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Design and Implementation of Fuzzy Controller for Non-Linear Thermally Insulated MIMO Greenhouse Building Utilizing Weather Conditions and Ground Temperature

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DESIGN AND IMPLEMENTATION OF FUZZY CONTROLLER FOR NON-LINEAR THERMALLY INSULATED MIMO GREENHOUSE BUILDING UTILIZING WEATHER CONDITIONS AND GROUND TEMPERATURE

Raghed Abdul Menam Al Housari

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Electrical Engineering

Under the Supervision of Dr. Farag Omar

June 2018

Declaration of Original Work

I, Raghed Abdul Menam Al Housari, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled *"Design and Implementation of Fuzzy Controller for Non-linear Thermally Insulated MIMO Greenhouse Building Utilizing Weather Conditions and Ground Temperature"* , hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Farag Omar, in the College of Engineering at UAEU. This work has not previously been presented or published or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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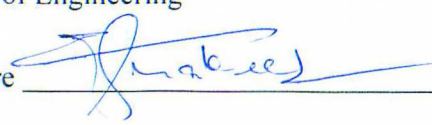
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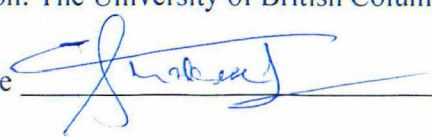   College of Engineering

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Abstract

The increased demand of electricity and water consumption for cooling and heating processes together with the continuous increase in earth temperature due to greenhouse gases emission urged the utilization of sustainable, affordable and clean energy resources. Globally, the biggest amount of water is consumed for agricultural purposes. Domestically, in Abu Dhabi Emirate, the agriculture sector consumes over 50% of the supplied water. Part of this consumption is due to the evaporative cooling approach that is typically used in cooling greenhouses. This approach utilizes a large amount of water and energy to maintain the greenhouse temperature within the desired range. Ground Heat-Exchanger is an environmentally-friendly solution used for heating or cooling applications. It is based on seasonal temperature difference between the ground and the ambient which varies with depth. As depth of ground increases, the temperature fluctuation decreases because of the soil high thermal inertia and the time lag in temperature fluctuation between the surface and the ground. The aim of this thesis is to design a control system using fuzzy logic controller to study the feasibility of utilizing weather conditions and soil temperature in cooling or heating processes of a special type of greenhouses. The proposed control system takes a decision of either utilizing the outside weather conditions or using the soil temperature. The study is conducted on a thermally insulated greenhouse system equipped with ground-to-air heat exchanger, actuated windows, fans, and sensors and the proposed controller performance is compared to a logical and conventional ON/OFF controllers. Results show the proposed control system is capable of maintaining the greenhouse temperature within the desired range for most of the day hours in winter utilizing only the weather and soil temperatures. However, when the temperature is extremely hot, especially in summer, the ground heat exchanger can be only used for pre-cooling with a capability of reducing the ambient temperature of about 6ºC on average. In such extremely hot periods, an auxiliary cooling unit has to be deployed for further cooling. In addition, results reveal that fuzzy controller consumes less power than the logical and the ON/OFF controller when operating the system actuators.

Keywords: Ground Heat Exchanger, GHE, Sustainable Energy, Fuzzy Controller, Greenhouse.

Title and Abstract (in Arabic)

تصميم نظام تحكم مرن يستخدم تغيرات الطقس الخارجية وحرارة باطن الأرض للتحكم في درجة حرارة بيت زراعي معزول حرارياً ومزود بأجهزة استشعار

الملخص

تعد الزيادة المستمرة في استهلاك الماء والكهرباء وارتفاع درجة حرارة الأرض بسبب الاحتباس الحراري والغازات الدفيئة حافز رئيسي لاستخدام مصادر طاقة بديلة مستدامة ونظيفة. عالمياً، يعد استهلاك الماء لأغراض زراعية هو الأعلى نسبة مقارنة مع مصادر الاستهلاك الأخرى. على الصعيد المحلي، أكثر من 50% من استهلاك الماء في إمارة أبوظبي يذهب للقطاع الزراعي وجزء كبير من هذه المياه تستخدم في عملية التبريد بالتكثيف للمحافظة على درجة الحرارة المرغوبة للبيوت الزراعية. يعد استخدام درجة حرارة باطن الأرض في عمليات التبريد والتدفئة من الحلول البيئية المستدامة والنظيفة حيث أن درجة حرارة سطح الأرض تختلف عن درجة حرارة باطنه إذا قيست في نفس الوقت مما يجعل باطن الأرض مصدراً للتبادل الحراري في معظم أيام السنة. الهدف من هذا البحث هو تصميم نظام تحكم للمحافظة على درجة حرارة البيوت الزراعية بالاستفادة من حرارة الجو الخارجية وحرارة باطن الأرض. يعمل نظام التحكم بأخذ قراءات درجات الحرارة لداخل البيت الزراعي وخارجه وإجراء مقارنة بينهما لاتخاذ قرار إما باستخدام درجة الحرارة الخارجية عن طريق فتح النوافذ أوتوماتيكياً أو باستخدام درجة حرارة باطن الأرض أو بتشغيل نظام التبريد الإضافي. أظهرت النتائج أن استخدام حرارة باطن الأرض على عمق 2.5 متر يساعد على المحافظة على درجة حرارة البيت الزراعي عند حوالي 27 درجة مئوية مما يجعل استخدام حرارة باطن الأرض ملائماً للتدفئة في الشتاء وللتبريد الأولي في الصيف في مناخ دولة الإمارات. كما أكدت الدراسة على أهمية دراسة مناخ المنطقة وخواص التربة ومتطلبات المشروع الذي ستستخدم فيه حرارة الأرض قبل تصميم نظام التبادل الحراري وتحديد العمق المناسب.

مفاهيم البحث الرئيسية: التبادل الحراري مع باطن الأرض، طاقة متجددة، طاقة نظيفة، بيوت زراعية، نظام تحكم مرن

Acknowledgements

Dedication

To my beloved mother

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List of Abbreviations

ANFIS	Adaptive Neuro-Fuzzy Inference System
BHE	Borehole Heat Exchanger
COP	Coefficient of Performance
EAHE or EAHX	Earth-to-Air Heat Exchanger
EWHE	Earth-to-Water Heat Exchanger
GCHE	Ground Coupled Heat Exchanger
GHC	Greenhouse Controller
GHE	Ground Heat Exchanger
GSHE	Ground Source Heat Exchangers
ICS	Infinite Cylindrical Source
NGMA	National Greenhouse Manufacturers Association
ODBC	Open Database Connectivity
PVC	Polyvinyl Chloride

Chapter 1: Introduction

1.1 Overview

Greenhouses are used to maintain favorable conditions to plants by controlling temperature, relative humidity, water irrigation, fertilizers and other greenhouse variables throughout the year. Controlling these variables results in reduction of water and power consumption as well as better yield quality. Different approaches have been used to control and monitor the greenhouses; some of these approaches are based on physical models while others are based on an input-output relationship or data training models. This thesis aims to develop a control architecture for an innovative greenhouse system. The innovative greenhouse is thermally insulated and equipped with ground-to-air heat exchanger, fiber optics lighting system, actuated windows, fans, and environmental sensors such as temperature, humidity and wind speed sensors. The proposed control system is designed to maintain the greenhouse temperature and humidity by utilizing the ambient weather conditions through automated windows and the ground thermal status through the ground heat exchanger. It is tested in simulation over one year by mathematical modeling of the greenhouse room temperature and ANFIS modeling of the greenhouse room humidity. This research is a part of the following project "Development of a Novel Vegetable Farming Chamber Utilizing Zero-Water Cooling and Natural Lighting "Towards a Green Organic Farming" / DUAEU/SQU 01_06_15/12.

1.2 Statement of the Problem

The increased demand of electricity and water consumption for cooling and heating processes together with the continuous increase in earth temperature due to greenhouse gases emission emerged the utilization of sustainable, affordable and clean energy resources. World widely, biggest amount of water is consumed for agricultural purposes. Domestically, in Abu Dhabi Emirate, agriculture sector consumes over 50% of the supplied water [1]. Part of this consumption is due to the evaporative cooling technique that is used in many greenhouses to cool down the system. This technique consumes big amount of water and energy especially in hot climate like UAE where temperature approaches 50ºC in summer days. In this research a fuzzy based control system is proposed and studied to maintain the greenhouse temperature and humidity by utilizing weather conditions and a ground source heat exchanger (GSHE) for cooling or heating the greenhouse system. To test the proposed control system over one complete year, the greenhouse temperature and humidity are modeled using different approaches. Since the greenhouse room is thermally insulted, a mathematical model is developed to represent the greenhouse temperature. Also, since the humidity is affected by many variables and is complex to model mathematically, ANFIS model is developed to represent the greenhouse humidity. The work done in this research can be implemented in building automation, sustainable buildings design and in systems that have more than one actuator controlling the same variable. The main objectives of this research are the following:

1- Developing a fuzzy-based controller to the newly thermally insulated greenhouse system to maintain the greenhouse environment by utilizing ground thermal energy and weather conditions.

2- Minimizing the fans power consumption used for cooling/heating the greenhouse system.

3- Comparing the performance of controlling the innovative greenhouse system between the conventional ON/OFF controller, the logical controller and the fuzzy-based controller.

The novelty of this theses:

1- Proposing a control system that can maintain the thermally insulated greenhouse with utilizing sustainable energy resources (ambient temperature and ground heat)

2- Developing an algorithm that controls two different actuators that are assigned to control the same variable which is the greenhouse temperature.

Chapter 2: Relevant Literature

2.1 Ground Heat Exchanger

As depth of ground increases, the temperature fluctuations at the surface of the ground decreases because of the soil high thermal inertia and the time lag in temperature fluctuation between the surface and the ground. Many factors affect the ground temperature distribution such as the structure and physical properties of the ground, the ground surface cover and the climate conditions. The ground temperature distribution has three separate zones which are, sequentially listed from surface to inner: the surface zone, the shallow zone and the deep zone [2]. In the surface zone, the ground temperature is sensitive to short-time weather changes and has a depth of 1 meter from the surface. However, the temperature in the shallow zone is nearly constant and its distribution depends on the seasonal cycle weather conditions. The temperature in this zone is close to the average annual air temperature and the zone depth depends on the soil type extending from 1 meter to 8 meters for dry light soils and can reach up to 20 meters in moist heavy sandy soil. In the deep zone, which is below the shallow zone, the temperature is practically constant and rises slowly with depth, with an average gradient of around 30ºC/km [3]. Since the temperature is almost constant in the shallow and deep zones, the ground temperature is always higher than that of the average outside air temperature in winter and is lower in summer. This difference in heat makes the ground heat exchanger an attractive, sustainable, energy-efficient and environmentally-friendly way for cooling/heating systems especially that most of the energy demands in buildings is consumed by these systems.

The idea of using earth as a heat sink was known in about 3000 B.C. where Iranian underground air tunnels were used for passive cooling [4]. However, the concept of a

ground source heat exchanger was first known in Switzerland in 1912 and lasted until gas and oil replaced it in the 1950s [5]. It consists of circulating medium (water, air or antifreeze solution) that passes through pipes buried in the ground to extract heat from the environment in summer and dumps it to the ground and vice versa in winter. The yield of thermal energy at higher temperature is based on a reverse Carnot thermodynamic cycle [3]. Usually a heat pump is coupled to a heat exchanger system to increase the thermal transfer efficiency. In fact, the efficiency of a Ground Heat Exchanger depends mainly on its type, design, pipe configuration and length, type of backfill materials and ground thermal conductivity (sand rock, concrete, etc.).

Main types of Ground Source Heat Exchangers (GSHE or GHE)

Different classifications have been done in the literature for the Ground Source Heat Exchangers. However, the most common GSHEs are discussed and shown in Figure 1. The classification done below considers only the ground, which includes underground soil or underground water, as heat sink.

I.   Earth-to-Air Heat Exchangers (EAHE or EAHX)

Earth-to-Air Heat Exchangers (shown in Figure 1 (a)) basically consist of pipes which are buried in the ground at a depth of about 2 meters, coupled with air as a heat transfer medium. The EAHE system forces the outside air through the pipes to be cooled or heated and then mixes it with the indoor air of the room [6]. It uses underground soil as a heat sink for space heating in winter or space cooling in summer. Despite the fact that EAHEs are one of the fastest growing applications of renewable energy in the world, with 10% annual increase in installation numbers [4], the efficiency of this type is lower than the other types due to the low thermal capacity of the circulating medium. Therefore, it is mainly used in pre-heating or pre-cooling

processes. In addition, EAHEs often require a large surface area for installation, and make use of large diameter tubes to reduce the pressure drop. On the other hand, the main advantages of EAHE systems are their simplicity, low operational and maintenance costs, the capability of providing fresh air to rooms and the independence of the building design.
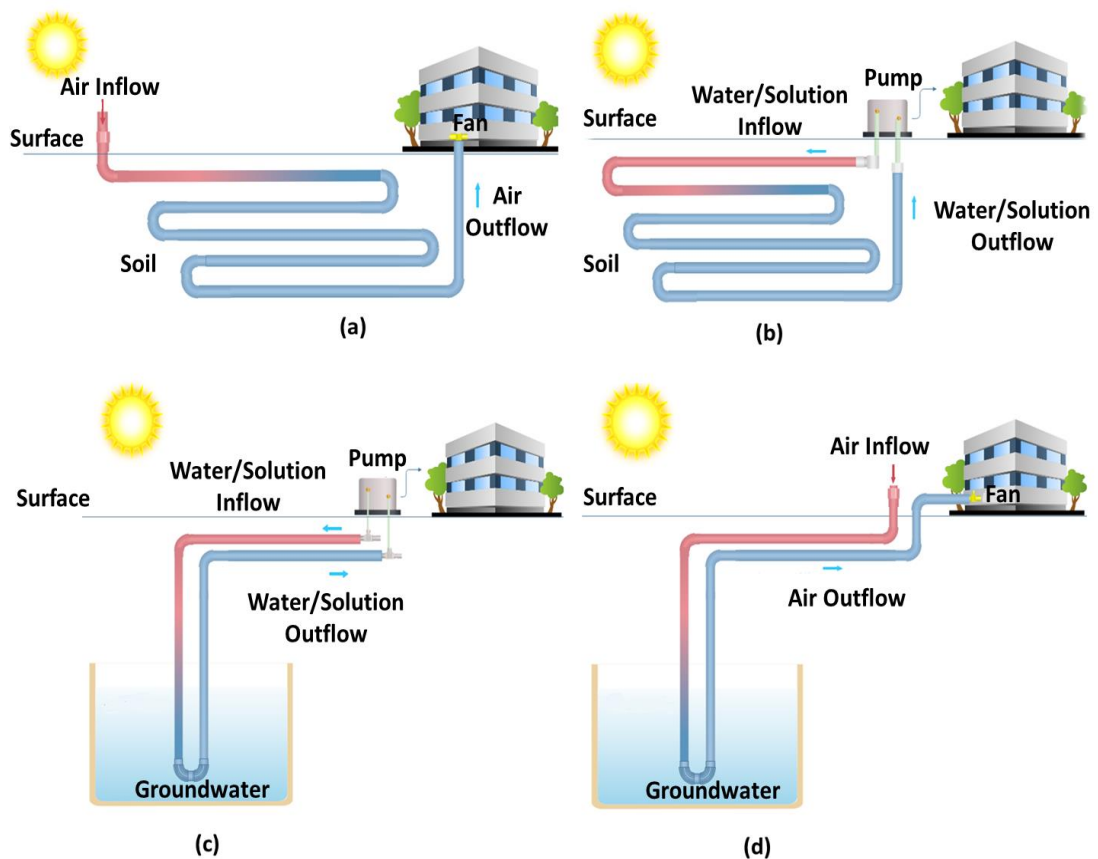
Figure 1: Types of ground heat exchangers

Many studies have been conducted to evaluate the EAHE performance and efficiency. In [7], a quasi-steady state, three-dimensional model was developed on computational fluid dynamics platform CFX 12.0 to evaluate the heating potential of EAHE system. In addition, a EAHE was built in central India with polyvinyl chloride

pipes buried at 2 meter depth to validate the simulation results. It was observed that the rise in air temperature is faster in the initial length of the pipe and then it gradually became steady in the remaining length. Around 10°C drop was measured between the inlet and the outlet of the EAHE.

In [8], an underground air tunnel system for greenhouse cooling was designed and installed in Izmir, Turkey and the exergetic performance characteristics were determined. In addition, exergoeconomics was used to determine the design parameters of a closed-loop EAHE for greenhouse heating. The results showed that, the main resources for exergy destruction in the system are losses in the blower and heat exchanger.

A study was conducted in Kuwait by Al-Ajmi et al. [9] to evaluate the cooling capacity of EAHE in a desert climate. Simulation showed that EAHE can reduce the indoor temperature by 2.8°C during summer peak hours. Also, the results showed that EAHE has the potential to reduce the energy demand by 30% in the summer season.

Bansal et al. [10] found that integrating an evaporative cooler at the outlet of EAHE enhances its performance. Typically, the thermal performance of EAHE systems increase with the increase in length and depth of burial pipes while the decline in performance is observed with increased pipe diameter and air velocity. In fact, as air velocity increases, the convective heat transfer coefficient increases by a factor less than the duration in which air remains in contact with the ground making the latter effect is dominant [4].

II. Earth-to-Water Heat Exchangers (EWHE or GCHE)

Earth-to-Water Heat Exchangers (also known as Ground Coupled Heat Exchangers or Ground Coupled Heat Pumps) are known to be closed loop systems with a medium circulating (usually water or antifreeze solution) to transfer heat from

indoor environment to the sink which is the soil. Small diameter tubes are used with water, and an additional heat exchanger (water-air) is then used to transfer heat between the air and water. The EWHE general scheme is represented in Figure 1b. Normally, less pumping energy is required in these systems because the elevation required is less. An energy reduction of 30-40% and 20-40% can be achieved using GCHE for cooling and heating respectively [5]. In addition, these systems are thus cheaper and easier to install compared to the air-based systems. However, the required tube installation length is larger in the EWHE compared to an EAHE, but the tubes are much smaller.

III. Ground Water-to-Water Heat Exchangers

Ground Water-to-Water Heat Exchangers (known in many references as Ground Water Heat Pump) include the use of ground-water as a heat source or sink as shown in Figure 1c. In some applications the GEHP involves supplying water from the well to a heat pump or directly to the application. The main advantages of these systems are the low initial cost and that less surface area required. However, the disadvantages include the dependency on ground-water availability and the high maintenance cost due to corrosion in pipes.

IV. Ground Water-to-Air Heat Exchanger (Figure 1 (d))

Although the air utilization as a heat transfer medium is increasing in Ground-to-Air Heat Exchanger, there is not much experiments conducted in the Ground-Water-to-Air Heat Exchangers. This could be due to fact that the ground water is not always available near the residential or commercial buildings. Also, digging deep to reach the ground water and use it as a sink is quite expensive procedure which requires high initial cost and long piping loops.

GHE configurations and designs

I.   System configuration

Generally, there are two configurations of ground heat exchanger systems, open and closed loop systems. In open loop systems, ambient air is used as heat transfer medium which passes through tubes buried in the ground for preheating or pre-cooling and then the air is heated or cooled by a conventional air conditioning unit (if needed) before entering the building. However, the process is different when water/coolant is used as heat transfer medium and the ground water is utilized as a heat sink/source. In this process, the water is pumped from a well through pipes to transfer specific amount of heat and then rejected to the well again or to a suitable receptor [3]. This technique is usually used in Ground-Water-to-Water Heat Exchangers. However, using water/antifreeze solutions in open loop systems is not recommended due to environmental concerns such as leakage of chemicals to the ground water. On the other hand, the closed system has heat exchangers located underground and a heat carrier medium circulating within the heat exchanger. This type of system is cost-effective when there is an adequate yard space and the trenchers are easy to dig (i.e. dug prior to construction phase) [5].

II. Pipes Configuration

Different pipe configurations were used and studied in the literature, the main two types are the vertical and horizontal loops. The horizontal loops are easy to install in building construction where typically a 35–60 meter long pipes are needed per kW of heating or cooling capacity in closed system [2]. Horizontal loops designs consist of either single-pipe, parallel pipes or slinky pipes laid out at 1 meter to 2 meter depth [4]. The main advantages of using horizontal pipe configuration are simplicity and low capital cost. However, the main disadvantages include the need of big land area to

install the loop and that the horizontal loops are affected by ambient temperature fluctuation. On the other hand, vertical loops typically consist of U-tubes pipes installed at deep depths. Although the vertical pipes require high capital cost, but less piping is needed compared to horizontal loops. Deeper boreholes are more efficient in heat transfer, however, the construction cost for deep boreholes is more expensive than that of shallow ones because the deep digging process is done by specific expensive machines. Many applications especially for commercial or residential buildings with restricted area preferred the vertical loops systems over the horizontal ones [11].

III. Loop length design

Many designs and models were built and tested for piping configuration and length optimization. The length of the loop depends on many factors including the type of loop configuration used, the house heating and air conditioning load, soil conditions and local climate. The following results were found from different experiments [12]:

1- Decreasing the diameter of the pipes increases the cooling/heating efficiency.

2- Having several pipes of small diameter over which the flow rate is divided is better than having one big pipe as efficiency decreases with increasing the flow rate.

3- Long pipes with a small diameter are efficient in heat transfer but it will increase pressure drop in the pipes which will result in high fan/pump energy.

4- The least pressure loss is found when small flow rate per pipe and a large diameter pipes are used.

5- The Earth-to-Air Heat Exchanger effectiveness rises with longer pipes (checked range: 30–70 meters).

6- For horizontal loops, when pipes are buried in greater depths (3 meters instead of 1.2 meter), the effectiveness increases.

7- When pipe diameter was increased from 100 to 150 millimeters, the heating capacity of the system decreased. This is due to the reduction in the convective heat transfer coefficient. Also, increasing the pipe surface provides a lower air temperature at the pipe outlet which will decrease the heating capacity of the system.

8- 80% is considered to be the optimum value for ground-air heat exchanger effectiveness. If higher effectiveness is desired, the tube length or the number of tubes should be increased.

IV. Backfill material

Each rock type has a different thermal conductivity. The thermal conductivity of rocks is the ability of a material to conduct heat and it depends on the elements that form the rock. For example, rocks that are rich in quartz, like sandstone, have a high thermal conductivity, however, low thermal conductivity is found in the rocks that are rich in clay or organic material, like shale and coal. Considering the thermal conductivity of the backfill material is important for designing optimal and efficient ground heat exchangers.

Ground Heat Exchanger Modeling, Optimization and Control

Different modeling and optimization techniques have been studied in the literature to investigate and evaluate different types of GHEs. In fact, modelling, simulation and testing of GHE systems are essential steps for getting the best Coefficient of Performance (COP) which is the useful heat supplied by GHE over the work or electricity consumed by GHE. In [13], an optimization strategy for the outlet water temperature of Earth-to-Water Heat Exchanger was developed to control the variable

speed pump. The proposed strategy consists of two steps that use a model-based approach to simplify the heat exchanger components. The first step is using a rule-based sequence controller to determine the operating temperature of heat pumps. The second step is to determine the optimal combination of outlet water temperature and water flow rate that requires minimum energy. The proposed strategy can save up to 4.2% of cooling power consumption. A similar work was done in [14], where a closed loop of Earth-to-Water Heat Exchanger was used to extract heat from the ground at a distance of 1.5 meter and 2.5 meter. An algorithm was developed to find the optimal speed pump for the circulating water to extract the desired temperature from the ground. Results showed the system was able to reduce the room temperature between 3°C to 4°C. In [15], the thermal performance of Earth-to-Air Heat Exchangers was studied for summer cooling by developing a transient one-dimensional model of the heat exchanger. The Derating Factor, which is the ratio of deterioration in thermal performance for transient conditions over the thermal performance for steady state conditions, was used to evaluate the performance of the proposed model. It was found that, the thermal performance of EAHE in transient conditions is more sensitive to the variation of operating duration, pipe diameter and air velocity. Also, Dasare et al. [16] developed and validated a numerical model to predict the thermal performance of various types of Earth-To-Water Heat Exchangers with water-ethylene glycol used as a heat transfer medium. It was found that the soil thermal conductivity and the mass flow rate play important role in the amount of heat exchanged. Also, it was concluded that the depth of installation has a small effect on its performance. Moreover, three types of horizontal pipe configuration were studied which are linear, helical and slinky. It was found that the helical geometry is the best configuration for horizontal piping heat exchangers. In addition, many studies have been conducted on vertical GHEs. In

[17], an optimal design methodology for vertical U-tube ground heat exchangers (GHEs) systems was developed using entropy generation minimization and genetic algorithms techniques. The proposed optimization methodology decreased the total system cost by 5.5%, compared with the original design. Antonio Capozzaa, Michele De Carli and Angelo Zarrella concluded that, among the literature models, the ASHRAE method is the simplest procedure that could be used to promote the application of borehole heat exchangers (BHEs). It is based on the infinite cylindrical source (ICS) model, uses the monthly building energy demand and thermal load designs as inputs and provide the total length of borehole heat exchanger (BHE) for heating and cooling processes [18].

However, in 2016 Kose et al. [19] aimed to find the system identification model that best predicts the behavior of the GHE designs. The ARX model, Transfer Function model, Process model and the Hammerstein and Wiener Model were numerically compared. According to statistical criteria which includes the best fit, parameter estimation, validation of the model and structure of dynamic models, it was found that the model with the best performance is the Hammerstein-Wiener model.

The conducted research on different types of GHE have highlighted the efficiency of the GHEs when the optimum speed is found at which the speed of exchanging the temperature allow maximum heat transfer between the ground and the circulating medium. The optimum GHE speed can be found either by trial and error approach or by following certain equations and algorithm which differs from one GHE type to another.

2.2 Greenhouse

Greenhouse history

A greenhouse is a metal frame agricultural building used for cultivation and/or protection of plants, covered with translucent plastic or glass film which does not allow the passage of climatic changes inside. The aim of using greenhouses in agriculture is to reproduce the most suitable conditions for the growth and development of crops established inside with some independence of the external environment [20]. Despite the fact that the exact origin of growing plants in greenhouses is not documented historically, the idea of greenhouses was applied early around 30 A.D. to satisfy the Roman Emperor's craving for cucumber. A small greenhouse called specularium was built using translucent sheets of mica to grow cucumber all year round [21]. No glass or elaborate structures were used to grow plants, instead, plant materials were grown in pits covered with sheets of mica and the heat was obtained from decomposing manures and hot air flues [21]. The use of glass for protecting the plants was detected in France and England in 1385 [22] where tall side walls of glass and opaque roof greenhouses were constructed. In the 18th century the glass roofs were constructed, and minor improvements were made to greenhouse building. Greenhouse construction in the USA started in the early 20th century and flourished until World War II when many greenhouse companies turned their business to building construction and infrastructure manufacturing. Currently, the North America region started to invest again in this field and projected to be of the fastest-growing market for commercial greenhouse during the forecast period 2015–2020 [23].

Greenhouse glazing material

The greenhouse glazing material (or covering material) provides protection for the plants from excess cold, hail and rain and significantly affect the amount of sunlight reaching a crop and structure heat losses [24]. This material has to be carefully selected before structure selection since each glazing material has different characteristics, cost and support structure [25]. According to the National Greenhouse Manufacturers Association (NGMA), greenhouse glazing materials are classified into three main categories; plastic film, rigid plastic and glass.

I. Plastic Film

It is considered as the leading greenhouse glazing material because of its low price compared to the glass greenhouses. It includes polyethylene and polyvinyl chloride (PVC).

Polyethylene Film

Polyethylene Film material is very cheap compared to other greenhouse glazing materials. It is considered as the first choice for farmers around the world. Eighty percent of new greenhouses in the United States are made of air-inflated double-polyethylene film material [24]. Air is blown between the layers for insulation purpose. Polyethylene film is very light in weight, has moderate resistance to hail damage, moderate susceptibility to flammability and can be easily replaced with minimum man-power requirements which overcomes the short life-span drawback of this material that varies from one to four years [24].

Polyvinyl Chloride (PVC)

PVC is barely oxidized, but heat and light break its life-span down to 2 or 3 years. Heat loss (especially at night) is less when using the PVC film than the polyethylene material because it reduces the transmission of long wavelength infrared radiation.

II. Rigid Plastics

This type of glazing has very good light transmission properties. It is lighter than glass and thus requires fewer support bars in greenhouse structures. As plastic ages, it turns yellow and light transmission decreases. This material is not easily installed on curved roofs. It includes fiberglass-reinforced plastic, polycarbonate and polymethyl Mmethacrylate (PMMA) or Acrylic.

Fiberglass-reinforced Plastic (FRP) Rigid Panel

This type of glazing material has an impact resistance and superior strength that makes it useful in building greenhouse end walls. The light transmission through FRP is considered very good having 80-90% of clear glass transmission. It has a 10-year lifespan.

Polycarbonate

Polycarbonate material has low flammability rates, and very high impact resistance. It has higher light transmission than polyethylene film. It usually comes in two primary configurations: single layer and multi-layer sheets with the air between the sheet layers works as insulator and reduces heat losses. However, the transmitted light decreases as the number of sheet layers increases [24].

Polymethyl Methacrylate (PMMA) or Acrylic

This type of material also comes in two configurations as in the polycarbonate material. It has excellent light transmission, high impact resistance, high susceptibility to flammability, textured surface which diffuses light thus preventing condensation drip. It has a drawback in that it is not easily installed and requires more components than polyethylene film.

III. Glass

Glass is considered as the most expensive glazing material. Therefore, it is used in very large compartments in order to lower cost per unit area, improve efficiency and reduce heat loss through the greenhouse sidewalls [24]. It is very resistant to flammability and has the highest light transmission and clarity which increase the heat losses. Additionally, glass greenhouses tend to have a higher air infiltration rate, which leads to lower interior humidity [25]. Glass inherent resistance to ultraviolet radiation gives it the longest lifespan of about 30+ years since it does not degrade with time.

2.3 Greenhouse Climate Control

The greenhouse climate-control problem is to create a favorable environment to improve the development of the plantations and to minimize the production cost in terms of raw materials, water and energy consumption [26]. Controlling the greenhouse environment is mainly focused on controlling the water and fertilizers that feed the plants in one side, controlling the sunlight, CO_2, temperature, relative humidity and other environmental conditions that surround the plants on the other side. By controlling the greenhouse environment, better productivity of plants is gained, electricity and water consumption is reduced as well as human intervention in the

system [27]. However, the conventional greenhouse system is considered a nonlinear and complex thermal system because of the nature of the used structural material and the dependent relationship between the greenhouse system inputs' variables. Recently, greenhouses were fully automated and monitored using different methodologies and algorithms. Two main approaches are followed for modeling a typical greenhouse system and many controlling techniques are used in each approach. The first approach is the mathematical or physical modeling approach which uses the state space model and a set of differential equations obtained from the greenhouse system mass and energy balance equations. The second approach is a black box model approach that tries to approximate and control the behavior of the greenhouse system based on the input-output data of the process. However, the innovative greenhouse system used in this work is thermally insulated, which makes it different than the conventional types in terms of controlling and modeling. Below is a discussion of these approaches followed by a summery in Table 1 of the controlling techniques applied on both modeling approaches.

Blasco et al. [28] designed a controller that aims to minimize the cost and maintain the greenhouse temperature and humidity. Their controller consists of two fundamental elements, the first element is an accurate non-linear state space model that uses Genetic Algorithm (GA) to adjust the model parameters and establish a flexible cost index to minimize the energy and water consumption. The second element is a model-based predictive control that models the greenhouses processes using mass and energy balance where the controlled variables are relative humidity and temperature, the manipulated variables are windows opening, heating and fog systems and the disturbances are solar radiation, wind speed, outside temperature and outside

humidity. The designed controller required powerful computers to do the calculations in each sample; however, the sampling time was long enough (2 minutes) to overcome this problem. The controller was implemented in a plastic greenhouse with arch-shaped roof in the Mediterranean area. It was found that, the proposed controller worked the same as the ON/OFF controller with respect to temperature, better with respect to humidity and cost. Both the proposed controller and the ON/OFF controller were not able to keep the temperature and humidity exactly within the specified range.

In [29], a study was conducted to explore the suitability of the extended Kalman filter for automatic, on-line estimation and adaptation of parameters in physics-based greenhouse model. The model was developed by dividing the greenhouse into compartments and in each compartment the energy and moisture balance was determined from the physical processes. The extended Kalman filter was used to both reconstruct the states of the greenhouse model and to estimate the parameters online. It was found that the extended Kalman filter is quite robust for major disturbances but for minor disturbances like opening the window it was not good in parameters prediction. However, the study showed that the online parameter estimation with the Kalman filter improves the model fit over a longer time period.

A different approach for sampling and controlling the greenhouse environment was proposed in [30]. An event-based control system was presented where the control actions are executed in an asynchronous way. The dynamic evolution of the system variable is what decides when the next action will be executed. In other words, a new control signal is only generated when a change is detected in the system which increases the actuators life and reduces the energy consumed by the control system.

On the other hand, many studies proved that the black-box approach simplifies the greenhouse control problem and provides a reliable control to the system. Al-Aubidy et al. [31] presented fuzzy logic controller rules to control the temperature and humidity of a classical greenhouse building made of glass and metal. Their system gives the farmer the privilege to access and control certain devices remotely. The temperature and humidity status were divided into three categories, high, normal and low and accordingly the actuators were closed, opened or half opened. Lots of motors and ventilation units were used to implement this controller which requires high energy consumption that makes the controller not feasible from economical point of view.

Guerbaoui et al. [32] developed a fuzzy logic controller that regulates only the greenhouse temperature which is the most important factor in growing crops. The bound of temperature states were defined and triangular form membership functions were used. A real-time monitoring of greenhouse system was also implemented using fuzzy logic controller with LabVIEW software. Heating system, air supply and variable speed fan were installed to regulate the greenhouse temperature. It was found that it is not necessary to use mathematical model to control the greenhouse temperature since the fuzzy logic controller was able to do so with less complication. Additionally, the triangle form membership function used in ventilation and heater achieved simplified calculations.

Only few of the proposed controllers [28-42] studied the power cost of maintaining the greenhouse environment. In fact, lots of actuators (including motors and ventilation units) were used to implement the proposed controllers which indicates high energy consumption. In addition, no study was conducted on the operation hours of the greenhouse system actuators. Moreover, the work done in controlling the

greenhouse environment considers the conventional approaches for cooling/heating

the system. Also, a lack of experimental results is obvious in the proposed controllers.

Table 1: Summery of greenhouse climate control approaches

Reference number	Greenhouse Controlling approach	Modeling approach	Findings and Results
[26]	H$_2$ controller	Mathematical modeling	- The H$_2$ controller performance is slightly better than the conventional ON/OFF controller.
[32]	-Mamdani fuzzy logic controller -ON/OFF controller	Mathematical modeling	- ON/OFF controller experienced huge fluctuations of the actuators - The energy consumption of the fuzzy controller system is less than the ON/OFF one.
[33]	Adaptive Neuro-Fuzzy Inference System with Genetic Algorithm (GA)	Mathematical modeling	- Less set-point error when compared to fuzzy controller and ANFIS controller - Smoother controller signals which result in significant increase in actuators' life time.
[34]	Adaptive fuzzy controller	Mathematical modeling	--temperature and humidity inside the greenhouse are well tracked.
[35]	- Modified Smith predictor -PID controller tuned by genetic algorithms	Mathematical modeling	- The modified Smith predictor reduced settling time and no overshoot which improve actuators lifetime.
[36]	A hierarchical control approach is proposed for optimal operation of greenhouse	Mathematical modeling	- Optimal operation of the existing greenhouse control systems by incorporating weather forecasts, electricity price information, and the end-user preferences

Table 1: Summery of greenhouse climate control approaches (Continued)

Reference number	Greenhouse Controlling approach	Modeling approach	Findings and Results
[37]	Model predictive control (MPC) for temperature regulation	Mathematical modeling	Better performance is gained in terms of controller stability when compared to PI controller
[38]	Multilayer feedforward neural network	Elman neural network techniques	- The error of temperature and humidity are very high at some points. Controller performance could be improved if an adaptive neural controller or a multiple neural control strategy are adopted.
[39]	- Mamdani Fuzzy Logic Controller - ON/OFF with hysteric - Simple on/off	Mathematical modeling	fuzzy controller had more ability to maintain the greenhouse environment as compared with other controllers
[40]	-	hybrid neuro-fuzzy approach based on fuzzy clustering	- Artificial Neural Networks can be well adapted to model the greenhouse nonlinear behavior - Fuzzy logic handles well both numerical data and linguistic information

Table 1: Summery of greenhouse climate control approaches (Continued)

Reference number	Greenhouse Controlling approach	Modeling approach	Findings and Results
[41]	- Mamdani Fuzzy Logic controller - On/Off controller	Mathematical modeling	fuzzy Logic Controller is easy to design, highly adaptable and quick to perform.
[42]	Fuzzy logic controller developed by using the inverted fuzzy model.	Fuzzy model	- Some dynamics are not well presented by the fuzzy model - The proposed fuzzy controller is simpler and better in regulating the temperature when compared to a PI fuzzy controller

Chapter 3: Methods

Utilizing the ground temperature in pre-cooling/pre-heating processes has been used in different applications including greenhouses. However, automating the use of outside weather conditions to maintain the greenhouse environment is a new sustainable goal that needs a flexible controller to achieve it. To this end, a greenhouse controller (GHC) is designed based on fuzzy logic and implemented using Matlab R2016b fuzzy logic toolbox with a multiple inputs and multiple outputs (MIMO). The GHC is connected to a MySQL database via a wired network to extract the system inputs recorded by the sensors and provide the needed outputs. Recording the system inputs and outputs is important for analyzing the controller performance and stability. Also, MySQL database is selected because it is a free and open source database. In addition, it can be easily integrated with the Arduino microcontroller. Since the dynamic of greenhouse systems is slow, the measurements are recorded every two minutes and the controller processes these measurements and decides the outputs accordingly. Also, since designing a fuzzy controller requires a deep knowledge of the system inputs and actuators capabilities, the meteorological data are studied, and the soil temperature is approximated at different depths over one complete year. The performance of the GHC is compared to a logical and conventional ON/OFF controllers for greenhouse applications. To test the proposed controller for one complete year, the greenhouse temperature is modeled using mathematical equations. Below is a description of the collected data, soil temperature approximation, controllers design and control system architecture, EAHE design, greenhouse design, greenhouse temperature modeling and greenhouse humidity modeling.

3.1 Data Collection

Meteorological data is collected from National Center of Meteorology & Seismology in Abu Dhabi to model the soil temperature, study the outside weather conditions throughout the year and to set reasonable limits for the proposed controllers. In addition, a MySQL database is designed to include the experimental measurements collected by the sensors when doing real experiments in the farm. Sequential Query Language or SQL is a standard language for making interactive queries and updating a database such as Microsoft's SQL Server, and database products. The main reasons for choosing MySQL as a database are its scalability, open sourcing, high performance with high-speed load utilities, and compatibility with many programming languages including C, C++, JAVA and PHP.

3.1.1 Meteorological Data

Meteorological data of air temperature (ºC), relative humidity (%RH), wind speed (km/h) and sun duration (hours) are collected in hourly basis for one year to model the soil temperature at different depths and to determine the fuzzy logic controller input variables' limits. The data are measured at Al Ain Airport which is 31 kilometers far from UAEU-AlFoah farm where the experimental part is done. Table 2 shows the maximum, the average and the minimum values of the collected data in 2016.

