CONTROL ALGORITHMS FOR ENERGY SAVINGS

In irregularly occupied buildings

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Preface

This thesis is a result of the cooperation between the department of energy and the department of electronic of the University of Gävle. The idea of the thesis comes from the supervisor of this Thesis, Mr. Niclas Björsell.

I would like to thank to Jan Akander for his advices about the IDA program, to Nawzad Mardan for his counsels about where to find information about the background of the project, as well as Hans Wigö for his help in the early stages of this project with interesting related documentation and his support to this project making it valid for my master in energy systems.

To the University of Gävle for all the support with the software, simulations and information as well as access to the computer facilities in which do that.

But over all I want to thank to my supervisor Niclas Björsell, because without his help, counseling and guidance this thesis would not have been possible.

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Abstract

The Heating, Ventilation and Air Conditioning (HVAC) systems are nowadays in almost every new building, develop or improve better control strategies for them is very common, looking to have more energy efficiency and require less input parameters from the user. In this project, new control strategies based in previous theory models has been used with a new approach in order to find a good solution for irregular occupied spaces.

In this new approach a feed-forward filter with a fixed preheating time, using an algorithm based on an identified model, calculates how much degrees the temperature room can be decreased and regulate the power of the radiators to do it.

The results of this project displays that the chosen model have to be changed but the idea is interesting, because the simulations of the reference building give, with a preheating time of 2 hours, around 3°C of temperature reduction during 18 days and savings of 33% of the heat energy needed for the whole month.

Considering that buildings and the residential sector currently account for 40 percent of Sweden's energy consumption and around 25 percent of other countries like USA or Spain, and that irregular spaces are more or less a 10% of the governmental, institutional, academic or public buildings, the potential savings are not negligible.

The evaluation of this control strategy with its mathematical model as well as its results during the month of January and the behavior of the system along the year have been made with the help of IDA program for simulation of the reference building and its energy system.
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1. Introduction

1.1 Background

The HVAC systems are widely extended nowadays because the needs of air quality and thermal comfort with a reasonable installation, operation and maintenance cost.

The heating part in HVAC system consists into a heater which can transfer the energy by convection, conduction and radiation. This heater can transfer the energy to a fluid (liquid as water for example, or to a gas like air), and this fluid transfer the energy to the desired space through different means like fan coils, radiators, convectors (baseboard) or other heat exchangers. Most of the energy transfer is usually done by convection [1].

The ventilation is the process of replacing air into a space to control temperature, moisture, CO2 levels, fumes and so on. This ventilation can be forced or natural. The forced ventilation is normally done by an AHU (Air Handling Unit) with filters for the air and fans to move it. The natural ventilation is done without the use of fans or anything mechanical and depends of the pressure differences, architecture and design of the space [2].

The air conditioning and refrigeration looks for the removal of the excess of heat and uses the same means like the heating but reverse. The HVAC can be controlled by different ways, some of the most common are:

Feed- back (FB) controllers, this denotes a group of controllers with the common feature that the control signals are generated by comparing the measured value of the controlled variable to a reference value (See Figure 1). The difference between them is referred as the control error and is the input to the controller [2].
Feed-forward (FF) controllers, their main feature is the rejection of measurable disturbances reducing the impact of a disturbance on the controlled variable (See Figure 2). The basic idea is to use information about the disturbances and then anticipate the influence of them into the system. The system also can be controlled by feed-forward and feed-back controller together (See Figure 3) for a better performance combining the benefits of both systems [2].

The energy savings using an HVAC are about 15-20% [3] but this can improved more with certain changes in the system for improve its efficiency, like the nighttime strategies.
1.2 Nighttime strategies

This strategies are based in reduce the temperature during the night hours so by this way reduce the amount of energy used by the HVAC system. This is especially important in winter.

During the nighttime the temperature is reduced to a certain level until a determined hour in which the preheating time for the daytime starts, this preheating time usually have a boost in the power of the HVAC system to provide fast the energy needed for the space to reach the desired temperature. The temperature decrease faster as much cold is outside.

For this preheating time is necessary some calculations like the estimation of the preheating period of which this project will show more forward.

Typically the heating energy savings are around 5%, the cooling energy savings around 42% and the electrical energy savings around 2%. Good tuned night systems have a total energy savings of 7% but with an increase of the required peak power of around 300% [2].

This savings can appear to be scarce but have to consider that the driving force in the heating systems is the difference of temperatures between indoor and outdoor environment. In winter time all this kind of strategies are much more efficient because the higher difference of temperatures.

There are four typical curves to describe a controller for the nighttime strategies without feedback from the room temperature (See Figure 4).
Figure 4: The setpoint to the supply water temperature depends on the outdoor temperature (dotted line) and the nighttime setback (second graph). If there is a feedforward filter, the boost size and the preheating time are optimally chosen; the room temperature is constant during day and reduced during night. [6]

Doing simplified calculations (with the consequent errors), for example a typical winter day with -10°, with a temperature of 22° indoor, the difference $\Delta T$ is of 32° between indoor and outdoor; the nighttime strategies for practical reasons usually doesn’t go below 12° for protection of short-circuiting the ventilation system or damage to living things such as plants in the building.
This means a reduction of 10º from the daytime temperature and this corresponds a 31.25% of temperature reduction from the difference between indoor and outdoor, but this reduction is during only around 8 hours of the day and requires a peak of power (for the boost) at the beginning of the day, so the final calculation is that the total energy savings are more or less 5% [2].

1.3 The project purpose

The task was given by the electronic department in agreement with the director of the master in energy systems and the energy department of the University of Gävle.

The idea of this project is to implement and test a new control strategy with similarities with the nighttime strategies in order to evaluate if it works and can have good energy savings for irregularly occupied spaces. For this task, one scenario has been chosen from the multiple available scenario possibilities. The important thing is to check if the control strategy chosen works as well as its mathematical model, and if the model is wrong, check if the control strategy is still valid.

In this project simulations will be done for test the new control strategy, using a HVAC system and based only in the radiators. The radiators are heat exchangers which heat transfer is done almost by convection, with the energy provided by a boiler and moved through the system by pumps.

In few words, the different approach from the nighttime saving strategies is that in this project the preheating time will be known and check if the control strategy is able to heat up the temperature difference (from energy saving mode to normal function mode) during that preheating time. Also, simulations manipulating the flow valve of the radiators will be done for check if there is possible to use them to boost the power during the preheating.

The choice of irregular occupied spaces is because these spaces are not used frequently and there is a lot of research about energy savings in the regular occupied spaces, but not much of irregular ones and the end of the project have more sense and application on them [4].
1.4 The software

The complexity of the operations of the models that use this project and the desire of to do a study from different measures, there is necessary the utilization of a simulation software. This software is called IDA ICE (Indoor Climate and Energy) [5], with this program is possible to study the thermal indoor climate of a building as well as its energy use. The primary application area is building and energy systems simulation, but can be used in other fields.

