إقـــــرار

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Design of Sugeno Fuzzy Controller for HVAC in Large Building

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Design of Sugeno Fuzzy Controller for HVAC in Large Building

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This thesis is submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical Engineering

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نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة الدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ **لؤى عبدالرحيم سلمان خشان** لنيل درجة الماجستير في **كلية *الهندسة*** قسم/ **الهندسة الكهربائية– أنظمة التحكم** وموضوعها:

Design of Sugeno Fuzzy Controller for HVAC in Large Building

وبعد المناقشة العلنية التي تمت اليوم الثلاثاء 08 محرم 1435هـ، الموافق 2013/11/12م الساعة التاسعة صباحاً بمبنى القدس، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

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وبعد المداولة أوصت اللجنة بمنح الباحث درجة الماجستير في **كلية *الهندسة*/** قسم **الهندسة الكهربائية- أنظمة التحكم.**

واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق ،،،

مساعد نائب الرئيس للبحث العلمي وللدراسات العليا

أ.د. فـؤاد علي العاجز

DEDICATION

I would like to dedicate this research dissertation to my Father and my mother. There is no doubt in my mind that without their continued support and counsel I could not have completed this process. I also dedicate this work to all my lovely family members" brothers, sisters, wife, and lovely kids Noor Alhoda and Jana" who have been a constant source of motivation, inspiration, and support.

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Abstract

By

Loai A. Khashan

The Islamic University of Gaza, 2013

The advantage of fuzzy logic control is that it does not strictly need any mathematical model of the plant. It is based on operator experience, and it is very easy to apply. Hence, many complex systems can be controlled without knowing the exact mathematical model of the plant. In addition, fuzzy logic simplifies dealing with nonlinearities in systems. Fuzzy controller is used to control Heating, Ventilating and Air Conditioning (HVAC) System, which is time varying nonlinear system. This controller consists of two fuzzy levels. The first fuzzy level is controls two varying feedback parameters (Air temperature and Air quality) and to make the controller adapt with these changes. While the second level is controls the Error and Change of Error that comes from first level. In this thesis, a hierarchical Sugeno fuzzy controller will be designed .The proposed structure is used to reduce the number of rules and the computing time required for the simulation processes, so it is suitable for nonlinear temperature control for large low energy buildings with features such as large capacity and longtime delay. The controller is developed using a computer simulation of a virtual building contains most parameters of a real building. Fuzzy rules are learned from experts and system performance observations. The proposed controller is tested using Matlab/Simulink environment , the results show that the Sugeno controller has a good response compared to the Mamdani controller, which applied to the same system. Achieving these purposes will increase the thermal comfort and reduce energy consumption.

ملخص

من مميزات التحكم المنطقي الضبابي هو أنه لا يحتاج بدقة أي نموذج رياضي للنظام . لأنه يقوم على المعرفة العلمية للإنسان ، وأنه من السهل جدا أن يتم تطبيقه على الانظمة .المعقدة وبالتالي ، يمكن التحكم في العديد من الأنظمة المعقدة دون معرفة النموذج الرياضي الدقيق للنظام. وبالإضافة إلى ذلك ، المنطق الضبابي يبسط التعامل مع الانظمة الغير خطية .

يتم استخدام وحدة التحكم الضبابي للسيطرة على نظام التدفئة والتهوية و تكييف الهواء الذي يعتبر نظام غير خطي ومتغير مع الوقت .

المتحكم الهرمي الضبابي متكون من مستويين , المستوي الضبابي الاول ليتحكم في المتغيرات التي تحدث في المكان من تغير في درجه الحرارة او تغير في جودة الهواء وجعل المتحكم يتكيف مع هذه المتغيرات ويرسلها الى المستوي الضبابي الثاني الدي هو متكون من الخطأ و مقدار الخطأ الدي هو الفرق بين درجة الحرارة المطلوبة ودرجة حرارة المبني الدي يأتي من المستوي الضبابي الاول .

في هذه الأطروحة سيتم تصميم متحكم غامض هرمي بطريقة سيجنو . هذه الهيكلية صممت لكي تقلل من عدد من القواعد وبالتالي تقليل وقت الحوسبة اللازمة لعمليات المحاكاة لتعطي النتيجة الملائمة .

تم استعمال برنامج الما تلاب على الكمبيوتر لتطبيق هدا المتحكم ، فقد بينت النتائج أن المتحكم من نوع سيجينو لديه استجابة جيدة بالمقارنة مع وحدة تحكم ممداني التي طبقت على نفس نظام المبني الافتراضي مع الحرص على كل الحالات المتوقع حدوتها موجوده في هدا النظام .

تحقيق هذا الهدف من المتحكم يعمل على زيادة الراحة الحرارية و تقليل استهلاك الطاقة .

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Nomenclature

Adaptive Fuzzy Logic Control	AFLC
Center of Area	COA
Center of Maximum	COM
Center of gravity	COG
Data Base	DB
Digital to Analog Converter	DC
Fuzzy Associative Memory	FAM
Fuzzy Logic	FL
Fuzzy Logic Controller	FLC
Fuzzy Logic System	FLS
Fuzzy Rule-Based System	FRBS
Genetic Algorithm	GA
Genetic Fuzzy Rule-Based System	GFRBS
Genetic Fuzzy Systems	GFS
Heat ventilation air condition	HVAC
Knowledge Base	KB
Membership Function	MF
Multi-Input-Multi-Output	MIMO
Mean Of Maximum	MOM
Quality Method	QM
Rule Base	RB
Takagi- Sugeno-Kang	TSK
Single-Input-Single-Output	SISO
Weighted Average method	WAM

CHAPTER ONE   INTRODUCTION

1.1 Introduction :

The greatest energy consumption in buildings occurs during their operation rather than during their construction, there are many types of construction buildings, some of these buildings called low energy buildings. Low energy buildings are any type of buildings that from design, technologies and building products use less energy, from any source than a traditional or average contemporary building. In the practice of sustainable design, sustainable architecture, low-energy building, energy-efficient landscaping low-energy houses often use active solar and passive solar building design techniques and components to reduce their energy expenditure. The implementation of different control methodologies for controlling parameters of heating, ventilating and air-conditioning (HVAC) systems as a part of building automation systems and other energy consumption factors and energy sources were investigated [1]. Classical HVAC control techniques such as the ON/OFF controllers (thermostats) and the proportional-integral-derivative (PID) controllers are still very popular because of their low cost. However, in the end, these controllers are expensive because they operate at a very low-energy efficiency. Proper control of low energy buildings [2], which is more difficult than in conventional buildings due to their complexity and sensitivity to operating conditions, is essential for better performance. This thesis presents hierarchical fuzzy controller the HVAC system capable of maintaining comfort conditions within a thermal space with time varying thermal loads acting upon the system with high air quality. To achieve this objective, we carry out the design of an HVAC control system that counteracts the effect of thermal loads on the space comfort conditions. The controller achieves this objective by adapting the varying parameters of thermal loads acting upon the system and using the hierarchical fuzzy with two levels to take the appropriate control actions to maintain space comfort conditions.

First fuzzy level is adaptive level for varying parameters. It controls the deference temperature just after entering the room and the real temperature in the room. This variation in temperature is due to slow spread nature of heating the air in an open large spaces and it is due to changes happened in this space as large windows opened or any external disturbances [3]. The second varying parameter is the quality of air inside this space cause if people are crowded in this space CO_2 concentration will change and the need of new air is essential, so a new cold air must enter the space. These varying parameters are nonlinear and cannot be expected, when it will be changed such as adaptive controller is needed, also an intelligent controller as fuzzy control method is very useful and flexible with unknown systems[4].

1.2 Thesis Motivation and Objectives

1.2.1 Motivation

We have noticed a great academic attention to the study of lowering energy consumption and the concern of replacing the conventional temporal energy sources by renewable energy sources. Lowering energy consumption is important for renewable energy sources. Therefore, we have to find the most energy consumption in our life electricity use. Fuzzy theory is a great science, which, belongs to intelligent control theory; Fuzzy theory opened a large space to make researches, because it is near a human thinking method. Fuzzy logic controllers have an efficient performance over the traditional controller researches especially in nonlinear and complex model systems and did not need precise calculations. In this thesis, we search for the most energy consumption in our life and figured out that Heating, Ventilation and Air Conditioning in commercial and industrial environment. A design in the field of hierarchical fuzzy control of HVAC Systems will increase the knowledge of intelligent and lowering Energy consumption.

1.2.2 Objectives

The objective of this research is to reach lowest energy consumption in the building, If we look at previous studies for building loads and their energy consumption , we will find that HVAC (Heat, Ventilation and Air-conditioning) is the most energy consumption in the building. We desire to design an optimal controller to control the HVAC system to decrease the energy building needs.

A- We want to build a controller to control HVAC.

B- Many previous approaches have studied, implemented and they gave good results but building energy consumption still, the highest energy compared with other loads in the electricity network.

C- We want to study a new approach to reach the best controller and our assumption is to use fuzzy control (using Sugeno) methodology.

D- Our search will apply on a software model

E- Making a comparison between the result from Mamdani and Sugeno methodologies

1.3 Literature review

1. *In march 2013 (Fadi Alalami et.al.)* proposed hierarchical fuzzy controller for building automation systems to reach lowest energy consumption using Mamdani approach [5] and he used the Mamdani method to get the optimal solution I will design Sugeno fuzzy control to improve the result that El_Alalami controller accomplished.

2. *In march 2012 (Mohammad Hassan Khooban et.al.)* designed Optimal Fuzzy Proportional-Integral-Derivative Controller (OFPIDC) for controlling the air supply pressure of a Heating, Ventilation and Air-Conditioning (HVAC) system [6]. They used fuzzy controller to tune the PID controller. PID controller was suggested to supply air pressure control of a Heating Ventilation and Air-Conditioning (HVAC). That's mean it must know the mathematical model , it is practically impossible to find an exact mathematical model for these systems, fuzzy controller is well adapted to the subjective concept of thermal comfort and easily handles multi-criteria objectives of thermal comfort and energy saving without any need to mathematically model the system.

3. *In August 2010 (Raad Z. Homod et.al*.) proposed hybrid PID-cascade controller for HVAC system[7]. Since HVAC systems are nonlinear, multi input multi output with interrelated parameters, time varying , nonlinear and very complex and exposed to uncertainties, Therefore, intelligent controllers, especially fuzzy logic controller could be a good alternative which dealing and cover all uncertainty.

4. *In 2003 (Jose M. Beni ´Tez, et.al.)* presented the use of genetic algorithms to develop smartly tuned fuzzy logic controllers dedicated to the control of heating, ventilating and air conditioning systems [8]. Concerning energy performance and indoor comfort requirements, they used Mamdani fuzzy, in this study I will used Sugeno fuzzy to improve the result.

1.4 Contribution

In this thesis, hierarchical fuzzy controller has been constructed which is used to control Heat, Ventilation and Air condition Systems for large buildings and large closed spaces. In this thesis, two level fuzzy controllers are designed and apply at HVAC system using Matlab software. These controllers have been tested using Matlab/Simulink program under different temperatures and load variation conditions.

In this thesis, Sugeno fuzzy controller is used and the result are compared with Mamdani fuzzy controller from previous studies. The results show the superiority of Sugeno model. The novel approach which proposed in this thesis is designing hierarchical fuzzy (Sugeno method) for unknown HVAC equation model.

1.5 Thesis Organization

The remaining chapters of this thesis are organized as follows:

Chapter 2 presents review and introduction to fuzzy logic and its application, fuzzy sets operations, the main concepts in fuzzy sets such as membership functions, and linguistic variable and Hierarchical fuzzy.

Chapter 3 introduce building management system .

Chapter 4 presents a review and introduces some basic principles of HVAC system ,The design of hierarchical Fuzzy Controller and Simulation results are presented to show the performance of the proposed control system and comparing the obtained results with previous studies which is presented in Chapter 5 . Chapter 6 presents conclusions and final comments

CHAPTER TWO FUZZY LOGIC CONTROL

2.1 History of Fuzzy Logic

In 1965, Lotfi A. Zadeh of the University of California at Berkeley published "Fuzzy Sets," which laid out the mathematics of fuzzy set theory and, by extension, fuzzy logic[9]. Zadeh had observed that conventional computer logic could not manipulate data that represented subjective or vague ideas, so he created fuzzy logic to allow computers to determine the distinctions among data with shades of gray, similar to the process of human reasoning. Zadeh published the first paper on fuzzy set theory in early 1965's , which presented not as a control methodology, but as a way of processing data. This approach to set theory was not applied to control systems until the 1970's due to insufficient small-computer capability prior to that time. Professor Zadeh reasoned that people do not require precise, numerical information input, and yet they are capable of highly adaptive control.

In 1974, Mamdani published the first paper for fuzzy applications. Mamdani method proposed as an attempt to control a real application in steam engine. The fuzzy inference system proposed by Mamdani; known as the Mamdani model in fuzzy system literature [10].

In 1985, Takagi and Sugeno published the paper of fuzzy systems. The fuzzy inference system proposed by Takagi and Sugeno known; as the T-S model in fuzzy system literature.

There are several advantages of using fuzzy control over classical control methods.In 1980's Japanese were the first to use fuzzy logic in application. Japanese and Korean companies are using fuzzy logic to enhance things like computers, air conditioners, automobile parts, cameras, televisions, washing machines, and robotics.

2.2 Fuzzy Logic

2.2.1 Introduction

Fuzzy logic is an extension of Boolean logic by Lotfi Zadeh in 1965 based on the mathematical theory of fuzzy sets, which is a generalization of classical set theory. By introducing the concept of degree in the verification of a condition, allowing a condition of being in a state other than true or false, fuzzy logic provides a very valuable flexibility to use reasoning, which makes it possible taking into account the inaccuracies and uncertainties. One of the advantages of fuzzy logic to formalize human reasoning is that the rules are set in natural language.

Fuzzy Logic is one of the most talked-about technologies to hit the embedded control field in recent years. It has already transformed many product markets in Japan and Korea, and has begun to attract a widespread following In the United States. Industry watchers predict that fuzzy technology is on its way to becoming a multibillion-dollar business [11].

It is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth. In the (Boolean) logic we see that the results for any operation can be true or false if we refer to true by (1) and the false by (0) then the result may be (1) or (0).

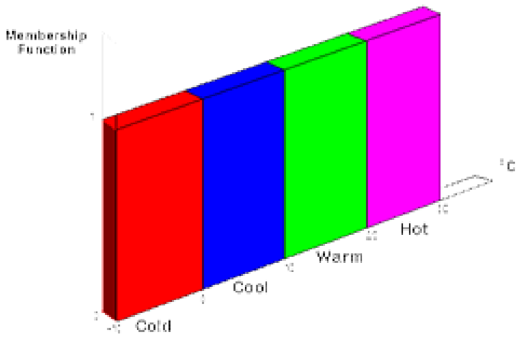

Figure 2.1a: Classical Sets

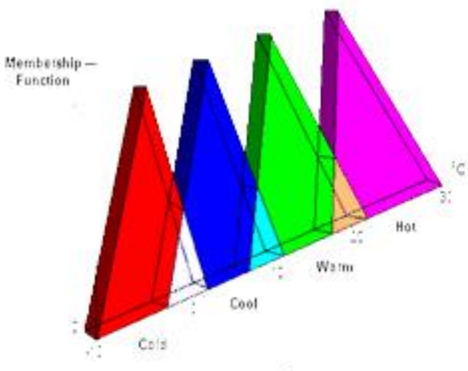

Figure 2.1b: Fuzzy sets

Figure (2.1a) shows an example for classical set that has two values true or false. We see that the classical set has crisp boundary. This example shows an age example: the man is old if he is between 40 years and 60 years in that interval all age has the same degree (1). In addition, outside of this interval, it has (0) degree. However, there is problem; what about 39 years and 11 months, is the man young! No he is old but has degree less than the 40 years, but in the Classical sets there are not degrees there are two values 1 or 0. Therefore, what is the solution; fuzzy sets give the solution see figure (2.1b).

The essential characteristics of fuzzy logic as founded by Lotfi Zadeh are as follows:

- In fuzzy logic, exact reasoning is viewed; as a limiting case of approximate reasoning.
- In fuzzy logic, everything is a matter of degree.
- Any logical system can be fuzzified.
- In fuzzy logic, knowledge is interpreted as a collection of elastic or, equivalently, fuzzy constraint on a collection of variables.
- Inference is viewed; as a process of propagation of elastic constraints.

2.2.2 Why Use Fuzzy Logic?

There are many reasons:

1- Fuzzy logic is used to control the complex and nonlinear systems without making analysis for these systems.

2- Fuzzy control enables engineers to implement the control technique by human operators to make ease of describing the systems.

3- Fuzzy logic is flexible with any given systems. If any change is happened in the system are does not need to start from the first step, but he can add some functions on top of it.

4- Fuzzy logic can be blended with conventional technique to simplify their implementation.

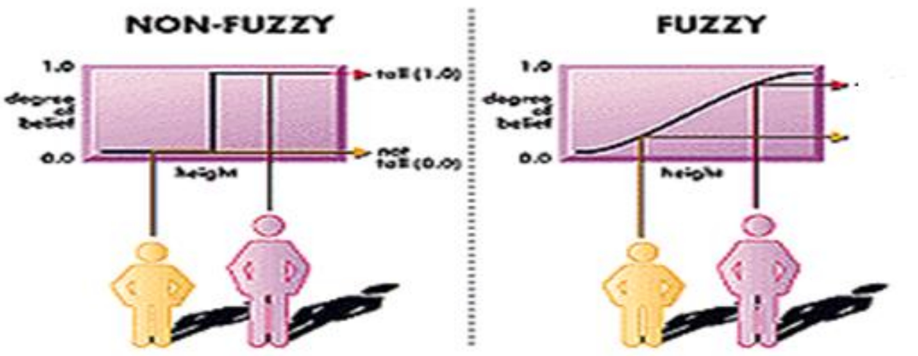

Figure 2.2a: Fuzzy and non-fuzzy

2.2.3 Conventional Control Verses Fuzzy

In crisp sets, an element in the universe has a well-defined membership or non-membership to a given set. Membership to a crisp set ″A" can be defined through a membership function defined for every element ″x" of the universe as[12]:

$$\mu_A(x) = \begin{cases} 1 & x \in A \\ 0 & x \notin A \end{cases}$$

Nevertheless, for an element in a universe with fuzzy sets, the membership function can take any value between ″0" and ″1". This transition among various degrees of membership can be thought of as conforming to the fact that the boundaries of the fuzzy sets are vague and ambiguous. An example of a graphic for the membership function of a crisp set is illustrated in figure (2.2b) .

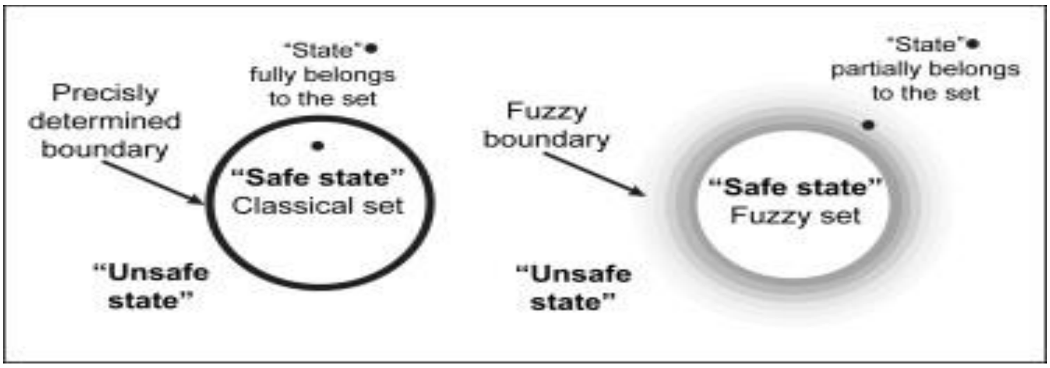

Figure 2.2 b: Fuzzy and Classical Sets

Fuzzy membership of an element from the universe in this set is measured by a function that attempts to describe vagueness. In fuzzy logic, linguistic variables take on linguistic values, which are words with associated degrees of membership in the set. Thus, instead of a variable temperature assuming a numerical value of 70 C^{o}, it is treated as a linguistic variable that may assume, for example, linguistic values of "hot" with a degree of membership of 0.7, "very cool" with a degree of 0.6, or "very hot" with a degree of 0.92. Each linguistic term is associated with a fuzzy set, each of which has a prescribed membership function.

Formally, a fuzzy set is defined as a set of pairs where each element in the universe "F" has a degree of membership associated with it:

$$A = \{(x, \mu_A(x)) \mid x \in F, \mu_A(x) \in [0,1] \}$$

The value $\mu_A(x)$ is the degree of membership of object "x" to the fuzzy set "A" where $\mu_A(x) = 0$ means that x does not belong at all to the set, while $\mu_A(x) = 1$ means that the element is totally within the set.

2.3 Fuzzy Sets

2.3.1 Membership Function (MF)

1) Features of Membership Function:

- Core: comprises of elements "x" of the universe, such that $\mu_A(x) = 1$
- Support: comprises of elements "x" of universe, such that $\mu_A(x) > 0$
- Boundaries: comprise the elements "x" of the universe $0 < \mu_A(x) < 1$
- A normal fuzzy set has at least one element with membership

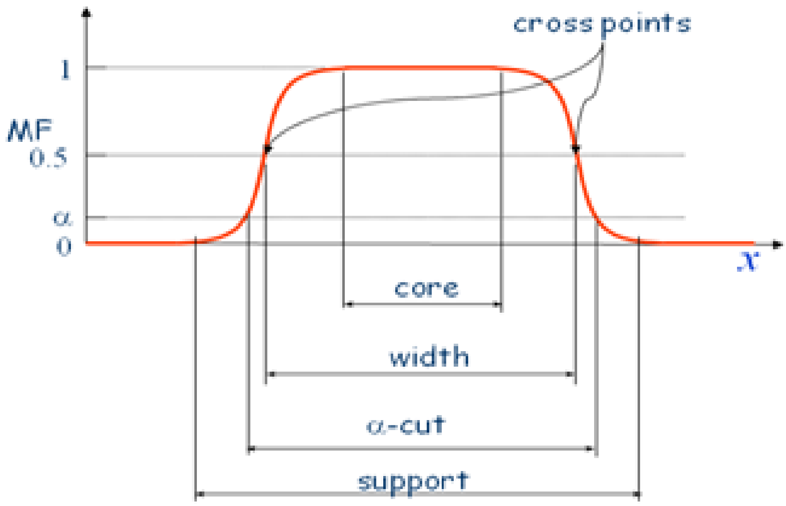

Figure 2.3: MF Terminology

For fuzzy set, if one and only one element has a membership = 1, this element is called as the *prototype* of set, and "A" *subnormal* fuzzy set has no element with membership=1.