Table 2: Metrological data collected from Al Ain Airport in 2016

	Air Temperature (ºC)	Relative Humidity (%)	Wind Speed (km/h)	Sun Duration (h)
Maximum	47.1	100	52	12
Average	29.8	42.6	14	10
Minimum	9.8	5	0	4

Accordingly, the input variable limits of the fuzzy controller are selected to be from 0ºC to 55ºC for air temperature, from 0 % to 100% for relative humidity and from 0 to 55 km/h (0 m/s to 15 m/s) for wind speed. The margins added to the input variable limits are based on the fact that the meteorological data are collected in a shadowed area and averaged. In addition, the limits are specified to suit the indoor and outdoor controller's inputs. Moreover, the hourly measured meteorological data gives an indicator of how the controller should be designed. For example, Figure 2 shows the periodic temperature changes every 24 hours approximately at different seasons. Also, Figure 3 shows a time lag between the temperature cycle and the relative humidity cycle (i.e. when the humidity is maximum the temperature is minimum).
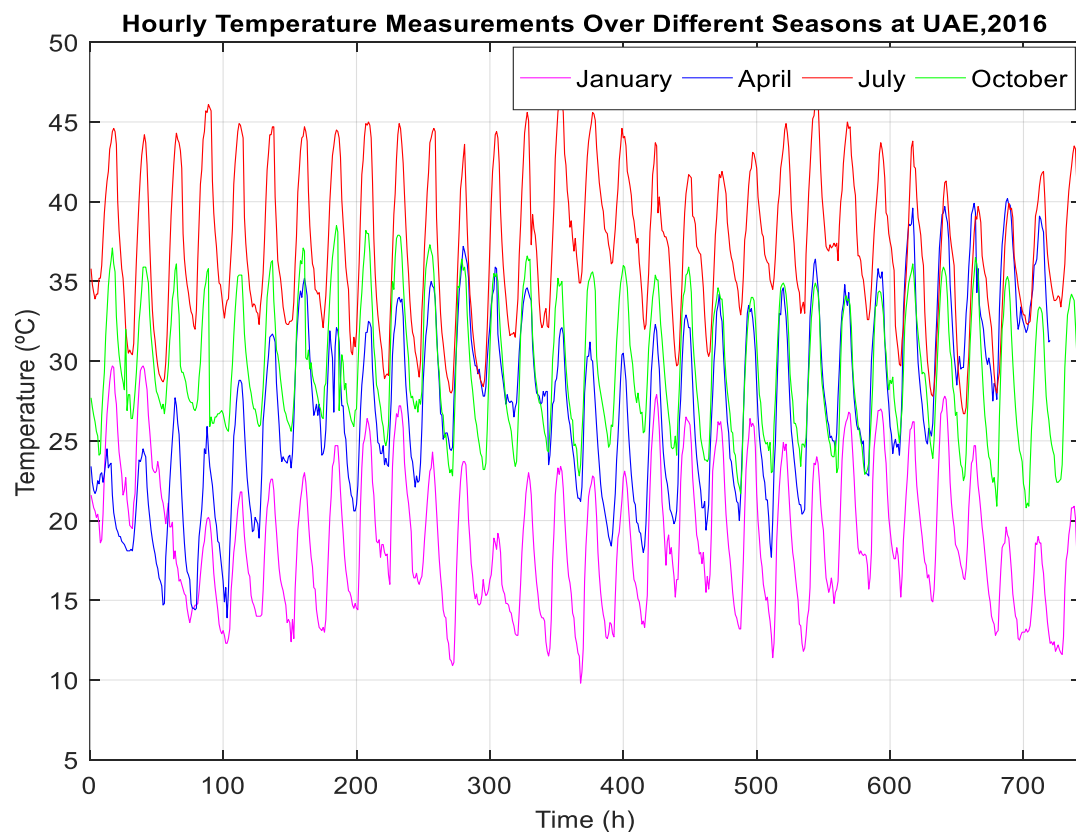
Figure 2: Hourly temperature changes in different seasons
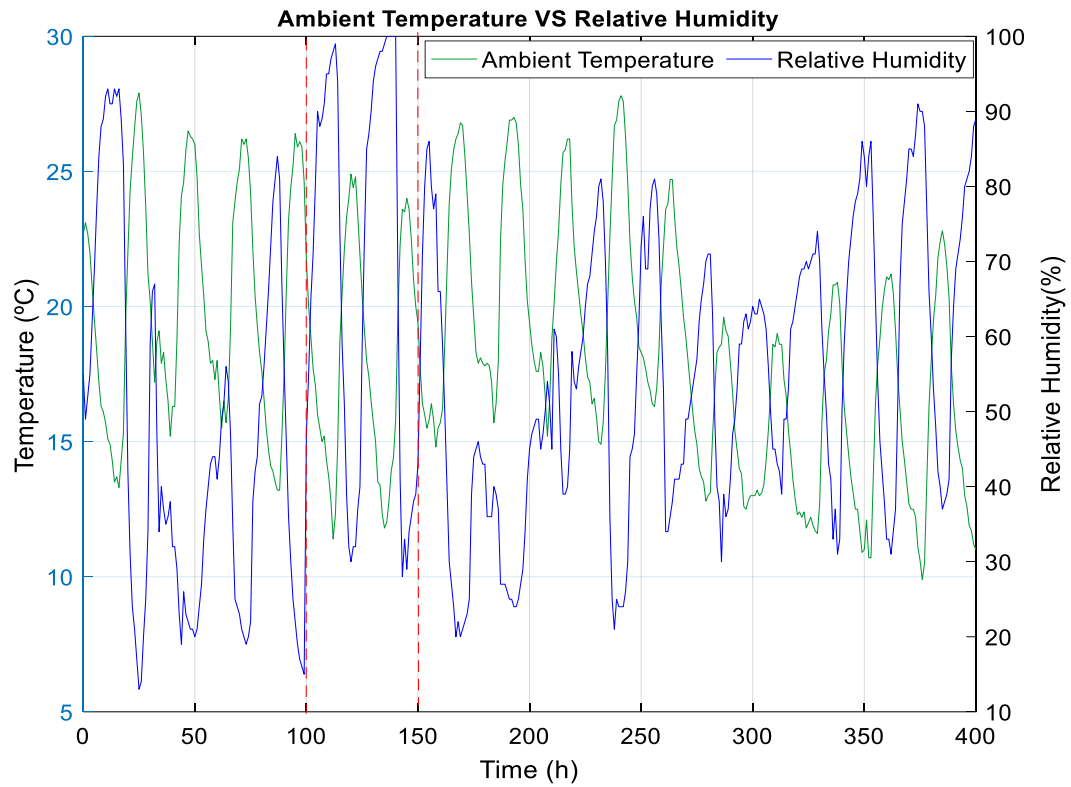
Figure 3: Hourly temperature and humidity changes

3.1.2 Experimental data

MySQL database is used to record the sensors data and the controller outputs. The database is designed with four tables that are indoor measurements table, outdoor measurements table, and controller outputs table. The connection between the MySQL database and the controllers is done via ethernet. Also, ODBC, which is a standard Microsoft Windows interface, is used for communication between the database management systems and the proposed controllers.

3.2 Research Design

To design the controller's inputs and outputs, a deep knowledge of the system actuators is required. Since different heat sources are utilized (the soil temperature and

the weather conditions) to control the greenhouse room temperature, the soil temperature has to be studied throughout the year. A soil temperature approximation is done below, and the controller design is discussed. Also, the greenhouse room model is developed to test the controller performance and compare between the proposed fuzzy controller and the typical controllers over one complete year.

3.2.1 Soil Temperature Approximation

Designing robust controller requires deep knowledge about the system actuators. Since the ground heat is utilized in this research, soil temperature at different depths throughout the year is investigated below. This knowledge helps in deciding the depth at which the GHE should be buried for the greenhouse application. In addition, it helps in deciding when to use the ground heat exchanger and at what capacity. The purpose of modeling the soil temperature is to see the relationship between the depth and the soil temperature in UAE climate and to decide how to use the GHE in different weather conditions. To model the soil temperature, the hourly ambient temperature over the year of 2016 is used to model the soil as a function of time and depth as the following [43].

$$Tsoil(z,t) = T_m - T_p e^{\left(-z\sqrt{\frac{\omega}{2\alpha}}\right)} \cos(\omega(t - \varphi) - z\sqrt{\frac{\omega}{2\alpha}}) \qquad (1)$$

where,

T_m is the annual average temperature of the ambient air which equals to 29.8°C

T_p is the annual peak of the monthly average temperature, which equals to 16.8°C and is tuned to 9.8°C to match the real ambient temperature when the depth is zero.

z is the soil depth from the surface, which equals to 2.5 meter.

ω is the rate of change of the function argument in units of radians per hour, which

equals to $\frac{2\pi}{365.242189\times24}$ $(\frac{rad}{h})$

α is a parameter depends on soil thermal conductivity, soil heat capacity and average

soil density. It is estimated to be 0.0013 $(W * m^2/J)$

φ is the phase shift in radiant at which the temperature was the minimum and it equals

to 21 days.

To ensure a good approximation of the soil temperature, the derived equation in (1) is

plotted when the depth is zero and compared to the real ambient temperature as shown

in Figure 4. The temperature fluctuations at zero depth is not represented by equation

(1) because it is designed to simulate the deep soil temperatures (i.e. it gives the daily

average of the soil temperature).
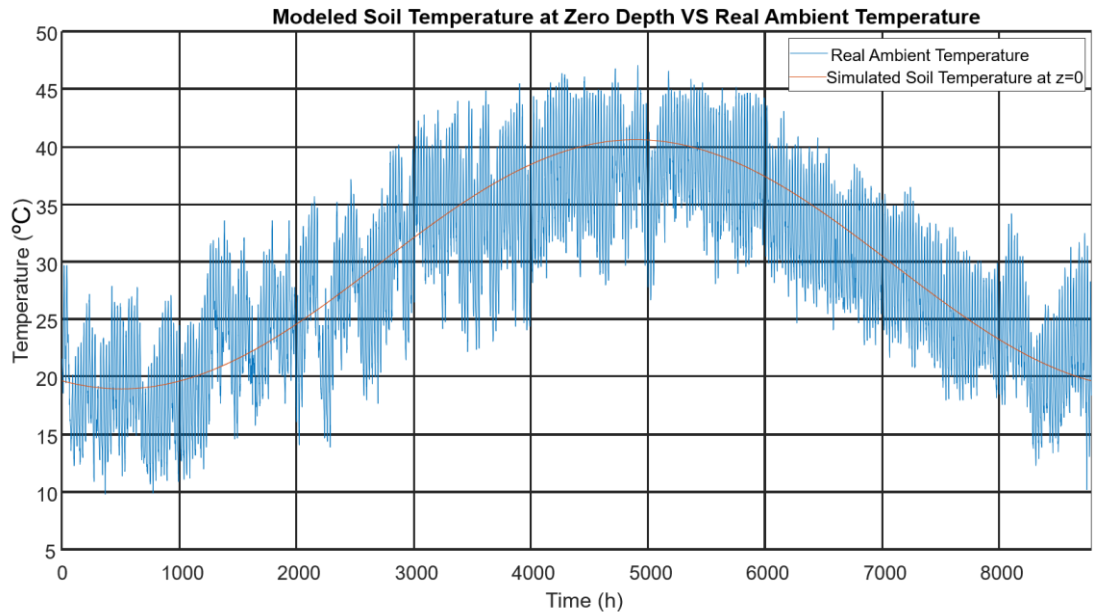
Figure 4: Soil temperature at zero depth

In addition, the soil temperature is plotted at different depths as shown in

Figure 5. It can be seen that at 0.5 meter depth, the soil temperature follows the ambient

temperature to some extent. In addition, as depth increases the soil temperature amplitude decreases until it becomes almost constant and equals to the yearly average ambient temperature. Moreover, since the UAE climate is hot most of the year's day, utilizing the maximum negative soil temperature in the first half of the year can be done at 1.5 meter and 2.5 meter depth. Also, to validate the soil temperature approximation results, the soil temperature is measured experimentally at 0.5 meter, 1.5 meter and 2.5 meter depths in UAEU Al-Foah Farm. Figure 6 shows the recorded soil temperature data from Mar. 1st, 2018 at 12:00 am to Mar. 18th, 2018 at 2:30 pm. The data collected experimentally reveals that the soil temperature at 0.5 m is sensitive to the ambient temperature.
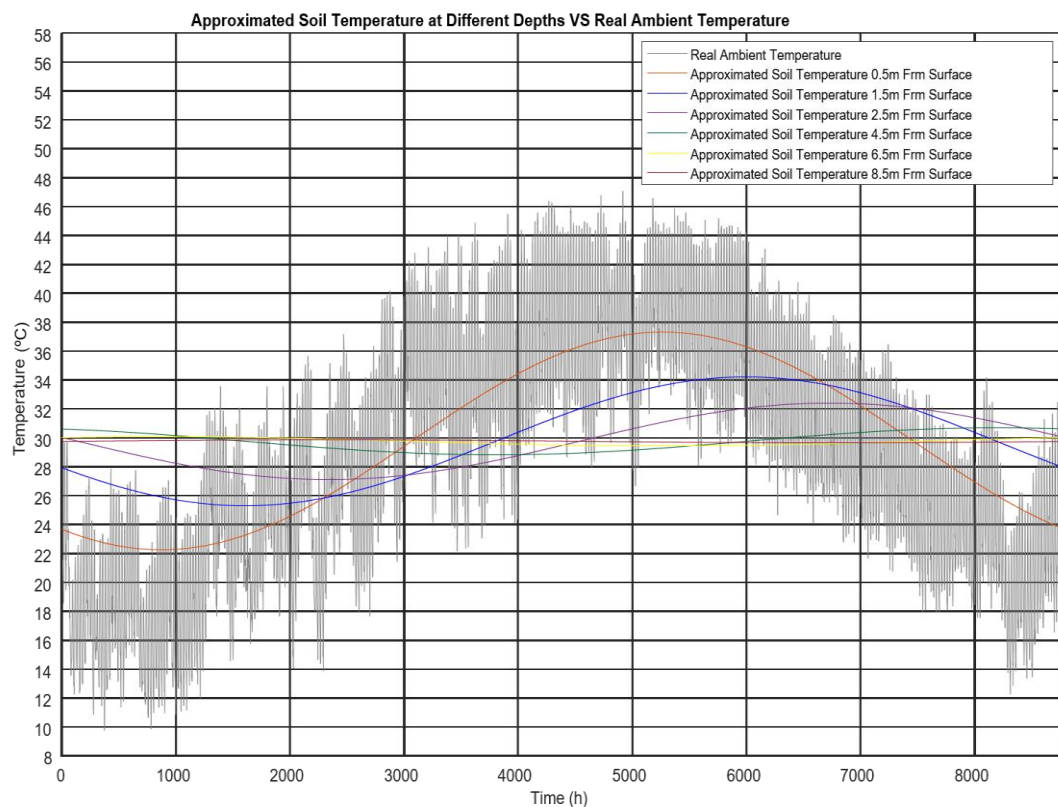
Figure 5: Soil temperature model at different depths
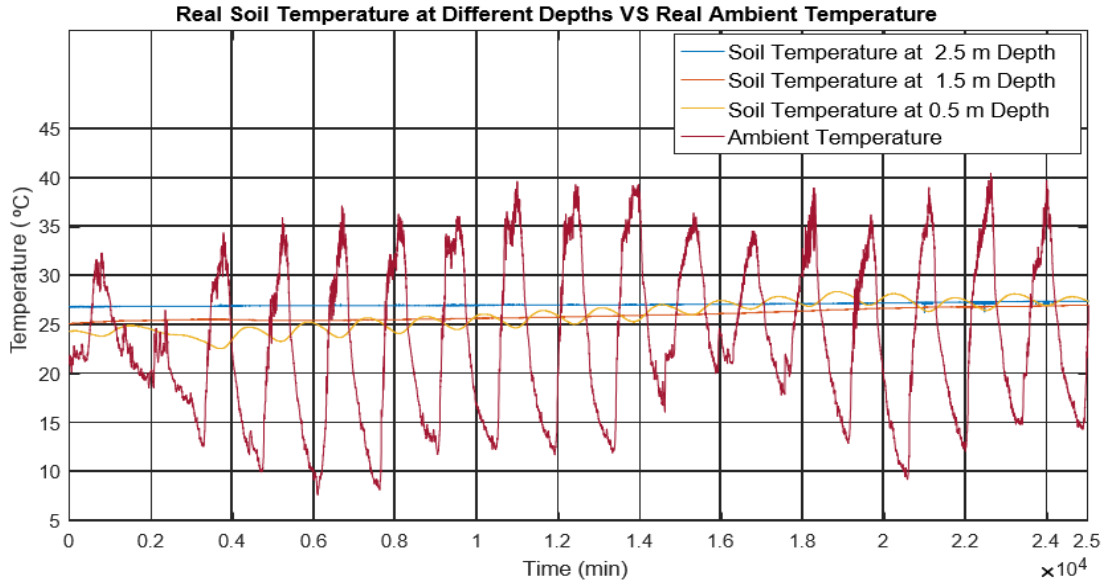
Figure 6: Experimental soil temperature at different depths

Figure 7 shows the measured soil temperature and the approximated soil temperature at 2.5 meter and 1.5 meter depths where the difference between the measured and the simulated values is less than 0.5°C. The soil temperature at 2.5 meter depth shows more stability than at 1.5 meter which will help in designing the controller actions. Therefore, the GHE is deployed at 2.5 meter depth.

Having further investigation, Table 3 shows a comparison between the ambient and the soil temperature at 2.5 meter depth. The average soil temperature is 28.9°C with ±2.7°C fluctuation. It can be seen that the soil temperature at 2.5 meter depth is lower than the ambient temperature in summer and higher in winter. The maximum ambient temperature occurs in July with 47.1°C where the maximum soil temperature at the same month is 30.6°C. However, the maximum soil temperature occurs in October with 7.4°C lower than the maximum ambient temperature at the same month. Also, the minimum ambient temperature happens in January with 9.8°C and the minimum soil temperature happens in April with about 10 degrees less than the ambient temperature. This observation shows clearly that the soil temperature at 2.5

meter depth can be used in cooling/heating or in pre-cooling/preheating processes depending on the desired temperature.
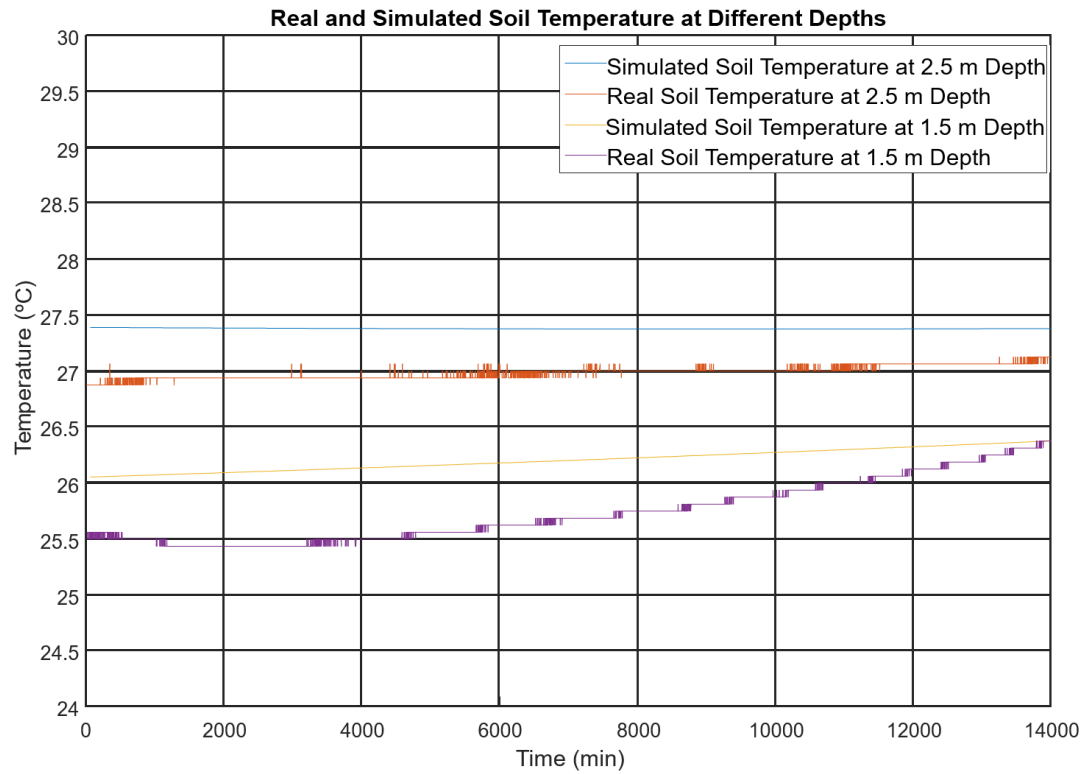
Figure 7: Experimental and modeled soil temperature at different depths

Table 3: Comparison between ambient and simulated soil temperature at 2.5m depth

Time of peak temperatures		Ambient Temperature (°C)	Soil Temperature (°C)
Maximum	July	47.1	30.6
	October	39.9	32.5
Minimum	January	9.8	28.9
	April	13.9	27.1
Yearly Average Temperature		29.8	29.8

3.2.2 GHC Architecture and Design

A fuzzy-based controller is designed, tested and compared to a conventional ON/OFF controller. The inputs to each controller are the main environmental variables for cultivation which are temperature and humidity for both ambient and inside the greenhouse. Also, to ensure a safe operation, the wind speed is recorded to indicate the suitability of opening the windows and utilizing the weather conditions. The greenhouse temperature and humidity are controlled based on the desired temperature and the outside weather conditions. The outputs of the controllers are the extension/retraction percentage of the linear actuators which controls the opening of the greenhouse windows allowing for a thermal exchange and sunlight transmission. In the cases where opening the windows is not convenient, due to undesired ambient weather conditions, the fans are used to extract heat using the installed EAHE system.

The performance of the controllers is tested considering cultivation of lettuce. Lettuce has an optimum growing temperature between 21ºC to 25ºC and optimum relative humidity between 50% to 70%. These values are advised by agricultural experts who consider the UAE hot climate conditions and accordingly denoted as T_{min}, T_{max}, H_{min} and H_{max}, respectively.

3.2.2.1 Fuzzy-Based GHC

Figure 8 shows the proposed fuzzy-based control system architecture. Details of each component is presented next. Thorough comparison and discussion of the performance of both controllers are presented in Chapter 4.
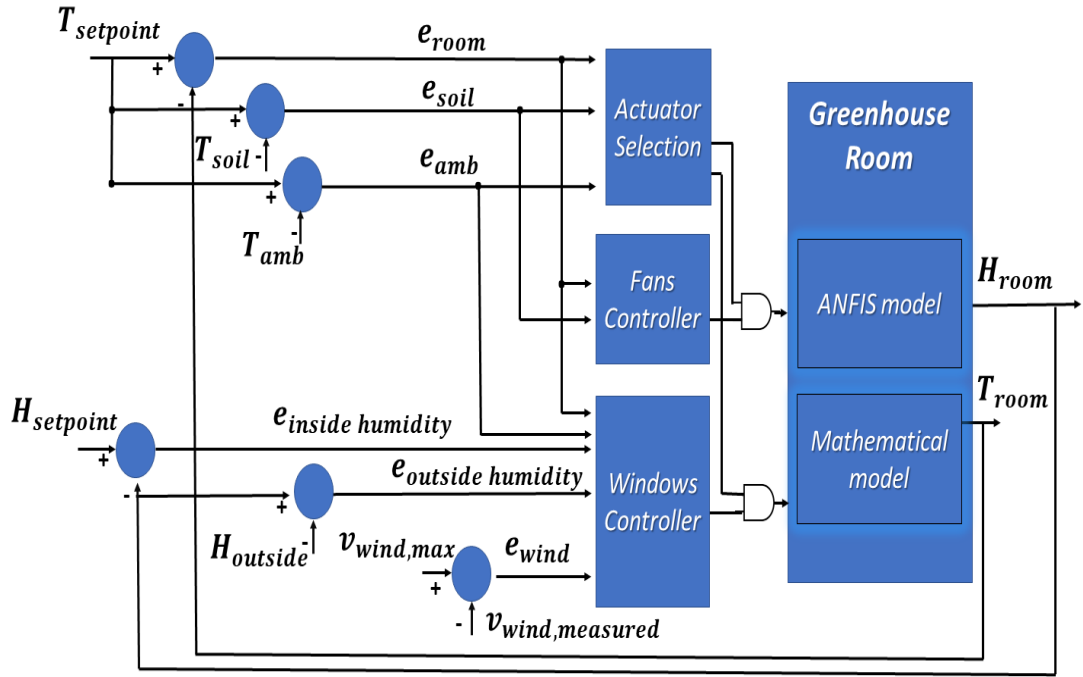
Figure 8: Greenhouse control system architecture

I. Actuator Selector

The proposed greenhouse system uses mainly two natural energy resources which are the soil temperature and the ambient weather conditions to control the greenhouse environment. The soil temperature is utilized by running the fans attached to the GHE and the ambient weather conditions are utilized by automatically opening and closing the windows with varying percentages. To this end, two Sugeno fuzzy controllers are developed to control each actuator. The goal is to make the room temperature error approaches zero. The control strategy followed to achieve this goal is based on calculating the error of room temperature, outside temperature and soil temperature. A decision is taken based on the greenhouse's variables error and the actuators errors. This strategy is implemented in the actuator selector function. The actuator selector

receives three inputs which are the errors of the soil, ambient and room temperatures from the set point of the room temperature and computed as

$$e_{room} = T_{set-point} - T_{room} \qquad (2)$$

$$e_{amb} = T_{set-point} - T_{amb} \qquad (3)$$

$$e_{soil} = T_{set-point} - T_{soil} \qquad (4)$$

Since the windows are controlled based on the ambient temperature and the GHE is controlled based on the soil temperature, the error of weather temperature is input to the windows controller and the error of soil temperature is input to the fans controller. Also, the error of the greenhouse room temperature is inserted in both controllers. Using the error instead of fixed values generalize the designed fuzzy controllers to be used with any desired setpoint without the need to change the rules.

It is important to mention that the temperature control is the most crucial element to the plant as all plants are very sensitive to the surrounding temperature. In fact, most crops including lettuce can survive in low temperature for some time but cannot survive at high temperatures. Therefore, the humidity control is only considered when the temperature is tolerable.

Using the computed errors, the actuator selector decides on which actuator should be used. The actuator receives zero logic value should be set off or completely closed. Figure 9 illustrates all possible scenarios of the room, soil and ambient temperatures with respect to the temperature set point and T_{max}. Figure 9 also includes the appropriate actuator that should be selected for each scenario. It should be noted here that the actuator selector always chooses the actuator that can take the room temperature faster to the set point. Table 4 summarizes the actuator selection decisions

of the 24 scenarios in 10 cases using the computed temperature errors, e_{room}, e_{soil} and e_{amb}. After deciding which energy source is to be utilized, the decision is passed to the related fuzzy controllers to activate the relevant actuator that are designed also using the errors between the desired set point and the measured variables.
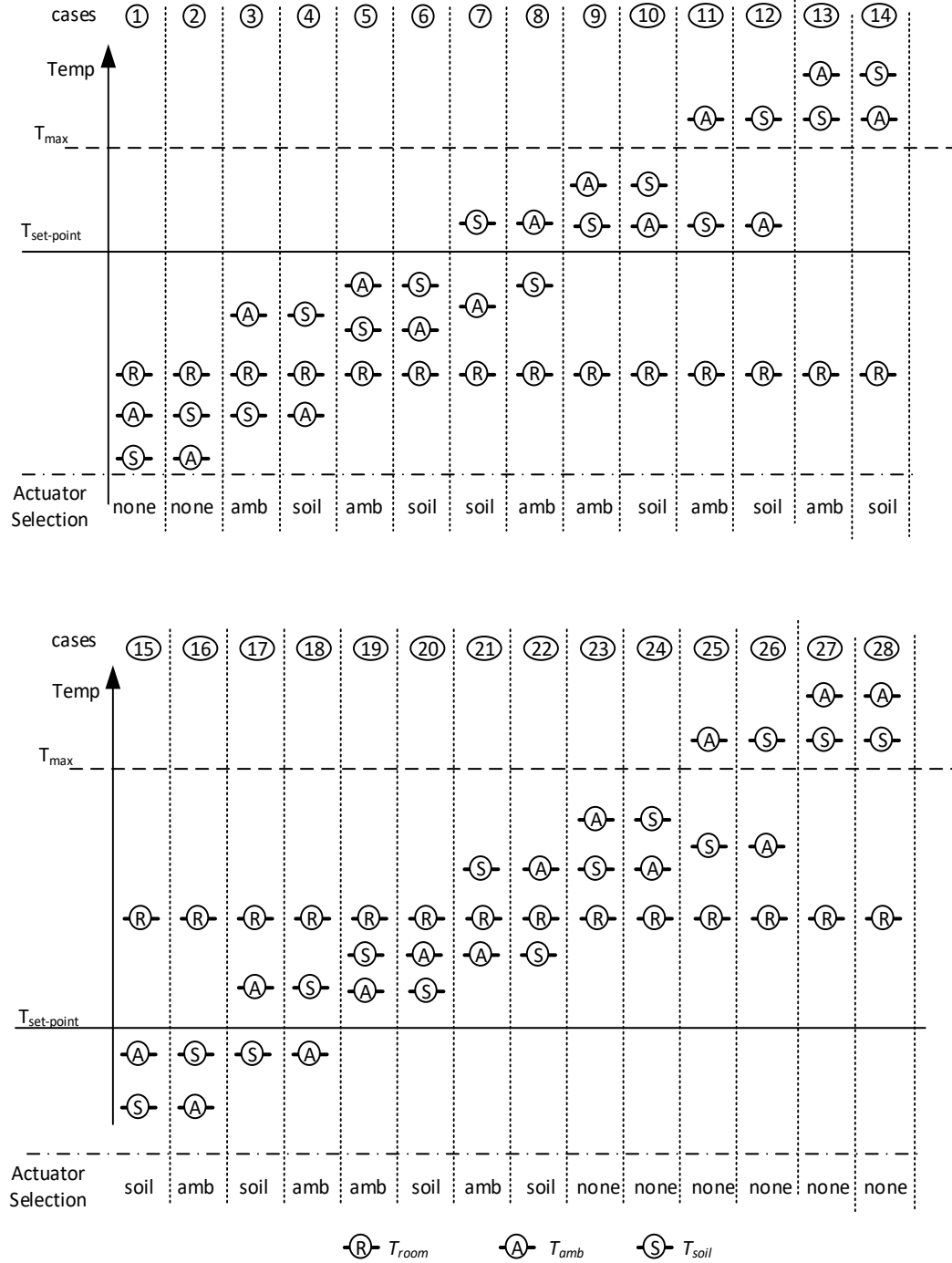
Figure 9: All possible scenarios of room, ambient and soil temperatures

Table 4: Error scenarios and decision

Room Error	Actuators Error	Decision
$e_{room} > 0$	$e_{soil} > e_{room}$, $e_{amb} > e_{room}$	None
	$e_{soil} > e_{room}$, $e_{amb} < e_{room}$	Weather utilization (amb)
	$e_{soil} < e_{room}$, $e_{amb} > e_{room}$	Soil utilization (soil)
	$e_{soil} < e_{room}$, $e_{amb} < e_{room}$, $e_{amb} < e_{soil}$	Weather utilization (amb)
	$e_{soil} < e_{room}$, $e_{amb} < e_{room}$, $e_{soil} < e_{amb}$	Soil utilization (soil)
$e_{room} < 0$	$e_{soil} < e_{room}$, $e_{amb} < e_{room}$	None
	$e_{soil} > e_{room}$, $e_{amb} < e_{room}$	Soil utilization (soil)
	$e_{soil} < e_{room}$, $e_{amb} > e_{room}$	Weather utilization (amb)
	$e_{soil} > e_{room}$, $e_{amb} > e_{room}$, $e_{amb} > e_{soil}$	Weather utilization (amb)
	$e_{soil} > e_{room}$, $e_{amb} > e_{room}$, $e_{soil} > e_{amb}$	Soil utilization (soil)

II. Fan Fuzzy Logic Controller

a. Structure

A Sugeno fuzzy controller is designed for the fan controller with two inputs and one output. The main structure of the fan fuzzy controller is shown in Figure 10. The controller inputs are e_{room} and e_{soil} and the output is the percentage of the fans flow rate. This percentage is then processed to provide the number of fans running which

controls the overall flow rate from the GHE to the greenhouse room in real implementation. The processing of the fan controller output value is explained later in this section.
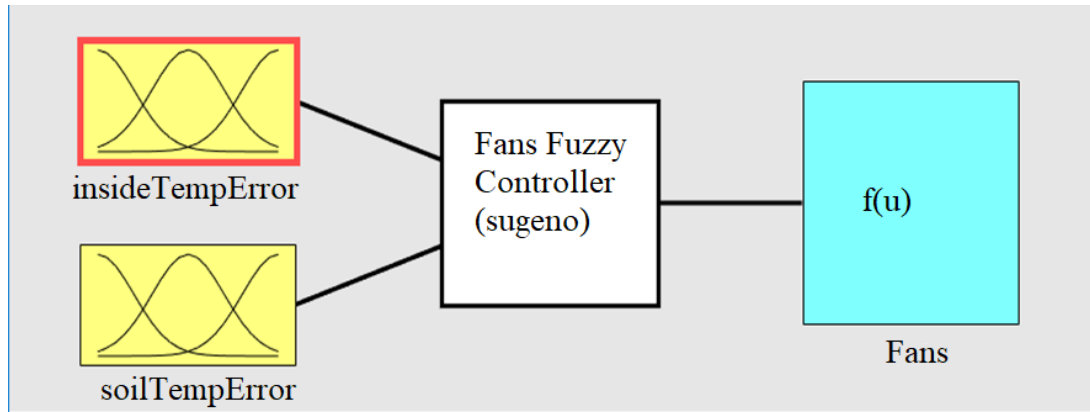
Figure 10: Fans fuzzy controller structure

b. Number of membership functions

Five membership functions are designed for the temperature input control. Based on agriculture experts, most crops optimum temperatures lie between 15℃ and 25℃ which are donated as T_{min} and T_{max} respectively. Therefore, the temperature in the greenhouse can be classified into cold, normal and hot where the temperature below the optimum range is cold, within it is normal and above it is hot. However, since the ground temperature at 2.5 meter depth is fluctuating between 27.1 and 32.5 as in Table 2, the use of ground heat exchanger when the greenhouse temperature is the same as the soil temperature will just consume power without providing any cooling to the system. Hence, the output of the fan fuzzy controller should be 0 in this case and an additional membership function is needed to detect this case. Also, to cover the temperature range for most of the crop, an extra membership function is added to separate between the cold and the very cold temperatures. For example, for the crops

that have an optimum temperature of 15°C, the minimum ambient temperature which is 9.8°C is considered cold but it is considered extremely cold for the crops that has an optimum temperature of 25°C. The membership functions are extremely cold, cold, normal, hot and extremely hot.

c. Limits of membership functions

Deciding the limits of the input variables is done based on the meteorological data presented in section 3.1.1. Also, deciding the limits of each membership function is done with the guidance from agricultural experts who consider the crop optimum temperature and humidity and the UAE imbalance hot and dry climate. The limits of the membership functions are found for each variable as the following:

Two ranges have to be considered when designing the membership functions which are the total range and the membership functions ranges, as illustrated in Figure 11. Finding the total range of each input variable is important to avoid having values beyond this range which may cause a drop in the controller performance. For example, if the total range is set to be between 10 and -10 and an error is found to be -12, the controller may crash at this point or make a random decision. The total range design has to ensure that all the errors values lie in the range and margins can be added to the total range without affecting the fuzzy decision. Since most of crops grow in temperatures between 15°C to 25°C and the ambient temperature varies between 47.1°C to 9.8°C the total error range for the room temperature error is between $[(T_{min} - T_{max,ambient}), (T_{max} - T_{min,ambient})]$ assuming the ambient air temperature propagates to the greenhouse room with some attenuation and delay. Also, since the soil temperature at 2.5 meter length varies between 32.5°C to 27.1°C, the error range for the soil temperature is between $[(T_{min} - T_{max,soil}), (T_{max} - $

$T_{min,soil}$)]. Since the soil temperature depends mainly on the GHE design and configuration, a margin is added to the soil temperature error which will generalize the designed input variable without affecting the controller decision. For the membership functions range limits, the crisp input of the greenhouse room temperature error is shown in table 5. The range of each membership is found by the plant tolerance of each status. For example, most crops have ±2°C tolerance for optimum temperature set-point. Lettuce has an optimum temperature between 21°C and 25°C and therefore the set point is selected to be 23 and the ±2°C is considered in the zero membership function range.

Although some cases may not appear with the current GHE and the temperature set-point, the input ranges are designed to cover all the cases even when the set-point is changed, or the soil temperature which is affected by the GHE design is changed.
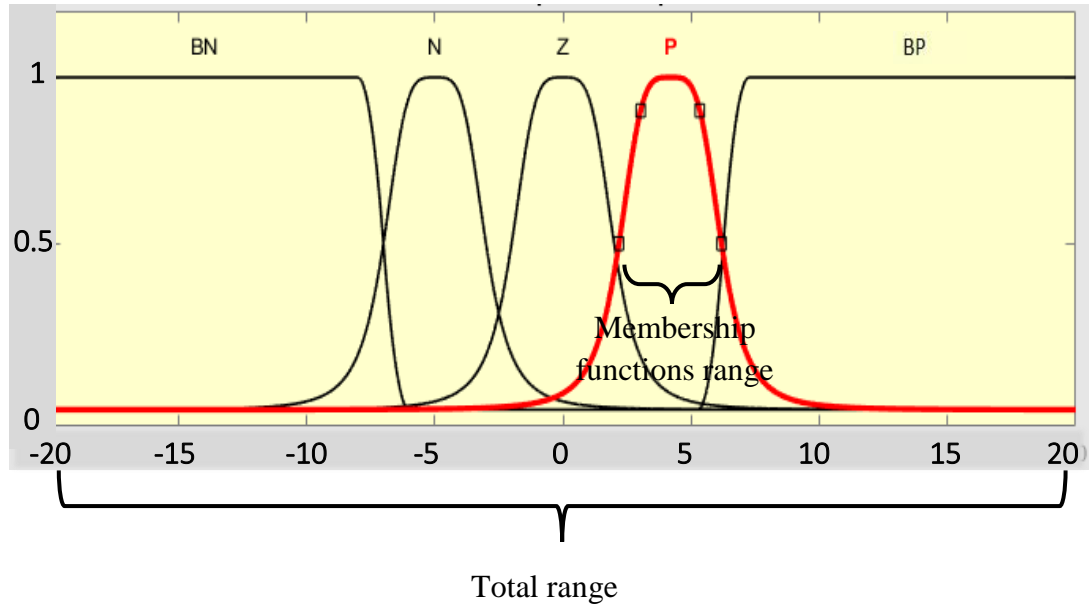

Figure 11: Membership function range and the total range

Table 5: Crisp input range of greenhouse room and soil temperatures errors

Crisp Input Range of the error	Fuzzy Membership Name	Temperature physical meaning
<-7	Big Negative (BN)	Extremely hot
-2 to -7	Negative (N)	Hot
-2 to 2	Zero (Z)	Normal
2 to 7	Positive (P)	Cold
>7	Big Positive (BP)	Extremely cold

d. Shape of membership functions

Deciding the shape of the membership functions is important for taking the correct decisions. The choice of membership function shape is based on providing smooth transition in inputs status which will affect the outputs and the actuators operation and maintenance cost as well. Also, the membership function's shape should equally accommodate the range at which the controlled variable is optimum. Figure 12 shows the most common membership functions of the fuzzy controller and the selection criteria for each input variables follows.

Z-shape membership function is selected to cover the temperatures errors for the extremely cold conditions. The slope of this function is found by trial and error approach.

For the middle membership functions, the triangular, gaussian and dsigmoidal membership functions are eliminated because they cannot provide an equal weight to the acceptable temperature range. The trapezoidal membership function is also eliminated because it cannot provide smooth transition in input variables. Gbell,

gaussian2 and pi-shape all can be used because they provide an equal weight to the temperature range and smooth transition for the input variables. Therefore, the gbel membership function is selected with the slope of both sides is determined by trial and error method.

For extremely hot temperature error, the s-shape or sigmoidal membership functions can be selected to cover the temperature. The s-shape membership function is selected with the slope is found by trial and error approach. Figure 13 shows the final design of the greenhouse room temperature error and Figure 14 shows the final design of the soil temperature error.

