MASTER

Model-based design of an intelligent thermostat

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Model-based design of an Intelligent Thermostat

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This thesis is based on work performed at Applied Micro Electronics AME B.V., The Netherlands. The main technical contributions have been made in the context of a product. All references to this product, including the product perspectives of the outcomes of the work have been removed from the public version of this thesis.

The complete version of this thesis is confidential. When access to this full version is required for (academic) audit purposes, please contact the supervisor of the thesis work.
ABSTRACT

The thermostat is a product used in almost every household. However the development regarding this product has been standing still the last years. The evolvement in connectivity between the different devices used in a household makes it possible to extend such a device in order to increase its performance. Extra information can be gathered from the internet in order to decrease energy use or improve control of the room temperature while smartphones and tablets can be used to increase the user’s interaction comfort.

One of the difficult tasks in the development of such a thermostat is the method of validation. Several scenarios, including different type of houses, climate conditions and central heating systems need to be considered in order to determine the performance under different circumstances. Simulation of the scenarios is desired since it is impossible to test all scenarios in practice.

In this thesis a model-based design trajectory for a thermostat was created and applied onto a self-learning thermostat model. Multiple components were developed in order to validate the thermostat on each layer in the design trajectory. This includes development of a simulation environment, validation framework and an embedded framework. The validation framework includes several scenarios and performance aspects used to judge the thermostats quality.

The conducted case study showed the thermostat was able to satisfy the constraints in this thesis in both simulations as in practice. The use of a proposed function for one of the learn parameters showed to satisfy one of the constraints in only a short period of time. However further tuning of other parameters showed only minor differences in the different other performance aspects of the used thermostat. The latter was related to the constraints being rather severe. The embedded implementation showed the thermostat was able to satisfy the constraints set by AME in practice. The same results were used to show that the approximation of the simulation model is accurate enough to use as indication if the thermostat would satisfy the constraints used in this thesis in practice.
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1. INTRODUCTION

Consumer electronics play a large role in today’s modern society. Using terms like ‘smart’ or ‘intelligent’ existing consumer electronics are being reinvented with the intention to increase the users comfort using new technologies. Most of these applications try to use the evolvement in connectivity between different devices to extend the application with extra information to increase the performance of the device.

The same phenomenon is starting to rise for the thermostat in which already the first products start to show up which for example try to improve the user’s comfort in the scheduling of such a thermostat. This includes trying to identify patterns in the user’s behaviour concerning the temperature setting and providing an easy way to set up the desired schedule, for example using the internet. Almost each household uses a thermostat to regulate its central heating system and other improvements concerning the users comfort with new technologies can still be made, this includes energy use or improved control of the temperature.

The main problem in the development of such a thermostat is the method of validation. The performance of the thermostat needs to be considered in different scenarios to make sure the desired performance constraints are always satisfied. Different type of houses, climate conditions and central heating systems are all examples of aspects which can influence the performance of the thermostat. Since covering all these scenarios by deployment of the thermostat in practice is not a realistic solution, a simulation environment has to be used.

In this project a model-based design trajectory will be created which incorporates the problem stated above. With the use of model-based design fast iterations are possible, one of the requirements made by AME for this project. Different versions of a thermostat should be able to use the same trajectory for quick deployment onto an embedded system.

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The model concerns an On/Off thermostat, meaning it has no influence on the boiler set point temperature. However the trajectory will be designed to support this feature to provide future development of such a thermostat possible. The thermostat is self-learning and will try to derive the building’s characteristics in order to satisfy a number of constraints set by AME.

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The first step will be to create or/and find simulation models which combined provide the possibility to accurately simulate the environment in which the thermostat resides. Figure 1 shows a simplistic overview of such a model. The model can be divided into three subsystems, the building and climate model, the central heating system and the thermostat
itself. As can be seen the thermostat has the support for changing the setpoint temperature of the boiler. In the second layer the simulation model of the thermostat is replaced by a block which represents the PIL implementation. The other two models, simulating the environment, will be able to communicate with the PIL to support PIL simulation.

The second step incorporates the development of a validation framework that can be used across all the layers of the design trajectory, as seen in Figure 1. This includes the analysis of the difference performance aspects on which the performance of the thermostat model can be validated as well as a derivation of the used test scenarios.

The third and final step will consist of the validation of the existing thermostat on all layers including possible tuning and further improvement of the model. Furthermore a comparison will be made between the response of a building in practice and the response of the same building in the used simulation model. This is done to validate the accuracy of the used simulation model in the design trajectory. This step includes the generation of the PIL version of the thermostat as well as an embedded framework used to generate the embedded implementation of the thermostat. CONFIDENTIAL PARAGRAPH

Summarizing the steps the following aims can be set for this Master project:

- Create a model-based design trajectory for the a thermostat
- Create a validation framework that can be used across all layers of the design trajectory
- Validate the thermostat by AME on all layers in the design trajectory using the validation framework and possibly improve the thermostat.
- Validate the design trajectory with realistic case study including actual deployment

When addressing the aims presented in the previous section, the following contributions have been achieved in this Master project:

- Development of a simulation model which can be used on an arbitrary thermostat model under the condition that certain basic information is available. The model makes use of an existing building and climate model and a new developed model for the central heating system.
• A framework for an embedded system, with support for changing the boiler setpoint temperature, which makes it possible to easily deploy any thermostat model under the condition that certain basic inputs and outputs are used.
• Development of a validation model which can be used in combination with the simulation model to derive the several performance aspects of a thermostat. The same validation model can be used for derivation of the performance aspects of the embedded implementation using logging data.
• Validation and tuning of the existing On/Off model by AME including a larger modification to the model to satisfy the constraints set by AME.
• Validation using the embedded framework was done of both the performance of the thermostat model in practice as the accuracy of the used simulation model using logging data. The results showed the thermostat was to be able to satisfy the different constraints in practice. Furthermore, the simulation model proved to be accurate enough to derive an indication of the performance of the thermostat in practice.
1.1. OUTLINE OF THE THESIS
The thesis will be organized as follows:

Chapter 2 describes the used models to simulate the environment of the thermostat. The chapter describes both existing as well as solutions developed during this project. Chapter 3 describes the thermostat model developed by AME including the proposed modifications made to the model. Furthermore a look is taken at any related work concerning the same subject. In chapter 4 the validation approach used to determine the performance of the thermostat is discussed. This includes the used test scenarios for the simulations as well as the definitions of the performance aspects. Chapter 5 describes the implementation of the thermostat on the embedded system using the developed framework. In chapter 6 the results of the validation of the thermostat on the different layers in the design trajectory are discussed. This includes a validation of the accuracy of the used simulation model. The last chapter, chapter 7, concludes the thesis with a summary of the presented work and a discussion on the gained results. Furthermore suggestions are given for any future work.
2. Modelling the Environment

This chapter will discuss the available models to simulate the environment of the thermostat. CONFIDENTIAL PARAGRAPH

The first section will discuss the available and used building and climate model after which the second section concerns the central heating system.

2.1. Building and Climate Model

This section describes the available models which simulate the building and climate of the environment.

2.1.1. AME Building Model

A simple building model was developed by AME which was the basic starting point to test the first few iterations of the thermostat model. The model is based on Equation 1, Equation 2, Equation 3 and Equation 4. The same equations play a large role, as will be shown later in the next chapter, in the self-learning method of the thermostat.

In these equations $T_{Subsystem}$ is the subsystem's temperature in K, $C_{Subsystem}$ is the subsystem's thermal capacity in J/K, $R_{Subsystem1,Subsystem2}$ is the thermal resistance between subsystem1 and subsystem2 in K/W and $P_{Subsystem,in}$ and $P_{Subsystem,out}$ are the amount of energy flowing respectively into and out of the subsystem per second in W. $P_{Subsystem1,Subsystem2}$ indicates the amount of energy flowing from subsystem1 to subsystem2 per second in W. The used subscripts 'Rad', 'Room', 'Env' respectively correspond to the radiator subsystem, the room subsystem and the environment subsystem.

$$\frac{dT_{Room_i}}{dt} = \frac{P_{Room_i,in} - P_{Room_i,out}}{C_{Room_i}}$$

Equation 1

Equation 1 shows the rate of change in room temperature based on the difference between the energy going in and out of the room. The later value is divided by the total capacity of the room to get the increase or decrease in temperature per second when this amount of energy is available in the room. The amount of energy flowing into the room, $P_{Room,in}$, comes from the central heating system and is further derived in the next section.

$$P_{Room_i,Room_j} = \frac{T_{Room_i} - T_{Room_j}}{R_{Room_i,Room_j}}$$
Equation 2

Equation 2 indicates the amount of energy flowing between two rooms. This is calculated by taking the temperature difference between the rooms divided by the thermal resistance of the walls between the rooms.

$$P_{\text{Room}_i, \text{Env}} = \frac{T_{\text{Room}_i} - T_{\text{Env}}}{R_{\text{Env,Room}_i}}$$

Equation 3

The above Equation 3 denotes the amount of energy flowing out of the room into the environment. This equation is largely the same as Equation 2 however this time the difference between the room and the outside temperature is divided by the thermal resistance of the outside walls among the corresponding room.

$$P_{\text{Room}_i, \text{out}} = P_{\text{Room}_i, \text{Env}} + \sum_{j \in \text{adj}(i)} P_{\text{Room}_i, \text{Room}_j}$$

Equation 4

The last equation, Equation 4, gives the total amount of energy going out of a certain room. This consists of the amount of energy exchanged from the room to the environment and the amount of energy flowing between the adjacent rooms. The function \(\text{adj}(x)\) returns all indices of adjacent rooms for the room with index \(x\).

The first iterations of the model were mainly tested on a building with one room, since the building model was not yet extended for multiple rooms. This showed to be a good initial approximation of the functionality of the thermostat. Although a house with one room is not that realistic, the basic correctness of some of the functionality of the thermostat could be tested. With a number of modifications the model was able to simulate multiple rooms, but this also means more variables which need to be filled in. This in combination with the central heating system, described in the next section, a lot of variables need to be calibrated, which is a difficult and time consuming task. Especially when one wants to simulate multiple buildings, since for each building these variables are different. This, with a number of other reasons as will be discussed later on, is why this model of a building was not used further along this project in the developed simulation model.