2) Types of membership functions

Fuzzy set can be represented by its membership function. The shape of membership function depends on the application and can be monotonic, triangular, and trapezoidal or bell shaped as shown in figure (2.4).

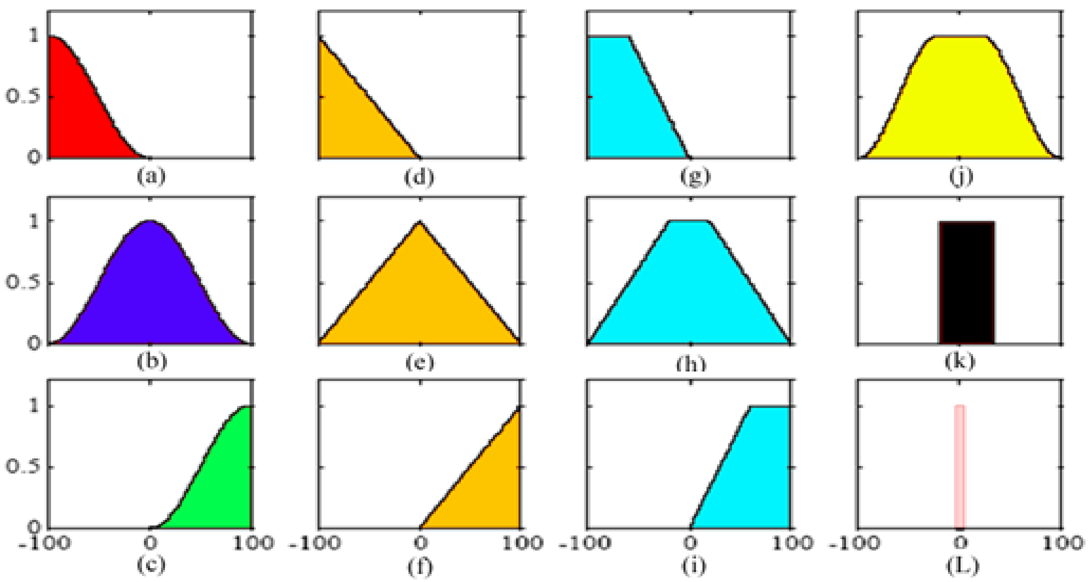

Figure 2.4: Different Shapes Of Membership Functions

(a) s_Function. (b) π_Function. (c) z_Function. (d-f) Triangular versions. (g-i) Trapezoidal versions. (J) Flat π_function. (k) Rectangle. (L) Singleton.

The membership function could be defined as a graphical representation of the quantity of participation of the inputs. It links a value with each of the inputs parameters that are treated, defines functional overlap amongst inputs, and finally defines an output parameter. The rules usually take the input membership parameters as features to establish their weight over the fuzzy output sets of the final output response. Once the functions are deduct, scaled, and combined, they have to be defuzzified into a crisp output, which leads the application[13].

2.3.2 Fuzzy Set Operations

Basic operations on sets in crisp set theory are the set complement, set intersection, and set union. Fuzzy set operations are very important because they can describe intersections between variables for a given element "x" of the universe, The following function for the set theoretic operations of complement, intersection, and union are defined :

1. Complement (NOT Operation):

Consider a fuzzy set "A" in universe "X". Its complement "Á" as shown in Figure (2.5)

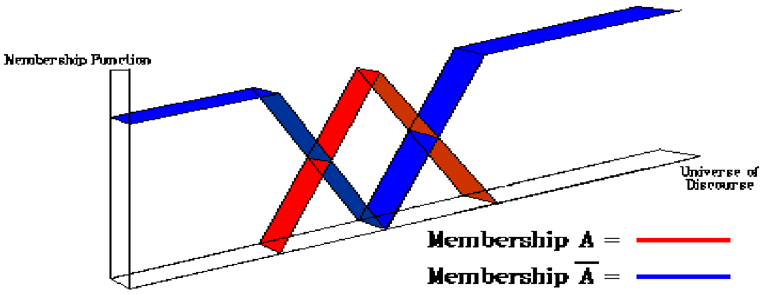

Figure 2.5: Complement Of Fuzzy Sets A

2. Intersection (AND Operation):

Consider two fuzzy sets "A" and "B" in universe "X", as shown in Figure (2.6).

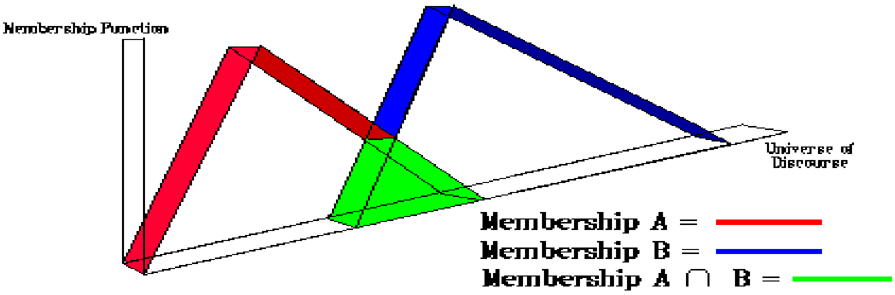

Figure 2.6: Intersection If Fuzzy Sets A and B

min operator $\mu A(x)$ and $\mu B(x) = \min \{ \mu A(x), \mu B(x)\}$

3. Union (OR Operation):

Consider two fuzzy sets "A" and "B" in universe "X". $A \cup B$ is the whole area covered by the sets as shown in Figure (2.7)

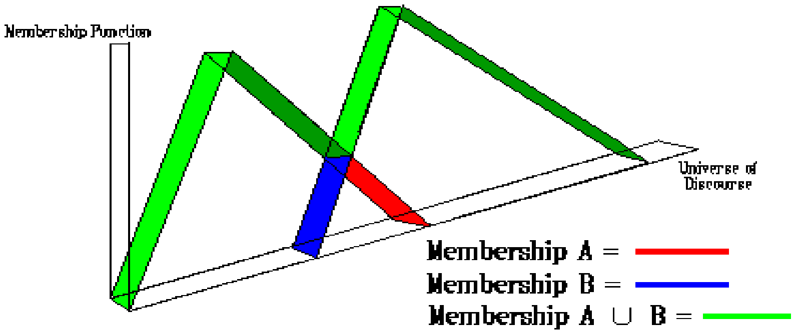

Figure 2.7: Union Of Fuzzy Sets A and B

Max operator $\mu A(x)$ *or* $\mu B(x) = \max \{\mu A(x), \mu B(x)\}$

2.4 Fuzzy Controllers

There are many types of fuzzy logic controller available but the most important are mamdani and sugeno methods .

2.4.1 Mamdani method

It is the most commonly used fuzzy inference technique. In 1974, Professor Ebrahim Mamdani of London University built one of the first fuzzy systems to control a steam engine and boiler combination. He applied a set of fuzzy rules supplied by experienced human operators. The Mamdani-style fuzzy inference process is performed in four steps [14] :

1) Fuzzification of the input variables
2) Rule evaluation.
3) Aggregation of the rule outputs
4) Defuzzification

To illustrate the fuzzy inference , let us examine a simple two-input one-output problem that includes three rules:

Rule (1) …. IF X is A3 OR Y is B1 THEN z is C1

Rule (2)…. IF X is A2 AND Y is B2 THEN z is C2

Rule (3)…. IF X is A1 THEN z is C3

Step 1: Fuzzification

The first step in the application of fuzzy reasoning is a Fuzzification of inputs in the controller, which is to take the crisp inputs, x1 and y1, and determine the degree to which these inputs belong to each of the appropriate fuzzy sets. It means that to every crisp value of input we attribute a set of degrees of membership (mj, j=1,n) to fuzzy sets defined in the universe of discourse for that input figure (2.8).

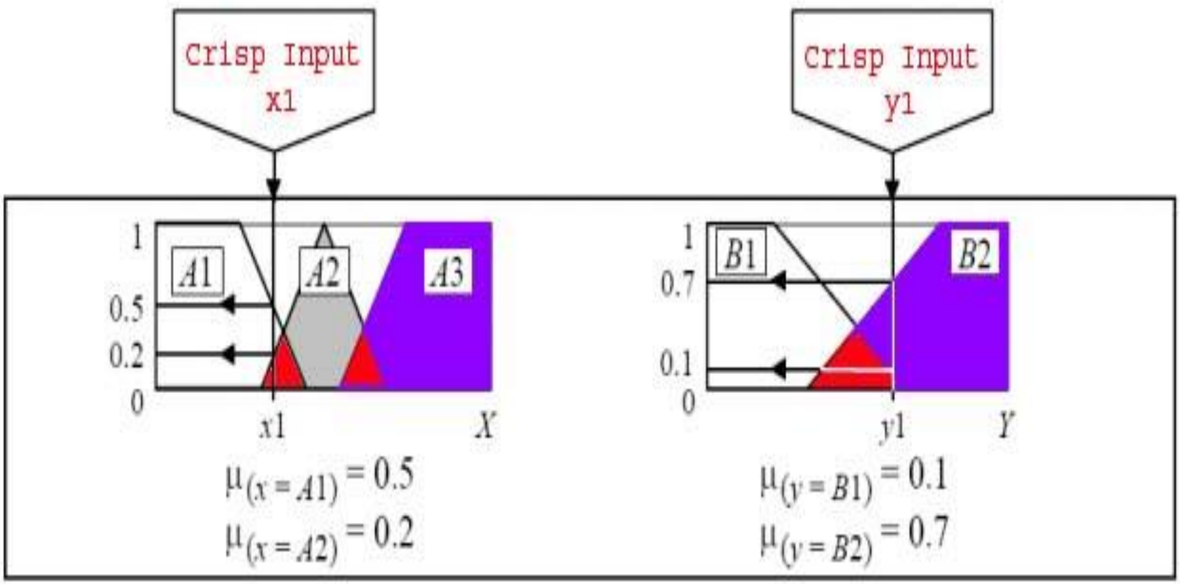

Figure 2.8: Fuzzification Stage

Step 2: Rule evaluation

The second step is to take the fuzzified inputs, $\mu(x{=}A1) = 0.5$, $\mu(x{=}A2) = 0.2$, $\mu(y{=}B1) = 0.1$ and $\mu(y{=}B2) = 0.7$, and apply them to the antecedents of the fuzzy rules. If a given fuzzy rule has multiple antecedents, the fuzzy operator (AND or OR) is used to obtain a single number that represents the result of the antecedent evaluation. This number (the truth value) is then applied to the consequent membership function. To evaluate the disjunction of the rule antecedents, we use the OR fuzzy operation. As shown Operations with fuzzy sets the most used approach for the union is to get the maximum: $\mu A \cup B(x) = max\ [\mu A(x), \mu B(x)]$.

Similarly, in order to evaluate the conjunction of the rule antecedents, we apply the AND fuzzy operation intersection which used minimum approach: $\mu A \cap B(x) = min\ [\mu A(x), \mu B(x)]$.

The rule evaluations are clearly appears in Figure (2.9) .

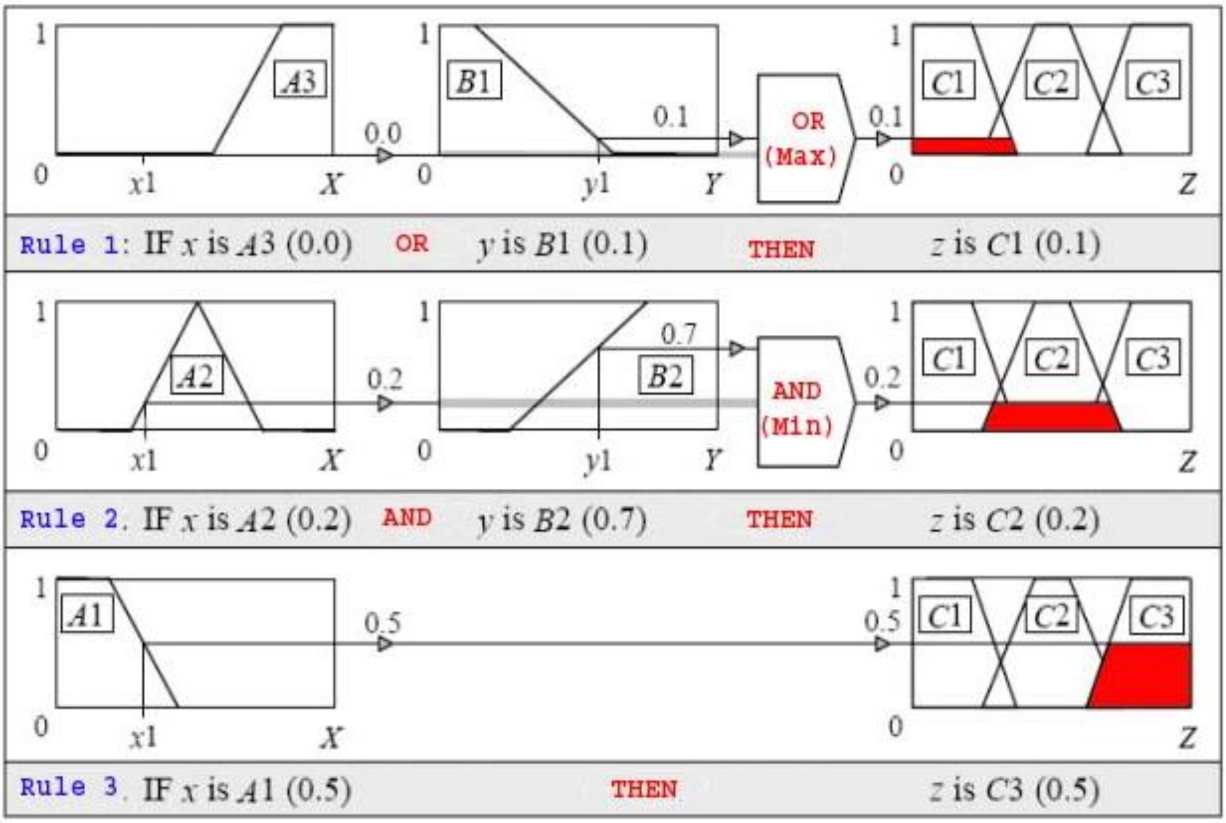

Figure 2.9: Rule Evaluation in Mamdani Method

The most common method of correlating the rule consequent with the truth value of the rule antecedent is to cut the consequent membership function at the level of the antecedent truth. This method is called clipping. Since the top of the membership function is sliced, the clipped fuzzy set loses some information. However, clipping is still often preferred because it involves less complex and faster mathematics, and generates an aggregated output surface that is easier to Defuzzify.

Step 3: Aggregation of the rule outputs

Aggregation is the process of unification of the outputs of all rules. We take the membership functions of all rule consequents previously clipped (Max-Min Composition) or scaled (Max-Product Composition) and combine them into a single fuzzy set figure (2.10).

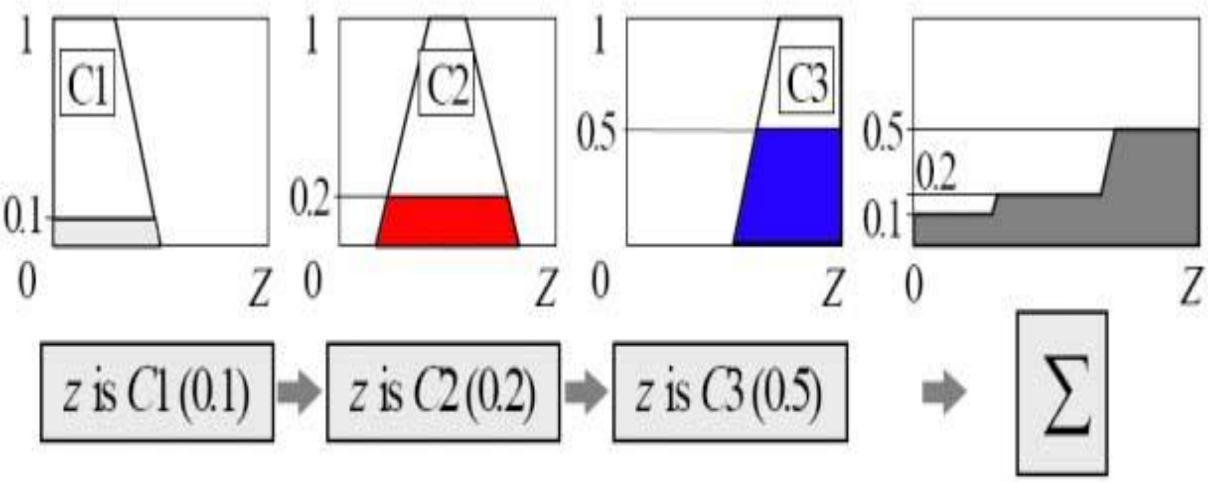

Figure 2.10: Aggregation Stage in Mamdani Method

Step 4: Defuzzification

Defuzzify the aggregate output fuzzy set into a single number. This step will be explained in details in section 2.4.6. However, in this example we used the center of gravity (COG) method to solve the defuzzification as shown in Figure (2.11).

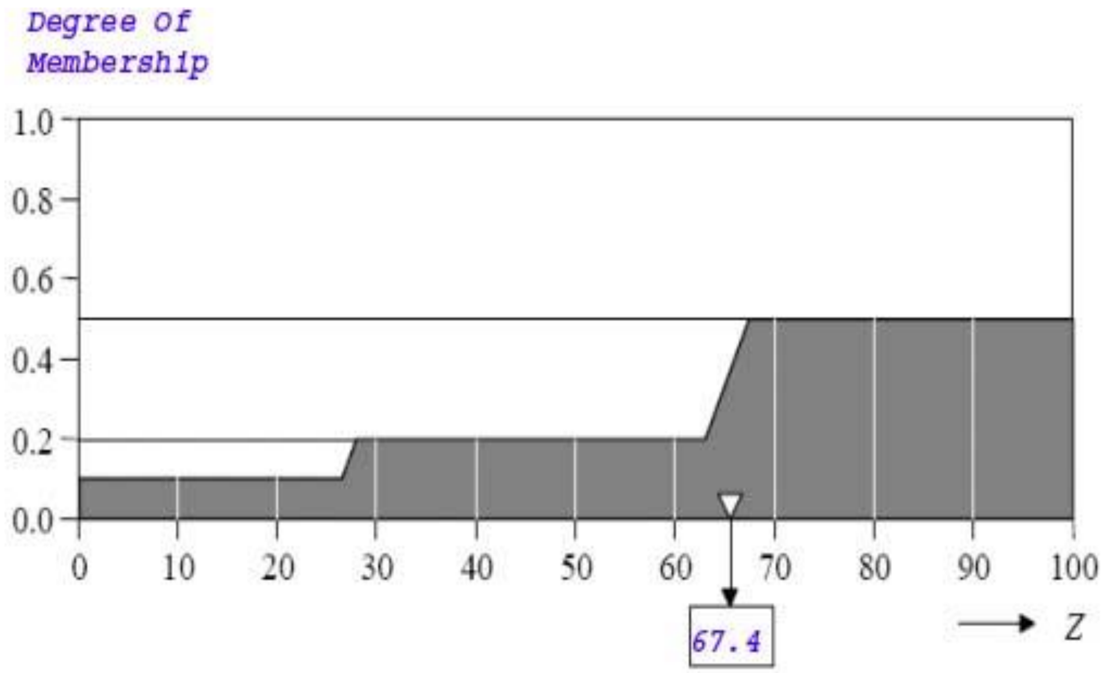

Figure 2.11: COG Approach in Defuzzification Stage

2.4.2 Sugeno method

Since Mamdani's pioneering works on fuzzy control motivated by Zadeh’s approach to inexact, there have been numerous studies on fuzzy reasoning. Most fuzzy controllers have been designed, based on human operator experience and/or control engineer knowledge. It is ,however ,often the case that an operator cannot tell linguistically what kind of action he takes in a particular situation. In this respect, it is quite useful to provide a method of modeling the control actions using numerical data. In 1985, Takagi-Sugeno-Kang (TSK) suggested using a single spike, a singleton, as the membership function of the rule consequent, and they suggested another approach that uses equation consequent in place off singleton consequent. A singleton, or more precisely a fuzzy singleton, is a fuzzy set with a membership function that is unity at a single particular point on the universe of discourse and zero everywhere else. Sugeno-style fuzzy inference is very similar to the Mamdani method. Sugeno changed only a rule consequent. Instead of a fuzzy set, he used a mathematical function of the input variable .The format of the Sugeno-style fuzzy rule is [15]:

IF X is *A* AND *Y* is *B* THEN Z is *f* (*x*, *y*)

Where X, Y and Z are linguistic variables; *A* and *B* are fuzzy sets on universe of discourses *X* and *Y*, respectively; and *f* (*x*, *y*) is the mathematical function. The most commonly used is zero-order Sugeno fuzzy model it can be described in the following form:

IF X is *A* AND *Y* is *B* THEN Z is k

Where *k* is constant.

In this case, the output of each fuzzy rule is constant. Singleton spikes represent all consequent membership functions.

The Figures (2.12, 2.13, and 2.14) illustrate the idea for TSK, which likes Mamdani steps.