Triangular	Trapezoidal
Gaussian	Gbell
Dsigmoid	Gaussian2
Pi-shape	Z-shape
S_shap	Sigmoidal
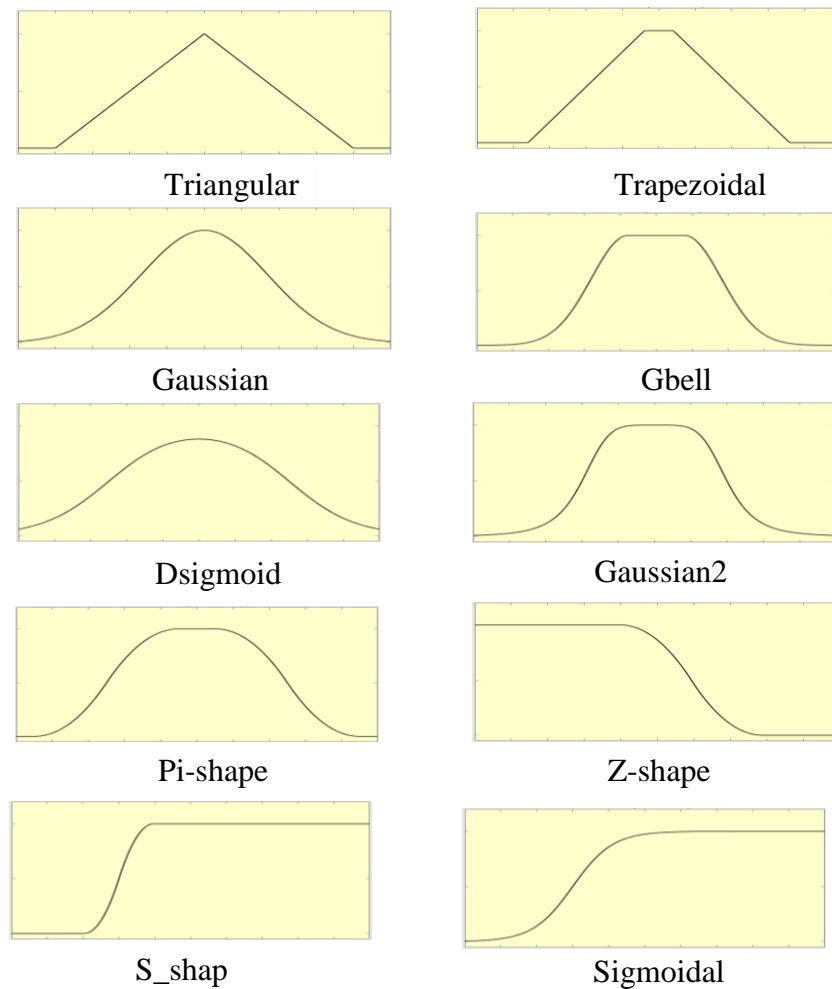
Figure 12: Fuzzy membership functions
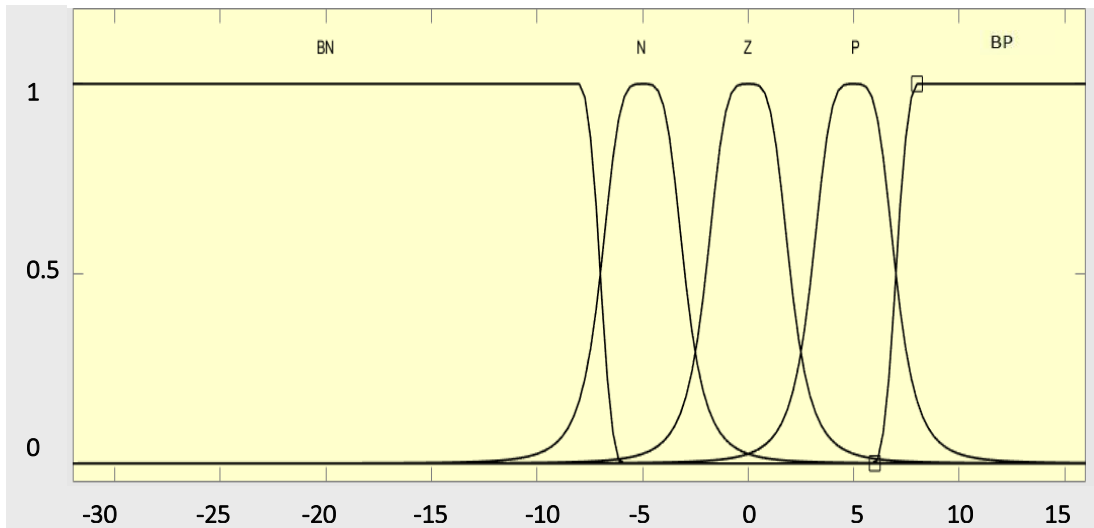
Figure 13: Greenhouse room temperature error input design
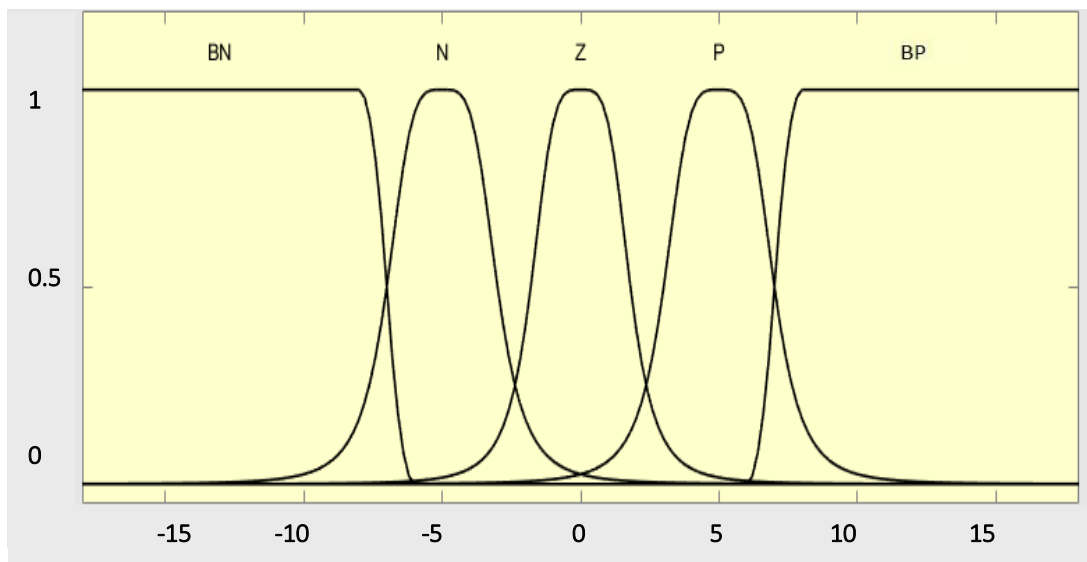
Figure 14: Soil temperature error input design

e. Fans controller output

Five membership functions are selected with constant values type and parameters of 0, 25, 50, 75 and 100 to represent the fans controller output. The output of the fan fuzzy controller is processed in real implementation to provide the number of fans running to the system. For example, if the percentage between 0 and 25 one fan is

commanded to run and if it is between 25 and 50 two fans are commanded to run and so on. Different interpretation can be done of fans fuzzy output depending on the hardware implementation and the system set-up. Figure 15 shows the output membership functions of the fans fuzzy controller. The defuzzification process is explained later in this chapter.
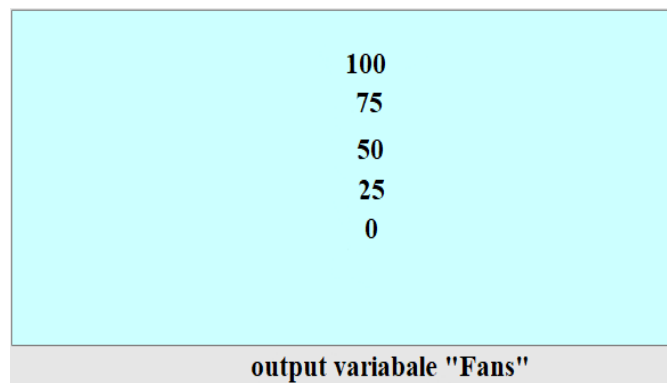
Figure 15: Fans fuzzy controller output membership function

f. Fuzzy rules

The fuzzy rules shown in Table 6 are designed based on the following facts (based on experts' inputs):

1- Considering the UAE hot and imbalanced climate, when the outside temperature is cold (winter season) the heat exchanger will be in heating mode.

2- When outside temperature is hot or extremely hot (summer season), the heat exchanger will be in pre-cooling mode where an extra auxiliary cooling unit may be needed.

3- Since the temperature has dominant effect on plants growth, more weight is given to maintain the inside temperature than the inside humidity as

advised by the agricultural experts. The humidity is only looked at when the inside temperature is tolerated.

4- Plant diseases and fungi are expected when the environment is moist.

5- The speed of the fans for optimum heat exchanging is tested before running the system and all the fans are adjusted to run at that speed.

6- Since the heat removed or pumped is proportional to the air flow rate and the temperature differences, if the temperature difference is low, then a high airflow speed is required. But if the temperature difference is high, a lower airflow speed can be used. If there is no temperature difference, then there is no need to run the fans.

7- In heating mode, the fan effort can be reduced slightly, as colder weather is less harmful for plants as compared to the hot weather.

The highlighted cells in Table 6 show the cases when an auxiliary cooling/heating unit should be running. Also, Figure 16 shows the temperature control surface of the fans.

Table 6: Fuzzy rules for temperature control for fans

$e(t)_{room}$ / $e(t)_{soil}$	BN	N	Z	P	BP
BN	100	0	0	25	25
N	100	0	0	50	50
Z	100	100	0	100	75
P	75	75	0	0	100
BP	50	50	0	0	0
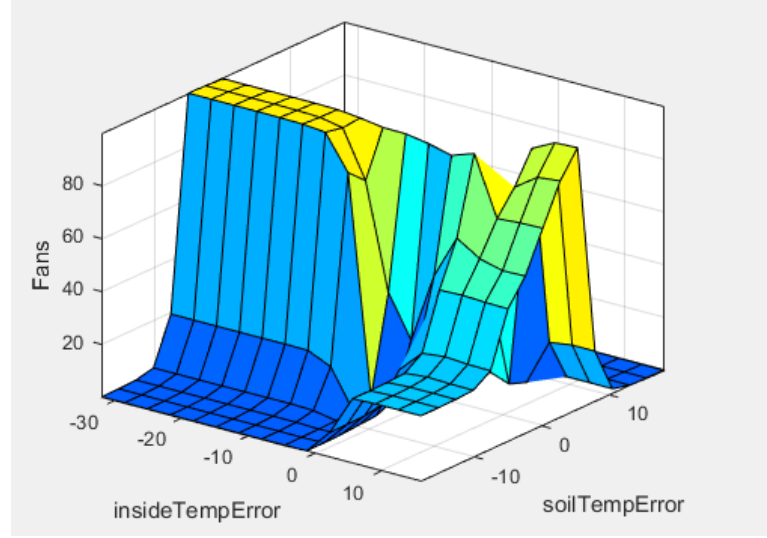
Figure 16: Fuzzy surface of the fans temperature control

III. Window Fuzzy Logic Controller

a. Structure

A Sugeno fuzzy controller is designed for controlling the greenhouse windows to maintain the greenhouse temperature and humidity. The controller has five inputs which are e_{room}, $e_{ambient}$, $e_{inside\ humidity}$, $e_{outside\ humidity}$ and e_{wind} and one output which is the windows linear actuators extraction/retraction. Figure 17 shows the main structure of the windows fuzzy controller.
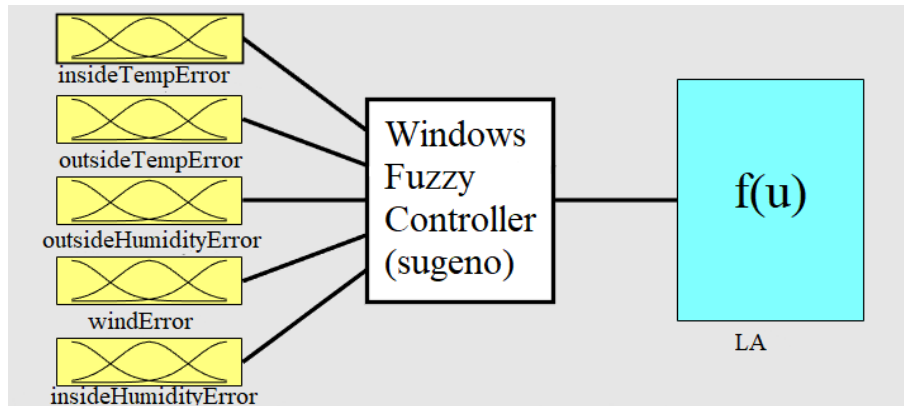
Figure 17: Windows Fuzzy controller structure

b. Number of membership functions

Temperature

The number of temperature error membership functions follows the same selection criteria as described in the fans fuzzy controller. Accordingly, five membership functions are selected to represent the temperature error input variables in the windows fuzzy controller.

Humidity

The crop humidity is only maintained when the temperature is tolerable and is classified as wet normal or dry. For many crops the optimum humidity is within 50% to 70%, as advised by agriculture experts. Based on Table 2, the UAE relative humidity varies from 5% to 100% with an average of 42.6%. Therefore, the humidity can be classified into dry, normal or wet and hence three membership functions are designed for humidity control.

Wind Speed

Wind speed is only considered when operating the windows and it can be classified either strong or acceptable. Therefore, only two membership functions are needed to represent the wind speed status.

c. Limits of membership functions

Temperature

The total limit of the room temperature error input is the same as the one found in the fans controller. However, the total limit of the ambient temperature error input is $\left[\left(T_{min} - T_{max,ambient}\right), \left(T_{max} - T_{min,ambient}\right)\right]$. The crisp input of the

greenhouse room temperature and ambient temperature errors is described in table 5 where the same range is followed as the room and soil error.

Humidity

Humidity control happens through utilizing of weather conditions whenever the temperature is tolerable. The inside humidity error is calculated by $e_{inside\ humdity} = H_{setpoint} - H_{inside}$ and the outside humidity error is found by $e_{outside\ humdity} = H_{setpoint} - H_{outside}$. Based on the fact that the UAE humidity varies between 0% and 100% and most crops lives in humidity 50% -70%, the humidity error range is $\left[(H_{min} - H_{max,ambient}), (H_{max} - H_{min,ambient})\right]$. Table 7 shows the crisp input error of the inside and outside humidity.

Table 7: Crisp input range of humidity error variable

Crisp Input Range of the error	Fuzzy Membership Name	Humidity physical meaning
<-10	Negative (N)	Wet
-10 to 10	Zero (Z)	Normal
>10	Positive (P)	Dry

Wind Speed

Wind speed error is calculated by $e_{Wind} = W_{setpoint} - W_{measured}$. If the wind speed is greater than or equal to the maximum acceptable wind speed, then the windows are closed to ensure safe environment and operations. The wind is considered strong at speeds higher than 28 km/h which is classified as Near Gale in Beaufort Wind scale [44]. Accordingly, and considering the UAE wind speed which varies between 0

km/h and 52 km/h, the wind speed error limits varies between -24 and 28 where the negative value represents a strong wind status.

d. Shape of membership functions

Temperature

The design criteria of selecting the temperature error of the fans controller is followed in the temperature error of the windows controller. Figure 18 shows the final design if the ambient temperature error input variable.
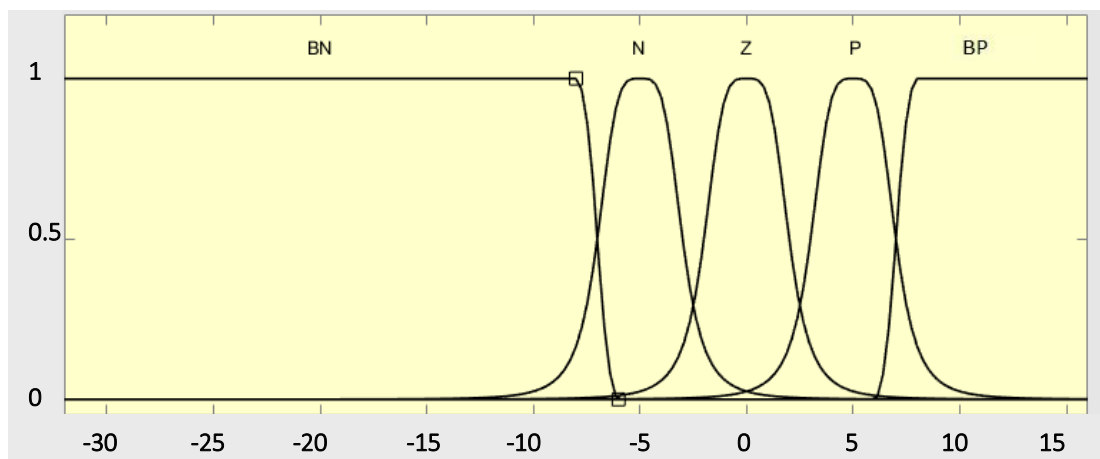
Figure 18: Ambient temperature error input variable design

Humidity

Three ranges are considered for humidity error input variable as shown in Table 7. The zero-membership function is the best that can cover the humidity error below the minimum range. The slope of this function is found by trial and error approach. The middle membership function which represents the normal range is selected to have a gbel shape with the same criteria used in selecting the middle temperature membership function. The slope is also determined by the trial and error approach. Humidity error above the maximum value is represented by s membership functions

and the slope is found by trial and error approach. Figure 19 shows the final design of the humidity error membership function.
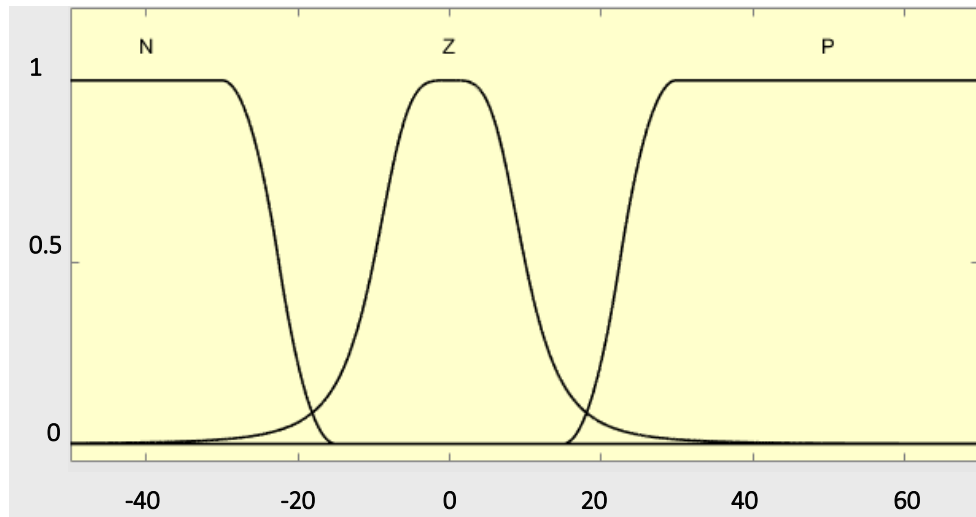
Figure 19: Humidity input variable design

Wind Speed

The membership functions of the wind speed input are designed so that gradual window closure percentage as wind speed approaching the maximum acceptable limit. The linear actuator started to decrease gradually and smoothly at speeds higher than 26 km/h (7.2 m/s) until it fully closes at speed equal or higher to 28 km/h (7.8 m/s). The z membership function is used to cover the acceptable range of the wind speed error and the s membership function is used to cover the strong range of the wind speed error. The slope of both membership functions is found by trial and error approach. Figure 20 shows the final design of the wind speed input variable.
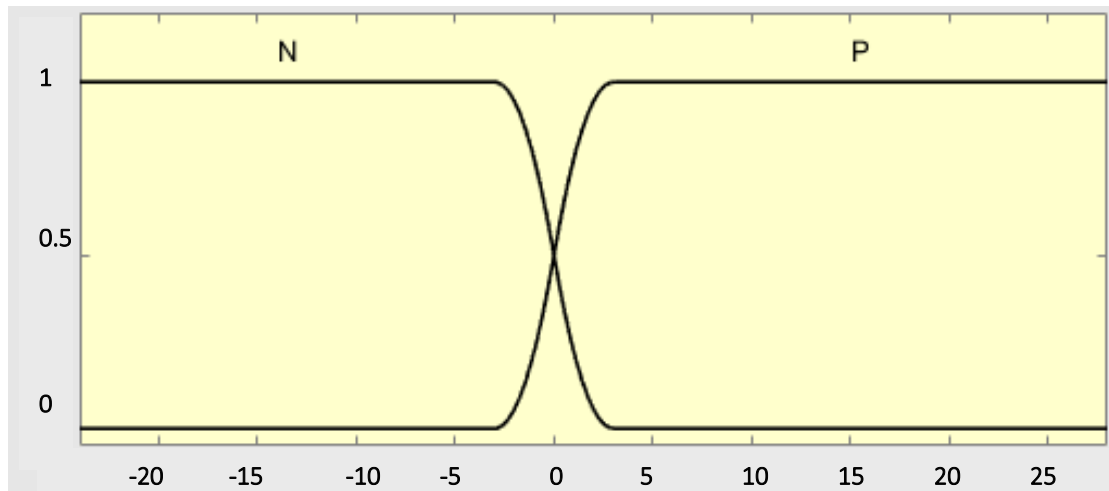
Figure 20: Wind speed input variable design

e. Windows controller output

Five membership functions are selected with constant values type and parameters of 0, 25, 50, 75 and 100 to represent the windows opening percentage. The output of the fuzzy controller is processed before transmitting it to the actuator in real implementation. For example, if the output of the fuzzy controller is y and the linear actuators need x time to fully open (100%), the power flows to the actuator for a time equal to $y * x / 100$. Also, the previous state of the linear actuator is always considered before switching the power circuit. For example, if the windows actuators are commanded to open 50% at time $t1$ and then commanded to open 60% at $t2$, the power will flow to actuators for time equals $(60 - 50) * x/100$. Figure 21 show the output membership function of the windows fuzzy controller.

100
75
50
25
0

output variabale "LA"
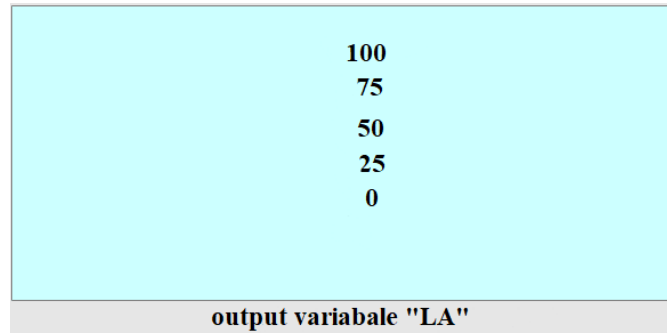
Figure 21: Windows fuzzy controller output membership function

f. Fuzzy rules

The fuzzy rules of the ambient temperature control are shown in Table 8 and the fuzzy surface if the temperature control is shown in Figure 22. The highlighted cells in Table 8 show the cases at which the temperature is tolerable, and the humidity control is allowed.

Table 8: Fuzzy rules for temperature control for windows

$e(t)_{room}$ / $e(t)_{amb}$	NB	N	Z	P	PB
NB	0	0	0	25	50
N	50	0	0	25	50
Z	100	100	100	100	100
P	75	50	0	0	50
PB	100	75	0	0	0
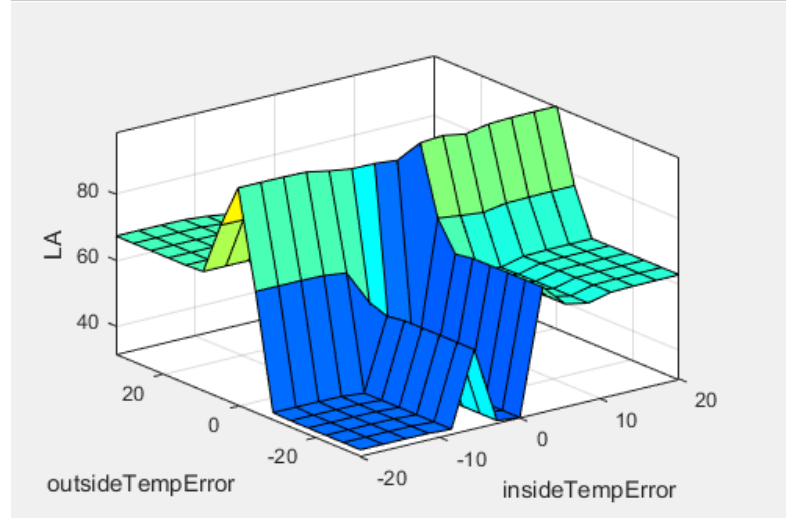
Figure 22: Fuzzy surface of the windows temperature control

To control the humidity, the rulers of the windows actuators are extended to include the humidity input variable whenever the outside temperature is tolerable (i.e. cold or normal). Table 9 represents the action taken for humidity control assuming the wind speed is always acceptable (if it is not, the outside humidity cannot be utilized). As described in Table 7, if inside humidity is negative (wet) and the outside humidity is positive (dry) or vice versa, the windows are commanded to open 75% to adjust the greenhouse humidity. Also, if the outside humidity is within the acceptable range, the windows are commanded to open 100%.

Table 9: Fuzzy rules for humidity control

$e(t)_{out.hum}$ ╲ $e(t)_{in.hum.}$	N	Z	P
N	0	0	75
Z	100	100	100
P	75	0	0

IV. Defuzzification

The defuzzification is the process of transforming the fuzzy results into a crisp output. Many methods are followed in defuzzification process such as Center of Sums method, Center of gravity method, center of area, weighted average method and maxima methods. For the designed Sugeno fans and windows fuzzy controllers, the weighted average, also known as weighted average of all rule outputs (wtaver), method is followed to defuzzify the results.

a. Weighted average method

This method is valid for fuzzy sets with symmetrical output membership functions and produces results very close to the center of area method. This method is less computationally intensive. Each membership function is weighted by its maximum membership value where the output is calculated by

$$Defuzzification \text{ output} = \frac{\sum \mu(x)y}{\mu(x)}$$

Where x is the input variable, $\mu(x)$ is the corresponding membership function value of the input x and y is the output that is defined by the fuzzy rule.

b. Illustrative example

Considering the fans fuzzy controller, if the input value of e_{room} is -5, the N membership function has a degree of 1 and the Z membership function has 0.01 degree as shown in Figure 23. Also, if the input value of e_{soil} is 7 the degree of BP and P membership function is 0.5 as shown in Figure 24.
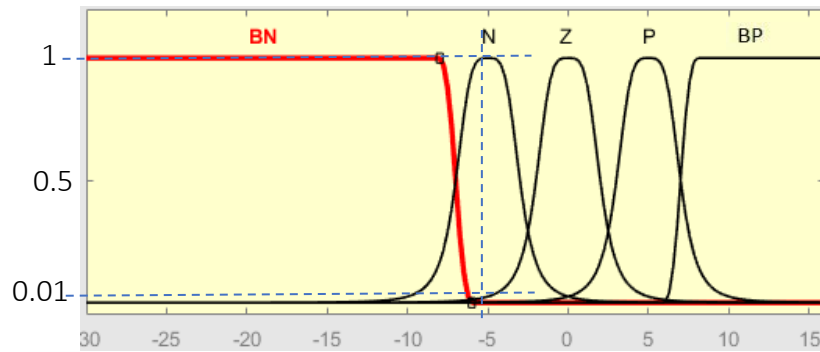
Figure 23: Membership function degree of the room temperature error input
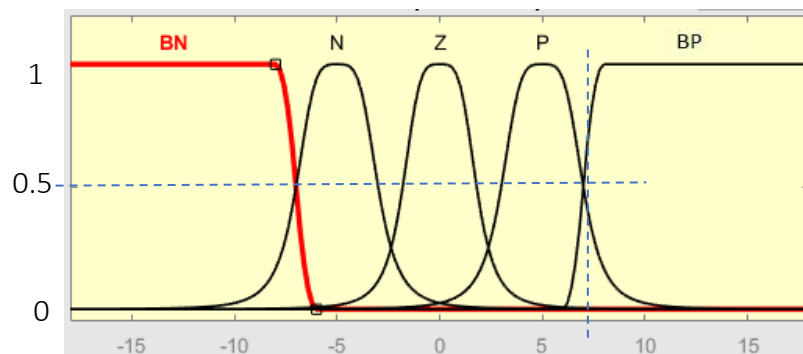
Figure 24: Membership function degree of the soil temperature error input

In addition, if the rules that are corresponding to theses input variables are as Figure 25 shows, the defuzzied output can be calculated as

$$Defuzzification\ output = \frac{75(1 + 0.5) + 50(1 + 0.5)}{1 + 1 + 0.5 + 0.5} = 62.5$$

1. If (insideTempError is N) and (soilTempError is P) then (Fans is 75) (1)
2. If (insideTempError is N) and (soilTempError is PB) then (Fans is 50) (1)

Figure 25: Corresponding fuzzy rules

Figure 26 illustrates in graphics how the defuzzification of the two input variables is done.
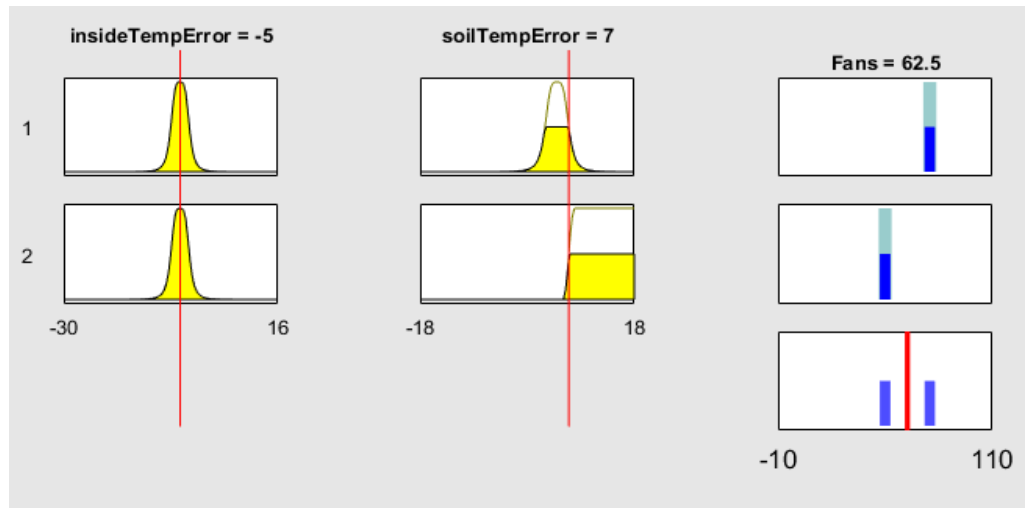
Figure 26: Defuzzification of the input variables

3.2.2.2 Logical GHC

A logical controller is developed with the same rules followed in the proposed fuzzy-based controller. The purpose of developing this controller is firstly to see the fuzzy-based controller effect on the actuators operations compared to the logical controller. Secondly, to investigate the greenhouse climate control using the logical and the fuzzy-based controllers and to study the effect of having smooth inputs membership functions and fuzzy outputs on maintaining the greenhouse environment.

The logical controller consists of the selector, which is discussed in the previous section, and a detailed if-then statements conditions for fans and windows control but with discrete output values. For example, in the fuzzy-based GHC, the percentage opening of the windows could be any value between 0% and 100%, however, in the logical GHC the percentages can be either 0%, 25%, 50%, 75% or

100% and no values in between can be selected. The conditions used in the logical controller are designed based on the fuzzy rules tables discussed before. Table 10 shows the conditions followed in designing the fans logical controller and Table 11 shows the conditions followed in designing the windows fuzzy controller.

Table 10: Logical GHC decision for fans output

Conditions	Action
$2 < e_{room} < 7 \ and -2 < e_{soil} < 2$	Run 100% (4 fan)
$e_{room} < -7 \ and -7 < e_{soil} < 2$	
$-7 < e_{room} < -2 \ and -2 < e_{soil} < 2$	
$e_{room} > 7 \ and \ 2 < e_{soil} < 7$	
$e_{room} < -2 \ and \ 2 < e_{soil} < 7$	Run 75% (3 fans)
$e_{room} > 7 \ and -2 < e_{soil} < 2$	
$e_{room} < -2 \ and \ e_{soil} > 7$	Run 50% (2 fans)
$e_{room} > 2 \ and -7 < e_{soil} < -2$	
$e_{room} > 2 \ and \ e_{soil} < -7$	Run 25 % (1 fans)
Else	No fan is running (0%)

Also, as mentioned before, the humidity is considered when the temperature is tolerable and the cases at which the humidity is considered are highlighted in yellow and shown in Table 11.

Table 11: Logical GHC decision for windows output

Conditions	Action
$-2 < e_{\text{amb}} < 2$	Open windows 100%
$e_{room} < -7 \; and \; e_{\text{amb}} > 7$	
<mark>$-2 < e_{\text{amb}} < 7 \; and \; -10 < e_{\text{out.hum}} < 10$</mark>	
$e_{room} < -7 \; and \; 2 < e_{\text{amb}} < 7$	Open windows 75%
$-7 < e_{room} < -2 \; and \; e_{\text{amb}} > 7$	
<mark>$-2 < e_{\text{amb}} < 7 \; and \; e_{in.\text{hum}} > 10 \; and \; e_{\text{out.hum}} < -10$</mark>	
<mark>$-2 < e_{\text{amb}} < 7 \; and \; e_{in.\text{hum}} < -10 \; and \; e_{\text{out.hum}} > 10$</mark>	
$e_{room} < -7 \; and \; -7 < e_{\text{amb}} < -2$	Open windows 50%
$-7 < e_{room} < -2 \; and \; 2 < e_{\text{amb}} < 7$	
$e_{room} > 7 \; and \; e_{\text{amb}} < -2$	
$e_{room} > 7 \; and \; 2 < e_{\text{amb}} < 7$	
$2 < e_{room} < 7 \; and \; e_{\text{amb}} < -2$	Open windows 25%
Else	Close windows (0%)

3.2.2.3 Conventional ON/OFF GHC

The ON/OFF controller is a simple feedback controller used typically in many temperature control applications. It is chosen for its simplicity in designing and implementation especially for the applications at which the process stability is not essential [45]. In typical applications, the ON/OFF controller is implemented as a thermostat where the sensed temperature is compared to a set value and the thermostat outputs either ON or OFF depending on the mode of operation and the measured

temperature. For example, if the thermostat is used in heating mode, the thermostat would output ON whenever the room temperature falls below the set point. On the other hand, if the thermostat is set for cooling mode, it outputs ON if the sensed temperature exceeds the set point. In any of the modes, the ON signal is simply to switch on the related heating or cooling unit. In conventional greenhouses, thermostats are the most common devices used for controlling heating and cooling equipment [45]. All types of thermostat such as the electrical, mechanical and differential thermostats work as a switch that is connected to the actuators power circuit as shown in Figure 27.
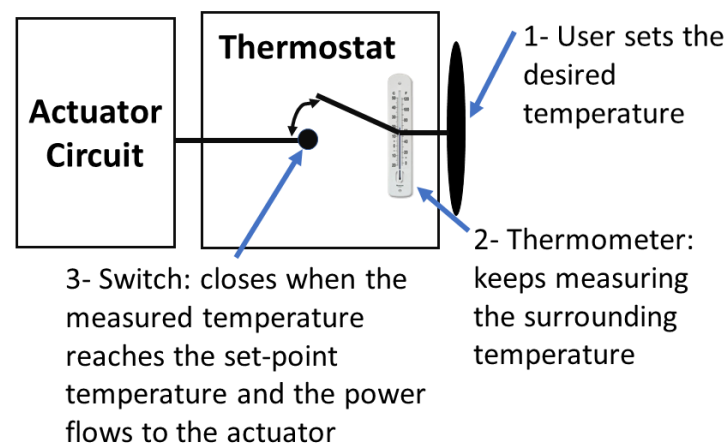
Figure 27: Thermostat working principle

For the newly developed greenhouse, the main idea is to use the outdoor weather conditions and the soil temperature in a favorite way to reduce the cooling demand on an AC unit. For plant cultivation, typically there is a recommended range of temperature which is denoted as Tmin, Tmax. Since there are two set points for the temperature variable and two actuators to be controlled (GHE, Windows), there should be no single thermostat but rather a combination of thermostats, temperature sensors

and comparators wired in a logic circuit to represent the ON/OFF controller logic as shown in Figure 28. It should be noted here that all thermostats used in this controller are cooling mode thermostats. The ON/OFF controller assigns the system actuators to either fully open or fully close (the control signal is either 0% or 100%) depending on the position of the controlled variable relative to the setpoint. Since two environmentally friendly heat sources are controlled in the proposed system, the controller commands the windows to open whenever the outside temperature is within the desired temperature range to allow heat transfer inside the greenhouse system. On the other hand, the soil temperature is used when the greenhouse temperature is above the maximum temperature and the soil temperature is below the greenhouse temperature which is a pre-cooling mode. Also, the soil temperature is used in heating mode when the greenhouse temperature is below the minimum desired temperature. Fans ON in this system means the GHE is running at full capacity (maximum flow rate) with the optimum speed. Running the four fans can be interpreted in other systems as having maximum heating/cooling flow rate from the heat exchanger.
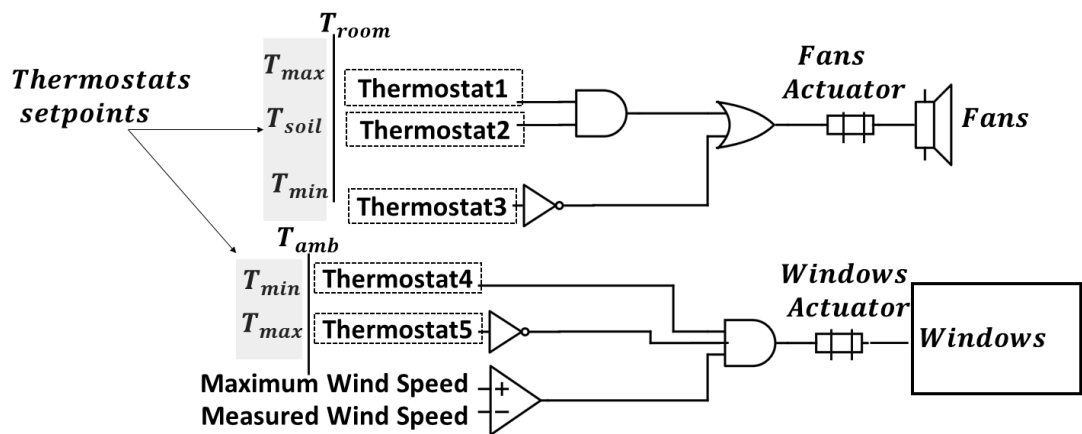
Figure 28: ON/OFF controller logic

3.2.3 Earth-to-Air Heat Exchanger Design

An EAHE is used to thermally exchange heat between fresh air and soil to allow a reasonable cooling with minimum energy and water consumption. The inlet of the heat exchanger is the outside air where a thermal exchange happens in eight PVC pipes buried 2.5 meter below the ground surface. The outlet of the heat exchanger is placed inside the greenhouse building to cool it down in summer and heat it up in winter. The heat exchanger is constructed with eight PVC pipes of 90 millimeter diameter, 2 millimeter thickness and 24 meter long. The pipes are laid horizontally and parallel to each other with 1 meter separation gap as shown in Figure 29.
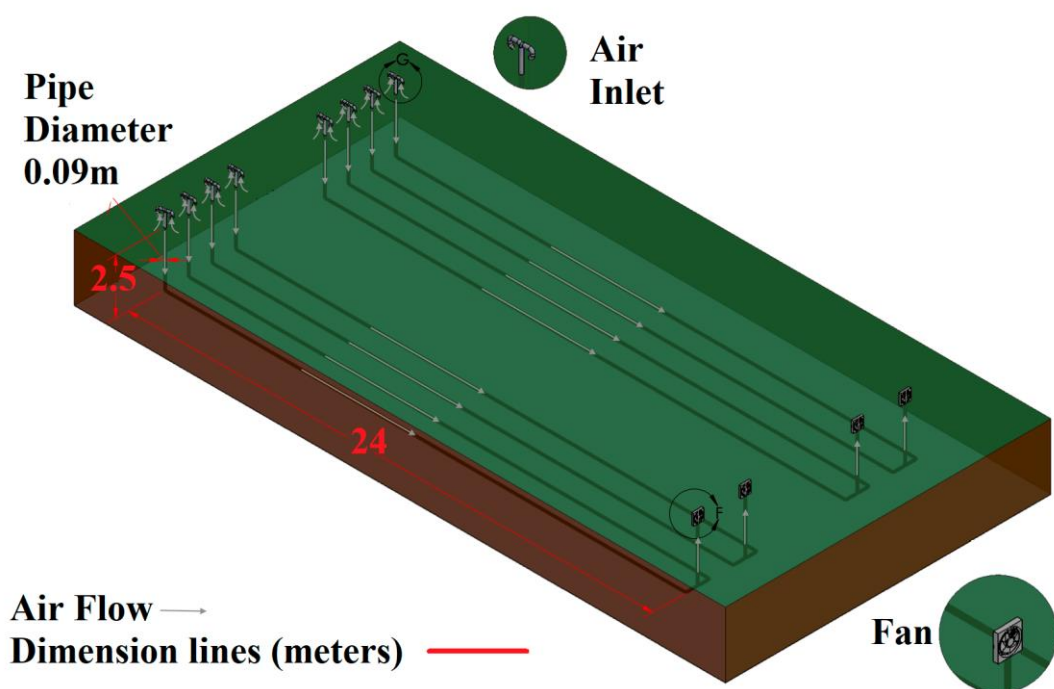
Figure 29: Schematic diagram of the proposed EAHE system

3.2.4 Greenhouse Design

An innovative greenhouse structure is built in one of the UAE University farms with the dimensions of 6 meter long, 4 meter wide and 2.5 meter high. The proposed greenhouse structure is thermally insulated and equipped with an EAHE system, four fans to extract heat from the ground, actuated windows, a sunlight collector system, and integrated with environmental condition sensors. Furthermore, since the greenhouse building is insulated, the plant sunlight exposure can only be allowed either through the actuated windows, if the weather permits, or using sunlight collector system. The greenhouse prototype and the ground heat exchanger are shown in Figure 30. The insulation material used in the greenhouse is Polyurethane foam which has a thermal resistance of 4.5 K·m^2/W at 100 mm and is shown in Figure 31.

Figure 30: The greenhouse porotype system

Figure 31: The greenhouse insulation material

3.2.5 Hardware Implementation
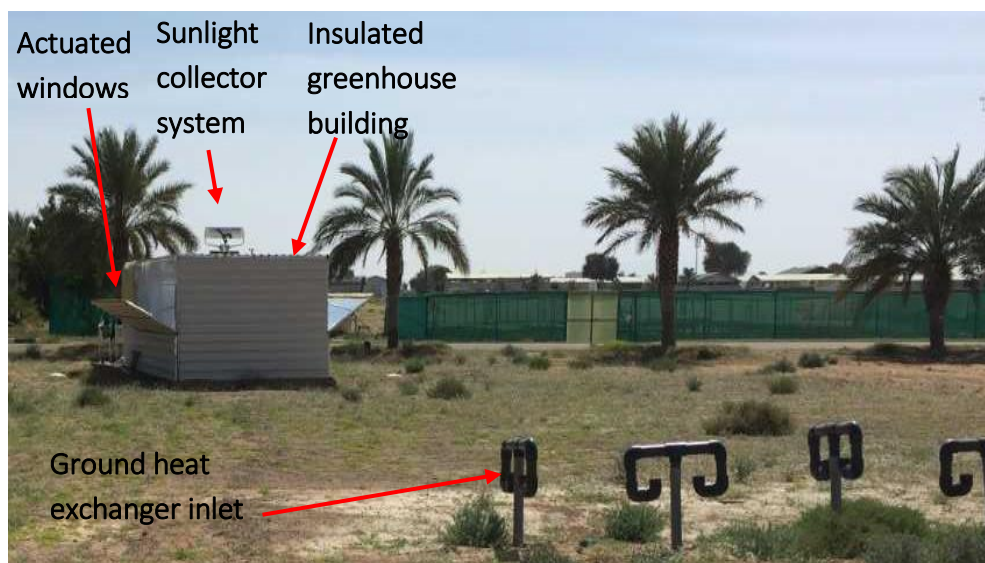
This part includes all the components and sensors that are used to implement the proposed controller experimentally in the greenhouse system. A wired sensor network is deployed based on agricultural requirements to provide more reliable sensory communication with the controller hardware. The measurements are collected by Arduino microcontrollers and logged in the MySQL database via a wired local area network (LAN). The detailed MySQL tables are included in Appendix A. In this section the hardware components are explained in detail with the specifications and the connection to the database and control system.

