POLITECNICO DI MILANO

Department of Electronics, Information and Bioengineering

Master's Degree in Automation and Control Engineering

A SYSTEM FOR THERMAL MANAGEMENT IN A RESIDENTIAL BUILDING

The thesis presented by:

Abhishekh Subbaraj, 899860

Supervisor:

Prof. Alberto Leva

2019/2020

PAGE INTENTIONALLY LEFT BLANK

Table of Contents

LIST OF FIGURES

RINGRAZIAMENTI

First, I like to thank Professor Alberto Leva, Ing. Michael Metzger and Equa Srl team for the collaboration and constant support and made this thesis possible.

Next, I extend my gratitude and special thanks to my family members, especially to my parents without their support, I could not be able to dream of studying in this esteemed university.

At last, I thank all my friends Arvind, Prasad, Seenu, Akhil, Suganth, Abhisheik, Harrish, Jawahar, Mullai and my dear friend Aadil

SOMMARIO

La tesi inizialmente fornisce una panoramica dettagliata sugli edifici intelligenti e sulla loro efficienza energetica. Vengono discussi i principali problemi che s'incontrano nel progettare e nel realizzare un edificio intelligente e come superarli. Inizialmente, la parte modellistica del lavoro viene condotta in OMEdit e consiste in un'analisi dettagliata del monitoraggio e del controllo di temperatura e umidità, dei flussi di massa ed energia e dell'energia consumata. Un modello di impianto completo è stato sviluppato in Modelica e con esso viene condotta un'analisi del processo. Sulla base dell'analisi effettuata in fase di modellazione, vengono scelti i componenti hardware ed il controller adatto, ovvero ESP32. La parte di programmazione del lavoro è stata condotta in IDE Arduino in linguaggio embedded C e il controllo della temperatura e dell'umidità della stanza è stato realizzato con l'aiuto di HMI Nextion. L'intero progetto ha condotto allo sviluppo di un singolo dispositivo utente detto Smart Control Box. Inoltre, sono stati sviluppati e implementati diversi algoritmi di controllo sia nella modellazione che nell'hardware. Infine, l'estensione a una piattaforma mobile che utilizza l'IoT è presentata come lavoro futuro.

ABSTRACT

The thesis initially gives a detailed overview of the smart buildings and their energy efficiency. The major problems faced in designing and realizing a smart building and how to overcome those problems are discussed. Initially, the modeling part of the work is done in OMEdit and cosists of a detailed analysis of monitoring and control of temperature and humidity, of the mass and energy flows rate, and of the energy consumed. A complete plant model was developed in Modelica and an analysis and the process was carried out. Based on the analysis carried out in the modeling, the hardware parts are chosen and the suitable controller i.e. ESP32 was chosen. The programming part of the work was carried out in Arduino IDE in Embedded C language and the control of room temperature and humidity was realized with the help of Nextion HMI. The entire project led to the development of a single user device called the Smart Control box. Moreover, different control algorithms were developed and implemented in both Modeling and hardware. Finally, the extension to a mobile platform using IoT is presented as future works.

CHAPTER 1
INTRODUCTION

This chapter is dedicated to the reasoning behind the thesis work. We are going to introduce the Smart Buildings and Building Automation Context, focusing on the main goals of Building Energy Management Systems. In the first section, 1.1 Smart Buildings Overview and Energy Efficiency are carried out. In the second section 1.2 State of the Art Analysis is carried out. Then the central thesis objectives based on the instruction given by the Professor are presented in section 1.3. Finally, the structure of the thesis document is presented in section 1.4 to have a quick look at the report by the reader.

Nowadays, Digital Technology is a vital component in many control systems. Digital Feedback Controllers transmit measurements computes control action periodically at constant step. We are going to explain the reasons why it is important to maintain an environment as comfortable as possible while minimizing the energy. We would like to focus our attention on how to control in an optimal and computationally efficient manner a system composed by rooms, with specific reference to the case with energy storage in the tank and HVAC System. Since the Optimization Problem could be very complex, also due to the presence of constraints in this work we specifically focus on proposing a way to lighten the consequent computational effort. To this end, we first analyze the typical optimization problem concerning a thermal system equipped with energy storages which are necessary for the supervision and management of the energy flow in different systems of the buildings are operated which is necessary for the reduction of the energy footprint and the energy bill in both residential and industrial environments. Then we propose a control strategy to be applied to our system and we formally analyze it.

1.1 Smart Buildings Overview & Energy Efficiency

Smart Buildings have been explored and developed over the last three decades, but they have gained more and more interest in recent years and the word "smart" has started to appear more frequently in roadmaps and industrial reports.

"Smart Buildings are buildings that combine and account for intelligence, enterprise, control, and construction as an entire building system with adaptability at the core to view for building progression: energy and efficiency, endurance, comfort, and satisfaction. The increased amount of information available from a wide range of sources will allow these systems to become adaptable and enable a smart building to prepare itself for a higher comfort level".

The fundamental step within this thesis to have a clear idea of the Smart Building. The potential users sometimes can call the smart buildings that can be remotely accessed to control the devices by turning them on and off. In the background of Building Automation, Smart Building refers to those building were the significant number of diverse objects such as sensors, actuators, heat pumps, control devices, and protocols cooperating to monitor the indoor environment and to take decisions over it with the main goal of increasing and maintaining the comfort of the occupants as good as possible. These systems are usually controlled by a Building Management System (BMS) able to automatically manage and self-organize under some user-specified policies. In our thesis, we define smart a building that permits the cooperation between objects like sensors, devices, and appliances and systems that can self-organize according to some policies which can deal with different fields.

The Smart Building should guarantee the following features,

- **User Comfort:** This means improving the atmosphere of the occupants of the building by controlling the different aspects of the home environment such as temperature, humidity, brightness, and air quality of the room.
- **User Safety:** This means improving user security in case of system failures (short circuit) and the case of disruption.
- **Energy Efficiency:** This means reducing the waste (e.g. do not irrigate if it is raining) and use the resources as economically as possible without impacting negatively on the user experience.

- **User Life:** This means adapting the system's behavior in the way to meet the user's needs.

From the technical point of view, a smart building is a distributed control system that is present to increase the comfort, safety, and efficiency of the construction itself. The standard IT architecture of Smart building is divided into many parts. In the lowest part of the structure, we find the hardware level which includes a network of sensors that are distributed throughout the room and collects the data and a network of actuators that change the behavior of the system. Sensors and Actuators interact with the Building Management system (in the middle) i.e. based on the information got from the sensors the BMS decides how to act on the actuators. Finally, to easily interact with the system, there is an additional level that provides a communication interface between the user and the system. **Figure 1.1** shows the basic architecture of a smart building,

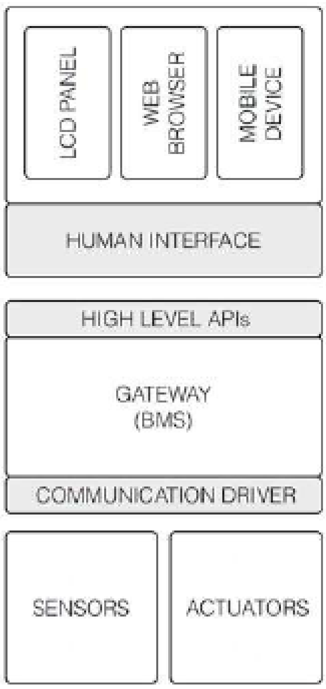

Figure 1.1: Basic Architecture of a Smart Building

An HVAC system is one whose technology aims in providing environmental comfort (thermal comfort) and indoor air quality inside the building. In a normal building, HVAC can usually be programmed and interacted with a Smart Control box. The complexity of these systems varies concerning complexity and the nature of the building like homes, apartment and hotels have simpler HVAC systems with a central unit which has a simple policy and easily editable. On the other hand, it is complex and commercial buildings, the plants are distributed with multiple central and can be controllable and editable only by the administration with many thermostats.

The major point between the commercial and normal HVAC systems is the type of control loop which is used for performing the required actuation for maintaining a good environment. One is the traditional set point which is set by the users on the Smart Control box. Modern Thermostat has an underlining control of this closed-loop system. The main problems are related to how they interact with users. First, not always the user knows the exact setpoint for having enough and satisfactory comfort and not excessive energy consumption. This often translates into overheating or overcooling of the environment or a continuous interaction with a system brings to a waste of energy or not bringing the immediate comfort environment. Secondly, these systems do not consider all the different preferences of the occupants i.e. the inserted set point is supposed to be good for all the people inside the room or building. The traditional set point-based control loop is shown below,

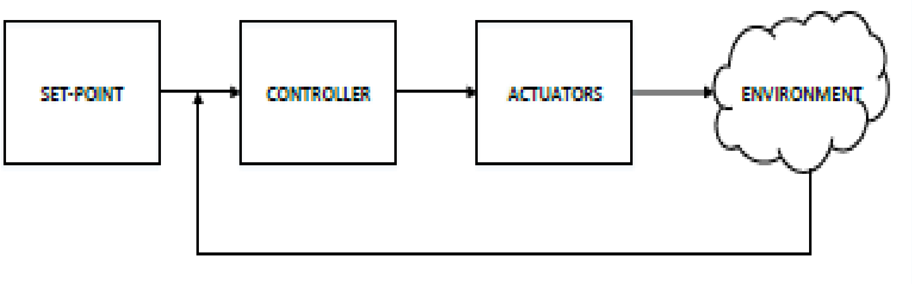

Figure 1.2: Traditional Set point-based control loop

1.2 State of the Art Analysis

The first-ever constructive building were primitive shelters made from stones, sticks, animal skin, and other natural materials. While, they hardly resembled the steel, glass, cement that make up our modern-day buildings such as homes, offices, schools, hospitals, same as the early day structure, the modern buildings have the same purpose of providing a comfortable space for the people who are inside.

If we look deep down, the present-day buildings are a complex succession of structures, systems, and technology. Over time each of the components inside a building has been developed and improved continuously to reduce the consumption of energy usage and the cost effect in a building. This allows the modern-day building owners to make lighting, security, heating, ventilation, and air conditioning systems to work independently based on the input conditions. In today's modern world, energy matters a lot and there is a necessity of using them in an optimized manner to have zero percent wastage. Many people are beginning to look outside the four walls, and which allows them to consider the impact of the variation in building power usage on the electrical grid and the global environment. The cost function adopted to optimize efficiency or to track some energy consumption is defined based on the thermal energy balance within the building structure and thermal phenomena related to maintain the constant and comfortable temperature environment in a building. The Cost effect analysis is made based on energy usage and can make explicit the dependence of thermal heat exchange as a function of indoor and outdoor temperatures and other environmental conditions.

For this technological expertise to be possible, we are using the sensors, actuators, and heat pump along with the HMI and Internet thus all together becomes a Smart control box and with all these things a building can communicate its state of the temperature, state of the humidity to the state of operators, to the electrical grids and also to the computers and a building system like this are known as the smart buildings. These intelligent buildings use IT during the operation to connect with a variety of subsystems, which typically operate independently and so the system can share the information to optimize the total building performance. In a brief, Smart buildings look beyond the building equipment within the four walls, which allows us to empower with new levels of visibility and actionable information.

1.3 Thesis Objectives

In the current modern world, the number of manufactures which produce hardware technologies is increasing. Many Smart Control Platforms provide solutions for the smart building, in which most of them offer both fully developed priced version and some of them give open source community software. The main notion of this thesis to transform a smart building in a theoretical point of view by developing a model in Open Modelica to view the amount of energy consumption and air temperature, relative humidity inside the room and also the main notion of the thesis in hardware platform is to develop a "Smart Control Box" in Equa SRL company where the supervision(metering) and the management(control) of the energy flow in different systems of the buildings are operated which is necessary for the reduction of the energy footprint and energy bill in both residential and commercial buildings. The hardware is developed using the open-source platform named Arduino IDE and Nextion Editor. The first phase of the work deals with the development of a complete building model using Open Modelica and the second phase of the work deals with the development of the Smart control box using the open-source community.

As said above in the above phase of the thesis work, I have developed a Smart Building energy model and Smart Control Box for the residential and commercial is to monitor and control the room temperature and also to maintain the human comfort in a building and finally, I have also extended the study by developing a small dashboard for monitor the temperature and humidity and control of relay switches during emergency times for the android mobile devices.

Finally, the data collected from the rooms are analyzed. Based on the analysis we have developed small applications such as average floor temperature, relative and absolute humidity, and average energy flow rate in different actuators by using the open Modelica model. This will ease the work for the person who is monitoring the building premises and for the peoples who are utilizing the building area.

1.4 Literature Survey

In this section, the state of the art in the context of energy optimization in building systems is presented. Our research domain has been very flourishing, and this shows that there is a lot of interest in this issue. The research surveys were done with these keywords "energy storage and building", "energy storage and optimization in a building" and "energy systems, control, and optimization in a building".

1.5 Purpose of Literature Survey

The main purpose is to provide a sort of literature review about the management of energy storage systems in buildings. Afterward, considering the existing research trends, we would like to fill some gaps related to aspects that have not been examined up to now. We want to focus on the optimal control of a building equipped with energy storage.

Efficient energy use, sometimes simply called energy efficiency, is the goal to reduce the amount of energy required to provide the optimal temperature. There are many motivations to improve energy efficiency since reducing energy use reduces energy costs. This fact may result in a financial cost saving to consumers if the energy savings offset any additional costs of implementing an energy-efficient technology. Improving energy efficiency is a goal desired in a lot of sectors, like in the appliances sector, in the building design, in industry, and in the automotive sector. In particular, energy efficiency has proved to be a cost-effective strategy for building economies without necessarily increasing energy consumption. As a result, the optimal control of a building for heating is relatively straightforward. The need for control in buildings usually resides in the mechanical and electrical systems that are installed to maintain a comfortable and safe indoor environment. A wide range of these systems can be found in buildings including heating, ventilating, air-conditioning (HVAC), lighting, security, elevators, escalators, and fire detection. All these systems use energy and in the case of HVAC energy is used to maintain temperature, humidity, and air quality at levels by the building purpose. For this reason, the building sector is the largest energy consumer in the world. Therefore, it is economically, socially, and environmentally significant to reduce the energy consumption of buildings. Achieving considerable energy reduction in buildings may require rethinking the whole processes of design, construction, and operation of a building.

We will focus on the specific issue of obtaining energy efficiency in buildings. Energy use and utility costs can be reduced significantly by distributing thermal energy more efficiently and by more closely meeting the needs of building occupants. This thermal problem is very complex due to the overcoming of stricter requirements. For example, the use of diversified energy sources involves systems increasingly interacting. We focus on the rising role of thermal energy storage. Their optimal control results in valuable energy efficiency achievement.

1.6 Areas of Research

The Areas of Research that are relevant to this work are basically those on "energy storage and building", "energy storage and optimization in a building" and "energy systems, control, and optimization in a building".