For Defuzzification stage it's better to use Weighted Average method (WA):

$$WA = \frac{\mu(k1)\times k1+\mu(k2)\times k2+\mu(k3)\times k3}{\mu(k1)+\mu(k2)+\mu(k3)} = \frac{0.1\times 20+0.2\times 50+0.5\times 80}{0.1+0.2+0.5} = 65 \qquad \text{eq. (2.1)}$$

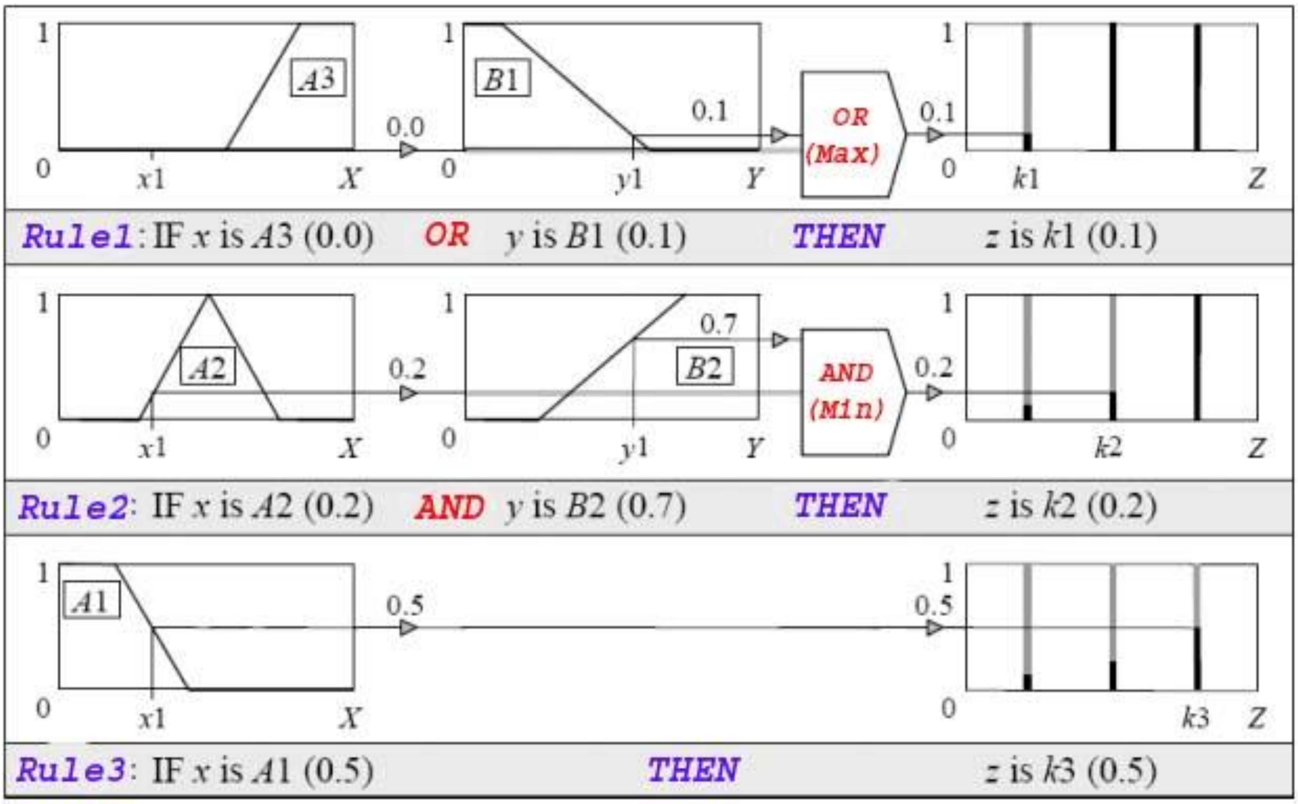

Figure 2.12: Rule Evaluation Stage in TSK Method

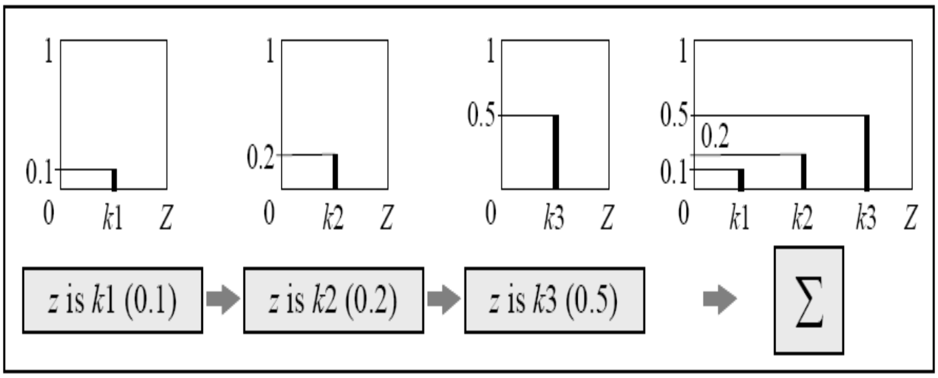

Figure 2.13: Aggregation Stage in TSK Method.

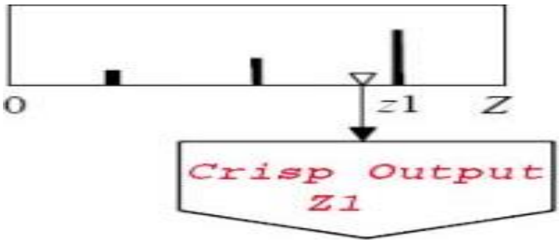

Figure 2.14: (WA) Method in Defuzzification Stage.

The overall fuzzy logic controller "FLC" appear in Figure (2.15)

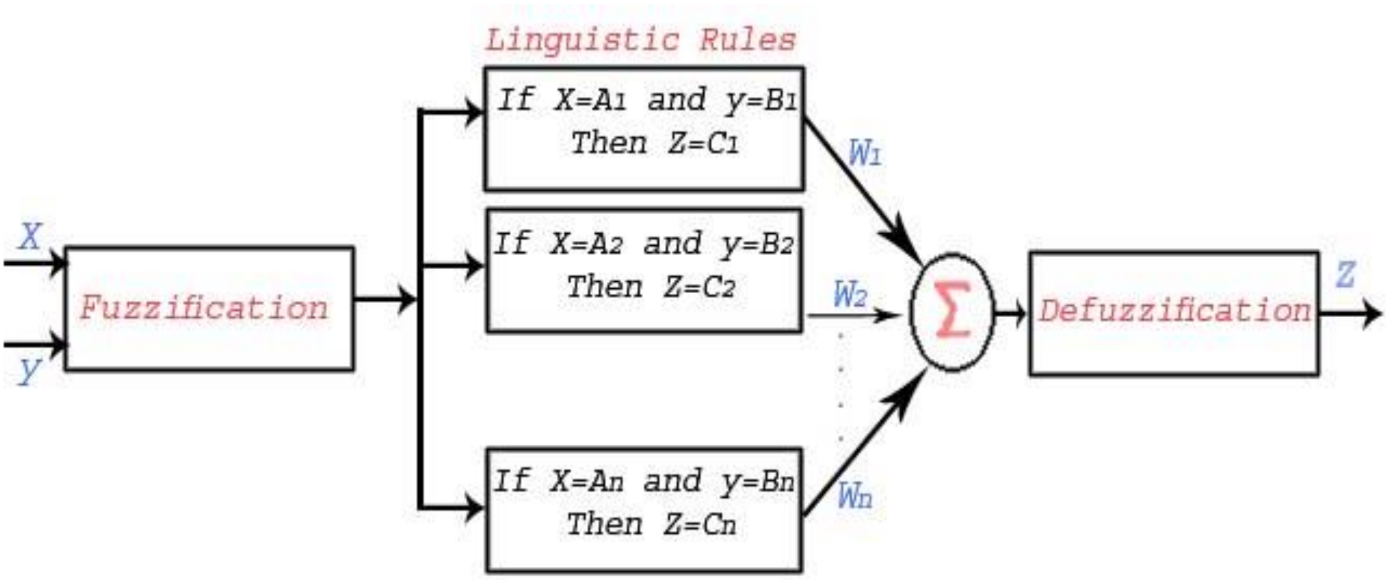

Figure 2.15: General Structure of Fuzzy Logic Control Part of The System

2.5 Advantages and Disadvantages of Two Methods

2.5.1 Advantages of the Mamdani Fuzzy method:

- It is intuitive and simple to build.

- It is widely used for second order systems with both linear and nonlinear characteristics [16].
- It has widespread acceptance.
- It is well suited to human feeling.

2.5.2 Disadvantages of the Mamdani Fuzzy method:

- It is only suited to the long delay system, such as the temperature control system, since it is too simple to control the process quickly.
- It needs additional device to improve the efficiency, when it controls the high frequent input system.

2.5.3 The advantages of Takagi-Sugeno Model:

- It is computationally efficient.
- It works well with linear techniques (e.g., PID control) [16].
- It works well with optimization and adaptive techniques.
- It has guaranteed continuity of the output surface.
- It is well suited to mathematical analysis.
- It can optimize the parameters of the output to improve the efficiency.

2.5.4 Disadvantages of the Sugeno Fuzzy method

- It is not intuitive.
- When using the higher order Sugeno method, it is complex.

2.6 How to make a decision Mamdani or Sugeno

- Mamdani method is widely accepted for capturing expert knowledge. It allows us to describe the expertise in more intuitive and more human-like manner. However, Mamdani-type fuzzy inference entails a substantial computational burden.

- On the other hand, Sugeno method is computationally effective and works well with optimization and adaptive techniques, which makes it very attractive in control problems, particularly for dynamic nonlinear systems [17].

2.7 Hierarchical Fuzzy Control:

we have seen various concepts associated with fuzzy logic and control. In order to design a fuzzy system with a good amount of accuracy, an increase in the number of input variables to the fuzzy system results in an exponential increase in the number of rules required. If there are n input variables and m fuzzy sets are defined for each of these, then the number of rules in the fuzzy system is m^n, this can be shown with the help of a small example. Suppose there are 5 input variables and for each variable 3 fuzzy sets are defined, then the total number of rules is 243.Now, suppose the number of fuzzy sets is increased to 5 (to increase the accuracy of the system), then the new number of the rules would be 3120. Thus resulting a huge increase in the number of the rules. The idea behind the construction of a two-level hierarchical scheme is to make a layered structure of control where each layer takes into account a certain number of variables and gives a single variable as the output. Hence the complexity of the system reduces, and along with it, the number of rules to be framed[18].

A hierarchical fuzzy rule based control strategy is proposed for the optimum control of the heating system. Fuzzy rule based controllers are widely used on systems with high uncertainties and can be interpreted linguistically. The rules are of the following forms and are as shown in Figure 2.16:

Rule Level 1: IF A1 is LOW & B1 is HIGH Then C2 is 3.4

Rule Level 2: IF C2 is LOW & D2 is HIGH Then E3 is 5.6

Rule Level 3: IF E3 is LOW & F3 is HIGH Then G4 is 1

Fuzzy rules are generated from optimization results calculated for values of the inputs at the centers of the fuzzy sets. Even if it is assumed that each of the fuzzy input variables is described by 5 fuzzy sets, the total number of rules would be very large (625). Therefore, It would take many years to generate the rules and they would be very difficult to understand. A hierarchical approach is adopted to reduce the number of fuzzy rules to 25 rules each level only which mean (75) rules for whole system with reduction of (550) rules with conventional method.

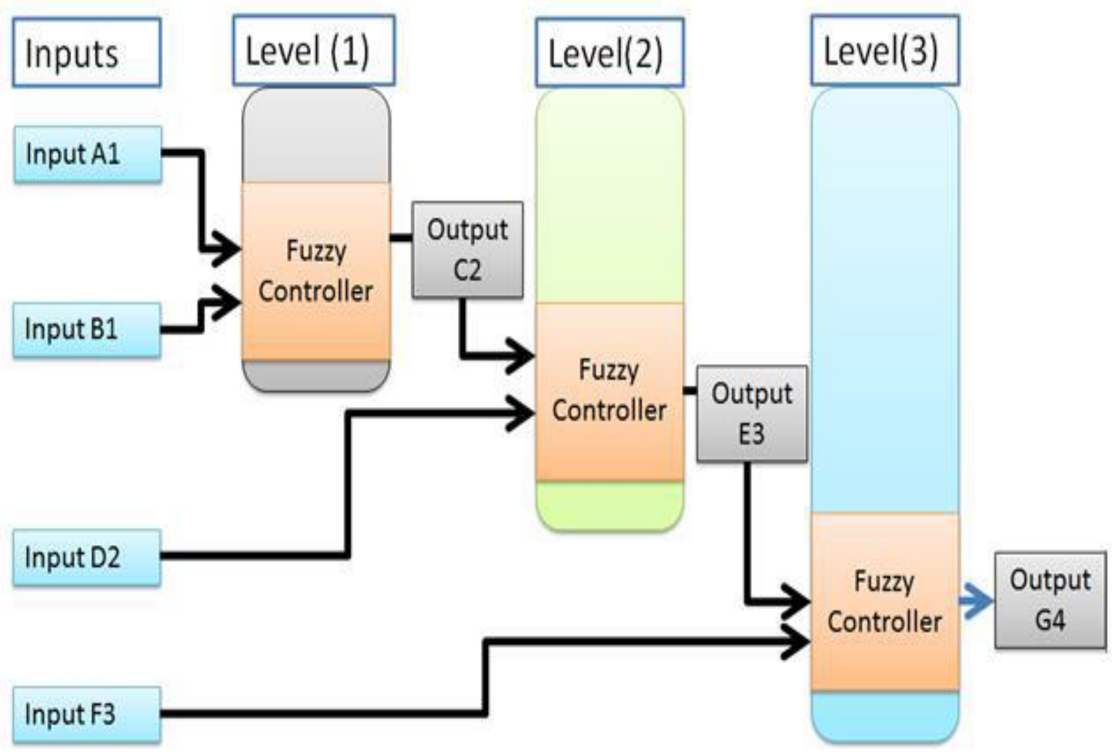

Figure 2.16: A three level Hierarchical Fuzzy control

The control strategy is split into 3 levels. At the first level, the date, time, schedule and prediction of the future outdoor temperatures are used to decide which of the rules at the second level and third level will be used. At the second level, predictions of the future solar radiation, outdoor temperature and internal load are used to find the optimal tank and building temperatures.

At the third level, the room and tank temperature set points are used, together with a measurement of the current solar radiation and an estimate of the excess energy that is currently available, to determine the control command for each device in the heating system.

CHAPTER THREE BUILDING AUTOMATION SYSTEM

3.1 Introduction

In recent years, the quality and complexity of mechanical and electrical systems in buildings have been increased. Integrated systems like building automation system are suitable alternatives to monitor, control and manage the modern structures with complex control functions.

Building automation describes the advanced functionality provided by the control system of a building. A building automation system (BAS) is an example of a distributed control system. The control system is a computerized, intelligent network of electronic devices designed to monitor and control the mechanical, electronics, and lighting systems in a building. BAS core functionality keeps the building climate within a specified range, provides lighting based on an occupancy schedule, monitors system performance and device failures, and provides malfunction alarms (via email and/or text notifications) to building engineering/maintenance staff. The BAS functionality reduces building energy and maintenance costs when compared to a non-controlled building. A building controlled by a BAS is often referred to as an intelligent building or a smart home[19].

A BAS is an integration of subsystems like heating, ventilating and air-conditioning system (HVAC), lighting control, and automatic fire alarm system and security system see figure (3.1). Carlson (1991) reported a BAS is a more effective and efficient control tool to be used for building. Automatic control of indoor parameters is provided by Building automation systems (BAS) (Kastner et al., 2005).According to Kastner, the core and root of BAS is the automation of heating, ventilation and air-conditioning systems in large functional buildings. The primary goals of using BAS are saving energy and decreasing the cost. A BAS is an integration of several subsystems like heating, ventilating and air-conditioning (HVAC) control, illumination control, fire security system, security and access control, power monitoring and transportation control [20].

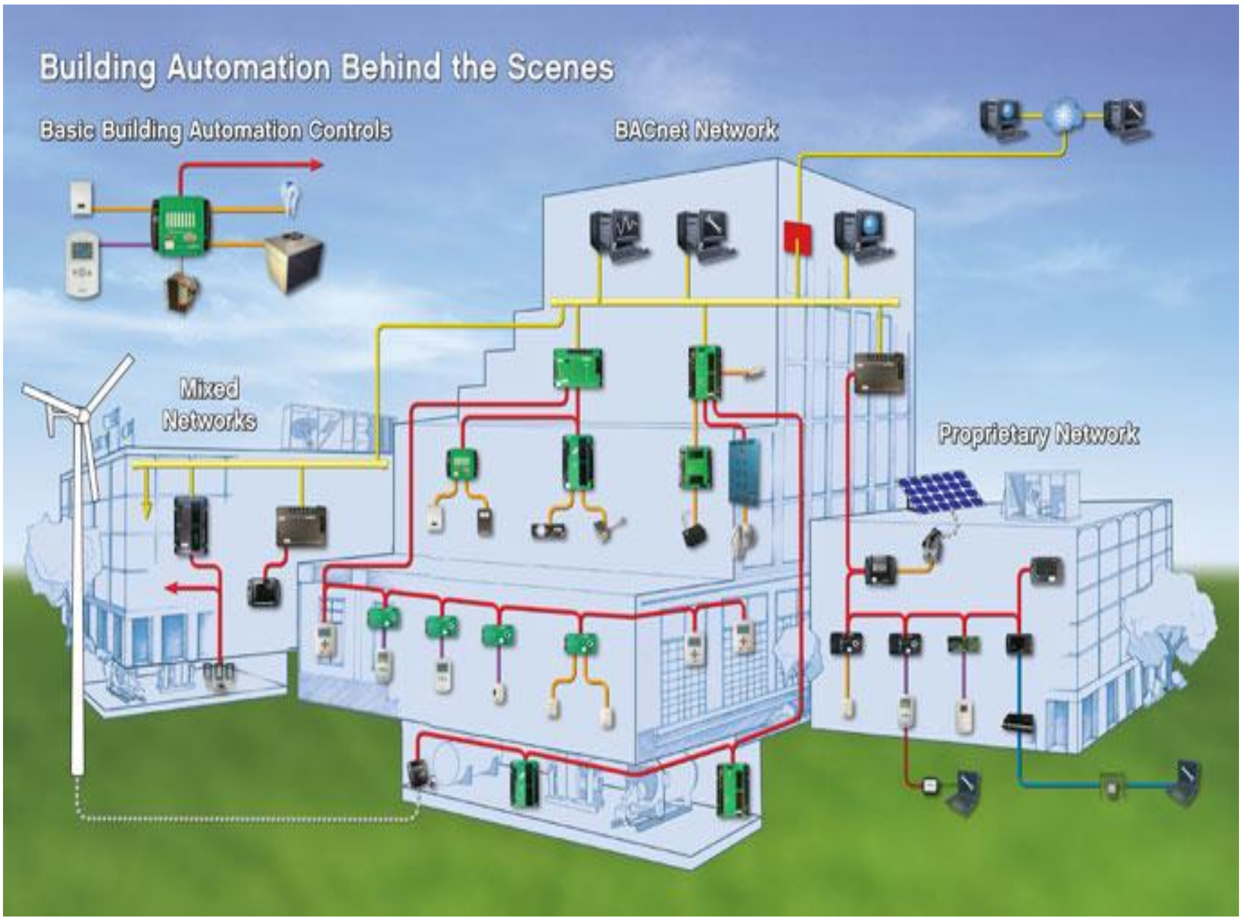

Figure 3.1 :Building Automation behind the scenes

The tasks of these subsystems are helping to understand and realize the situation of building performance, measuring building energy consumption, optimizing system running strategy and improving system management. Although, at first glance the building automation and the building control appear the same, by this definition building control is deduced as a part of building automation. After the early 1970s, while the oil price shocked everyone, the need for power saving arose and highlighted the automation related to energy managing. Control of active systems like HVAC was applied significantly for BAS to save energy and cost [21].

3.2 Functions of BMS:

Building Management System (BMS) is a high technology system installed on buildings that controls and monitors the building's mechanical and electrical equipment such as air handling and cooling plant systems, lighting, power systems, fire systems, and security systems see figure (3.2) .

It Controls heating and cooling, manage the systems that distribute this air throughout the building (for example by operating fans or opening/closing dampers), and then locally control the mixture of heating and cooling to achieve the desired room temperature and monitor the level of human-generated CO2, mixing in outside air with waste air to increase the amount of oxygen while also minimizing heating/ cooling losses[22].

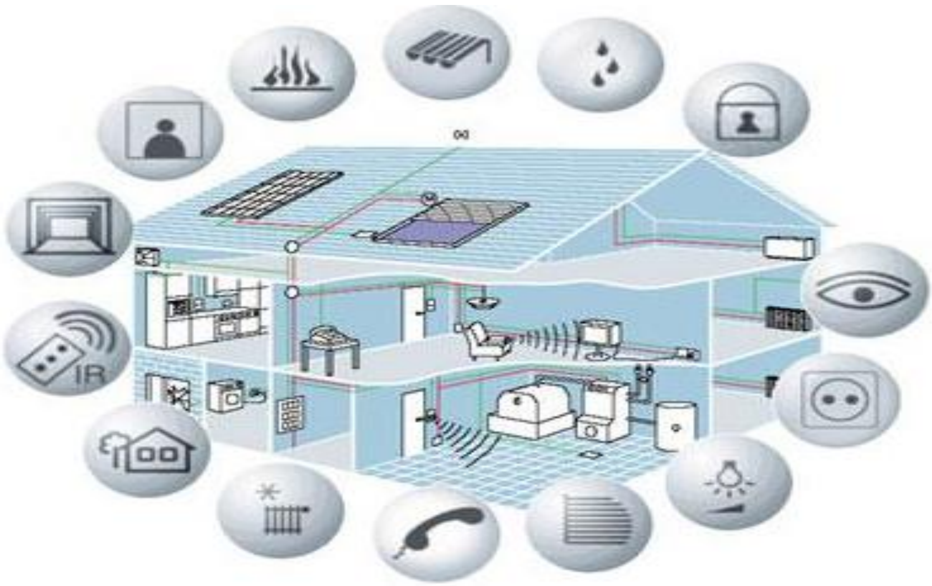

Figure 3.2: Function of BMS

3.3 Why do we need a Building Management System

All Buildings have some form of mechanical and electrical services in order to provide the facilities necessary for maintaining a comfortable working environment. These services have to be controlled by some means to ensure, for example, that there is adequate hot water for sinks, that the hot water in the radiators is sufficient to keep an occupied space warm, that heating with ventilation and possibly cooling is provided to ensure comfort conditions wherever, irrespective of the number of occupants or individual preferences see figure (3.3).