Sensors

Different environmental sensors are connected and deployed at different locations inside and outside the greenhouse system. The main criteria for selecting the system's sensors are to be weather proof, operates in high temperatures and can be easily integrated with the Arduino microcontroller. The sensors are elongated to cover all the greenhouse building and the signal integrity of the elongated sensors is tested. Also, four temperature sensors of type DS18B20 are deployed at the fans outlet to measure the GHE temperature.

The sensors that are used in controlling the greenhouse system are described in this section.

I. Temperature Sensor

Figure 32: DS18B20 waterproof temperature sensor

Specification:

- Digital Thermometers provide 9-bit to 12-bit Celsius temperature measurements

- Operates in -55ºC to +125ºC

- ±0.5ºC Accuracy reading of temperatures from -10ºC to +85ºC

- Connected to digital input pin

- Input voltage is 5 V

- Requires specific library and does not need calibration

II. Humidity and Temperature Sensor

Figure 33: DHT11 Digital Humidity and Temperature Sensor

Specification:

- Operates in 0 to 50ºC

- Humidity readings accuracy is 5% accuracy

- Temperature readings accuracy is ±2ºC

- Maximum of 1 Hz sampling rate (once every second)

- Connected to digital input pin

- Input voltage is 5 V

- Requires specific library and does not need calibration

III. Wind Speed Sensor

Figure 34: Wind speed sensor

Specifications:

- Testing Range: 0.5 m/s to 50 m/s

- Start wind speed: 0.2 m/s

- Resolution: 0.1 m/s

- Accuracy: Worst case 1 m/s

- Max Wind Speed: 70 m/s

- The sensor is connected to analog pin for data measurements

- Input voltage 7-24 VDC , Output: 0.4 V to 2 V

- No specific library is needed

- Calibration: the wind tunnel is used to calibrate the wind sensor where a linear relationship between the wind speed and the measured voltage is found as shown in Figure 35. The equation that related the wind speed with the measured voltage is in (5)

$$\text{Wind speed} = 7.6391 * \text{voltage} + 0.4282 \qquad (5)$$
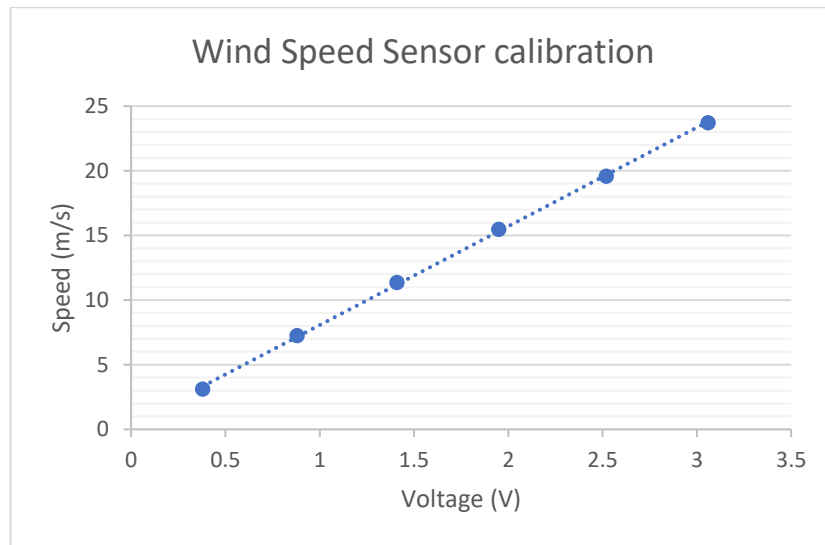
Figure 35: Wind speed sensor calibration

System Actuators

Two actuators are used in the proposed system which are fans and linear actuators. It is important to mention here that the fans selection criteria are related to the GHE design which is beyond the thesis scope. In addition, the choice of the linear actuator motors is done based on calculations that handles the needed torque and force for actuating the windows which is also beyond the thesis scope. However, the power of the fans is connected to a 240/110 transformer and controlled by a relay module connected to digital pins in the Arduino microcontroller. Moreover, the power of the linear actuators is provided by 12 VDC convertor that is controlled by a relay module connected to a digital pin in the Arduino microcontroller.

I. Fans

Figure 36: Inline fan

Specification

- Power: 68W Current: 0.62 A , 60 HZ

- Noise Level: 49 dB

- Fan speed: 2500 rpm

- Safe temperature range for operation: - 104ºF to 149ºF; Safe air-humidity

  range: 5% to 95% RH (Relative Humidity)

- Input voltage is 110 VAC

II. Linear Actuators

Figure 37: Linear actuator

Specification

- Draws 9 A (200 lbs); 7.6 A (600 lbs)

- Stroke 4 - 24 inches

- Force 200 lbs and 600 lbs

- Speed 0.39"/sec (600 lbs); 1.60"/sec (200 lbs)

- Operational Temperature -25ºC~+65ºC

- Noise db<45(A)

- Input voltage is 12 VDC

The fans installed in the greenhouse building that extract heat from the ground and the linear actuators which control the windows are shown in Figure 38.

| (a) | (b) |

Figure 38: The greenhouse actuators (a) inline fan (b) linear actuator

Micro-controller design criteria, programming and sampling rate

An open source, multiple digital and analog inputs pins, and multiple digital output pins microcontroller is needed to read the sensors measurements, sample the data and perform the controller decision. The Arduino-mega microcontroller is selected because of its compatibility with many sensors and its large number of inputs and outputs pins. It also can work in temperatures between -40℃ to 85℃ so it is safe to be placed inside the greenhouse protection from dust and water droplets. The specifications of the Arduino-mega micro controller used are listed below:

-Operating Voltage: 5 V

- Input Voltage (recommended): 7-12 V

- Input Voltage (limits): 6-20 V

- Digital I/O Pins: 54 (of which 14 provide PWM output)

- Analog Input Pins: 16

- DC Current per I/O Pin: 40 mA

 - DC Current for 3.3 V Pin: 50 mA

- Flash Memory: 256 KB of which 8 KB used by bootloader

 - Clock Speed: 16 MHz

Because of the slow dynamic of the greenhouse system, the Arduino reads the sensors measurements every two minutes. It then sends the data to the database via the ethernet shield, reads the controller outputs and sends the signal to two relays connected to 110 V and 12 V to control the fans and the linear actuators respectively. The code running in both Arduino controllers is shown in Appendix B.

Hardware connection with the database

MySQL to Arduino Connector is a library used to connect the Arduino with the database server. This library implements the MySQL client communication protocol where the SQL statements are encoded to insert data and run small queries in the MySQL server. The communication method recommended for this technology is the Ethernet wired communication which is based on the Wiznet W5100 ethernet chip. The Wiznet W5100 provides a network (IP) stack capable of both TCP and UDP. An Arduino ethernet shield is used to allow the communication between the database and the microcontroller.

Hardware Integration

Figure 39 shows the entire hardware layout where two Arduino microcontrollers are used for sensor measurements, sampling and sending control signals to the actuators and Figure 40 shows part of the real system connection. Figure 39 shows the Arduino mega micro-controller is supplied by 9 V power and the temperature and humidity sensors that are distributed inside and outside the greenhouse system are supplied with 5 V from the Arduino board. Also, two step-down power transformers are used in this system to operate the actuators. One to convert the 220 VAC socket power to 12 VDC with 30 A maximum current to power the wind speed sensor and the linear actuators and the other to convert the 220 VAC socket power to 110 VAC with 3 kW to power the fans. Since the maximum current drawn by each linear actuator motor is 9 A, and the two adjacent linear actuators have to operate together to open/close one window, a maximum current of 18 A is drawn when opening one window and a maximum 36 A is needed if the two windows are opening simultaneously. As we have a 12 VDC, 30 A power supply to the actuators, the two windows cannot open simultaneously. Therefore, six relay modules that work as single-pole single-throw switches are used to open/close the windows as shown in Figure 41. The relay works as the following, if the windows are commanded to open, switches 1,2 and 5 are closed for a specific time and then switch 5 opens and switch 6 closes to allow the power to flow to the other motors and open the other window. The same thing is done when closing the windows but with switch 3 and 4 closed to reverse the power direction. On the other hand, the four fans are connected to a 110 V power supply and controlled by a four inputs relay modules that also work as single-pole single-throw switches. Also, Figure 42 shows the integrated system closed loop flow.
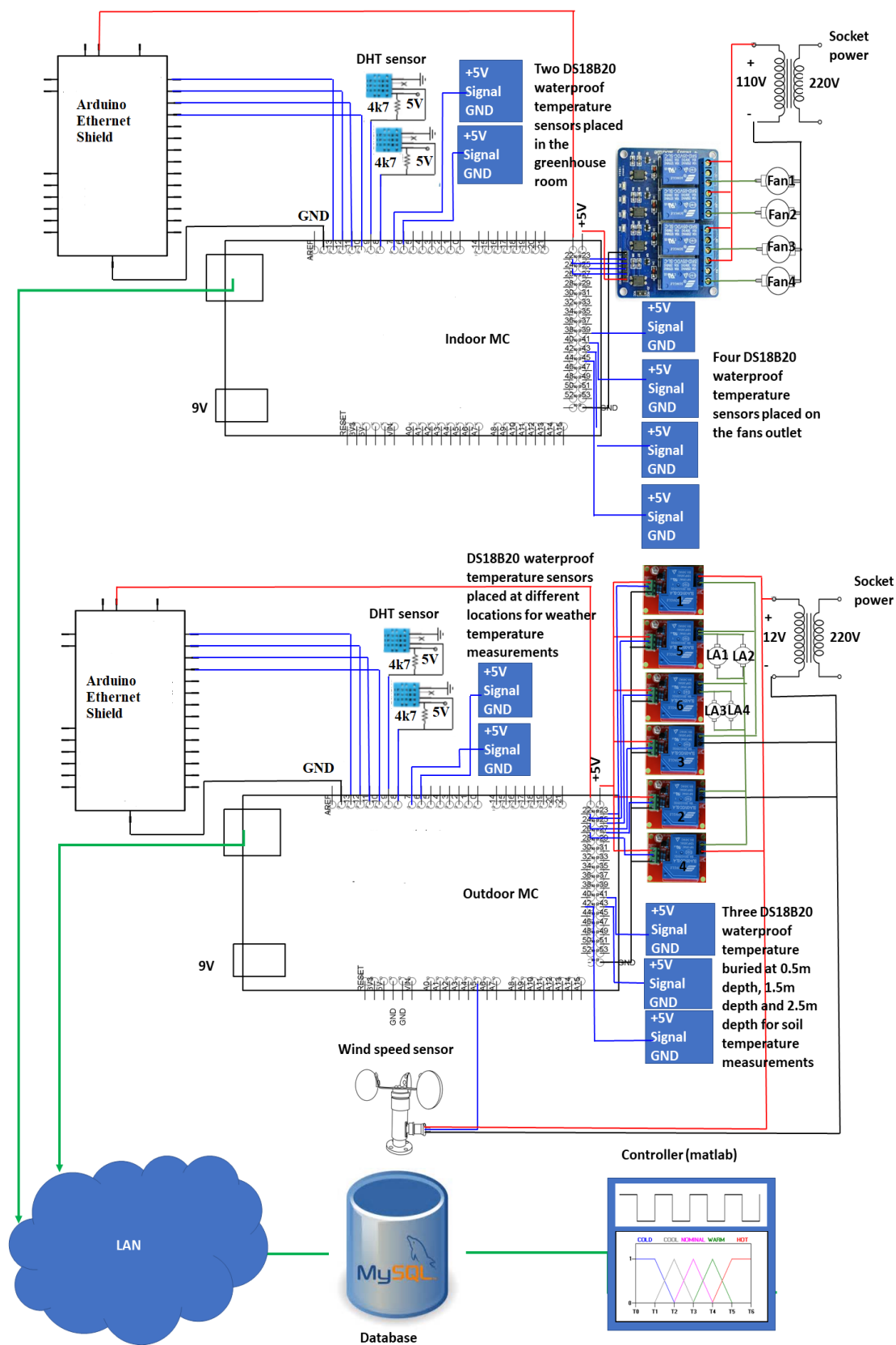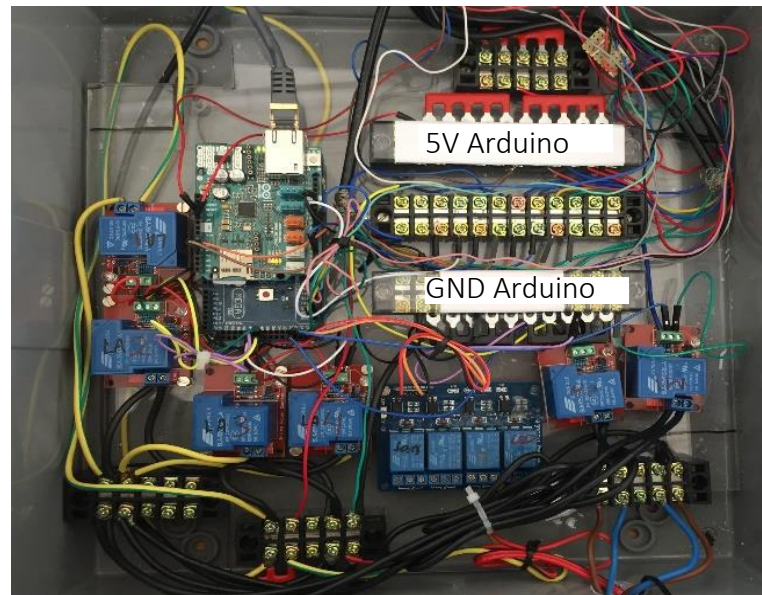
Figure 39: System layout
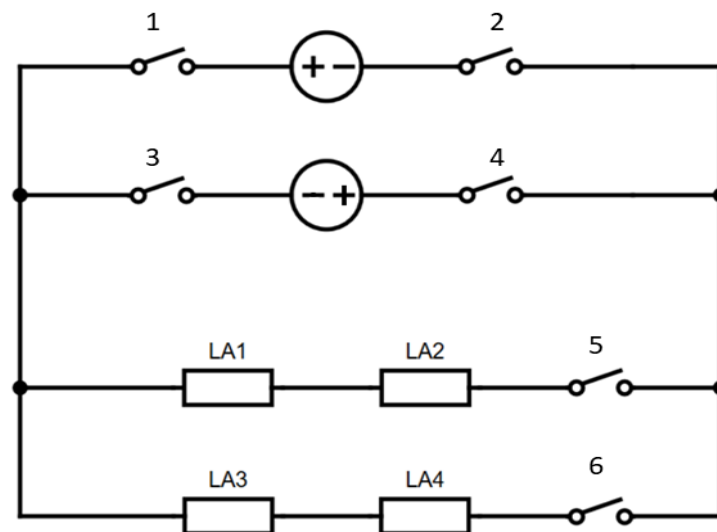
Figure 40: System connection
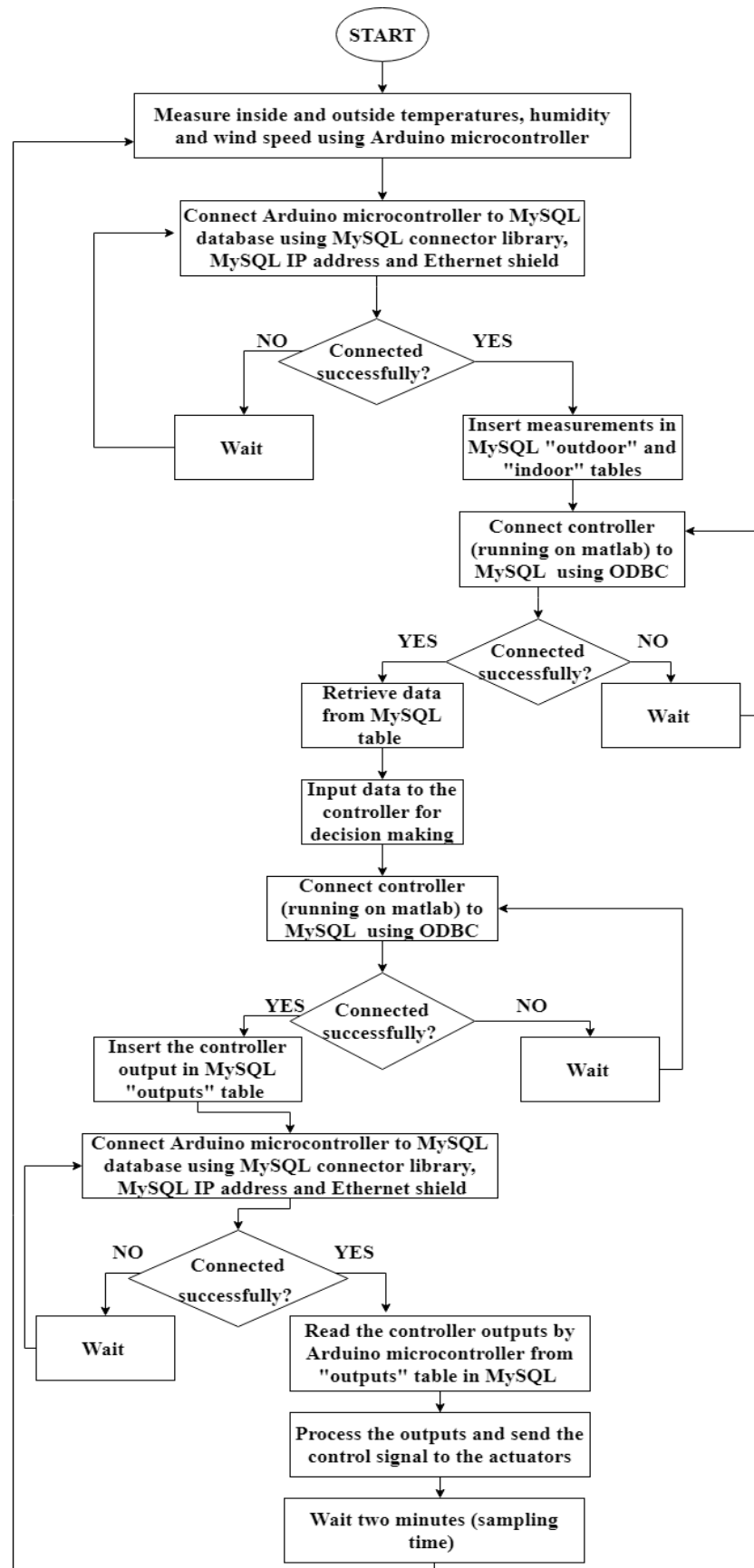

Figure 41: Linear actuator connection

Figure 42: Integrated system closed loop flow

3.2.6 Greenhouse Room Thermal Modeling

The purpose of modeling the greenhouse room temperature is to test the proposed controllers over one complete year and to compare the simulation results with the experimental ones. Assuming the heat is perfectly exchanged with the ground which means the outlet of the heat exchanger is equal to the soil temperature when enough flow rate is considered, the greenhouse room is modeled as the following:
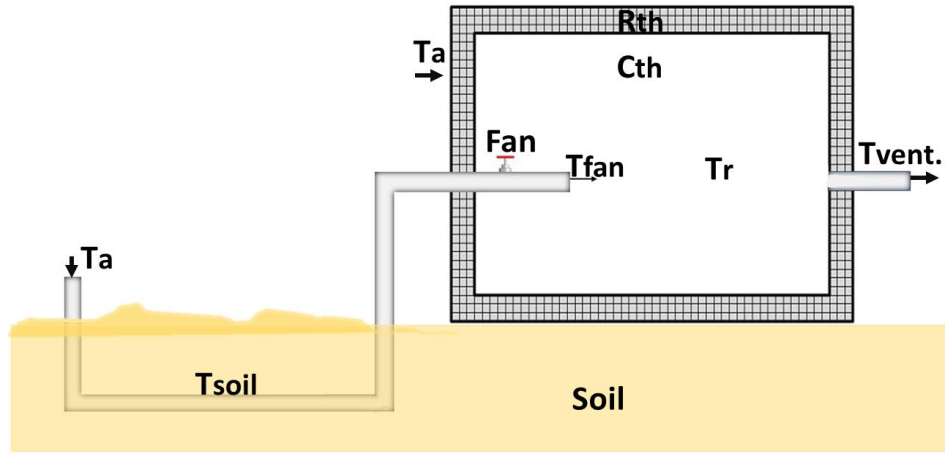
Figure 43: The greenhouse room thermal modeling

$$\dot{T}r = \frac{1}{C_{th}}[q_{in}(t) - q_{out}(t)] \tag{6}$$

$q_{in}(t)$ is the input heat flow in Watt and $q_{out}(t)$ is the output heat flow in Watt where:

$$q_{in,ambient}(t) = \frac{T_a(t) - T_r(t)}{R_{th}} \tag{7}$$

$$q_{in,fan}(t) = V_{air}(t) \times T_{fan}(t) \times C_p \times \rho_{air} \tag{8}$$

$$q_{out,vent.}(t) = V_{wind}(t) \times T_a(t) \times C_p \times \rho_{air} \tag{9}$$

All the parameters and variables are explained in Table 12.

Substituting equations 7, 8 and 9 in equation 6 we get:

$$\dot{T}r = \frac{1}{C_{th}} \left(\frac{1}{R_{th}} (T_a - T_r) + C_P \rho_{air} V_{air} (T_{fan} - T_r) + C_P \rho_{air} V_{wind} (T_a - T_r) \right) (10)$$

The value of $R_{th} C_{th}$ is found using experimental data by trial and error approach and

is equal to 10000. This value provides a good representation of the greenhouse room

model to study the controller performance.

Table 12: Greenhouse room thermal modeling parameters and variables

Parameter/ Variable	Description	Value	Unit
R_{th}	Thermal resistance of the greenhouse which equals to the thermal resistance at 100 mm divided by the greenhouse area at which the insulation material is used	4.5/(6*4+2 *6*2.5+2* 4*2.5) = 0.06	K.s/J
C_{th}	Thermal capacity of the greenhouse building which equals to $$\frac{10000}{R_{th}}$$	166666	J/K
C_p	Air specific heat capacitance	1000	J/[kg.K]
ρ_{air}	Air density at 22°C	1.225	kg/m³
$q_{in,fan}(t)$	Rate of thermal energy transferred from fan to the room		J/s
$q_{out,vent.}(t)$	Output heat flow due to windows opening		J/s
$q_{in,ambient}(t)$	Input heat flow from the ambient temperature		J/s
$V_{air}(t)$	Air volume flow rate from the GHE which equals to number of fans x air speed that exits from the fan x cross sectional area of the fan outlet right		m³

Table 12: Greenhouse room thermal modeling parameters and variables (Continued)

Parameter/ Variable	Description	Value	Unit
$V_{wind}(t)$	Air volume flow rate from the windows which equals to the cross-sectional area of windows opening x wind speed		m³
$T_{fan}(t)$	The GHE outlet temperature which is assumed to be equal to the soil temperature at 2.5 meter depth		K
T_a	Ambient temperature		K
T_r	Room temperature		K

3.2.7 Greenhouse Room Thermal Modeling Validation

To validate the greenhouse room temperature model, the greenhouse temperature is recorded experimentally for three consecutive days and plotted against the simulation results as shown in Figure 44. The simulation result matches the experimental result with small differences which validates the room temperature model derived in section 3.2.6.
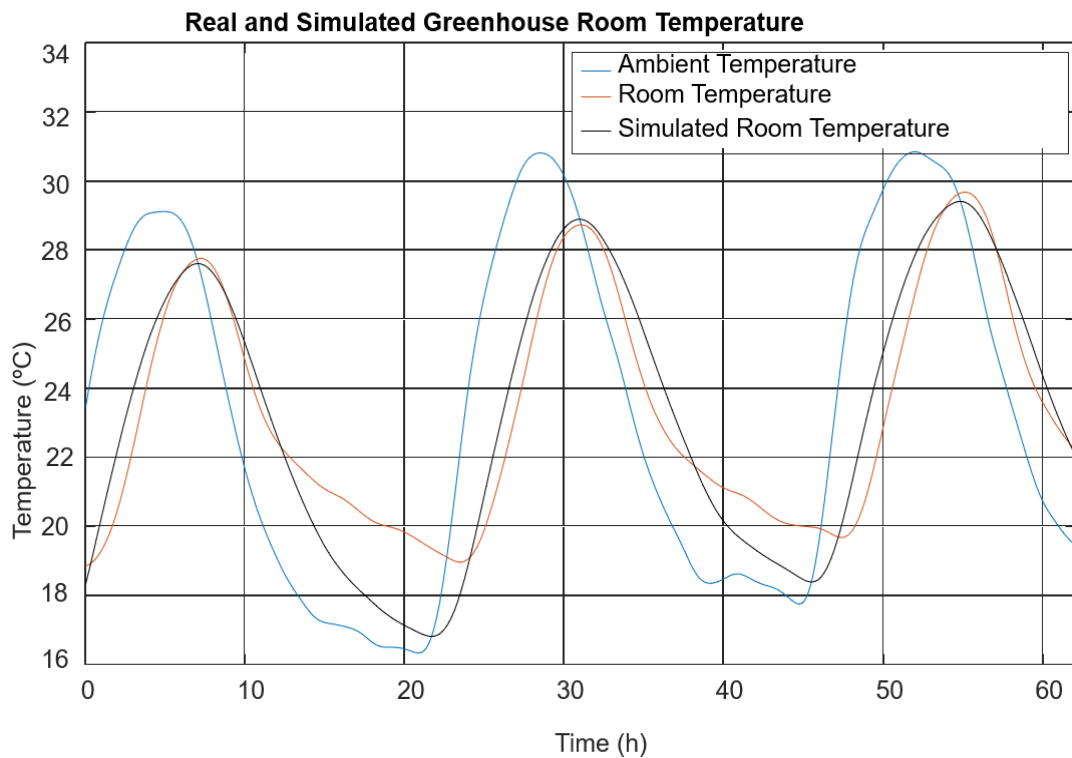
Figure 44: Real and simulated greenhouse room temperature

3.2.8 Greenhouse Room ANFIS Humidity Modeling

Artificial intelligent approaches including neural networks and fuzzy inference system have been widely used to model and predict complex systems and outputs. Testing the proposed controller in simulation requires a representative model for the greenhouse humidity. In literature, there are two ways to predict the greenhouse output variables which are the mathematical modeling approach and the black-box approach. Using the mathematical modeling for predicting the greenhouse humidity is complex because the system's variables are dependent on each other with different undetermined relationships. For example, if the windows are opened 80% and the wind speed, inside temperature, outside temperature and outside humidity have certain values, then finding the inside humidity is complex if a mathematical approach is developed because many dependent variables are involved in this model. Therefore,

using ANFIS system provides a good estimation of the inside humidity without the need of mathematical equations. To predict the greenhouse humidity, an adaptive neuro-fuzzy inference system (ANFIS), which is a fuzzy system that uses neuro-adaptive learning methods to determine the membership function parameters, is developed. Sugeno fuzzy inference system is designed with six inputs which are ambient temperature, ambient humidity, wind speed, room temperature, windows opening percentage and number of fans running. The predicted output of the ANFIS system is the greenhouse humidity. The purpose of using ANFIS in this system is to find a relationship between the inside humidity and the input variables and system actuators. All the required data are collected experimentally from the new greenhouse building over one month and used to model the inside humidity using the black-box approach. The output of the ANFIS system is the greenhouse humidity which is affected by the input variables and the actuators. To train the ANFIS system, about seven thousand samples are collected experimentally from the greenhouse system and used for training with hybrid optimization method and sub clustering technique. The structure of the ANFIS system is shown in Figure 45. The average testing error is 1.5 with 121 nodes and 8 fuzzy rules. Also, three thousand samples are used to test the ANFIS system. Figure 46 shows the trained ANFIS system with 10 epochs.
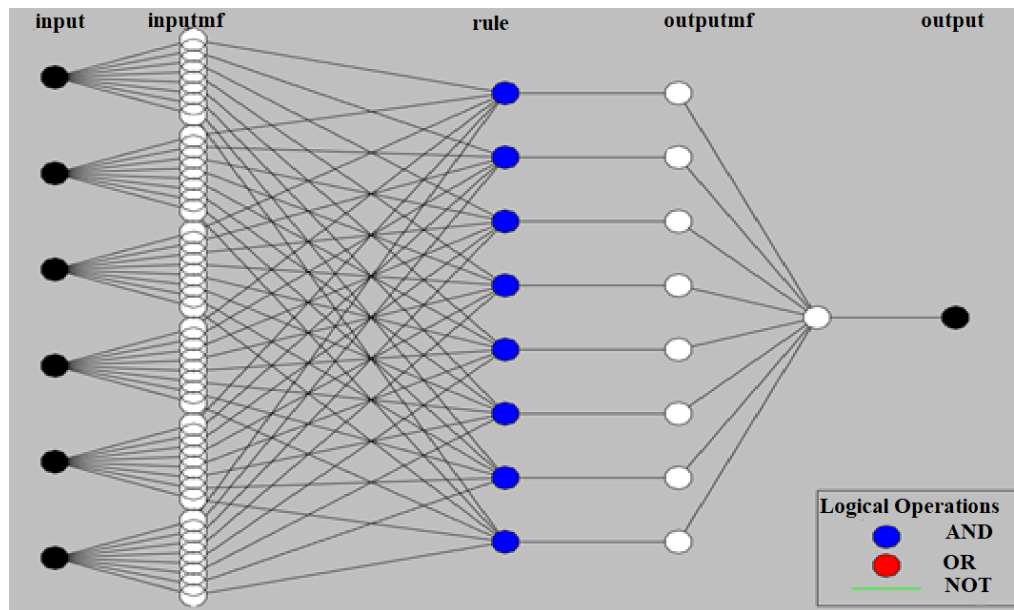
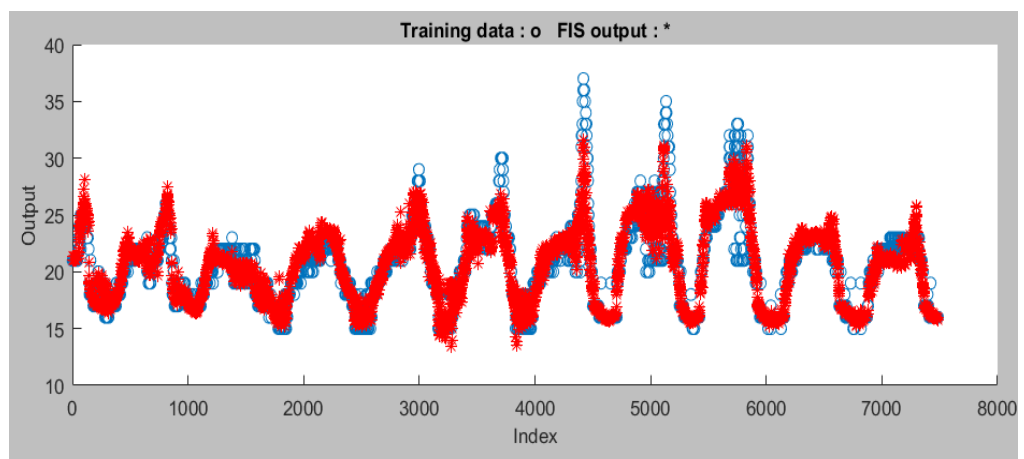Figure 45: ANFIS structure for greenhouse humidity prediction

Figure 46: Training results of the ANFIS system

Chapter 4: Results and Discussion

This chapter presents simulation and experimental results of the proposed fuzzy-based control architecture. The simulation is performed on the temperature and humidity control of the greenhouse using the mathematical model and artificial intelligence ANFIS model presented in Chapter 3. The performance of the fuzzy controller for controlling the greenhouse temperature is compared to the logical and conventional ON/OFF controllers. Model parameter evaluation for the GHE and the greenhouse as well as the control system performance are discussed thoroughly.

4.1 Greenhouse Temperature and GHE

4.1.1 Simulation Results

The greenhouse model is tested with the GHE set at various capacities to examine the capabilities of the GHE. Since the main driving thermal source is the ambient temperature, a one-year record of local temperature data is used to simulate the greenhouse model response over one year. Figure 47 shows the hourly real ambient temperature of 2016, the modeled soil temperature as per equation (1) and the response of the greenhouse model. The greenhouse model response is examined for five settings of fan operations, i.e. 0 fan, 1 fan, 2 fans, 3 fans and 4 fans running with GHE gain equals to 75%. It can be observed that when no fan is running, the greenhouse room temperature follows the ambient temperature with some attenuation and delay. However, when the GHE is utilized with one fan, the greenhouse temperature starts to follow the soil temperature with some fluctuation until it almost becomes the same as the soil temperature when four fans are running. In addition, the difference between greenhouse room temperature when four fans are running compared to when one fan

is running is about 1.5ºC. Moreover, running one fan makes the greenhouse system sensitive to the ambient temperature. However, when two, three or four fans are running the system is less affected by the ambient temperature. Moreover, the difference in temperature when running two, three or four fans is very small and hence the decision of the running number of fans depends on the required heating/cooling speed in the control system.
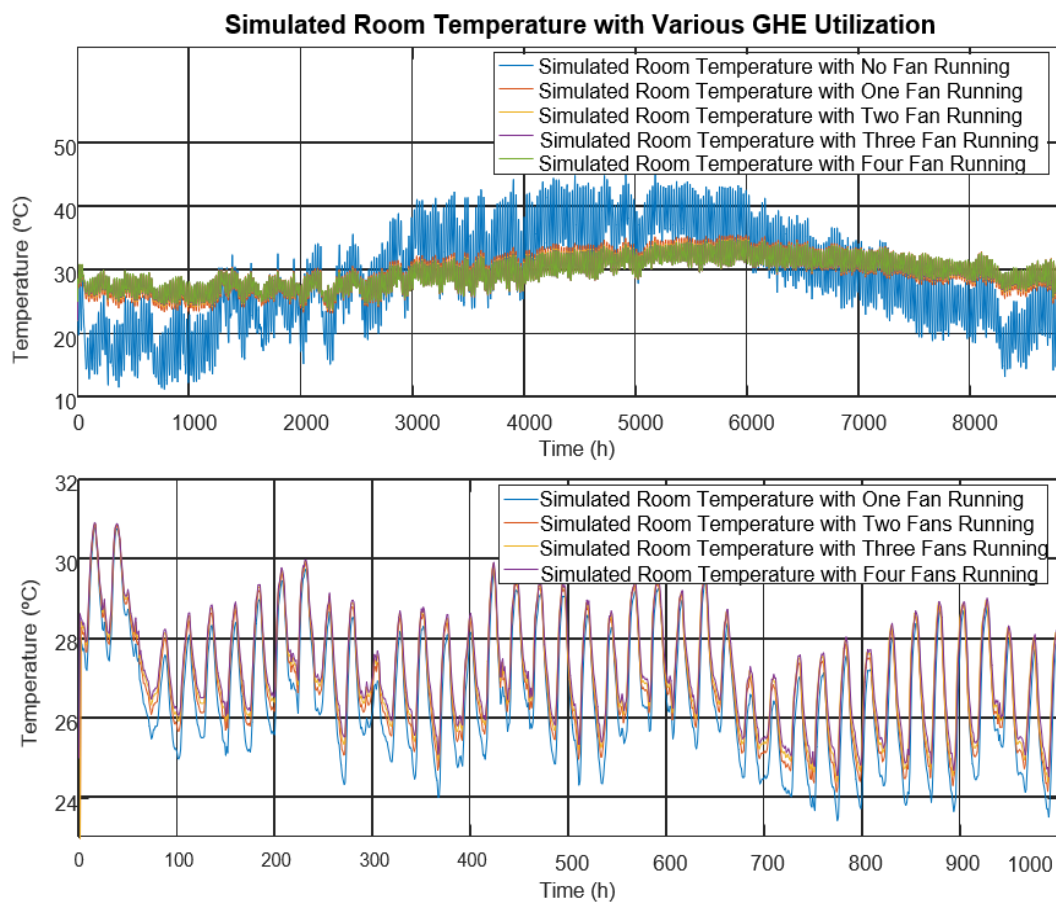

Figure 47: Simulated room temperature when utilizing the GHE at various capacities (a) complete year (b) first 1000 hours of the year

4.1.2 Experimental Results

The performance of the GHE is examined experimentally with 4 fans running. First, the ambient and greenhouse temperatures were recorded every two minutes for two consecutive days starting from Jan. 23rd, 2018 12:00 am to Jan. 24th, 2018 with no fan running. Then, the same temperatures were recorded for two days but with four fans running. Figure 48 shows the results of both tests. Figure 48.a shows the greenhouse temperature when the heat exchanger is not utilized (i.e. no fan is running). It can be seen that, the experimental greenhouse temperature follows the outside temperature with attenuation in amplitude and some delay. Figure 48.b shows that the greenhouse temperature remains almost constant at 26ºC when the heat exchanger is fully utilized (i.e. 4 fans running). Table 10 shows the maximum and the minimum ambient and greenhouse temperatures for the two tests of using the GHE (no fans and 4 fans).

