIS system based on both Mamdani and Sugeno FIS techniques was run to estimate the reduction in costs resulted by the afore mentioned algorithm. The rule base was generated by the algorithm shown in figure 21:

Algorithm 2 Automatic Rule Generator for SC

```
Temp_Nodal ← {VL,L,M,H,VH}
Occupancy ← {VL,L,M,H,VH}
EC ← {VL,L,M,H,VH}
for Temp_Nodal ⌊1⌋ to Temp_Nodal ⌊n⌋ do
    for Occupancy [1] to Occupancy[n] do
            Compute Score
            If Score = 0 or Score = 1 then
            EC = VL
            else if Score = 2 then
            EC = L
            else if Score = 3 or Score = 4 then
            EC = M
            else if Score = 5 or Score = 6 then
            EC = H
            else
            EC = VH
    end for
end for
```

Figure 21-Fuzzy Rule Base Generator for ScREC

The score is computed by using two member functions Occupancy and mean Nodal temperature at that given time instance. In the computation of score the predesignated weights to the nodes and connections were taken in consideration. Equation 8 was used to compute the score is as following:

$$\text{Score\_SC} = \sum_{i=1}^{2} W(vi) \qquad (8)$$

The v_i for SC is shown in the table 3:

i	**v_i**
1	$\text{Temp}_{\text{Nodal}}$
2	Occupancy

Table 3-input member functions SC

Moreover, the sample of the rule-base which was generated for the supercomputing facility, can be used to determine the energy consumed by the ScREC. In the same manner as CRAC this FIS was also run for twelve hours in an iterative manner after the interval of every five minutes. The sample of the rule-base is given in table 4:

Sample of rules defined in the proposed CRAC FIS rule base

#Rule	$Temp_{Nodal}$	Occupancy	EC
1	L	VL	VL
2	L	L	L
3	L	M	M
4	L	H	M
5	L	VH	H
6	M	VL	L
7	M	L	M

Table 4-CRAC Rule base Sample

Now after thoroughly examining the methodology of both preservation and estimation of power of CRACs and SC, we would have a look at the simulation-based results.

Chapter 4

4 Results and Findings

In this chapter we will have a look at the various member functions of each FIS. Along with that we will also observe how changing various parameters will have an effect on the power conservation. In the end we will also look into the differences of output shown by Mamdani and Sugeno type FIS systems.

4.1 Member Functions for CRAC:

The input membership functions for CRAC are nodal temperature and room temperature. As the role of CRAC in a server room is to lower the temperature of nodes by lessening the room temperature.

Hence it is crucially dependent upon these two. Following are the input member ship functions of CRAC for Mamdani FIS respectively in equation 9 and 10. They are also represented respectively in figure 22, 23, 24 and 25 for both Mamdani and Sugeno.

$$T\_nodes\_crac(x) = \begin{Bmatrix} VL \; if \; 0 \le x \le 15 \\ L \; if \; 10 \le x \le 30 \\ M \; if \; 23 \le x \le 45 \\ H \; if \; 38 \le x \le 60 \\ VH \; if \; 54 \le x \le 76 \end{Bmatrix} \quad (9)$$

$$T\_room(x) = \begin{Bmatrix} VL \; if \; 0 \le x \le 4.5 \\ L \; if \; 2.5 \le x \le 10 \\ M \; if \; 8.3 \le x \le 14.5 \\ H \; if \; 13.5 \le x \le 20 \\ VH \; if \; 19 \le x \le 25 \end{Bmatrix} \quad (10)$$