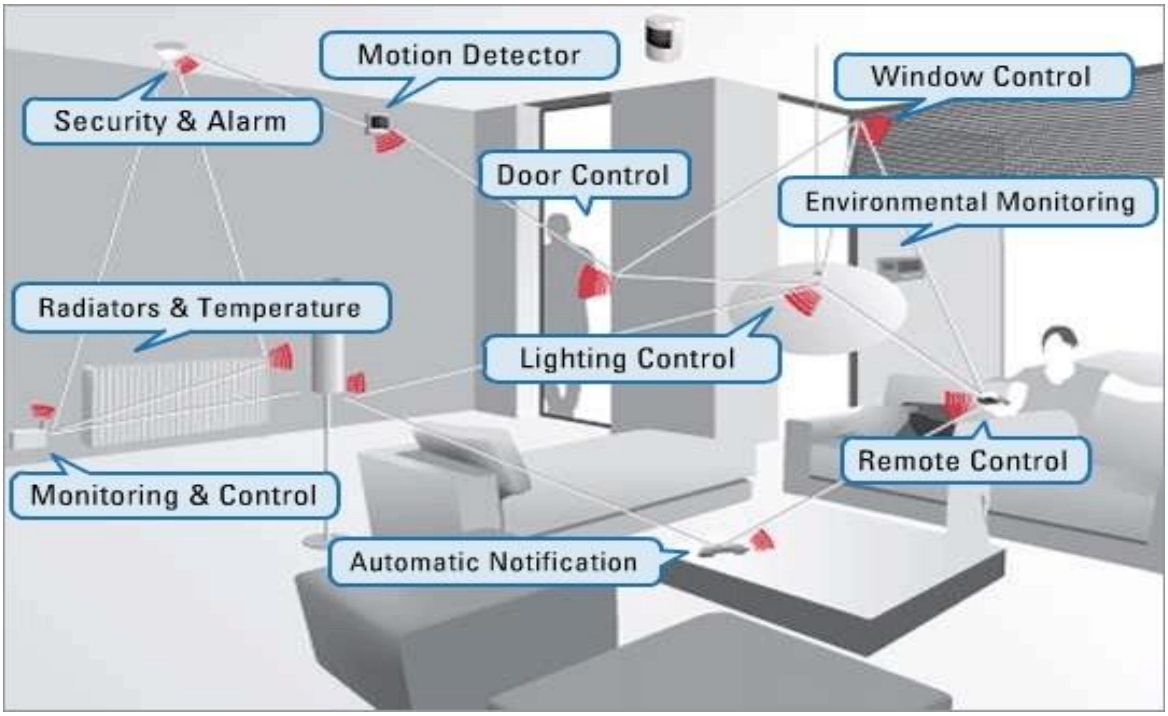

Figure 3.3: Control in Building

Basic controls take the form of manual switching, time clocks or temperature switches that provide the on and off signals for enabling pumps, fans or valves etc.

The purpose of a Building Management System (BMS) is to automate and take control of these operations in the most efficient way possible for the occupiers/business, within the constraints of the installed plant[23].

3.4 How does it work

The BMS is a “stand alone” computer system that can calculate the pre-set requirements of the building and control the connected plant to meet those needs. Its inputs, such as temperature sensors and outputs, such as on/off signals are connected into outstations around the building. Programs within these outstations use this information to decide the necessary level of applied control. The outstations are linked together and information can be passed from one to another. In addition a modem is also connected to the system to allow remote access

The level of control via the BMS is dependent upon the information received from its sensors and the way in which its programs tell it to respond to that information. As well as offering a precise degree of control to its environment, it can be made to alarm on conditions that can't meet specification or warn of individual items of plant failure.

Occupancy times for different areas are programmed into the Building Management System such that the plant is brought on and off to meet the occupier requirements. These times are often under optimum start control.

This means that the heating plant is enabled, at a varying predetermined time, to ensure that the heated space is at the set desired temperature for the start of the day. The Building Management System therefore, based on the outside air temperature the space temperature and the building structure, determines the plant start time[24].

Benefits of BMS:

• Increased levels of comfort and thus, more satisfied occupants.

• Possibility of individual room control.

• Increased productivity.

• Effective monitoring and targeting of energy consumption.

• Improved plant reliability and life.

• Effective response to HVAC-related complaints

• Low operating cost.

• Efficient use of building resources and services

• Rapid alarm indication and fault diagnosis

• Good plant schematics and documentation

• Ease of information availability problem diagnostics.

• Computerized maintenance scheduling.

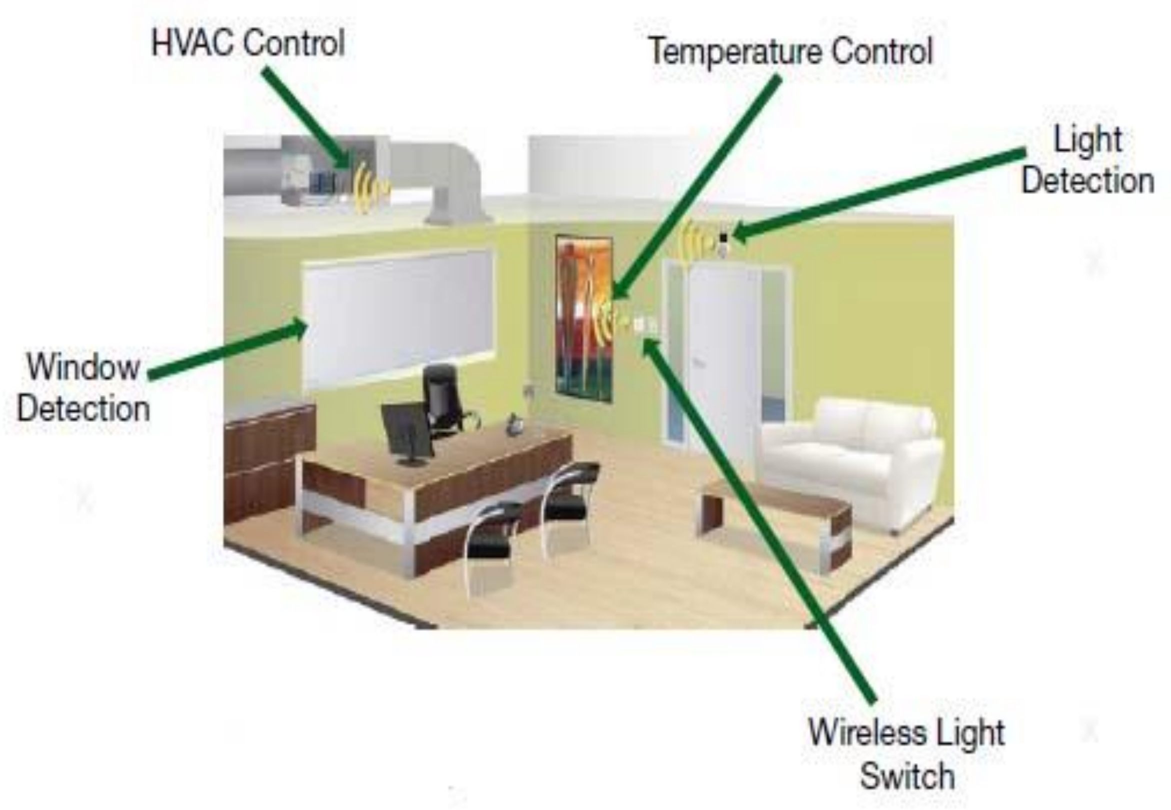

Figure 3.4 Benefits of Building Management System

3.5 Practical benefits

Energy-effective systems balance a building's electric light, daylight and mechanical systems for maximum benefit.

Enhanced lighting design is more than an electrical layout. It must consider the needs and schedules of occupants, seasonal and climatic daylight changes, and its impact on the building's mechanical systems see figure (3.5)[25] .

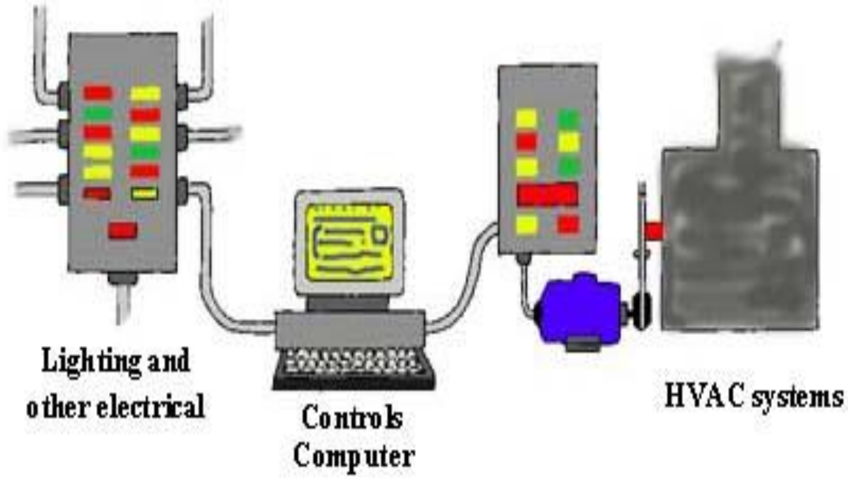

Figure 3.5: Control in Building Management System

3.5.1 lighting systems

Adding daylight to a building is one way to achieve an energy-effective design. Natural daylight 'harvesting' can make people happier, healthier, and more productive see figure (3.6). And with the reduced need for electric light, a great deal of money can be saved on energy. Nearly every commercial building is a potential energy saving project, where the electric lighting systems can be designed to be dimmed with the availability of daylight. Up to 75% of lighting energy consumption can be saved. In addition, by reducing electric lighting and minimizing solar heat gain, controlled lighting can also reduce a building's air conditioning load.

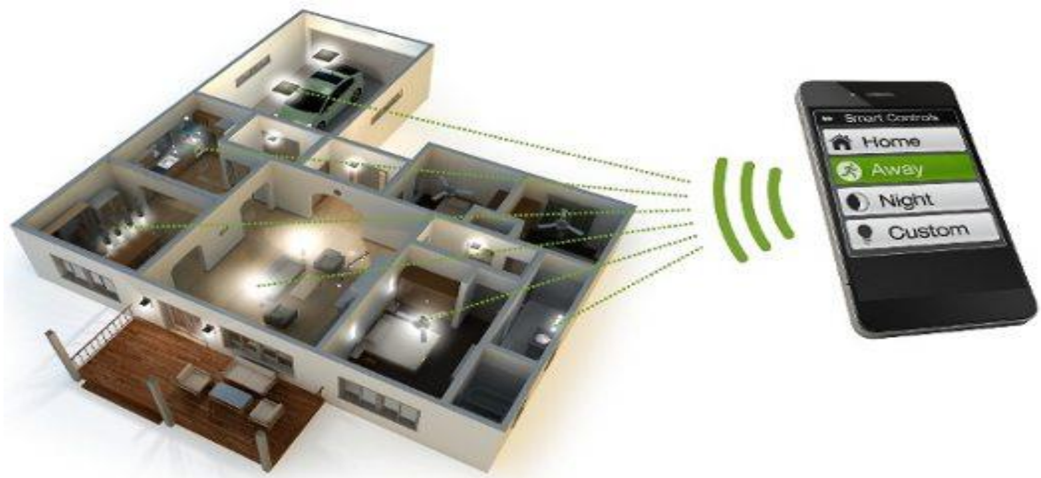

Figure 3.6: Control Lighting in Building Management System

3.5.2 Mechanical systems

The HVAC system and controls, including the distribution system of air into the workspaces, are the mechanical parts of buildings that affect thermal comfort. These systems must work together to provide building comfort. While not usually a part of the aesthetics of a building, they are critical to its operations and occupant satisfaction[26].

Many people cope by adding fans, space heaters, covering up vents, complaining, conducting 'thermostat wars' with their co-workers, or simply leaving the office. Occupants can be driven to distraction trying to adjust the comfort in their space. Improper temperature, humidity, ventilation, and indoor air quality can also have significant impacts on productivity and health. When we are thermally comfortable we work better, shop longer, relax, breathe easier, focus our attention better.

In order to provide a comfortable and healthy indoor environment the building mechanical system must see figure (3.7) [27]:

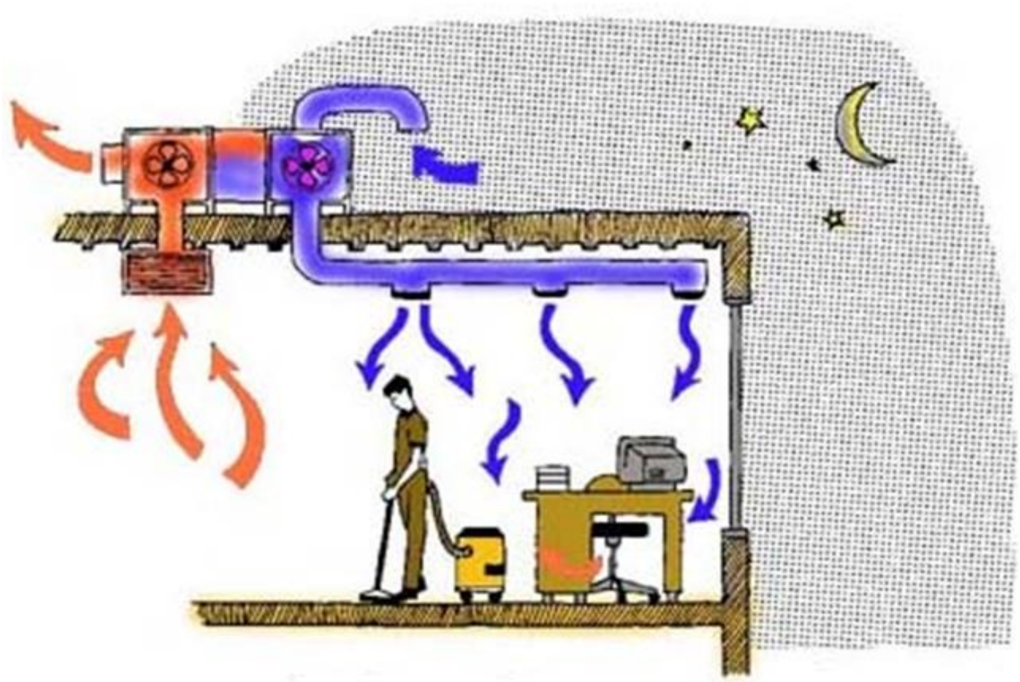

Figure 3.7: HVAC in Building Management System

- Provide an acceptable level of temperature and humidity and safe guard against odors and indoor air pollutants.
- Create a sense of habitability through air movement, ventilation and slight temperature variation.
- Allow the occupant to control and modify conditions to suit individual preferences.

3.6 **Saving energy In Building Management System**

Heating is the most power consumption in a building, a study of energy consumption in USA is shown in Figure (3.8).

Normally, thermal comfort depends on a great number of parameters such as air velocity, mean radiant temperature, people's activity, etc.

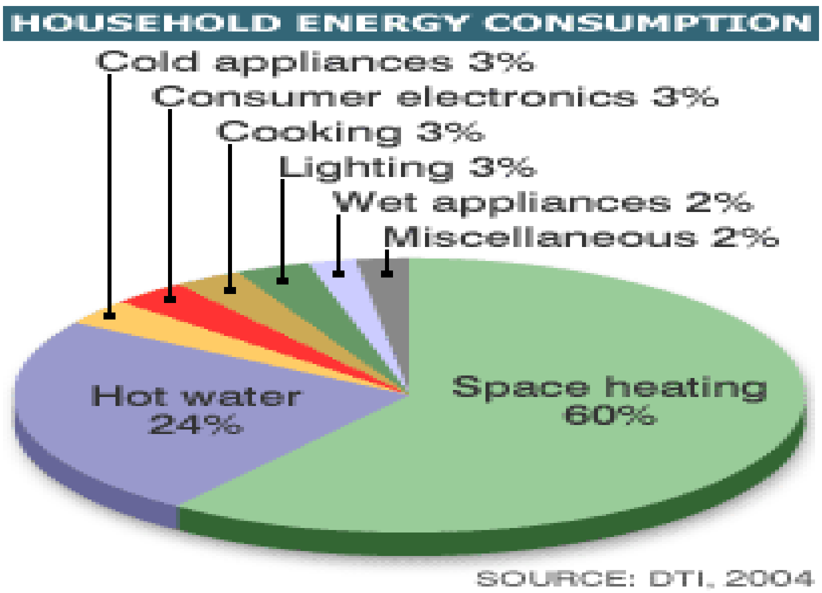

Figure 3.8: Energy consumption

Building automation is the solution to reduce energy use while maximizing the comfort levels of occupants. Using various sensors (occupancy, temperature, humidity, etc.) and controllers connected together, building administrators can monitor and control lighting/HVAC devices and systems more efficiently see figure (3.9)[28].

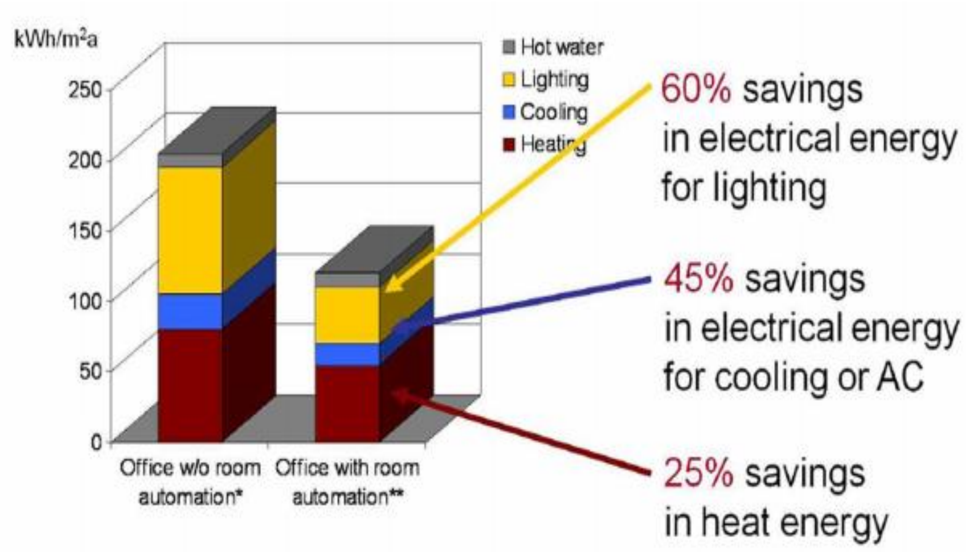

Figure (3.9) Saving energy in Building Management System

CHAPTER FOUR HEAT VENTILATION AIR CONDITION SYSTEM

4.1 Introduction

HVAC (pronounced either ‘H-V-A-C” or “H-VAK”) is an acronym that stands for “heating, ventilation and air-conditioning.” Often installed into a single system, these three functions of the HVAC system are closely interrelated to provide thermal comfort and to maintain good indoor air quality. HVAC is sometimes referred to as climate control because it provides heating, cooling, humidity control, filtration, fresh air, building pressure control, and comfort control [29]. HVAC is one of the largest consumers of energy in the hospitality industry, constituting approximately 30 percent or more of total costs. HVAC systems that operate properly are essential in lodging facilities and contribute to employee productivity and guest satisfaction. Because HVAC systems account for so much electric energy use, almost every facility has the potential to achieve significant savings by improving its control of HVAC operations and improving the efficiency of the system it uses through proper design, installation and scheduled maintenance. The invention of the components of HVAC systems went hand-in-hand with the industrial revolution, and new methods of modernization, higher efficiency, and system control are constantly introduced by; companies and inventors worldwide. The three central functions of heating, ventilating, and air-conditioning are interrelated, especially with the need to provide thermal comfort and acceptable indoor air quality within reasonable installation, operation, and maintenance costs. HVAC systems can provide ventilation, reduce air infiltration, and maintain pressure relationships between spaces Figure 4.1 shows an example of HVAC.

The means of air delivery and removal from spaces is known as room air distribution [5].

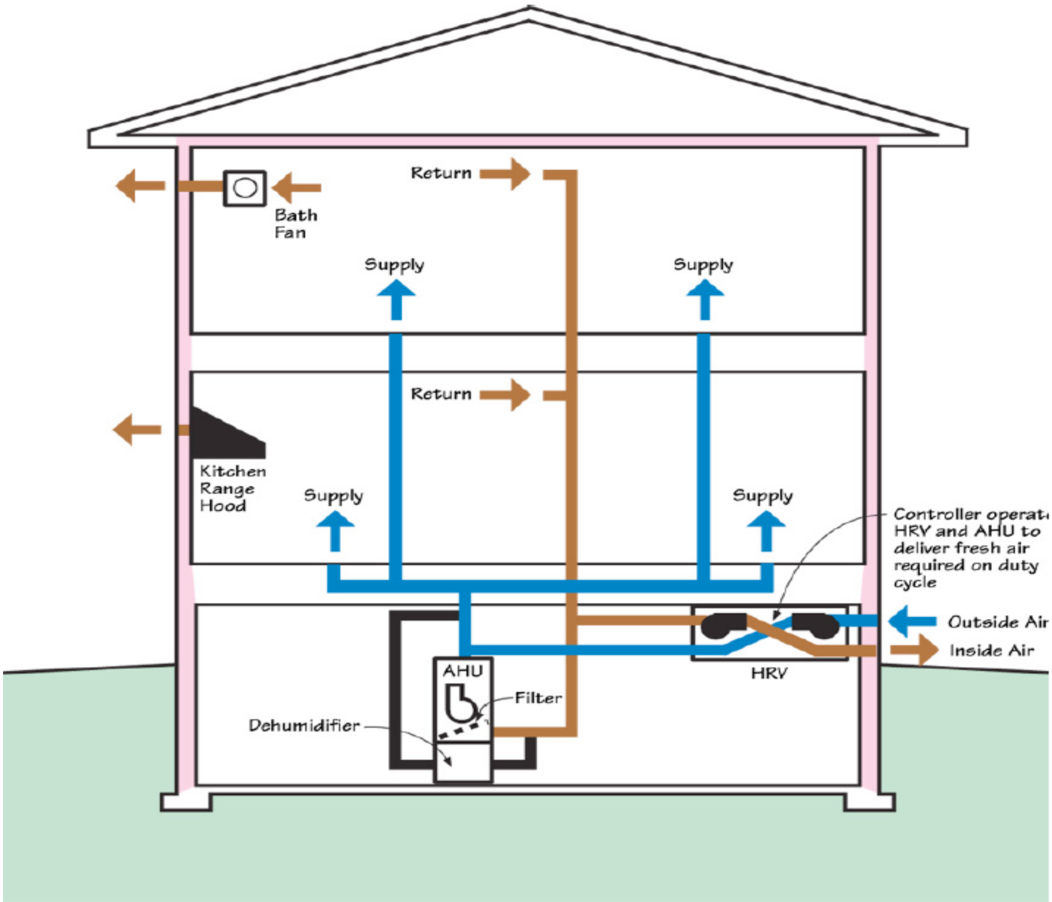

Figure 4.1: A small, single-zone residential heat, cooling, filtration and ventilation system .