The development and implementation of different types of energy storage technologies where each one used in a specific application has led to the emergence of storage as a crucial element in the management of energy flow from renewable sources, allowing energy to be released during peak hours when it is more valuable. Thermal energy storage (TES) is considered one of the most important advanced energy technologies and increasing attention has recently been given to the utilization of this essential technique for thermal applications, ranging from heating to cooling, particularly in buildings. Several studies have revealed that TES systems can be practically applied in a wide range of industrial applications. In this area, they have a considerable high potential for more effective use of thermal energy equipment and for facilitating large-scale energy substitutions from the economic point of view. TES appears to be the only solution to correct the mismatch between the supply and demand of energy, significantly contributing to meet society's needs for more efficient and environmentally energy usage. We can surely state that TES is a key component of any successful thermal system in buildings and a good TES should allow minimum thermal energy losses, leading to energy savings, while permitting the highest possible extraction efficiency of the stored thermal energy. Although TES is used in a huge variety of applications, the benefits achieved by the systems fulfill the same purposes, as increasing generation capacity such as energy demand is seldom constant over time and the excess generation available during low-demand periods can be used to charge a TES to increase the effective generation capacity during high-demand periods, shifting energy purchases to low-cost periods and also this is the demand-side application of the previous purpose and allows energy consumers subject to time-of-day pricing to shift energy purchases from high to low-cost periods and increasing system reliability. It is important to highlight that the selection of a TES system depends on a lot of critical factors as the storage period required, economic viability, and operating conditions, which in turn are influenced by several parameters. Since substantial energy savings can be realized by TES, nowadays the development of these systems is considered as an advanced energy technology; their use has been attracting increasing interest in several thermal applications such as active and passive solar heating, water heating, cooling and air-conditioning and they are presently identified as the most economic storage technology for building heating, cooling, and air-conditioning applications.

The three dominant research trends of control arise out of our literature review. The first one is related to the Model Predictive Control (MPC), the most used control strategy for building systems and storage management. The second one concerns studies on demand-side control and correlated techniques like peak shaving, load shedding, and load shifting. The last trend is referred to as an economic issue concerning dynamic energy tariffs and cost function definitions for optimization problems.

1.7 Existing Methodology

In existing methodology, here we are going to see about Model Predictive Control, Demand Side Control and Correlated techniques, and Economic issues.

1.7.1 Model Predictive Control

The Model Predictive Control is one of the most recent control strategies applied to thermal systems in buildings. We underline that in the past different control approaches were used. The control strategy was decentralized or at most, there was an integration only between local systems. As already stated, in our work we analyze the use of the MPC approach in buildings. According to any generic process control problem, the objective of MPC is to satisfy the output requirements most efficiently, hence with the least amount of input (i.e. energy). Because energy is a cost, control in buildings, as in most other applications, can be translated to an economic optimization problem: the problem can be stated as the minimization of the integral of the energy usage subject to constraints on the measured variables. To this end, most of the considered papers focus on the model predictive control method of thermal energy storage in building systems. The main idea of predictive control is to use the model of a plant to predict the future evolution of the system. At each sampling time, starting at the current state, an open-loop optimal control problem is solved over a finite horizon.

The optimal command signal is applied to the process only during the following sampling interval. At the next time step, a new optimal control problem, based on new measurements of the state, is solved over a shifted horizon. Applications of MPC have become increasingly prevalent due to their ability to handle the multivariable/nonlinear nature of the dynamics, constraints, and optimality in an integrated fashion.

In paper [1], to minimize energy consumption while satisfying the unknown but bounded cooling demand of a campus building and operational constraints, a Model Predictive Control (MPC) for the operation of the chiller is designed to optimally store the thermal energy in a tank by using predictive knowledge of building loads and weather conditions. The goal of finding the optimal control sequence that satisfies the required cooling load and minimizes electricity usage is achieved by solving the following optimization problem: the optimization cost function J is given by the minimum of the energy consumption price over the considered prediction horizon (24hours with a control sampling time of 1 hour). The minimization problem is solved concerning the control variables of the model and the simulation results shown are very promising: the daily electricity bill can be significantly reduced of 24.5%, compared to the current heuristic manual control sequence.

The simulation results in paper **[2],** show how the MPC control method is a way to reduce energy costs in buildings. The economic objective function designed is intended to minimize the total electricity expense, seen as a combination of energy and demand costs. This function is subject to the dynamic model constraints and the temperature comfort constraints, to achieve the comfort level of the building. This optimization procedure is repeated, and a new program is solved in subsequent time steps when new measurement data are available.

In paper **[3],** to compare the different tariff schemes and investigate
the need for an additional storage device, the optimal building response is computed by applying MPC. As in the previous works, the optimal control input to the building is computed by solving an MPC problem that minimizes the cost of electricity consumption.

The approach utilized in paper **[4],** is to apply dynamic optimization techniques to computer simulations of buildings and their associated cooling systems for a range of conditions to determine the maximum possible savings. In this paper, two different optimization problems are proposed. The first one is applied to the system model and it is used to determine the minimum operating costs if future ambient conditions and internal gain inputs are known. The true optimal performance results provided a basis for identifying the potential savings as compared with conventional control strategies. The optimal control of the considered cooling system, that takes advantage of the thermal capacitance of the building, involves minimizing an integral of operating costs over a day while satisfying required constraints; the optimal solution is a trajectory of controls throughout the specified optimization period. The other optimization problem proposed tries to minimize the peak electrical demand over a day and so the minimized cost function is the maximum total building electrical use for the day. The results of this study show that using optimal control, both energy costs and peak electrical use can be significantly reduced through proper control of the intrinsic thermal storage within building structures.

In paper **[5],** which is highlighted as MPC is a control methodology that can naturally and systematically be used to improve building thermal comfort, decrease peak demand, and reduce total energy costs. A simple example of a single thermal mass model is considered and an MPC problem is formulated to minimize total heating and cool energy consumption, minimizing the peak power consumption and maintaining the building zones within the desired temperature range despite predicted load changes. In this paper, the Model Predictive controller obtained is compared to a proportional controller designed to reject the load without predictive information and it inputs zero power when the space temperature is within the comfort range, otherwise, it uses a proportional control law. Comparing model predictive and proportional control, it emerges that the two controllers use the same energy for the same amount of constraint violation and increased comfort violation corresponds to lower energy use for both controllers. In the closed-loop simulation, it comes to light that the peak power consumption is reduced by 89% relative to the proportional controller when the MPC is used. This behavior is obtained by taking advantage of the predictive knowledge of the disturbance and using the space thermal storage.

1.7.2 Demand Side Control and Correlated techniques

Demand-side management is the modification of consumer demand for energy through various methods, from control in the strict sense of the term up to financial incentives. The goal of demand-side management is to encourage the consumer to use less energy during peak hours or to move the time of energy use to off-peak times. The related technique, called load shifting, consists of shaping the energy profile delivered to a building, exploiting the possibility of storing energy for later use. Peak demand management does not necessarily decrease total energy consumption but could be expected to reduce the need for investments in networks or power plants for meeting peak demands. An example, on which we will focus on our thesis, is the use of energy storage units to store energy during off-peak hours and discharge them during peak hours.

In this point of view, the authors of paper **[2]** focus on the fact that in the United States about 70% of electricity is consumed in commercial and residential buildings and, to make it worse, the peak demands of building cooling or heating usually occur around the same period during the day. This situation makes the electricity consumption at the peak time, known as demand, extremely high relative to the average consumption level; the high peak demand dictates that the power generation capacity has to be at least equal to the peak demand, or a blackout would occur. If the peak demand can be reduced by properly making use of storage capacity or managing the consumption pattern to be more friendly to the power generation, the efficiency of existing power plants is improved. Therefore, there is a great interest to reduce the peak demand by shifting part of the peak load away from the peak time, implementing storage systems, such as using the building thermal capacity, while always keeping thermal comfort as the goal. In conclusion, it is stated that a desirable demand response control strategy should accomplish the following objectives simultaneously: optimize the trade-off between the energy consumption and demand cost by taking advantage of the time of use price difference, make use of the building thermal storage to store and release cooling dynamically and handle real-time and predicted changes of load disturbances, weather, and price changes.

1.7.3 Economic issues

This trend of research considers a fundamental aspect related to energy, which is its integration with economic issues related to energy costs and tariffs.

As highlighted in paper **[1],** the development of highly efficient heating and cooling systems is necessary to reduce the building energy consumption and this goal is important from both an environmental and an economical point of view. The enhanced efficiency for a wide range of innovative heating and cooling systems depends on the active storage of thermal energy. As further proof of the fact that the economic issue should be strongly considered in all optimization problems concerning energy, the cost function J used in paper **[1]** is given by the minimum of the energy consumption price over the considered prediction horizon.

Also, in paper **[2],** it is stated that since energy is a cost, control in buildings can be translated to an economic optimization problem which results in the minimization of the integral of the energy cost subject to constraints on the measured variables. It is highlighted how, employing control logic at a high enough level, even an economic signal, like energy price, is measurable and this is an important improvement over the current state of the art: the proposed control strategies incorporate economic optimization as well as setpoint regulation. It is stated that a desirable demand response control strategy should necessarily accomplish the objective of optimizing the trade-off between energy consumption and demand cost by taking advantage of the time of use price difference. To this end, as already mentioned before, the economic objective function designed in paper [17] is intended to minimize the total electricity expense, seen as a combination of energy and demand costs; this function is subject to the dynamic model constraint and the temperature comfort constraint, to achieve the comfort level of the building

1.8 Document Structure

Chapter 2 describes the problems faced during the energy storage and control and it tells about the case study analysis on how to overcome those problems in an orderly manner.

Chapter 3 describes the hardware which is chosen and also the technical requirements to develop a Smart Control Box for the control of energy flow to different systems in the building which is necessary for the reduction of the energy footprint and the energy bill in the building.

Chapter 4 describes the Open Modelica and the components used for the simulation. We will have a look upon the design of the components done in Open Modelica which is necessary for the Modelling. We also have upon the types of control used in our model to simulate the entire mass of the energy flow and the calculation of the amount of the energy consumed in the thermal model.

Chapter 5 detailed analysis of the Modelling work and the results achieved in the Modelling work. Here we will also have the experimental results on the Smart Control Box which is done during the testing stage. Also, the mobile device deployment is done by using the IP Address which is to monitor the ambient condition of the building.

CHAPTER 2
PROBLEM STATEMENT
AND CASE STUDY ANALYSIS

This chapter describes the problems faced during the energy storage and control. Also, we will have a case study analysis on how to overcome those problems in an orderly manner. In the context of thermal environment control, two main goals can be identified: providing thermal comfort to all the building occupants and minimizing energy consumption. In the following section, we are going to briefly present a theoretical introduction to the concepts of thermal comfort and energy consumption, for then presenting how these are the two main goals when considering the smart environmental control.

2.1 Problem Description

The Major problems faced during the energy control in a smart building are maintaining the optimal temperature in a room based on the thermal comfort of the humans and to control the airflow which is a crucial and intrinsic part of heat and moisture control in a smart building. Another major problem is to save the energy in a building and to use the energy during the appropriate required amount of time. Airflow through enclosure can also carry exhaust gases, odors, and sounds through enclosures as well as mold spores and off-gassing generated within the enclosure is therefore often a major cause of performance (e.g. comfort, health, energy, durability) problems. Water vapor diffusion while amenable to simple analysis is often an insignificant source of moisture in modern building envelopes. Wintertime exfiltration condensation is often acknowledged as a common building performance problem in cold climates. Warm weather infiltration condensation is often a problem in warm and humid climates. Based on the analysis the problems faced during thermal comfort are,

Analysing the traditional control loop shown in **Figure 1.2**, based on the exact set-point, we can identify three main issues:.

- In a residential building, the main problem is that the occupants do not know which optimal set-point to provide to the thermostat, turning into an inadequate interaction with the control system. As an example, consider a single occupant not satisfied with the environment because he is feeling hot. He will then set a set-point with a smaller temperature. Two cases can occur: the temperature is not small enough, meaning that the user will still feel uncomfortable and will have to set a new set-point; or the temperature is too small, meaning that this time the user may start feeling cold instead of hot, but on the other side there will be excessive and useless energy consumption.
- In commercial and complex building, usually occupants do not have any kind of control over the environment, which is subjected to strict energy savings policies from the administration. Hence, if people cannot control the environment, they cannot control their thermal comfort. This translates into a situation that if a person is feeling uncomfortable, he remains uncomfortable (unless to perform some adaptive actions).
- People have different preferences about their thermal comfortable environment. When the number of people inside a room is high (for instance an office, a library, a gym, an airport), the probability that those preferences are conflicting drastically increases, possibly arising technical issues on the actuation system. Here we can then state that the main problem is that the two main objectives for a thermal environment controller, the occupant's thermal comfort and energy consumption minimization, are conflicting. Thus, we can see that the two goals are in an inversely proportional relationship, that is, the energy consumption minimization decreases when the occupant thermal comfort maximization increases.

Another major problem that is to be discussed here is energy savings in a building. When designing a building, it is important to take into consideration its energy efficiency, which is defined as,

$$\frac{EnergyConsumed}{BuiltArea}$$

In reality, more factors are influent over the energy efficiency: for instance, the material that can be reused when the building is dismantled and the activity level of the building - that is, whether it is used or rarely occupied. Since most energy consumption derives from HVAC systems, the design choices when installing systems such as those are fundamental. Adopting newer and more green heat pump (like ground source) can further decrease energy consumption. Also, the adoption of sustainable energy sources such as solar panels is always effective. Another source of energy consumption is represented by the way occupants interact with the HVAC and in the second phase also to the electronic devices: often they tend to overheat or over-cool the environment, resulting in a waste of energy. It has been proving that making them aware of their energy consumption is an effective first weapon in energy savings. This thesis aims to provide users an easy tool for avoiding over-heating and over-cooling. Other solutions are analyzed in Chapter 3. Considering the energy consumed along the energy grid, it has been shown that 70% is consumed by commercial buildings [1], of which an important contribution is given by HVAC and lighting systems. Nowadays, energy efficiency is a concert that has been addressed also by institutions: European Commission targeted a reduction of 20% in energy efficiency in a building within 2020 and 30% within 2030. The goal of reducing energy consumption not only has a sustainable reason, but also an economic one: the interests of managers and company holders (as well as families) are of course to reducing outcomes and expenses as much as possible.

2.2 Description of the Case Study

The case study initially deals with the survey conducted with Politecnico Di Milano Students on their preference for energy savings and sustainability and their comfort. In the second phase of the case study deals with the importance of energy flow control in the building and on how to overcome the problems faced during the renewable energy management and their techniques will be discussed.

Here is the case study to experimentally validate the problem presented in the previous section. We conducted a survey in a study room at Politecnico di Milano, called “Acquario”. The room has 200 seats and 12 computer desks. On the long sides, the room is provided with stained glass and two double-door entrances. The light is provided both by natural light coming from the outside and artificial light from the lamps attached to the walls and the desks. The room has a centralized HVAC system, which can be controlled only by the administrators from a different room. Thus, occupants have no kind of control over the environment. Also, the heating and cooling are subjected to strict policies, common for all the environments in Politecnico (usually depending on the specific season). This means that often the HVAC does not respond to the actual needing of the occupants, moreover in the year where the room is most occupied (e.g., during exam sessions). The survey was conducted on 01 February 2020, in the form of questionnaires in google sheets. The questionnaires were sent to 100 people of which 68 male and 32 female and indeed 94 people answered the questionnaires. Regarding the age, only 2 were over 30 while all the others were between an age range of 21-30 (a pretty obvious result, since the environment, is in a public university). The demographic results are synthesized in Table 2.1.