The program works with a model which consists of physical components like walls, windows, valves and controllers. But also indoor air quality, thermal comfort, airflows, thermal models, CO2, moisture calculation, vertical temperature gradients, wind and buoyancy of the airflows, leakages, and a lot of more things that makes this program a very good tool for simulate a complete linked building model [6].

The IDA ICE has been developed at the Swedish Institute of Applied Mathematics (ITM) along with the Department of Building Services Engineering at the Royal Institute of Technology (KTH), Stockholm. The first version was released in 1998 and had a model library written in NMF (Neutral Mode Format) [Sahlin and Sowell 1989]. NMF is a language for modeling dynamical systems with differential algebra [5].
1.5 State of art

About the background of this project there are ideas widely developed since the 80’s. There is a good amount of literature about it and the most common subject is to analyze free-cooling during night to reduce the cooling of the day, in several cases covering a combination of daytime and nighttime strategies. The last investigations about night-time strategies compare conventional strategies (shut off and constant flow rate) with FF (Feed-forward) based strategies (Indoor Air Quality focusing and thermal focusing) [2].

The investigation nowadays is usually more focused into a better controlling of the HVAC systems with MPC (Model Predictive Control) or new MPC models [7] with only a few of FF-based control [8]. MPC controllers use dynamic models of the object to control and its control signals are generated by optimization equations [9].

There is also works in the field of thermal comfort and by the way reduce the energy usage with hierarchical predictive control strategies [10], or studies about passive climate control, the effect of moisture and internal coating effect [11].

The global idea is that the majority of the work in the field is based more in the ventilation systems and less in the water systems (radiators). And the night-time strategies developed don’t focus further the current developed things. To the best of our knowledge, the project can be considered novel.
1.6 Outline of the thesis

In Chapter 2 the mathematical model for the simulations, the control strategy and the theory for calculate its parameters is described as well as the theory of the flow valves and the simulation software.

The reference building and the objective room is described in Chapter 3 as well as the simulation model with some of its physical properties and how to build it on the simulation software and also how identify the control strategy parameters with the simulation software.

In Chapter 4 the results are exposed for the month of January with test of the model for different preheating times and the corrections for the model. Also some evaluations for different time of the year and different flow through the flow valve of the radiators have been made as well as a heat balance for the month of January in order to give an idea about if the control strategy is efficient.

In Chapter 5 the discussion of the thesis result as well as its pros and cons have been exposed. The conclusion, in Chapter 6, has the major results and suggestions for further projects or improvements that might be interesting to do.
2. Theory

2.1 Nonlinear method

This theory is based on the ideas of the licentiate thesis author [6] but with new approach. This new idea consist in consider the preheating time fixed and calculate how much temperature can be decreased from the room during the energy saving time, in order to the system be able to heat up to the desired room temperature this difference (the degrees from reduced temperature to desired room temperature) in the preheating time.

The temperature depends of the radiators of the room and the outdoor temperature. There are perturbations that affects to the room temperature like the solar radiation, people inside, furniture and so on. Because the objective of the project, all the disturbances except the solar radiation will be ignored to be considered nonexistent.

The system is presumably described by the state-space model; it’s a mathematical way to describe typically physical linear systems:

\[ x(t + 1) = Ax(t) + B_1 u(t) + B_2 w(t) \]
\[ y(t) = C x(t) \] (2-1)

This is a time-discrete model where:

- \( y(t) \) is the indoor temperature
- \( w(t) \) is the outdoor temperature
- \( u(t) \) is the supply water temperature
- \( x(t) \) is a state variable

While, A, B\(_1\), B\(_2\) are matrixes, in this project will only be used the scalar values: a, b\(_1\), b\(_2\).
There is a common solution for a heat controller who describes the feedforward commented before as well as the variables in form of block diagram (See Figure 5).

![Block Diagram of Heat Controller](image)

**Figure 5: Common solution for heat controller**

The characterized model for heating systems in buildings is a first order model.

\[
y(t + 1) = ay(t) + b_1 u(t) + b_2 w(t)
\]  
(2-2)

The idea is to predict the room temperature \(m\) step ahead under the preheating time. And base of that, the assumption is that with a fixed preheating time chosen by the user, the system can predict how many degrees can be decreased during the backoff time (from now on this is the name given to the time which the system is saving energy because reducing the degrees in the room) [6].

The room temperature \(m\) steps ahead can be calculated with the equation (2-2), assuming that the supply water and outdoor temperatures are known.

\[
\hat{y}(t + m|t) = a^m y(t) + b_1 \left[ \sum_{i=0}^{m-1} a^i u(t + m - 1 - i) \right] + b_2 \left[ \sum_{i=0}^{m-1} a^i w(t + m - 1 - i) \right]
\]

(2-3)

This expression can be simplified assuming certain things. First of all, the heat exchanger dynamic behavior is faster than the room dynamics and can be treated consequently as instantaneous, \(u(t)\) can be equalized with the control signal. Also the future control signal \(u(t)\) and future outdoor temperature \(w(t)\) are constant during the heating period.
This is a good assumption since the temperature controller is usually equipped with feedforward compensation (see Figure 5). With a precise feedforward all outdoor temperature changes will be erased by the control signal. Consequently the control signal can be seen as constant as well as the outdoor temperature.

Assuming these suppositions, the predicted room temperature can be rewritten as:

\[ \hat{y}(t + m|t) = a^m y(t) + b_1 \left[ \sum_{i=0}^{m-1} a^i \right] u(t) + b_2 \left[ \sum_{i=0}^{m-1} a^i \right] w(t) \]

\[ = a^m y(t) + b_1 \frac{1 - a^m}{1 - a} u(t) + b_2 \frac{1 - a^m}{1 - a} w(t) \]

\[ = a^m \left[ y(t) - b_1 \frac{1}{1 - a} u(t) - b_2 \frac{1}{1 - a} w(t) \right] + b_1 \frac{1}{1 - a} u(t) + b_2 \frac{1}{1 - a} w(t) \]  

\[ (2-4) \]

There is an alternate approach, study how much higher the room temperature can be with increased supply water temperature compared to what it would have been with the supply water remaining at the backoff temperature (from now on this is the name given to the temperature which the system is decreasing during the backoff time). For check this alternative two further predicted values of \( y(t+m) \), the predicted room temperature provided that the supply water remains low at the \( u(t) \) will be denoted by \( \hat{y}_0(t + m|t) \) satisfying

\[ \hat{y}_0(t + m|t) = a^m y(t) + b_1 \left[ \sum_{i=0}^{m-1} a^i \right] u(t) + b_2 \left[ \sum_{i=0}^{m-1} a^i \right] w(t) \]  

\[ (2-5) \]