4.2 Components of the HVAC:

Heat ventilation air condition is consist of several blocks: the System block, bypass system, Air quality controller, heat exchanger, and controller and Air Handling Unit (AHU)see Figure (4.2).

4.2.1 Furnace:

A furnace unit is typically large, and requires its own space within a building. It is often installed in the basement, in the attic, or in a closet. The furnace pushes the cold or hot air outward into the ducts that run through every room in the building. Throughout the ducts, there are vents that allow the warm or cool air to pass into rooms and change their interior temperature.

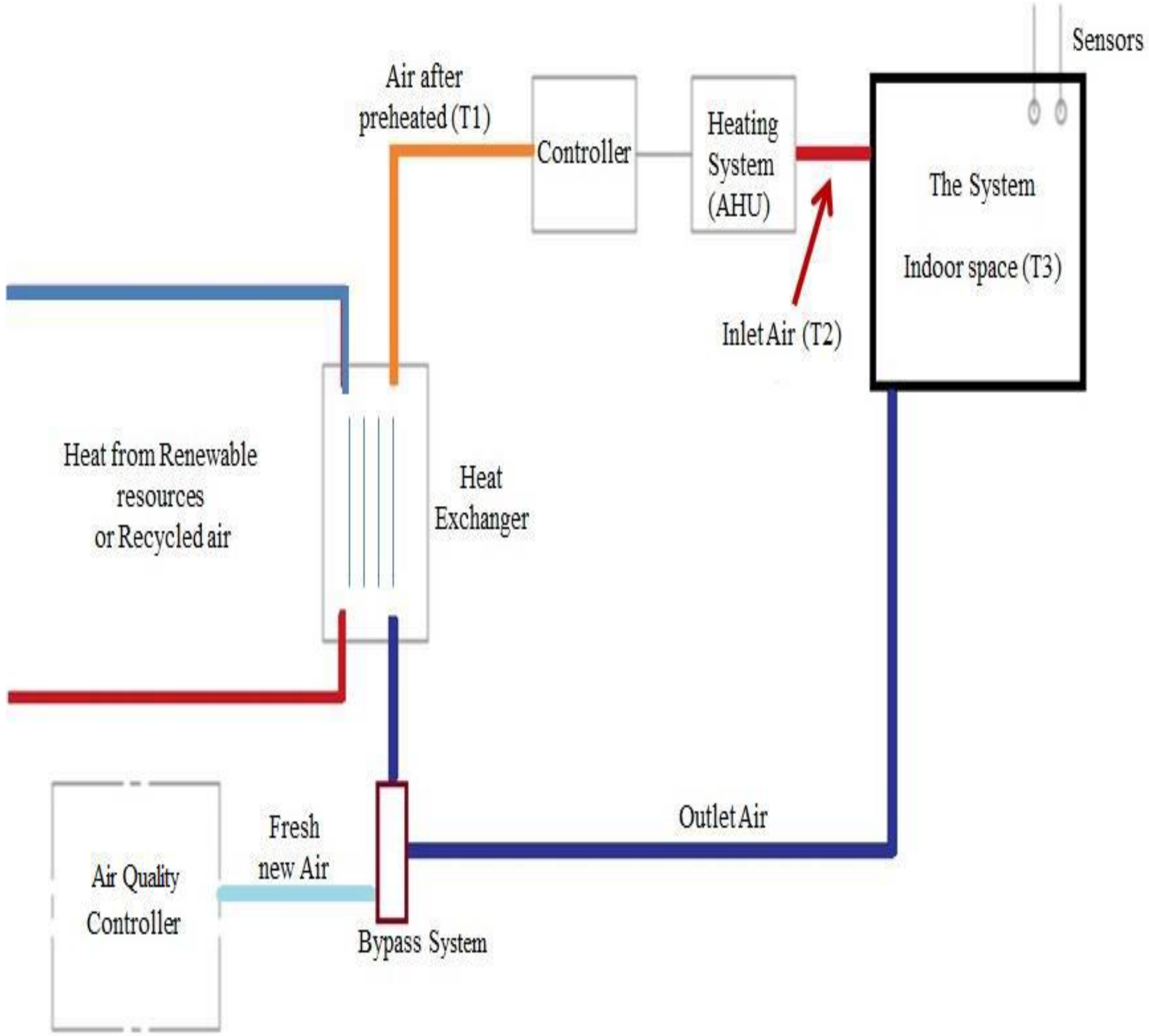

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Figure 4.2 : HVAC system

4.2.2 Heat Exchanger

Heat exchangers reside in the housing of every furnace unit. When the thermostat see Figure (4.3) , activates the furnace, the heat exchanger begins to function as well. Either air is sucked into the heat exchanger, from the outside or from a separate duct, which pulls cool air out of the building's rooms. This type of duct is called a cold air return chase. When the cool air comes into the heat exchanger, it is quickly heated and blown out through the ducts to be dispersed into the building. If the furnace operates on gas, the heating is accomplished by gas burners. If it uses electricity, it is done via electric coils [31].

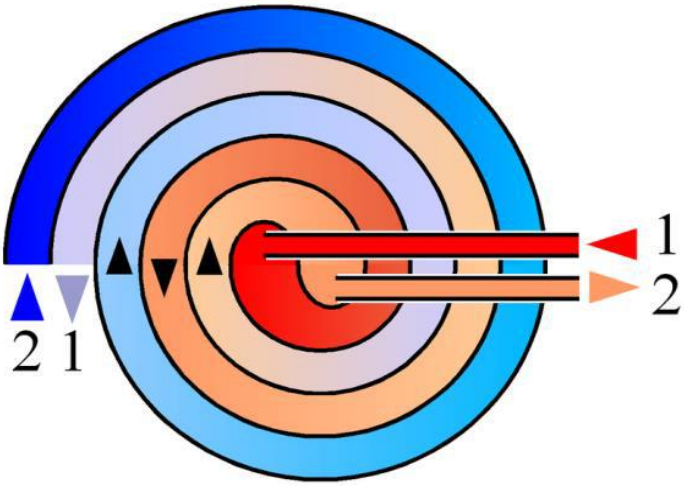

Figure 4.3: A Spiral Heat Exchanger

4.2.3 Evaporator Coil

Like heat exchangers, evaporator coils are also part of the furnace unit. However, they serve the opposite function to that of heat exchangers. They are also attached to a different part of the furnace. Instead of being within the furnace housing, they are installed inside a metal enclosure that is affixed to the side or the top of the furnace. Evaporator coils are activated when cool air is needed. When triggered, the evaporator coil supplies chilled air, is picked up, by the furnace blower and forced along the ducts and out through the vents. The internal design of an evaporator coil resembles that of a car's radiator. Evaporator coils are connected to the HVAC system is condensing unit, which is typically located on the exterior of the building.

Condensing unit is installed outside the building, separate from the furnace. Inside the condensing unit, a special kind of refrigerant gas is cooled through the exchange of heat with the air outside. Then, it is compressed and condensed into liquid form and sent through a tube or a line made of metal. This tube runs straight to the evaporator coil. When the liquid reaches the coil, a series of small nozzles spray the liquid, lowering its pressure and allowing it to resolve back into gaseous form. During the evaporation of liquid to gas, heat is absorbed, causing a sudden drop in temperature and supplying cold air for the furnace blowers. The refrigerant gas is then sent back outside to the condensing unit, and the process is repeated again to generate additional cold air.

4.2.4 Refrigerant Lines

Refrigerant lines are the metal tubes that carry the liquid to the evaporating coil and return the gas to the condensing unit. Refrigerant lines usually are made from aluminum or copper. They are designed to be durable and functional under extreme temperatures.

4.2.5 Thermostat

The thermostat controls the function of the furnace. It is directly connected to the furnace and includes temperature-sensing technology as well as user controls. A thermostat is usually positioned somewhere within the building where it can easily discern temperature and remain accessible to users. A large building may have more than one thermostat to control different areas of the structure. The inhabitants of the building can manually set the thermostat to a certain temperature. If the air in the room or building is too cold, the heat exchanger kicks in and blows heat through the vents. If the room is too warm, the condensing unit and evaporator coil start to function, and the air conditioning system sends cool air throughout the building or to one particular section of the building.

4.2.6 Ducts

Heating ducts are put in during the construction of a home or a building. They are often run through the ceiling. In each room, at least one rectangular opening is cut into the duct so that a vent or vents can be installed.

4.2.7 Vents

Vents are usually rectangular in shape. They are placed in the ceiling see Figure (4.4), with their edges corresponding to the opening in the duct above. As warm or cool air pours through the ducts, vents allow it to disperse into the rooms below. Vents are usually made of metal, which can handle a wide range of temperatures.

. Figure 4.4 : The Vents of HVAC

4.2.8 Air Handling Unit (AHU):

An air handler, or air handling unit often abbreviated to AHU, is a device used to condition and circulate air as part of a heating, ventilating, and air-conditioning (HVAC) system. An air handler is usually a large metal box containing a blower, heating or cooling elements filter racks or chambers, sound attenuators, and dampers. Air handlers usually connect to a ductwork ventilation system that distributes the conditioned air through the building and returns it to the AHU. Sometimes AHUs discharge supply and admit return air directly to and from the space served without ductwork. Small air handlers, for local use, are called terminal units, and may only include an air filter, coil, and blower; these simple terminal units are called blower coils or fan coil units. A larger air handler that conditions 100% outside air is known as a makeup air unit (MAU). An air handler designed for outdoor use, typically on roofs, is known as a packaged unit (PU) or rooftop unit (RTU).Air handlers may need to provide heating, cooling, or both to change the supply air temperature, and humidity level depending on the location and the application. Such conditioning is provided by heat exchanger coils, within the air handling unit air stream; such coils may be direct or indirect in relation to the medium providing the heating or cooling effect. Direct heat exchangers include those for gas-fired fuel-burning heaters or a refrigeration evaporator, placed directly in the air stream. Electric resistance heaters and heat pumps can be used as well. Evaporative cooling is possible in dry climates.

4.2.9 Bypass System:

Automatic by-pass system can be used in HVAC systems to circulate the air and enter a fresh new air, by-pass system must maintain the same ratio of air enters and out the indoor space.

This is to ensure a stable pressure inside the building Figure 4.5 shows example how bypass system work. If the air flow of 100 m3/h enters the indoor space; the same amount of air stream has to leave the indoor space. Fuzzy controller can control automatic bypass system to get smooth transition ratio between fresh and recycled air. In addition, the rest of bad quality hot recycled air will enter heat exchanger

4.3. Example of a HVAC System:

A single-zone HVAC system is shown in Figure 4.6. It consists of the following components: a heat exchanger (air conditioner), a circulating air fan, the thermal space, the chiller providing chilled water to the heat exchanger, connecting ductwork, dampers, and mixing air components. In our discussion, we assume the system is operating on the cooling mode (air conditioning). The basic operation of the system in the cooling mode is as follows

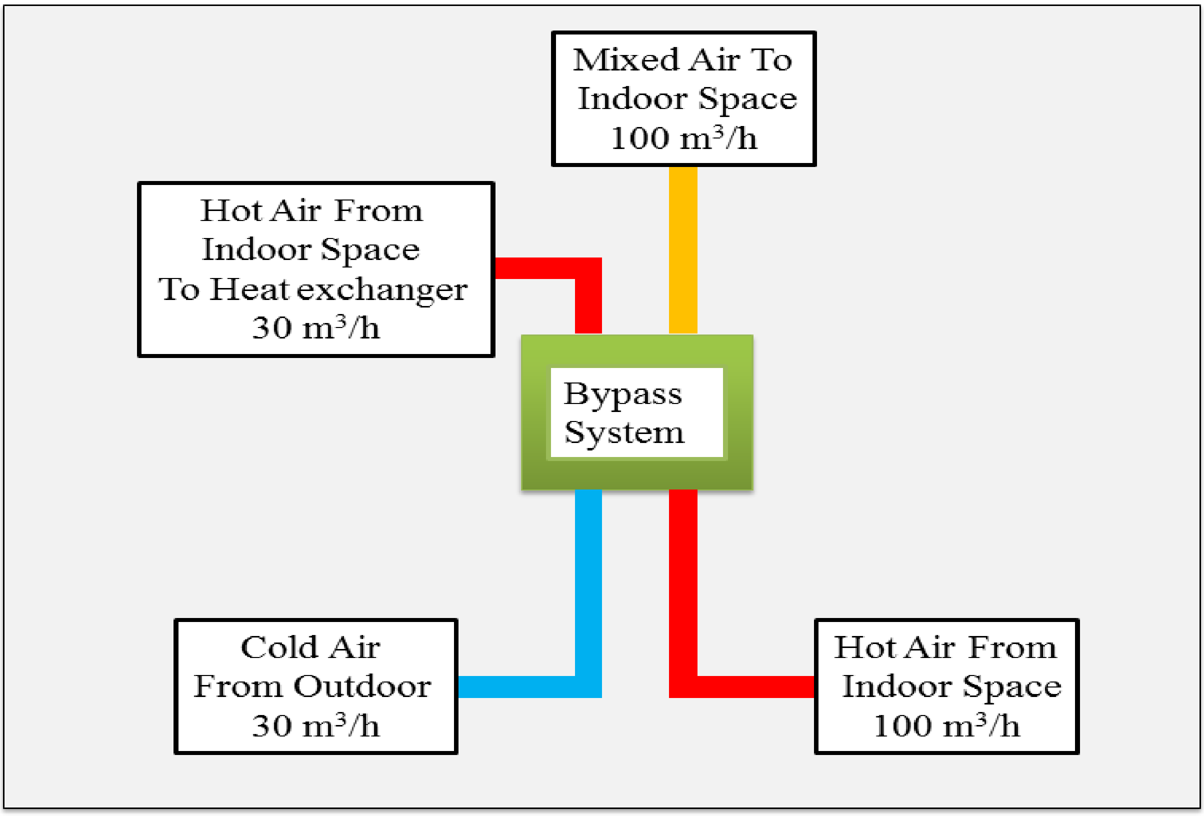

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Figure 4.5: Example of bypass system

• First, 25% of fresh air is allowed into the system and it gets mixed with 75% of the recirculated air (position 5) at the flow mixer.

• Second, air mixed at the flow mixer (position 1) enters the heat exchanger where it gets conditioned.

• Third, the air coming out of the heat exchanger already is conditioned to enter the thermal space, and it is called supply air (position 2).

• Fourth, the supply air enters the thermal space to offset the sensible (actual heat) and latent (humidity) heat thermal loads acting upon the system.

• Finally, the air in the thermal space is drawn through a fan (position 4), 75% of this air is recirculated and the rest is exhausted from the system.

The controller maintains the thermal space temperature and humidity at the set points of 71 F, and 55% RH (relative humidity), respectively

The control inputs for the system are the pumping rate of cold water from the chiller to the heat exchanger and the circulating airflow rate using the variable speed fan. These set of control actions characterize the HVAC system as:

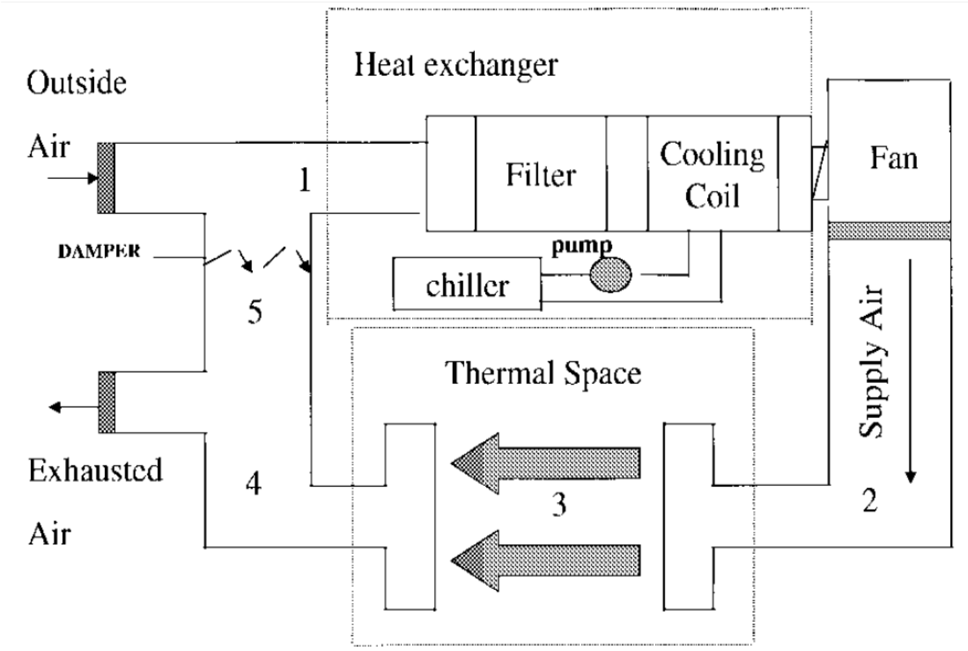


Figure 4.6: Model of the HVAC system.

• A variable-air-volume system (VAV) that results in the lowest energy consumption

• A variable chilled water flow rate system that allows a reduction of pump energy at light loads.

4.4 HVAC Controls:

The capacity of the HVAC system is typically designed for the extreme conditions. Most operation is part load/off design as variables such as solar loads, occupancy, ambient temperatures, equipment and lighting loads.. etc. keep on changing throughout the day. Deviation from design shall result in drastic swings or imbalance since design capacity is greater than the actual load in most operating scenarios. Without control system, the system will become unstable and HVAC would overheat or overcool spaces.

4.4.1 The controlled Parameters

A proper environment is described with four variables

- Temperature

While everybody can judge no single environment satisfactory, it varies between people, regions and countries. Uniformity of temperature is important to comfort. The temperatures should not vary within single zone or change suddenly or drastically.

- Humidity

Humidity is the presence of water vapor in air and it affects human comfort. Usually air is humidified to between 25 -45% during winter and dehumidified to below 60% during summer. Any figure outside this range shall produce discomfort and indoor air quality (IAQ) problems.

- Ventilation

"Ventilation for Acceptable Indoor Air Quality" recommends minimum ventilation rates per person in the occupied spaces. In many situations, local building codes stipulate the amount of ventilation required for commercial buildings and work environments. The recommended value of outside air is typically 20 cubic feet per minute (CFM) for each occupant. The ventilation rates specified effectively dilutes the carbon dioxide and other contaminants created by respiration and other activities; it supplies adequate oxygen to the occupants; and it removes contaminants from the space. The ventilation rates greater than recommended are sometime required controlling and where cooling is not provided to offset heat gains.

- Pressure

Air moves from areas of higher pressure to areas of lower pressure through any available openings. A small crack or hole can admit significant amounts of air, if the pressure difference are high enough (which may be very difficult to assess). The rooms and buildings typically have a slightly positive pressure to reduce outside air infiltration. This helps in keeping the building clean.

4.5 An overview of conventional control systems in buildings:

Surveys have shown that conventional control systems in buildings have been carried out using the following methods or combinations of them:
classical controllers see Figure (4.7), Digital controllers and Fuzzy controllers. Regarding the increase in the nonlinearity and uncertainty in recent building structures, mathematical description of the system has become more difficult or impossible by Classical control is involved with mathematical models of the system that govern the relationships between system inputs and outputs. Processing of inputs and feedbacks from the previous state is used by control algorithm to optimize the control of the system in the next time step.
Due to measurement inaccuracies or incomplete observation of the process state, the control of complex processes is tremendously cumbersome. In other words, classical control and mathematical models are vulnerable to inaccurate and noisy inputs or feedbacks, making them disadvantageous. Digital computer is used for real-time control of system; in contrast with classical control systems figure (4.8), digital control utilizes the digital or discrete technology instead of analog components.

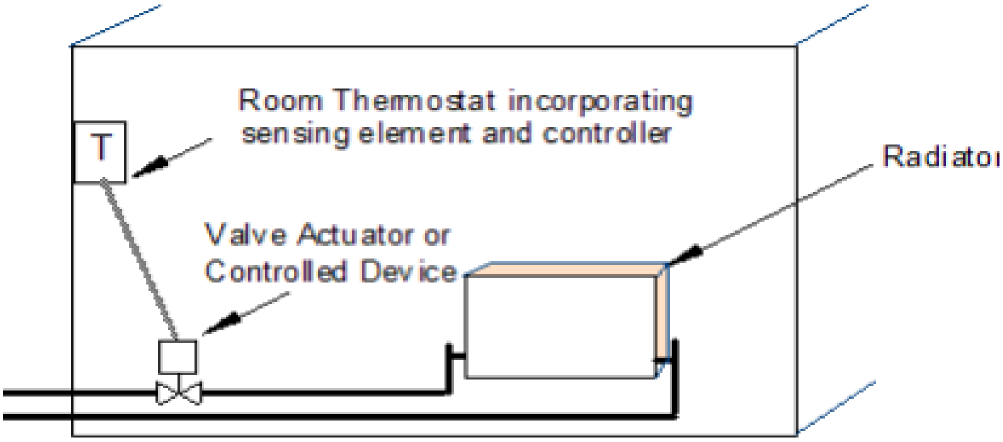


Figure (4.7) Room Temperature Control

The major reason why analog technology simply is replaced by digital technology was cost. The numbers of control loops increase the cost of analog system, linearly. Despite the large initial cost of digital system, the cost of additional loop is small.