Gender	Age		Total
	Under 30	31-50	
Male	62	2	**64**
Female	30	-	**30**
Total	62	2	94

Table 2.1: General Information of the survey

Figure 2.1 and 2.2 shows the number of occupants who use the study room and the numbers of hours which they stay in there. It is interesting to see that the students that stay more for a prolonged period are also the students that use most frequently the study room, whereas students not used to this study room do not stay for a long time.

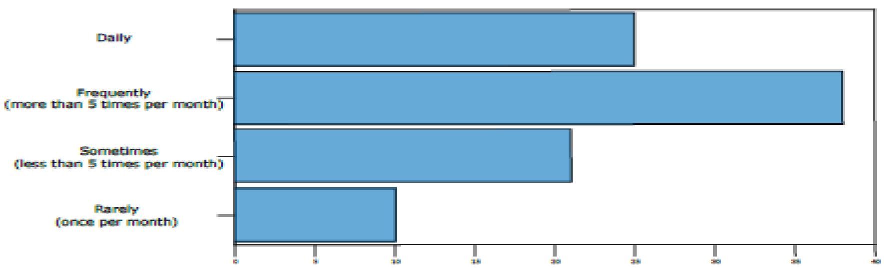

Figure 2.1: Day frequency with which the occupants who use the study room.

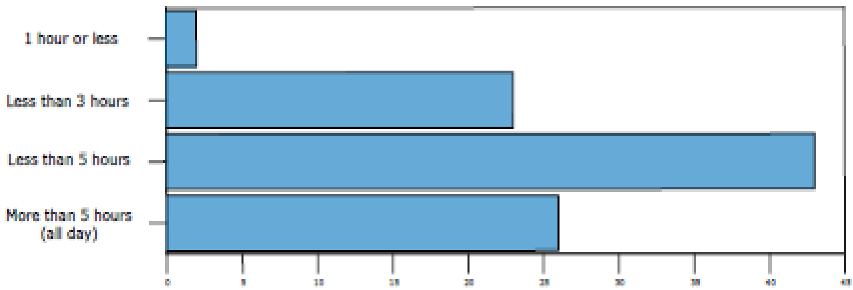

Figure 2.2: Average number of hours with which the occupants use the study room.

Through the survey a question was asked regarding the overall environmental satisfaction, the source of dissatisfaction, and how having control over the environment through HVAC accessibility could help in achieving comfort according to the study room occupants. Regarding the overall satisfaction, the results are shown in Figure 2.3, where appears that students at that moment were satisfied with the environment. The cause can be identified by the fact that the room was not too crowded, and the outside spring weather was good. Figure 2.4 shows the percentage of whether the occupants think their comfort would increase if they would have access to the control system, or not. Most of the occupants are positively convinced about that.

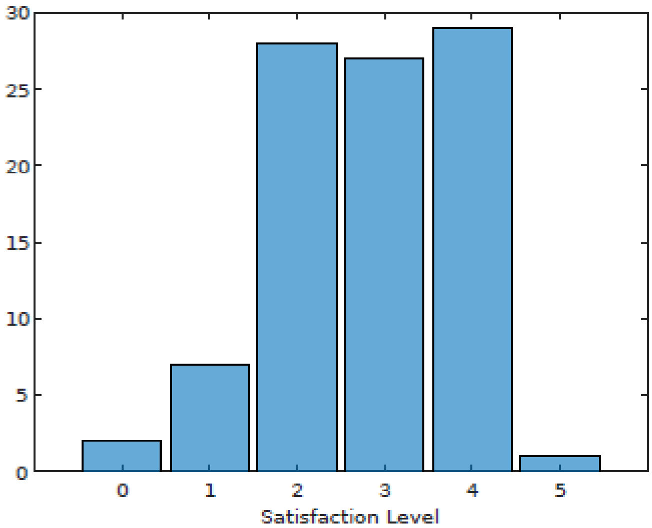

Figure 2.3: Overall Satisfaction of the study room occupants.

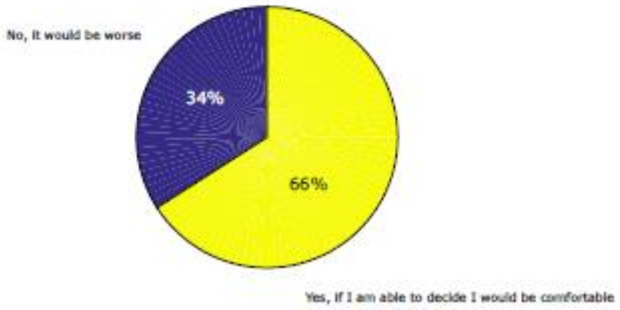

Figure 2.4: Question Result: Do you think that having control over the environment could help you in achieving thermal comfort?

Figure 2.5 shows instead if they would know how to satisfy all the occupants by choosing a standard value. Also, in this case, they are convinced that a standard value (e.g., 22◦C) could achieve a common comfortable environment, without considering the personal difference between everyone.

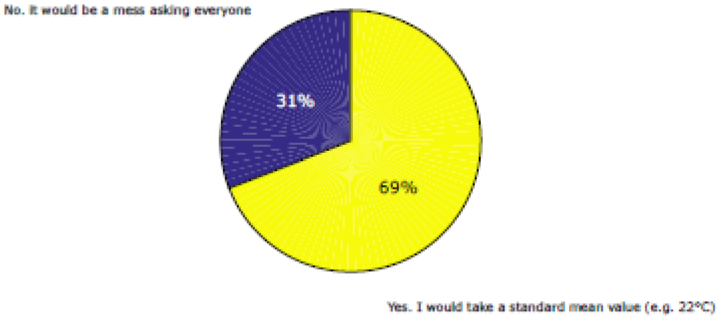

Figure 2.5: Question Result: If you were able to control the thermostat, would you know which temperature to set to achieve a thermal comfort good for all?

Finally, Figure 2.6 shows which factors the occupants consider most important. Unsurprisingly, most people think more about their comfort than energy sustainability, which is more of an administration issue.

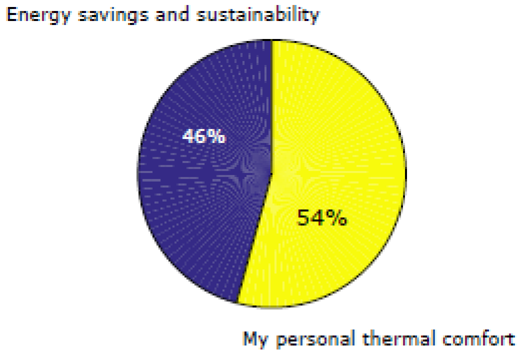

Figure 2.6: Question Result: According to your value sets, which factors do you consider the most important?

This result confirms our supposition regarding providing control to the occupants: they are convinced about the usefulness of having control over the environment, suggesting that providing a user-friendly and easy accessible HVAC could satisfy them all; they tend to rely on standard value, suggesting that an HVAC should provide a personalized comfort model; they tend to think first on themselves, suggesting that the HVAC should provide an underlining energy savings approach.

Back for a momnet to our onjectives, this thesis aims to provide a smart control box that can provide the optimal temperature and to assess the conflicting problem of providing thermal comfort to occupants while minimizing energy consumption. Different types of Control Methodologies were followed like traditional control, learning-based control.

Traditional control is represented by those systems which only aim to minimize the power consumption through the control of temperature, leaving the assessment of thermal comfort to the users. Standard On/Off switch systems, thermostats, and the Proportional, Integral, and Differential (PID) control are the most used controllers, all of them allowing a simple structure and a low initial cost, even though they do not provide enough accuracy and quality. On/Off control is the simplest one, providing only two kinds of inputs and outputs: maximum or zero. The control is completely left to the user, who switches the HVAC system when he/she wants. They do not autonomously provide neither thermal comfort nor energy saving.

Thermostats can behave autonomously on a prior user programming, and to control the environment just on the temperature changes. The PID controller, despite its long time, still stands thanks to the simplicity of its implementation. However, these kinds of controllers do not take into consideration the user's thermal comfort, which still must provide the controller with the exact personal ideal value.

Learning-based control represents more a feature in several industrial thermostats. It consists in the application of machine learning techniques for allowing the control system to learn occupants' preferences and activity patterns to automatize the control process. Learning approaches can be applied to both Traditional, Advanced, and MPC control. Some examples of machine learning techniques are Neural Networks [6], [7] and Support Vector Machine [9], while an iconic example of industrial application of learning thermostat is Nest [8]. This approach can give benefits in the overall user experience, but only in terms of the autonomy of the control action, which is still based on set-point.

Even though based on the survey human comfort was given higher priority than energy savings control, in this thesis the both are aimed at a higher perspective to be achieved. Two types of control were implemented in the software model and the hardware. These two types of control were used to overcome the problems seen in the above section. One is Energy flow control of a building and the other is Temperature and humidity control of all rooms in a building.

2.2.1 Energy Flow Control

Energy flow control is one of the control methodologies used here in both software modeling and later implemented in hardware. Airflow control from HVAC systems, room heater, and dehumidifier are being controlled in the model. Hysteresis control methodology is used in the hardware for energy flow control. In further, based on the comfort level of human and room temperature the room heater will be automatically switched on and off so that the energy flow of the water and gas produced from HVAC (Heating Ventilation and Air Conditioning) is controlled. Based on the feedback of the human comfort level and the room temperature, the control signal will be sent to HVAC system through MODBUS communication protocol to switch on and off the

HVAC system to control the flow of the gas, This control methodology is very efficient and the energy consumption is also very less for the entire building. Different control algorithms are written in the Arduino Embedded C Programming and Nextion Editor HMI which is implemented in the Hardware part. These are one of the control methodologies on how to spend the energy in a cost-efficient manner and to have a comfortable environment and further details about the hardware will be seen in chapter 3.

2.2.2 Temperature & Humidity Control

Temperature & Humidity Control is one of the control methodologies used here in both software modeling and later implemented in hardware. Temperature & Humidity control from the room heaters, a dehumidifier is being controlled in the model. Hysteresis temperature-based control and PI set point-based control methodologies were used in the software modeling and implemented in the hardware. In further hysteresis control, based on the room temperature and humidity, the heat pump is switched on and off to control the energy flow in a building. In PI control methodology, the room temperature is controlled based on the set point in the HMI and all the temperature and humidity of the room in a building are controlled and monitored through the smart box in a building. Different control algorithms are written in the Arduino Embedded C Programming and Nextion Editor HMI which is implemented in the Hardware part. These are one of the control methodologies where the temperature can be set as a set point for every room in a building to have a comfortable environment all over the building.

CHAPTER 3
HARDWARE PLATFORM

In this chapter, we will have a detailed description on the hardware which is chosen and also the technical requirements to develop a Smart Control Box for the control of energy flow to different systems in the building which is necessary for the reduction of the energy footprint and the energy bill in the building.

3.1 System

The system consists of the controller and HMI Display chosen and the required wire connection for the entire setup of the Smart Control Box. The system is used for the control of the energy flow in a building and to maintain a comfortable environment inside the building. There will be continuous monitoring of the temperature and humidity of all the rooms in a building by using this smart control box. The users will also have the option of changing their room temperature according to their convenience inside this system. Earlier at the start of the thesis, a complete system model was done in the Open Modelica Software, and the complete hardware setup for developing as a prototype was made. After under several research of the hardware, a controller named “ESP32” was chosen and solid-state relays, DHT22 temperature, and humidity sensor, and a control driver for the heat pump was chosen. ESP32 named as Esperiff systems, one of the cheapest and efficient microcontrollers with all features like BLE (Bluetooth enable function), Wi-Fi was chosen among other controllers. These are the hardware components used for developing into the complete system.

The main aim of this system is to provide a better solution environment with this cheapest and efficient microcontroller because already many existing systems are present by using different controllers like PLC (Programmable Logic Controller), Raspberry Pi and Arduino. To overcome this the ESP32 hardware chosen. Earlier the entire process was started with the development and continuous monitoring of temperature and humidity using web browser-based control in mobile phones and PC.

Then the Nextion HMI (Human Machine Interface) was taken and the continuous monitoring of temperature and humidity has been implemented into the HMI with the help of ESP32 Microcontroller. Then the solid-state relay switch was placed on the touch screen panel for switching on/off control of the heat pump. Once these processes were done then the control algorithm was implemented into the microcontroller for testing the entire process of the system.

3.1.1 Introduction to ESP32 and Arduino IDE

Esp32 is a series of the low-cost, low-power system on chip microcontrollers with integrated Wi-Fi and dual Bluetooth. The Esp32 series employs a Tensilica Xtensa LX6 microprocessor in both dual-core and single-core variations and includes built-in antenna switches, RF balun, power amplifier, low-noise receive amplifier, filters, and power management modules. Esp32 is created and developed by Esperiff systems, a Shanghai-based Chinese company, and is manufactured by TSMC (Taiwan Semiconductor Manufacturing Company, Limited) using their 40nm process. It is a successor to the ESP8266 microcontroller.