2.1.2. REMOVED SECTION
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2.1.3. CONCLUSION
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2.2. CENTRAL HEATING SYSTEM

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Since only a number of simple user made central heating systems were found, often systems in which hot air is used to heat up the room instead of a boiler and radiator system, a central heating system developed by AME will be used. In this section two central heating system are discussed, one including only the simulation of a radiator and an extended version which simulates both the response of the radiator and the boiler. The latter was mainly developed to provide the capability of changing the boiler setpoint during running time.

2.2.1. AME RADIATOR MODEL

The described basic building model developed by AME included a simple central heating system. In this system the heating source is seen as one large radiator which divides its energy along the several rooms. The system is based on Equation 5, Equation 6, Equation 7 and Equation 8.

\[
\frac{dT_{\text{Rad}}}{dt} = \frac{P_{\text{Rad,in}} - P_{\text{Rad,out}}}{C_{\text{Rad}}}
\]

Equation 5

Equation 5 denotes the rate of change of the radiator temperature in seconds and depends on the amount on energy flowing into and out of the radiator along with the capacity of the radiator. The amount of energy going into the radiator is either 0 when the heating is turned off or equal to a pre-defined constant when the heating is turned on.

\[
P_{\text{Rad,Room}_i} = \frac{T_{\text{Rad}} - T_{\text{Room}_i}}{R_{\text{Rad,Room}_i}}
\]

Equation 6

\[
P_{\text{Room}_i,in} = P_{\text{Rad,Room}_i}
\]

Equation 7

Equation 6 and Equation 7 show the amount of energy flowing out of the radiator and into a certain room. The latter depends on the difference in temperature between the room and the radiator and the thermal resistance between the two.

\[
P_{\text{Rad,out}} = \sum_{i \in \text{rooms}} P_{\text{Rad,Room}_i}
\]

Equation 8

The total amount of energy going out of the radiator is equal to the sum of all rooms, as stated by Equation 8.
2.2.2. **AME Boiler and Radiator Model**

The original central heating system developed by AME did not suffice for accurate simulations. It lacked the ability to provide a boiler temperature from which the model automatically derives the correct temperature and response for the radiators. With the previous model the correct behaviour could be approximated for a certain boiler temperature by choosing the right radiator set point and capacity with a number of simulations. However when a thermostat wants to emulate the effect of a lower boiler temperature the simple choice of choosing a lower radiator temperature during running time is not enough. Since often changes to the capacity of the large radiator in the model are needed to make the simulation sufficiently accurate.

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3. **Thermostat Model**

This chapter will give a description of the thermostat model made by AME as well as a discussion of any the related work concerning an intelligent thermostat.

3.1. **Existing On/Off Thermostat Model**

A model which includes an algorithm concerning an On/Off boiler was provided by AME. The algorithm in this model makes use of two main learning parameters a thermal time constant, in short TTC, and a delay parameter for the central heating, called Delay_Off. These parameters are used to derive the characteristics of the building in order to satisfy the constraints set by AME.

Both learning parameters are briefly discussed in the following subsections since they play a large role in the performance of the algorithm and thus also in this project. The model further uses a number of other parameters which for example determines the magnitude of the adjustments when the TTC value is not correct. A determination of the best values for these parameters is performed during the validation.

3.1.1. **TTC**

The thermostat makes use of a user-defined schedule and tries to reach the desired target temperature at the scheduled transition. In order to do this the thermostat needs to learn at which time the heating should be turned on.

The TTC is seen as the single characteristic parameter to determine the start time to reach the target temperature at the scheduled time. In reality the system is much more complex and the equivalent TTC parameter used by the thermostat is no longer a constant, but varies with the outside temperature.

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3.1.2. **Delay_Off**

The Delay_Off parameter relates to the overshoot in temperature when the heating has been turned off but the radiators are still heating the room. Using this parameter the model determines at which time the boiler should be turned off while still reaching the desired target temperature in order to prevent an overshoot higher than the constraint set by AME. The room will be further heated up to the desired temperature because of the delay between the boiler being turned off and the radiator to stop heating the room.

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3.2. ** Proposed On/Off Thermostat Model**
This section will discuss the larger changes made to the existing On/Off model by AME to improve the performance.

3.2.1. REMOVED SECTION
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3.2.2. ADDED FEATURES
The model was also extended with some extra features to satisfy a number of requirements set up by AME regarding the functionality of the model. These extensions are discussed in the following subsections.

3.2.2.1. SCHEDULE
The thermostat uses a pre-defined schedule to determine the next target temperature. This schedule was originally a hardcoded pulse generator for testing purposes. The pulse generator simply switched between a low (night) and a high (day) temperature for a certain period of the day. The specification stated that the user can enter a weekly schedule consisting of a maximum of 10 schedule transitions a day with a resolution of 15 minutes. To satisfy this requirement an input was added to the thermostat which accepts a matrix with a fixed size of 2 by 70, consisting of the temperature and time of 7 days times 10 transitions. For each scheduled transition the temperature in degrees Celsius and the start time in minutes are noted. In the model the pulse generator was then replaced with a new block which has the schedule and desired time as an input and the corresponding setpoint for the specified time as an output.

3.2.2.2. MANUAL TEMPERATURE SETTING
Initially the model developed by AME did not support a manual temperature override and only followed the predefined schedule. A manual temperature setting is used when the user wants to manually override the temperature in the pre-defined schedule. The thermostat should then discard the current target temperature and takes the user set manual temperature as its current target. This feature is implemented by an override of the current schedule when the manual temperature is non-zero. The manual temperature together with a scheduled time equal to the current time is given to the thermostat as possible next target. The thermostat will always accept this as its new target since no other target will be available with an earlier scheduled transition time. When the manual temperature is restored back to zero the model switches back to the use of the schedule.