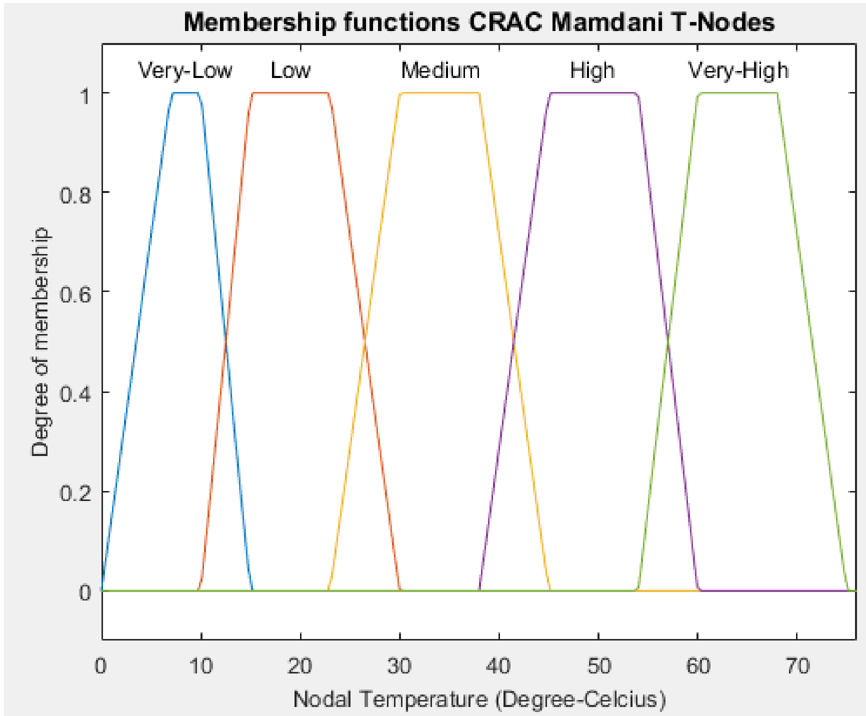

Figure 22-MF-Mamdani-CRAC T-Nodes

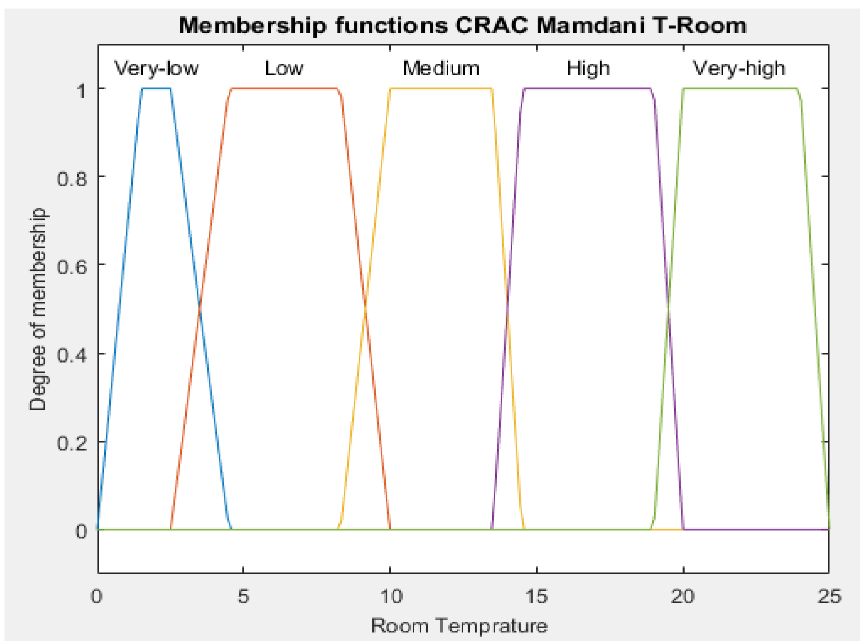

Figure 23-MF-Mamdani-CRAC T-Room

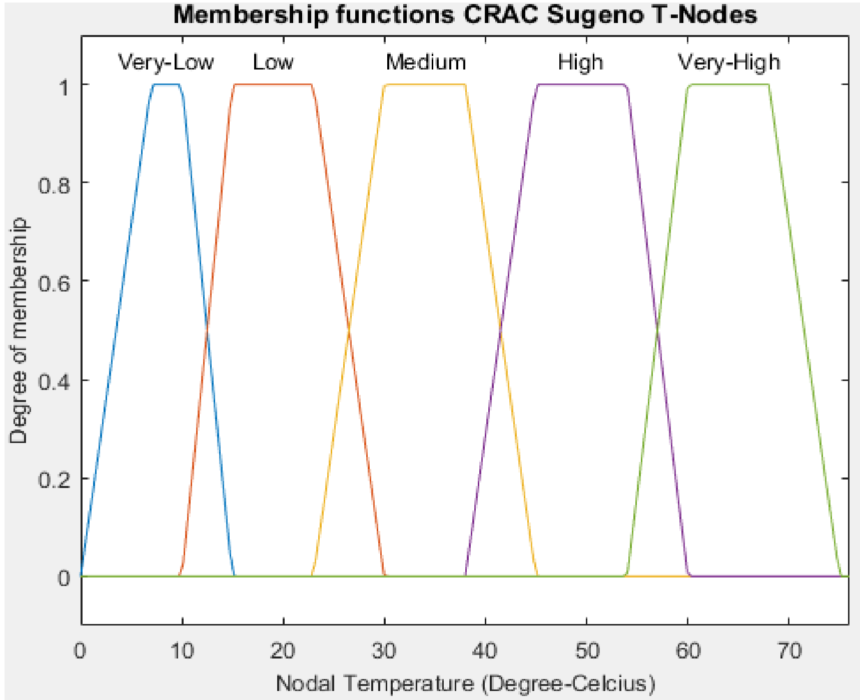

Figure 24-MF-Sugeno-CRAC T-Nodes

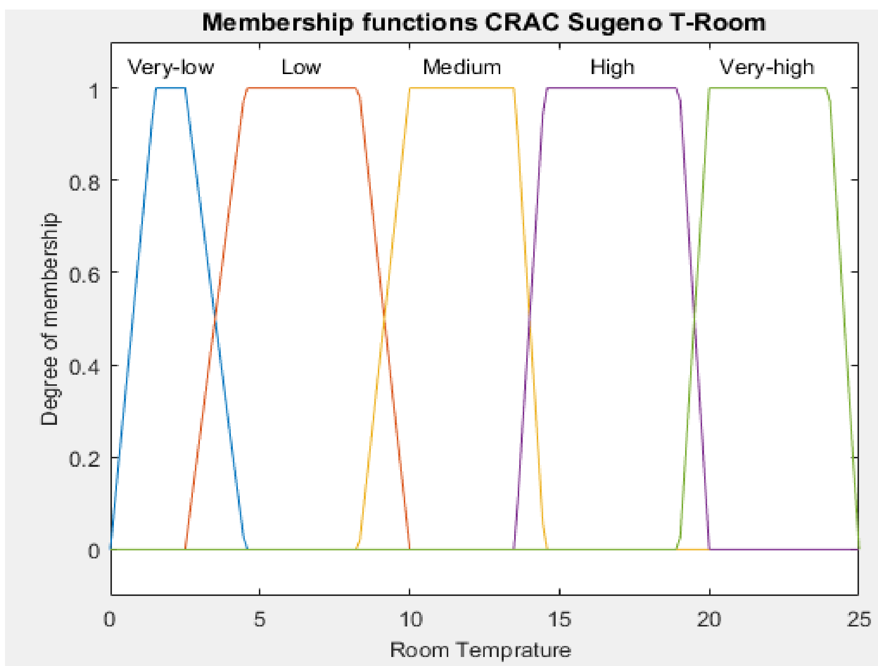

Figure 25-MF-Sugeno-CRAC T-Nodes

However, the output member function for CRAC can only be represented in the form of a Mamdani member function (as per figure 26 and equation 11) as Sugeno FIS does not have an output member function.

$$CRAC\_out(x) = \begin{cases} VL \; if \; 0 \leq x \leq 8 \\ L \; if \; 6.5 \leq x \leq 15 \\ M \; if \; 13 \leq x \leq 20 \\ H \; if \; 17 \leq x \leq 28 \\ VH \; if \; 24 \leq x \leq 38 \end{cases} \qquad (11)$$

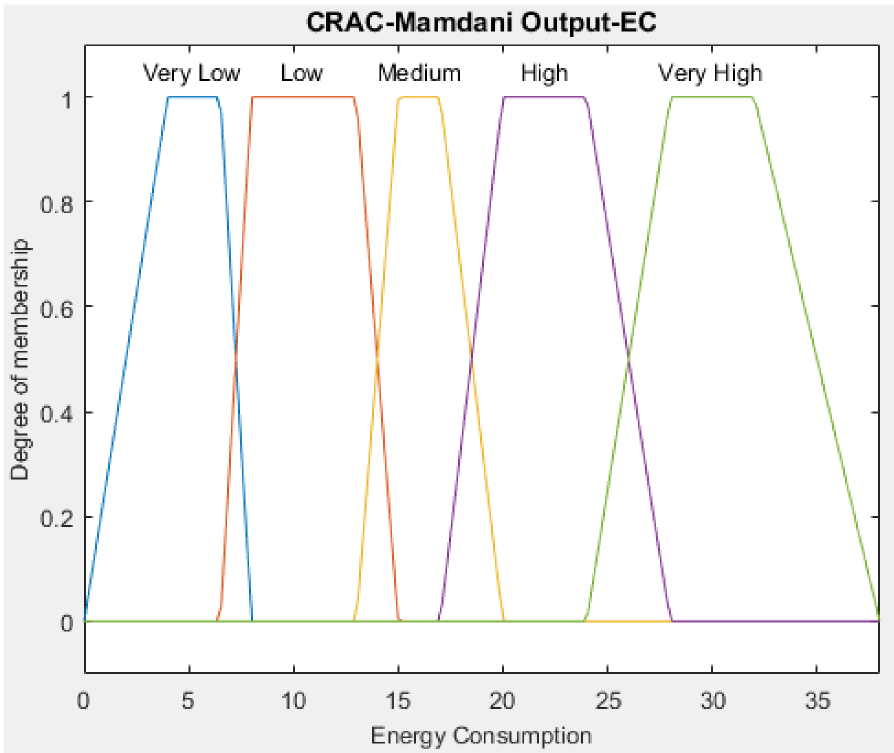

Figure 26-MF Mamdani-Output-CRAC

As it is evident from the pictures above that the membership functions consist of five ranges from very low to very high.

4.2 Member Functions for SC:

The input member functions for super computer are the temperature of nodes and the occupancy among nodes. The output in this case power consumption is directly proportional to the number of nodes occupied and the temperature of those nodes. In equation 12, 13 and 14 input membership functions for mamdani SC are shown, while in figure 27, 28, 29, 30 and 31, these input and output member functions in both Sugeno and Mamdani FIS, however, the output membership function just belongs to the Mamdani FIS.

$$T\_nodes\_sc(x) = \begin{Bmatrix} VL \; if \; 0 \leq x \leq 12 \\ L \; if \; 7 \leq x \leq 24 \\ M \; if \; 18 \leq x \leq 46 \\ H \; if \; 39 \leq x \leq 60 \\ VH \; if \; 57 \leq x \leq 76 \end{Bmatrix} \quad (12)$$

$$Occupancy\_nodes(x) = \begin{Bmatrix} VL \; if \; 0 \leq x \leq 7 \\ L \; if \; 4 \leq x \leq 13 \\ M \; if \; 11 \leq x \leq 19 \\ H \; if \; 17 \leq x \leq 26 \\ VH \; if \; 24 \leq x \leq 32 \end{Bmatrix} \quad (13)$$

$$SC\_out(x) = \begin{Bmatrix} VL \; if \; 0 \leq x \leq 21 \\ L \; if \; 15.5 \leq x \leq 31.5 \\ M \; if \; 28.5 \leq x \leq 47.5 \\ H \; if \; 38.5 \leq x \leq 53 \\ VH \; if \; 50 \leq x \leq 66 \end{Bmatrix} \quad (14)$$