Besides, \( \hat{y}_1(t + m|t) \) indicate the predicted room temperature if the supply water temperature is raised to \( u(t) + \Delta u \). Then,

\[ \hat{y}_1(t + m|t) = a^m y(t) + b_1 \left[ \sum_{i=0}^{m-1} a^i \right] (u_2(t) + \Delta u) + b_2 \left[ \sum_{i=0}^{m-1} a^i \right] w(t) \]  

\[ (2-6) \]
The difference between $\hat{y}_1(t + m|t)$ and $\hat{y}_0(t + m|t)$ is the increment in room temperature, $\Delta \hat{y}(t + m|t)$ and is developed:

$$\Delta \hat{y}(t + m|t) = \hat{y}_1(t + m|t) - \hat{y}_0(t + m|t)$$

$$= a^m y(t) + b_1 \left( \sum_{i=0}^{m-1} a^i \right) u(t) + b_2 \left( \sum_{i=0}^{m-1} a^i \right) w(t)$$

$$- \left( a^m y(t) + b_1 \left( \sum_{i=0}^{m-1} a^i \right) u(t) + b_2 \left( \sum_{i=0}^{m-1} a^i \right) w(t) \right) = b_2 \left( \sum_{i=0}^{m-1} a^i \right) \Delta u(t)$$

$$= b_1 \cdot \left[ \frac{1 - a^m}{1 - a} \right] \cdot \Delta u(t)$$

The input $\Delta u(t)$ it's known and the necessary temperature rise $\Delta \hat{y}(t + m|t)$ is the difference between the actual and required room temperature and is continuously measured. The values of $a$ and $b$ are model parameters and will be explained how to find them it in chapter 2.3.

This formula is important because on it is based the main calculations of the system controller and testing its accuracy or validity is one of the goals of this project.

With all of this, the assumption is that with a fixed preheating time, the system will calculate the amount of temperature that can be decreased (backoff temperature) along the backoff time, in order to heat up the difference during the fixed preheating time. If the model is correct, the temperature of the room should be capable of increase from the backoff temperature to the desired room temperature approximately during the selected preheating time [6].
2.2 Finding the values of the time constant and the gain

In order to find the discrete time parameters \( a \) and \( b \), is necessary to start looking for the time continuous system, and it can be modeled as

\[
\dot{y}(s) = \frac{1}{\tau} \cdot y(s) = \frac{K}{\tau} \cdot x(s)
\]  

(2-8)

Where \( K \) is the gain and \( \tau \) is the time constant.

To distinguish the continuous time from the discrete time, we will use for continuous time \((s)\) and \((t)\) will be for discrete time. The input signal of the model, which is needed for get the \( \Delta \text{in} \) (input difference) of the controller, will be like the following (See Figure 7)
And its output shape where we can take the $\Delta_{\text{out}}$ (output change) and the Time constant of the controller (See Figure 8)

![Graph representing the block diagram output](image)

Figure 8: Graph representing the block diagram output

The value of the time constant, $\tau$, and the gain, $K$, are needed for the calculations of the equations for the system parameters. The time constant, ($\tau$), is the required time for the system to reach the 63% of the desired output temperature and is taken from the output curve. The value of $K$ is the proportional value from the difference of outputs to the difference of inputs, and is calculated with the formula:

$$K = \frac{\Delta_{\text{out}}}{\Delta_{\text{in}}}$$  \hspace{1cm} (2-9)
2.3 Discrete time models and system parameters

The discrete time models are differential equations used to describe events for which is usually taken in consideration to use time at fixed intervals. With the time constant and the gain calculated in 2.2, now is possible to calculate the system parameters a and b.

The discrete time equation for this project is:

\[ y(t + 1) = a * y(t) + b * x(t) \]  

(2-10)

Where the formulas to calculate the constants are:

\[ a = e^{-h/\tau} \]  

(2-11)

\[ b = K * (1 - e^{-h/\tau}) \]  

(2-12)

With \( H = 15 \text{ min} \) that is a typical value for \( h \) (sampling time);

With these values and the fixed \( m \) value, will be possible to solve the controller equation:

\[ \Delta \hat{y}(t + m|t) = b * \left[ \frac{1-a^m}{1-a} \right] * \Delta u(t) \]  

(2-13)

Where \( m \) is the prediction horizon that is taken from the desired preheating period along with the sampling time with the formula:

\[ m = \frac{\text{Desired preheating period}}{\text{Sampling time (h)}} \]  

(2-14)
2.4 Block diagram for the model

The IDA program works (in order to introduce the model) with block diagrams in the schematic of the model. Because that, this block diagram has been designed in order to satisfy the previously commented equations and get the desired result.

![Block diagram of the designed model](image)

The block diagram (See Figure 9) consist of two add blocks (the ones with a + and -), two multiplier blocks (the ones with an X), two constant blocks (one for the controller constant with the formula \( b(1-a^m)/(1-a) \) and other with the 21), one schedule block and the core of all of them, the PI controller. All the blocks can be edited and their characteristics changed if needed.

The block 21, is a block with a constant value that will be the desired room temperature during the time in which the room will be used. The time schedule regulates this usage time and the energy saving time, serving as an input of the value of the entrance \( \Delta u(t) \).
2.5 The valve flow coefficient

The valve flow coefficient (Kv valve from now on) is the name given to the valve which influence in the flow that enters in the radiator and is also called flow coefficient. When flow goes through a valve or any other restricting device it loses some energy. The flow coefficient is a designing factor which relates head drop (Δh) or pressure drop (ΔP) across the valve with the flow rate (Q) [12].

\[ Q = K \sqrt{\frac{\Delta P}{S_g}} \]  

\( Q \): Flow rate  
\( \Delta P \): Pressure Drop  
\( S_g \): Specific gravity (1 for water)  
\( K \): Flow coefficient Kv or Cv

At same flow rate, higher flow coefficient means lower drop pressure across the valve.

Opening the valve during the preheating time will increase the power provided by the radiator during the preheating time due to an increase of the flow in the radiator [12].

But this can give a problem to the system and it’s that during the time in which the flow is higher in the radiators of the designed space, the radiators of the rest of the building will receive less pressure consequently. This pressure drop should be not too high or appreciable so, it could not affect at all to the system, this issue will not be studied in this project.
3. Method

3.1 The reference building

The reference building is located in Gävle, more specifically in the University of Gävle. The building contains a wide variety of rooms, but this project will focus in one in particular, the conference room 99:515. It is located on the fifth floor, and has one external wall with a window facing south-east. It is marked with a red circle in Figure 11.

![Figure 11: Plane of the building and the test room](image_url)

The room has around 32 m².

The building heating system uses district heating. Inside the rooms, the radiators are placed under the windows. The room is ventilated with an AHU.
The floor plan of the building in the IDA program is:

![Figure 12: IDA ICE Floor plan in 2D view](image)

The room is the one marked in the figure by the mouse, the orientation is south-east (can be shown in the compass of the top left corner), and this is important in matter of sunlight and sun energy during the year, especially during winter time in which the heat from the sun can help the room to be heated, also has been taken the climate conditions of Stockholm/Bromma (because the inexistence of data in the program for Gävle) and the determination of try to be as much realistic as possible.

The synthetic climate of winter that the program allows the user to use (made by mathematical equations and models) is used only in specific test and will be notified in this report when this will happen.
The 3d view of the floor plan is:

![Figure 13: Floor plan of the building in 3D view](image)

The next is a 3d view in +Z which means that the superior half of the Z-axis of the image has been cut for observe inside the floor plan [9].