ESP32 is capable of functioning reliably in industrial environments, with operating temperatures ranging from –40°C to +125°C. Powered by advanced calibration circuitries, ESP32 can dynamically remove external circuit imperfections and adapt to changes in external conditions. Esp32 is engineered for mobile devices, wearable electronics, and IoT applications, ESP32 achieves ultra-low power consumption with a combination of several types of proprietary software. ESP32 also includes state-of-the-art features, such as fine-grained clock gating, various power modes, and dynamic power scaling. ESP32 is highly integrated with in-built antenna switches, RF balun, power amplifier, low noise receives amplifier, filters, and power management modules. ESP32 adds priceless functionality and versatility to your applications with minimal Printed Circuit Board (PCB) requirements. ESP32 can perform as a complete standalone system or as a slave device to a host MCU, reducing communication stack overhead on the main application processor. ESP32 can interface with other systems to provide Wi-Fi and Bluetooth functionality through its SPI / SDIO or I2C / UART interfaces. The Functional block diagram of the Esp32 is shown below

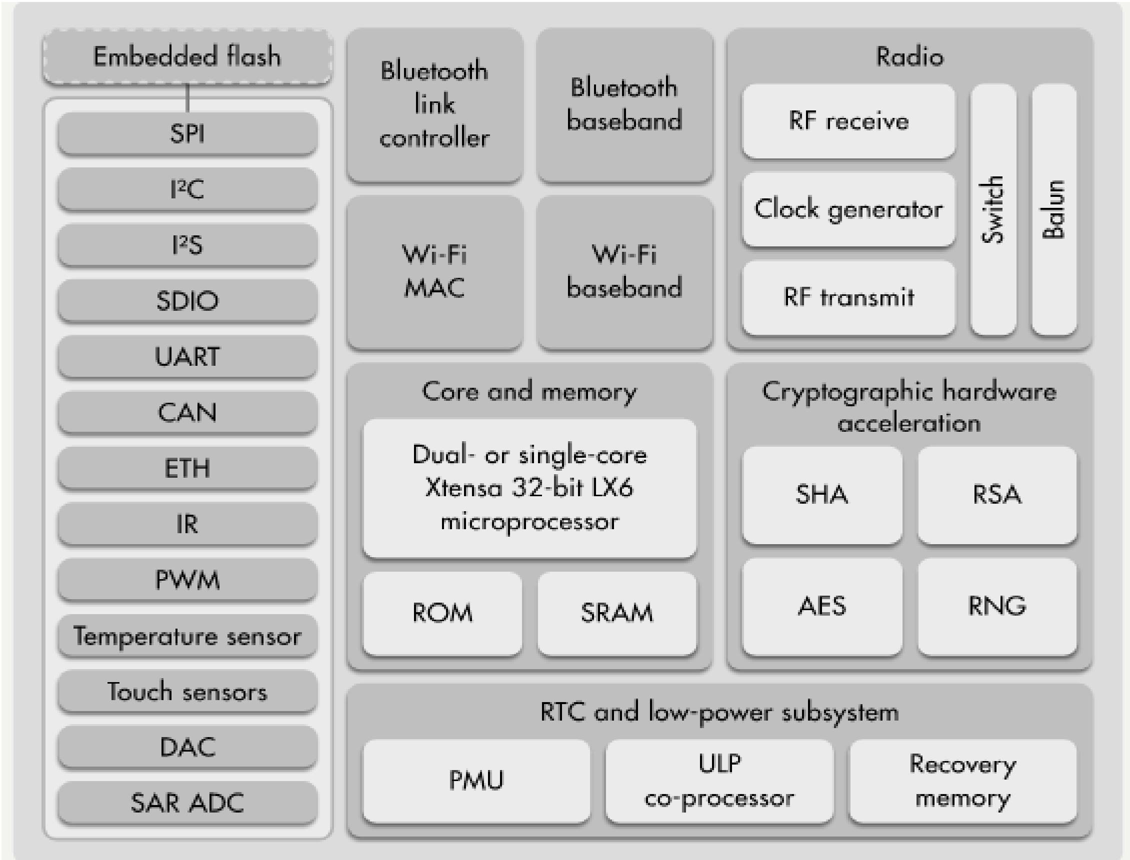

Figure 3.1: Functional Block Diagram of ESP32 Microcontroller

ESP-WROOM-32 Microcontroller model type is used in the hardware here. The ESP-WROOM-32 is a universal Wi-Fi + BT + BLE MCU module that it is powerful and versatile for low-consumption sensor networks and demanding tasks such as voice encoding, audio streaming, and MP3 decoding and so on. The Specifications of ESP32 Microcontroller are,

- The core of this module is the ESP32-D0WDQ6 integrated circuit, which is scalable and adaptable. Two CPU cores can be controlled or powered individually. The clock frequency can be adjusted from 80 MHz to 240 MHz and the user can turn off the CPU and use the low power coprocessor to continuously monitor the status changes of the peripherals or if some analog exceeds the threshold.
- The ESP32 also integrates a wide range of peripherals, including capacitive touch sensors, Hall sensors, low sense amplifier noise, SD card interfaces, Ethernet interfaces, high-speed SDIO / SPI, UART, I2S, and I2C.

- The ESP32 includes
  - 448 KB ROM for program start-up calls and kernel function, 520 KB on-chip SRAM for data and instruction storage.
  - 8 KB of SRAM in the slow RTC memory, RTC, which can be accessed by the co-processor in deep sleep mode.
  - 8 KB of SRAM in the RTC, RTC Express Memory, which can be used for data storage and access by the host CPU during RTC boot in deep-sleep mode.

The ESP32 Specification diagram is shown below,

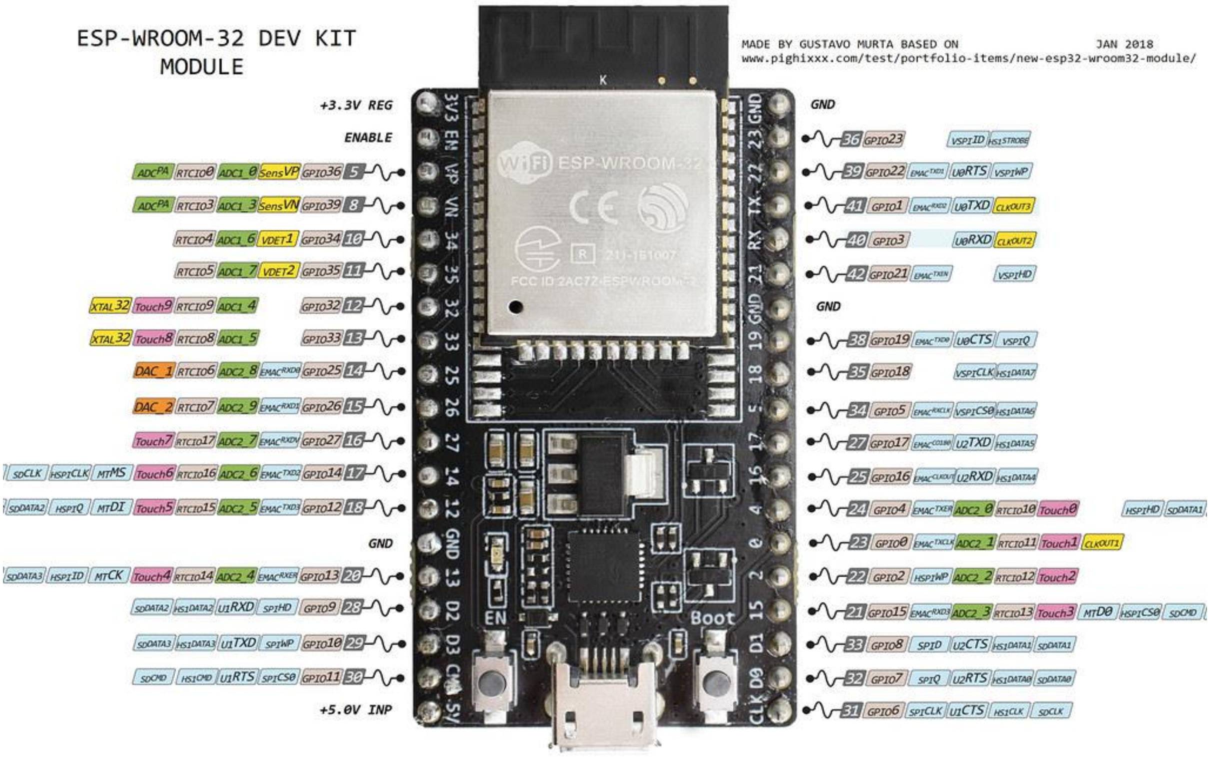

Figure 3.2: ESP32 Specification Diagram

The Arduino IDE platform is used for writing the program for the entire operation which is carried out in the smart control box. Arduino IDE is open-source software that is mainly used for writing and compiling the C, C++ code into the Arduino Module. It is an official Arduino software, making code compilation too easy that even a common person with no prior technical knowledge can get their feet wet with the learning process. It is easily available for operating systems like MAC, Windows, Linux, and runs on the Java Platform that comes with inbuilt functions and commands that play a vital role in debugging, editing, and compiling the code in the environment.

User-written code only requires two basic functions, for starting the sketch and the main program loop, that is compiled and linked with a program stub *main()* into an executable cyclic executive program with the GNU toolchain, also included with the IDE distribution. The main code, also known as a sketch, created on the IDE platform will ultimately generate a Hex File which is then transferred and uploaded in the controller on the board. The IDE environment mainly contains two basic parts: Editor and Compiler where the former is used for writing the required code and later is used for compiling and uploading the code into the given Arduino Module. This environment supports both C and C++ languages.

3.1.2 Introduction to NEXTION HMI & NEXTION Editor

Nextion is a Human Machine Interface (HMI) solution combining an onboard processor and memory touch display with Nextion Editor software for HMI GUI project development. Nextion HMI display connects to peripheral MCU via TTL Serial (5V, TX, RX, GND) to provide event notifications that peripheral MCU can act on, the peripheral MCU can easily update progress and status back to Nextion display utilizing simple ASCII text-based instructions. The main mission of the Nextion HMI is to reduce the HMI GUI development boards. It is a great solution to monitor and control processes that are mainly applied to IoT applications. There are several Nextion display modules, with sizes ranging from 2.4" to 7". The Nextion has a built-in ARM microcontroller that controls the display, for example, it takes care of generating the buttons, creating text, store images, or change the background. The Nextion communicates with any microcontroller using serial communication at a 9600 baud rate. So, it works with any board that has serial capabilities like Arduino, Raspberry Pi, ESP8266, ESP32, and so on.

The HMI display used in the hardware is Nextion Enhanced Version NX4827K043_011 4.3" inch display and its specifications are

- Resolution of about 480*272 and the Flash memory of about 32MB.
- Has RAM of about 8192 Byte and EEPROM of about 1024 Byte.
- Has 8 GPIOs and Main Control Unit (MCU) of about 108 MHZ.

The hardware diagram of Nextion HMI is shown below,

Figure 3.3: Nextion HMI Enhanced Version NX4827K043_011 Display

Nextion Editor Software is used to design the display according to user convenience. The software is user friendly and it helps the user to create his display in a short period. By using the Nextion Editor software, users can quickly develop the HMI GUI by drag-and-drop components (graphics, text, button, slider, etc.) and ASCII text-based instructions for coding how components interact at the display side. The Nextion Editor software offers an easy way to create an intuitive and superb touch user interface even for beginners. Add a static picture as a background, define functions by components, you can make a simple GUI in minutes. The easy drag and drop components and simple ASCII text-based instructions will dramatically reduce your HMI project development workloads.

3.1.3 Open Source Community

In the majority of the Controller Software available in the market are providing the open-source community with different functionalities and of courses, each one has pros and cons of its own. For using the service, we do not need to pay anything to the service provider. On the other hand, the product provider is under development (i.e., In Continuous testing stage), so it is not as stable as the paid versions. By using the open-source, we are not restricted to follow the manuals; we have many open doors to use utmost.

Arduino IDE is named as “Community Edition” and the version provided is 1.8.12. Nextion Editor software is open source and the latest software version is 1.60.2.

3.2 Technical Requirements

This section describes the software skill set requirements for both platforms. The reader can find similarities in requirements; this is because both platform bases are different and then a detailed description of the instrument requirements such as sensors, actuators, and so are presented in detail. Here we will have a detailed look at the software requirements for modeling work and the hardware requirements which is necessary for a prototype. All the major components used for the hardware will be completely discussed here.

3.2.1 Software Requirements

The OpenModelica Connection Editor (OMEdit) Software is used for Modelling the entire process in a smart building. To get started with OpenModelica Connection Editor one should have basic knowledge in programming such as MATLAB, Simulink. The programming of the controller should have basic knowledge in programming such as C, C++, and further, we should have an introduction to web page-based programming language scripts such as HTML and CSS for using the Arduino IDE platform. For usage of the Nextion HMI Editor should have basic knowledge in programmings such as PLC, SCADA, and HMI and has an excellent GUI.

3.2.2 Hardware Requirements

The Hardware requirements for the development of smart box are ESP32 Microcontroller, Solid-state relay, HVAC (Heating Ventilation and Air Conditioning), HMI touch screen, Control Driver, SMPS (Switch Mode Power supply), TTL Converter (MODBUS Communication), DHT22 Temperature & Humidity Sensor, Jumper wires and Electrical wires. On handling these equipment safety precautions are taken to avoid serious injuries.

A solid-state relay (SSR) is an electronic switching device that switches on or off when a small external voltage is applied across its control terminals. SSRs consist of a sensor which responds to an appropriate input (control signal), a solid-state electronic switching device that switches power to the load circuitry, and a coupling mechanism to enable the control signal to activate this switch without mechanical parts. The relay may be designed to switch either AC or DC to the load. It serves the same function as an electromechanical relay but has no moving parts.

Figure 3.4: Solid State relay

A Wilo Para 25-130/9-87/iPWM1 AC Heat pump used in our prototype for testing. It is a glandless circulation pump with cast iron or composite pump housing and threaded clipped connection and it is an EC (Electronic Control) motor with automatic power adjustment and self-protecting modes. The Specifications of Wilo Heat pump are,

- Runs at speed of 500 – 4540 RPM.
- Maximum power consumption is within 3 – 87W.
- The maximum current required is between 0.03 – 0.66A.

The PWM control values of the Wilo Para Heat Pump are,

- <5 - Pump runs at maximum speed.
- 5-85 – Pump speed decreases linearly from maximum to minimum.
- 85-93 – Pump runs at the minimum speed (operation).
- 85-93 – Pump runs at the minimum speed (start-up).
- 93-100 – Pump stops (Standby).

Figure 3.5: Wilo Para Heat Pump.

A 3.3V to 15V Optocoupler (Control Driver) is used for controlling the speed of the Wilo Heat Pump. When the temperature set point is set by the user, the heat pump should be varied according to the temperature to supply the required amount of water to the heater. The main purpose of the optocoupler is to boost the voltage from the microcontroller and it acts signal level voltage converter to the heat pump. This optocoupler changes the 3.3V supplied from the microcontroller to 15V Max to the heat pump. Based on the setpoint, the control driver will send the appropriate PWM control signal to vary the speed of the Heat pump. The Signal level voltage converter i.e., Optocoupler is shown below,

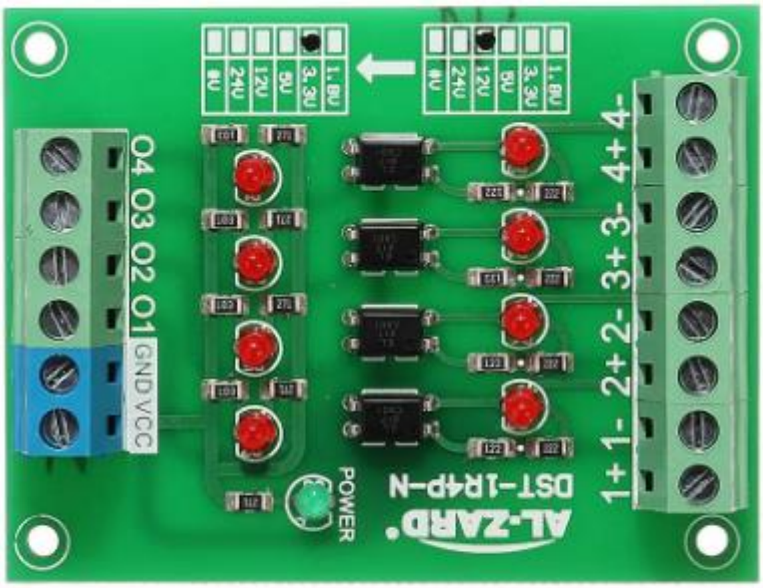

Figure 3.6: Optocoupler

The DHT22 is a low-cost digital temperature and humidity sensor with a single wire digital interface. It uses a capacitive humidity sensor and a thermistor to measure the surrounding air and spits out a digital signal on the data pin (no analog input pins needed). The sensor is calibrated and does not require extra components so you can get the right to measuring relative humidity and temperature. It is quite simple to use but requires careful timing to grab data. We can only get new data from it once every 2 seconds. The DHT22 Temperature and Humidity Sensor is shown below,

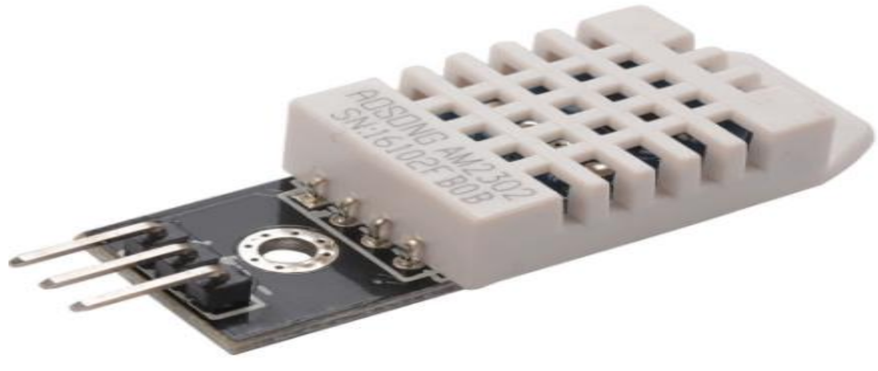

Figure 3.7: DHT22 Temperature and Humidity Sensor

These were the hardware requirements for developing the smart box and these components were handled with intensive safety measures as it may cause severe injuries.