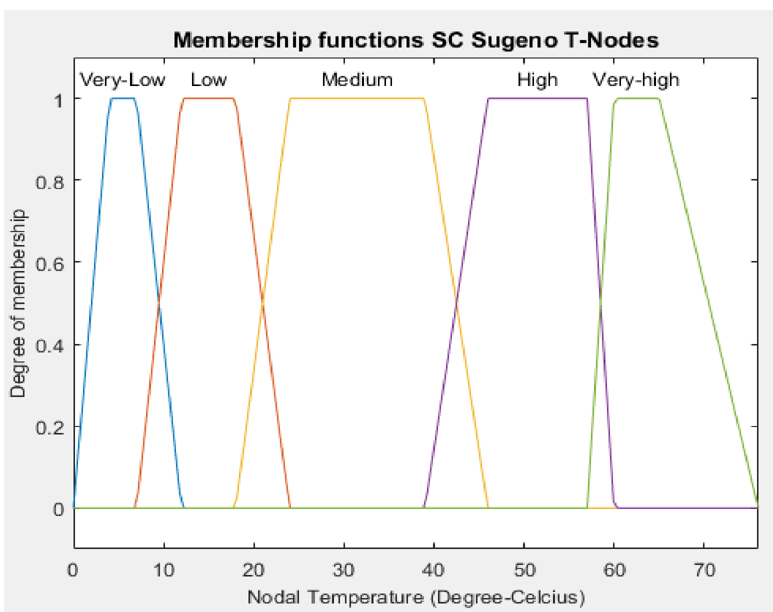

Figure 27-MF-Sugeno-SC T-Nodes

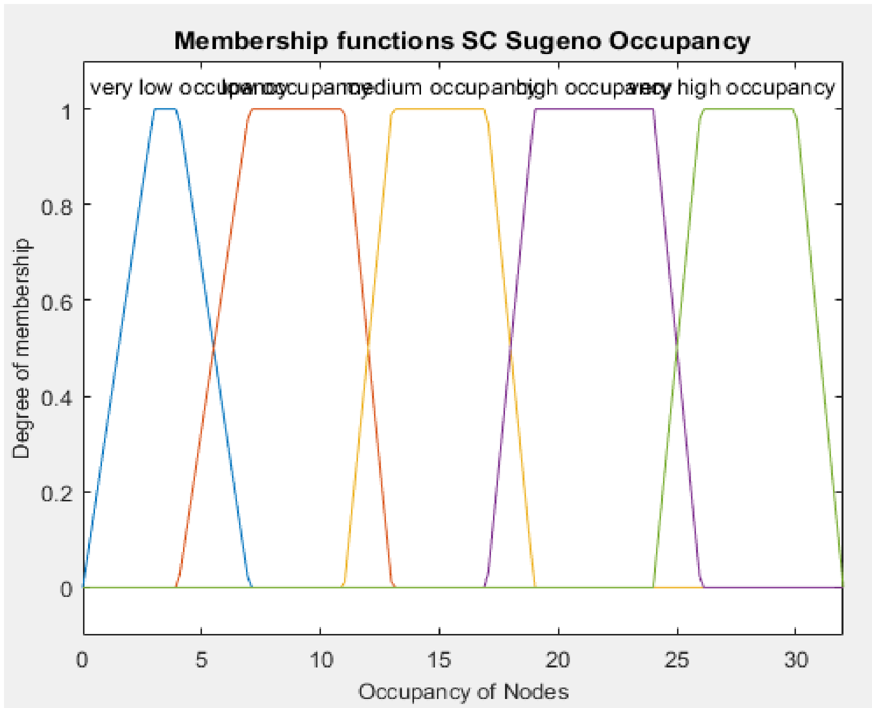

Figure 28-MF-Sugeno-SC Occupancy

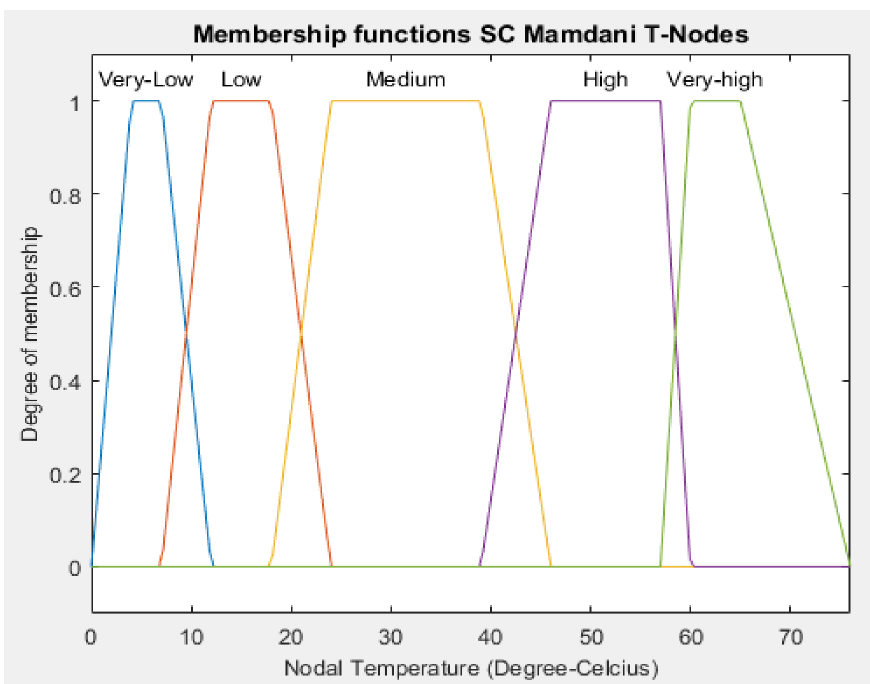

Figure 29-MF-Mamdani-SC T-Nodes

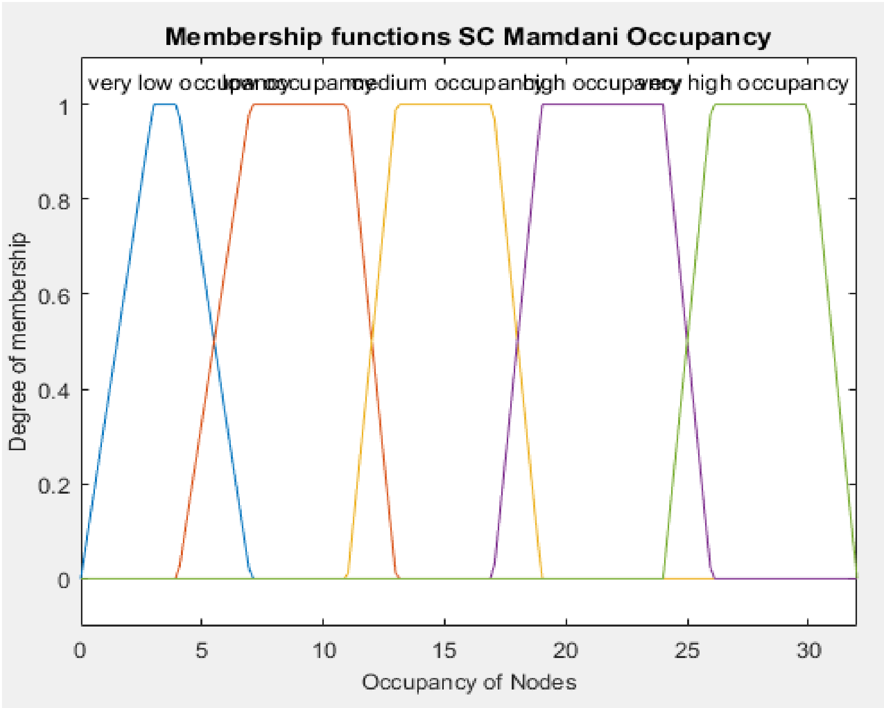

Figure 30-MF-Mamdani-SC Occupancy

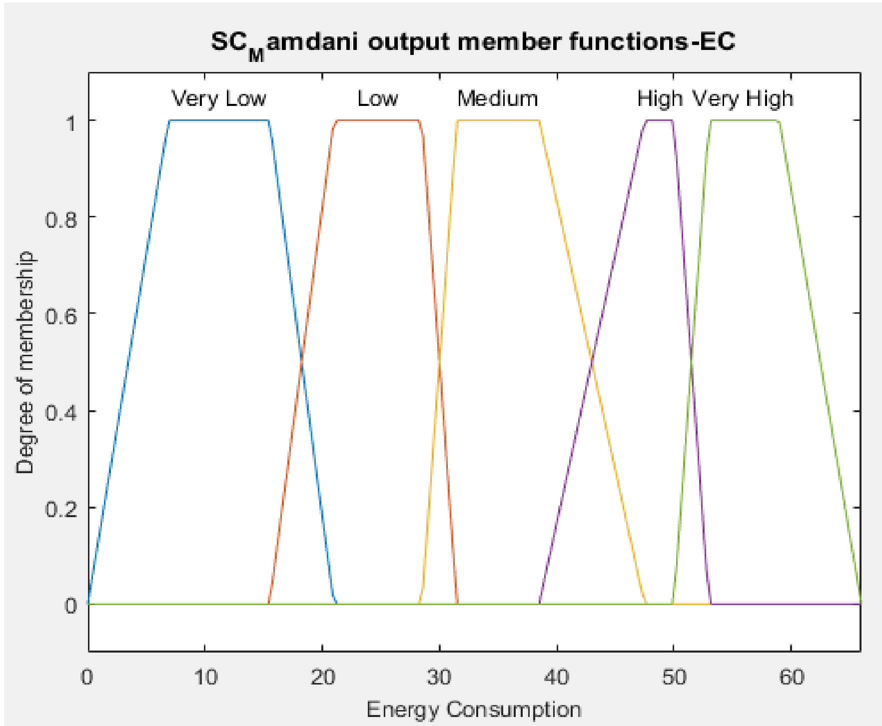

Figure 31-MF-SC-Output-EC

4.3 Comparison between energy consumption to various work-loads:

The pre-determined load of SC is about 66 kilo-watt and of CRAC is about 36 kilo-watt. So, when our control is applied during various instances of time and workloads the result vary accordingly. The depiction of the variable results at 30%, 60% and 90% workload is shown in figure 32, 33 and 34. In which one can clearly see that how the load of SC grows and the load of the CRAC varies corresponding to it.