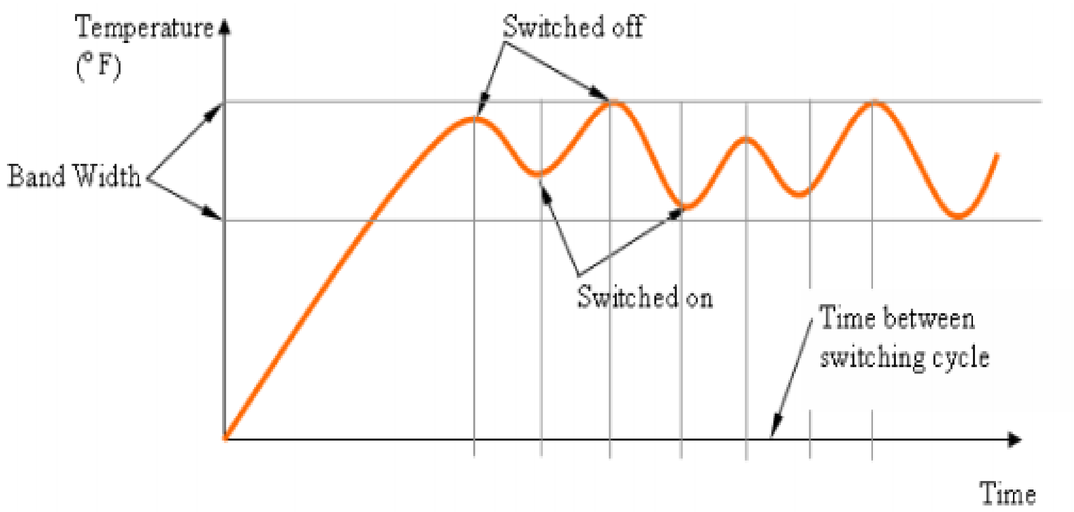


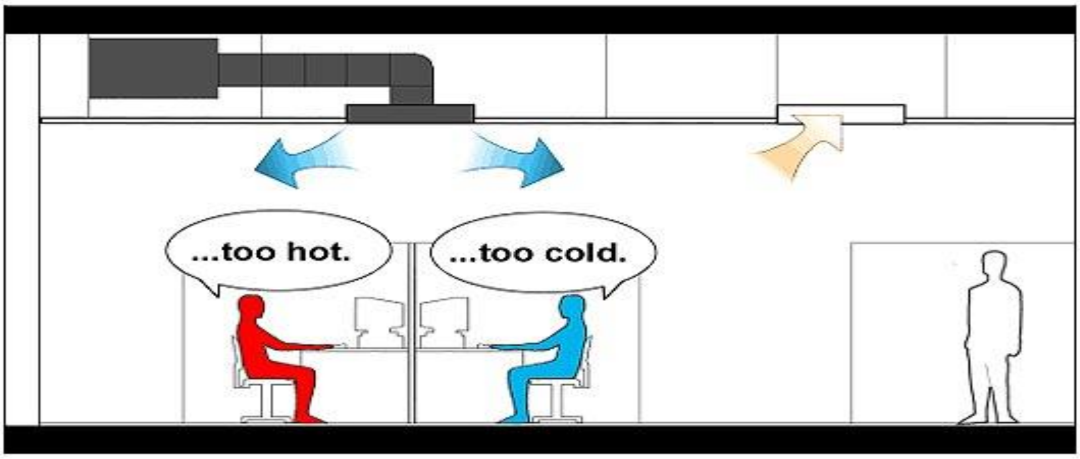
Figure (4.8) open loop control

4.6 Benefits of a Control System

Controls are required for one or more of the following reasons:

- Maintain thermal comfort conditions figure (4.9).
- Maintain optimum indoor air quality

- Reduce energy use
- Safe plant operation
- To reduce manpower costs
- Identify maintenance problems
- Efficient plant operation to match the load
- Monitoring system performance



- Figure 4.9 : Maintain thermal comfort

There has been extensive research in the realm of control systems for HVAC systems since the oil crisis of the 1970s. The research works that have been done are all based on a linearized mathematical model of the HVAC plant and the controllers are designed using linear quadratic regulator theory. The research work presented here exploits the inherently nonlinear nature of the HVAC process to design a feedback controller that will have a better performance over a wider range of loading conditions. Our objective is to design an HVAC control using fuzzy controller (Sugeno method) aiming to maintain comfort conditions within a thermal space, without energy waste. The importance of the problem at hand lies on the impact that energy efficient HVAC systems can have on industrial and commercial energy consumption.

CHAPTER FIVE DESIGNED SUGENO FUZZY LOGIC CONTROLLER FOR HVAC SYSTEM

5.1 Introduction

The air-handling plant of large building can be designed to cope with wide range of operating conditions. Because weather and occupants‟ activities change significantly and periodically from day to night and from season to season; the air-conditioning process is highly nonlinear and the interaction between temperature control and air quality control loops is significant .Thus to control such system we need robust controller. Classical control design methods that based on a single nominal model of the system may fail to create a control system that provides satisfactory performance . Intelligent controller structure must be used with time variant nonlinear system and varying parameters. Therefore, we use a novel control method that is adaptive hierarchical fuzzy control for HVAC system using Sugeno method. This new method works well without knowing the model of the system or its parameters, in this thesis we will depend on random feedback from a virtual system and the controller will adapt to these random feedback to give the desired results that is needed in the building, the control system is flexible to changes that controller want. One important task of a central heating system is accurately maintaining the desired room temperature to maintain a good comfort level and lower energy consumption. Therefore, the heating power has to be adequately adapted. Manual heating control is complex and imprecise, so modern control systems adjust the heating power automatically especially in large open zone buildings. Heating is the most power consumption in a building. Therefore, we will work to get best control compared with previous studies in this field in order to reach stability .So we can reduce energy consumption. In this chapter, we will explain the overall system and the proposed controller results will be shown. We implement the vertical system with Matlab as a simulation program. The overall HVAC system is shown in Figure 5.1, It consists of several blocks: the System block, bypass system, Air quality controller, heat exchanger, controller and air handling unit (AHU),for more details of these components, refer to chapter 4.

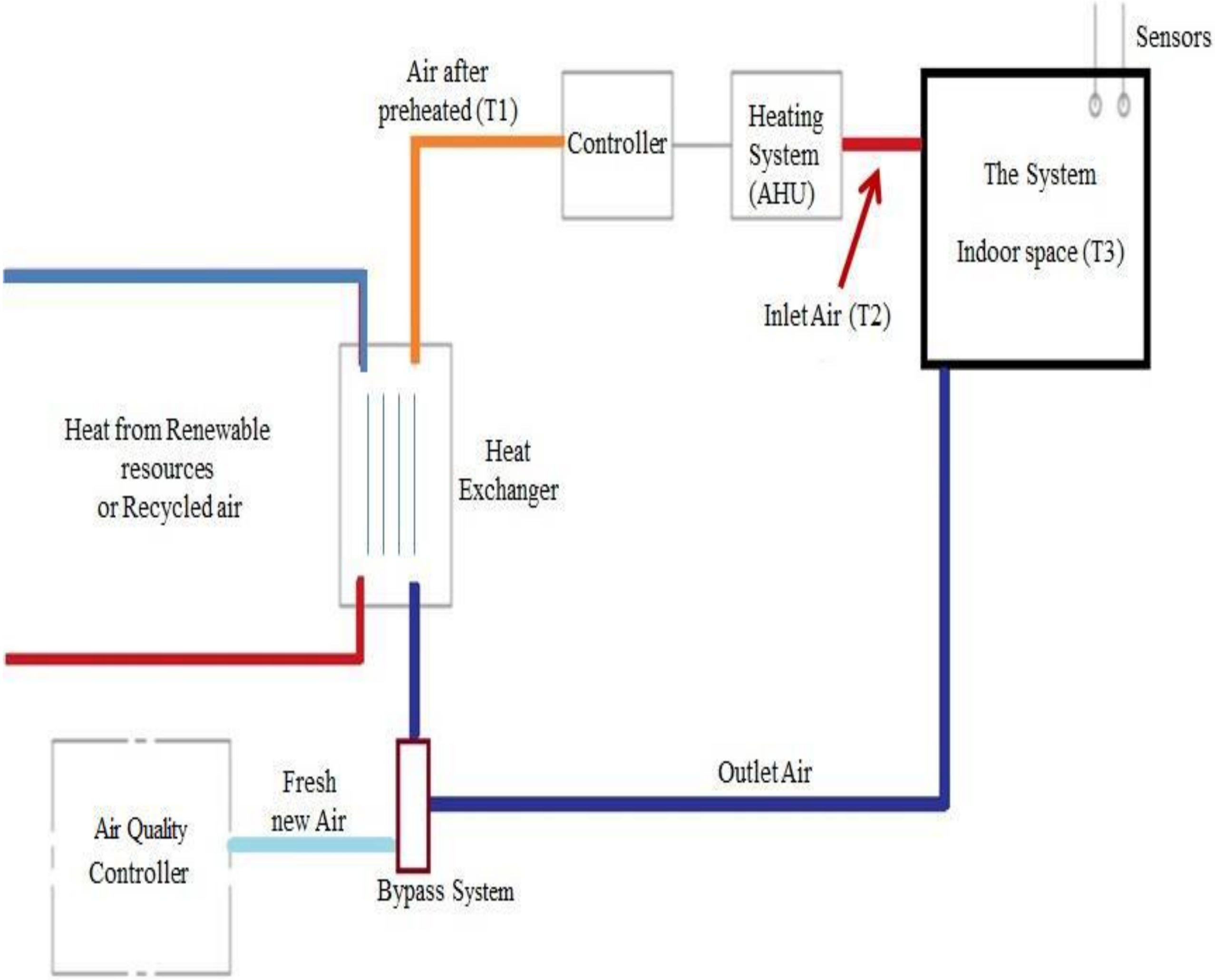


Figure 5.1: HVAC system

5.2 HVAC System

The System consists of:

- System: Air temperature inside the room or hall.

- Fuzzy Level1: Control the error of varying parameters to adjust main controller.
- Fuzzy Level2: The main temperature controller.
- Disturbances: As opening windows or doors and CO_2 concentration.
- Temperature T0: The reference Air Temperature.
- Temperature T1: Air Temperature after disturbances.
- Temperature T2: Air Temperature after being heated from heating system (AHU).
- Temperature T3: Air Temperature inside the room.
- Desired performance: Is rules of fuzzy controllers from system experts see Figure 5.2.

5.3. A hierarchical fuzzy controller:

In order to design a fuzzy system with a good amount of accuracy, an increase in the number of input variables to the fuzzy system results in an exponential increase in the number of rules required. Therefore, we use hierarchical fuzzy logic control. In addition, our system is time variant nonlinear system so we prefer use hierarchical fuzzy controller in this thesis. In large buildings as malls and hypermarkets and large centers it is extremely hard to get mathematical model to the system, there for we have to adapt the varying parameters and the essential varying parameters ara:

- Occupants Crowded and the amount of heat needed.
- Air quality degradation and need of fresh air.
- Doors and windows opening make disturbance of the system.

Therefore, it is hard to expect these varying parameters offline or online. Applying the principle fuzzy control, the proposed controll system structure is shown in Figure (5.2).

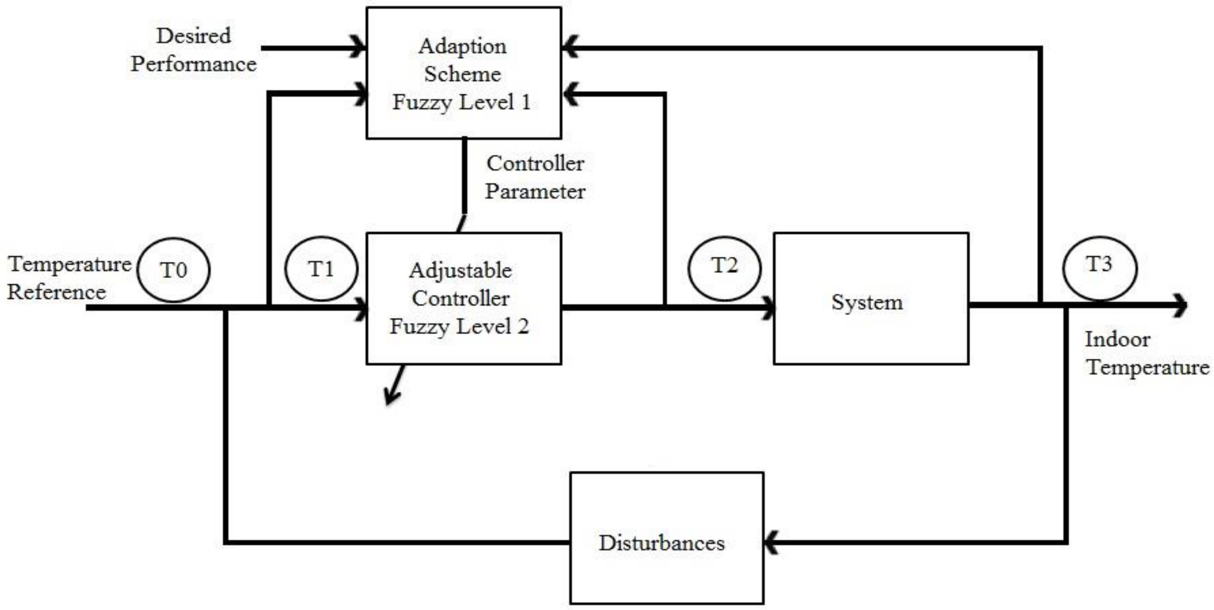


Figure 5.2: Fuzzy Controller Scheme

5.4 Simulation on Matlab/Simulink

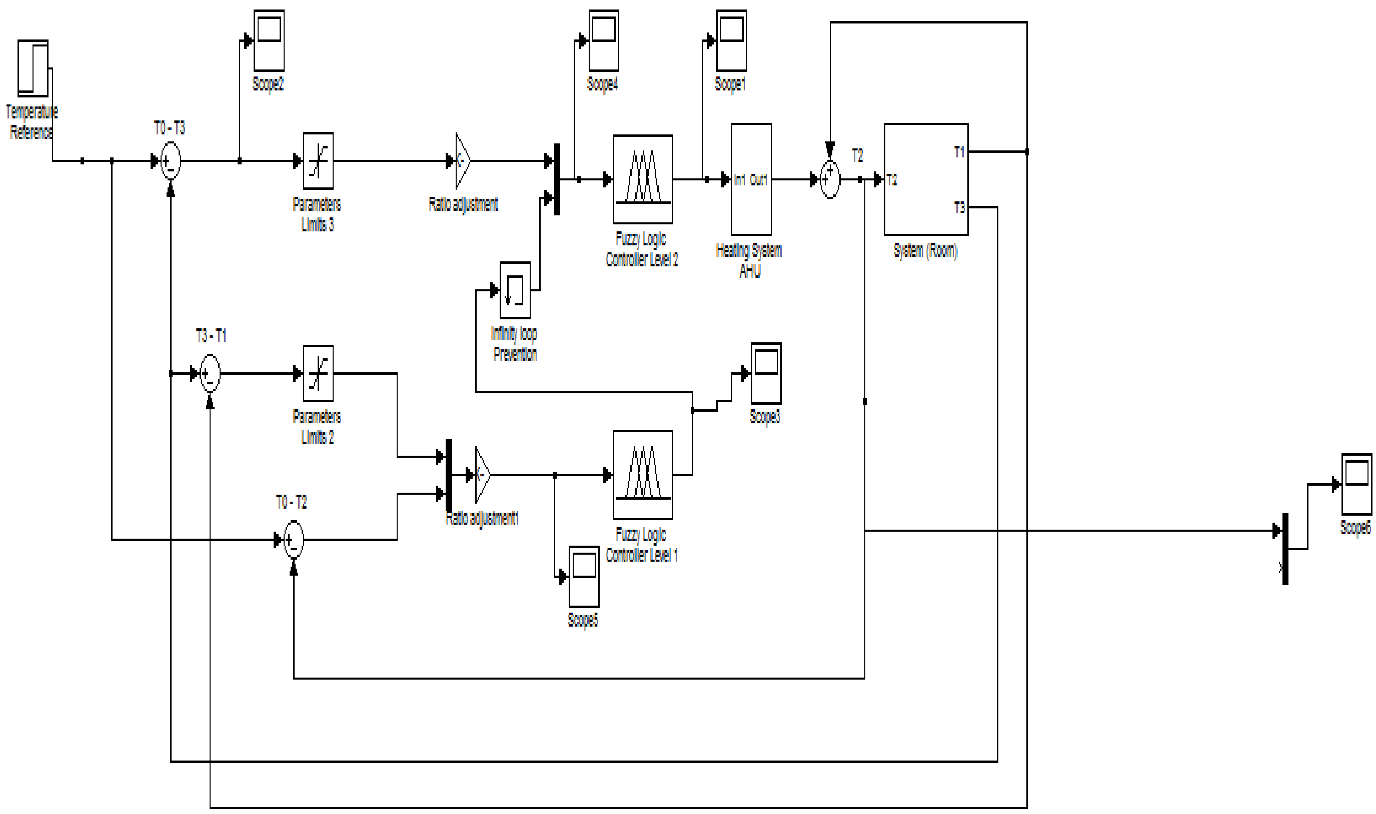


Figure 5.3: HVAC Controller Simulink block diagram

5.4.1 Indoor system block

System block are consists of several block the general structure inputs outputs is shown in Figure 5.4; one input is (T2) air temperature that enters the system and two outputs (T1) and (T3) air temperature after disturbances and room air temperature and these outputs from the system are the time varying parameters.

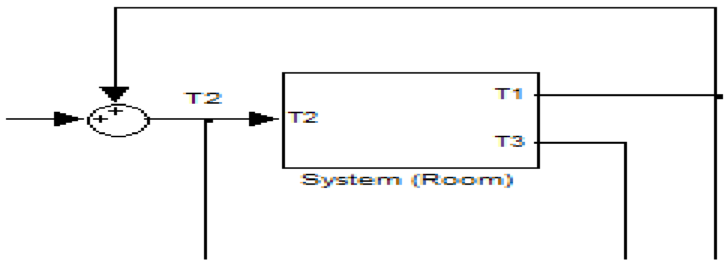


Figure 5.4: Indoor space block

Since T1 and T2 are varying parameters so we can suppose random values for these parameters but real logic values, we build it after experience of system nature we deal with. Figure 5.5 shows the structure of system block.

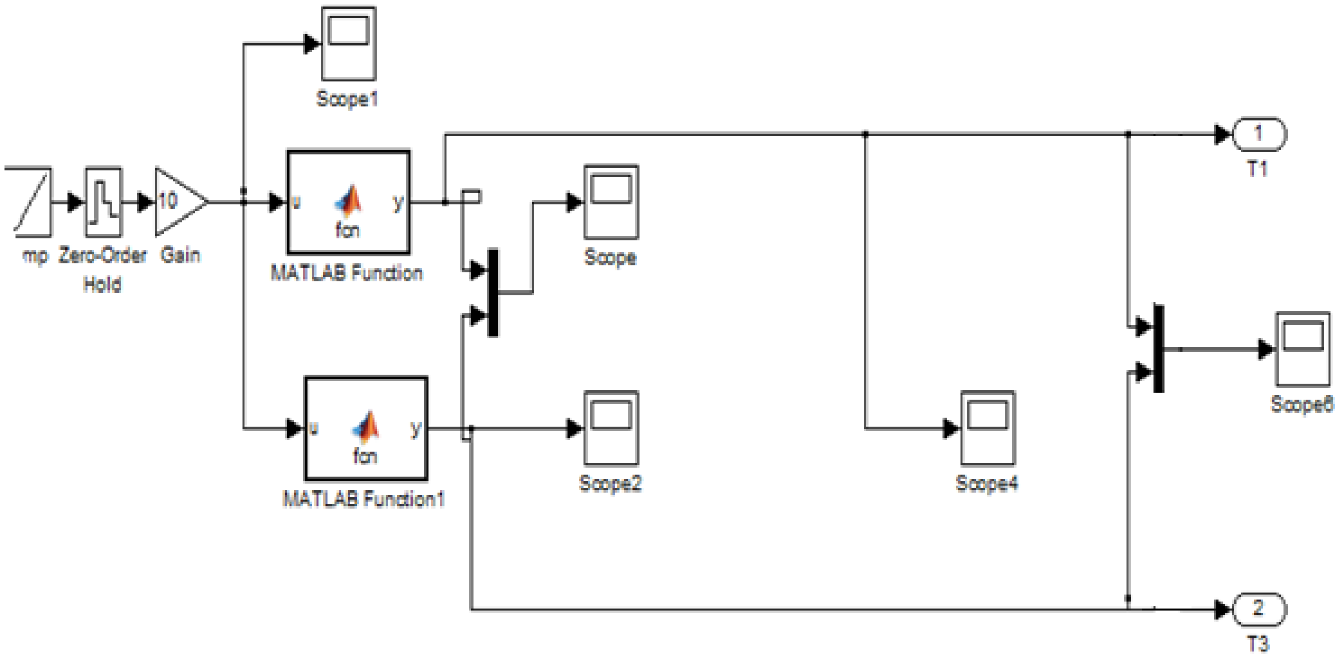


Figure 5.5: Indoor space system structure

In system block, we use a Matlab function that depends on C language to write the function that contains the action, which can be happened during system running. Matlab function depends on time; time block is used to get a time varying system then we use Zero-order hold to discretizes time from continuous to discrete and we applied this step cause Matlab can't calculate large fuzzy operations continuously with complicated close loop. Result of this system block is shown in Figure 5.6.

We suppose that the initial air temperature value will be -20 C ° for both T1 and T3 and same temperature until it reach 20 C° and this because in beginning of the day we predict that no new air is needed then a variation in temperature between T1 and T3 is happened due to disturbances we previously talked about.