Table 13 shows that the proposed GHE is able to increase the greenhouse room temperature by about 7ºC when compared to the room temperature without GHE utilization. However, comparing between the maximum greenhouse room temperature when GHE is not utilized and when it is utilized shows that utilizing the GHE in this period of the year (winter season) gives similar temperature value when it is not utilized, which means the GHE can work in heating mode in winter but cannot work in pre-cooling mode.
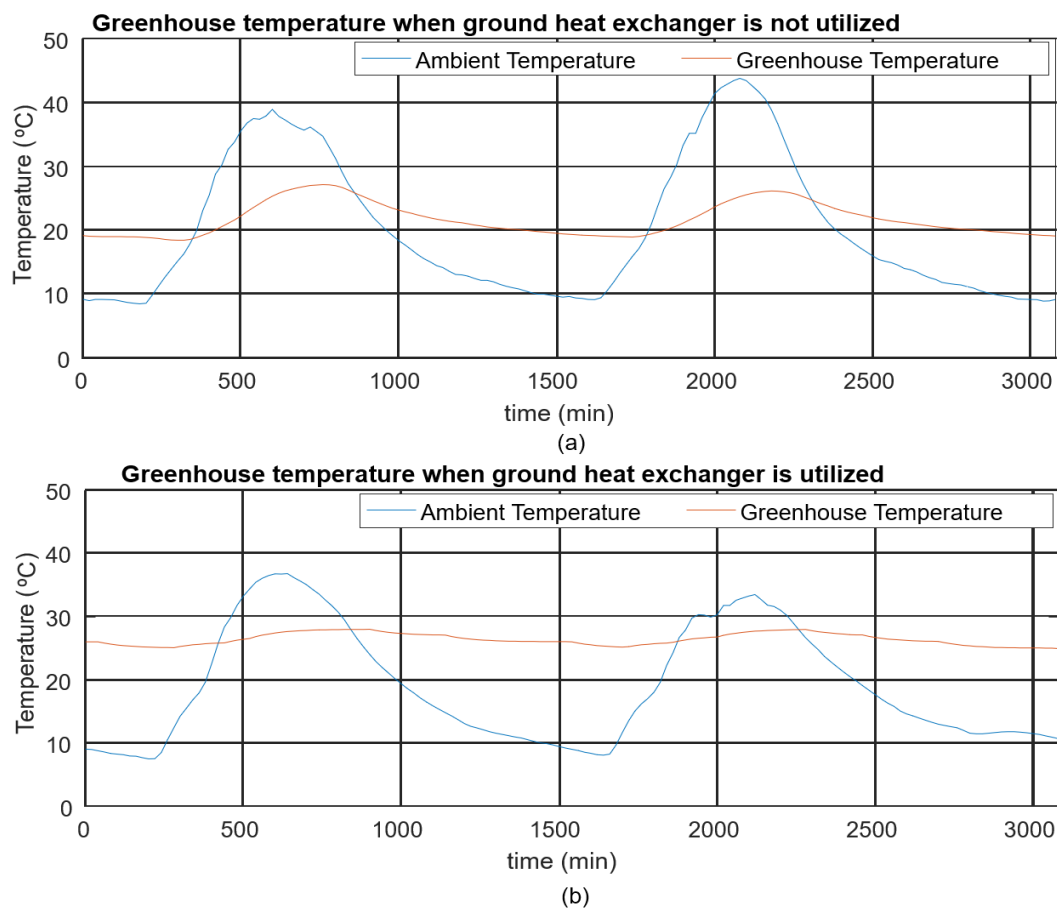
Figure 48: Real greenhouse room temperature (a) when GHE is not utilized
(b) when GHE is fully utilized

Table 13: Comparison between ambient and greenhouse room temperatures when
GHE is utilized and when not utilized

		GHE is not utilized		GHE is utilized	
		Minimum	Maximum	Minimum	Maximum
Ambient Temperature	First cycle	8.44	38.9	7.5	36.9
	Second cycle	9.113	43.78	8.086	33.56
Greenhouse Temperature	First cycle	18.5	27.19	25.07	27.98
	Second cycle	19.01	26.18	25.17	27.95

Moreover, the simulated room temperature was plotted against the real room temperature when the GHE is fully utilized and the results are shown in Figure 49 where it can be seen that the simulated room temperature when four fans are running follows the soil temperature. Also, the measured greenhouse room temperature when four fans are running is very close to the simulation results.
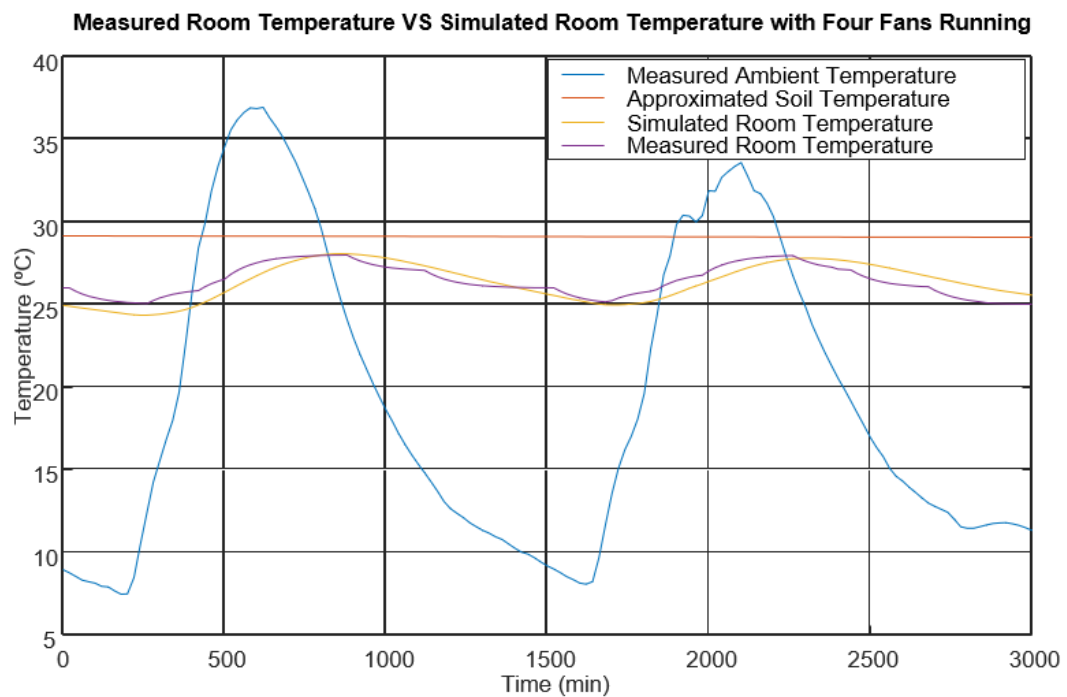

Figure 49: Real and simulated greenhouse room temperature when GHE is fully utilized

Also, Figure 50 shows the air temperature at the fans outlet, the ambient temperature and the wind speed. It can be observed that the fluctuation of wind speed has no effect on the ground heat exchanger's performance.
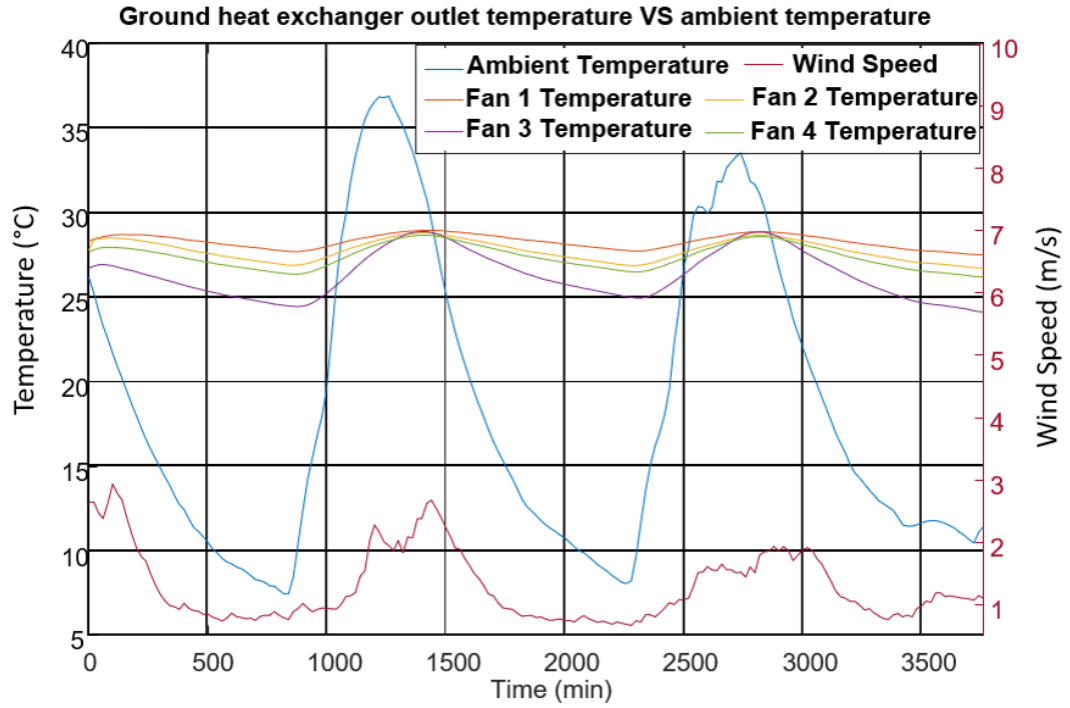
Figure 50: Fans temperature compared to wind speed when GHE is fully utilized

4.2 Fuzzy-Based GHC Results

The proposed fuzzy controller is simulated in Matlab Simulink 2016 as shown in Figure 51 and the detailed block diagram is included in Appendix C.1. The simulation time is set or one complete year (8782 hours) with real ambient temperature, relative humidity and wind speed data. The simulation results of controlling room temperature and humidity using the proposed fuzzy controller over one complete year are shown in Figure 52. The simulation reveals that a total energy of 496 kWh is consumed by the fans over one complete year as fans run for 7295 hours and 68 watt is consumed per hour. Also, the linear actuators are open/close 472 times over one year. The average room temperature is 26.8ºC.

The simulation results over one year is divided into four seasons and discussed individually in this section. A season begins in the first of the month at which the equinoxes and solstices happen according to the meteorological definition [46].
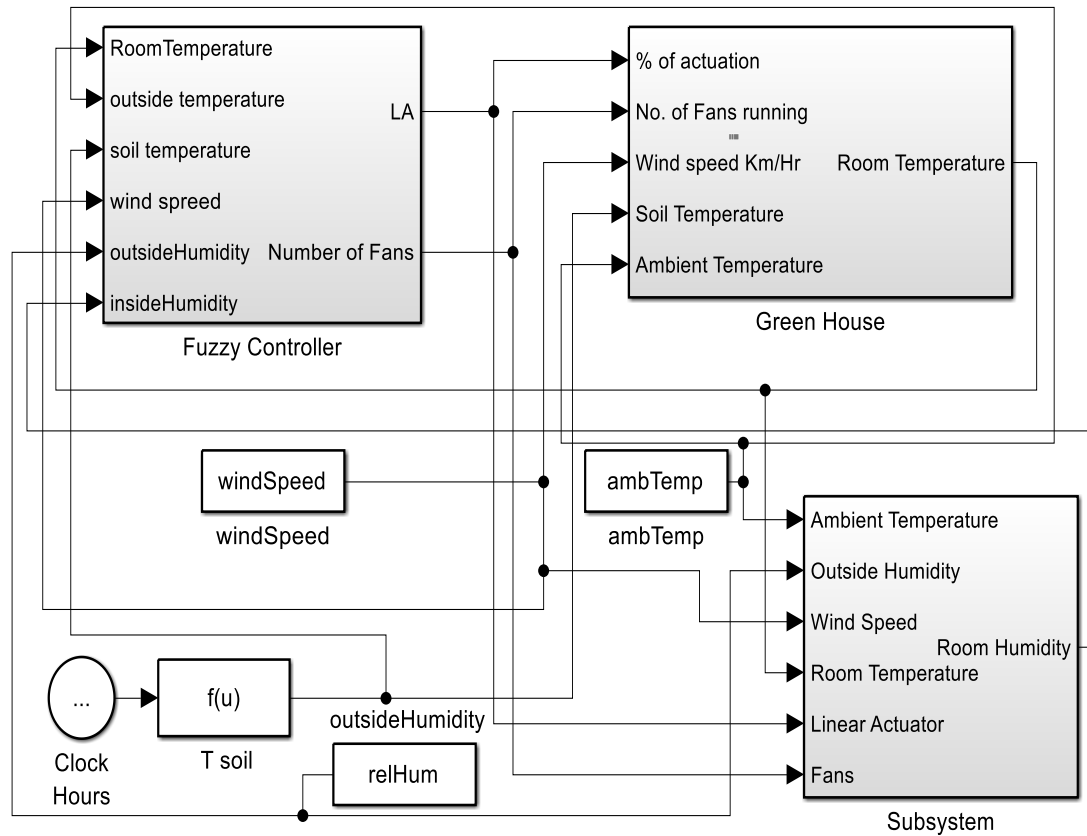
Figure 51: Fuzzy controller simulation in Simulink
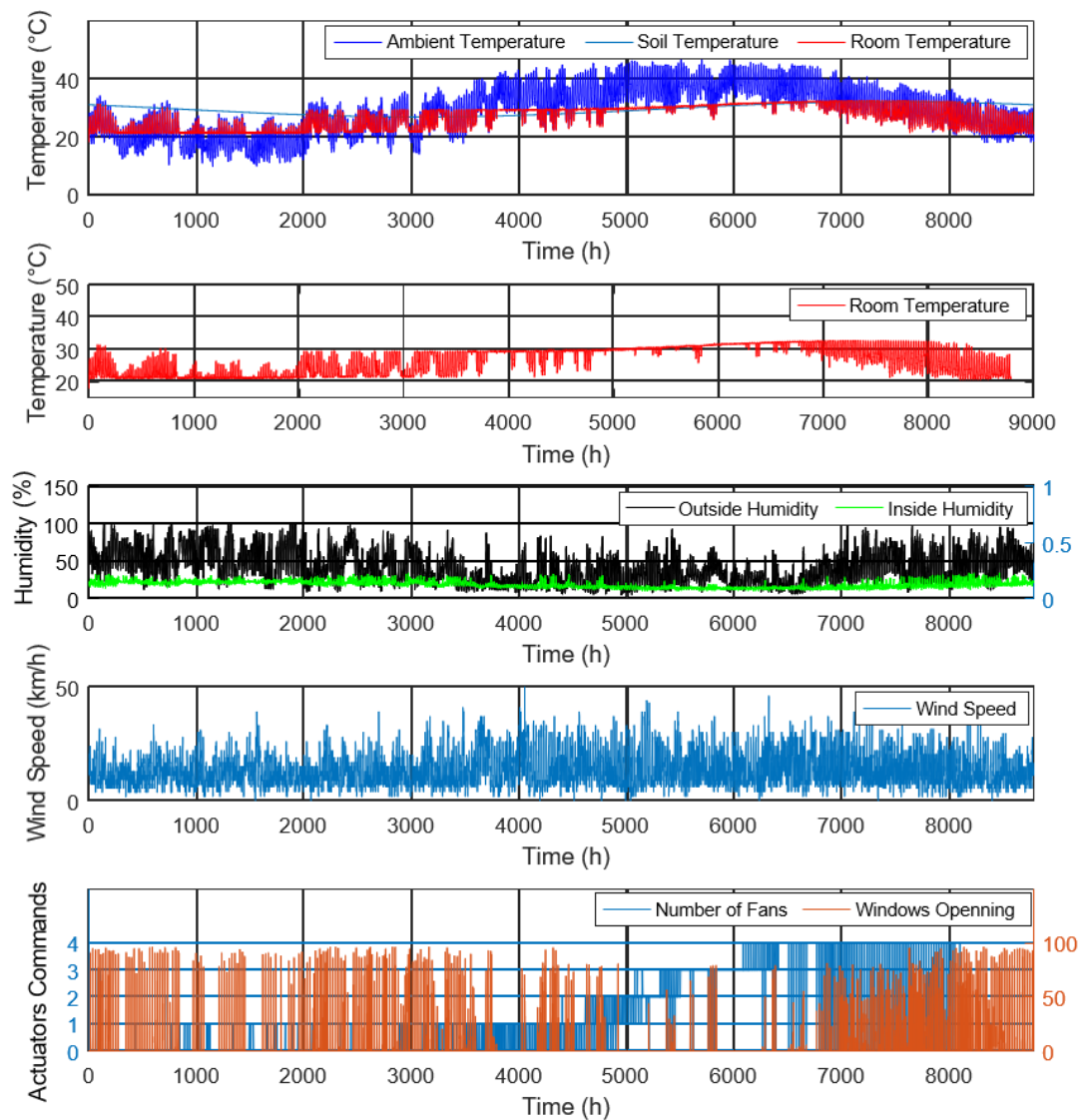
Figure 52: Fuzzy control of temperature simulation results over one year

Winter (from 1st of December to 29th of February):

The fuzzy controller performance in the winter season is plotted in Figure 53. Figure 53 shows that running one fans is sufficient to keep the greenhouse room temperature within the acceptable range by utilizing the GHE temperature. In addition, the outside weather conditions are utilized more than the GHE in this season. The GHE prevents the greenhouse room temperature from rising above the soil temperature during day hours. The fans run in this season for 39 hours with 2.7 kWh power

consumption. In this season the windows open/close 106 times for ventilation and cooling purposes. The average room temperature is 22.6ºC which is within the acceptable range.
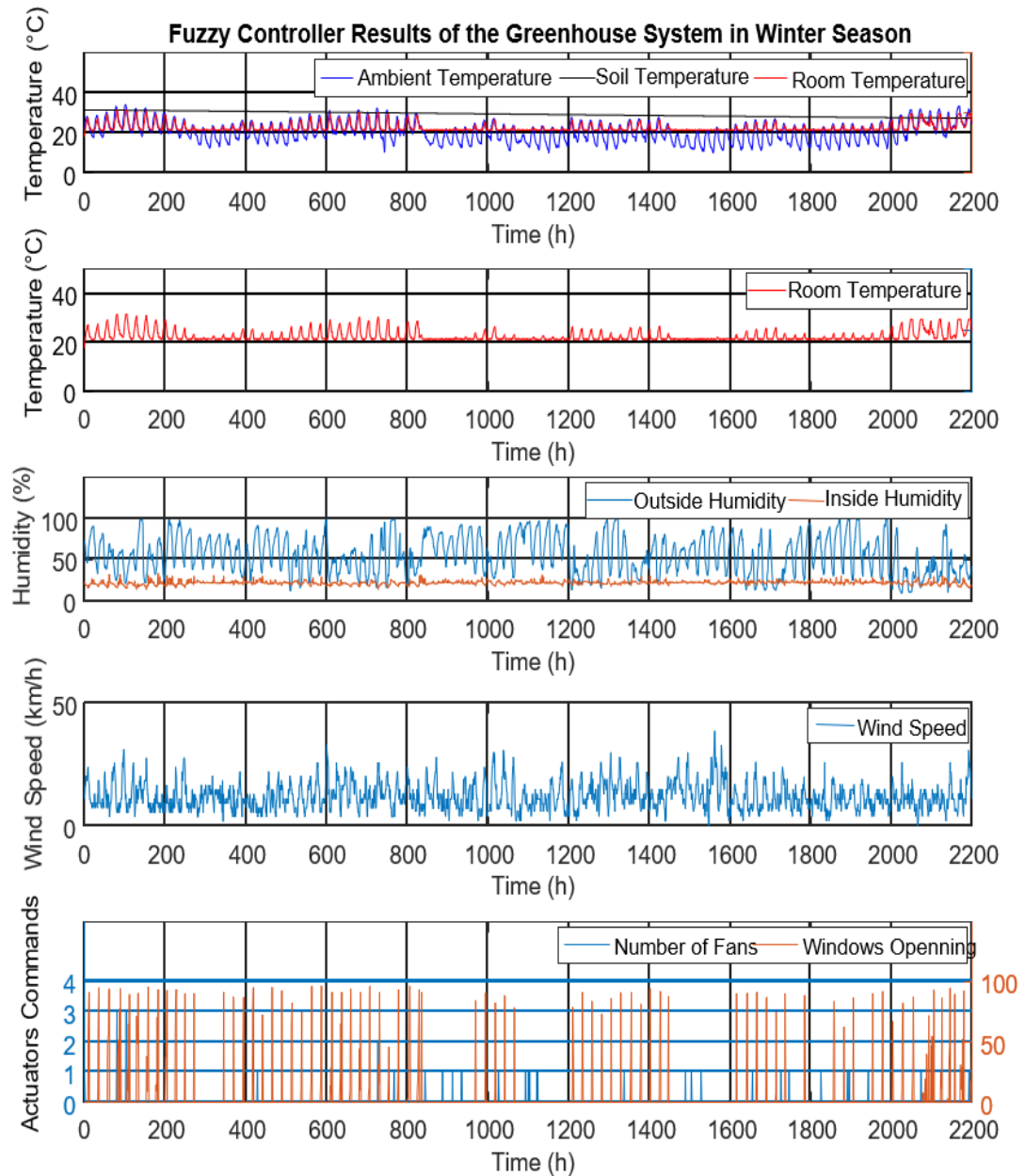
Figure 53: Fuzzy controller simulation results in winter season

Spring (from 1st of March to 31st of May):

The fuzzy controller results in the spring season is shown in Figure 54.

Figure 54 shows that the outside temperature is utilized for cooling the greenhouse

room temperature in the first half of the season. Also, the GHE is used for pre-

cooling in the second half of the season. In addition, the wind speed range exceeds

the maximum wind in some hours of this season which stops the controller decision

in utilizing the outside weather conditions. Moreover, the controller commands are

fluctuating especially in the second half of the season. Using the fuzzy controller in

this season consumes a power of 25.5 kWh with windows open/close 124 times.
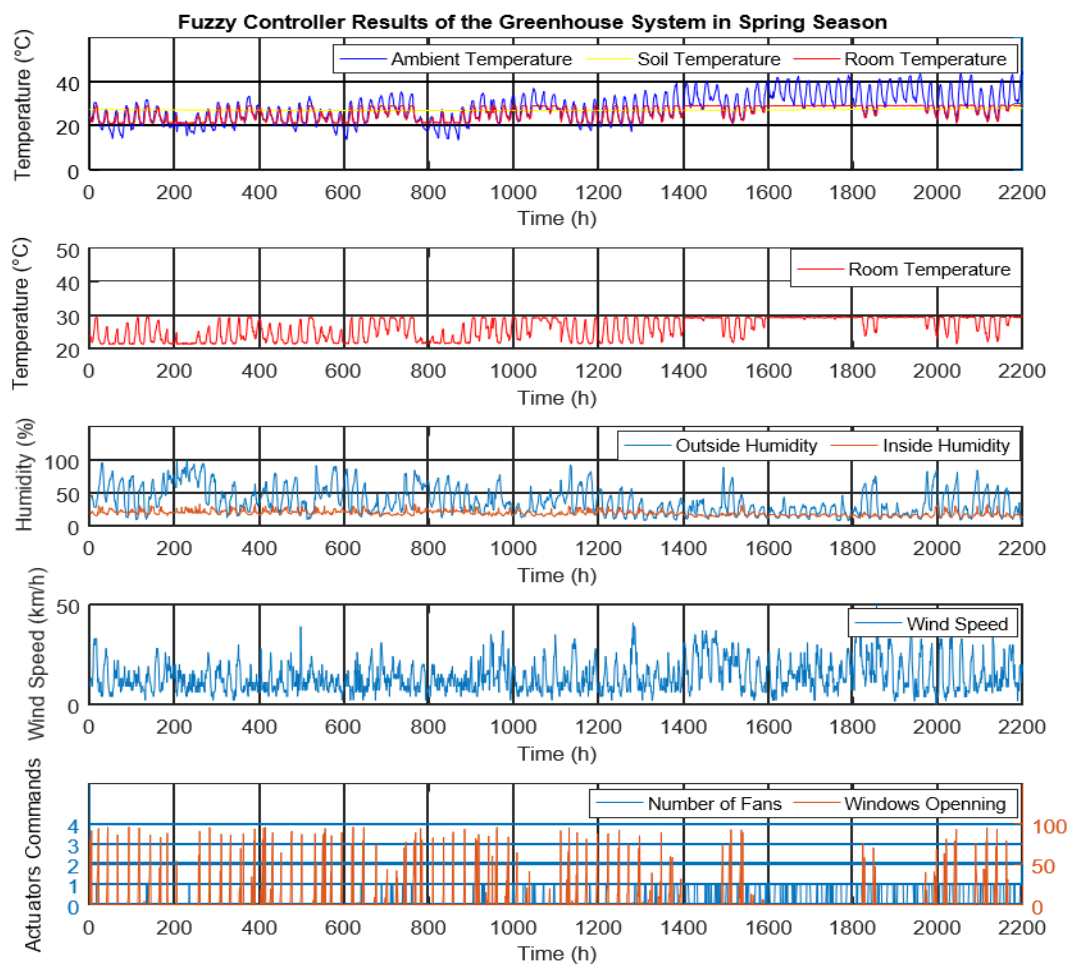
Figure 54: Fuzzy controller simulation results in spring season

Summer (from 1ˢᵗ of June to 31ˢᵗ of August):

      The fuzzy controller performance in the summer season is plotted in Figure 55. In this season the GHE is utilized for pre-cooling purpose. Also, the GHE is utilized with maximum capacity during day hours. However, during night hours the fuzzy controller utilizes less number of fans. The fans run in this season for 4833 hours with 328 kWh power consumption and the windows open/close 35 times. The controller fluctuation is very small in this season and the pre-cooling load is carried by the fans only.
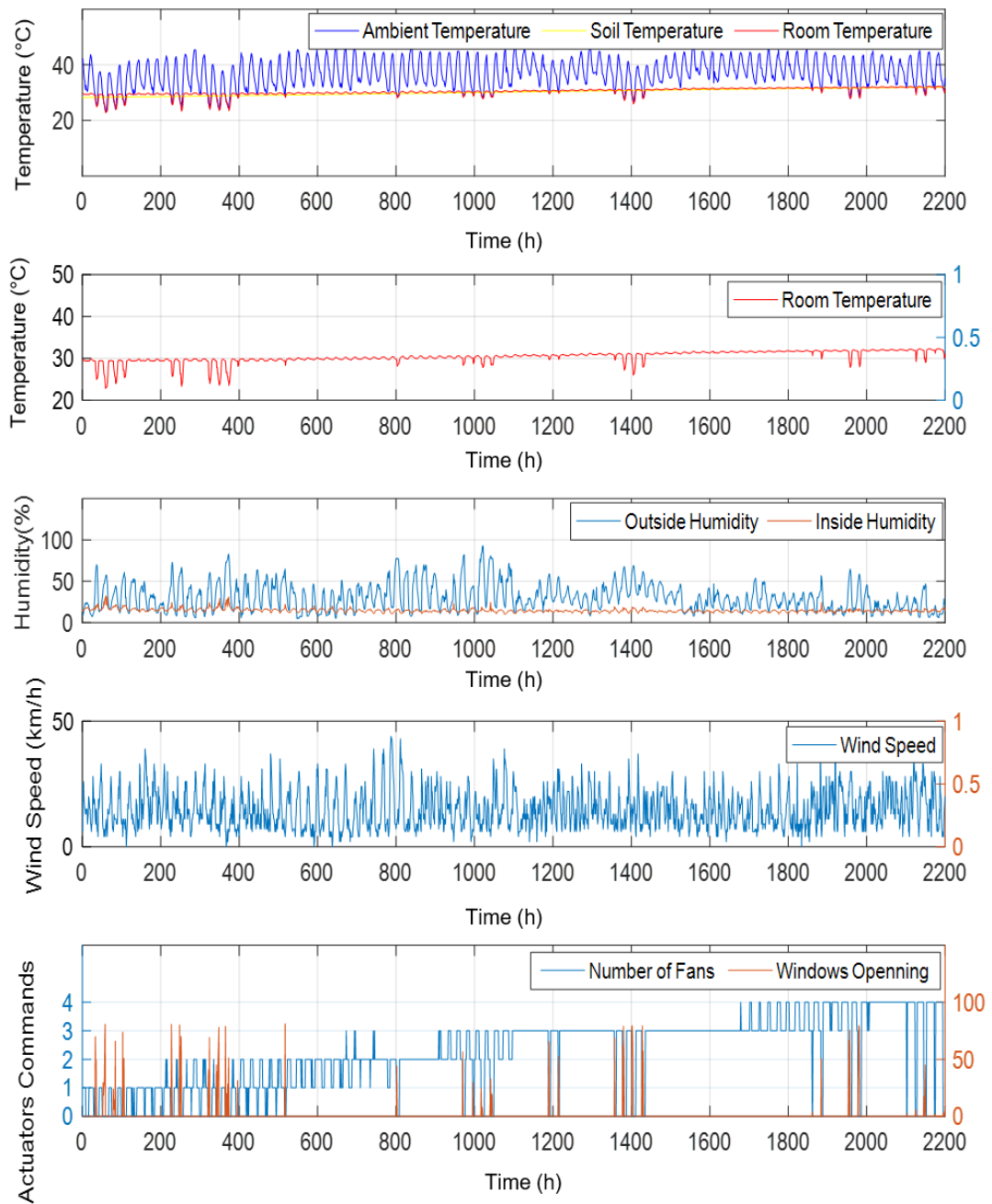
Figure 55: Fuzzy controller in summer season

Fall (1st of September to 30th of November):

The fuzzy controller results in fall season are shown in Figure 56. In the first half of this season the GHE is utilized to pre-cool the greenhouse temperature and the ambient temperature is utilized in the second half of the season. Using the fuzzy

controller in this season consumes a power of 139 kWh with windows open/close 206 times.
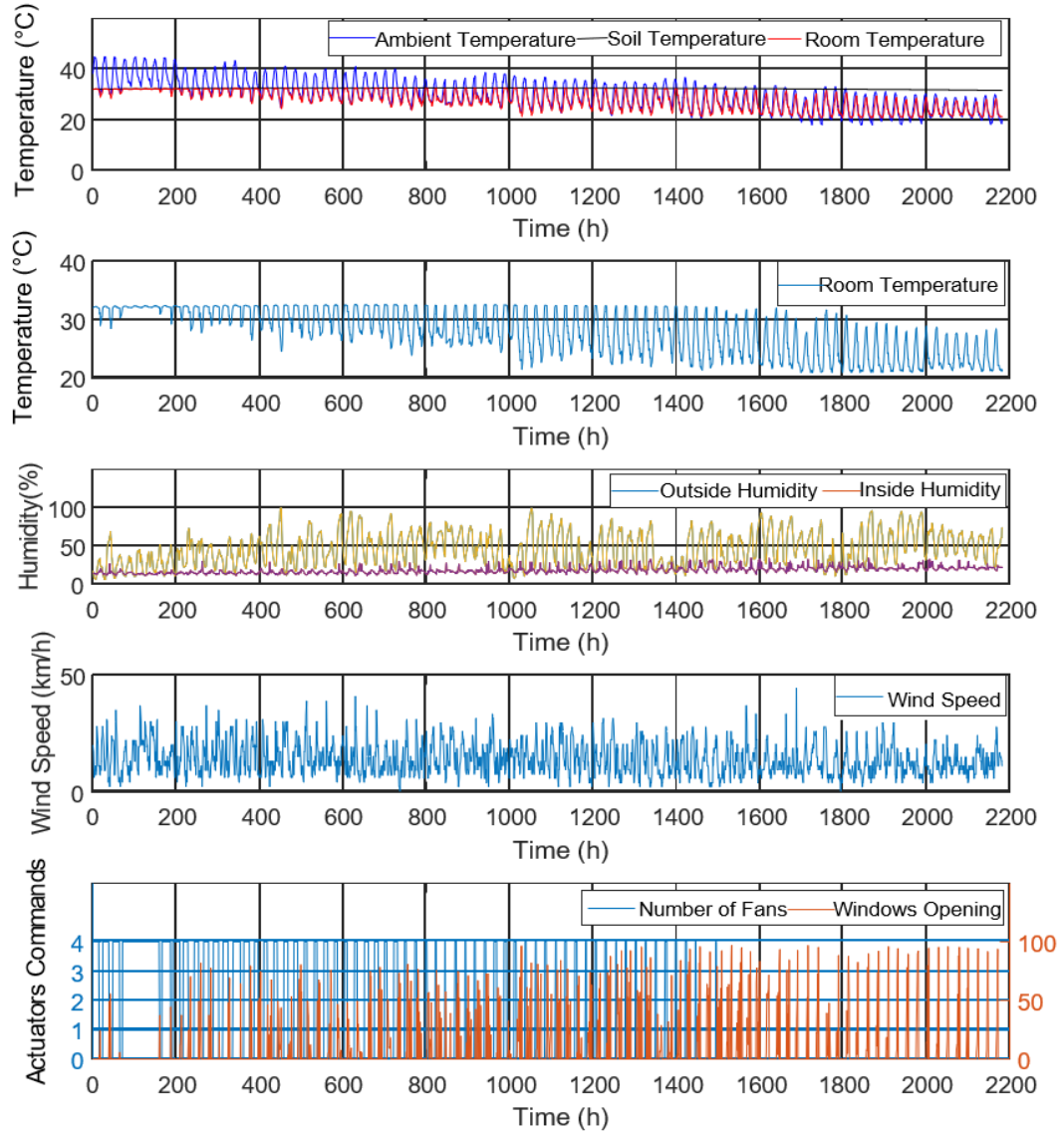
Figure 56: Fuzzy controller in fall season

4.3 Logical GHC Results

The proposed logical controller is simulated in Matlab Simulink 2016 as shown in Figure 57. The detailed block diagram is included in Appendix C.2. The simulation covers one year (8782 hours) with a real ambient temperature and wind speed records. The simulation results of controlling the room temperature using logical controller is shown in Figure 58. Simulation shows that a total energy of 727.6 kWh is consumed by the fans over one year. Also, the linear actuators are operated 307 times to fully open and close the windows over one year.
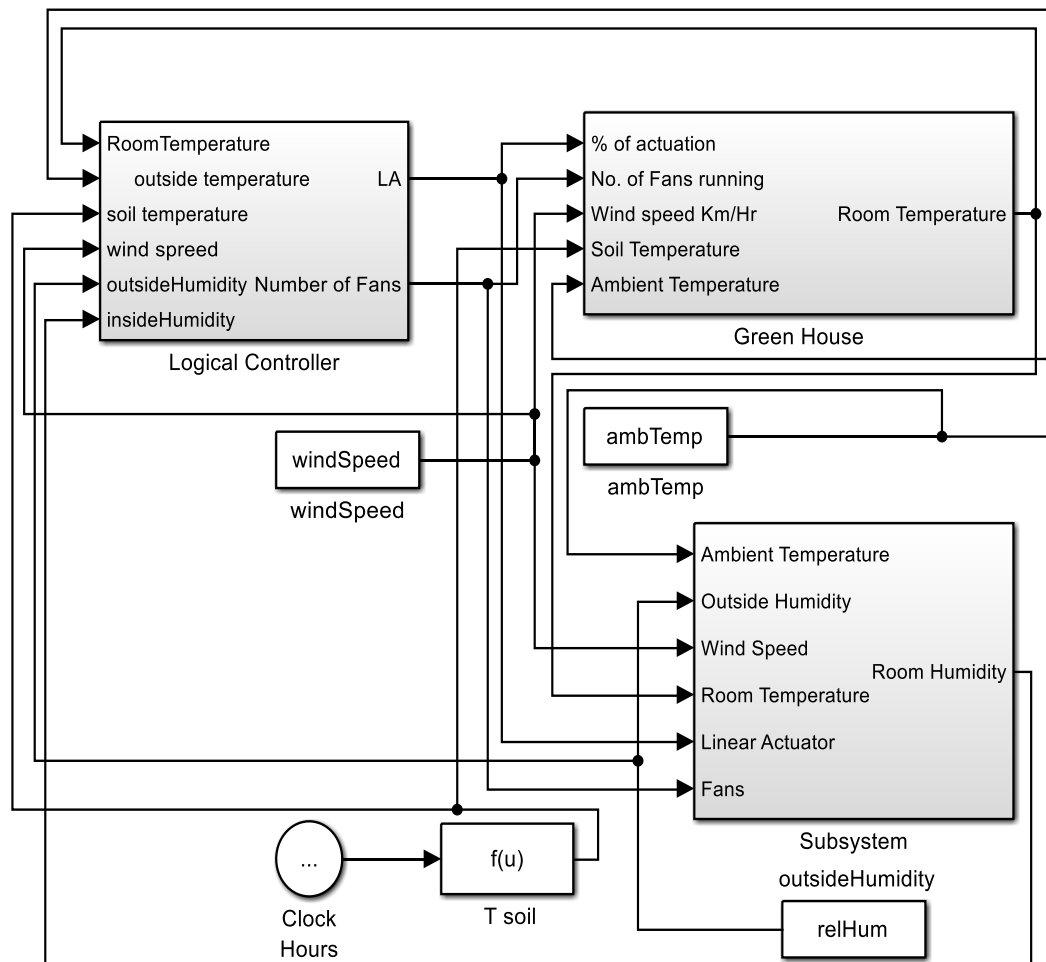
Figure 57: Simulated logical controller for greenhouse room temperature control
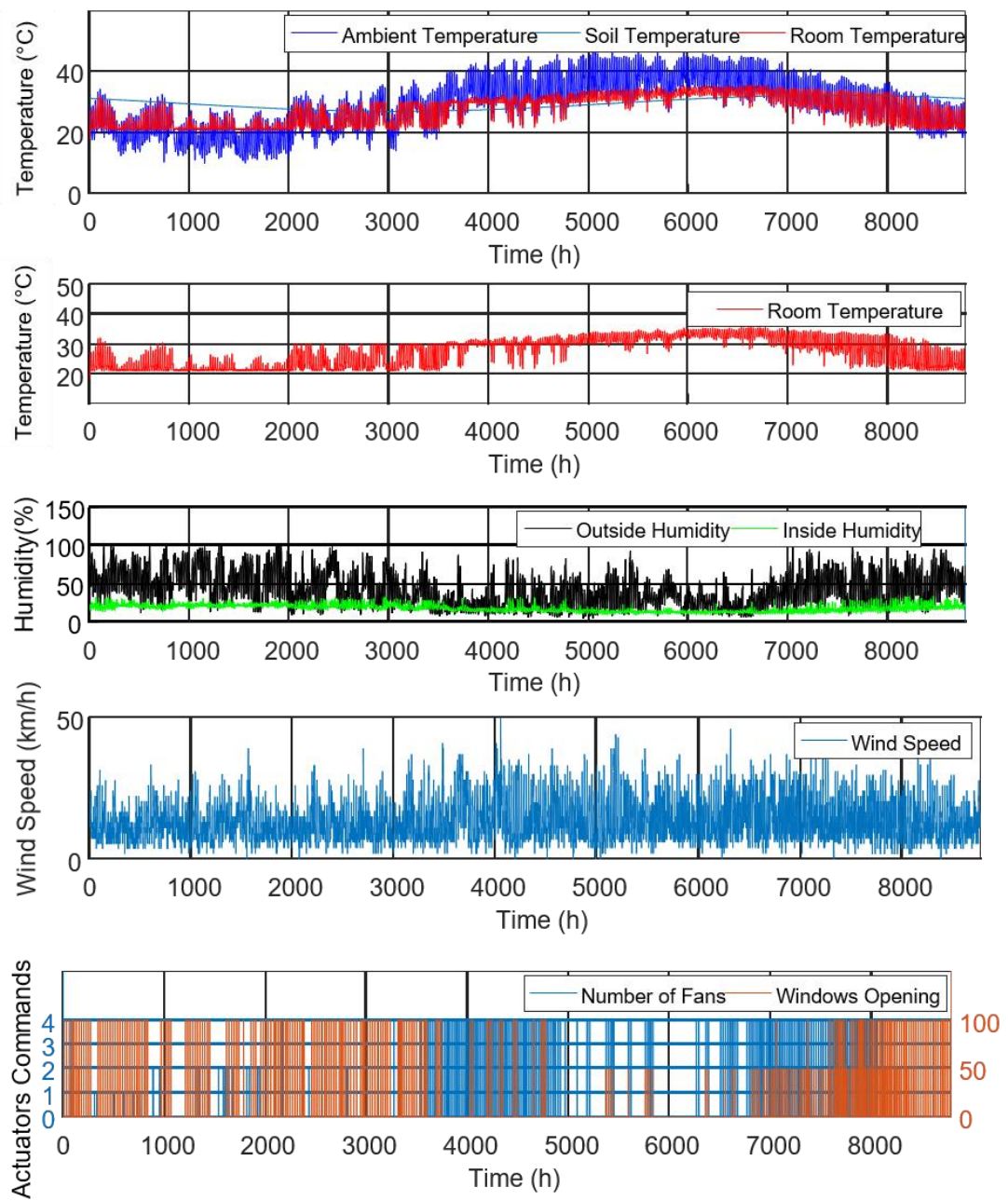
Figure 58: Simulation results of the logical controller for one year

Winter (from 1st of December to 29th of February):

The logical controller performance in the winter season is plotted in Figure 59. From Figure 59 it can be observed that the GHE works in heating mode most of the

winter days and the outside weather conditions are utilized more than the soil temperature for ventilation.
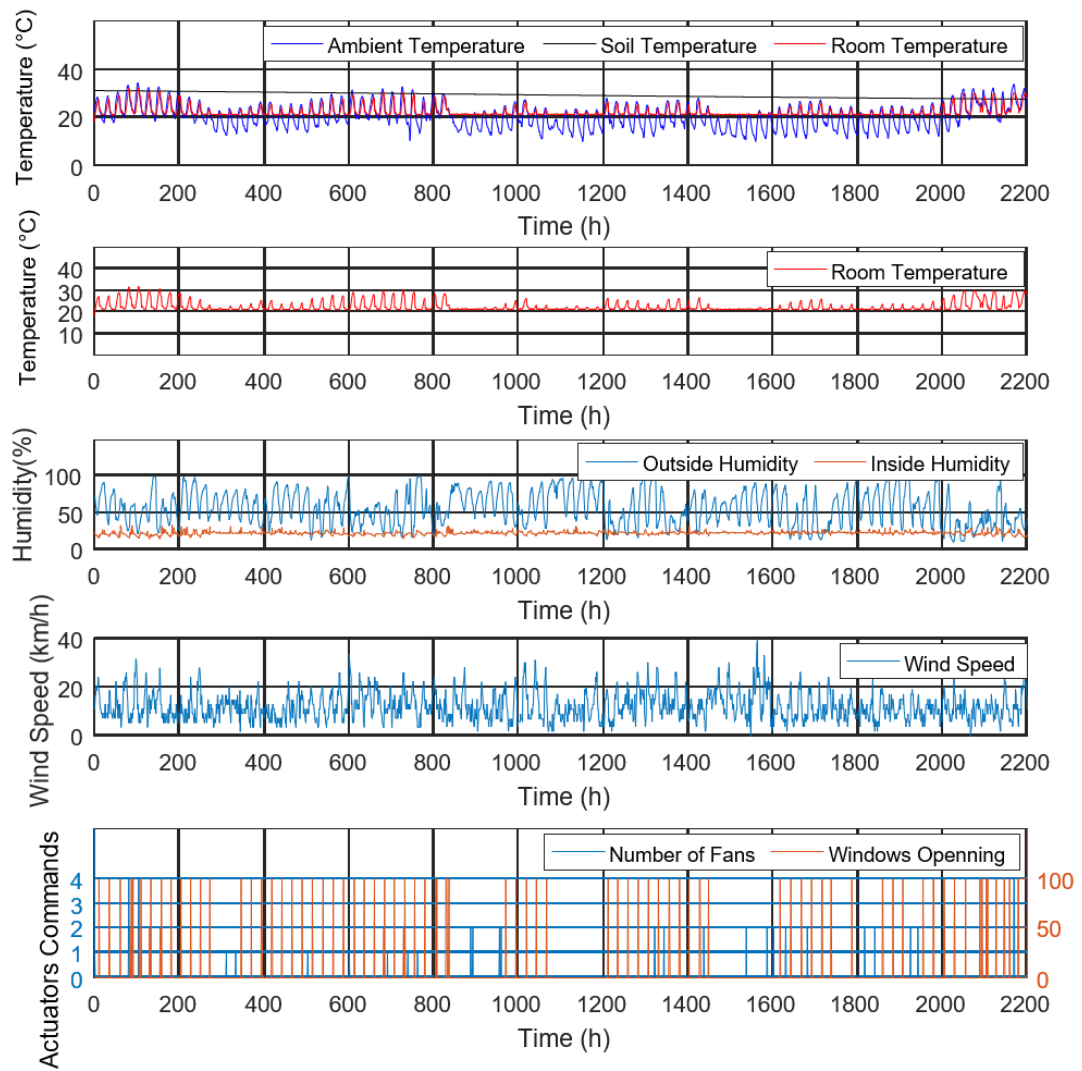
Figure 59: Logical controller in winter season

Also, the wind speed in this season exceeds the maximum speed which blocks the controller action of utilizing the outside weather conditions at some hours. In this season, the four fans work for 64 hours which consumes 4.4 kWh and the windows open and close 94 times.