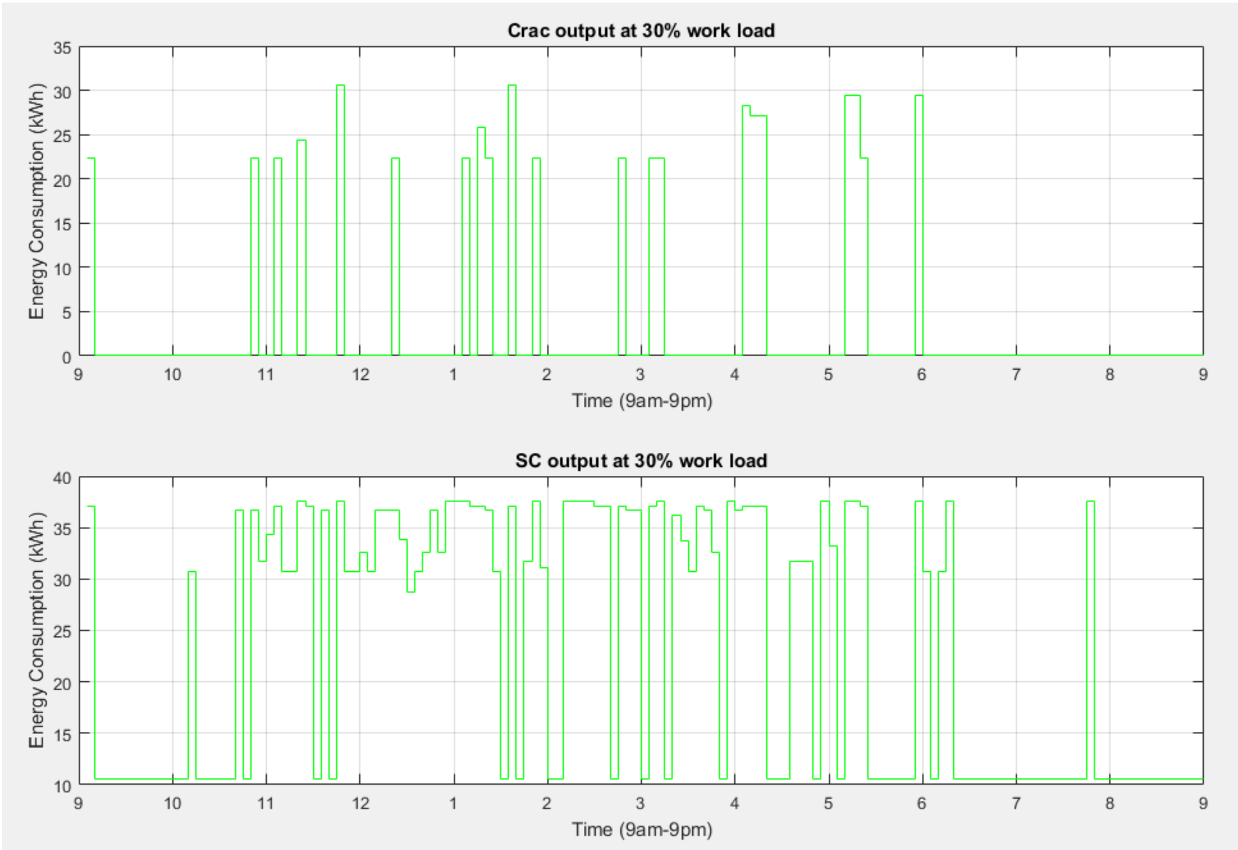

Figure 32-Output at 30% workload

Figure 33-Output at 60% workload

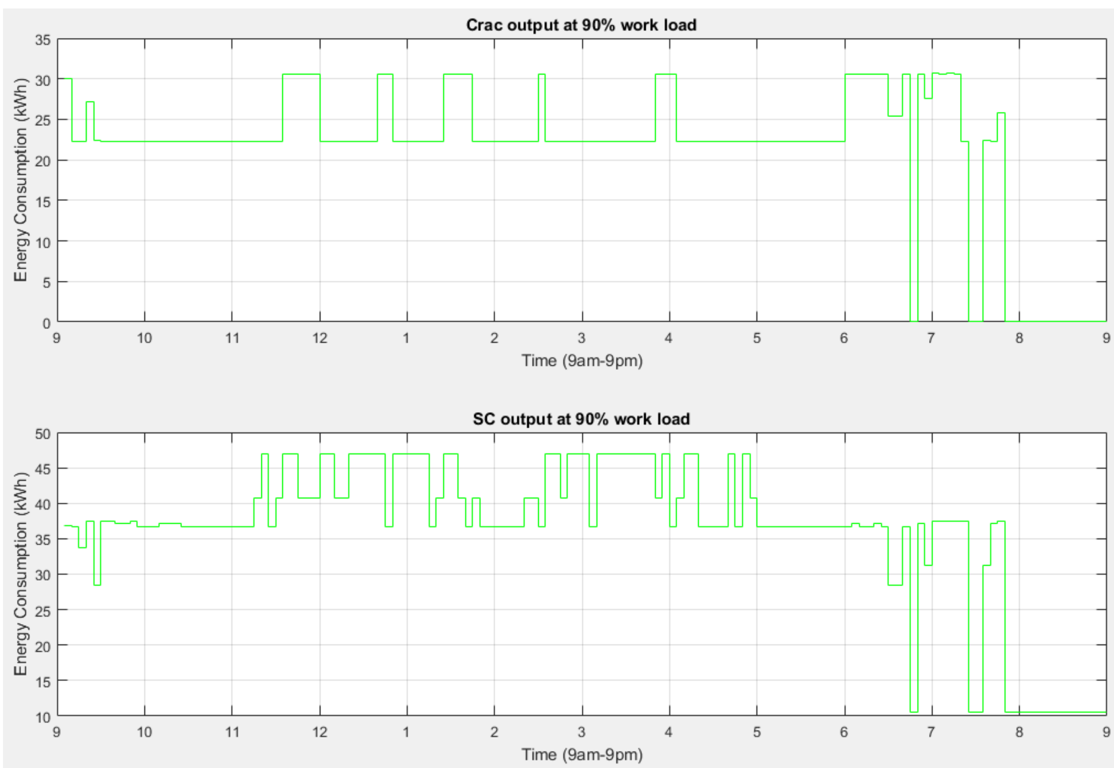

Figure 34-Output at 90% workload

4.4 Difference between outputs of Sugeno and Mamdani:

After comparing the workloads at various instances, we would look into the computationally intensive Mamdani FIS and Sugeno FIS. As our system is a multiple input and single output (MISO) system hence Sugeno FIS should depict more suitable results for us. It is visible in the results as per 35 and 36 where red line represents Sugeno FIS and the green one represents Mamdani FIS and the power consumption is better in Sugeno FIS.