3.3. RELATED WORK / FUTURE WORK
So far only the On/Off by AME is discussed, this section looks at related work in the area of more advanced thermostats. There are several research papers which use different approaches to either optimize the accuracy, minimize the energy usage or both of a thermostat. However most of these papers do not explicitly mention results. This is why
only a few statements are made in the discussions of these algorithms regarding their performance. The same holds for the used models for the environment, house and central heating, which are often only partially discussed.

The first paper [1] gives an overview of the different approaches available to control an indoor building environment and states that they can be divided into three categories, namely:

- Conventional methods consisting of:
  - Classical control – which uses dead zones for energy conservation however overshoots were not accounted for
  - Optimal, predictive and adaptive control – includes PID and fuzzy logic controllers
- Computational intelligence – makes use of evolutionary algorithms, solutions from the upcoming papers concerning the use of genetic algorithms belong to this category
- Agent-based intelligent control systems – divides the system in a number of controllers that solve sub-problems, a so called multi-controller system.

Paper [2] and [3] belong to the first category and both make use of a combination of a fuzzy and PID control to regulate a central heating system. The first paper [2] tries to analyse the advantages and disadvantages of both controlling strategies. The results show that it is better to use fuzzy logic for the heating up and a PID controller for regulation when the desired temperature was reached. This is related to the fact that PID controller suffers from large overshoots after a transition to a high temperature while fuzzy logic controllers suffer from a steady-state error. The paper uses a simple model to show that the algorithm has a small overshoot and an accurate steady-state, although no exact numbers were mentioned.

In the second paper, [3], of the first category fuzzy control rules are used for the self-tuning of the PID controller parameters. The paper derives a mathematical model for a large heating system connected to a network with a lot of users in a residential area. The paper uses this to test the algorithm. Results show that the fuzzy PID controller is preferred when the characteristics of the heating system change over time. Since the used model for the heating system is based on a different setting, namely a heating system for multiple houses, no further use of this model is applicable in this project.

Papers [4] [5] and [6] belong to the second category, concerning computational intelligence, and make use of genetic algorithms to optimize PID or fuzzy logic controllers. In paper [4] a genetic algorithm is used to tune a fuzzy logic controller used for the control of HVAC (heating, ventilation and air conditioning) systems. In addition to other related problems the paper notes that it has two specific restrictions which make it more complex, namely:
Evaluation is based on multiple objectives (energy usage, occupant thermal comfort etc.) which make the search complex due to the fact that a trade-off has to be obtained among the different criteria.

The accuracy of the controller depends on simulations which usually take a long time, causing the run time of the algorithm to be extremely long.

The fitness function in the genetic algorithm, together with a provided trustworthy set of weights for the multiple objectives, is used to address the first restriction. For the second restriction a number of approaches which increase the convergence speed of the genetic algorithm are used. The paper concludes with a number of experiments done using two real test sites. These results show that the proposed solution performs much better than a standard On-Off controller and shows the improvements concerning the objectives that need to be taken into consideration.

The second paper [5] of the second category uses a genetic algorithm to tune the parameters of a PID controller in HVAC systems. The solutions used in this paper concern two parameters, the proportional gain and the integral gain. The overshoot, settling time and mean squared error were taken into account in the fitness function. The settling time denotes the time needed before the temperature is kept in between a certain range from the desired setpoint temperature. The results of the paper, computed using a simulation program called HVACSIM+, were an overshoot of 0.381°C with 14,5s settling time, using the genetic algorithm approach. The use of the Ziegler-Nichols method, which is a classical method for tuning PID parameters, showed an overshoot of 0.992°C and settling time of 358,0s. In other words the increase in performance using this method is rather large when compared to a classical method.

Paper [6], which is the final paper of the computational intelligence category, uses a combination of a genetic algorithm together with a fuzzy logic controller. The genetic algorithm tries to find the optimal values for the PMV (a measure for the indoor thermal comfort, further discussed in the next chapter), CO2 and illuminance levels while minimizing the energy usage with this fitness function. These values are used to adjust the membership functions of the labels used in the fuzzy logic controller. This controller is used to maintain the indoor comfort. The difference of this paper with other papers is that the system gives the users the possibility to give their own requirements using a smartcard system and uses a slightly different method for optimizing the fuzzy logic controller. The genetic algorithm uses the (new) user’s smartcard data to generate optimal values for the fuzzy logic controller. The paper gives a test using a real building, which shows that the decrease in energy usage is rather high, while still providing the users comfort requirements. However the tests ran in this paper use a long learning period and an amount of initial data must be available.