![Figure 14: 3D view of the floor plan in +z-axis](image)
3.2 The system of the building

The simulation takes in consideration several things like the following [13].

**The building**
- Ceiling
- Frontage (facade)
- Floor
- Solar radiation (through window)
- Wall
- Window

**Ventilation**
- Air exchange in the room
- Inlet air
- Outlet air

**Heating system**
- Heat balance in the room
- Radiator
- Heat exchanger for district heating
- Pipe
- Valve

**Control system**
- Feedforward compensation for outdoor temperature
- PI-controller

The Figure 15, shows all a room decomposed showing the previously commented parts.

![Figure 15: Components of the model](image-url)
The building has different parts, the standard plant, with the boiler for the radiators and the chiller, along with the pipes. Each part of the plant has a schedule for design specified timing options if desirable, but is not the case of this project. The standard plant schematic in the program (See Figure 16) is the main part of the HVAC system because here is where the heating takes place and where the values of the boiler can be changed.

![Diagram](image)

**Figure 16: Plant schematic**

The setpoint for supply hot water, is where the sensor of outdoor temperature enters as input in the module marked with the red circle. This is of capital importance because depending on how is the outdoor temperature, the hot water temperature supplied to the building changes. Depending on the region and the variance of the ambient temperature, the diagram varies; in this case the diagram comes from an outdoor temperature curve from the Sweden’s weather institute provided by the supervisor of this thesis.
The relationship between supply water temperature and the outdoor temperature can be seen in Figure 17.

**Figure 17: Controller for supply heating water temperature data**

This data, corresponding to the next graph, is the temperature curve that the hot water inside the radiators follow in order to heat during the year, being 55°C the highest temperature during the coldest days of winter.

**Figure 18: Graph of supply water temperature dependent of the ambient temperature**
Also, the AHU system of the building has its own schematic, a standard one.

Here, the air temperature of the room supplied by the ventilation is constant to 16° by default. But the system gives the chance to change it and the heat exchanger, boilers, moisture, CO2 and so on.

The temperature of the air ventilation can also be changed with the variation of the outdoor temperature, but this change has not been contemplated because it is already being considered in the standard plant which controls the heating and its more efficient in this matter than the AHU.

In this simulation, there is one simplification (which is not too important in matter of errors in the global system), and it is that the other rooms except the one of the study have ideal heaters/coolers.
This ideal heaters and coolers are used by default in those spaces not important to enter in details and gives typical operation values for rooms used daily. They are not connected to the standard plant physically (as in the next figure shows) and are not connected to any surfaces of the room (like an standalone unit). The default capacity is given based on the m² of the floor area and controlled by a PI module in order to keep the temperature inside the specified temperature setpoint shown in the next figure.

![Control Setpoints](image)

**Figure 20: Control setpoints for the surrounding rooms to the objective room**

In this control, there are a lot of parameters that can be changed globally for those rooms not important for the study in order to ensure the correct function of the simulation depending of the situation.

Therefore, the ideal heaters and coolers just give an average and balanced amount of power in order to simplify the simulation and reduce the amount of entered data.
The parameters which can be changed in the ideal heater are shown in the next figure.

![Ideal heater parameters](image)

**Figure 21: Ideal heater parameters for the surrounding rooms**

The value of the maximum power can be modified but the program can give it by default depending on the area of the floor. The other parameters could be important in the room of study but are not relevant in the other rooms for this project.

All of this rooms (including the object of study) are separated by walls, the characteristic of these walls in absence of data from the manufacturer of the building, has been assumed to be the following, based by database of the program as adequate for this climate.

![Building defaults](image)

**Figure 22: Walls, ceilings, glazing and doors for the simulated building**
The internal walls have been the only ones changed and this was in order to reduce the amount of gypsum of the walls because the default of the program was a way higher than the reality of our rooms.

The building rooms are connected by its own schematic which interconnects them with the HVAC and the standard plant in order to supply all of them of their ventilation and heat.

The room objective (See Figure 23) of this project is marked in red circle.

Figure 23: General schematic of the interconnection between all the spaces of the building with the HVAC
The only one room with connection with the plant (Figure 16) is the objective room, because, as previously has been commented the ideal heater/coolers from the other rooms are not connected to it.

Here also can be specified the kind of climate will have the simulations, some will be with Synthetic (winter), this is an option given by IDA to simulate with artificial winter climate temperatures, and others will be the climate data from Stockholm, Bromma-1977 (taken from the database of the program, is the closest one existent). The simulations with synthetic winter will be those of verifying the final model (Chapter 4.3), the rest of simulations will be done with Stockholm, Bromma-1977. The changes will be that one is artificial and the other one have real values from the climate during 1977. The synthetic is used for a simplified and with less aberration climate, good for checking the model. The Stockholm one is used in the project for a more real simulation and also because due to the high amount of operations that the program has to do in some cases is better to use a real climate chart.

3.3 The objective room

The simulation room (see Figure 24) is the room in which the simulations are based and where all the characteristics can be adapted to our simulation.

Figure 24: Test room main window with resume of the data
This room is a conference/meeting room of 32 m$^2$ with its lights (9 lamps of 35 Watts) and furniture (table, chairs, projector, whiteboard, etc...).

The distance to the ceiling has been measured, but the distance of the floor height above the ground has been put a number higher than 1 in order to consider (at effects of the program) that the room is not situated in the ground floor. So the simulations take effect with consideration of the floor as the ceiling of the floors below it.

The ventilation values are the standard for a comfortable space with a supply and return air for CAV (Constant Air Volume) counting also with the leakage calculation.

Below all this data, appear each one of the borders of the room (floor, ceiling, and the four walls). Each one of it with its correspondent data (area, azimuth, slope, U-value, thickness, layer material, etc…) in order of surfaces, but the program also gives the opportunity of modify/observe the data from the windows, openings, AHU, leaks, room units and so on, as well as images of each border with the details on it like the following figure that shows the external wall of the room.

![2D view of the disposition of the windows and radiators in the test room](image)

**Figure 25: 2D view of the disposition of the windows and radiators in the test room**

Here can observe the radiators location, with the same geometry than the original of the real room and the windows location and could modify any of its characteristics. This is for example very important in certain simulations in the case of the windows because modifying certain things like the shading, the disturbance of the sun can be mitigated.
The windows of the room (See Figure 26) has been adapted for this project, in determined simulations an external shading has been added, but when this happen it will be explained in the report.

The main part in the characteristics of the room (template) is the part called “Room units”, here the program puts the heating/cooling units, and in this case, there are the radiators, because the project is focused in its control for the desired heating of the room. Because the inexistence of data about the radiators, the power of them and the characteristics has been assumed from [14], the radiators are of 2x0.3 meters so a rough calculation for this measures are around 1000 Watts and the characteristics are:
The simulation room has no coolers because this system has been designed to work during winters (for obvious reasons) and the test of the behavior of the radiators alone was the main idea. Because this, during the peaks of the sun or months warmer than winter sometimes the temperature rises over 21º but this only means that the system can get no profit during these period.