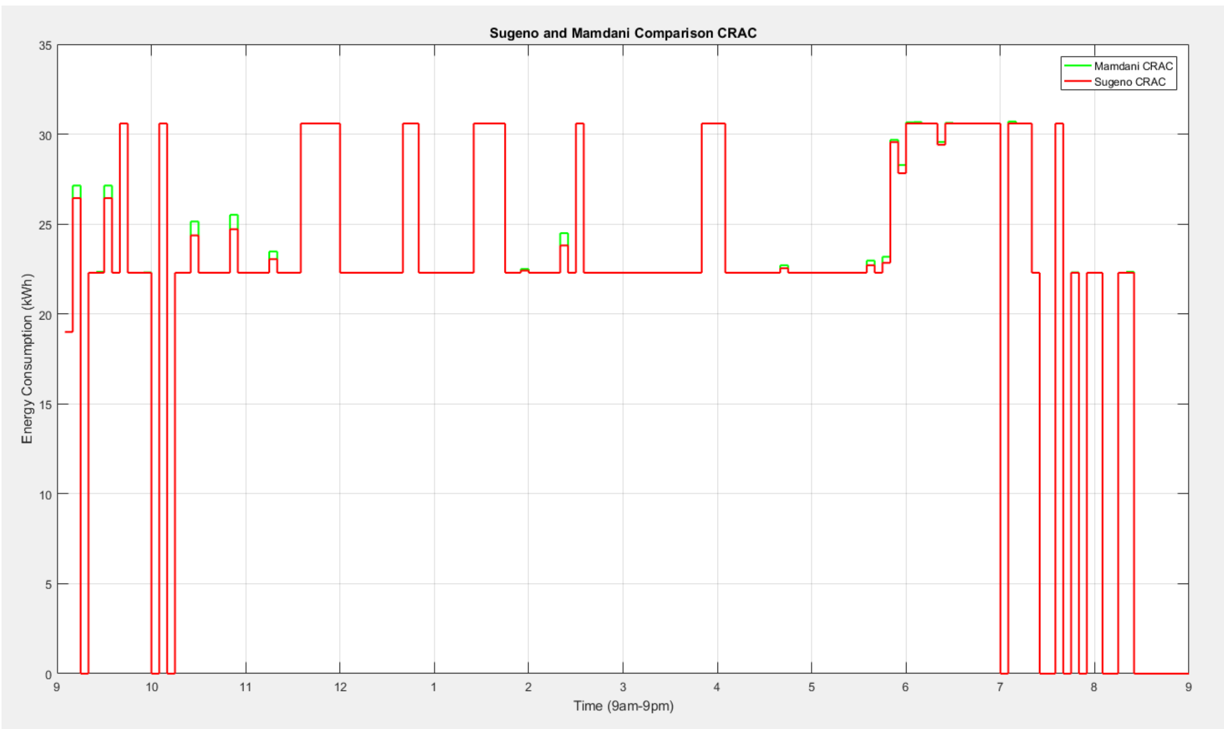

Figure 35-Sugeno vs Mamdani- CRAC

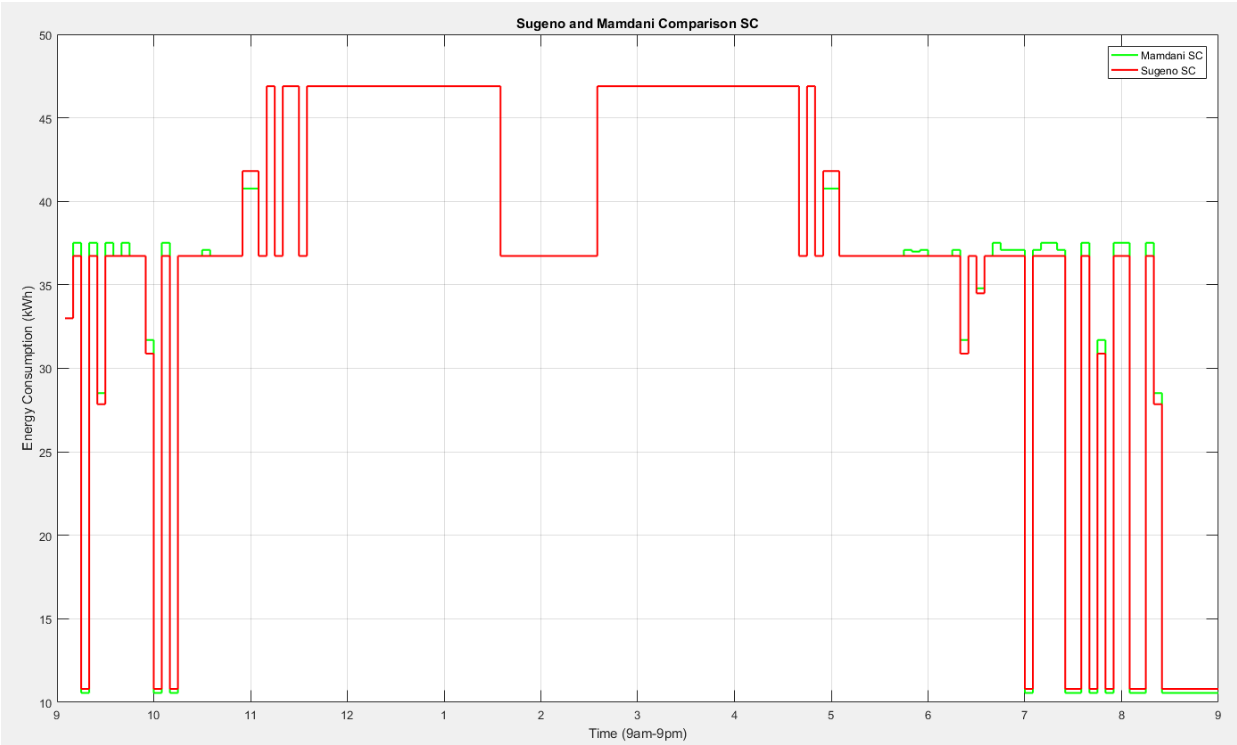

Figure 36-Sugeno Vs Mamdani SC

4.5 Power Consumption with and without NCT:

With the help of the recommendations given in the NCT controller we were able to create a model. The results of those model studies showed up to 30 percent decrease in the overall power consumption of the ScREC. Sugeno FIS showed a little better result than Mamdani. Figures 37 and 38 show the power preservation separately in CRAC and SC along with monthly saving.

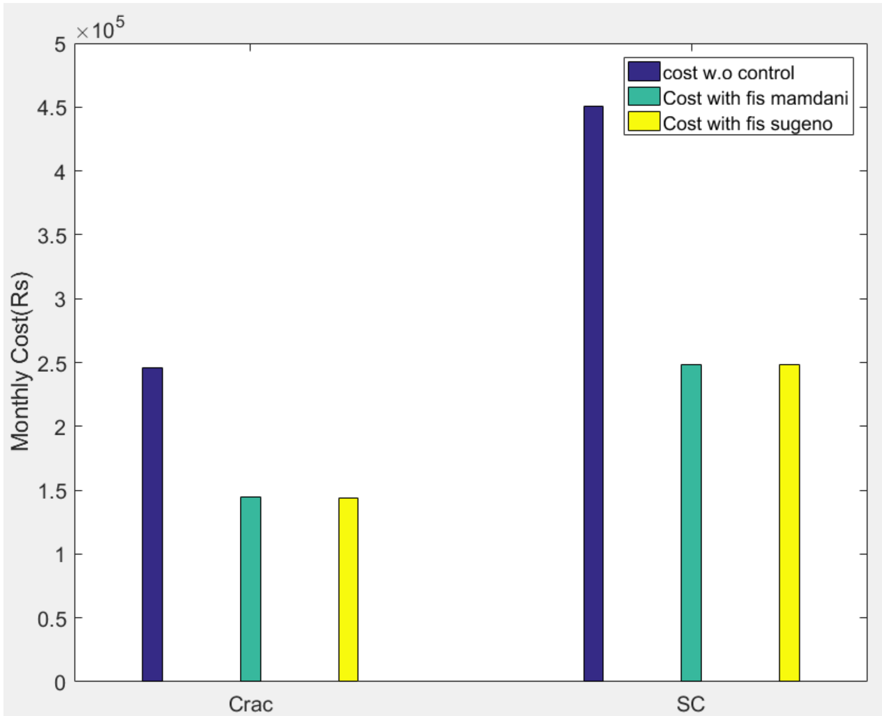

Figure 37-Power preservation (separately)

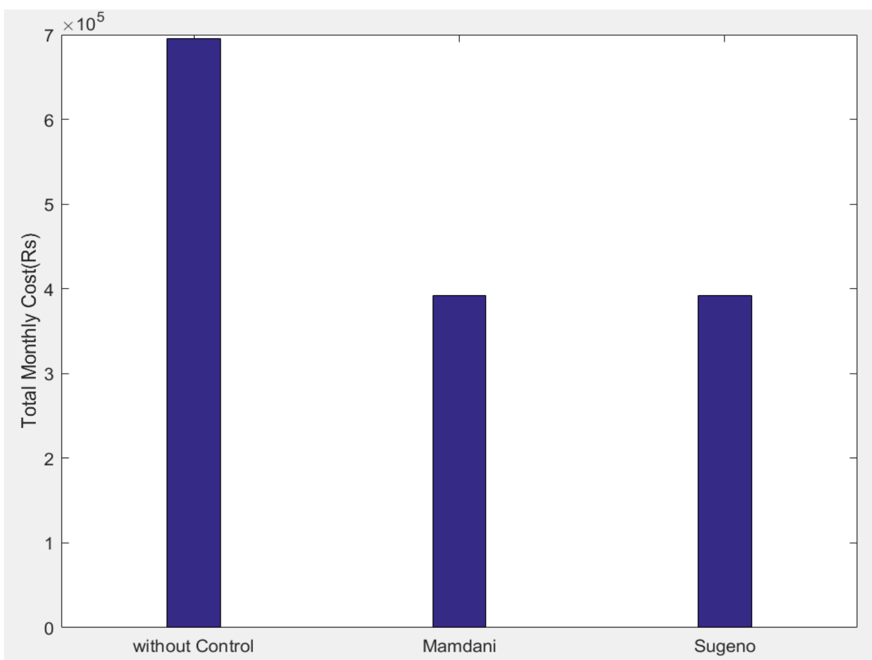

Figure 38-Total Preservation (Monthly)

Chapter 5

5 Conclusion and Future Works

In this chapter, we will summarize the observations of the results and the future work based on our research work.