Spring (from 1ˢᵗ of March to 31ˢᵗ of May):

The logical controller results in spring season are shown in Figure 60. In the spring season, the logical controller keeps the greenhouse room temperature within the acceptable range by utilizing the weather conditions in the first half of the season and the GHE is used in pre-cooling mode in the second half of the season. The wind speed range exceeds the maximum wind in some hours of this season, and hence the controller decision in utilizing the outside weather conditions is sometimes interrupted.
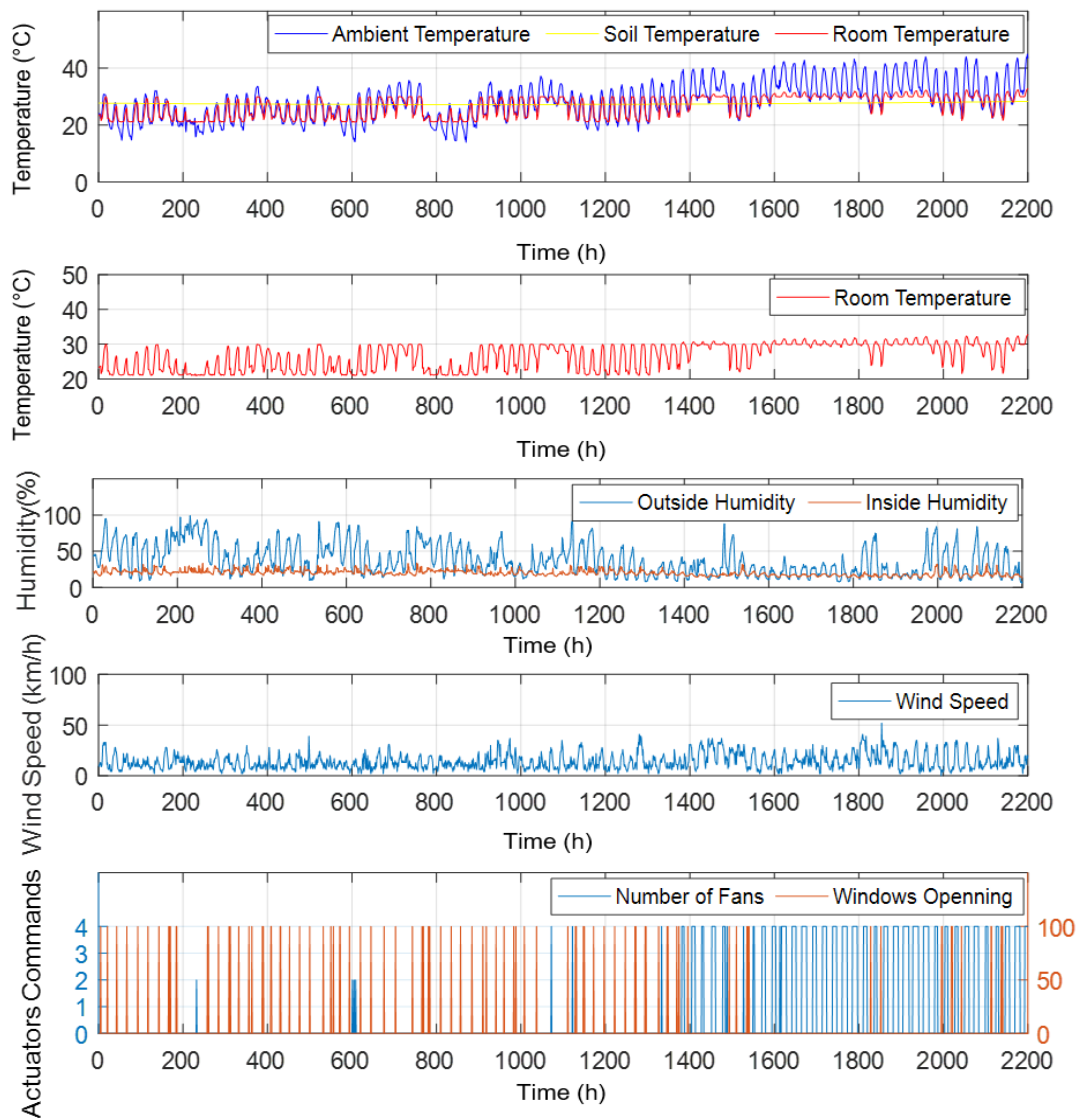
Figure 60: Logical controller in spring season

In this season, the four fans run for 1240 hours (which equals to 84.3 kWh) and the windows open and close 90 times. Moreover, an auxiliary cooling unit has to be used to cool the greenhouse temperature for an average amplitude of 1.6℃. The fluctuations of the logical controller commands are also high in this season.

Summer (from 1st of June to 31st of August):

The logical controller performance in the summer season is plotted in Figure 61. In this season the ground temperature utilization is dominant. The fans operate for 7332 hours which equals to 498.6 kWh and the windows are commanded to open and close 13 times during night hours. By utilizing the GHE the controller is capable of keeping the greenhouse room temperature at about 32℃ on average. The fluctuation in controller commands is less than the previous two seasons.
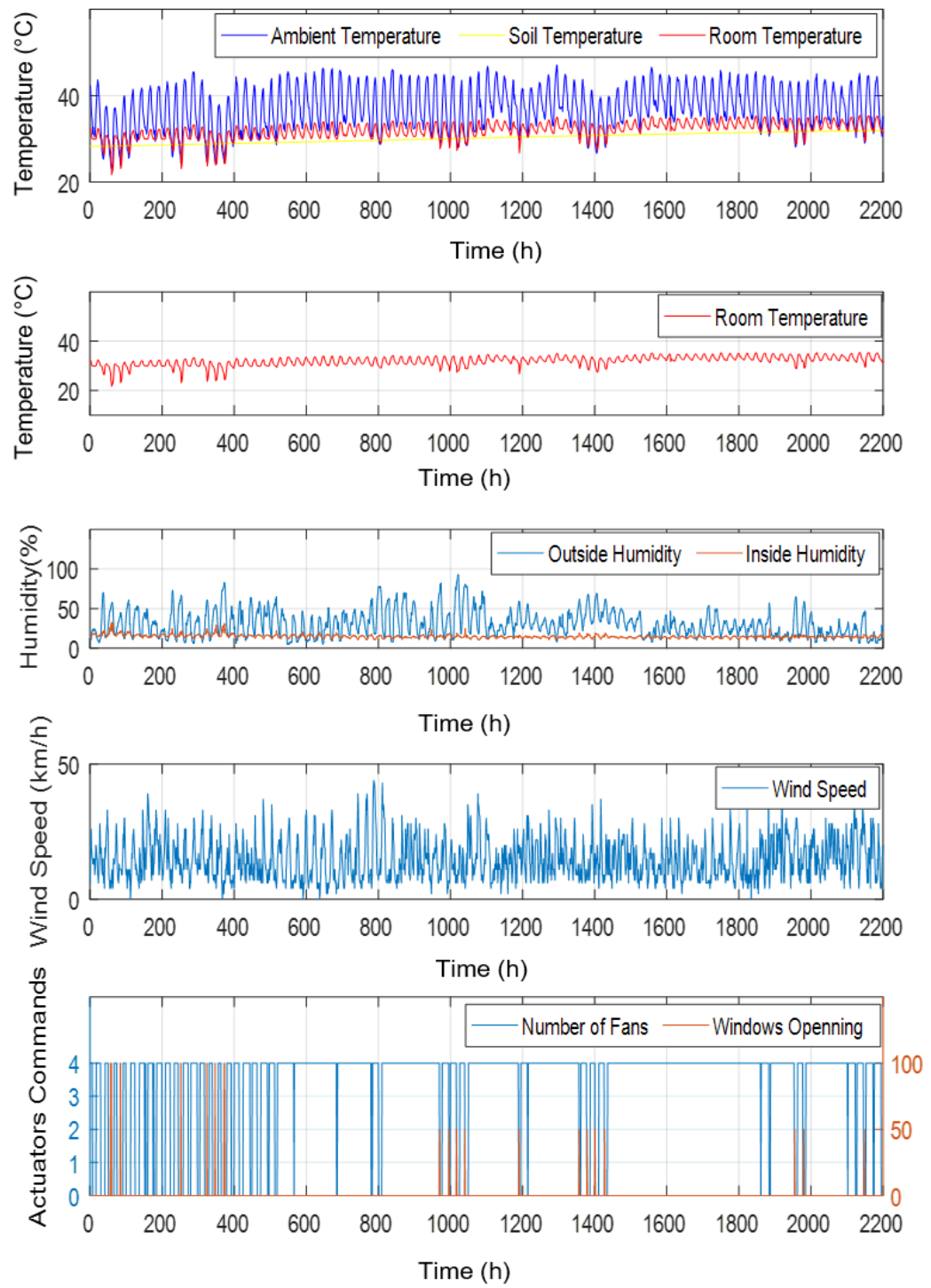
Figure 61: Logical controller in summer season

Fall (1st of September to 30th of November):

The logical controller results in the fall season are shown in Figure 62. In this season, the four fans run for 2064 hours which equals to 140.4 kWh and the windows open and close 110 times. An auxiliary cooling unit is needed to cool down the room temperature of 3.5℃ amplitude on average. The wind speed in this season exceeds the accepted speed and triggers the controller to block the outside weather condition utilization in some hours. At the beginning of this season, the GHE is used for pre-cooling purpose. However, the weather utilization is dominant in the second half of the season.
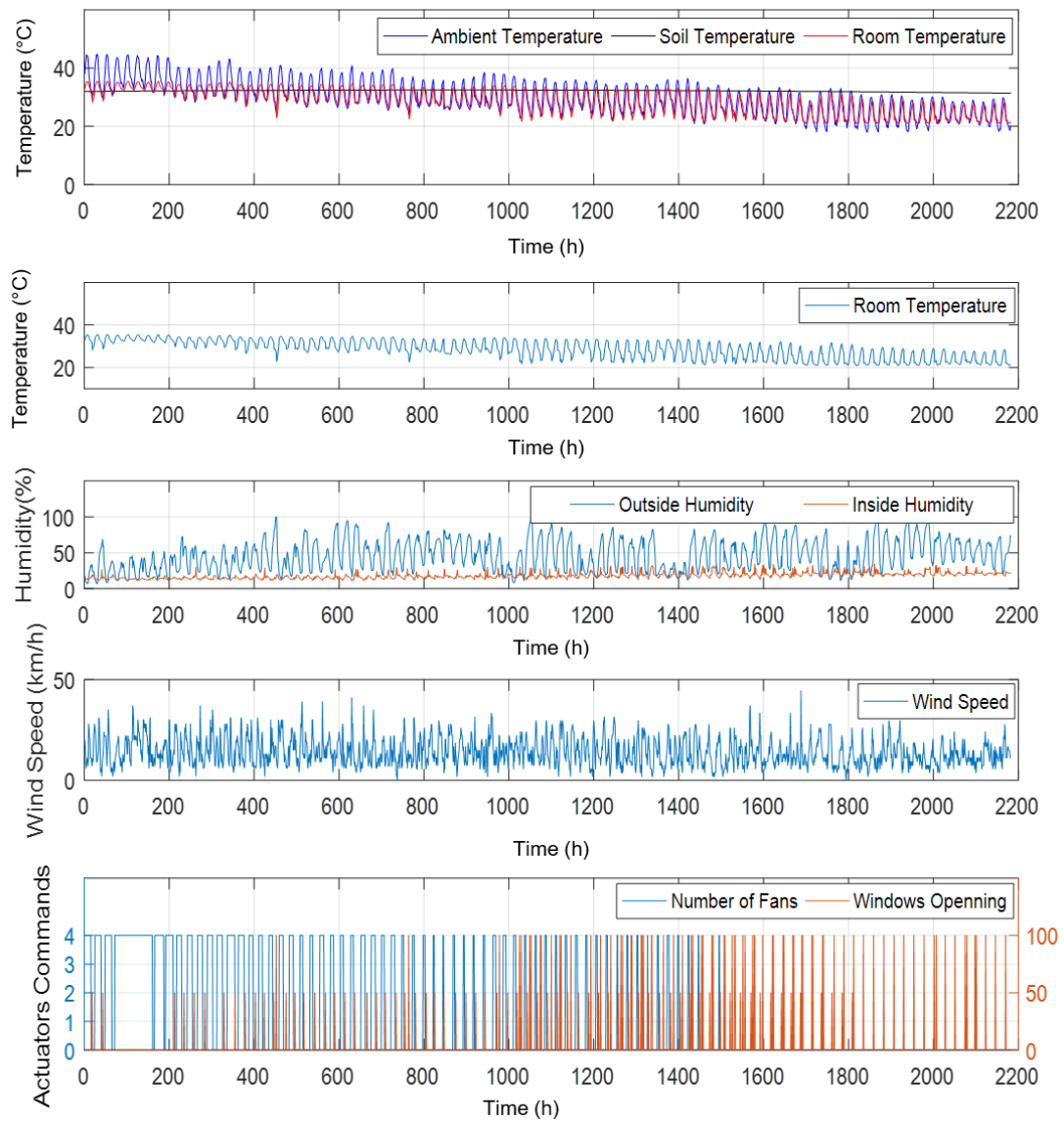
Figure 62: Logical controller in fall season

4.4 ON/OFF GHC Results

The ON/OFF controller is simulated in Matlab Simulink 2016 as shown in Figure 63. The detailed block diagram is included in Appendix C.3. The simulation covers one year (8782 hours) with a real ambient temperature and wind speed records. The simulation results of controlling the room temperature using ON/OFF controller is shown in Figure 64. Simulation shows that a total energy of 1553 kWh is consumed

by the fans over one year. Also, the linear actuators are operated 1341 times to fully

open and close the windows over one year.
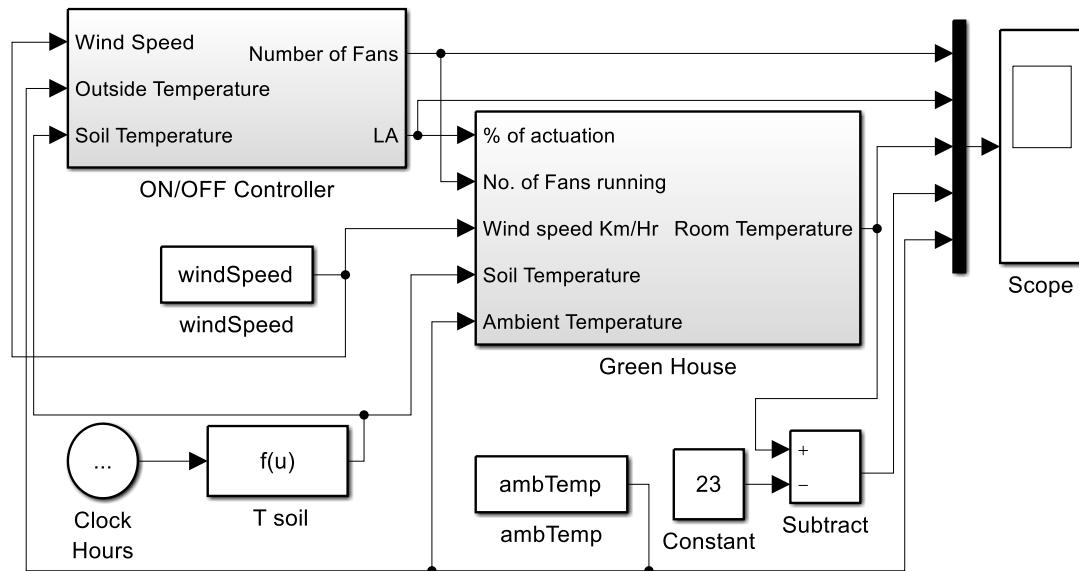
Figure 63: Simulated ON/OFF controller for greenhouse temperature control
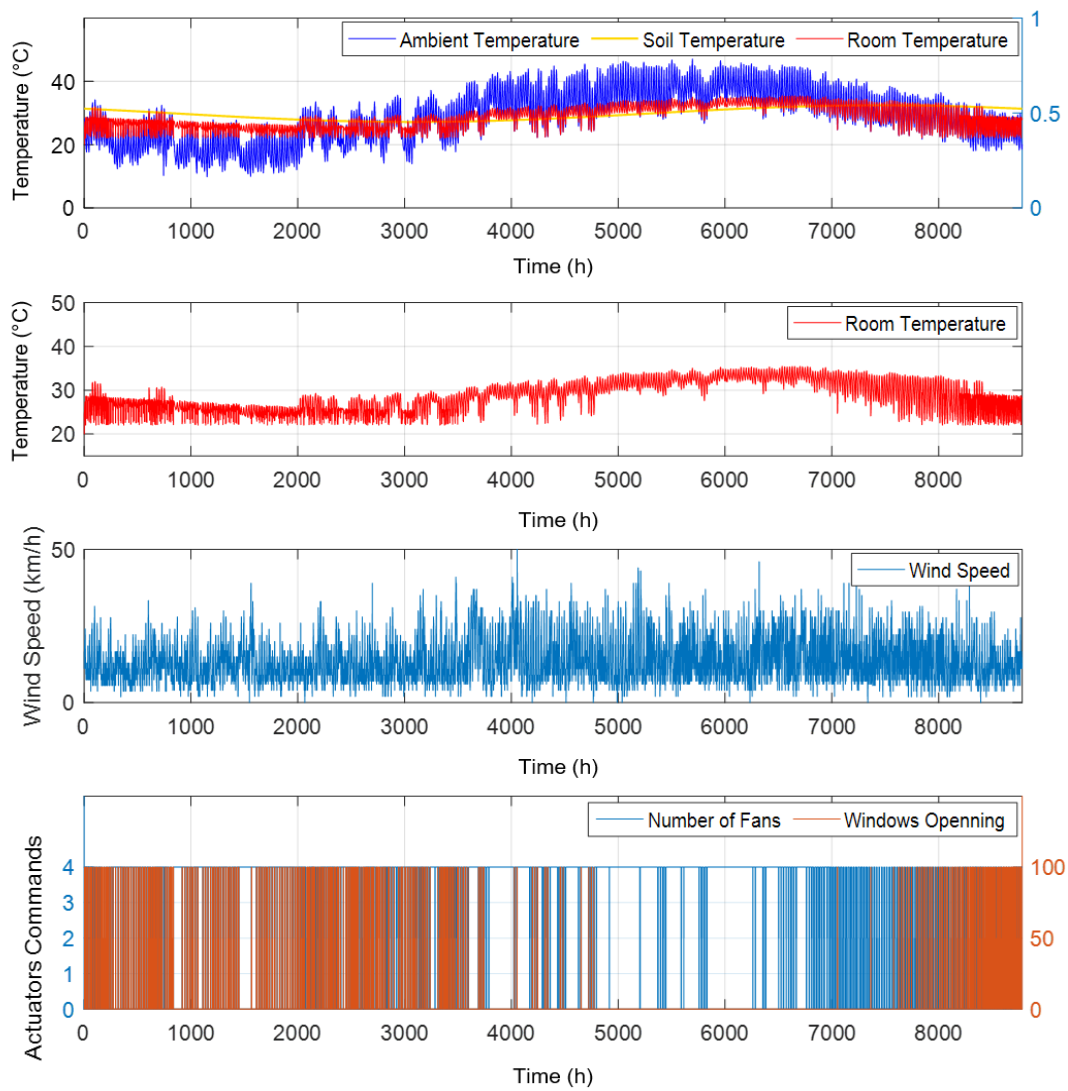
Figure 64: Simulation results of the ON/OFF controller for one year

Winter (from 1ˢᵗ of December to 29ᵗʰ of February):

The ON/OFF controller performance in the winter season is plotted in Figure 65. From Figure 65 it can be observed that the GHE works in heating mode most of the winter days. In addition, the outside weather conditions are utilized for ventilation purpose by opening side windows.
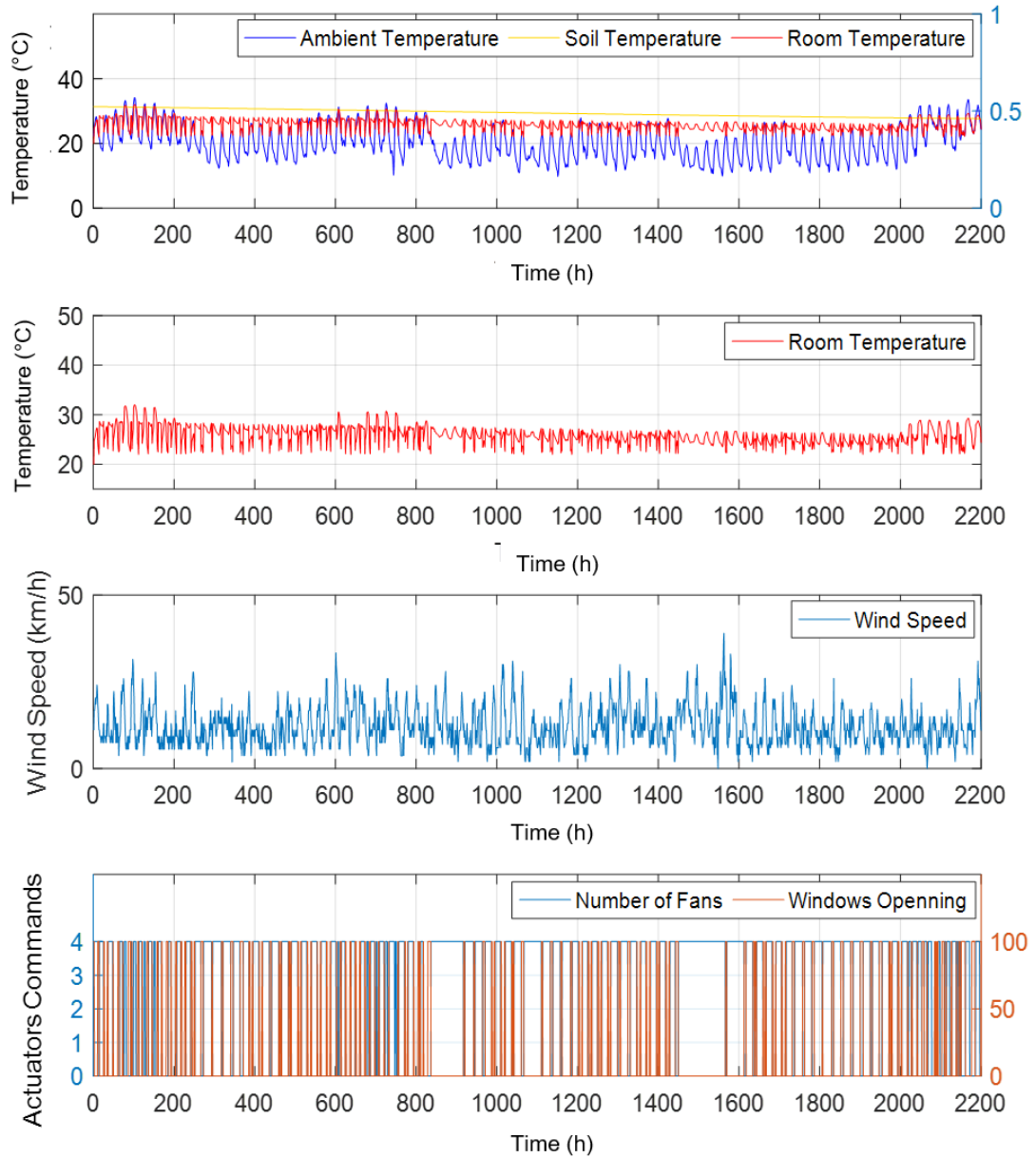
Figure 65: ON/OFF controller in winter season

Also, the wind speed in this season exceeds the maximum speed which blocks the controller action of utilizing the outside weather conditions at some hours. In this season, the four fans work for 5332 hours which consumes 362.5 kWh and the windows open and close 541 times. An auxiliary cooling unit is needed at which the room temperature exceeds the desired range and neither the ground temperature nor

the weather conditions can be utilized. The average needed auxiliary cooling amplitude is 0.4ºC. The fluctuation in controller commands is high and may affect the actuators in the long term.

Spring (from 1ˢᵗ of March to 31ˢᵗ of May):

The ON/OFF controller results in spring season are shown in Figure 66. In the spring season, the ON/OFF controller keeps the greenhouse room temperature within the acceptable range by utilizing the GHE for heating purpose in cold hours. Also, when the ambient temperature is within the acceptable range, the windows open and the ambient air is used to heat up the greenhouse. However, the GHE is not used in pre-cooling mode in spring season because soil temperature is close to the ambient temperature. The wind speed range exceeds the maximum wind in some hours of this season, and hence the controller decision in utilizing the outside weather conditions is sometimes interrupted.
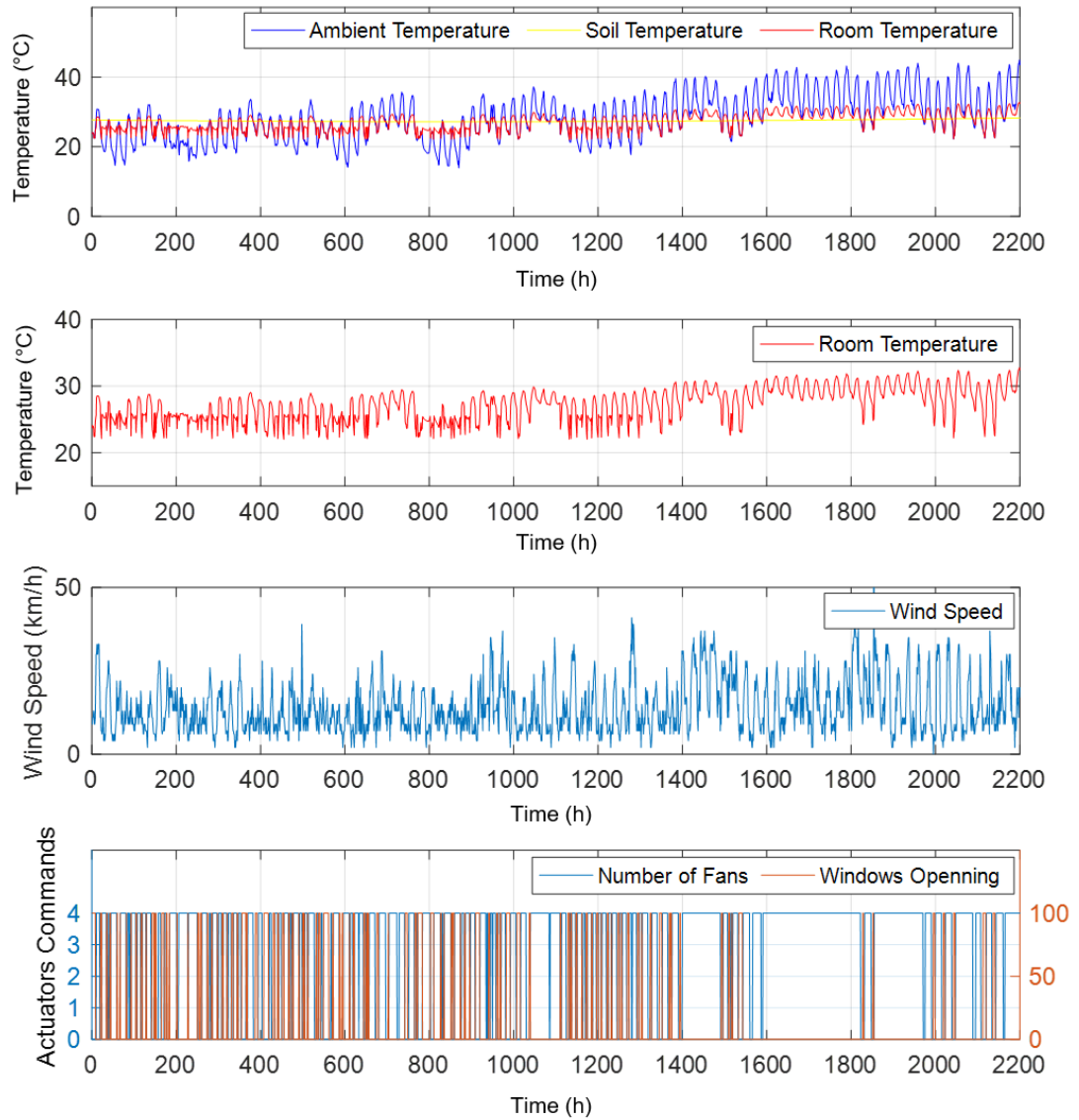
Figure 66: ON/OFF controller in spring season

In this season, the four fans run for 5928 hours (which equals to 403.1 kWh) and the windows open and close 427 times. Moreover, an auxiliary cooling unit has to be used to cool the greenhouse temperature for an average amplitude of 2.0ºC. The GHE is utilized for heating purpose and the outside weather conditions are only utilized for ventilation purpose. The fluctuations of the ON/OFF controller commands are also high in this season.

Summer (from 1ˢᵗ of June to 31ˢᵗ of August):

The ON/OFF controller performance in the summer season is plotted in Figure 67. In this season the four fans are operating in pre-cooling mode for 8148 hours which equals to 553.8 kWh and the windows are commanded to open and close 17 times during night hours. By utilizing the GHE the controller is capable of keeping the greenhouse room temperature at about 32ºC on average. The advantage of using the GHE is overwhelming in this season. Comparing the greenhouse room temperature when the GHE is not used and when the controller is used with the GHE, an auxiliary cooling unit is needed for further cooling of about an average amplitude 7ºC. Also, the weather conditions are utilized at night hours and the fans are utilized during the day hours for pre-cooling purpose. The fluctuation in controller commands is less than the previous two seasons.
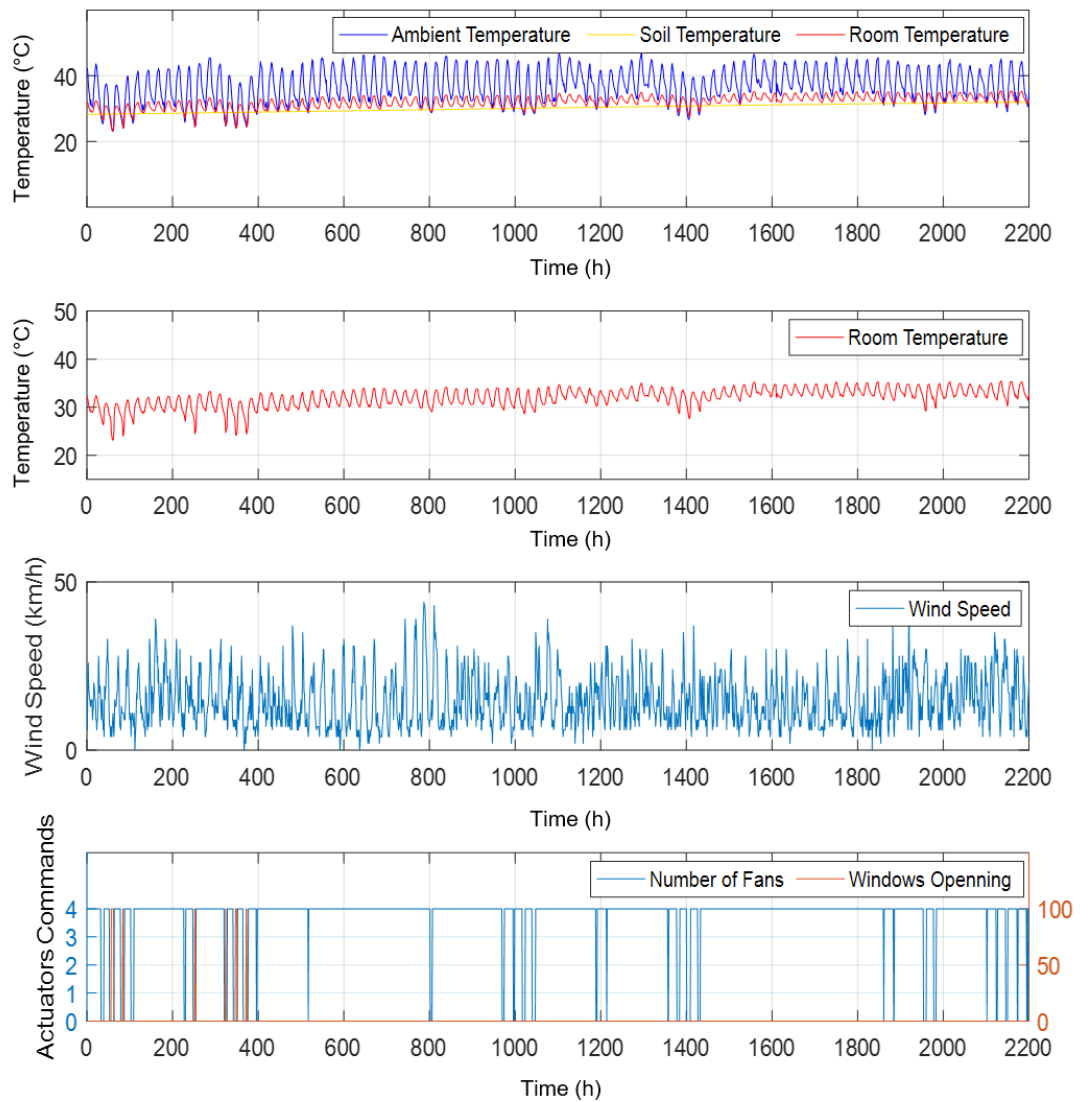
Figure 67: ON/OFF controller in summer season

Fall (1st of September to 30th of November):

The ON/OFF controller results in the fall season are shown in Figure 68. In this season, the four fans run for 3436 hours which equals to 233.6 kWh and the windows open and close 356 times. An auxiliary cooling unit is needed to cool down the room temperature of 4.5°C amplitude on average. The wind speed in this season exceeds the accepted speed and triggers the controller to block the outside weather condition utilization in some hours. At the end of this season, the GHE is used for

heating purpose. The controller commands fluctuation at the first 400 hours of this season is low, however, it starts to increase after that.
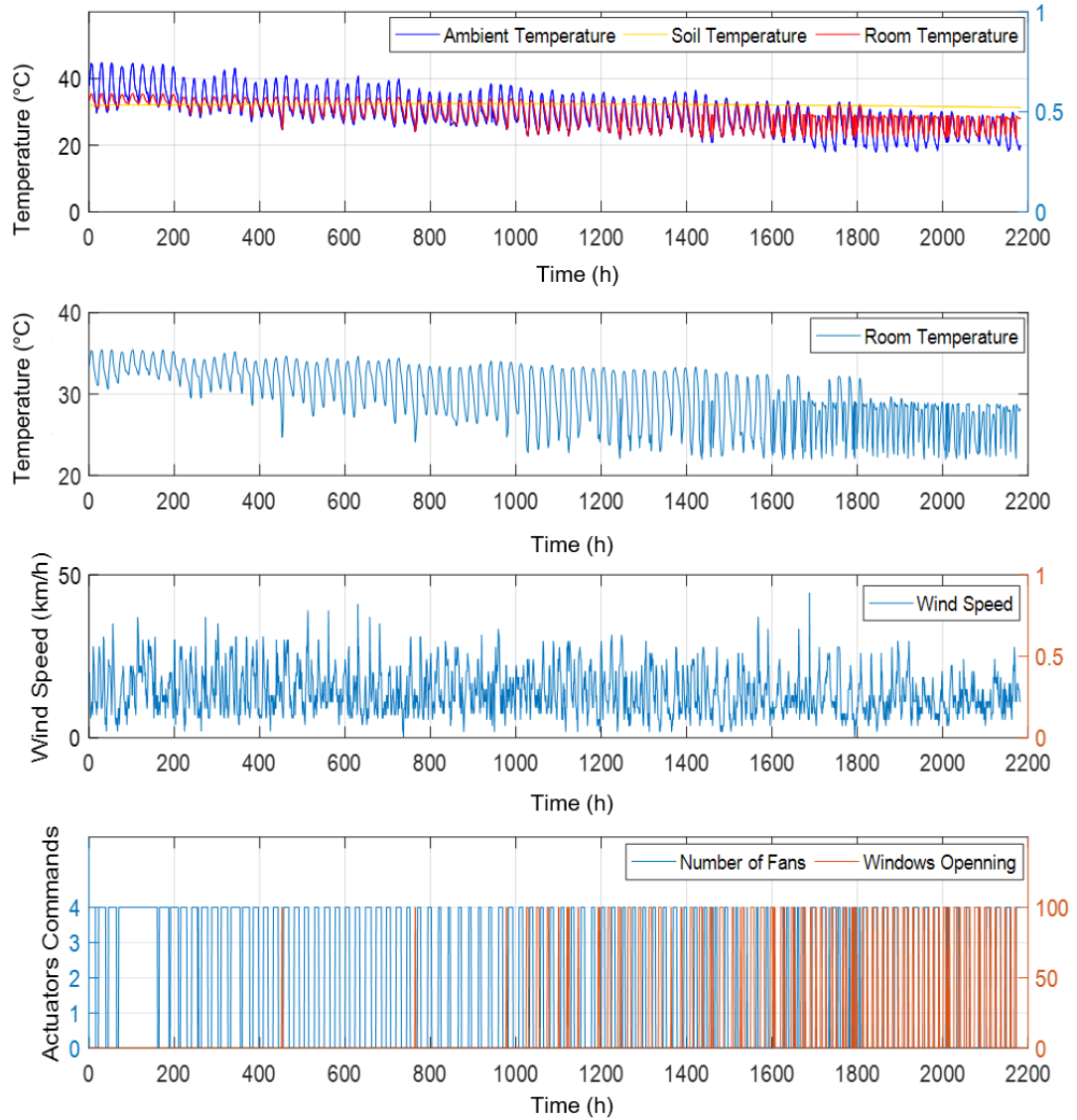
Figure 68: ON/OFF controller in fall season

4.5 Comparison Between Proposed Controllers

A comparison between the proposed fuzzy-based controller and the logical and ON/OFF controllers performance in each season is shown in Table 14. The fans

operation hours mentioned in the tables counts the number of fans running. For example, if it is an ON/OFF controller and the fans operating hours mentioned is 6904 then the GHE is utilized for 6904/4= 1726 hours where 4 is the number of fans used to fully utilize the GHE. Moreover, and to have a better understanding of the GHE effect on the greenhouse room temperature, the ON/OFF controller is run without fans and allowed to control the window actuators only.

Table 14 shows that the fans consumption in the ON/OFF controller is much higher than the fuzzy controller in all seasons, however, the numbers are close to each other in summer season at which the GHE is fully utilized for pre-cooling purpose. The biggest difference in fans operation is in winter season where the fuzzy controller commands the fans to work for 5908 hours while the ON/OFF controller commands it for 661 operation hours. This huge difference is due to the decision taken by the fuzzy controller that specifies the needed number of fans for heating/cooling based on how far the room temperature from the desired temperature.

It is important to mention that, in both controllers an AC unit may be needed if the renewable energy resources are saturated (i.e. the soil temperature or the weather conditions cannot be utilized to maintain the greenhouse temperature). This unit works independently if the control system fails to keep the room temperature below the maximum allowable value. If the temperature exceeds the maximum allowable value an auxiliary unit will switch ON independently until the temperature drops below the T_{max}.

Table 14: Comparison between ON/OFF, logical and fuzzy controllers

Season	Control	Fans operating hours (h)	Fans power (kWh)	Window open/ close count	Avg. room temp. (ºC)	Avg. Ambient temp. (ºC)	Avg. error
Full Year	Fuzzy	7295	496	472	26.8	28.9	-1.8
	Logical	10700	727	307	27.4	28.9	-2.4
	ON/OFF	22844	1553	1341	28.5	28.9	-3.5
Winter	Fuzzy	39	2.7	106	22.6	20.3	0
	Logical	64	4.4	94	22.5	20.3	0
	ON/OFF	5332	362.6	541	25.4	20.3	0.4
Spring	Fuzzy	375	25.5	124	26.2	28.5	-1.2
	Logical	1240	84.3	90	26.6	28.5	-1.6
	ON/OFF	5928	403.1	427	27.0	28.5	-2.0
Summer	Fuzzy	4833	328.6	35	30.4	37.1	-5.4
	Logical	7332	498.6	13	32.0	37.1	-7.0
	ON/OFF	8148	554.1	128	32.0	37.1	-7.0
Fall	Fuzzy	2048	139.3	206	27.9	29.6	-2.9
	Logical	2064	140.4	110	28.5	29.6	-3.5
	ON/OFF	3436	233.6	356	29.5	29.6	-4.5

Chapter 5: Conclusion

This research studied the performance of two proposed controllers in maintaining the greenhouse environment by utilizing ground temperature and weather conditions. A fuzzy based control system is proposed and compared with the logical and conventional ON/OFF controllers to maintain the innovative greenhouse temperature and humidity. The controllers were simulated and tested in simulation using Matlab Simulink R2016b and real meteorological data over one complete year. Results showed that the proposed fuzzy-based controller can maintain the greenhouse temperature on most days of the year better than the logical and ON/OFF controllers. However, in summer all controllers were working in pre-cooling mode and further cooling unit is needed to reduce the greenhouse temperature by about 7℃ amplitude on average. Also, simulation showed that the ON/OFF controller consumed higher power and showed higher fluctuation in room temperature when compared to the logical and the fuzzy controllers. However, the actuators' power consumptions of the fuzzy controller and the logical controller are close. As a conclusion, the GHE can be used for heating purpose without the need for an auxiliary heating unit. However, it can be only used for pre-cooling in summer where it has the capability of maintaining the greenhouse temperature at 30.4℃ on average the entire season with the fuzzy-based controller. The proposed control system utilized the outside temperature and humidity to maintain the greenhouse temperature and humidity at a certain range. However, results showed that a fog system is needed to maintain the greenhouse humidity as the outside humidity cannot be utilized with the temperature most of the time. The proposed control system provides enough cooling for most of the year and reduces the cooling load in summer season.