3.3 Smart Control Box

In this section, we will have the main functionalities performed by the Smart Control Box and the detailed description of the project code used for developing the prototype. The Smart Control box has the functionalities of monitoring and controlling the temperature and humidity and also used for controlling the energy flow in different systems of the building which is necessary for the reduction of the energy footprint and energy bill in both residential and industrial environments. In the smart control box, two different types of control strategies were followed. These two control strategies were followed so that energy flow usage was very efficient and the environment of all rooms in the building was maintained perfectly.

3.3.1 Control of Energy Flow

The Control of energy flow is one of the major functionalities of the smart box. The main reason for the control of energy flow is due to the control strategies which are followed in the smart box i.e., in the controller. The Hysteresis control algorithm and PI Control Strategy were followed to control the flow of energy and to maintain the optimal temperature and humidity inside all the rooms in a building. The energy flow is maintained by switching on and off the heat pump automatically based on the temperature maintained inside the room. By doing this the energy flow is maintained and the cost of energy spent will also be minimum.

The hysteresis control algorithm is used for switching on and off the heat pump automatically based on the temperature maintained inside the building. The control algorithm is written in the Arduino IDE platform and is tested and ran in the microcontroller before going into the testing of the real-time hardware. The Mass of flowrate of the water is directly proportional to the temperature maintained inside the room in a building.

In the PI control algorithm, the temperature setpoint is set by the user, and based on the set point the PWM control values are sent to the heat pump to maintain the appropriate temperature inside the room in a building. By using this control algorithm, the heat pump runs at the appropriate speed to control the flow of energy in the system. The PWM control values are directly proportional to the temperature setpoint maintained inside the room in a building. These are the strategies followed in the system to control the energy flow in a building.

3.3.2 Monitoring and Control of room temperature and humidity

The Control of Temperature and humidity is one of the major functionalities of the smart box. Initially, the monitoring of temperature and humidity from the DHT22 Sensor was done with the help of ESP32 and Nextion HMI. This part of the program was tested and then it was implemented in the hardware for the testing. The Monitoring of temperature and humidity was done by developing the web server in the Mobile phones, PC, Tablet. Then it was tested for monitoring the temperature and humidity in the Nextion HMI.

In the Hysteresis Control algorithm, the heat pump will be switched on and off based on the reachable temperature inside the room. The maximum and minimum temperature which is to be maintained is written in the algorithm to attain the optimal temperature inside the room. In the PI Control algorithm, the user has the option of setting the room temperature on his/her preference. In both these algorithms, the temperature and humidity play as the major important factors to obtain the optimal condition inside the building. The monitoring and control of temperature and humidity of a room in Nextion HMI is shown below,

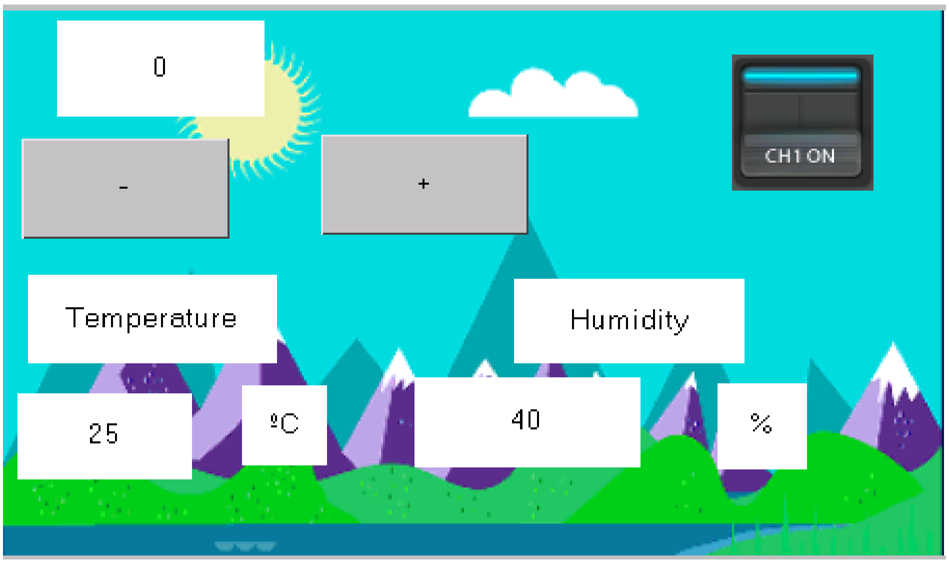

Figure 3.8: HMI of Smart box

3.3.3 Air & Mass of the Water Flow Control

The Air and Mass of the Water flow control are one of the major functionalities of the smart control box. The flow of air from the room heater is directly proportional to the mass of the water flow from the tanks to the heater. The temperature of the air which is blowing from the heater is not the same as the room temperature because there may be many external disturbances inside the room. Based on the flow rate of the water the optimal air temperature is blown out from the heater.

3.3.4 Flow Chart of the system

A flow chart is another important diagram to describe the dynamic aspects of the system. It is a flowchart to represent the flow from one activity to another activity. The activity can be described as an operation of the system. The control flow is drawn from one operation to another. In this flow chart, the entire operation which is carried in the smart control box of the system is carried out. The Flow chart of the entire system of a room is shown below,

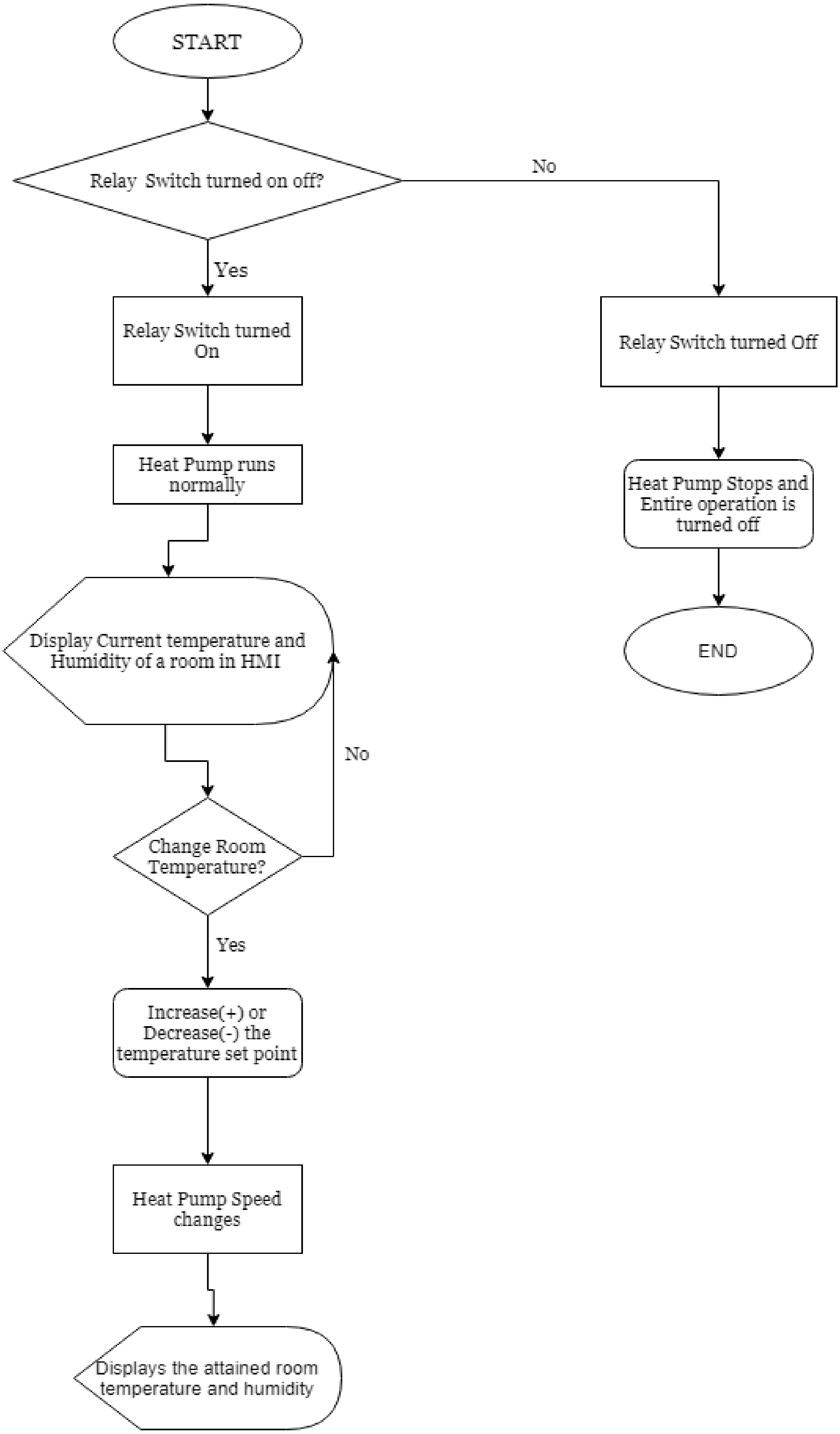

Figure 3.9: Flow Chart of the System

3.3.5 Schematic Circuit Diagram

The Schematic Diagram tells about the hardware connection which is given in the Smart control box. The Major components included in the schematic diagram are ESP32 Microcontroller, Solid State Relay, Heat Pump, Solenoid Valve, Heater, DHT22 Sensor, Optocoupler (Motor Driver Control) and Nextion HMI. From ESP32 the connections are given to the DHT22 Sensor and the serial communication from the microcontroller is given to the HMI and the I/O Pin 21 is connected to the solid-state relay. There is a separate three-phase load connected to the heat pump. Optocoupler is used here to boost the voltage from the microcontroller (3.3V) to the AC Motor (15V). Based on the set temperature in the nextion HMI, the microcontroller sends a signal to the Optocoupler to run the heat pump at the optimal speed to obtain the required temperature inside the room. The DHT22 sensor monitors the temperature and humidity inside the room and sends the data to the microcontroller and the microcontroller sends that retrieved data to the HMI for display.

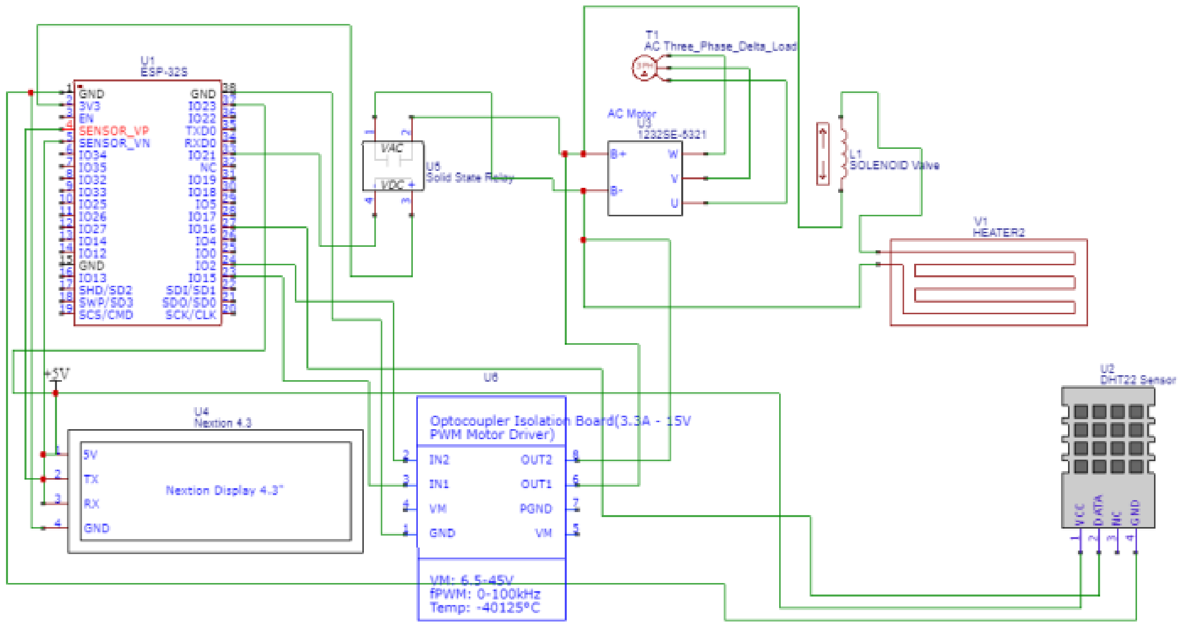

Figure 3.10: Schematic Circuit Diagram

For the sake of clarity, a block diagram of the entire process has been included for an easier understanding of the schematic diagram. The Block Diagram is given below,

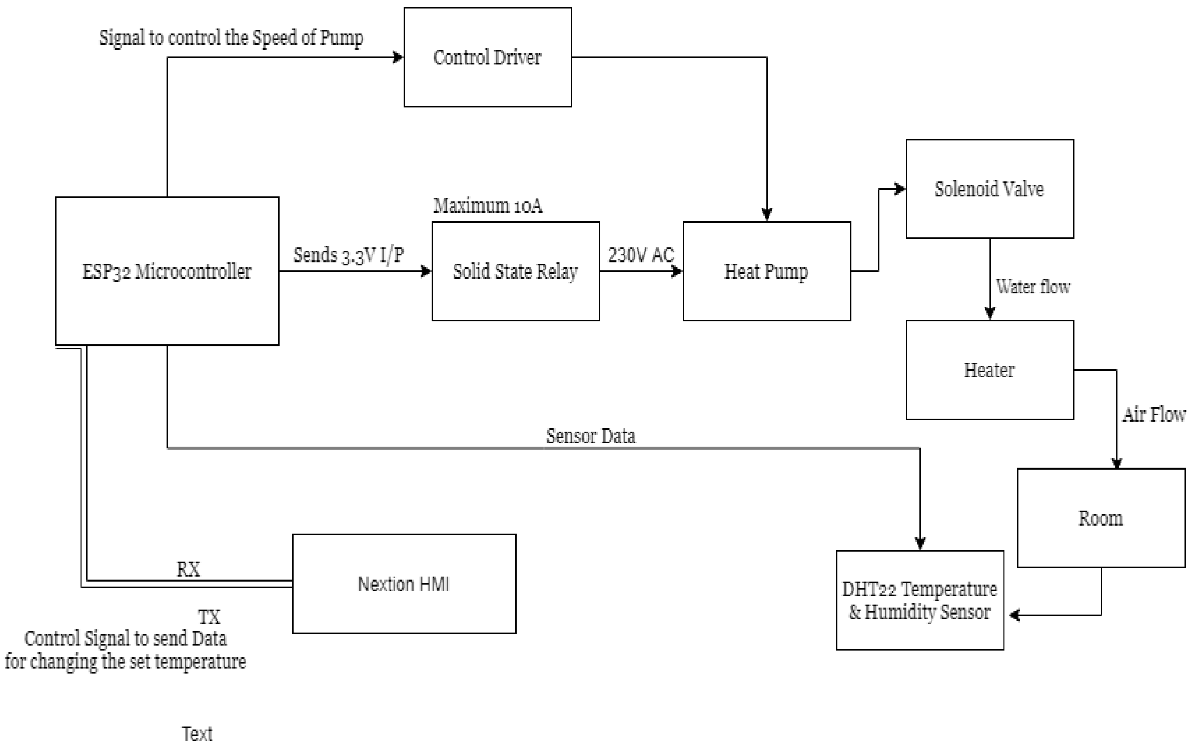

Figure 3.11: Block Diagram of the Plant

3.4 Communication

Communication is one of the important factors for the entire process of the system. Without communication, it is very difficult to transmit the data to the other system. In the hardware, two types of communication were established. One is the serial communication and the other is MODBUS Communication used by the ESP32 Microcontroller and Nextion HMI for the control of energy flow and temperature inside the room.