5.1 Conclusions:

Our problem at hand was to develop a model for the reduction of operating cost of small and medium data centers like ScREC facility. We achieved that by turning of the idle nodes, and then shifting the new workload to those nodes which have the least temperature. This single handedly reduced the mean nodal temperature and thus the room temperature. With reduced nodal and room temperature the CRAC automatically lowered the speed of its compressor. Now to estimate the power consumption it was cumbersome to develop a mathematical model of all the servers along with CRAC. Hence to avoid crisp logic FIS was used separately to get the output of both CRAC and SC. The output of FIS showed that the model is applicable for reducing the power consumption of that facility.

5.2 Future Works:

In future this model can be enhanced through real time data by implementing it on the SC. Multi-disciplinary course of action could be adopted in which the thermal aware workload allocation could attract practical knowledge from the field of Computer Science. Along with that a more robust electrical control can reduce the power loss at CRAC's end.

With the practical implementation the member functions of the FIS can also be enhanced. Most of all these results can be implemented on a data center in real time and a more efficient software-based framework can be built to incorporate all these features.

The fuzzy estimation technique could be combined with thermodynamics-based techniques to formulate a new method for keeping the temperature profile of datacenter to a minimum. Furthermore, the results from FIS can be refined by training and testing through sophisticated techniques like neural networks.