### 3.4 Building the model in IDA

When you build the environment and room of study, the program gives the chance to create a mathematical model of it in order to modify those parts of the model which the user want to tune at its liking. The program does that and translates it to a block model in order to simplify the work with it for the user.
When the program builds the model, it builds the default one with the data introduced of the building/rooms (See Figure 28).

![Figure 28: Basic schematic of the project room](image)

At the top of the figure, there is the exhaust air and supply air of the ventilation (VAV) and at the left, marked with red circle, there is the most important thing here for the simulations, the water radiators. The radiator have an input for the signal from the controller and the sensor for the surrounding air temperature, both of them vital for this project. The rest of the model is not worthy of explain in this thesis because nothing more will be changed.
There will be a number of blocks available for the program to add to the schematic for build the desired model shown and commented in chapter 2.4. For build that block diagram, several blocks will be used. The typical add module (See Figure 29), the 1 input can be changed to -1 if necessary, and that is useful for create feedforward or feedback controllers.

![Figure 29: Schematic of the add block](image)

The product block (See Figure 30) which multiplies the two values which enters on it.

![Figure 30: Schematic of the multiplier block](image)

The constant block (See Figure 31), which serves for introduce the constant you desire as input for other blocks or elements of the schematic.

![Figure 31: Schematic of the constant block](image)

The core of the controller, the PI controller (See Figure 32) with its input measure in the left, the pic control setpoint in the top and the output in the right.

![Figure 32: Schematic of the PI block](image)

And at last, the schedule block (See Figure 33) and it is also a very important block because with it can be controlled the input signal level along with controlling its the time.

![Figure 33: Schematic of the Schedule block](image)
3.5 System identification (τ and K)

With the blocks of chapter 3.4, it is possible to calculate time constant and gain by means of a step response. For build the step response only the schedule block is needed. With it introduce a variation in the input of the radiators from one fixed value to other (∆IN) and observe in the results and graph of the simulation the ∆OUT which is the difference between the output temperature at 25% of the input and the temperature at 75% of input signal (See Figure 34).

![Diagram of the step response input](image)

**Figure 34: Diagram of the step response input**

Following these instructions and using the formulas of chapter 2.2 calculate the gain is done, but for the calculation of τ is required more specific (and accurate) data, that is provided in form of an excel sheet by the IDA. It provides (if the users requires it) an excel sheet with all the values of the temperature and the corresponding time of them.

Since τ is the value of time at which the temperature output difference is at its 63% of the total increase, is easy to calculate the difference of maximum and minimum temperature in the system throughout the simulation time and calculate at what time the system has reached that 63% point and by the way have τ. An excel sheet with the values of the energy balance can also be taken from the program and will be of use in the energy saving study of January.
4. Results

The results are based in the mean air temperature. Also, in the energy balances, the key value is the energy from heating units. In all the cases, except the base case, for reduce the interference of the sun in the measures of the expected heating time, an external shading has been added to the building. This will cause that the value can be used in rooms with no windows or with poor sun reception as well as in normal windowed rooms (the sun will produce a different but not worse heating time during certain hours of the day, but this will be taken in consideration by the compensation of the controller so no excess of energy will happen).

4.1 Base case

This case is for establish an example of how the system answer before implement the control system designed. The simulation have a default control system (See Figure 35), 2 PI blocks (one for each radiator) controlling that the temperature is between the setpoints (like ideal heater explained before).

![Schematic of the base model with 2 PI blocks](image)

Figure 35: Schematic of the base model with 2 PI blocks
The climate used for the simulation has been Stockholm, Bromma – 1977, because a synthetic winter will be more regular (which is not interesting) and to observe if there is peaks of temperature in the climate that affect the results before the simulation of the controller.

The integration time of the PI (default value is 300 sec) in this simulation and all the following simulations is of 150 seconds (2 minutes and half).

This is the normal function of the room with the default controller which controls only the temperature setpoints. The peaks are because the sun and is because the climate taken (Stockholm, Bromma-1977). Here can be viewed how the low temperature of the windows decrease the operative temperature as was commented before in the next chapter.

![Figure 36: Temperature graph of the base case (mean air temperature and operative temperature vs time in hours)](image)
This is the heat balance from the room in the default situation (base case), can be appreciable the influence of the sun during certain hours and how is the room loosing heat through the walls as well as the power used by the radiators to maintain the 21º I not more than 700 Watts in the room.

![Heat balance of the base case](image)

Figure 37: Heat balance of the base case (watts vs time in hours)

### 4.2 Step response

#### 4.2.1 Calculation of the parameters

The initial simulations were focused in simple simulations in matter of get the value of the time constant, required for the knowledge of the required preheating time of the room. This simplified simulation is based the project consider that the room is always empty (with no occupant), with the equipment turned off and no lighting during the coldest month of the year. A step response has been introduced in the schematic of the model with a “schedule” module.
The new schematic for this simulation (See Figure 38) have a schedule block and no PI controllers.

![Figure 38: Schematic of the step simulation](image)

The schedule block is connected to both of the radiator’s inputs. No feedback from the radiators (the output sensors of the radiators are open) the system takes the data from them but no control measurements are done because them in this paragraph. The schedule introduced inside the module is: the system will work at 25% during all days of the month except from 10 to 28 during which days the system will work at 75% of the total power.
The schedule for the step response described before in the system is showed in Figure 39:

![Graph and control of the schedule block](image)

**Figure 39: Graph and control of the schedule block**

This is where $\Delta in$ of the formulas come.

$$\Delta in = 0.75 - 0.25 = 0.5 \degree C$$

The sampling time will be the whole month of January from 00:00 of January 1$^{st}$ to 24:00 of January 30.

And the results of the simulation produce the following temperature graph:

![Output graph from the step response](image)

**Figure 40: Output graph from the step response (temperature vs time in hours)**
In the graph can be observed that the operative temperature are in certain points around 0.7°C less, this is because this temperature is the mean temperature of the heat emitted by the surfaces, the convection and the mean air temperature; so, since we have windows, the operative temperature always will be lower.

In this project for the calculation of the model, only the mean air temperature will be taken into consideration because is the unique value that the system can measure, the model don’t have access to any measurements of the operative temperature, only have access to the mean air temperature sensor situated in the radiators.

The simulation also gives the energy balance which is interesting to observe in order to check that everything is working correctly, that there are no leakages or excessive sun interference (See Figure 41).

![Figure 41: Heat balance of the step response (watts vs time in hours)](image-url)
The small down peaks are caused by the sun because its interference can’t be completely removed from a windowed room. The walls and the windows will suck a portion of the energy of the room because its higher temperature during certain periods of time and the normal heat transfer between rooms. With all of these, the program generates an excel file in which the values of the temperature and time during the whole month can be viewed.

With this data the calculation of Tau is as follows:

\[ \Delta out = 24.8 - 21.8 = 3^\circ C \]

This is the difference in degrees between the temperature during the time in which the system was working at 25% and the system working at 75%.