Paper [7] concerns the third category and makes use of the multi-controller strategy to decompose the temperature control in a set of independent controllers, each solving a sub-
problem. A supervisor controller decides which of the independent controllers is allowed to be active. The thermostat in this paper consists of the following individual controllers:

- Set point generator – this supplies the new temperature according to the user-defined schedule at a self-learned time period before the new room temperature needs to be achieved.
- Bang-bang up and bang-bang down – these will respectively want to be active when the current set point is largely negative or largely positive in relation to the current room temperature
- On/off – this one wants to be active when the current temperature is only a small factor above the set point
- Modulating – want to be active when the current temperature is only a small factor below the set point

Furthermore neural networks are used to adapt the parameters of the controllers using past performance. The advantage of this approach is that the problem can easily be divided into sub problems and solved separately. The paper shows results using a test in a real house which only indicates the correct behaviour of the algorithm, in other words, showing the right controller being active at each sub-problem, but no further performance analysis is done.
4. **VALIDATION APPROACH**

This chapter will describe the validation approach for the different versions of the thermostat model. Where a different versions could mean simply a different set of parameters or certain modifications to the model. The validation method takes both the On/Off version as a version which supports a change in boiler temperature into consideration. Furthermore the several performance aspects of the model as well as the test scenarios are described. The scenarios include the used type of house, schedule and climate data. The last section regards the used simulation model for validation.

4.1. **PERFORMANCE ASPECTS**

4.1.1. **OVERVIEW**

ISO 7730 [10] is an international standard for the ergonomics of the thermal environment. In the standard a number of statements are made about thermal comfort as well as a calculation of an index on a 7-point thermal sensation scale called PMV, predicted mean vote.

The predicted mean vote uses a number of parameters including the metabolic rate, type of clothing, air velocity, temperature and humidity. But since most of this information is not available and the influence of only the air temperature cannot easily be derived PMV will not be used in this project.

In the standard a global statement regarding thermal comfort which is related to the project is made:

- A peak-to-peak variation of less than 1K while maintaining the set point temperature will have no influence on the comfort. Higher peak variations can decrease comfort.

The constraint set by AME regarding the average control accuracy, given in section 4.1.3, satisfies this condition. The thermostat should be able to maintain a setpoint having no influence on the comfort of the user if it satisfies the requirements by AME.

4.1.2. **DEFINITIONS**

Before the performance aspects are defined a number of definitions including their calculation are given.

**Average control accuracy**

This represents the accuracy for maintaining the temperature at a certain set point and will be measured by taking the average difference between the set point and the room
temperature. The lower the value for the average control accuracy the better the thermostat was able to maintain the setpoint temperature.

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Under/Overshoot
This represents the peaks under or over the set point and is calculated when one of the following conditions is true:

- The heating is on and a maximum or minimum has been detected
- The heating has only been turned off a certain amount of time and a maximum is detected. This is used to detect a maximum which is caused due to the delay of the radiator system.

Heating cycle
The device needs time to learn the system's characteristics. The amount of time it takes for the thermostat to attain reliable parameters depends on how often heat is requested. Therefore, the learning period can only be specified in terms of 'heating cycles', which is the number of scheduled temperature transitions that are associated with a boiler temperature adjustment. In other words, scheduled temperature transitions for which the thermostat did not have to perform an action do not count as heating cycles.

Estimated transition time accuracy
The estimated transition time represents the time needed for a certain temperature transition. The difference between the estimated transition time and the actual needed transition time indicates the accuracy of this value.

The estimated transition time accuracy is only calculated for the temperature transitions to a higher temperature. This is done since the thermostat does not have any influence on the cooling of the room. Meaning in a standard schedule consisting of day and night temperatures the deviation in time would only be calculated for transitions to the day temperatures. The transition time to such a night temperature does not depend on the performance of the thermostat but mostly on the isolation of the house.

Energy use
The energy use is expressed as the daily percentage that the heating was turned on with respect to the efficiency of the boiler at the current setpoint. For example, when the boiler was turned on 60% of the time but at a boiler temperature of 60 °C rather than 80 °C the effective percentage would probably be lower. Say the energy use at 60 °C is a factor 0.8 of that of 80 °C, the percentage the boiler has been turned on would then be 0.8*60 = 48%. In case of the On/Off model this efficiency will be constant since the setpoint is not influenced by the thermostat. If the boiler has its own regulation for the boiler setpoint this option could be used, for example for a variant of the thermostat which wants to influence the boiler's set point. The relation between the efficiency of the boiler and a certain setpoint should be known to use this compensation option regarding the efficiency.


**Degrees per hour**

In the validation of the model a variable called the degrees per hour, DPH, is used. This is seen as an extra help variable to give an indication how fast the room or boiler heats up. This was mainly used to determine the parameters for the central heating system and thermal resistance between the radiators and the rooms. When a transition to a higher temperature for either the room or boiler has finished the corresponding DPH value for both is calculated.

4.1.3. **Performance Aspects and Constraints**

To derive the several aspects on which the performance of the model can be checked each individual characteristic of the model with possible indications for performance is noted. Furthermore constraints are laid on the different versions of the thermostat model which need to be met to be a “suitable” thermostat for this project. These constraints were set by AME and include one guideline which could be changed if it turns out not to be feasible.

The following constraints were set by AME:

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Using these constraints and other available aspects of the regulation the following performance aspects were derived:

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4.2. **Experimental Setup**

This section will describe the used scenarios for validation.