6 References and Appendix

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Appendix A

The code of our designed program is following:

```
close all;
clear;
clc;

%% FIS%%
CRAC_FIS_Mamdani = newfis('CRAC.fis');
% Input_Parameters%%

CRAC_FIS_Mamdani.input(1).name = 'Nodal Temperature (Degree-Celcius)';
CRAC_FIS_Mamdani.input(1).range = [-0.001 76];      % Temprature range of Xeon
e5520 Processor
CRAC_FIS_Mamdani.input(1).mf(1).name = 'Very-Low';
CRAC_FIS_Mamdani.input(1).mf(1).type = 'trapmf';
CRAC_FIS_Mamdani.input(1).mf(1).params = [-0.001 7 10 15];
CRAC_FIS_Mamdani.input(1).mf(2).name = 'Low';
CRAC_FIS_Mamdani.input(1).mf(2).type = 'trapmf';
CRAC_FIS_Mamdani.input(1).mf(2).params = [10 15 23 30];
CRAC_FIS_Mamdani.input(1).mf(3).name = 'Medium';
CRAC_FIS_Mamdani.input(1).mf(3).type = 'trapmf';
CRAC_FIS_Mamdani.input(1).mf(3).params = [23 30 38 45];
CRAC_FIS_Mamdani.input(1).mf(4).name = 'High';
CRAC_FIS_Mamdani.input(1).mf(4).type = 'trapmf';
CRAC_FIS_Mamdani.input(1).mf(4).params = [38 45 54 60];
CRAC_FIS_Mamdani.input(1).mf(5).name = 'Very-High';
CRAC_FIS_Mamdani.input(1).mf(5).type = 'trapmf';
CRAC_FIS_Mamdani.input(1).mf(5).params = [54 60 68 75];

CRAC_FIS_Mamdani.input(2).name = 'Room Temprature ';
CRAC_FIS_Mamdani.input(2).range =[-0.001 25];
CRAC_FIS_Mamdani.input(2).mf(1).name = 'Very-low';
CRAC_FIS_Mamdani.input(2).mf(1).type = 'trapmf';
CRAC_FIS_Mamdani.input(2).mf(1).params = [-0.001 1.5 2.5 4.5];
CRAC_FIS_Mamdani.input(2).mf(2).name = 'Low';
CRAC_FIS_Mamdani.input(2).mf(2).type = 'trapmf';
CRAC_FIS_Mamdani.input(2).mf(2).params = [2.5 4.5 8.3 10];
```

```
CRAC_FIS_Mamdani.input(2).mf(3).name = 'Medium';
CRAC_FIS_Mamdani.input(2).mf(3).type = 'trapmf';
CRAC_FIS_Mamdani.input(2).mf(3).params = [8.3 10 13.5 14.5];
CRAC_FIS_Mamdani.input(2).mf(4).name = 'High';
CRAC_FIS_Mamdani.input(2).mf(4).type = 'trapmf';
CRAC_FIS_Mamdani.input(2).mf(4).params = [13.5 14.5 19 20];
CRAC_FIS_Mamdani.input(2).mf(5).name = 'Very-high';
CRAC_FIS_Mamdani.input(2).mf(5).type = 'trapmf';
CRAC_FIS_Mamdani.input(2).mf(5).params = [19 20 24 25];

% Output Parameters %%

CRAC_FIS_Mamdani.output(1).name = 'Energy Consumption';
CRAC_FIS_Mamdani.output(1).range = [-0.001 38];
CRAC_FIS_Mamdani.output(1).mf(1).name = 'Very Low';
CRAC_FIS_Mamdani.output(1).mf(1).type = 'trapmf';
CRAC_FIS_Mamdani.output(1).mf(1).params = [-0.001 4 6.5 8];
CRAC_FIS_Mamdani.output(1).mf(2).name = 'Low';
CRAC_FIS_Mamdani.output(1).mf(2).type = 'trapmf';
CRAC_FIS_Mamdani.output(1).mf(2).params = [6.5 8 13 15];
CRAC_FIS_Mamdani.output(1).mf(3).name = 'Medium';
CRAC_FIS_Mamdani.output(1).mf(3).type = 'trapmf';
CRAC_FIS_Mamdani.output(1).mf(3).params = [13 15 17 20];
CRAC_FIS_Mamdani.output(1).mf(4).name = 'High';
CRAC_FIS_Mamdani.output(1).mf(4).type = 'trapmf';
CRAC_FIS_Mamdani.output(1).mf(4).params = [17 20 24 28];
CRAC_FIS_Mamdani.output(1).mf(5).name = 'Very High';
CRAC_FIS_Mamdani.output(1).mf(5).type = 'trapmf';
CRAC_FIS_Mamdani.output(1).mf(5).params = [24 28 32 38];

%% SC FIS
SC_FIS_Mamdani = newfis('SC.fis');
% Input_Parameters%%

SC_FIS_Mamdani.input(1).name = 'Nodal Temperature (Degree-Celcius)';
SC_FIS_Mamdani.input(1).range = [-0.001 76];      % Temprature range of Xeon
e5520 Processor
SC_FIS_Mamdani.input(1).mf(1).name = 'Very-Low';
```

```
SC_FIS_Mamdani.input(1).mf(1).type = 'trapmf';
SC_FIS_Mamdani.input(1).mf(1).params = [-0.001 4 7 12];
SC_FIS_Mamdani.input(1).mf(2).name = 'Low';
SC_FIS_Mamdani.input(1).mf(2).type = 'trapmf';
SC_FIS_Mamdani.input(1).mf(2).params = [7 12 18 24];
SC_FIS_Mamdani.input(1).mf(3).name = 'Medium';
SC_FIS_Mamdani.input(1).mf(3).type = 'trapmf';
SC_FIS_Mamdani.input(1).mf(3).params = [18 24 39 46];
SC_FIS_Mamdani.input(1).mf(4).name = 'High';
SC_FIS_Mamdani.input(1).mf(4).type = 'trapmf';
SC_FIS_Mamdani.input(1).mf(4).params = [39 46 57 60];
SC_FIS_Mamdani.input(1).mf(5).name = 'Very-high';
SC_FIS_Mamdani.input(1).mf(5).type = 'trapmf';
SC_FIS_Mamdani.input(1).mf(5).params = [57 60 65 76];

SC_FIS_Mamdani.input(2).name = 'Occupancy of Nodes';
SC_FIS_Mamdani.input(2).range = [-0.001 32];
SC_FIS_Mamdani.input(2).mf(1).name = 'very low occupancy';
SC_FIS_Mamdani.input(2).mf(1).type = 'trapmf';
SC_FIS_Mamdani.input(2).mf(1).params = [-0.001 3 4 7];
SC_FIS_Mamdani.input(2).mf(2).name = 'low occupancy';
SC_FIS_Mamdani.input(2).mf(2).type = 'trapmf';
SC_FIS_Mamdani.input(2).mf(2).params = [4 7 11 13];
SC_FIS_Mamdani.input(2).mf(3).name = 'medium occupancy';
SC_FIS_Mamdani.input(2).mf(3).type = 'trapmf';
SC_FIS_Mamdani.input(2).mf(3).params = [11 13 17 19];
SC_FIS_Mamdani.input(2).mf(4).name = 'high occupancy';
SC_FIS_Mamdani.input(2).mf(4).type = 'trapmf';
SC_FIS_Mamdani.input(2).mf(4).params = [17 19 24 26];
SC_FIS_Mamdani.input(2).mf(5).name = 'very high occupancy';
SC_FIS_Mamdani.input(2).mf(5).type = 'trapmf';
SC_FIS_Mamdani.input(2).mf(5).params = [24 26 30 32];

% Output Parameters %%

SC_FIS_Mamdani.output(1).name = 'Energy Consumption';
SC_FIS_Mamdani.output(1).range = [-0.001 66];
SC_FIS_Mamdani.output(1).mf(1).name = 'Very Low';
```

```
SC_FIS_Mamdani.output(1).mf(1).type = 'trapmf';
SC_FIS_Mamdani.output(1).mf(1).params = [-0.001 6.9 15.5 21];
SC_FIS_Mamdani.output(1).mf(2).name = 'Low';
SC_FIS_Mamdani.output(1).mf(2).type = 'trapmf';
SC_FIS_Mamdani.output(1).mf(2).params = [15.5 21 28.5 31.5];
SC_FIS_Mamdani.output(1).mf(3).name = 'Medium';
SC_FIS_Mamdani.output(1).mf(3).type = 'trapmf';
SC_FIS_Mamdani.output(1).mf(3).params = [28.5 31.5 38.5 47.5];
SC_FIS_Mamdani.output(1).mf(4).name = 'High';
SC_FIS_Mamdani.output(1).mf(4).type = 'trapmf';
SC_FIS_Mamdani.output(1).mf(4).params = [38.5 47.5 50 53];
SC_FIS_Mamdani.output(1).mf(5).name = 'Very High';
SC_FIS_Mamdani.output(1).mf(5).type = 'trapmf';
SC_FIS_Mamdani.output(1).mf(5).params = [50 53 59 66];



%% Rules Base System CRAC %%
total_run_S_CRAC = 0;
for i=0:4 %Nodal
    for j=0:4  %room tem
        Score_S_CRAC = (i+j);
        total_run_S_CRAC = total_run_S_CRAC +1;
        CRAC_FIS_Mamdani.rule(total_run_S_CRAC).antecedent = [i+1 j+1];
        if(Score_S_CRAC == 0)||(Score_S_CRAC == 1)
            CRAC_FIS_Mamdani.rule(total_run_S_CRAC).consequent = 1;

        elseif(Score_S_CRAC == 2)
            CRAC_FIS_Mamdani.rule(total_run_S_CRAC).consequent = 2;

        elseif(Score_S_CRAC == 3)||(Score_S_CRAC == 4)
            CRAC_FIS_Mamdani.rule(total_run_S_CRAC).consequent = 3;

        elseif(Score_S_CRAC == 5)||(Score_S_CRAC == 6)
            CRAC_FIS_Mamdani.rule(total_run_S_CRAC).consequent = 4;
        else
            CRAC_FIS_Mamdani.rule(total_run_S_CRAC).consequent = 5;
        end
```

```
        CRAC_FIS_Mamdani.rule(total_run_S_CRAC).weight = 1;
        CRAC_FIS_Mamdani.rule(total_run_S_CRAC).connection = 1;

        CRAC_antecedent = CRAC_FIS_Mamdani.rule(total_run_S_CRAC).antecedent;
        CRAC_consequent = CRAC_FIS_Mamdani.rule(total_run_S_CRAC).consequent;

    end
end
%% CRAC Sugeno
CRAC_FIS_Sugeno = mam2sug(CRAC_FIS_Mamdani);
%% Rules Base System SCREC %%
total_run_SCREC = 0;
for i=0:4 %Nodal
    for j=0:4  %room temp

        Score_S_SC = (i+j);
        total_run_SCREC = total_run_SCREC +1;
        SC_FIS_Mamdani.rule(total_run_SCREC).antecedent = [i+1 j+1];
        if(Score_S_SC == 0)||(Score_S_SC == 1)
            SC_FIS_Mamdani.rule(total_run_SCREC).consequent = 1;

        elseif(Score_S_SC == 2)
            SC_FIS_Mamdani.rule(total_run_SCREC).consequent = 2;

        elseif(Score_S_SC == 3)||(Score_S_SC == 4)
            SC_FIS_Mamdani.rule(total_run_SCREC).consequent = 3;

        elseif(Score_S_SC == 5)||(Score_S_SC == 6)
            SC_FIS_Mamdani.rule(total_run_SCREC).consequent = 4;

        elseif(Score_S_SC == 7)||(Score_S_SC == 8)
            SC_FIS_Mamdani.rule(total_run_SCREC).consequent = 5;
        end
        SC_FIS_Mamdani.rule(total_run_SCREC).weight = 1;
        SC_FIS_Mamdani.rule(total_run_SCREC).connection = 1;

        SC_antecedent = SC_FIS_Mamdani.rule(total_run_SCREC).antecedent;
        SC_consequent = SC_FIS_Mamdani.rule(total_run_SCREC).consequent;
```

```
    end
end
%% SC Sugeno
SC_FIS_Sugeno = mam2sug(SC_FIS_Mamdani);

%% DATA SET %%
Room_Temprature = [15 16 16 17 16 17 15 16 17 16 17 15 ...
    18 18 17 18 17 18 16 17 15 16 17 16 ...
    18 19 18 15 16 17 20 21 22 22 24 15 ...
    15 17 18 19 18 19 17 20 21 19 16 18 ...
    16 18 16 19 20 21 22 24 19 18 17 19 ...
    19 18 15 16 17 21 18 19 16 18 17 19 ...
    17 18 16 19 17 19 16 18 16 20 21 22 ...
    19 19 16 15 16 17 18 19 16 18 19 16 ...
    15 16 18 19 17 16 18 19 15 16 18 20 ...
    21 22 21 22 24 22 21 22 21 20 22 23 ...
    21 22 20 19 18 19 18 17 18 19 16 18 ...
    16 18 17 15 19 16 20 21 22 24 22 20];



Set_temprature = 40;
Nodal_state=randi([1,2],1,32);
T_nodes=randi([40,80],1,32);
SC_nodes(1,:)=Nodal_state;
SC_nodes(2,:)=T_nodes;
Temp_nodes=SC_nodes;

%% CONTROL MODULE %%

load_p = load_prob();
for interval=1:144 %144 INTERVALS OF 5 MINUTES EACH PER DAY
    Temp_nodes=Node_transition(Temp_nodes,load_p(interval),1-
(load_p(interval)));
    [T_Nodes_Mean, Occupancy]=Mean_occupancy(Temp_nodes);
    delta_TT = T_Nodes_Mean- Set_temprature;            % calculates difference
b/w Mean nodal temprature and desired value
```

```
    if(delta_TT >= 0)                                          % decide whether
to turn the CRAC ON or OFF
        Crac = 1;
    else
        Crac = 0;
    end
    if Crac==1
        EC_FIS_CRAC_Mam(interval) = evalfis([T_Nodes_Mean
Room_Temprature(interval)],CRAC_FIS_Mamdani);
        EC_FIS_CRAC_Sug(interval) = evalfis([T_Nodes_Mean
Room_Temprature(interval)],CRAC_FIS_Sugeno);
    else
        EC_FIS_CRAC_Sug(interval) = 0;
        EC_FIS_CRAC_Mam(interval) = 0;
    end
    EC_FIS_SC_Mam(interval) = evalfis([T_Nodes_Mean Occupancy],SC_FIS_Mamdani);
    EC_FIS_SC_Sug(interval) = evalfis([T_Nodes_Mean Occupancy],SC_FIS_Sugeno);

end

%% COST CALCULATION %%
%CRAC
Sum_CRAC_wofis = 36*12; %%actual load measurement
Cost_CRAC_wofis_daily = Sum_CRAC_wofis*18.95;
Cost_CRAC_wofis_monthly = Cost_CRAC_wofis_daily*30;
Sum_CRAC= sum(EC_FIS_CRAC_Mam/12);              %Units of consumption is in
KWH_Mamdani
Daily_cost_CRAC_wfis=Sum_CRAC*18.95;
Monthly_cost_CRAC_wfis= Daily_cost_CRAC_wfis*30;
Sum_CRAC_Sug= sum(EC_FIS_CRAC_Sug/12);              %Units of consumption is in
KWH_Sugeno
Daily_cost_CRAC_wfis_Sug=Sum_CRAC_Sug*18.95;
Monthly_cost_CRAC_wfis_Sug= Daily_cost_CRAC_wfis_Sug*30;

%SC
Sum_SC_wofis = 66*12; %%actual load measurement
Cost_SC_wofis_daily = Sum_SC_wofis*18.95;
Cost_SC_wofis_monthly = Cost_SC_wofis_daily*30;
```

```
Sum_SC= sum(EC_FIS_SC_Mam/12);
Daily_cost_SC_wfis=Sum_SC*18.95;
Monthly_cost_SC_wfis= Daily_cost_SC_wfis*30;
Sum_SC_Sug= sum(EC_FIS_SC_Sug/12);
Daily_cost_SC_wfis_Sug=Sum_SC_Sug*18.95;
Monthly_cost_SC_wfis_Sug= Daily_cost_SC_wfis_Sug*30;

%Total
Total_wofis = Cost_CRAC_wofis_monthly + Cost_SC_wofis_monthly;
Total_wfis_Mam = Monthly_cost_CRAC_wfis + Monthly_cost_SC_wfis;
Total_wfis_Sug = Monthly_cost_CRAC_wfis_Sug + Monthly_cost_SC_wfis_Sug;

%% Plots %%
figure; %Seperate costs of SC and CRAC with Mamdani and Sugeno and without
bar([Cost_CRAC_wofis_monthly, Monthly_cost_CRAC_wfis,
Monthly_cost_CRAC_wfis_Sug;Cost_SC_wofis_monthly, Monthly_cost_SC_wfis,
Monthly_cost_SC_wfis_Sug],0.2)
ylabel('Monthly Cost(Rs)');
legend('cost w.o control','Cost with fis mamdani','Cost with fis sugeno');
set(gca, 'XTickLabels', {'Crac', 'SC'});
set(gca,'FontSize',15);

figure; %Total costs of SC and CRAC with Mamdani and Sugeno and without
bar([Total_wofis; Total_wfis_Mam; Total_wfis_Sug],0.2)
ylabel('Total Monthly Cost(Rs)');
set(gca, 'XTickLabels', {'without Control','Mamdani','Sugeno'});
set(gca,'FontSize',15);
member functions
figure;
plotmf(SC_FIS_Sugeno,'input',1)
title('Membership functions SC Sugeno T-Nodes')
figure;
plotmf(SC_FIS_Sugeno,'input',2)
title('Membership functions SC Sugeno Occupancy')
figure;
plotmf(SC_FIS_Mamdani,'input',1)
title('Membership functions SC Mamdani T-Nodes')
figure;
```

```
plotmf(SC_FIS_Mamdani,'input',2)
title('Membership functions SC Mamdani Occupancy')
figure;
plotmf(SC_FIS_Mamdani,'output',1)
title('SC_Mamdani output member functions-EC')

figure;
plotmf(CRAC_FIS_Sugeno,'input',1)
title('Membership functions CRAC Sugeno T-Nodes')

figure;
plotmf(CRAC_FIS_Sugeno,'input',2)
title('Membership functions CRAC Sugeno T-Room')

figure;
plotmf(CRAC_FIS_Mamdani,'input',1)
title('Membership functions CRAC Mamdani T-Nodes')

figure;
plotmf(CRAC_FIS_Mamdani,'input',2)
title('Membership functions CRAC Mamdani T-Room')

figure;
plotmf(CRAC_FIS_Mamdani,'output',1)
title('CRAC-Mamdani Output-EC')

figure;
plot(load_p)
xlabel('Time(9am-9pm)')
ylabel('Probability')
set(gca, 'XTick', (0:12:144))
set(gca,'xlim',[0 144]);
set(gca,'xticklabels',{'9','10','11','12','1','2','3','4','5','6','7','8','9'});
title('Probability of load arrival')


figure;
plot(1 - load_p)
```

```
xlabel('time')
ylabel('probability')
title('Probability of load departure')

figure;
subplot(211)
stairs(EC_FIS_CRAC_Mam,'g')
title('Crac output at 90% work load')
xlabel('Time (9am-9pm)');
ylabel('Energy Consumption (kWh)');
set(gca, 'XTick', (0:12:144))
set(gca,'xlim',[0 144]);
set(gca,'xticklabels',{'9','10','11','12','1','2','3','4','5','6','7','8','9'});
grid on;
subplot(212)
stairs(EC_FIS_SC_Mam,'g')
title('SC output at 90% work load')
xlabel('Time (9am-9pm)');
ylabel('Energy Consumption (kWh)');
set(gca, 'XTick', (0:12:144))
set(gca,'xlim',[0 144]);
set(gca,'xticklabels',{'9','10','11','12','1','2','3','4','5','6','7','8','9'});
grid on;

figure
stairs(EC_FIS_CRAC_Mam,  'g-', 'LineWidth',1.5);
hold on;
stairs(EC_FIS_CRAC_Sug, 'r-', 'LineWidth',1.5);
hold on;
title('Sugeno and Mamdani Comparison CRAC')
xlabel('Time (9am-9pm)');
ylabel('Energy Consumption (kWh)');
set(gca, 'XTick', (0:12:144))
set(gca,'xlim',[0 144]);
set(gca,'xticklabels',{'9','10','11','12','1','2','3','4','5','6','7','8','9'});
legend('Mamdani CRAC','Sugeno CRAC','Location','northeast');
grid on;
```

```
figure
stairs(EC_FIS_SC_Mam,  'g-', 'LineWidth',1.5);
hold on;
stairs(EC_FIS_SC_Sug, 'r-', 'LineWidth',1.5);
hold on;
title('Sugeno and Mamdani Comparison SC')
xlabel('Time (9am-9pm)');
ylabel('Energy Consumption (kWh)');
set(gca, 'XTick', (0:12:144))
set(gca,'xlim',[0 144]);
set(gca,'xticklabels',{'9','10','11','12','1','2','3','4','5','6','7','8','9'});
legend('Mamdani SC','Sugeno SC','Location','northeast');
grid on;
```