Tau (\(\tau\)) is the value at which the room reaches the 63% of the final temperature.

In this case \(\tau = 18.43\) hours.

Using the formulas of chapter 2.2, the value of the gain is:

\( h = 0.25 \) Because the 15 min of sampling time are 0.25 parts of an hour

\[ K = \frac{\Delta out}{\Delta in} = \frac{3}{0.5} = 6 \]

So, with the chapter 2.3 formulas (2-11) and (2-12), finally the system parameters “a” and “b” are:

\[ a = e^{-h/\tau} = e^{-0.25/18.43} = 0.986 \]

\[ b = K * (1 - e^{-h/\tau}) = K * (1 - a) = 0.08 \]

With these constants, now is possible to calculate the predicted room temperature and consequently the degrees the system can reduce in order to do the energy savings during the periods of no usage of the room.
4.2.2 Calculation of the model constants

With the previous calculations of $a$ and $b$ now can solve the formula (2-13) from chapter 2.3:

$$\Delta \hat{y}(t + m|t) = b \left( \frac{1 - a^m}{1 - a} \right) \Delta u(t)$$

Where:

$\Delta \hat{y}(t + m|t) =$ possible room temperature reduction

$\Delta u(t) =$ control signal

$m =$ prediction horizon

The control signal has a maximum of 100% (or 1), $\Delta u(t) = 1 - u(t)$ at time instant $t$, so it’s the difference between the actual value, $u(t)$, and the maximum, 1.

The constant value is calculated depending of $m$, the prediction horizon, which is directly related with the "desired preheating period" that will be the maximum preheating time allowed to the system for reach the desired temperature from the temperature of its "energy saving mode".

The calculation of $m$ depends of $h$ (sampling time), because for example if:

$h = 15$ min $= 0.25$ hours

And the desired preheating period is of 2 hours, the value of $m$ will be:

$$m = \frac{2}{0.25} = 8$$

Because this, $m$ will be calculated for each case in its paragraph. The point here is that the system formulas taken (from the theory) are designed the way that the system will decrease an amount of temperature equal to the temperature the system is able to raise during the desired preheating period.
4.3 Verifying final model

The measures of the following evaluations and results are based on the mean air temperature. The operative temperature is not considered as has been said in chapter 4.2.1; but there is more things that this project has taken into consideration but for reasons of time couldn’t expand or explain as much as the author would desire; for example, the energy savings. The heat balance of the simulations is usually commented along with its graphs and those without high importance have been added to the Appendix.

4.3.1 Schedule for the simulation of the final model

All the models simulated in the results with the exception of the Base case and the Step mode case are simulated with a backoff schedule which marks when and how long is the temperature saving period and when the room in usage is. The backoff schedule is the following:

![Figure 42: Backoff schedule configuration](image)

During the days from 10-28 of January (if its other period will be specified in its paragraph) the controller will receive -1 from the schedule (-100%) and it will calculate how much can decrease the temperature during that period to ensure that will be ready at the desired temperature during the days from 1 to 10 and 28 to the end of the month. This temperature decrease will be the temperature decrease that the system can do for energy savings.
From now on *backoff temperature* will be the name for the temperature that the system can decrease during the energy saving time because is able to heat up the difference to 21°C in the room during the desired preheating time.

### 4.3.2 Model with preheating time of 2 hours

First of all is to calculate the constant value which will enter in the controller as input depending of the desired preheating time.

With 2 hours of preheating time and \( h = 15 \) min of sampling time, the value of \( m \) as be seen in chapter 4.2.2: \( m = 8 \)

With this value of \( m \), the constant value for the controller is:

\[
b \ast \left[ \frac{1 - a^m}{1 - a} \right] = 0.6167
\]

Now, building now the final model seen in 2.4 with the blocks explained in 3.1.4, the schematic of IDA with the blocks will be as follows:

![Figure 43: Schematic of the final model](image-url)
In the schematic can be observed that there 2 constants, the one marked with red circle is the temperature setpoint, this temperature will be the desired temperature when the room is in use. The other constant is the previously calculated value.

The climate used in this simulation has been synthetic winter. With the control system and the values calculated, the temperature graph is:

![Temperature graph of the final model with preheating time of 2 hours](image)

*Figure 44: Temperature graph of the final model with preheating time of 2 hours*

The backoff temperature during the saving period is of: $\Delta T = 21 - 20.5 = 0.5 \, ^\circ C$, so 0.5 $^\circ C$ can be saved during the whole backoff time in the room with this m. Can also be observed that the climate simulation here is more constant unlike the base case because that synthetic climate. The difference between the operative temperature and mean air temperature is around 0.5$^\circ$C too, the reason has been said in chapter 4.2.1.

Here can be observed that the heating period is of less than 0.2 hours, this means that the model formulas taken are not working as it should, because if the formulas work fine, the heating period will be of 2 hours, because is the period specified by the numbers.
In Figure 45 can be observed that the heating period is of less than 0.2 hours, this means that the model formulas taken are not working as it should, because if the formulas work fine, the heating period will be of 2 hours, because is the period specified by the numbers.

Figure 45: Detailed temperature graph of the preheating period (2 hours)
4.3.3 Model with preheating time of 12 hours

To calculate the constant, with 12 hours of preheating time and \( h = 15 \) min of sampling time, the value of \( m \) is: \( m = 48 \)

With this value of \( m \), the constant value for the controller is:

\[
 b \cdot \left( \frac{1 - a^m}{1 - a} \right) = 2.87
\]

In this simulation, the constant entering the multiplier has changed to the calculated value. This simulation is with synthetic winter.

![Temperature graph for a preheating time of 12 hours](image)

**Figure 46: Temperature graph for a preheating time of 12 hours**

Here can be observed that the backoff temperature is much lower than before and that is obvious because with a higher preheating period the temperature can decrease more because have more time to raise up to the desired temperature.

The temperature decrease is of \( \Delta T = 21 - 18.4 = 2.6 \degree C \)
In the focused graph (See Figure 47) can be observed that the heating time is now of around 1 hour, this plus the error observed in the previous case (with 2 hours of preheating time) means with no doubt that the model is not working as desired. A handmade solution for this will be made in the next chapter (4.4).

Figure 47: Focused temperature graph of the preheating time period (12 hours); temperature vs time (hours)
4.4 Correction of the model

Because the detected errors in the model, there is a correction that can be made and its to
tune the \( b \) constant to a value that modify the results to those more close to the expected. Is
handmade correction and in further projects would be interesting to investigate in the model
equations necessary for reach this values.

For this correction is necessary to select a desired preheating time; this time will be 2 hours
\( (m=8) \). The backoff schedule will be the same as before.

Due to the high influence of the sun in the simulations external shading has been added to
the windows (like in the step 3.2.4) for all the simulations made with this corrected model.

After several simulations, the closest one to the reality is 3.3.