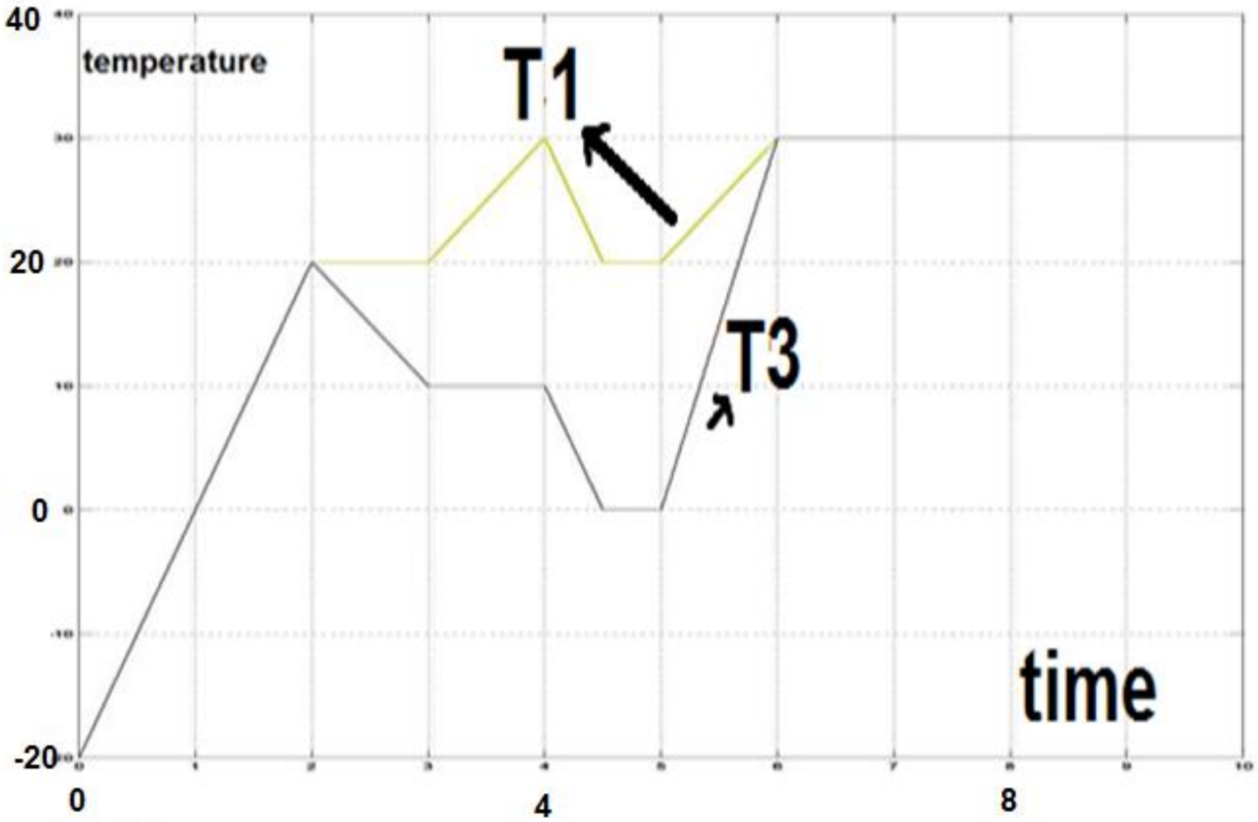


Figure 5.6: Air temperature T1 and T3

Controllers performance in the period between -20 C° and 30 C° or until system stability we be supervised and studied to know if the controller give the desired performance or not.

5.4.2 Heating System

Heating system (AHU) is a device changes the air temperature from low degrees to higher degrees; and the controller gives the orders for this system to which degree the air must be heated. There are many sizes and capacities of heating systems. In this research, it is assumed that Heating System is ideal with gain of 30 degrees immediately and this assumption is from experts. Heating system block is shown in Figure (5.7).

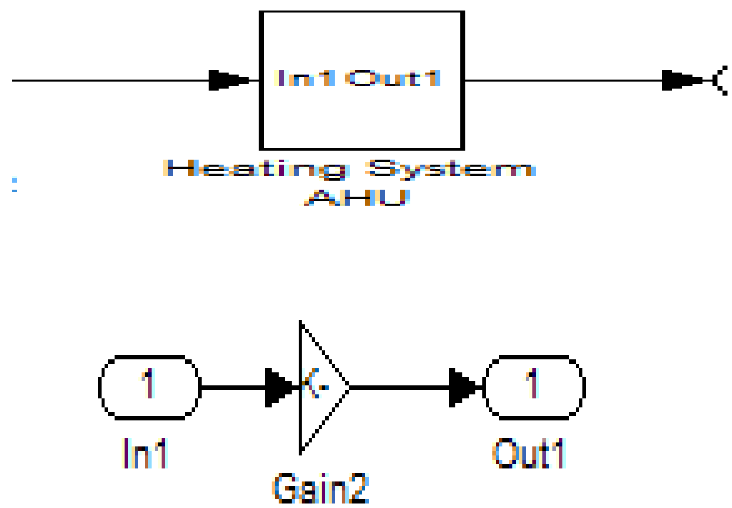


Figure 5.7: Heating System block

5.4.3 Fuzzy logic controller

In this thesis, Sugeno approach has been used to implement FLC for the HVAC system, FLC contains three basic parts: Fuzzification, Base rule, and Defuzzification.

1- Fuzzification

The fuzzy controller of the system uses Sugeno model has two inputs which are error and change of error which is to take the crisp inputs for example (T0 – T2) and (T3 – T1), (T0 – T2) is the difference between the reference Air temperature and Air temperature heating system and (T3 – T1) is the difference between Air temperature inside the room and the Air temperature after bypass system. Figure (5.8, 5.9 and 5.10) shows the membership functions of fuzzy controller using Fuzzy Toolbox of Matlab software. All have five membership functions.

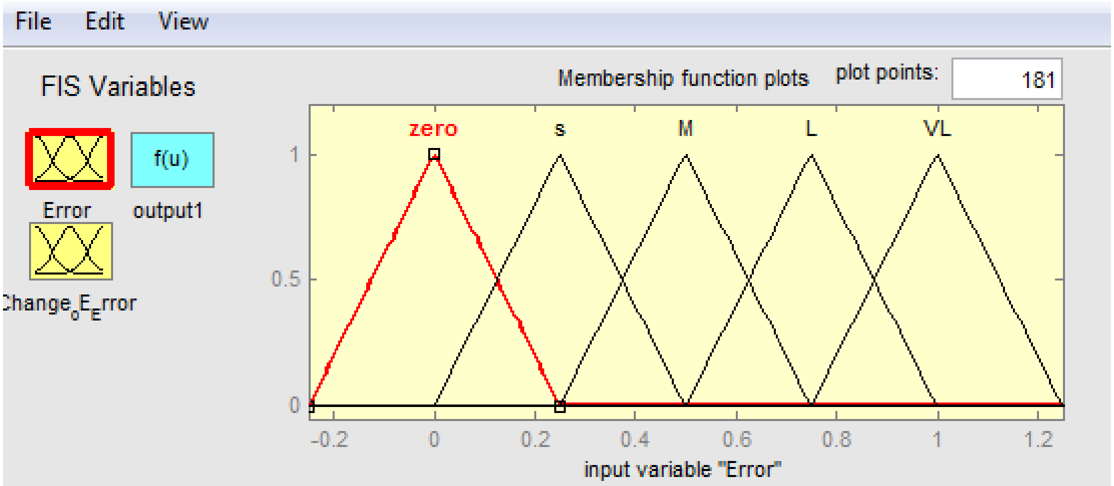


Figure 5.8: Membership Function of Input Error e

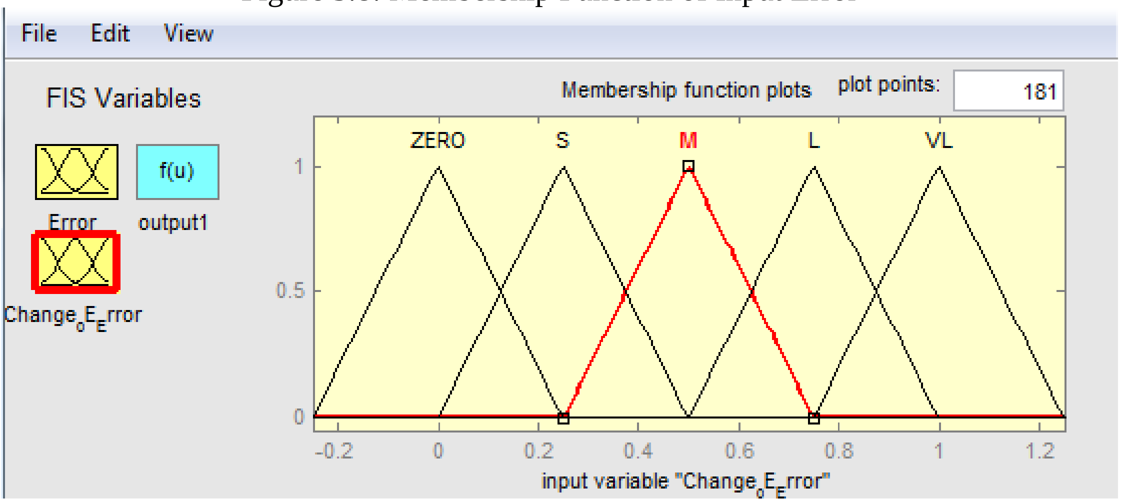


Figure 5.9: Membership Function of Input Change of Error Δe

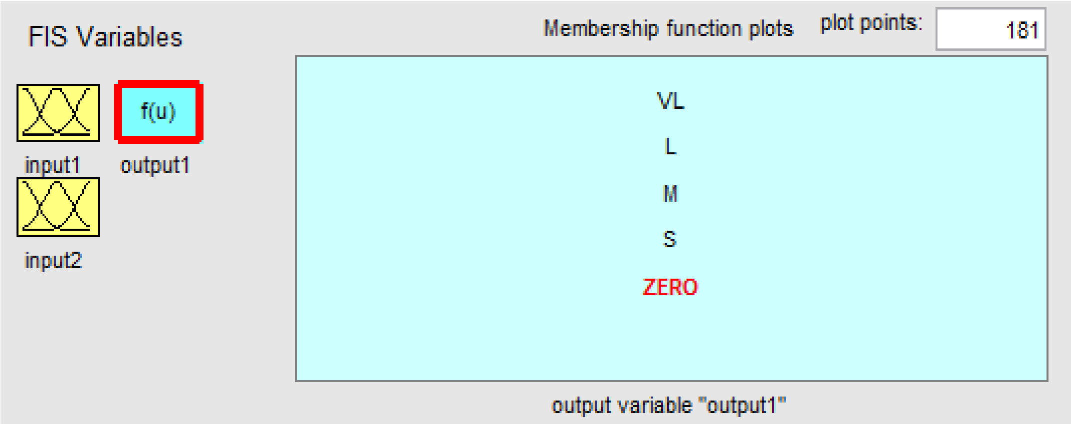


Figure 5.10: Membership Function of Output

A typical rule in a Sugeno fuzzy model has the form

- If Input 1= x and Input 2 = y, then Output is $z = ax + by + c$

That is mean If (error) =Zero and (Change in error) =L then output=L as shown below.

Output Rule Base

Zero =[-0.5 0.3 0]

S= [0.2 -0.5 0.22]

M= [0 -0.001 0.5]

L= [-0.003 -0.001 0.75]

VL= [-0.004 0.02 1]

If (Error is ZERO) and (Ch-Error is ZERO) then (output is zero).

As shown in appendix B.

We will show some examples of the output rule which represented as:

Zero =[-0.5 0.3 0]

This equation means:

Zero = $-0.5*x+0.3*y +c = -0.5*zero +0.3*zero +0$

2 Base Rule

The knowledge base defining the rules for the desired relationship between the input and output variables in terms of the membership functions illustrated in Table (5.1). The control rules are evaluated by an inference mechanism.

TABLE 5.1: THE LINGUISTIC VARIABLES

zero	Zero
S	Small
M	Medium
L	Large
VL	Very Large

Fuzzy associative memories (FAM) table for a two-input (Error and Change in Error), single-output fuzzy rule-based system for fuzzy controller is shown in Table (5.2):

TABLE 5.2: FUZZY CONTROL RULE BASE

Er	***Ch-Er***	***Zero***	***Small***	***medium***	***Large***	***Very large***
Zero		Z	S	M	L	VL
Small		S	M	L	VL	VL
Medium		M	L	VL	VL	VL
Large		L	VL	VL	VL	VL
Very large		VL	VL	VL	VL	VL

I have 25 rules in every controller (5^2) as shown in Appendix B, but in this paragraph, we will show some examples of these rules which represented as a set of:

IF Error is ... and Change of Error is ... THEN the output will …. As shown in In Figure 5.11

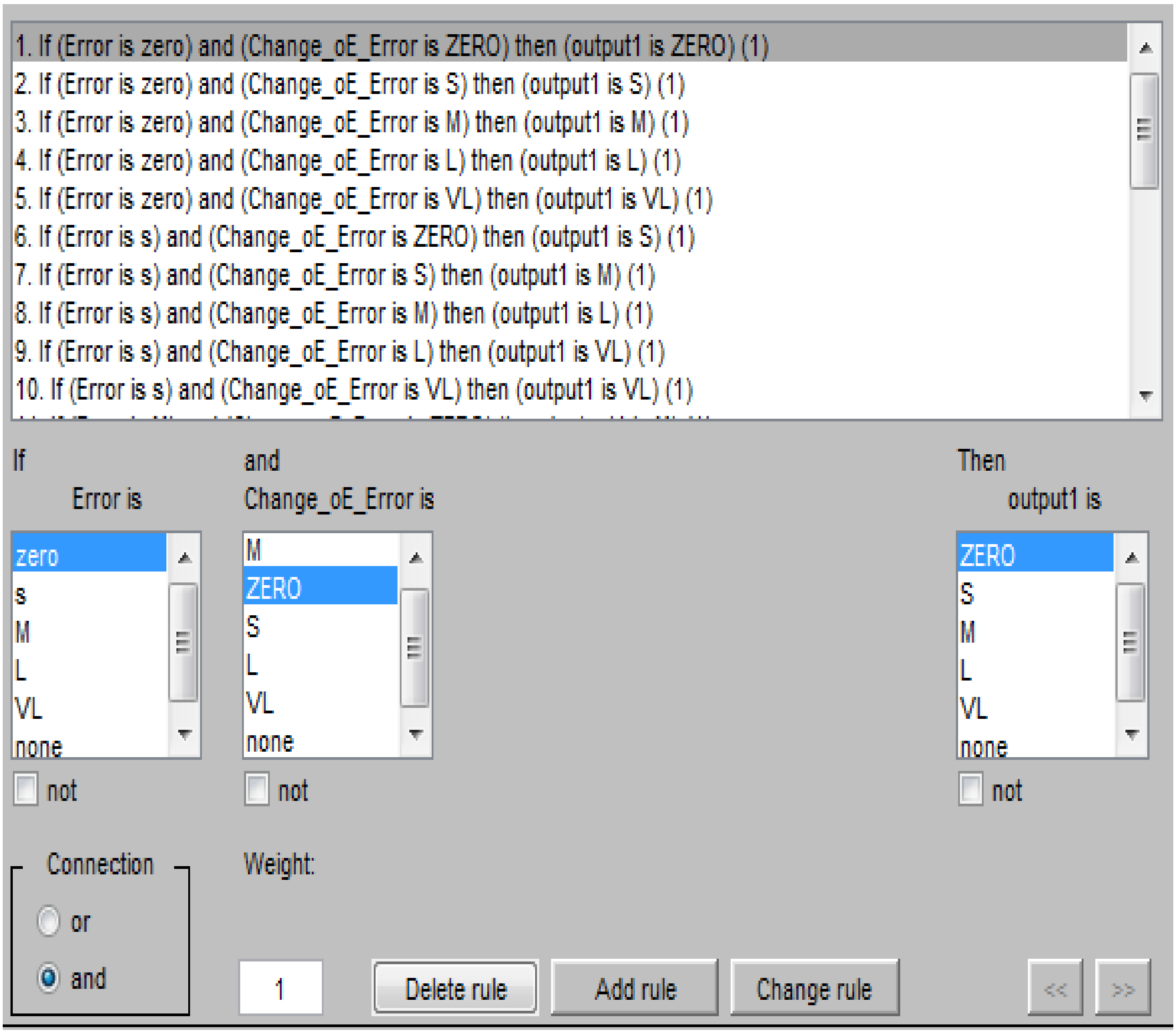


Figure 5.11: General Rule Base

1. If (Error is ZERO) and (Ch-Error is ZERO) then (output is zero).
2. If (Error is medium) and (Ch-Error is zero) then (output is medium).

3. If (Error is large) and (Ch-Error is very large) then (output is very large).

Figure (5.11) shown the surface of the base rules using FLC.

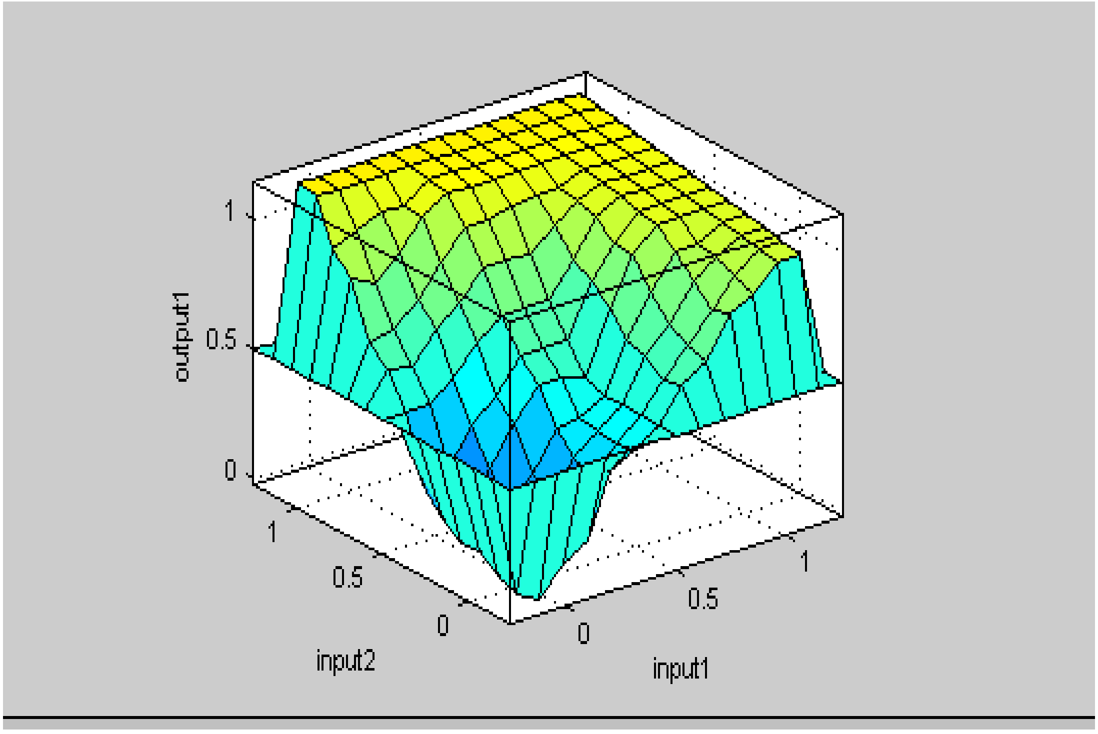


Figure 5.12:The Surface of Fuzzy Controller

3 Defuzzification

Defuzzification method is the final stage of the fuzzy logic control. After the inference mechanism is finished, the defuzzification method converts the resulting fuzzy set into crisp values that can be sent to the plant as a control signal.

Suppose the rules are of the form

If x is Xi then y= f (x) .

Combining results of all the rules leads to a weighted average

$$y = \frac{\sum_{i=1}^{m} \mu_{X_i}(x) f_i(x)}{\sum_{i=1}^{m} \mu_{X_i}(x)} \quad \text{eq. (5.1)}$$

Where m = number of rules.

5.5 Controller Design:

As we said before the system is time. Varying and we need an intelligent control as fuzzy control approach. The control method is depending on two control level; In first level fuzzy the inputs are the change of error .In second level Fuzzy inputs are the error and the result of fuzzy control level 1(Change of Error). Error is the difference between reference air temperatures (T_0) and the air temperature inside the room (T_3) - as any traditional close loop control - and fuzzy control level 1(Change of Error) correct control operation of fuzzy level 2 because of these reasons:

1- If a new fresh air enters the system there is no feedback for this change and based on that no change in the error T_0 . T_3.

2- The nature of heat spread is slow so we cannot know what is air temperature just after heating system .If we don't. take it in to consideration it never mind that heating system works as On / Off method (Open loop control for heating system)

Therefore, these problems make fuzzy control level 1 is very important to correct this control loop. Fuzzy control the first level of is adapted to the varying parameters if they come from disturbances or unexpected system performance.

5.6 Results:

1- Results of Mamdani method with a desired reference temperature of 30 C is shown in Figure 5.13.

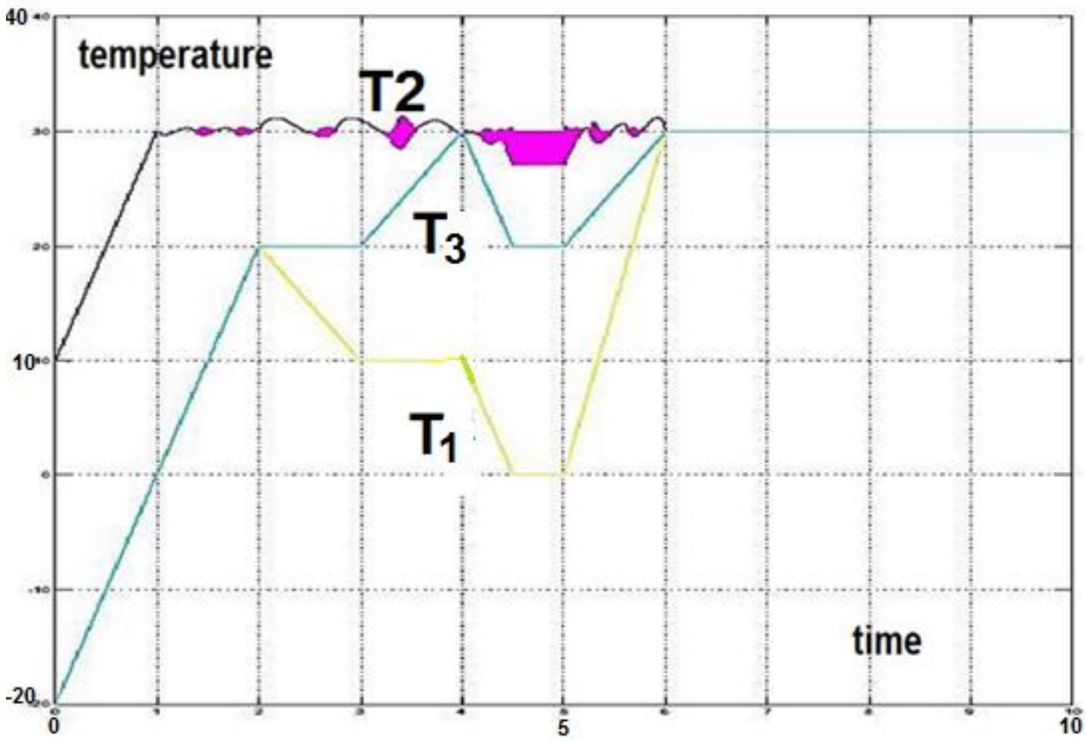


Figure 5.13: Mamdani Method result: Pink Line is T2, Yellow Line is T1 and Blue Line is T3

2- Results of Sugeno method with a desired reference temperature of 30 C is shown in Figure 5.14.