4.2.1. **Climate**

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To test the thermostats on several scenarios a week is chosen from each season excluding the summer. Furthermore the week after 30 December 1978 will be used to determine the performance of the thermostat in a strong cold winter. A week will loop a number of times to make it possible to run longer simulations with the same climate data and check if the thermostat is able to learn and improve its performance along the way. The model will also be tested on a full year to test the models performance on a realistic slow changing climate over time, for this purpose the previously stated average year from May 1974 till April 1975 is chosen. However a fast changing climate is also taken into consideration by testing the models performance on a combination of the weeks from each season. This climate scenario will consist of a combination of two times the week of each season after each other, giving a total of 8 weeks. Details of the climate data for the specific dates can be found in [9].
• **Spring** – 1st of May 1974
  - Average temperature 8.9 °C
  - Maximum temperature 17.4 °C
  - Minimum temperature 2.2 °C

• **Autumn** – 1st of November 1974
  - Average temperature 4.1 °C
  - Maximum temperature 10.2 °C
  - Minimum temperature -1.6 °C

• **Winter** – 1st of January 1975
  - Average temperature 2.7 °C
  - Maximum temperature 11.6 °C
  - Minimum temperature -3.3 °C

• **Strong winter** – 30rd of December 1978
  - Average temperature -9.6 °C
  - Maximum temperature -1.4 °C
  - Minimum temperature -16.7 °C

4.2.2. **House model**
To simulate the situations of diversity in house capacity two houses of different size will be used, one of a small sized house and one of a large house. The main characteristics of the houses are:

- 3 floors
- 1st and 2nd floor divided into 3 zones
  - Zone 1, 1/2 of surface
  - Zone 2, 3/8 of surface
  - Zone 3, 1/8 of surface
- 3rd floor consists of 1 zone
- Small house is 80m²
- Large house is 160m²

Figure 2 shows a 3D representation of the layout of the house.

![Figure 2 - A 3D representation of the used house in the scenarios](image)
Furthermore both houses will be tested with a central heating system in which each room has underfloor heating and a system in which each room has a radiator. This is done to test the thermostat on the different responses of the heating system. Underfloor heating is characterized as a slow reacting system both in increase as decrease of temperature in contrary to radiators where it is the opposite due to the difference in capacity and thermal resistance.

4.2.3. **SCHEDULE**

A typical schedule, given in table Table 1, will be used to simulate the behaviour of a normal household.

<table>
<thead>
<tr>
<th>Start-time End-time</th>
<th>00:00-07:00</th>
<th>07:00-09:00</th>
<th>09:00-12:00</th>
<th>12:00-14:00</th>
<th>14:00-17:00</th>
<th>17:00-23:00</th>
<th>23:00-00:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>18 °C</td>
<td>21 °C</td>
<td>18 °C</td>
<td>21 °C</td>
<td>18 °C</td>
<td>21 °C</td>
<td>18 °C</td>
</tr>
</tbody>
</table>

*Table 1 - Daily schedule used in the simulations*

The schedule consists of a pattern based on a household in which residents are present in the morning when they wake up after which they go to work or school. In the afternoon they are home for a brief period, from 12:00 to 14:00, after which they go back to school or work and are back home again for evening dinner.

4.2.4. **VALIDATION FRAMEWORK - SIMULATION MODEL AND PIL SIMULATION CONFIDENTIAL PARAGRAPHS**

4.2.5. **VALIDATION FRAMEWORK – EMBEDDED IMPLEMENTATION CONFIDENTIAL PARAGRAPHS**
5. **Model-Based Design**

This chapter will describe the implementation of the model onto an embedded system.

### 5.1. Removed Section

For the prototype an evaluation board will be used.

The board is extended with an expansion board and LCD module which provide an Ethernet port, SD card interface and LCD with touchscreen capability. These extra peripherals enable interaction with the user and add the possibility to log relevant data on an SD card. Furthermore the thermostat needs to know the room and outside temperature, to provide the board with this information two digital temperature sensors are connected to the board. One of the sensors is extended with a cable to make it possible to place the sensor outside. Since the sensors are digital the cable extension should not influence the results of the measurements. The status of the boiler will be controlled using a relay, since for an On/Off boiler the two wires coming from the boiler to thermostat simply needs to be shortcut to turn the boiler on or disconnected to turn it off. Polarity of the cables does not matter.

### 5.2. PIL Generation

### 5.3. Embedded Implementation

#### 5.3.1. Display

The framework will provide the user with a simple user interface to test the thermostat in practice. The interface on the LCD together with the touchscreen gives the user the possibility to increase or decrease the set temperature or introduce a manual temperature setting with an option to return back to the predefined schedule. The internal real time clock is used to keep track of time and makes it possible to follow the predefined schedule. Since the board has no on-board battery the LCD interface provides the possibility to set the initial time and date which are being shown on the screen after the setup. The LCD also shows the current room, outside and set point temperature as well as the status of the boiler. Furthermore the learn parameters are shown.
5.3.2. **Schedule**
A text file on the SD card is used to provide thermostat with a schedule, the text file includes the temperature and start time of each of the 10 scheduled transitions on a certain weekday. Since the number of transitions on a certain day is fixed to 10, duplicate transitions can be inserted to let the schedule contain less than 10 scheduled transitions. The two learn parameters are also stored during operation to prevent loss when the prototype is given a reset.

5.3.3. **Data Logging**
To make the analysis of the performance of the thermostat in practice possible multiple data values are logged during the operation of the prototype. To log the data the SD card interface is used on which for each day a new text file is created containing the logged data.

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Another purpose for the logged data is to simulate the behaviour of the environment in which the prototype operated using the building and climate model and the developed central heating system. The building and climate model will be provided with a house model equal to the test environment and will use the logged outside temperature data together with default values for the other climate data to approximate the climate in the test environment.