The mean occupancy ,node transition and load probability functions are given below respectively:

```
function [ mean, occupancy ] = Mean_occupancy( SC_data )

length = size(SC_data, 2);

count = 0;
sum = 0;
    states = SC_data(1,:);
    temps = SC_data(2,:);
    for j = 1:length
        if (states(j) == 2||states(j) == 1)
            count = count + 1;
            sum = sum + temps(j);
        end
    end
    mean = sum / count; %off nodes don't contribute in mean
    if count == 0
        mean = 0;
    end
    occupancy = count;
end

function [arr] = Node_transition( arr,A,D)
for i=1:size(arr, 2)
    x1=rand;
    x2=rand;
    if x1<=A && arr(1,i)==0 && arr(2, i) <= 60 %OFF TO ON PROBABILITY
        arr(1,i)=2;
    end
    if x2<=D&&arr(1,i)==2 %ON TO IDLE
        arr(1, i)=0;
    end
    if arr(1,i)==1
```

```
        arr(1, i)=0;
    end
end
function [y] = load_prob()
    x = 1:144;
    y1 = normpdf(x, 36, 20);
    y1(36:48) = y1(36);
    y2=normpdf(x, 48, 15);
    y2 = y2/y2(48)*y1(36);
    y3 = exp(-(1:36)/20);

    y=zeros(1, 144);
    y(1:48) = y1(1:48);
    y(48:60)=y2(48:60);
    y(61:108)=fliplr(y(13:60));
    y3=y3*y(108);
    y(109:144)=y3;
    y=y/max(y)*0.9;
```