A value of 3.3 in the constant requires a value of \( b \) of:

\[
b \cdot \left[ \frac{1 - a^m}{1 - a} \right] = 3.3
\]

\[
b = \frac{3.3}{\frac{1 - a^m}{1 - a}} = \frac{3.3}{\frac{1 - 0.986^8}{1 - 0.986}} = 0.433
\]

Is a value far away from the \( b \) calculated in the model (0.0808) and gives an estimate of
how wrong was the model.

With this constant value, the simulation has been done and this simulation and the further
ones will be done (as previously said) with the climate of Stockholm, Bromma-1977. The
only relevant graph in this part is the focused temperature graph which shows the validity
of the newt model values.
In Figure 48 can be observed the different climate simulation and also a higher backoff temperature difference, now the backoff temperature is $\Delta T = 21 - 17.7 = 3.3 \, ^\circ C$ this is $2.8 \, ^\circ C$ more than the previous calculated backoff temperature (for 2 hours of preheating time) with the model equations value (0.5 $^\circ C$).

Figure 48: Focused temperature graph 2 hours of real preheating time in the corrected model; temperature vs time (hours)

The focused graph shows how with 3.3 the heating time is around 2 hours for January (1 hour and 45 min), which satisfies the desired preheating time. So the system is able to heat that 3.3 $^\circ C$ in 2 hours.
The energy balance has a higher backoff temperature difference and it is reflected in the orange color, also can be observed the high peak during the preheating time because the needing of increase of power during this period in order to heat up all the temperature difference to the desired room temperature. Also can be observed how when the system enters into the backoff schedule, some of the heat is taken from the walls and floors from the surrounding rooms/areas.
4.5 Evaluation

4.5.1 Simulations during different time of the year

Noting that now the controller works as desired, several new simulations has been made with different months of the year with the previous calculated value of the constant of the controller: \( b \times \left[ \frac{1-a^m}{1-a} \right] = 3.3 \)

The climate is Stockholm-Bromma-1977 with external shading in the windows. The energy balance of the different months can be found in the Appendix A (A.1).

4.5.1.1 Simulations of the months

February

The graph for February is pretty similar to January, but the difference is on the focused graph in the heating slope around the hour 1350 (on day 25 of February).

![Focused temperature graph in the preheating time (2 hours)](image)

Here, the graph shows how the heating time is exactly 2 hours, needs a bit more time to heat up the 3.3 °C difference than in January (that needed 1 h and 45 min).
March

Here can be viewed that the backoff temperature is more or less the same than in January (3.3 °C) with certain peaks because the sun.

![Temperature graph March](image)

**Figure 51: Temperature graph march**

During March, the preheating time needed for reach the desired temperature is similar to January (and consequently lesser than February).

![Focused temperature graph March](image)

**Figure 52: Focused temperature graph march**
May

This month have a wide variety of backoff temperatures because the difference of temperature and sun. This month shows how is the climate changing because the end of the winter and the beginning of the spring.

![Temperature Graph May](image)

**Figure 53: Temperature graph may**

July

Even during the summer months from 1 to 2 degrees can be saved. Is interesting to observe how slow decrease the temperature from 21 degrees from the day 10, last at least 3-4 days for reach the optimal backoff temperature of this month (See Figure 54). This low temperature in the room compared to the temperature outdoor is probably because during the nights the temperature goes down around 19º and the system never heats up during the day. This can be observed in the heat balance of the appendix.
September

During this month the temperature is around 18 degrees which shows that the outdoor temperature (lesser than the summer period) is cooling more the room and faster, so the backoff temperature increases to around 2.5°C during certain days of the month.
November

The month of November enters again in a temperature behavior similar to January and February, this month is the last month of autumn and the winter will begin which have pretty low temperatures and consequently the highest backoff temperature possible.

![Focused temperature graph November](image)

**Figure 56: Focused temperature graph November**

The focused graph of November shows that during this month the backoff temperature calculated by the controller is not right, because the time needed for reach the 21°C mark is much higher than 2 hours.
December

December is the month more similar to January (our main simulation month) because it’s the beginning of the winter and the temperatures are quite close, but for evaluate this is better to go to the focused graph.

Figure 57: Focused temperature graph for December

This graph shows how this month have also bad calculated the backoff temperature from the controller, because the required preheating time is more than 2 hours (much less than November but still higher than 2 hours mark).
4.5.1.2 Evaluation of the month data

The values of the backoff temperature is more or less the same during the most cold months, and even in summer there is energy that can be saved but this has to be tested in real rooms during these months to check if there is true that with the value of the sun (that here has been highly reduced with the external shading because its high impact).

The following comparison (See Table 1) is a comparative between the evaluated months and the values obtained from its backoff temperature and mean power saving with the control strategy (with an approximation of the power in watt saved).

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean temperature before preheating (°C)</th>
<th>Backoff temperature (°C)</th>
<th>Mean power saving (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>17,9</td>
<td>3,1</td>
<td>600</td>
</tr>
<tr>
<td>February</td>
<td>17,9</td>
<td>3,1</td>
<td>500</td>
</tr>
<tr>
<td>March</td>
<td>17,7</td>
<td>3,3</td>
<td>350</td>
</tr>
<tr>
<td>May</td>
<td>19,5</td>
<td>1,5</td>
<td>450</td>
</tr>
<tr>
<td>July</td>
<td>19,25</td>
<td>1,75</td>
<td>400</td>
</tr>
<tr>
<td>September</td>
<td>18,5</td>
<td>2,5</td>
<td>400</td>
</tr>
<tr>
<td>November</td>
<td>17,8</td>
<td>3,2</td>
<td>300</td>
</tr>
<tr>
<td>December</td>
<td>17,9</td>
<td>3,1</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 1: Comparison of the measures between different months for the corrected model

The mean temperature before the preheating is around 18° during the winter and autumn months. In summer the backoff minimum temperature increases but there is still possible to save energy during this month’s according to the simulations.

The most important thing of this simulations is that the model correction has proven not valid for all the months and this is why is needed a new revised mathematical model for this application. During months like November the 2 hours of preheating was not enough and during December, January and February was more than enough, so, the system should always reduce during these months more the temperature because its possible to raise it during that 2 hours of preheating time, but instead of it, maintained a more or less constant backoff temperature.

The heat energy saved is a rounding mean value. The value in Watts is a value about the radiators, and how much they can reduce their output power from their normal function.
(maintaining the desired room temperature) of around 700 W. Decreasing from maybe 700 to 250 W the power used during the backoff schedule. This is the mean energy saving measured and is the value that appears in the Table 1. The most cold months, usually might be thought that could have more heat energy saved from the radiators, but during the spring months or summer months, the radiators shut off completely (they don’t provide any power as can be seen in the heat balances of the Appendix A), so, almost all the energy from them can be saved. This, of course, is no considering the leakages though walls from other rooms to the project room, but this is something that is not object of study in this project but could be interesting to study it in further projects.

4.5.2 Simulations varying the flow of the Kv valve

The real differences from increasing the flow by modifying the Kv valve are shown in a focused graph during the preheating period; a graph of the whole period will show nothing interesting.

When the “normal case” is mentioned, is referent to the case with the normal flow through the radiators (no increase made) that corresponds to chapter 4.4. The heat balance of these simulations can be found in the Appendix A (A.2).