5.3.4. **Program Structure**
When the program starts the several used peripherals are initiated and the touchscreen calibration is started when no previous values of calibration are found on the SD card. After which the user is provided with the setup of the real time clock. Before the actual process of the thermostat is started the initialization function is called and the schedule and possible learn parameters are read from the SD card and provided to the model.

5.3.5. **OpenTherm[11]**
OpenTherm is a standard communications protocol used between a central heating boiler and a thermostat. In the protocol the thermostat is the master while the boiler is the slave. The protocol can be used to change the boiler’s set point or get the outside temperature from the boiler. Since the same design trajectory will be used for a possible OpenTherm version of the thermostat the several developed components in the project support the adjustment of the boiler temperature. This includes the embedded framework in which the OpenTherm protocol was added. OpenTherm requires communication every second this is why a sequence of commands is defined in the framework which will be repeated indefinitely.

Whenever the model wants to change the boiler temperature it updates its local variable which contains the current boiler’s set point. The next time the command related to the boiler temperature is sent this value will be used. Whenever a response is received from the boiler, for example regarding the outside temperature, this is processed and provided to the
thermostat model. The same method can be used for other commands since the sequence in the framework can easily be modified to support other commands.
6. **Case Study**

Using model-based design a case study was conducted using the developed validation framework. In the following sections the results of each of these layers will be discussed.

6.1. **Simulation Results**

In this section the results regarding the validation of the simulation model of the thermostat are described. The simulation model in combination with the proposed scenarios was used to make an indication of the performance of the thermostat. In the following subsections the proposed improvement and the tuning regarding the adjustment of the learning parameters for the thermostat are discussed. Furthermore a simulation of a complete year is done using the best performing thermostat, derived from the several tests, to give an indication of the performance of the thermostat in a full year.

The different buildings and central heating systems used for testing can be divided into 4 types, namely:

- A small house with a radiator heating system
- A small house with an underfloor heating system
- A large house with a radiator heating system
- A large house with an underfloor heating system

One of the purposes of the different simulations is to try and found the best values for the parameters for each of these types of houses or possibly a value which covers a subset of them. The best performing values for the parameters can then be chosen based on the user's input at installation of the thermostat.

Since the numbers regarding the average control accuracy or over-undershoot are often rather small the choice was made to represent these results in percentages regarding the specified constraints. For example a value of 60% regarding the average control accuracy denotes that in this specific scenario the average control accuracy was 60% of the maximum allowed by the constraint set by AME. The other performance aspect, which is the energy use, is already given in percentages due to the fact that it represents the total percentage the heating has been on during the simulation. For all performance aspects the goal is to find the lowest, which is the best, value possible.

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Furthermore not all tables and results are discussed however trends found for a certain scenario often are seen in other scenarios as well. When this is the case a note is made in the text regarding which test scenarios show the same behaviour. Moreover when
modifications were made to the thermostat, for example an adjustment of one of the parameters, certain simulations were redone to see if the same trends were found.

6.1.1. REMOVED SECTIONS
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6.1.2. CONCLUSION / DISCUSSION
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6.2. PIL RESULTS
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6.3. EMBEDDED RESULTS
This section will discuss the results regarding the embedded implementation of the thermostat. CONFIDENTIAL PARAGRAPH

The prototype of the thermostat was tested in two different test environment of which the results will be discussed in the next subsections. In the final subsection a comparison is made between the response of the two test environments and a simulation implementation of these environments.

6.3.1. TEST ENVIRONMENTS
As stated earlier two test environments were considered for the embedded system implementation of the model. A more detailed description of these test environments will be given in this subsection.

TEST BUILDING 1
This building consists of one room which is well isolated and contains a number of large double glass windows. The used heating system is an underfloor system in combination with a boiler of 24kW which is set to 60 °C. The thermostat was tested in this building in two durations, one in which none of the optimizations, including the approximation function for the TTC, were not available and one in which these were available. Figure 3 gives a 3D representation of the building.

Summary of the building:
- 1 floor
- 1 zone
- A number of large windows (22.5m²)
• Floor surface of 40m²
• 24kW Boiler
• Underfloor heating
• Testing data:
  o 23-10-2013 – 28-10-2013
    ▪ Average outside temperature 14.98 °C
    ▪ Maximum temperature 26.19 °C
    ▪ Minimum temperature 10.06 °C
    ▪ Same schedule as test scenarios
  o 30-11-2013 – 13-12-2013
    ▪ Average outside temperature 4.82 °C
    ▪ Maximum temperature 16.02 °C
    ▪ Minimum temperature -1.48 °C
    ▪ Schedule in which the temperature is 18 °C and from 8:00 until 22:00 the temperature is equal to 21 °C

Figure 3 - A 3D representation of test building 1

TEST BUILDING 2
The second test environment is a garage which has its own boiler set at 80 °C and one rather large radiator. The walls of the garage are not well isolated. Furthermore, the same holds regarding the optimizations done on the thermostat for both the periods. Figure 4 gives a 3D representation of the building. In the second run the schedule for this garage was changed to a schedule with lower temperature.