3.4.1 Serial Communication

Serial communication is the process of transmitting data one bit at a time. In contrast, parallel communication is where data bits are sent. Parallel data transmission is faster than serial transmission but with several disadvantages:

- It needs more wires and therefore can be more expensive to implement.
- The greater number of wires limit it to shorter transmission distances.
- It is susceptible to clock skew, which limits the speed of transmission to the slowest of the links.
- Crosstalk is also an issue due to the proximity of the wires.

Serial data transmission answers all the above problems, most especially the first one, as cost and limited pins are common issues in microcontroller system design. Serial communication follows a simple protocol (rules to follow) to ensure correct transmission. The baud rate, or speed of transmission, is also part of the protocol. The sender and the receiver must have the same baud rate. The standard rates are as follows:

- 1200
- 2400
- 4800
- 9600
- 19200
- 38400
- 57600
- 115200

9600 is the most common and is the default baud rate for most serial terminals and simulators. The major communication protocol used in the ESp32 is UART. It stands for Universal Asynchronous Receiver Transmitter, a device which has a transmit (Tx) and receive (Rx) line. If you want to interface your micro to another device that uses serial communication, you need to connect the micro's Tx to the device's Rx and vice versa. The other communication protocols used in the ESP32 Microcontroller are,

- **SPI- Serial Peripheral Interface:** It can be a three-wire or four-wire protocol (fourth wire is Slave Select). One wire each is for the master to slave and vice versa. The third wire is for clock pulses.
- **I2C- Inter-Integrated Circuit-** It is an advanced form of USART. It is a two-wire communication. The first wire is for clock and the second wire is for data which is bi-directional. It is a comparatively new protocol invented by Phillips. There is one master and can be one or multiple slaves. Each slave has its unique address through which the master communicates to the slave. Also, it's much faster than UART communication.
- **Ethernet**– It is used in LAN cable and has 8 wires (4 pairs of Rx and Tx).

The serial communication is established between the ESP32 Microcontroller and Nextion HMI. This HMI supports serial communication for transmitting and receiving the data. So based upon this communication the DHT22 temperature and humidity sensor was selected to monitor the temperature and humidity in the HMI.

3.4.2 MODBUS Communication to HVAC

RS485 is a standard for serial data transmission that is like RS232 while using different electric signals. A benefit of the RS485 protocol is the ability to have several devices share the same bus. This means you do not need multiple RS485 interfaces to query multiple devices. A bus terminator must be used to accomplish this feat. The MODBUS RS485 protocol defines communication between a host (master) and devices (slaves) that allows querying of device configuration and monitoring. MODBUS messages relay simple to read and write operations on 16-bit words and binary registers often referred to as "coils". Slave devices only respond to requests from the host which always initiates the conversation. When you have several devices connected on the RS485 bus in parallel, each device requires a unique MODBUS Slave ID. Every MODBUS request begins with the host contacting the Slave ID of the target device and the answer begins with the Slave ID of the sending slave device. For MODBUS communication to work correctly you need to ensure proper configuration of your devices' Slave IDs.
A MODBUS Communication has been included but due to time constraints, the testing of the communication was not done. The main idea was to switch on and off the HVAC system automatically based on the temperature inside the room and this can be done only with the help of RS485 MODBUS Communication because the HVAC system supports only MODBUS Communication.

3.5 Control Strategy

Control Strategy is one of the very important parts of Industrial control systems. The Control strategies are made to make a system a much smarter and more efficient in usage to ease the work. The Control Algorithm is a type of logic programmed into a controller to analyze the error between the measured value (MV) and setpoint (SP). A Control algorithm is a process of changing the input to a system to obtain the wanted response (known as feedback). This logic helps the controller process field data and decide what to do. In this section, we have a look upon the control inputs in which the user can use to change the ambient condition. We will also have a look at the control algorithms used in the hardware. Two types of Control algorithms are used in the Smart Control Box, one is hysteresis control and the other is PI Control.

3.5.1 Control Inputs

Control Inputs is one of the very important parts of the control system. Before deciding about the control strategy, the entire nature of the system must be studied, and then the variables which need to be controlled must be decided to control the entire system. These Control Inputs plays a key role in all the closed-loop systems.

In the project, the main aim is to maintain the optimal temperature and humidity at the very low cost of energy. The main control input which is to be varied here is the mass of the water flow, Heat pump speed. Because based on these flow rates and speed of the heat pump only will decide the optimal temperature and humidity inside the building. The Mass of the water flow and speed of the heat pump is directly proportional to the temperature inside the building because both these variables are correlated to temperature. Based on these control inputs two types of control algorithms are written in the software programming part in the Arduino IDE platform.

3.5.2 Hysteresis Control

Hysteresis Control is one of the traditional controls of the control systems. It is on/off control action turns the output on/off based on the setpoint. The output frequency changes according to minute temperature changes as a result, and this shortens the life of the output relay or unfavorably affects some devices connected to the temperature controller. To prevent this from happening a temperature band called hysteresis is created between the ON and Off operations. The hysteresis control is shown in the graph below,

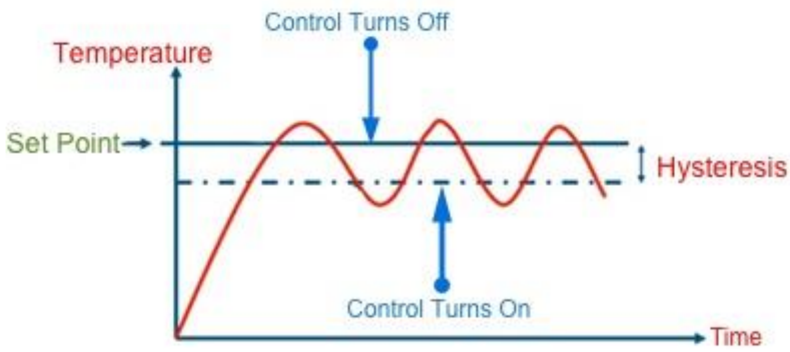

Figure 3.12: Hysteresis Control

In the system, the temperature setpoint is between 23°C and 25°C. When the temperature reaches 23°C the system should automatically turn on and when the system reaches 25°C the system should automatically turn off. This is the operation of the hysteresis control and here it turns on and off the heat pump based on the temperature set inside the building. This type of control is very much efficient to provide a better environment for humans inside the building.

3.5.2 PI Control

A variation of Proportional Integral Derivative (PID) control is to use only the proportional and integral terms as PI control. The PI controller is the most popular variation, even more than full PID controllers. The value of the controller output u(t)u(t) is fed into the system as the manipulated variable input.

$$e(t)=SP-PV$$

$$u(t) = u_{bias} + K_c\, e(t) + \frac{K_c}{\tau_I} \int_0^t e(t)dt$$

The u_{bias} term is a constant that is typically set to the value of u(t)u(t) when the controller is first switched from manual to automatic mode. This gives a "bumpless" transfer if the error is zero when the controller is turned on. The two tuning values for a PI controller are the controller gain, Kc, and the integral time constant τI. The value of Kc is a multiplier on the proportional error and integral term and a higher value make the controller more aggressive at responding to errors away from the set point. The setpoint (*SP*) is the target value and process variable (*PV*) is the measured value that may deviate from the desired value. The error from the setpoint is the difference between the *SP* and *PV* and is defined as e(t)=SP−PV.

In the system, the temperature is made as a set point and the user can set his/her suitable temperature to maintain a good environment inside the building. These control processes are done with the help of the PI Control algorithm in the Arduino IDE platform. Earlier the PI Control algorithm was tested in the modeling part in OpenModelica Connection Editor (OMEdit). The Gain (K) value was tuned and the Integral and time constant values were set to control the temperature to reach the steady state quickly.

3.6 Device Connectivity and Management

Since the Arduino IDE and Open Modelica are open-source, one can easily conclude that there will be a limitation in programming and modeling part of the work and only a very few features can be used. But there is no such limitation on both these platforms because depending upon the need of the project different libraries are downloaded from Github to develop the modeling part and programming work. All the wire connections of the hardware were done, and the wire connection of the heat pump device studied was studied completely from the manual to avoid any injuries while connecting the device. The device management of the HMI and Microcontroller was done perfectly because a single unknown change of component id or component name in the HMI will lead to the stoppage of the entire process. To manage the smart control box with no issues can be done by fixing it in the perfect place because small damage in the wire connection will lead to an error of the process. So, the Smart box must be handled with care in the building.

In the upcoming chapters, we will have a look at the modeling part of the work which is done in the OpenModelica tool and the experimental results obtained.

CHAPTER 4
MODEL DEVELOPMENT

In this chapter, we will have a detailed description of the Modelica and the components used for the simulation. We will have a look upon the design of the components done in Modelica which is necessary for the Modeling. We also have upon the types of control used in our model to simulate the entire mass of the energy flow and the calculation of the amount of the energy consumed in the thermal model.

4.1 Introduction to Modelica and OMEdit Tool

Modelica is an Object-Oriented Modelling and Simulation (OOMS) language developed in the last couple of decades. Its most relevant characteristics from the viewpoint of this work, are summarised below.

- It allows for equation-based modeling, i.e., component models are written independently of their interconnections.
- Owing to its equation-based nature it inherently allows for multi-physics modeling.
- It also allows us to mix equation- and algorithm-based modeling, which is extremely useful when it comes to representing digital control systems.

Because of the open architecture of Modelica which allows modifying the existing components, thus there is the possibility of employing impedance relations although Modelica designs for PDEs originally, the proposed mixed approach can be implemented in Modelica. The importance of the openness of the simulation tool to possible modifications increases as models and control methods on the electric network is being evolved regularly, thus a general model is out of topic. Together with its open-source nature, Modelica and the other simulation tools developed on it respond to the demands and expectations from a simulation tool stated in [10]. The advantages of Modelica over many other simulation languages at dealing with components from many engineering domains [11] gives the possibility of extending the electrical domain modeling to multi-domain modeling with internal control algorithms when needed.

Another advantage of Modelica is the object-oriented principle and the a-causal modeling. While object-oriented concepts enable proper structuring of models, the capability of non-causal modeling makes it easy to model for example power lines which are quite cumbersome to model using block-oriented languages such as Simulink [18]. As a consequence, from the viewpoint of this work, Modelica solves the systems in an object-oriented fashion, if one can achieve modeling the impedance relations in the same style, it is even possible to model the networks with the most cumbersome and complex mathematical expressions. For the author's convenience, Modelica is preferable over the modeling and simulation tools that use block diagrams when dealing with complex topologies.
OMEdit is part of the OpenModelica suite, a free software tool offering a complete Modelica environment. This brief description should suffice for motivating the choice of Modelica and OMEdit in this work.

4.2 Components

The library comprises the most primitive models and components like base components (Air, water, thermal components), aggregate components (Electrical, heating components), resistors, capacitors, inductors, grounds, and power sources, etc. Thus, validating the approach in the component level and then increases complexity step by step until the level of complex topologies like the whole plant model is achieved.
The Buildings and Plants libraries contain the major components for modeling the plant model. It contains important components like a water heater, pipes, valves, pumps, heater, and so on. The components section is of two types in buildings and plant library. One is based components that contain components like tanks, pipes, Air sink, Air source, Air pressure fixed component and the other aggregate components contain components like electric boiler, air capture coil, walls (Internal and exterior walls).

4.2.1 HVAC System

The HVAC system model, shown in Figure 4.1, is composed of Boolean input, two real input, and two air flanges. The air flanges are used for the supply of the gas from the HVAC to the mixing valve for heating the water. The HVAC System design is shown below,

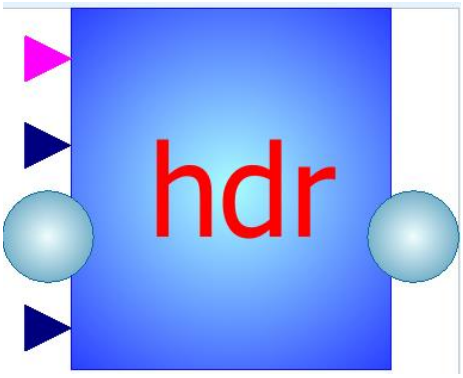

Figure 4.1: Modelica diagram for the HVAC System

The HVAC system is one of the major components used in the plant because the supply of the hot gas from HVAC will help to heat the water and to maintain a good atmosphere inside the building.

4.2.2 Floor Heater

The floor heater model, shown in Figure 4.2, is composed of inlet & outlet flanges, exchanging pipe, metal walls mass, internal and external convection correlations. The floor heater is shown below,

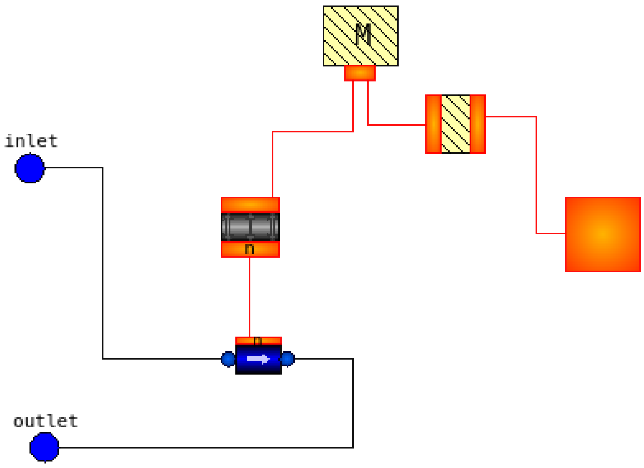

Figure 4.2: Modelica diagram for the Floor Heater Component

The Floor heater is one of the major components and is used to heat the room in a building and the usage of floor heater is more efficient than room heaters in a building because it maintains a good ambient temperature inside the room.