Increasing the flow by 25%

This increase is made modifying the flow that enter in both of the radiators, increasing it a 25% from 0.02388 to 0.02985 Kg/s.

In this focused graph (See Figure 58) of the preheating time can be observed that the required time for the preheating is lesser than with the normal flow through the radiators by around 15 minutes. Now the preheating requires 1 hour and a half to the system instead of the 1 hour and 45 minutes that were required in the normal flow case.
Increasing the flow by 50%

Now the flow is 0.03582 Kg/s.

The graph shows (See Figure 59) this time that the increase of 50% the flow through the Kv valve makes the system heats up faster. So consequently the preheating time required is lower than any other case studied for January. It requires a preheating time of 1 hour and 15 minutes to heat up all the backoff temperature; this means around half an hour less than the normal case.

Figure 58: Focused temperature graph for a flow increase of 25% through Kv valve (temperature vs time in hours)
4.5.3 Different measures

Energy savings estimation for the corrected model

Taking into consideration what said in 4.5.3, the energy saving calculation has been made only for the case of the corrected model (chapter 4.4) compared to the base case (chapter 4.1). The all the energy usage studied here from heating takes into consideration only the days from 10 to 28 of January which are the days that will be different from one case to another. For all of this, new heat balance (See Figure 60) from the base case is taken in order to use the same external shading that the corrected model has (Figure 49).
The heat balance of the corrected model is the same that is in chapter 4.4 and there is no need to put it again. With the excel sheet from their heat balances, the energy required for maintain the 21°C in the room during the month from day 10 to 28 in the base case is of 325 kWh. Considering that the building will have at least one energy saving strategies because typically much of the buildings nowadays have a nighttime strategies controller, this can save around 5% of the heat energy [1] so then, applying it to this, the final energy required would be around 309 kWh.

The same calculation in the corrected model yields a value of 97.5 kWh, but this is the energy provided only by the radiators during this time, also have to consider the heat leaked from the nearer rooms because the lowest temperature of the objective room, this heat transferred sum a total of 49.4 kWh, the total heat energy from both is 147 kWh (There is no other sources of heat transfer in this case), this means that the heat energy needs has been reduced around a 52% (Note: this is related to the backoff time, not the whole month).

This is of course a slanted value because is under the project conditions and during a very long period (18 days of heat savings) and further test for each specific application should be done because in rooms with more usage the savings would be lesser. Here this project is
considering only one use of the room in the month (not rare for this kind of rooms on the other hand), although during a long period (13 days from 1 to 10 and from 28 to 31).

Also, is important not lose of sight the peak power needed for heat up the room during the preheating time. The normal values of the system during the normal function is that the radiators of the room requires around 700 Watts along the month to maintain the temperature constant at 21º during the day and night. This peak of power put the power needs around 1700 W, but is also true that this peak last only 2 hours and decreases rapidly again during the following 6 hours until return to normalized values (all the peak means 76.2 kWh in terms of heat energy in the balance, so, is not an easy thing to obviate).
Considering the energy needed during the peak, the heat energy needs has been reduced to a 27% instead of 52%.

In terms of total amount of heat energy used during the whole month (the most clarifying value of all), the total energy required during the base case has been 554 kWh versus 371 kWh of the corrected model. So the final heat energy saves from all the month is of 183 kWh, a 33% of the total, and this is the value that this project will consider.

Besides, these are calculations only for the coldest month (supposedly) of the year, so, its important to study its viability along the year and not only during one month.
5. Discussion

The results given by the simulations show that the model presented in chapter 2.1 is not valid for this application at its current state with scalar values. The test made in chapter 4.3 displays that the model is not working as it should, so is failing in its mission. The model is still valid for this matter but using matrix values \((A, B_1, B_2)\) instead the scalar ones that probed to be not correct. This affects the control strategy, and seems that it should be changed in order to adapt to the new model. The evaluation for different months of the year, with same schedule, shown that the model is also not valid. The model doesn’t adapt correctly to the variations of each month and for example in certain months the preheating time is a bit higher than January and in other months are a bit lower.

The manual tuning of the constant values of chapter 4.4 proven that the idea has an interesting potential and the heat balance of chapter 4.5.3 also test that is supposedly efficient, but needs a good model behind it for squeeze all its potential.

This project could’ve delved more into some of the studied things, but, because time constrain, has been not possible. For example, deepening in the Kv valve study and how this flow increase affects the rest of the water radiant system and the load of it checking that the other rooms don’t lose heat because this and that the system can endure the peak of demand during the short amount of time.

Also could’ve been interesting to do a heat energy balance through the year and not only in January to check the global effect of the model and the year’s savings as well as the peaks of power needed for the preheating time and its economic viability.

Field test couldn’t be made because at the starting time of this project the spring season was advanced and the temperature rising more than desirable for the real measures of the impact in the room, but these tests could be good idea to be done in order to check all this results.

Overall, the thesis cast out a good idea of how the system will respond and with its 3.3°C of backoff temperature and around 33% of heat energy savings give a good amount of expectation for further projects in this field.
6. Conclusion

The study of the project has been an interesting and motivating work, the lack of time to further extend some results or dates for the project may not have been the best, but the results have been promising and encourage the future research on this.

The idea of the project has been proven valid (no its model) and the results of a temperature saving of 3.3°C and 33% of heat energy savings during January are pretty interesting. But in future projects could be interesting to investigate the effect of this temperature reduction in the heat loss of the surrounding areas through the walls and maybe study the viability of a better insulation of the internal walls for this kind of rooms in future buildings or adaptations in the existing ones.

For further projects, the main idea should be to found the right mathematical model for reach the desired values of the system constants and, if possible, change these constants for variables, because the test of chapter 4.5.1 shown that a constant value is not valid for all the months of the year, it should change in order to adapt to the requirements of time and temperature. These variables and math could be taken from the valid part of the space state model with matrix values like the equation (2-1).

Also, the tests with the flow of the Kv valves, demonstrate that for each increase of 25% of flow, the system saves around 15 minutes of preheating time. So, for further projects, would be interesting to study the way to implement flow variation in the model formulas and how it affects the rest of the system.

But last but not the least, in further projects should be studied the peak of power required for the preheating time and the ways to reduce it if necessary, maybe, as an idea, with a low power fan system integrated in the water radiators, that empowers the convection heat transfer and reduces the required power needed to heat up. [¡Error! No se encuentra el rigen de la referencia.]
7. References


5. Targo Kalamees. IDA ICE: the simulation tool for making the whole building energy and HAM analysis. Tallin Technical University.


13. IDA ICE 4.0, IDA Indoor Climate and Energy, Equa Simulation AB, Solna, Sweden.
APPENDIX A

A.1 Heat balances of the month simulations

A.1.1 February

A.1.2 March
A.1.3 May

A.1.4 July
A.1.7 December
A.2 Heat balance for the variations in the Kv valve.
A.2.1 Valve flow 25% increase

A.2.2 Valve flow 50% increase