Summary of the building:
• 1 floor
• 1 zone
• 1 large window (2m²)
• Floor surface of 15.75m²
• 24kW Boiler
• One large radiator as heating

• Testing data:
  o 24-10-2013 – 30-10-2013
    ▪ Average outside temperature 13.82 °C
    ▪ Maximum temperature 20.44 °C
    ▪ Minimum temperature 7.63 °C
    ▪ Same schedule as test scenarios
  o 7-12-2013 – 15-12-2013
    ▪ Average outside temperature 4.83 °C
    ▪ Maximum temperature 10.88 °C
    ▪ Minimum temperature -1.66 °C
    ▪ Same schedule as test scenarios in which the low temperature (18.0 °C) is replaced by 13.0 °C and the high temperature (21.0 °C) with 17.0 °C

6.3.2. Validation of Prototype Tests

This subsection shows the validation of the several test runs with the developed prototype. Two different versions of the prototype were used, this was related due to the fact that a first prototype was already tested before the analysis of all simulation data was complete. Although the time periods of the different tests do not include the maximum amount of learning period available to the thermostat, performance aspects were still derived to give an indication of the thermostats performance in the specified time period.

Building 1 Run 1 – October
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Building 1 Run 2 – December
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Building 2 Run 1 – October
Conclusion

The thermostat showed good performance in the practical test and in most cases the specified constraints were satisfied. However, certain unexpected behaviour not related to the actions of the thermostat or the error in the minimum boiler on time resulted in certain constraints not being satisfied. This includes the limitation in heat capacity for the first test environment and the different peaks shown in the second building. However in most cases the same constraints were satisfied when derived from a time period in which the latter phenomena did not occur.

For future test runs a look must be taken into the different peaks that occurred. Although this is most likely not a fault in the measurement since the peaks show a smooth curve to a certain temperature instead of a large deviation of a length of one time step. Furthermore, the thermostat temperature sensor in building 1 should be placed in a different spot. This would be done to see if the shown effect of the limitation in capacity was not related to a non-accurate room temperature measurement. If the latter seems not to be the cause a possible schedule with a lower temperature set point could be considered for future test runs.

6.3.3. Validation of the Simulation Model

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7. CONCLUSION

This chapter concludes the work presented in this thesis. First a summary about the work and contributions of the project is given after which possible future work is discussed.

7.1. WORK AND CONTRIBUTIONS

In this thesis a model-based design trajectory for a thermostat was created and applied onto a self-learning On/Off model made by AME. The layers in the trajectory consist of a simulation model, a PIL implementation and an embedded implementation of the thermostat. The thermostat simulation model in the first layer was provided by AME. For each of these layers a number of components were developed in order to realise derivation of the thermostat’s performance.

For the first two layers a simulation model was developed in order to simulate the environment surrounding the thermostat. This model can be used on an arbitrary thermostat model under the condition that certain basic information is available. The simulation model makes use of an existing building and climate model, and a model of a central heating system developed during this project. The central heating system has the option to change the boiler’s set point over time in order to support future work of other thermostats.

For the third layer a framework for an embedded system was made. The framework makes fast iterations of the thermostat model possible and supports the use of OpenTherm. OpenTherm introduces the ability to change the boiler’s setpoint and retrieve the outside temperature if supported by the boiler.

In order to determine the performance of the thermostat a validation framework was developed which can be used across all layers of the design trajectory. The framework includes a validation model which uses basic in and outputs in order to provide support for other thermostats as well. Using a number of scripts the same validation model can be used for logging data of the embedded implementation. The model derives several performance aspects for a thermostat. Two aspects were chosen to represent an indication of the performance of the thermostat. Other aspects were used to filter out versions of the thermostat which do not satisfy certain constraints.

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Finally the logging data from the embedded implementation was used to show that the thermostat was able to satisfy the constraints set by AME in practice. The same data was used to show the approximation of the simulation model is accurate enough to use as indication if the thermostat would satisfy the specified constraints in practice. The latter was done by reproducing the test environment and making a comparison between the response of the simulation and the response in reality.
Summarizing the above the following contributions were done in the thesis:

- Creation of a model-based design trajectory for a thermostat
- Creation of a validation framework which can be used across all layers of the design trajectory
- Development of an embedded framework to make fast iterations of the model possible
- A complete validation and improvement of the existing On/Off thermostat model made by AME
- A validation of the used design trajectory with the use of logged data from the embedded deployment of the thermostat
- The use of basic in and outputs and support for varying boiler setpoint for all components to support future work of a different thermostat

7.2. FUTURE WORK

Based on the work in this thesis there are different directions in which future work can be done:

The related work discussed in chapter 3 showed extensions in the area of an intelligent thermostat which can be used for future improvements. For example the use of a boiler set point in order to minimize energy usage or addition of individual regulation of temperatures in different rooms.

Extended research should be done regarding the problem of the simulation of one of the test environments. The first test environment, which uses an underfloor heating, showed a very slow increase in room temperature. Reproducing this response in the simulation model resulted in unexpected behaviour of the simulation. More research should be done regarding the cause of this behaviour, whether it is indeed related to the used central heating system or the building and climate model.

Other possible future work includes expansion of the scenarios used in this thesis. Although these try to cover the most common scenarios there are several other scenarios which can be considered. For example things like different temperature schedules, larger buildings, different isolation levels or the combination of both an underfloor as a radiator heating system. These are all other scenarios on which a thermostat can be tested using the developed simulation model.

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