4.2.3 Room Heater

The room heater model, shown in Figure 4.3, is composed of inlet & outlet flanges, exchanging pipe, metal walls mass, internal and external convection correlations. The room heater is shown below,

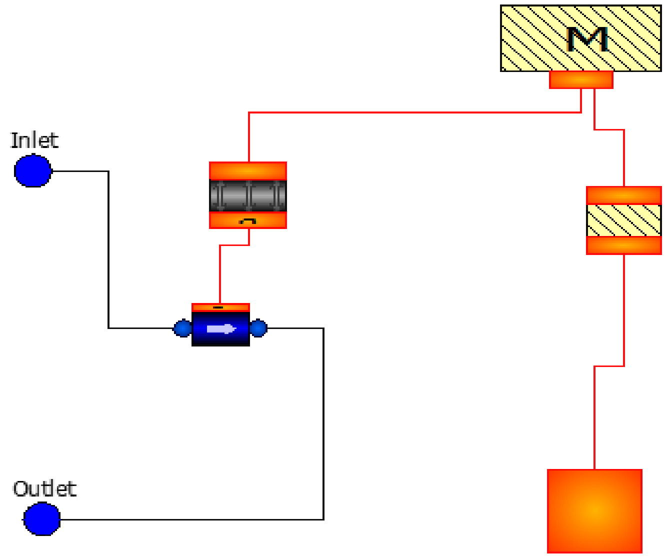

Figure 4.3: Modeling diagram for the Room Heater Component

The Room heater is one of the major components in a building and is used to heat the room and to maintain the good atmosphere inside the building.

4.2.4 Tank and Tank with coil

The tank and tank with coil model, shown in Figures 4.4 and 4.5, is composed of inlet & outlet water flanges, exchanging pipe, internal and external convection correlations. The tank and tank with coil are shown below,

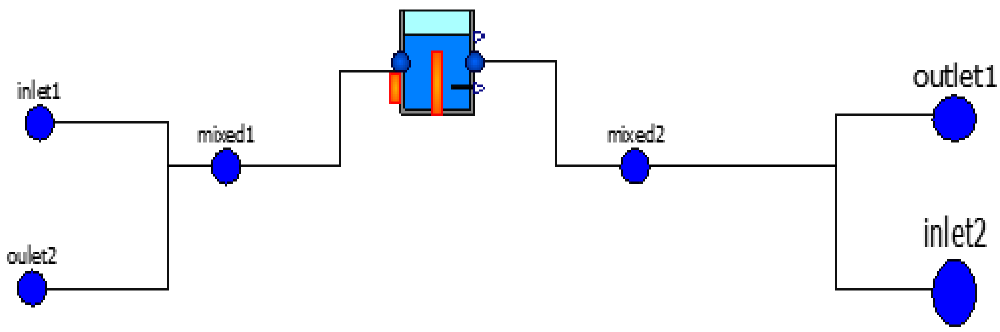

Figure 4.4: Modelica diagram for the tank component

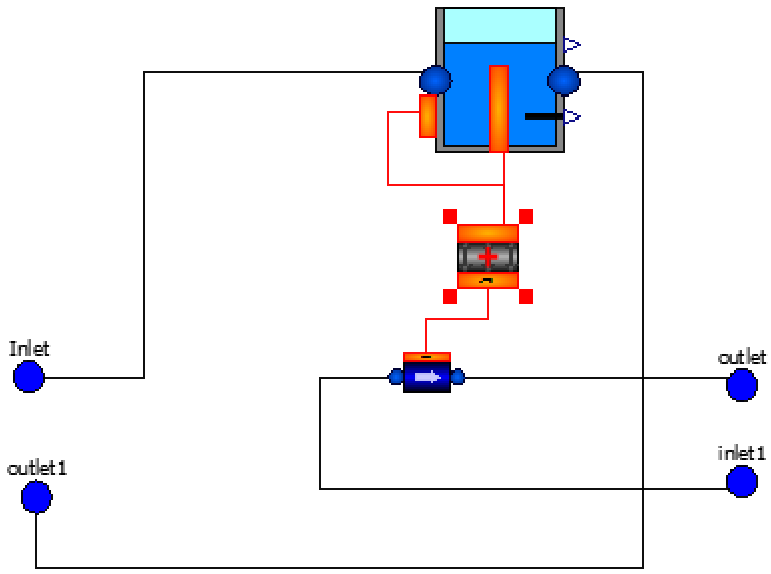

Figure 4.5: Modelica diagram for the tank with coil component

The tank and tank with coil are one of the major components in a plant building. The main purpose of the tank is to maintain the full quantity of the hot water and to supply the water to the pipes to heat the room heater or floor heater. The main purpose of the tank with coil is to maintain the full quantity of the hot water and to supply the hot water to the bathroom pipes and kitchen pipes. Thus, two tanks are essential in a plant building for maintaining renewable energy management.

4.3 Open-loop system control

The open-loop system control model, shown in Figure 4.6, is composed of Boolean input, real input, boiler, two-way valves, exchanging pipe, metal walls mass, internal and external convection correlations, exchange walls and air volume contained room. The open-loop system control is shown below,

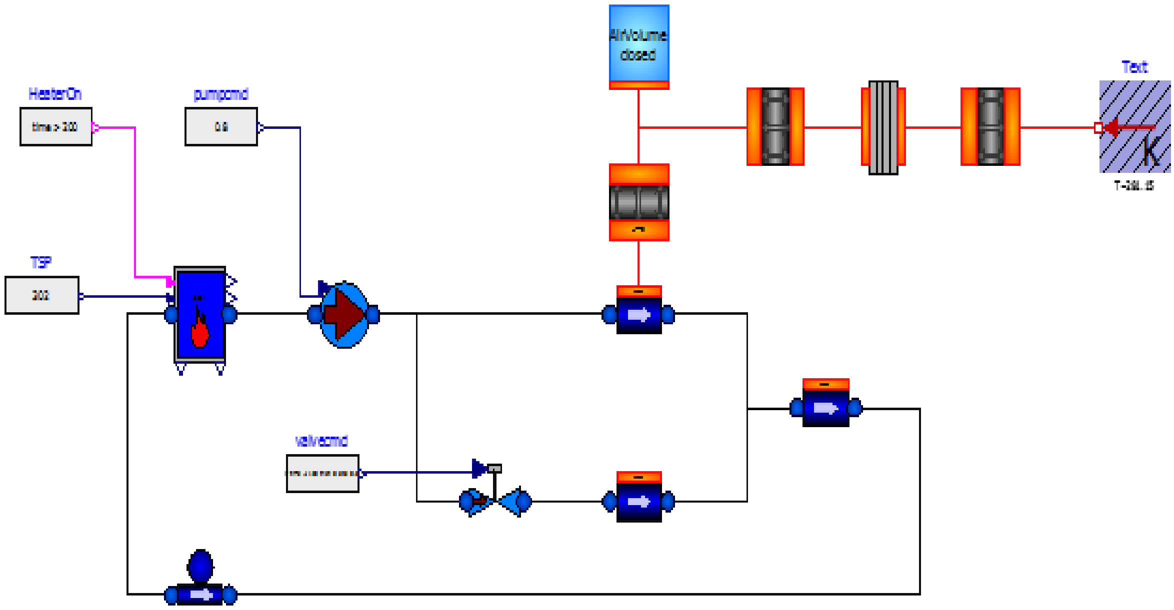

Figure 4.6: Modelica diagram for the open-loop system control

In the open-loop system control, there is no feedback on the temperature, and the heater will be turned on only after 200seconds. We have not included any controller in the open-loop system control. We have developed this model to have a basic understanding of the plant model and to check whether everything works fine by setting the attained temperature manually or not.

4.4 Closed-loop system control with PI

The closed-loop system control model, shown in Figure 3.7, is composed of Boolean input, real input, boiler, two-way valves, exchanging pipe, metal walls mass, internal and external convection correlations, exchange walls and air volume contained room, room heater, temperature sensor, dehumidifier, tank, and tank with coil. The closed-loop system control is shown below, The PI system control model of Figure 3.8, is composed of Boolean input, real input, boiler, PI controller, exchanging pipe, metal walls mass, internal and external convection correlations, exchange walls, air volume contained room and temperature sensor. The closed-loop system control is shown below,

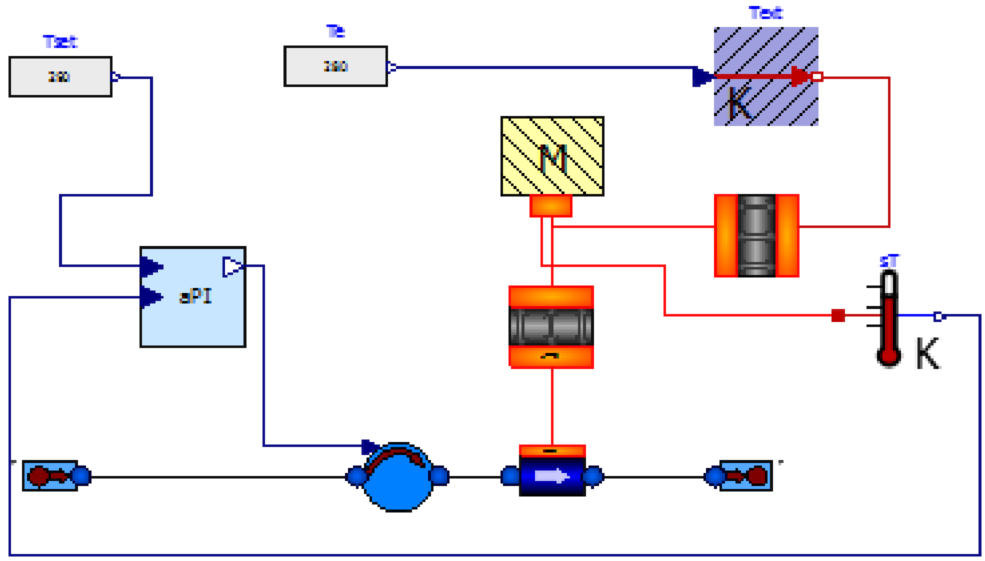

Figure 4.7: Modelica diagram for the PI control model

This PI control model was initially developed to have a clear idea of the control part of the work which is to be done. By using this PI controller, we can set the room temperature and it automatically calculates and supplies the required amount of gas and water to the heater to attain the setpoint temperature.

4.5 Thermal Model

The Thermal model, shown in Figure 4.8, is composed of Boolean input, real input, boiler, two-way valves, exchanging pipe, metal walls mass, internal and external convection correlations, exchange walls and air volume contained room, floor heater, temperature sensor, dehumidifier, tank, and tank with coil. The thermal model is shown below,

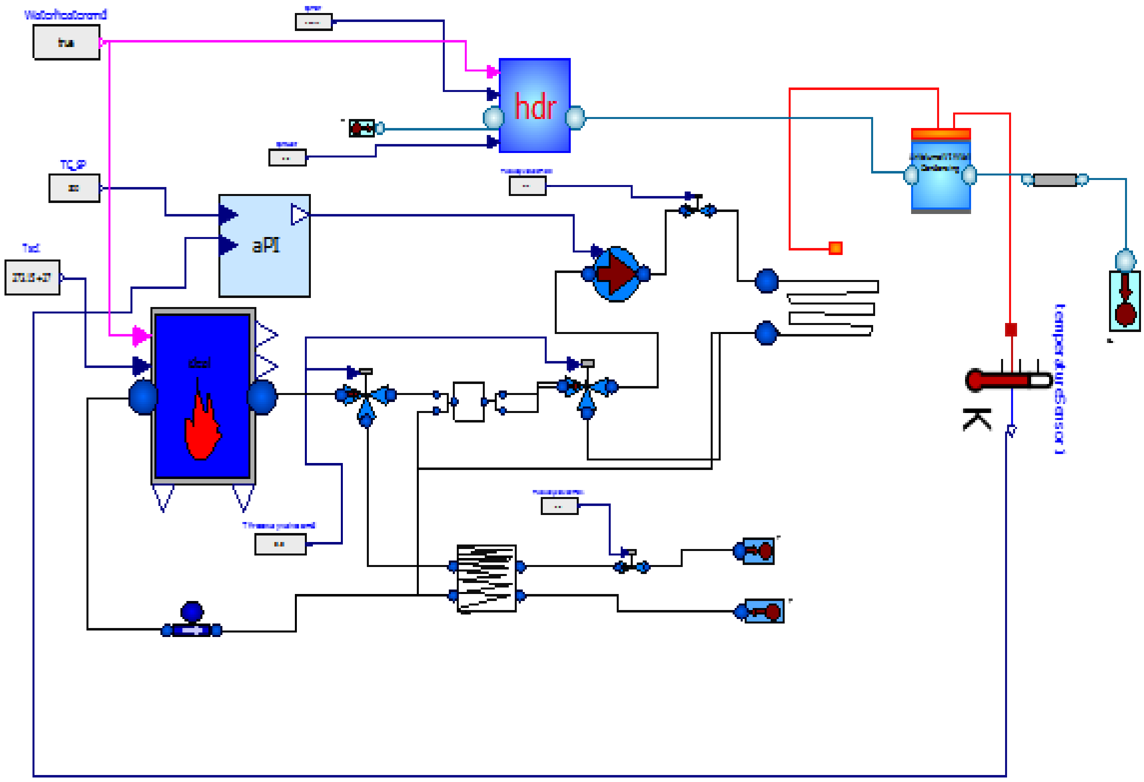

Figure 4.8: Modelica diagram for Thermal Model

This thermal model is the final complete model to control the room temperature and humidity based on human comfort. For this last model, we also present an example of the obtained simulation results.

CHAPTER 5

SIMULATION AND EXPERIMENTAL RESULTS

In this chapter, we will show results achieved in the Modeling work. Here we will also have the experimental results on the Smart Control Box which is done during the testing stage.

5.1 Open Modelica Analysis

In the Open Modelica part we will have look at the analysis of the temperature and humidity maintained inside the room, analysis of the mass of water flow, analysis of energy consumed.

The presented Modelica models were used to carry out several studies, not all reported here for brevity, that led to the following conclusions.

- **Concerning temperature and humidity control** the proposed scheme can maintain the room temperature setpoint and humidity.
- **Concerning the Analysis of Mass of the water flow,** the sizing of the components appears correct if the temperature set point is attained.
- **Concerning Analysis of Energy Consumed** when compared to baseline data, the scheme seems to offer some advantage in terms of switching on/off the heat pump based on the temperature setpoint inside the room to be maintained.