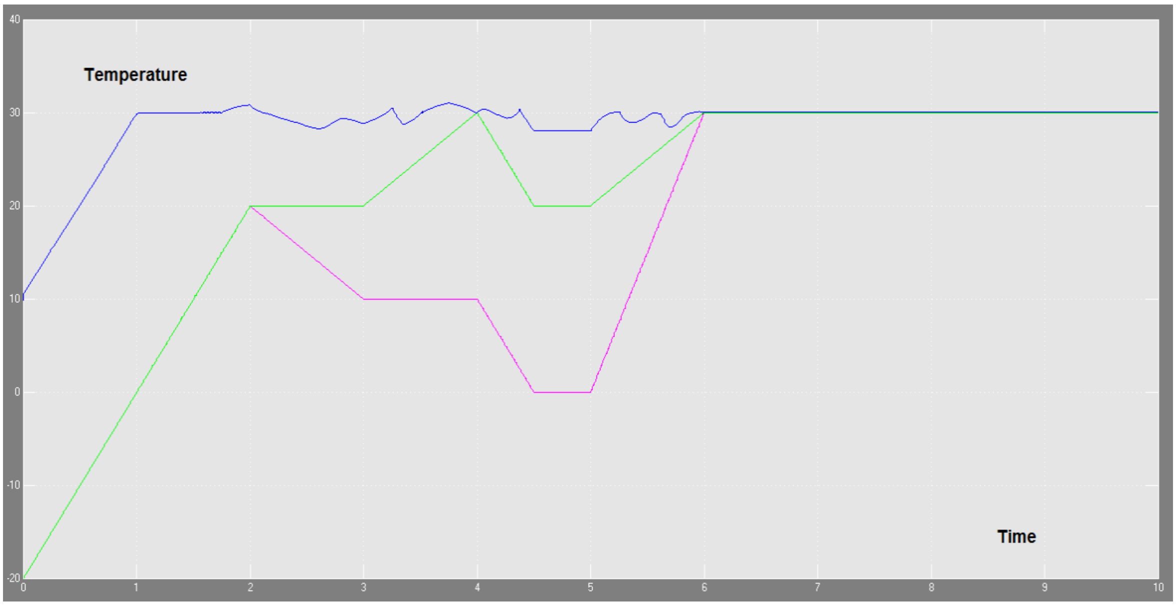


Figure 5.14: Sugeno Method result: blue Line is T2, Red Line is T1 and Green Line is T3

5.7 Comparison between Sugeno and Mamdani FLC

The results of applying the Sugeno FLC to control the HVAC system compared with a Mamdani controller applied on the same system by EL-Alami ,see Figure(5.16).

Figure (5.15) shows the effect of the two controllers:

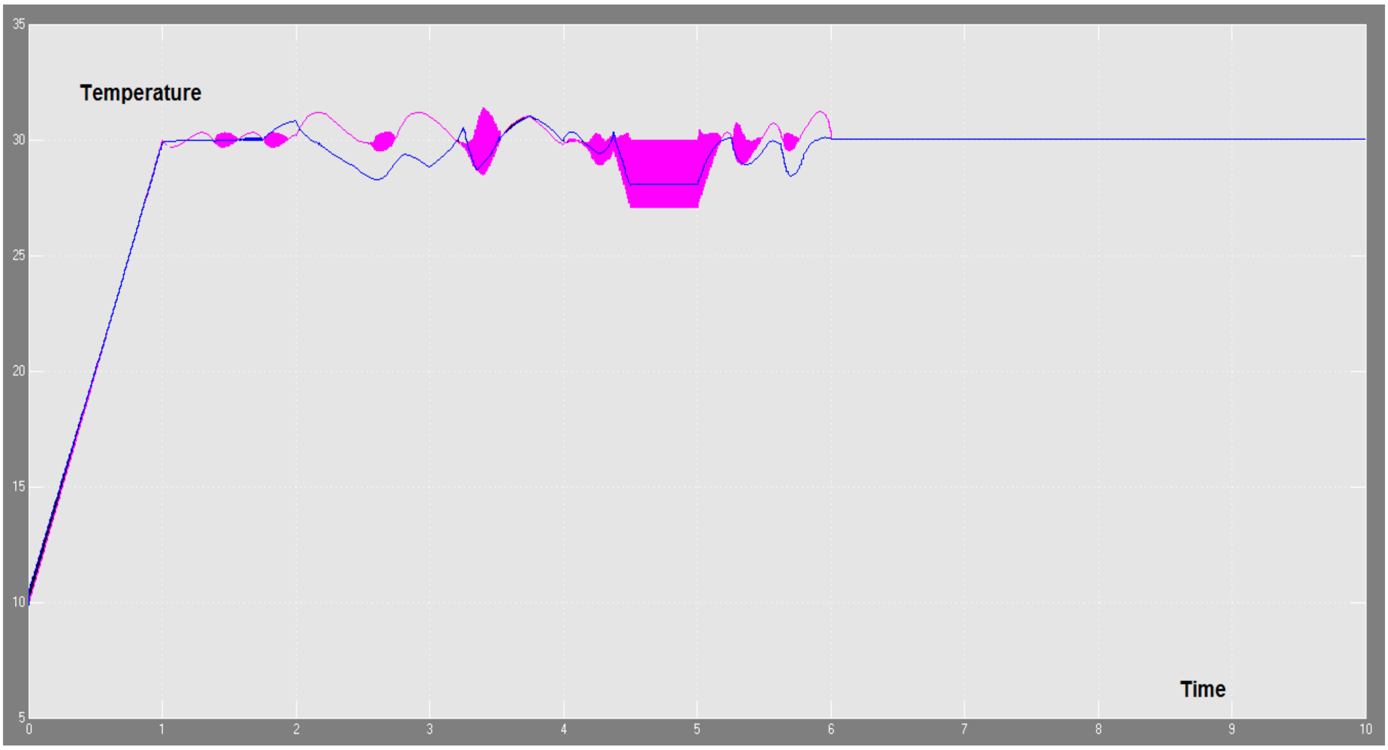


Figure 5.15: Output Degree of Two Controllers: blue line is Sugeno Controller red Line is Mamdani Controller.

By comparing, between the results of Mamdani and Sugeno methods as shown in Table (5.3) and Figure (5.15) we can find that Suegeno method give better response and improved the overshoot and undeshoot of the system at the same settling time.

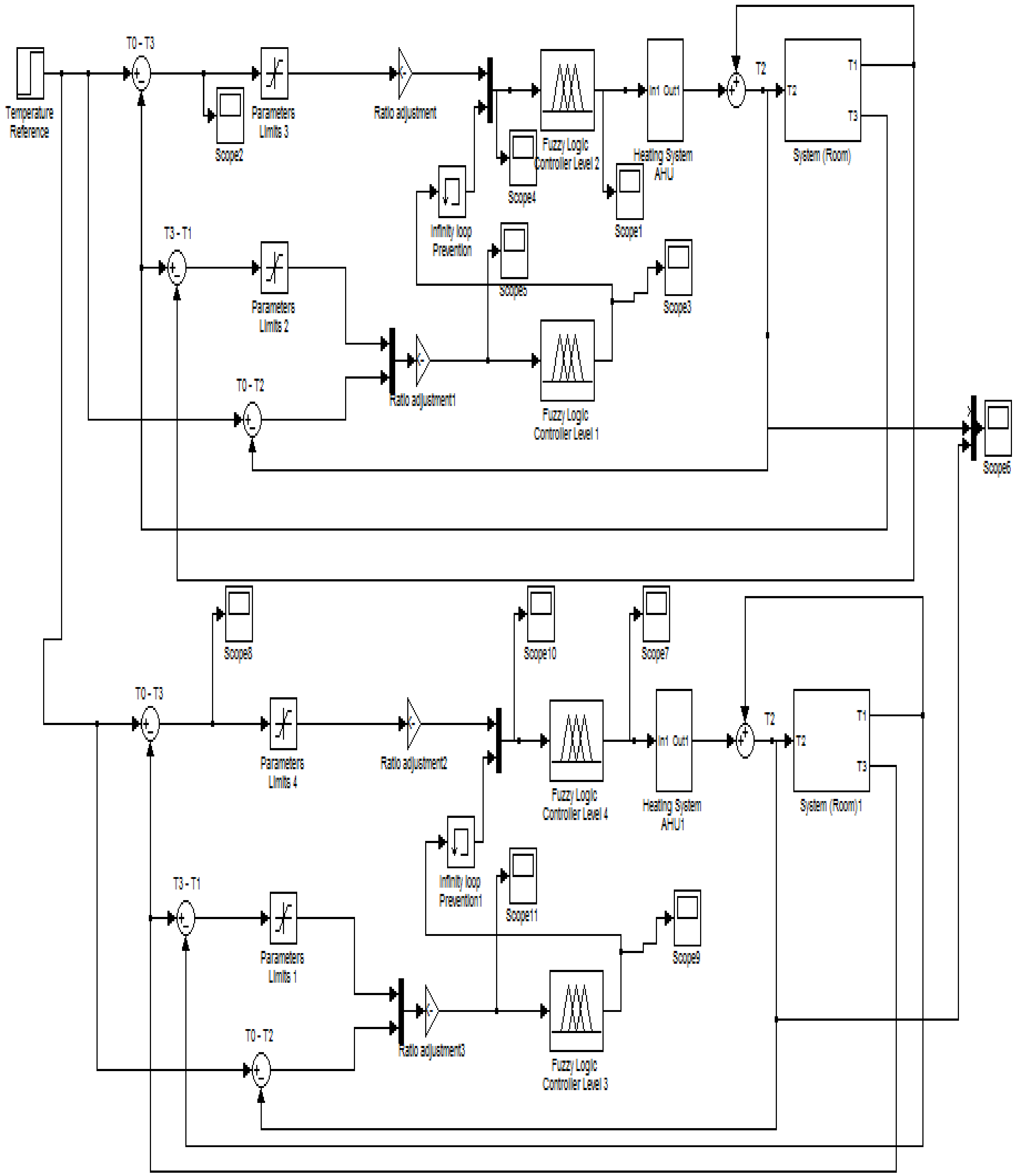


Figure 5.16 :HVAC (Mamdani and Sugeno Controllers) Simulink block diagram

Table (5.3) show the difference between Mamdani result and Sugeno result . We obtain the better response by comparative with Mamdani result ,we get the following

Table 5.3 : The difference between Mamdani result and Sugeno result

	Mamdani	Sugeno
Settling Time	6	5.7
Overshoot	31.4	30.9
undershoot	27	28

- The settling time is improved see Figure 5.17

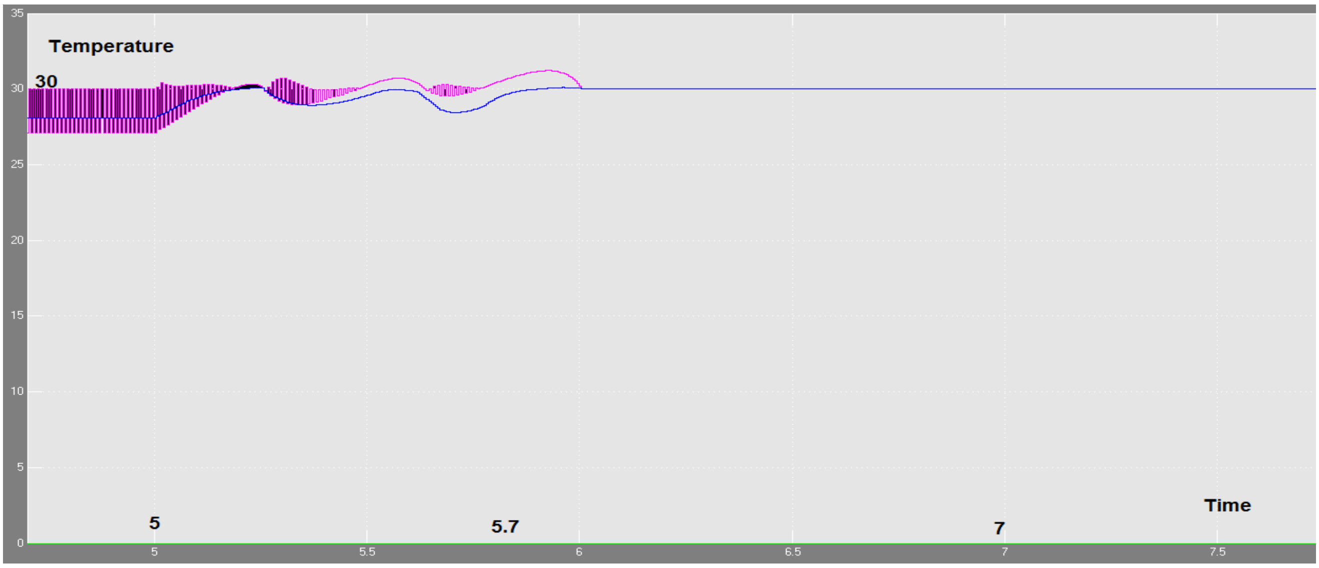


Figure 5.17:.Red line is Mamdani result, blue line is Sugeno result

- The overshoot is 30.9 c , it's near the desired temperature (30) ,see Figure (5.18)

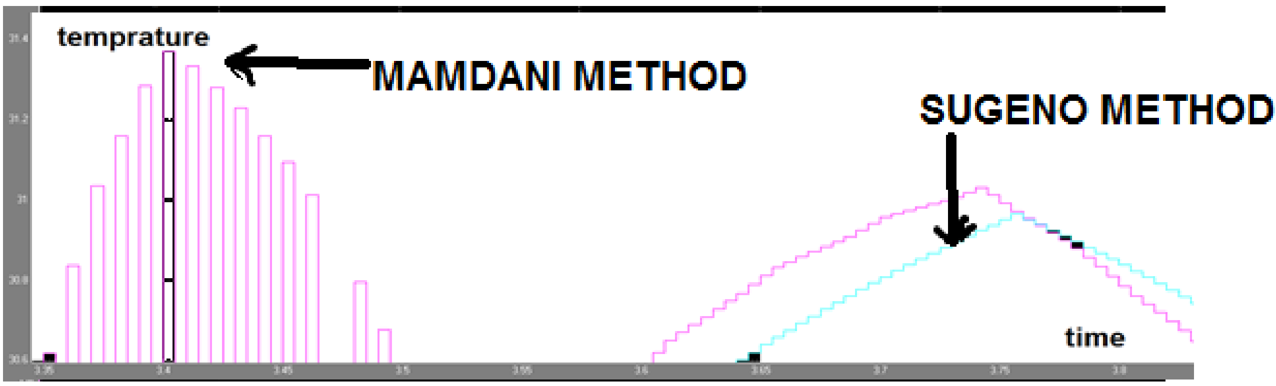


Figure 5.18: pink line is Mamdani result, blue line is Sugeno result

- The undershoot is 28 c, the undershoot is improved comparison with Mamdani controller, see Figure (5.19)

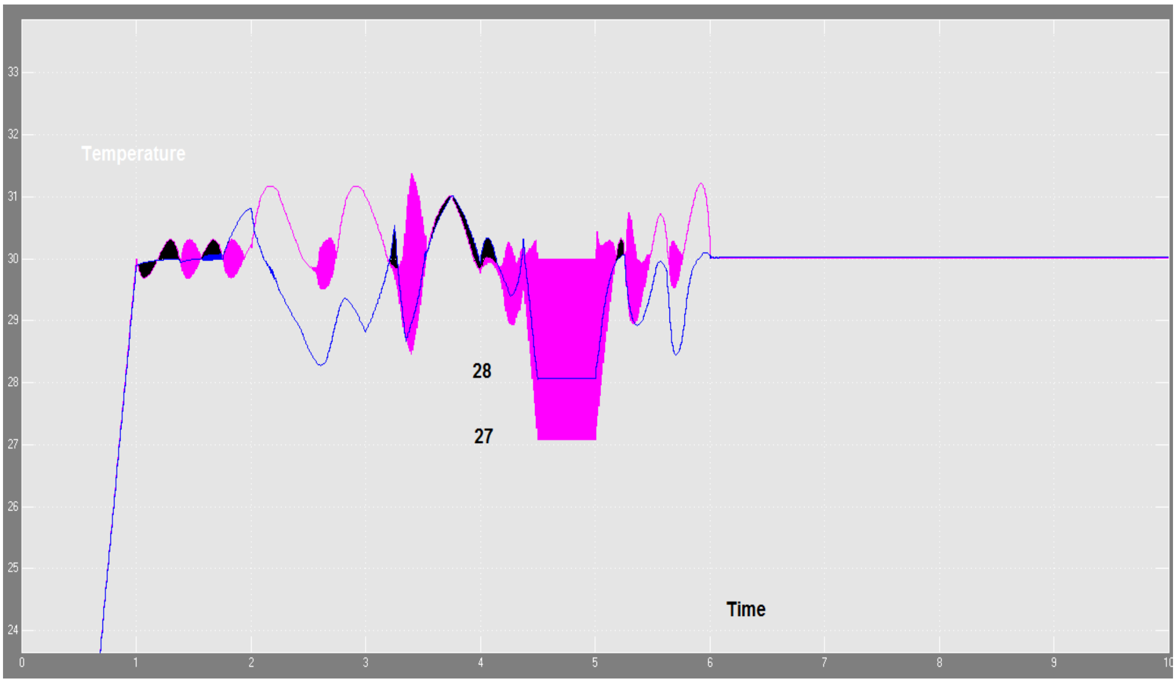


Figure 5.19 :Red line is Mamdani result, Blue line is Sugeno result

- After doing zoom we notice that result is more stable less oscillation , see Figure 5.20

Figure 5.20: pink line is Mamdani result, blue line is Sugeno result

CHAPTER SIX CONCLUSION AND FUTURE WORK

6.1 Conclusion

A hierarchical fuzzy control approach (Sugeno method) is introduced in this thesis to control a HVAC system for Large buildings. This approach reduces the fuzzy rule numbers but still maintains the linguistic meaning of fuzzy variables and adapt to changes and disturbances that may be happened to the system in any time. Hierarchical fuzzy method help to reduce the number of rules used in this controller and make it easy to understand rules evaluation and make it possible to increase the number of inputs without fearful of rules increase. Hierarchical fuzzy make it easy to partition the controller and this thing gives a better understand of controller running. This controller tested using Matlab/Simulink program.

The results show that the heat ventilation air condition (HVAC) systems by Sugeno fuzzy logic controller has a better response than a Mamdani fuzzy logic controller and give good results, Sugeno fuzzy logic control demonstrates better performance compared with Mamdani fuzzy logic control. It improve the undershoot ,overshoot and the settling time, and become more stable .Furthermore, fuzzy logic offers the advantages of faster design, and emulation of human control strategies.

Fuzzy logic control requires complete knowledge of the operation of the system by the designer.

6.2 Future Work

Consider this controller in a real place with a large space to study rules optimization and membership shapes and use of optimization technique such as Particular Swarm , genetic algorithm or any kind of optimization technique to reduce the number of rules and controlled the membership shapes to give better results.

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APPENDICES

Appendix (A) Indoor Virtual System Function Block Code

1- Temperature *(T3):*

```
function y = fcn(u)
a=((u.*2)-20).*(u>=0).*(u<20);
b=20.*(u>=20).*(30>u);
c=(u-10).*(40>u).*(u>=30);
d=(-u+55).*2.*(45>=u).*(u>=40);
e=20.*(50>=u).*(u>45);
f=(u-30).*(60>u).*(u>50);
g=30.*(u>=60);
y=(a+b+c+d+e+f+g);
```

2- Temperature (T1):

```
function y = fcn(u)
a=((u.*2)-20).*(u>=0).*(u<20);
b=(-u+40).*(u>=20).*(30>u);
c=10.*(40>u).*(u>=30);
d=(-u+45).*2.*(45>=u).*(u>=40);
f=(3.*u-150).*(60>u).*(u>=50);
g=30.*(u>=60);
y=(a+b+c+d+f+g);
```

Appendix (B) Fuzzy Rules

Fuzzy Rules For The Two Fuzzy Controllers:

1- IF *Input 1* is **Zero** and *Input 2* is **Zero** Then *Output 1* is **Zero**

2- IF *Input 1* is **Zero** and *Input 2* is **Small** Then *Output 1* is **Small**

3- IF *Input 1* is **Zero** and *Input 2* is **medium** Then *Output 1* is **medium**

4- IF *Input 1* is **Zero** and *Input 2* is **Large** Then *Output 1* is **Large**

5- IF *Input 1* is **Zero** and *Input 2* is **Very Large** Then *Output 1* is **Very Large**

6- IF *Input 1* is **Small** and *Input 2* is **Zero** Then *Output 1* is **Small**

7- IF *Input 1* is **Small** and *Input 2* is **Small** Then *Output 1* is **medium**

8- IF *Input 1* is **Small** and *Input 2* is **medium** Then *Output 1* is **Large**

9- IF *Input 1* is **Small** and *Input 2* is **Large** Then *Output 1* is **Very Large**

10- IF *Input 1* is **Small** and *Input 2* is **Very Large** Then *Output 1* is **Very Large**

11- IF *Input 1* is **medium** and *Input 2* is **Zero** Then *Output 1* is **medium**

12- IF *Input 1* is **medium** and *Input 2* is **Small** Then *Output 1* is **Large**

13- IF *Input 1* is **medium** and *Input 2* is **medium** Then *Output 1* is **Very Large**

14- IF *Input 1* is **medium** and *Input 2* is **Large** Then *Output 1* is **Very Large**

15- IF *Input 1* is **medium** and *Input 2* is **Very Large** Then *Output 1* is **Very Large**

16- IF *Input 1* is **Large** and *Input 2* is **Zero** Then *Output 1* is **Large**

17- IF *Input 1* is **Large** and *Input 2* is **Small** Then *Output 1* is **Very Large**

18- IF *Input 1* is **Large** and *Input 2* is **medium** Then *Output 1* is **Very Large**

19- IF *Input 1* is **Large** and *Input 2* is **Large** Then *Output 1* is **Very Large**

20- IF *Input 1* is **Large** and *Input 2* is **Very Large** Then *Output 1* is **Very Large**

21- IF *Input 1* is **Very Large** and *Input 2* is **Zero** Then *Output 1* is **Very Large**

22- IF *Input 1* is **Very Large** and *Input 2* is **Small** Then *Output 1* is **Very Large**

23- IF *Input 1* is **Very Large** and *Input 2* is **medium** Then *Output 1* is **Very Large**

24- IF *Input 1* is **Very Large** and *Input 2* is **Large** Then *Output 1* is **Very Large**

25- IF *Input 1* is **Very Large** and *Input 2* is **Very Large** Then *Output 1* is **Very Large**