Utilizing GHE in UAE climate proved that it can eliminate the need of an auxiliary heating unit and reduce the required cooling load. Despite the big variation in design and optimization techniques of the GHE, all the conducted experiments in different places of the world proved the efficiency of using the geothermal energy in cooling/heating processes. However, the ambient temperature, the soil physical properties and the application where the GHE is employed need to be taken into consideration before designing the GHE.

Future Work

The experimental power consumption of the actuators needs to be studied when running the ON/OFF controller and the fuzzy controller while having plants inside the greenhouse. This study should focus on how much power is saved when utilizing the weather conditions and the ground heat exchanger compared to the consumed power by the fans and the linear actuators in the long term. Also, it should focus on the actuators lifecycle and performance when each controller is deployed. Another study should be done to compare between the amount of water consumed for cooling purpose in the conventional greenhouses and the water consumption when the GHE and the controllers are used. More research should be conducted on the performance of GHEs for a long-term period considering the thermal load imbalance issue and the ground thermal recovery cycle. Future work should focus on providing comprehensive economic analysis together with COP for different designs of GHEs especially the air-to-ground heat exchangers which are considered to be affordable in many places because they do not require deep ground digging or ground water availability. In addition, more studies should be conducted on soil properties at different places and

at different times in the UAE to provide a map of best places for deploying ground heat exchanger for a certain application.

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Appendix A

Database Tables

Recording outdoor measurements

ID	time	insideTemp	insideHumidity	fan1Temp	fan2Temp	fan3Temp	fan4Temp	tempSensor1	tempSensor2	tempSensor3
50285	2018-02-26 19:58:37	27.875	16	27.6875	27.5	27.25	27.25	27.0000	26.0000	28.7500
50286	2018-02-26 19:59:54	27.875	16	27.6875	27.5	27.1875	27.1875	27.0000	26.0000	28.7500
50287	2018-02-26 20:01:13	27.8438	16	27.6875	27.5625	27.125	27.1875	27.0000	26.0000	28.6875
50288	2018-02-26 20:02:30	27.875	16	27.6875	27.5625	27.125	27.1875	27.0000	26.0000	28.7500
50289	2018-02-26 20:03:48	27.8438	16	27.6875	27.5	27.125	27.1875	27.0000	26.0000	28.6875

Recording indoor measurements

ID	Time	outsideTemp	outsideHumidity	windSpeed	tempSensor1	tempSensor2	depth2andhalf	depth1andhalf	depthhalf
10812	2018-02-27 15:53:24	29.9688	26	3.6392	30	29.9375	26.8125	23.3125	21.6875
10813	2018-02-27 15:55:37	29.8125	26	3.0418	29.75	29.875	26.8125	23.3125	21.75
10814	2018-02-27 15:57:52	29.875	26	3.6018	29.875	29.875	26.8125	23.375	21.75
10815	2018-02-27 16:00:06	29.7813	26	4.1619	29.6875	29.875	26.8125	23.375	21.75
10816	2018-02-27 16:06:49	29.875	26	2.1457	30	29.75	26.8125	23.375	21.75

Recording outputs

ID	time	linearActuator	fan	LED	emergencyShutDown	auxUnit
4643	2018-02-26 14:49:50	0	0	0	0	1
4644	2018-02-26 14:51:50	0	0	0	0	1
4645	2018-02-26 14:53:50	0	0	0	0	1
4646	2018-02-26 14:55:50	0	0	0	0	1
4647	2018-02-26 14:59:52	0	100	0	0	0

Appendix B

Arduino controller coding

```
[code]

#include <Wire.h>

#include <OneWire.h>

#include <Adafruit_Sensor.h>//common between light and dht sensors

#include <Adafruit_TSL2561_U.h>

#include <DHT.h>

//#include <DHT_U.h>

#include <Ethernet.h>

#include <MySQL_Connection.h>

#include <MySQL_Cursor.h>

#include <OneWire.h>

#include <SHT1x.h>

byte mac_addr[] = { 0x90, 0xA2, 0xDA, 0x10, 0x2F, 0x7B };

IPAddress server_addr(192,168,0,101);  // IP of the MySQL *server* here

char user[] = "indoorMC";           // MySQL user login username

char password[] = "";        // MySQL user login passwor

EthernetClient client;

//***************MySQL inquireis*************************//

char INSERT_DATA[] = "INSERT INTO gh.indoor(
insideTemp,insideHumidity,fan1Temp,fan2Temp,fan3Temp,fan4Temp) VALUES
(%s,%s,%s,%s,%s,%s)";

char query_outputs[] = "SELECT fan FROM gh.outputs ORDER BY Time DESC
LIMIT 1";

char query[128];
```

//************************Definitions*******************//

OneWire ds(8); // Fan1 temprature sensor on pin 10 (a 4.7K resistor is necessary)

OneWire ds1(9);// Fan2 temprature sensor on pin 9 (a 4.7K resistor is necessary)

OneWire ds2(31);

OneWire ds3(32); // Fan1 temprature sensor on pin 10 (a 4.7K resistor is necessary)

OneWire ds4(40); // INSIDE temprature sensor on pin 10 (a 4.7K resistor is necessary)

#define dataPin 6//expensive weather proof sensor

#define clockPin 7//expensive weather proof sensor

SHT1x sht1x(dataPin, clockPin);

#define fan1   22

#define fan2   23

#define fan3   24

#define fan4   25

int x_1=0 ; int x_2=0; double y=0; double T; double H;

double f1T=0;

double f2T=0;

double f3T=0;

double f4T=0;

double f3H=0;

double f4H=0 ; int fan1Value, fan2Value,fan3Value,fan4Value;

double T_old, H_old, f1T_old, f2T_old, f3T_old,f4T_old;

int MusurementNumber;

//For light sensors

Adafruit_TSL2561_Unified tsl = Adafruit_TSL2561_Unified(0x39, 12345); //0x39 is the default value which should be connected to the SCL and SDA pins

```
Adafruit_TSL2561_Unified ts2 = Adafruit_TSL2561_Unified(0x29, 12346); //0x29
should be connected in the reference pins

//For DHT Humidity and Temprature sensor

#define DHTPIN         3         // Pin which is connected to the DHT sensor.

#define DHT2PIN        2

#define DHT3PIN        5

#define DHTTYPE        DHT11     // DHT 11

#define DHT2TYPE        DHT11

#define DHT3TYPE        DHT11

DHT dht(DHTPIN, DHTTYPE);

DHT dht2(DHT2PIN, DHT2TYPE);

DHT dht3(DHT3PIN, DHT3TYPE);

//*********************************************************//

void setup(void)

{

pinMode(fan1,OUTPUT); //fan1 on pin 22

pinMode(fan2,OUTPUT); //fan2 on pin 23

pinMode(fan3,OUTPUT); //fan3 on pin 24

pinMode(fan4,OUTPUT);//fan4 on pin 25

digitalWrite(fan1 , 1);

digitalWrite(fan2 , 1);

digitalWrite(fan3 , 1);

digitalWrite(fan4 , 1);

dht.begin();

dht2.begin();

dht3.begin();

Serial.begin(1000000);
```

```
MusurementNumber =1;

sensor_t sensor;

//****************************************************************//

}

void loop(void)

{

 Serial.print("*****************Measurement#");

  Serial.print(MusurementNumber);

 Serial.println("******************");

//***************fans Temp. Sensors******************//

//-------------------------------------------------------------//

  //**DHT Humidity and Temprature sensor**//

 //-------------------------------------------------------------//

  float h1 = dht.readHumidity();

 // Read temperature as Celsius (the default)


  float t1 = dht.readTemperature();

 // Check if any reads failed and exit early (to try again).

 if (isnan(h1) || isnan(t1) )

Serial.println("Failed to read from DHT sensor!");

 f3T= t1;

 f3H= h1;

 Serial.print("DHT Humidity: ");

 Serial.print(f3H);

 Serial.print(" %\t");

 Serial.print("DHT Temperature: ");
```

```
  Serial.print(f3T);

  Serial.println(" *C ");

  delay(1000);

  float h2 = dht2.readHumidity();

  float t2 = dht2.readTemperature();

  if (isnan(h2) || isnan(t2)) {

    Serial.println("Failed to read from DHT sensor!");

  }

  Serial.print("DHT Humidity: ");

  Serial.print(h2);

  Serial.print(" %\t");

  Serial.print("DHT Temperature: ");

  Serial.print(t2);

  Serial.println(" *C ");

   delay(1000);

double T1= t2;

double H1= h2;

  float h3 = dht3.readHumidity();

  float t3 = dht3.readTemperature();

  if (isnan(h1) || isnan(t1) )

  Serial.println("Failed to read from DHT sensor!");

double  T2= t3;

double H2= h3;

  Serial.print("third DHT Humidity: ");

  Serial.print(H);

  Serial.print(" %\t");
```

```
Serial.print(" third DHT Temperature: ");

Serial.print(T);

Serial.println(" *C ");

/////////////////// FOR FIRST AND SECOND FANS TEMP. SENSORS///////////////

byte i;

byte present = 0;

byte type_s;

byte data[12];

byte addr[8];

float celsius, fahrenheit;

if ( !ds.search(addr))

{

  ds.reset_search();

  delay(250);

}

if (OneWire::crc8(addr, 7) != addr[7])

{

    Serial.println("CRC is not valid!");

    celsius=0;

}

Serial.println();

ds.reset();

ds.select(addr);

ds.write(0x44, 1);       // start conversion, with parasite power on at the end

delay(1000);     // maybe 750ms is enough, maybe not

// we might do a ds.depower() here, but the reset will take care of it.
```

```
present = ds.reset();

ds.select(addr);

ds.write(0xBE);         // Read Scratchpad

for ( i = 0; i < 9; i++)

{         // we need 9 bytes

  data[i] = ds.read();

}

int16_t raw = (data[1] << 8) | data[0];

if (type_s)

{

  raw = raw << 3; // 9 bit resolution default



  if (data[7] == 0x10)

  {

    // "count remain" gives full 12 bit resolution

    raw = (raw & 0xFFF0) + 12 - data[6];

  }

}

else

{

  byte cfg = (data[4] & 0x60);

  // at lower res, the low bits are undefined, so let's zero them

  if (cfg == 0x00) raw = raw & ~7;  // 9 bit resolution, 93.75 ms

  else if (cfg == 0x20) raw = raw & ~3; // 10 bit res, 187.5 ms

  else if (cfg == 0x40) raw = raw & ~1; // 11 bit res, 375 ms
```

```
    //// default is 12 bit resolution, 750 ms conversion time

  }

  celsius = (float)raw / 16.0;

  Serial.print("  Temperature = ");

  Serial.print(celsius);

  Serial.print(" Celsius, ");

 f1T= celsius;

 ////////////////////////////////SECOND////////////////////

 present = 0;

  if ( !ds1.search(addr))

  {

  ds1.reset_search();

   delay(250);

  }

  if (OneWire::crc8(addr, 7) != addr[7]) {

     Serial.println("CRC is not valid!");

    celsius=0;

  }

  Serial.println();

  ds1.reset();

  ds1.select(addr);

  ds1.write(0x44, 1);        // start conversion, with parasite power on at the end

  delay(1000);     // maybe 750ms is enough, maybe not

  // we might do a ds.depower() here, but the reset will take care of it.

  present = ds1.reset();

  ds1.select(addr);
```

```
  ds1.write(0xBE);        // Read Scratchpad

 for ( i = 0; i < 9; i++) {          // we need 9 bytes

  data[i] = ds1.read();

 }
raw = (data[1] << 8) | data[0];
 if (type_s) {

  raw = raw << 3; // 9 bit resolution default

  if (data[7] == 0x10) {

    // "count remain" gives full 12 bit resolution

  raw = (raw & 0xFFF0) + 12 - data[6];

   }

 }

 else

 {

  byte cfg = (data[4] & 0x60);

  // at lower res, the low bits are undefined, so let's zero them

  if (cfg == 0x00) raw = raw & ~7;  // 9 bit resolution, 93.75 ms

  else if (cfg == 0x20) raw = raw & ~3; // 10 bit res, 187.5 ms

  else if (cfg == 0x40) raw = raw & ~1; // 11 bit res, 375 ms

  //// default is 12 bit resolution, 750 ms conversion time

 }

 celsius = (float)raw / 16.0;

 Serial.print("  Temperature = ");

 Serial.print(celsius);

 Serial.println(" Celsius, ");

f2T= celsius;
```

```
/////////////////////////////third//////////////////

 present = 0;

  if ( !ds2.search(addr))

  {

   ds2.reset_search();

   delay(250);

  }

if (OneWire::crc8(addr, 7) != addr[7]) {

    Serial.println("CRC is not valid!");

    celsius=0;

  }

  Serial.println();

  ds2.reset();

  ds2.select(addr);

  ds2.write(0x44, 1);      // start conversion, with parasite power on at the end

  delay(1000);    // maybe 750ms is enough, maybe not

  // we might do a ds.depower() here, but the reset will take care of it.

  present = ds2.reset();

  ds2.select(addr);

  ds2.write(0xBE);       // Read Scratchpad

  for ( i = 0; i < 9; i++) {       // we need 9 bytes

   data[i] = ds2.read();

  }

raw = (data[1] << 8) | data[0];

  if (type_s) {

   raw = raw << 3; // 9 bit resolution default
```

```
    if (data[7] == 0x10) {

      // "count remain" gives full 12 bit resolution

      raw = (raw & 0xFFF0) + 12 - data[6];

    }

  }

 else

  {

    byte cfg = (data[4] & 0x60);

    if (cfg == 0x00) raw = raw & ~7;  // 9 bit resolution, 93.75 ms

    else if (cfg == 0x20) raw = raw & ~3; // 10 bit res, 187.5 ms

    else if (cfg == 0x40) raw = raw & ~1; // 11 bit res, 375 ms

  }

  celsius = (float)raw / 16.0;

  Serial.print("  Temperature = ");

  Serial.print(celsius);

  Serial.println(" Celsius, ");

 f3T= celsius;

 ////////////////////////////////fourth/////////////////////

 present = 0;

  if ( !ds3.search(addr))

  {

   ds3.reset_search();

   delay(250);

  }

  if (OneWire::crc8(addr, 7) != addr[7]) {

     Serial.println("CRC is not valid!");
```

```
    celsius=0;

  }

  Serial.println();

ds3.reset();

  ds3.select(addr);

  ds3.write(0x44, 1);        // start conversion, with parasite power on at the end

  delay(1000);     // maybe 750ms is enough, maybe not

  // we might do a ds.depower() here, but the reset will take care of it.

  present = ds3.reset();

  ds3.select(addr);

  ds3.write(0xBE);         // Read Scratchpad

  for ( i = 0; i < 9; i++) {          // we need 9 bytes

    data[i] = ds3.read();

  }

raw = (data[1] << 8) | data[0];

  if (type_s) {

    raw = raw << 3; // 9 bit resolution default

    if (data[7] == 0x10) {

      // "count remain" gives full 12 bit resolution

      raw = (raw & 0xFFF0) + 12 - data[6];

    }

  }

  else

  {

    byte cfg = (data[4] & 0x60);

    // at lower res, the low bits are undefined, so let's zero them
```

```
   if (cfg == 0x00) raw = raw & ~7;  // 9 bit resolution, 93.75 ms

   else if (cfg == 0x20) raw = raw & ~3; // 10 bit res, 187.5 ms

   else if (cfg == 0x40) raw = raw & ~1; // 11 bit res, 375 ms

  }

 celsius = (float)raw / 16.0;

 Serial.print("  Temperature = ");

 Serial.print(celsius);

 Serial.println(" Celsius, ");

f4T= celsius;

 ////////////////////////////insideTemp////////////////////

 present = 0;

 if ( !ds4.search(addr))

 {

   ds4.reset_search();

   delay(250);

 }

 if (OneWire::crc8(addr, 7) != addr[7]) {

    Serial.println("CRC is not valid!");

    celsius=0;

 }

 Serial.println();

 ds4.reset();

 ds4.select(addr);

 ds4.write(0x44, 1);       // start conversion, with parasite power on at the end

 delay(1000);    // maybe 750ms is enough, maybe not

  present = ds4.reset();
```

```
    ds4.select(addr);

    ds4.write(0xBE);        // Read Scratchpad

   for ( i = 0; i < 9; i++) {          // we need 9 bytes

     data[i] = ds4.read();

   }
raw = (data[1] << 8) | data[0];

  if (type_s) {

    raw = raw << 3; // 9 bit resolution default

    if (data[7] == 0x10) {

      // "count remain" gives full 12 bit resolution

      raw = (raw & 0xFFF0) + 12 - data[6];

    }

  }

  else

  {

    byte cfg = (data[4] & 0x60);

    // at lower res, the low bits are undefined, so let's zero them

    if (cfg == 0x00) raw = raw & ~7;  // 9 bit resolution, 93.75 ms

    else if (cfg == 0x20) raw = raw & ~3; // 10 bit res, 187.5 ms

    else if (cfg == 0x40) raw = raw & ~1; // 11 bit res, 375 ms

    //// default is 12 bit resolution, 750 ms conversion time

  }

  celsius = (float)raw / 16.0;

Serial.print(" Temperature = ");

  Serial.print(celsius);

  Serial.println(" Celsius, ");
```

```
double T3 = celsius;

 //////////////////////////INSERTING DATA>>>>>>>>>>>>>>>>>>>>>>

MusurementNumber ++;

char insideTemp[512] ;

int insideLightIntensity1= x_1;

int insideLightIntensity2= x_2;

int avgLightIntensity = (x_1+x_2)/2;

char insideHumidity[512];

char fan1Temp[512];

char  fan2Temp[512];

char fan3Temp[512];

char fan4Temp[512];

T= (T1+T2+T3)/3.00;

H= (H1+H2)/2;

dtostrf(H,1,4, insideHumidity);

dtostrf(T,1,4, insideTemp);

dtostrf(f1T,1,4,fan1Temp);

dtostrf(f2T,1,4, fan2Temp);

dtostrf(f3T,1,4, fan3Temp);

dtostrf(f4T,1,4, fan4Temp);

MySQL_Connection conn((Client *)&client);

 while (!Serial); // wait for serial port to connect

 Ethernet.begin(mac_addr);

 Serial.println("Connecting...");

 if (conn.connect(server_addr, 3306, user, password)) {
```

```
    delay(1000);

  }

  else

  {

   Serial.println("Connection failed.");

   delay(60000);

   return; //do the measurements again, failed connection

  }

MySQL_Cursor *cur_mem = new MySQL_Cursor(&conn);

sprintf(query, INSERT_DATA, insideTemp ,insideHumidity, fan1Temp,
fan2Temp,fan3Temp, fan4Temp);

 cur_mem->execute(query);    // Execute the query

   delete cur_mem;

   Serial.println("Data recorded.");

conn.close();

//***********************OUTPUTS****************************//

 while (!Serial); // wait for serial port to connect

  Ethernet.begin(mac_addr);

  Serial.println("Connecting...");

if (conn.connect(server_addr, 3306, user, password))

 {

   delay(1000);

row_values *row = NULL;

long fanValue;

MySQL_Cursor *cur_mem1 = new MySQL_Cursor(&conn);  // Initiate the query
class instance

 cur_mem1->execute(query_outputs);  // Execute the query
```

```cpp
column_names *columns = cur_mem1->get_columns(); // Fetch the columns
(required) but we don't use them.

// // Read the row (we are only expecting the one)
 do {

   row = cur_mem1->get_next_row();

   if (row != NULL) {

     fanValue = atol(row->values[0]);

    }

  } while (row != NULL);

  // Deleting the cursor also frees up memory used

  delete cur_mem1;

if(fanValue>=13)

{

fan1Value= 1; //run only one fan

if(fanValue>=38)

fan2Value=1;

if(fanValue>=63)

fan3Value=1;

if(fanValue>=88)

 fan4Value=1;

}

else

{

fan1Value = 0;

fan2Value = 0;

fan3Value = 0;

fan4Value = 0;
```

```
}
  // Show the result
  Serial.println("  fan = ");
  Serial.println(fanValue);
    Serial.println("  fan1 = ");
  Serial.println(fan1Value);
    Serial.println("  fan2 = ");
  Serial.println(fan2Value);
      Serial.println("  fan3 = ");
  Serial.println(fan3Value);
    Serial.println("  fan4 = ");
  Serial.println(fan4Value);
digitalWrite(fan1,!fan1Value);
digitalWrite(fan2,!fan2Value);
digitalWrite(fan3,!fan3Value);
digitalWrite(fan4,!fan4Value);
conn.close();
//delay(60000);
}
 else
 {
   Serial.println("Connection failed.");
   return; //do the measurements again, failed connection
 }
}
[/code]
```