5.1.1 Analysis of Temperature Control

The Analysis of temperature (PI) control was done in the model by comparing the temperature obtained with the temperature set point in the controller. The following analysis of temperature and humidity control is shown below,

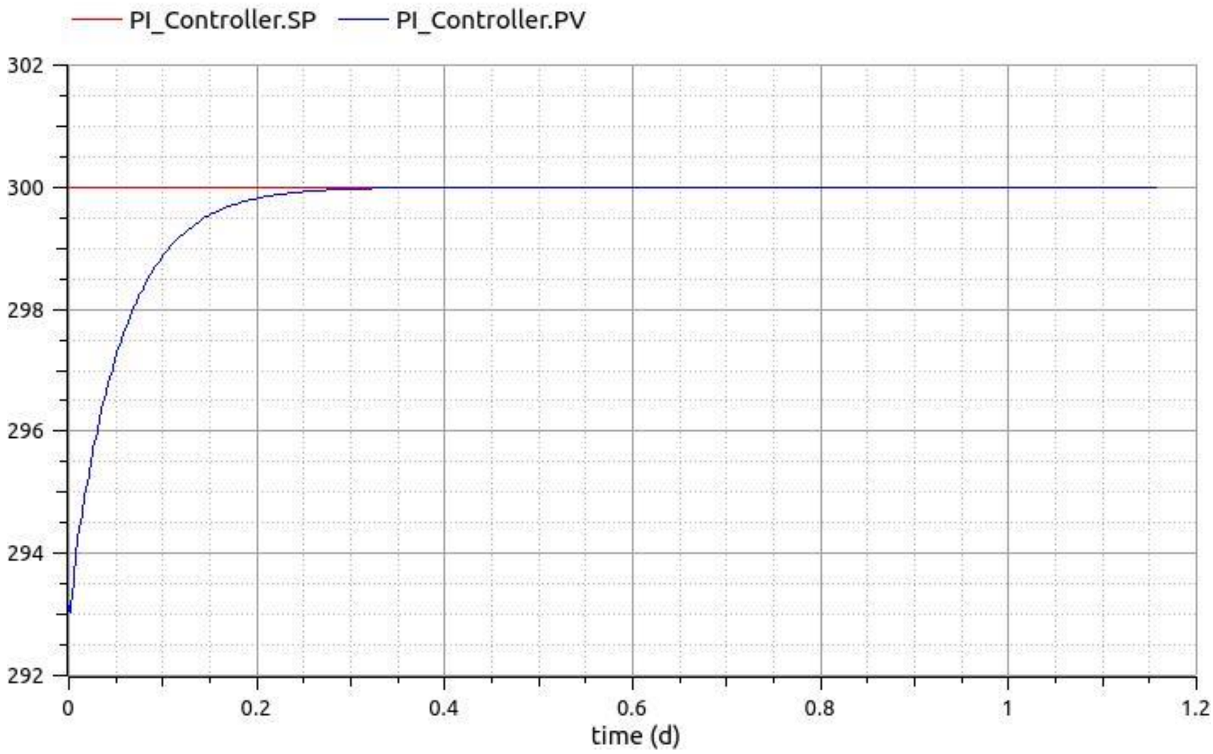

Figure 5.1: Graph Plot for PI Setpoint and Controlled Variable

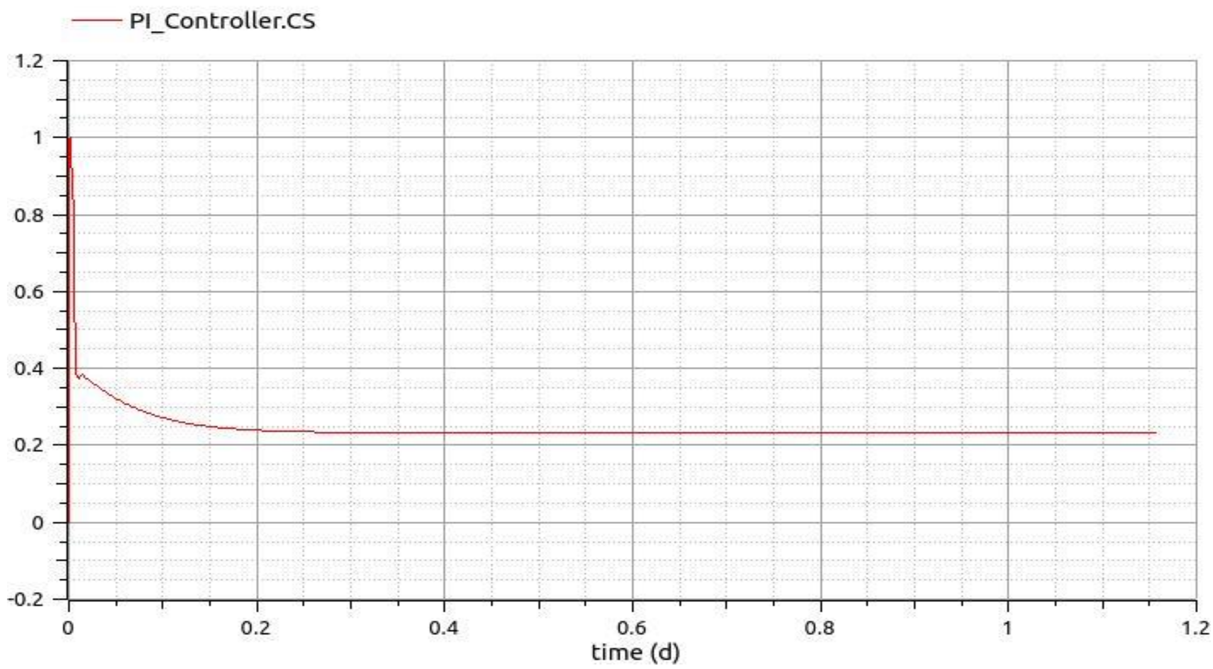

Figure 5.2: Graph Plot for PI Control Signal

5.1.2 Analysis of Mass of Waterflow

The Analysis of Mass of water flow was done in the model by comparing the temperature obtained with the temperature set point in the controller. The following analysis of the mass of water flow is shown below,

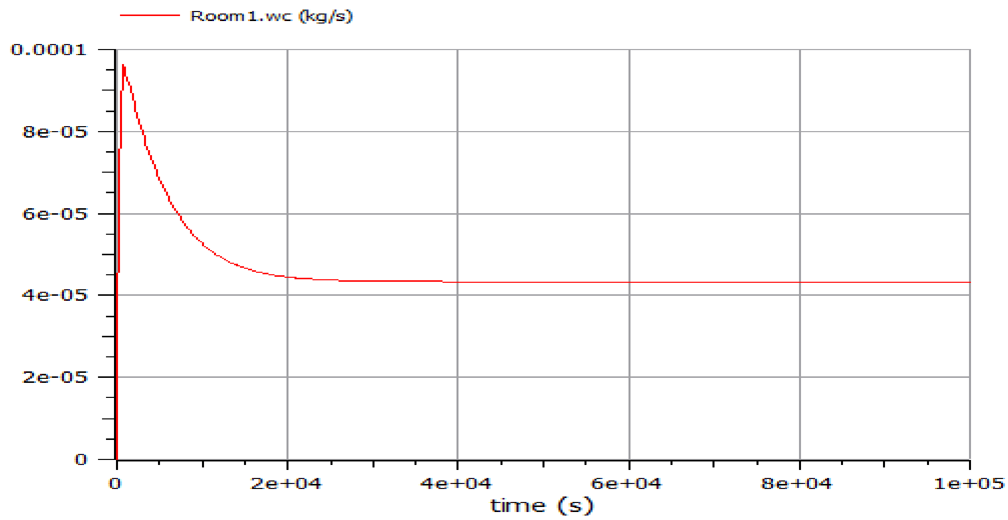

Figure 5.3: Analysis of Mass of water flow rate

5.1.3 Analysis of Energy consumed

The Analysis of energy consumed was carried to check the total heat flow and its consumed rate. This is done to check whether there is sufficient energy management in the model or not. The Analysis of the energy consumed is shown below,

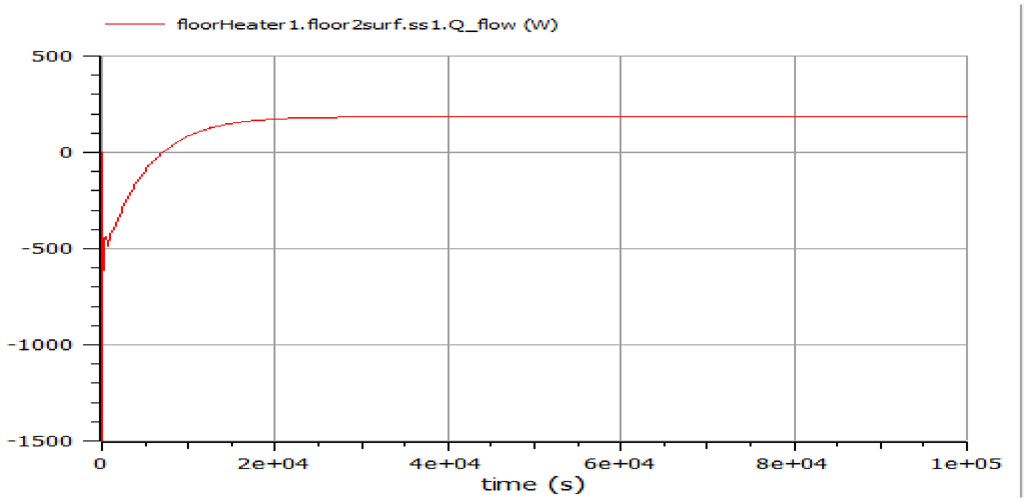

Figure 5.4: Analysis of Energy Consumed

5.2 Smart Control Box results

The monitoring of temperature and humidity, relay control and to set the room temperature control are the major functions carried out in the smart control box. By using the smart control box one can clear the point of view of the temperature maintained in all rooms in a building. The smart control box is one of the major devices in a building because without this an ambient good environment cannot be maintained especially during winter times.

5.2.1 Temperature and Humidity Analysis

During the development of the smart control box system initially, the monitoring of temperature and humidity was developed to check the temperature and humidity analysis inside the room. This was carried out with the help of Nextion HMI, Esp32 Microcontroller, DHT22 Temperature and humidity sensor, and jumper wires**.** The monitoring was done, and it is shown below,

Figure 5.5: Room temperature and humidity analysis in the Control box

5.2.2 Relay Control Analysis

The next step of work which was carried out in the smart control box was relay control analysis. The functioning of this work was done in the Arduino IDE platform and the software was implemented in the hardware and then the switching of relay control was done, The relay switching is done because during emergencies the relay switch can be turned off to stop the water flow rate. The relay switch (Dual state button) is shown in **Figure 5.5.**

5.2.3 PI Control Analysis

The PI control was followed to control the room temperature and humidity in the room by controlling the amount of water flow rate to the heater. The following strategy was implemented in the program by using PWM control logic, but the testing was not done. The PI control is followed by setting the room temperature in the smart control box which is shown in **Figure 3.8.**

5.2.4 Hysteresis Control Analysis

Hysteresis control is the second part of the control which is done to switch on and of the HVAC system based on the temperature maintained inside the room. The software was developed in the Arduino IDE platform and then implemented in the hardware. In the smart control box based on the minimum and maximum temperature, the heat pump will be switched on and off by using this control.

5.2.5 System results

Overall, with the prototype which was developed has attained the maximum good results and still, some work needs to be done to make much smarter and these works are included as future works which are needed to be done.

CHAPTER 6
CONCLUSIONS AND FUTURE WORK

This chapter summarizes the results of the thesis work and explains the possible future works.

Making the traditional building as "Smart Building" we are utilizing the resources without wastage. The point of thesis observing and controlling the physical parameters such as temperature and humidity and making them visualize in Smart control box with the help of Arduino IDE and Nextion Editor. Based on the results obtained we can have a general idea about the temperature that needs to be maintained in a building and we can improve the building environment if needed and we can also have a prediction about energy usage.

In the future, the smart control box will be implemented with MODBUS (RS 485) communication and IoT platform. The PID control algorithm will be implemented with the hardware to have an efficient energy flow and the mobile device deployment will also be done for the smart control box with the help of the IoT platform to have control and view about the smart building on the mobile phone from a far distance.

BIBLIOGRAPHY

1) Y. Ma, F. Borrelli, B. Hencey, A. Packard, and S. Borto_. Model predictive control of thermal energy storage in building cooling systems. Shanghai, P.R. China, 2009.
2) T. Salsburya, P. Mhaskarb, and S. J. Qinc. Predictive control methods to improve energy e_ciency and reduce demand in buildings. Computers and Chemical Engineering, 51:77-85, 2013.
3) F. Oldewurtel, A. Ulbig, M. Morari, and G. Andersson. Building control and storage management with dynamic tariffs for shaping demand response. Manchester, United Kingdom, 2011.
4) J. E. Braun. Reducing energy costs and peak electrical demand through optimal control of building thermal storage. ASHRAE Transactions, 96(2):876,887, 1990.
5) Y. Ma, A. Kelman, A. Daly, and F. Borrelli. Predictive control for energy-efficient buildings with thermal storage. IEEE Control Systems Magazine, 2012.
6) Jian Liang and Ruxu Du. Thermal comfort control based on neural network for HVAC application. In Proceedings of 2005 IEEE Conference on Control Applications, 2005. CCA 2005. pages 819–824. IEEE, 2005.
7) Jin Woo Moon and Sung Kwon Jung. Development of a thermal control algorithm using artificial neural network models for improved thermal comfort and energy efficiency in accommodation buildings. Applied Thermal Engineering, 103:1135–1144, 2016.
8) Nest. Nest Learning Thermostat.https://nest.com/thermostat/meet-nest-thermostat/, 2015. [Online; accessed 30/06/2015].
9) Jose Luis Gomez Ortega, Liangxiu Han, and Nicholas Bowring. Modeling and detection of user activity patterns for energy saving in buildings. In *Emerging Trends and Advanced Technologies for Computational Intelligence*, pages 165–185. Springer, 2016.

10) F. Casella and A. Leva. Modeling of thermo-hydraulic power generation processes using Modelica. *Mathematical and Computer Modelling of Dynamical Systems*, 12(1):19{33, 2006.

11) S. Mattsson, H. Elmqvist, and M. Otter. Physical system modeling with Modelica. *Control Engineering Practice*, 6:501{510, 1998.

12) Anastasios I Dounis and Christos Caraiscos. Advanced control systems engineering for energy and comfort management in a building.

13) AL Dexter, G Geng, and P Haves. The application of self-tuning pid control to hvac systems. In Control in Building Energy Management Systems, IEE Colloquium on, pages 4–1. IET, 1990.

14) Richard J De Dear, Gail Schiller Brager, James Reardon, Fergus Nicol, et al. Developing an adaptive model of thermal comfort and preference/discussion. *ASHRAE transactions*, 104:145, 1998.

15) FarshidShariatzadeh, ParasMandal, Anurag K. Srivastava, Demand response for sustainable energy systems: A review, application and implementation strategy, Renewable and Sustainable Energy Reviews, Volume 45, May 2015, Pages 343-350, ISSN 1364-0321.

16) Sarah Darby et al. The effectiveness of feedback on energy consumption. A Review for DEFRA of the Literature on Metering, Billing and direct Displays, 486:2006, 2006.

17) AI Dounis, MJ Santamouris, and CC Lefas. Implementation of artificial intelligence techniques in thermal comfort control for passive solar buildings. *Energy conversion and management*, 33(3):175–182, 1992.

18) Guang Geng and GM Geary. On performance and tuning of pid controllers in hvac systems. In Control Applications, 1993., Second IEEE Conference on, pages 819–824. IEEE, 1993.