Appendix C

C.1 Fuzzy Controller in Simulink
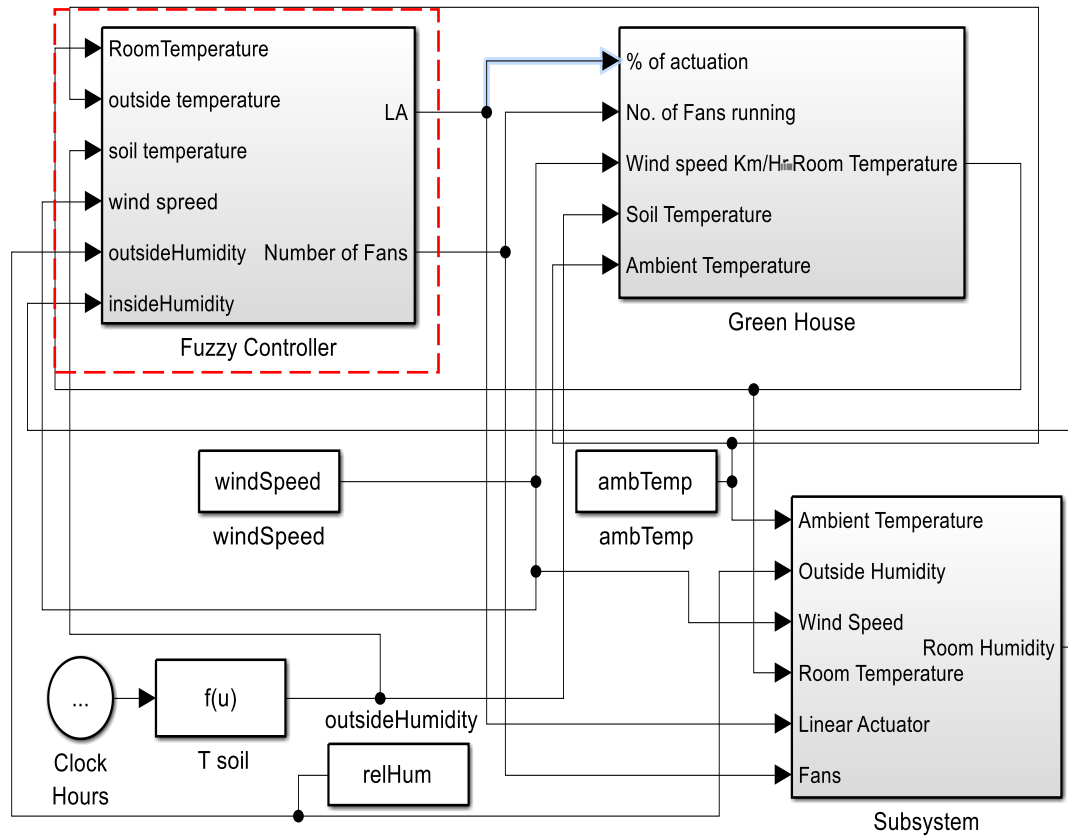
Fuzzy Controller Block
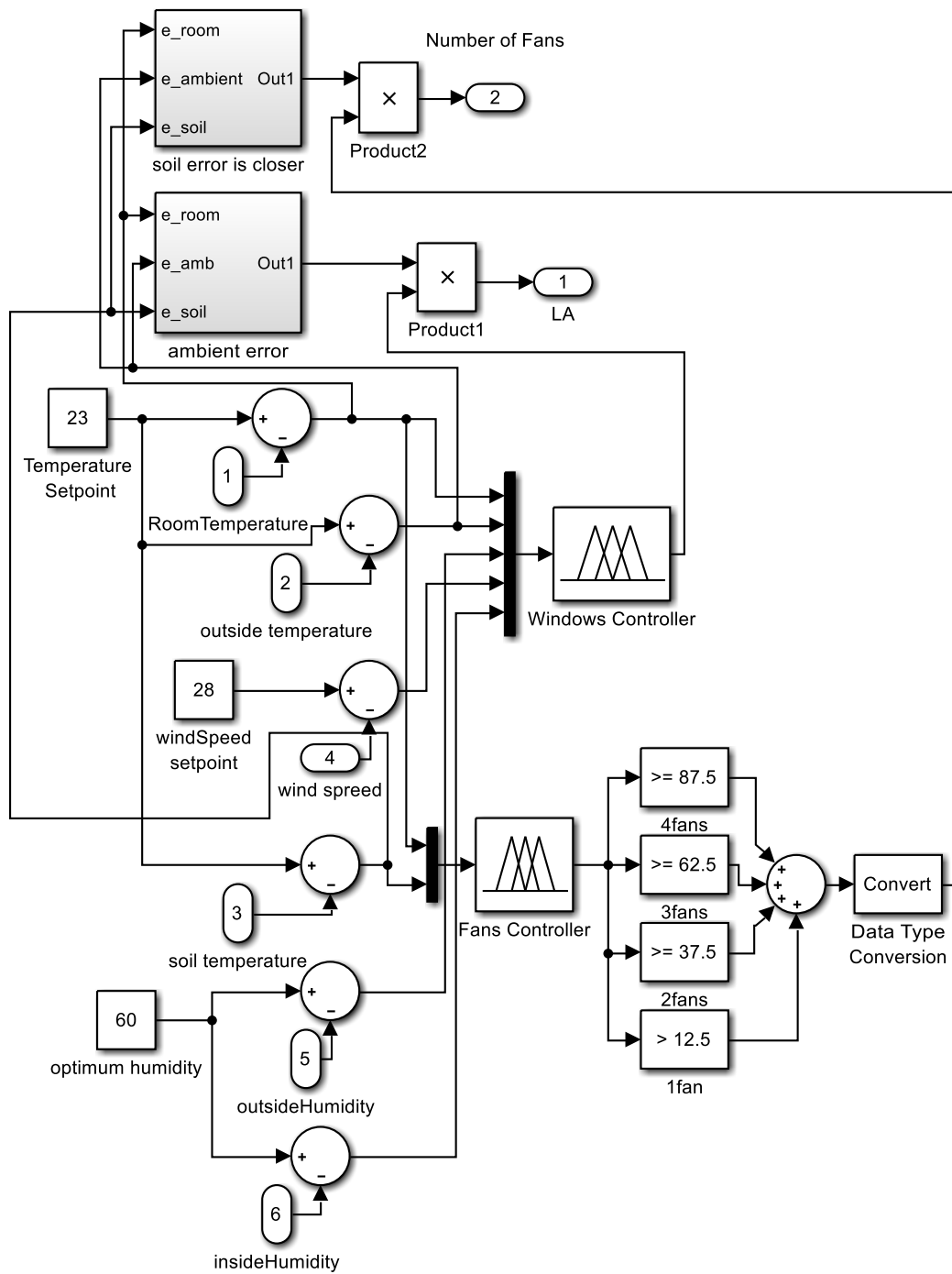
Soil Error Block
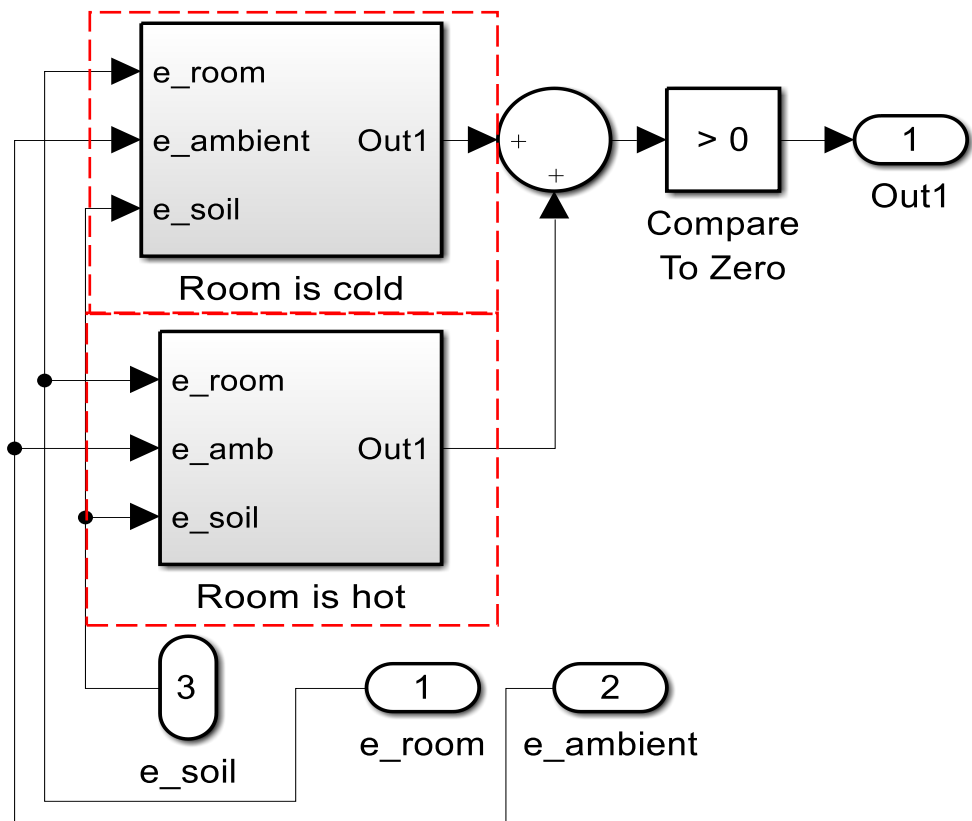
Room is cold Block
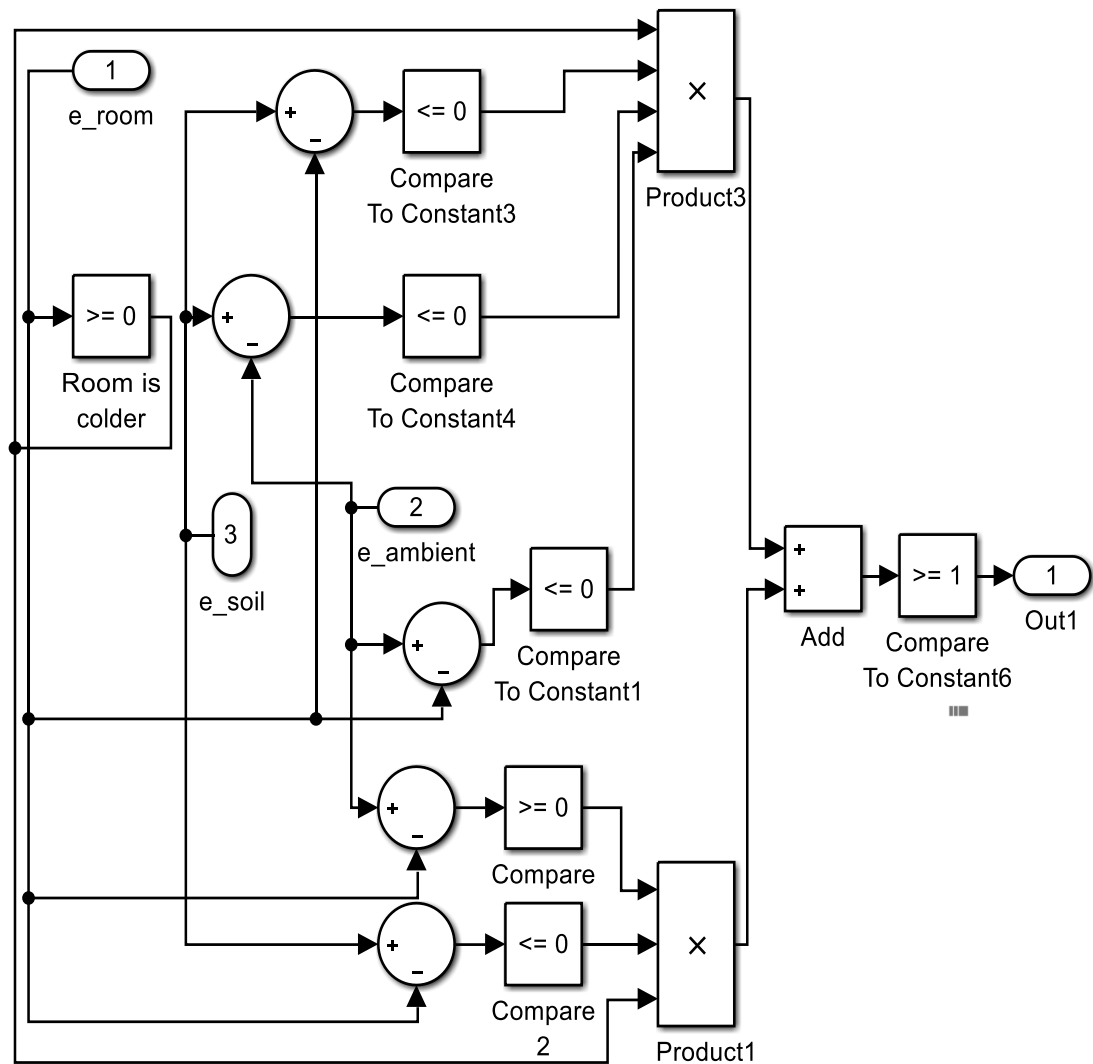
Room is hot Block
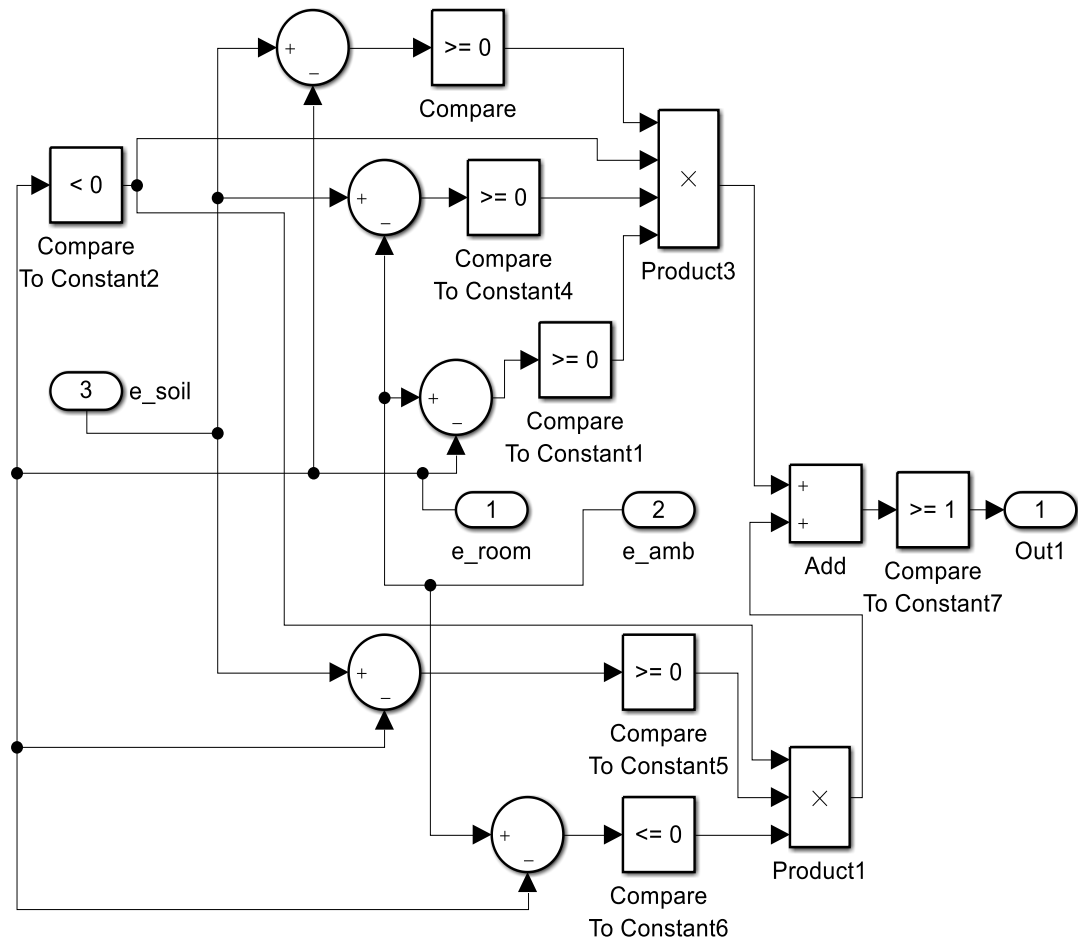
Ambient Error Block
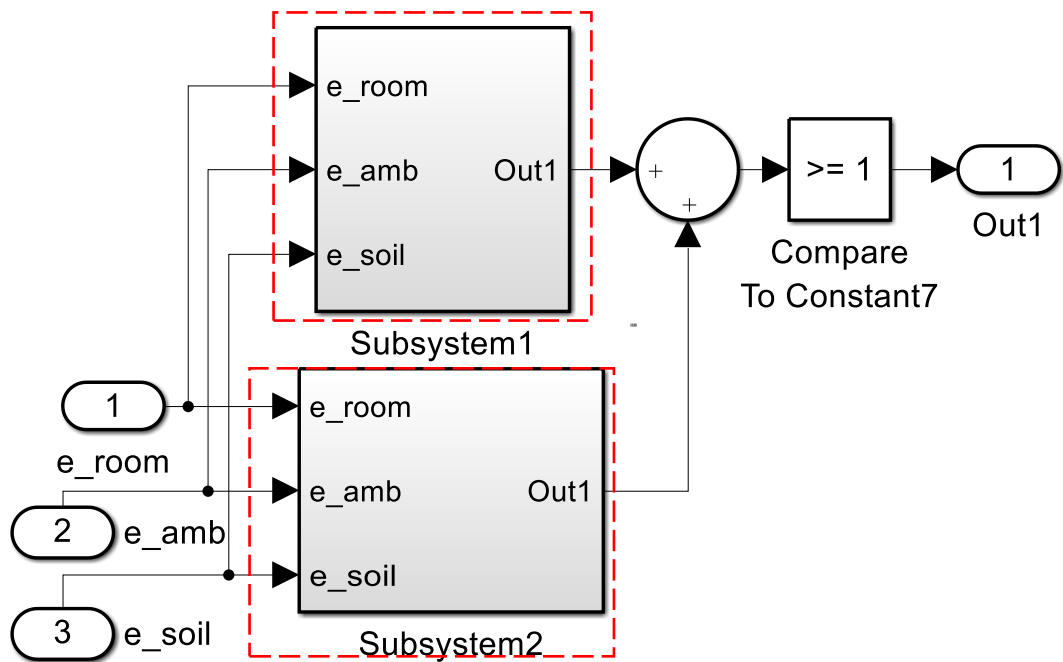
Subsystem1
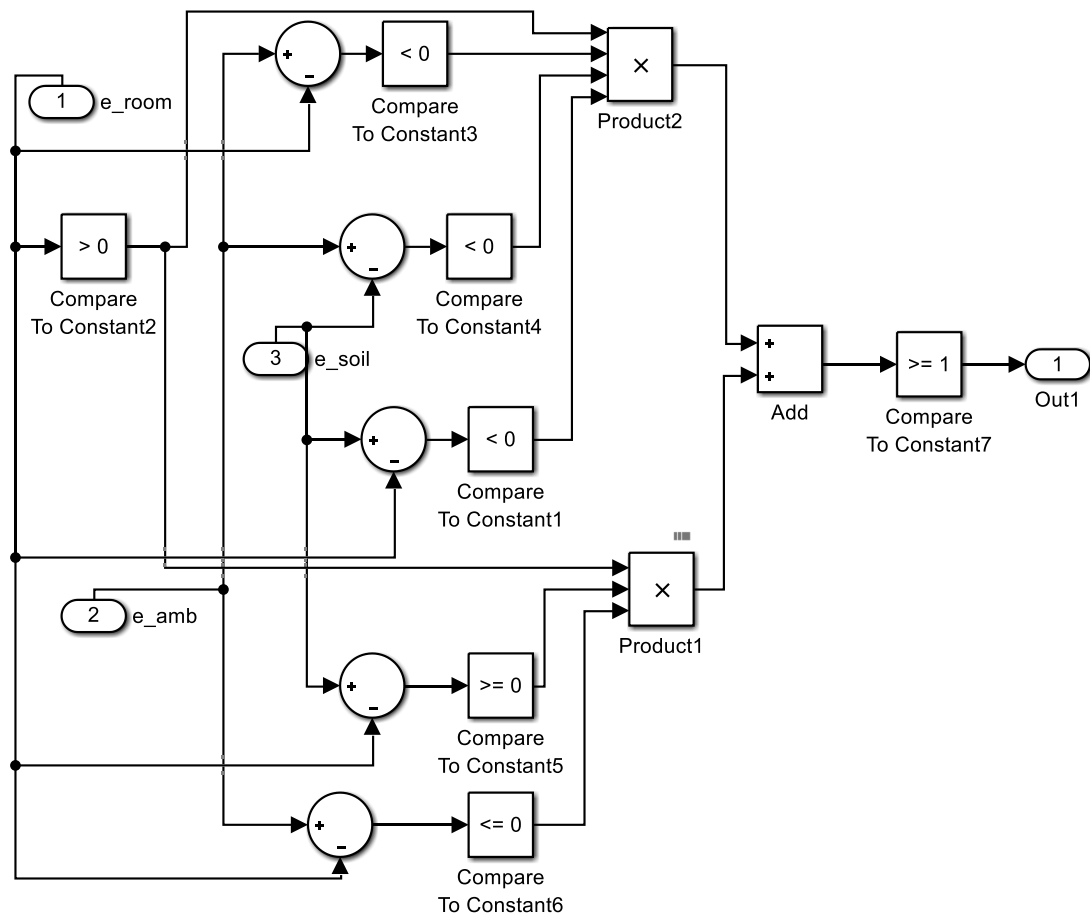
Subsystem2
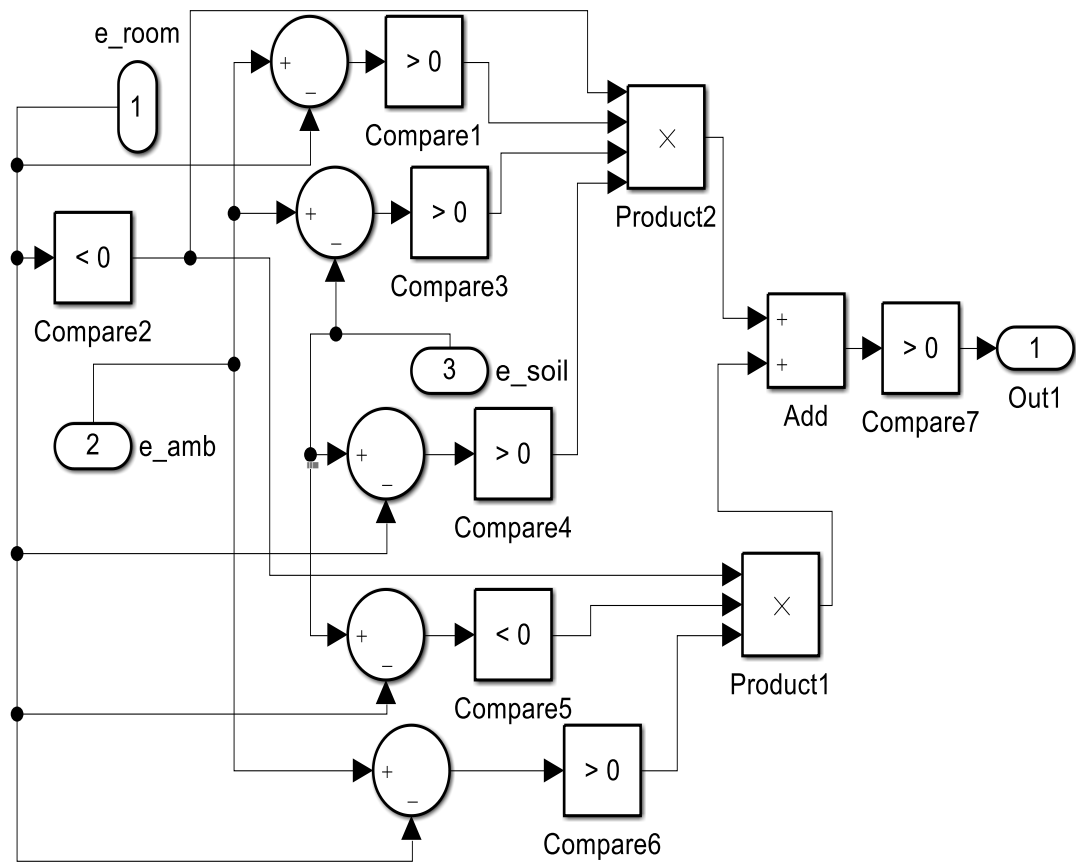
C.2 Logical controller in Simulink for both actuators
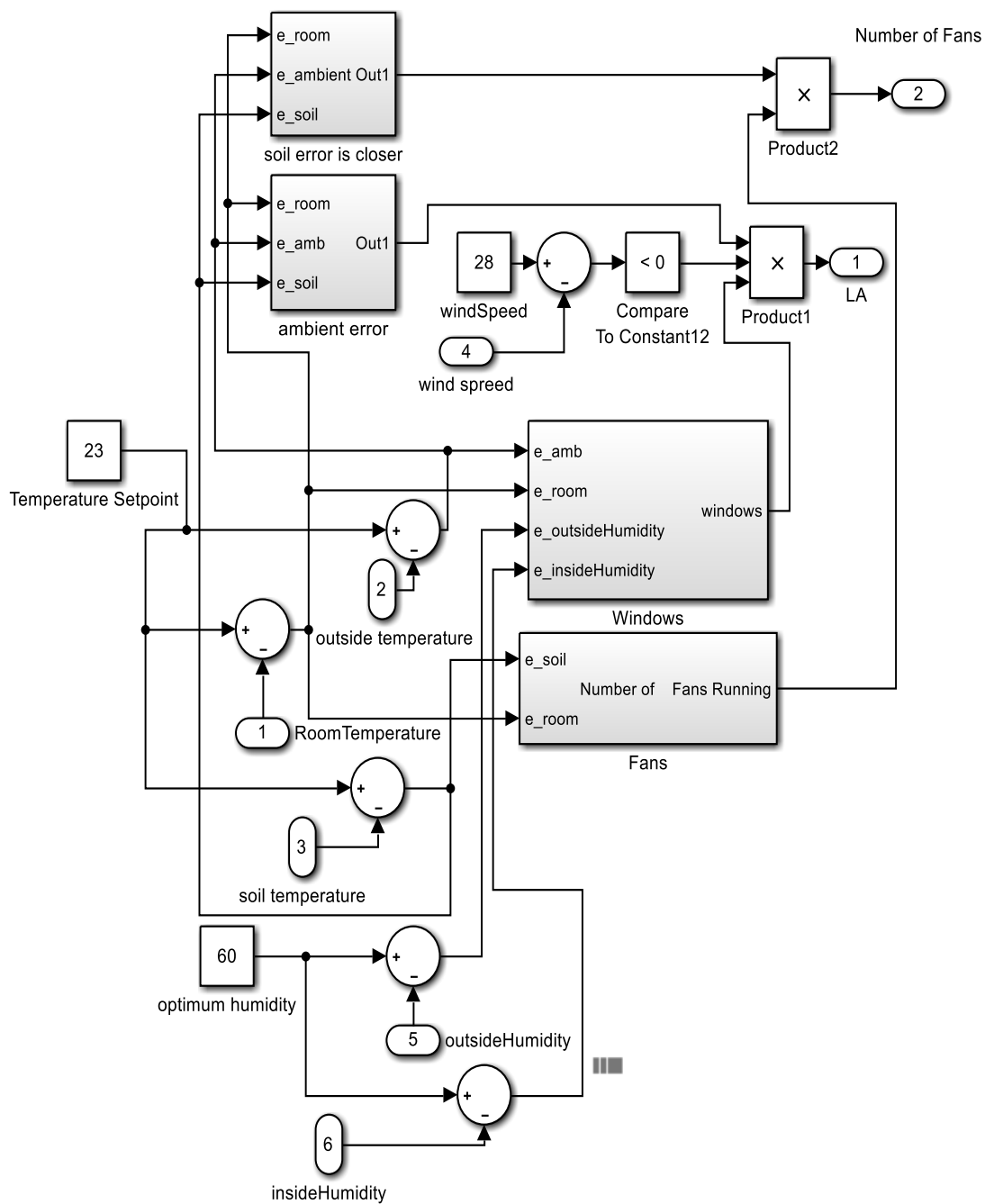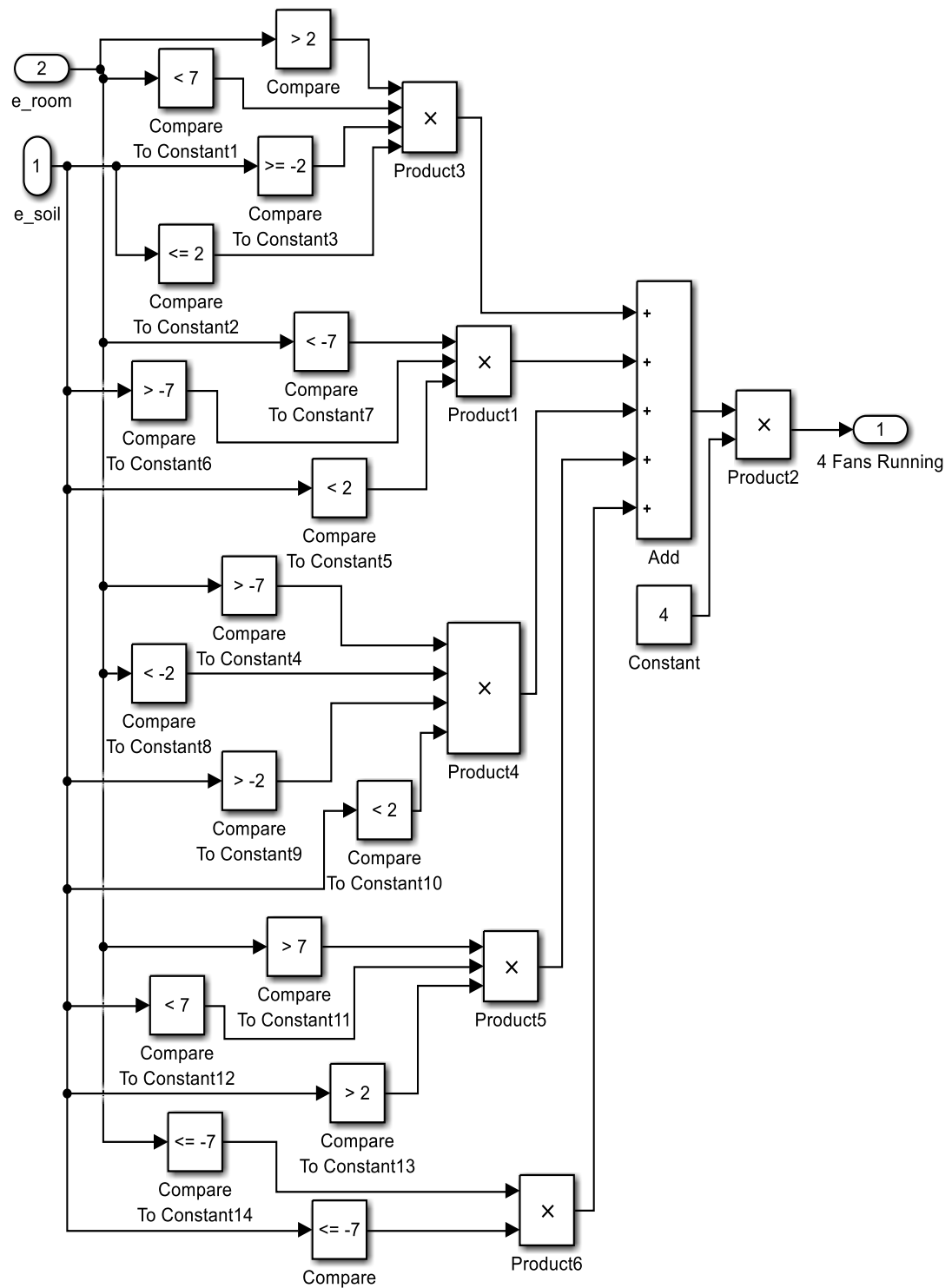
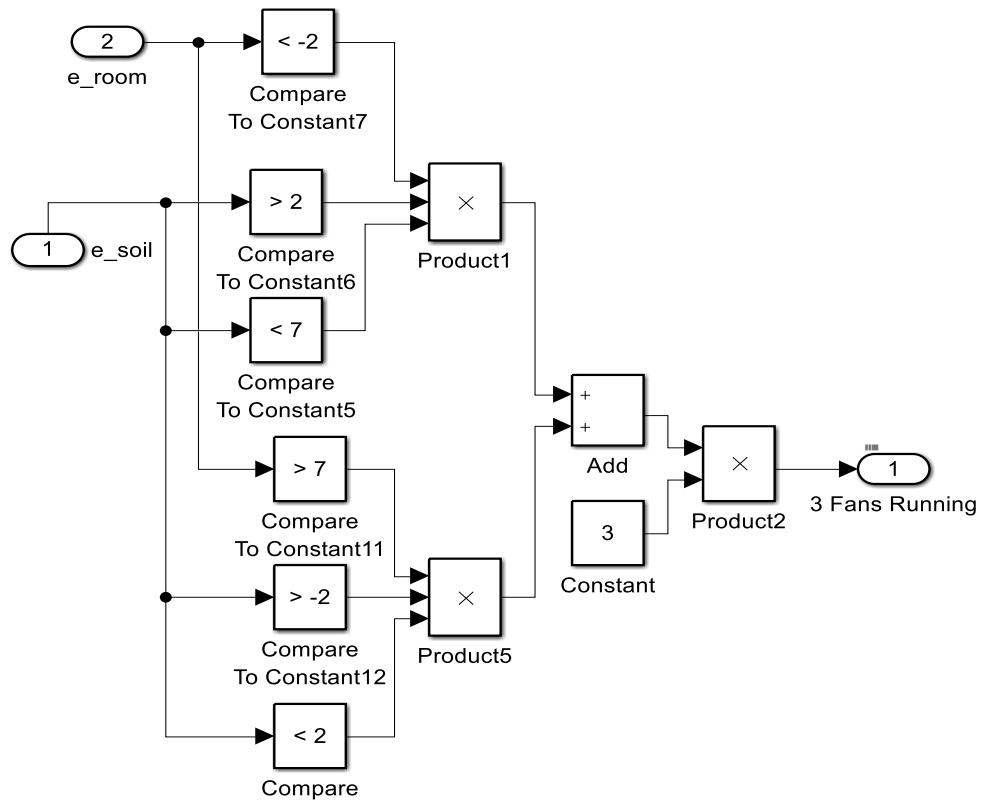**For linear actuator control (Windows Block)**
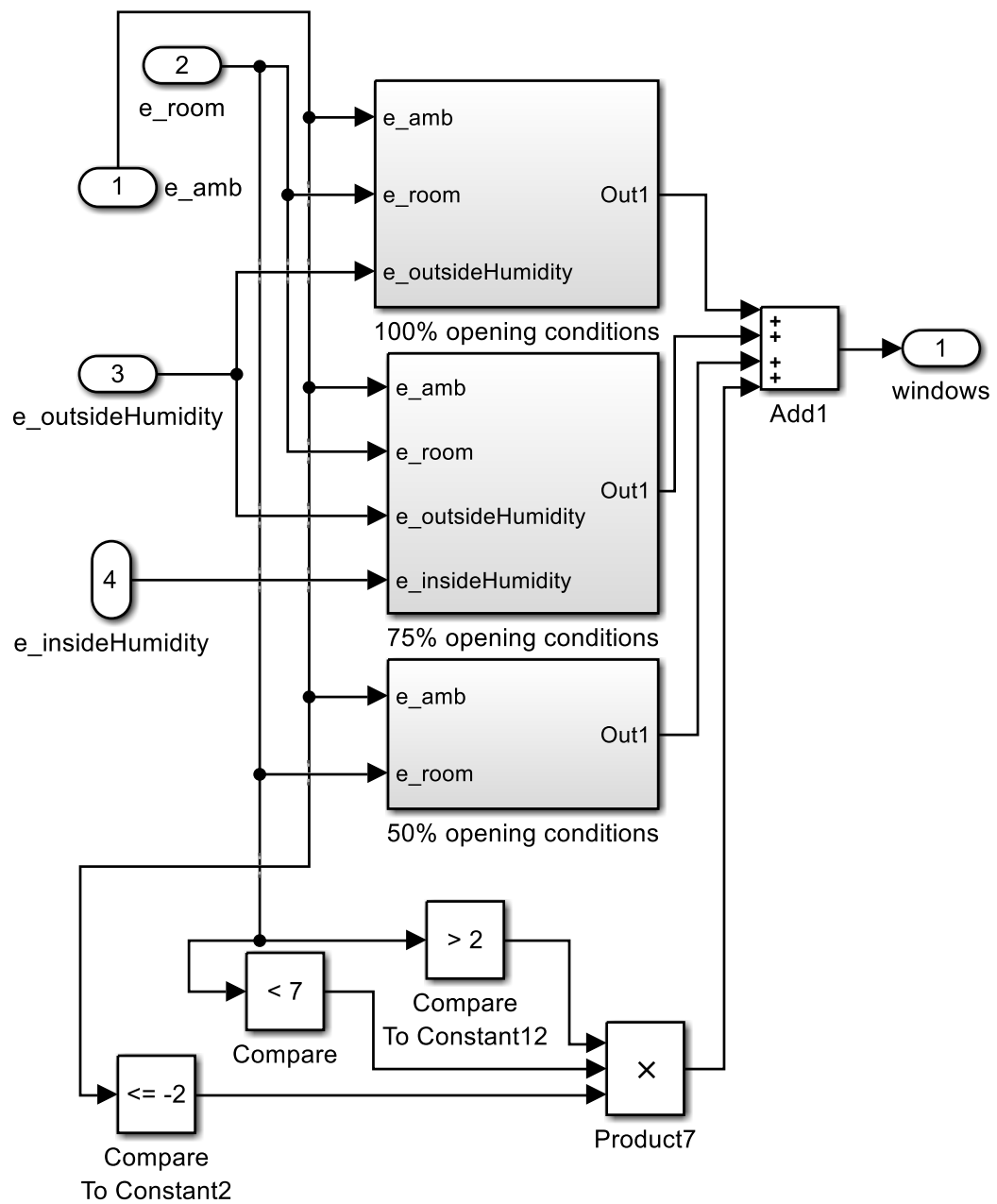
100% Block
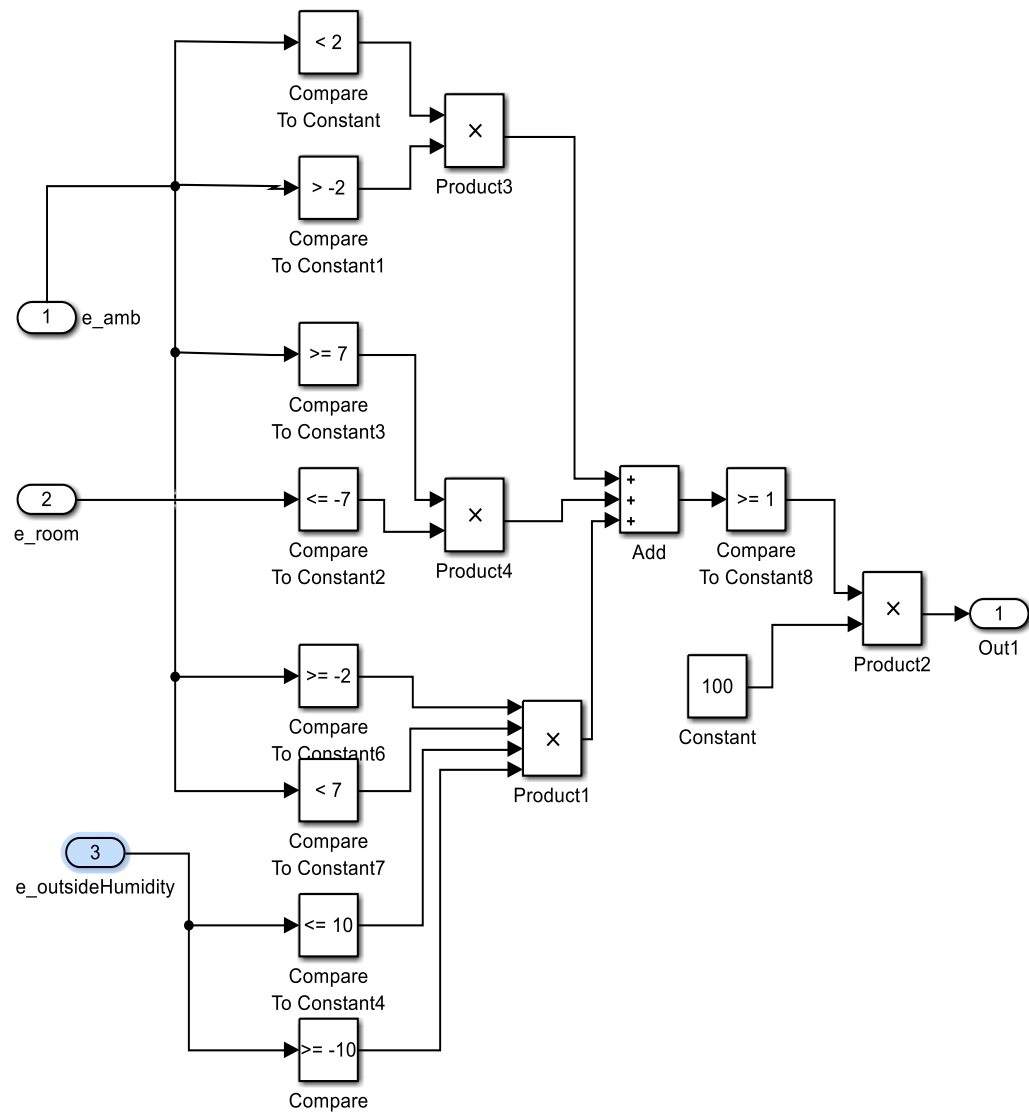
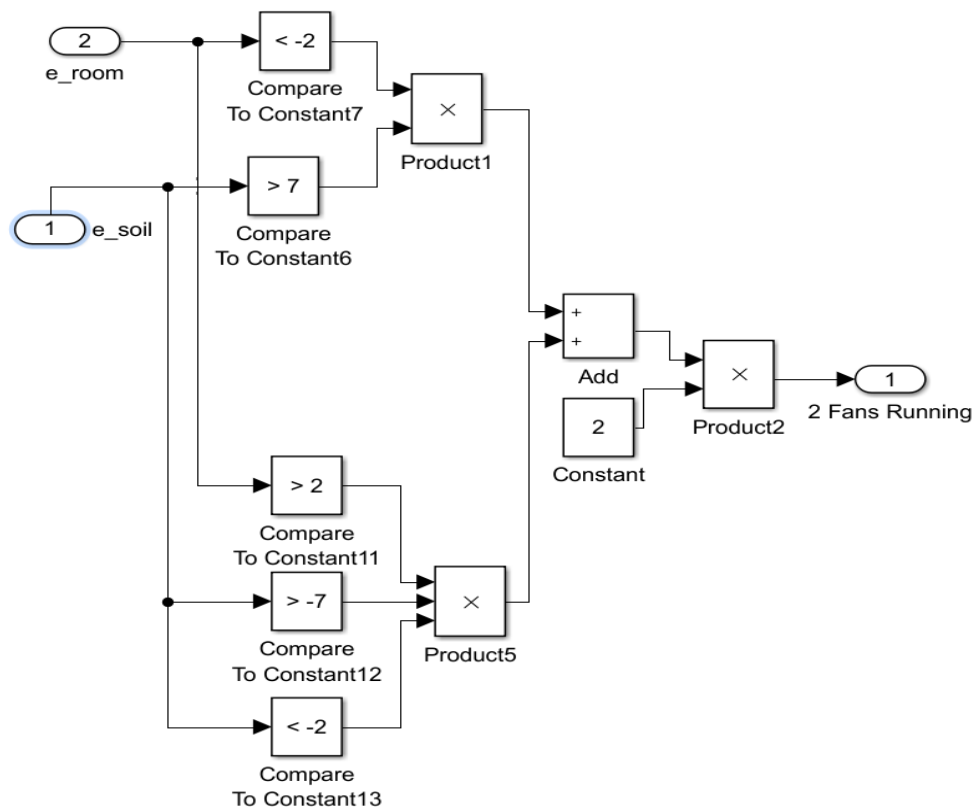**75% Block**
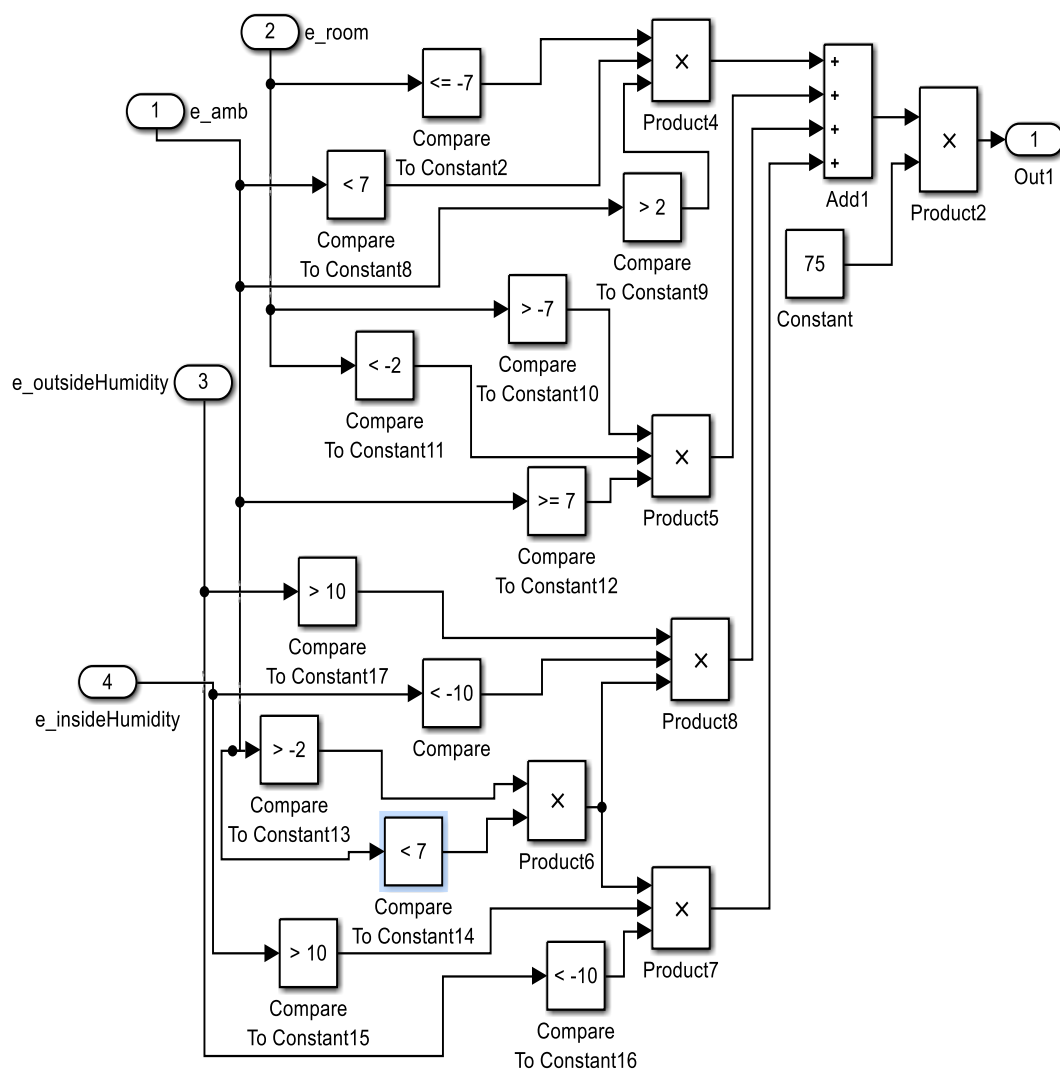
50% Block
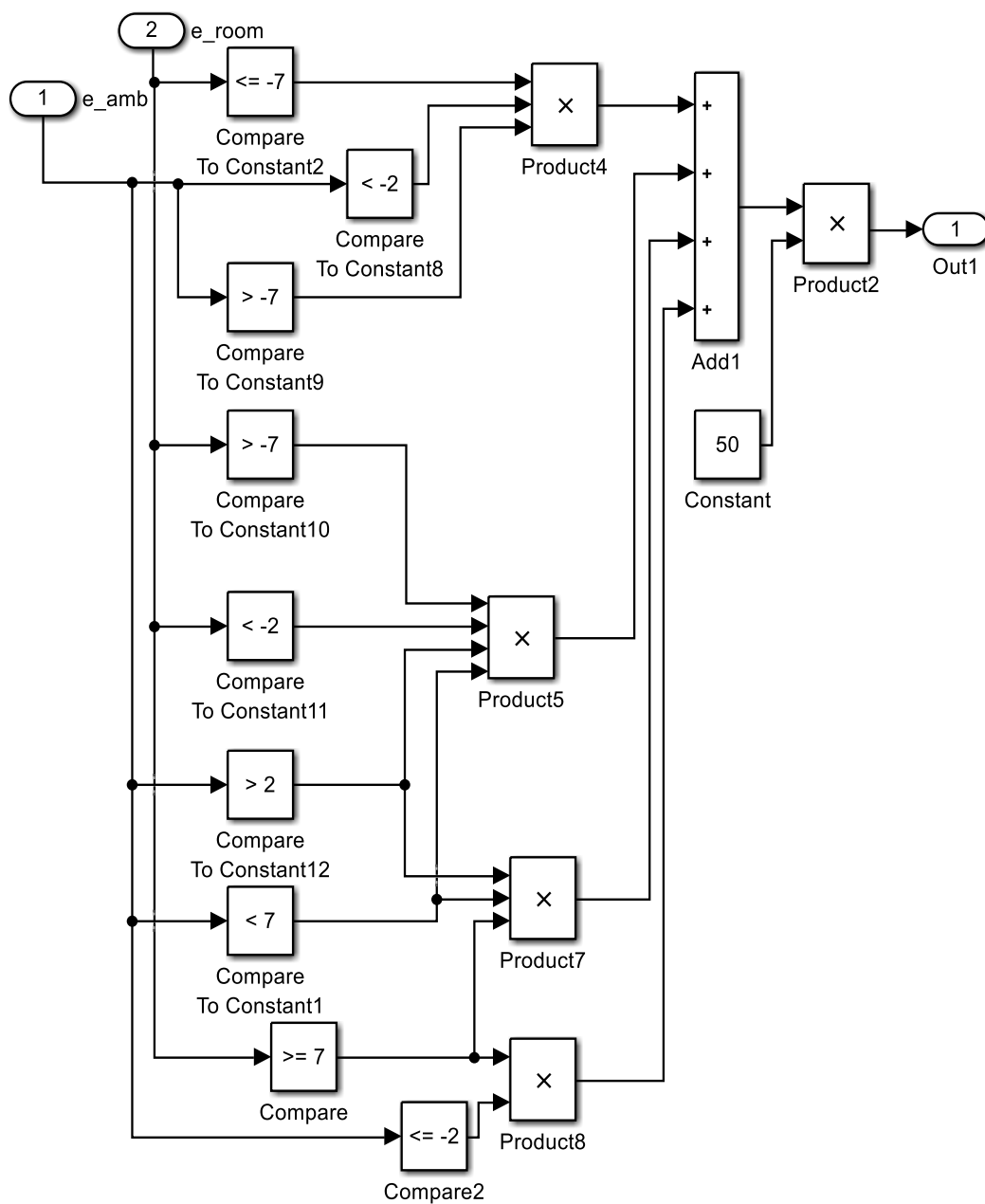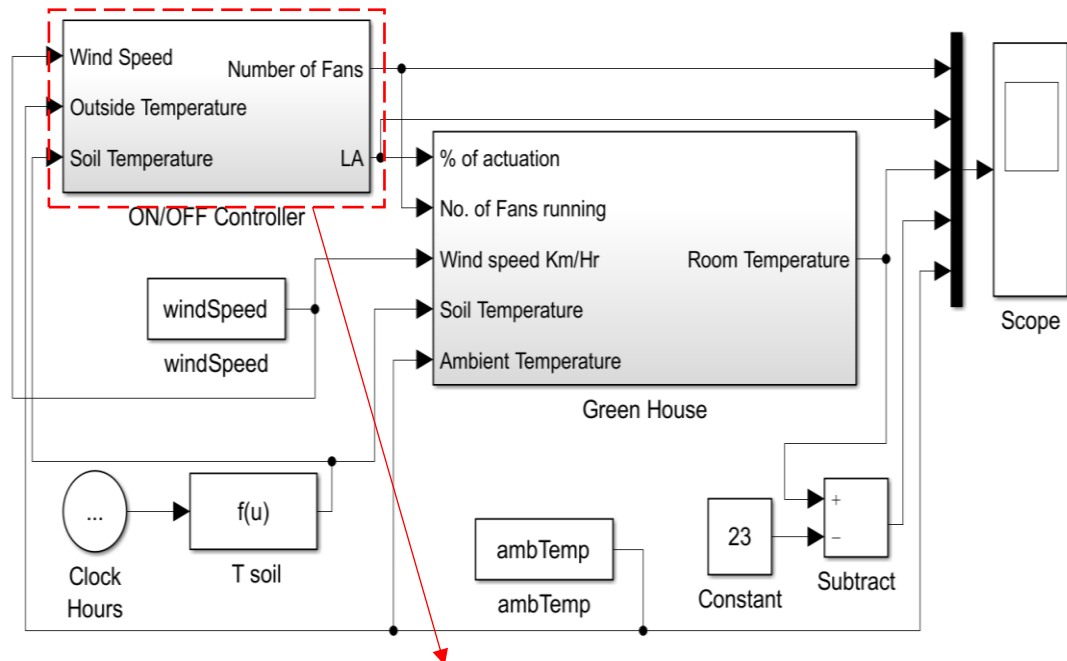
Fans Block
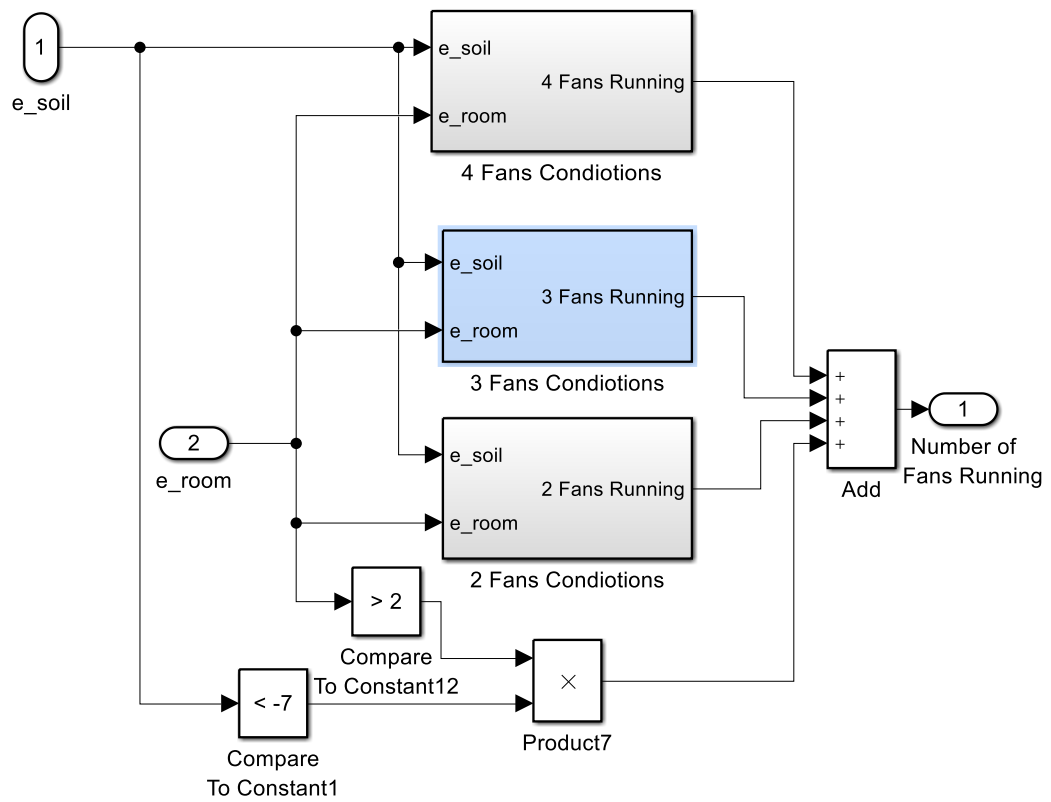
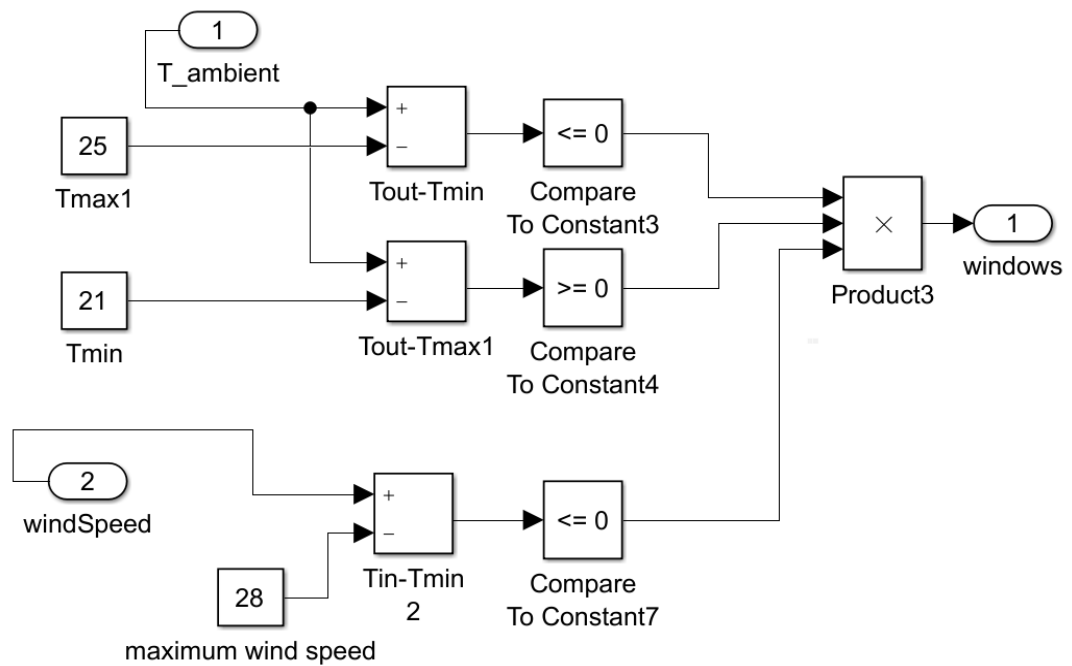**4 fans block**

3 fans block

2 fans block

C.3 ON/OFF controller in Simulink for both actuators
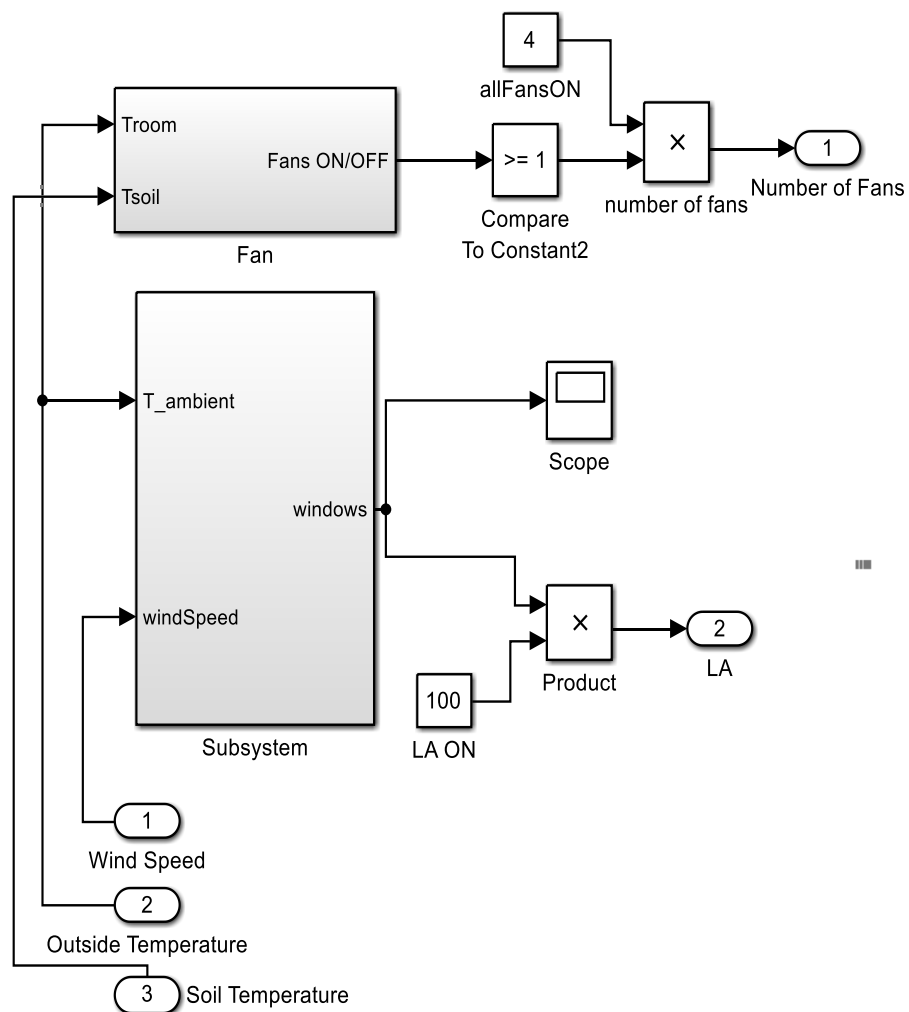
For linear actuator control (Linear Actuator Block)

ON/OFF controller in Simulink for fan control