Aalborg University
School of Engineering and Science

MSc Building Energy Design

OPTIMIZATION OF HEATING CONTROL IN EXISTING BUILDINGS

Master's thesis

Authors:

Gica Danes
Kremena Milenkova
Diana Zabusova

Supervisors:

Mingzhe Liu
Michal Pomianowski

In collaboration with

January 2017

AALBORG UNIVERSITY
STUDENT REPORT

Study Board of Civil Engineering
Thomas Manns Vej 23
9220 Aalborg Øst

Study secretary: Rikke Christensen
Phone (+45) 99 40 30 91
E-mail: rch@civil.aau.dk

Title:	**Optimization of heating control in existing buildings**
Semester:	**4th semester in M.Sc. in Building Energy Design**
Semester theme:	**Master Thesis**
Project period:	**September 2016 – January 2016**
ECTS:	**30**
Supervisors:	**Michal Pomianowski** **Mingzhe Liu**
Project delivery:	**13.01.2017**

Gica Danes

Kremena B. Milenkova

Diana Zabusova

SYNOPSIS:

The following Master thesis report focuses on optimization of heating control in existing buildings with the aim of reducing energy consumption. The project report includes both theoretical and practical investigations. The theoretical part aims to provide the reader with information about the heating system controls and common strategies for reducing heating energy consumption. The practical part includes a case study building in Aalborg, which is used for conducting energy and indoor climate measurements. The main research area is the implementation of setback strategy with programmable thermostats. The project is carried out in collaboration with MOE and Salus controls.

Pages: 91

Appendix: 24

By signing this document, each member of the group confirms participation on equal terms in the process of writing the project report. Thus, each member of the group is responsible for all contents in the project.

TABLE OF CONTENTS

PREFACE

This report is the result of master thesis project for Master of Science program in *Building Energy Design* (BED) at Aalborg University. The project is done by a group of three students in collaboration with the Danish engineering consultancy company *MOE*. The project duration was from 1st of September 2016 to 13th of January 2017. Successful examination based on the report rewards 30 ECTS and a completion of the master's degree.

The chapters of this report are recommended to be read consecutively, though the reader can find links to other parts of the report in the text. Cross references to other chapters include the number and title of the chapter in italic, for example *2.2 Ways to save energy with heating control*. The citing of information sources used in this report is done with Harvard referencing style. Bibliography is found in the end of the report body, followed by Appendices that are structured in alphabetical order.

ACKNOWLEDGEMENTS

We would like to thank Project Manager at MOE Simon Kamper for providing us with the idea for the project and describing the problem, the company has faced during their projects.

We are grateful to our project supervisors Associate Professor Michal Pomianowski and Assistant Professor Mingzhe Liu of the Department of Civil Engineering at Aalborg University. Their involvement and interest in our work during the whole process of writing the report motivated us, and we benefited from their guidance and supervision.

Furthermore, a thanks to the Technical Service Manager Jan Nødbak Andersen at Vester Mariendal School for agreeing to let us use the school building for performing the necessary investigations.

Finally, we would like to thank Business Director Nordic Jan-René Kristensen from Salus Controls for providing their products used in this project.

ABBREVIATIONS

AAU	Aalborg University
ACH	Air Change Rate
BR	Building Regulations
BREEAM	Building Research Establishment Environmental Assessment Method
CTS	from Danish: Building Management System
DGNB	from German: German Sustainable Building Council
DH	District Heating
DN	Diameter Nominal
DRY	Design Reference Year
HVAC	Heating, Ventilation and Air-conditioning
IC-Meter	Indoor Climate Meter
IDA ICE	IDA Indoor Climate and Energy
LEED	Leadership in Energy and Environmental Design
LMTD	Logarithmic Mean Temperature Difference
NMF	Neutral Model Format
NPV	Net Present Value
P	Proportional
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PT	Programmable thermostat
RH	Relative Humidity
RTD	Resistance Temperature Detector
TRV	Thermostatic radiator valve

NOMENCLATURE

A	Area	[m²]
B	Magnetic flux density	[Wb/m²]
Cm	Heat capacity	[J/K]
C_o	Concentration	[ppm]
C_p	Specific heat capacity	[J/kg K]
H	Heat transfer coefficient	[W/K]
L	Length	[m]
m	Mass	[kg]
$\dot{m}$	Mass flow	[kg/s]
n	Radiator factor	[-]
n	Air change rate	[h^{-1}]
Q	Power	[W]
q	Volume flow	[m^3/h]
Q_0	Nominal heat output	[W]
R	Thermal resistance	[m²K/W]
RH	Relative humidity	[%]
R_{si}	Internal surface resistance	[m²K/W]
R_{so}	External surface resistance	[m²K/W]
S	Valve authority	[-]
T	Temperature	[°C]
T_i	Indoor temperature	[°C]
T_o	Outdoor temperature	[°C]
T_r	Return temperature	[°C]
T_s	Supply temperature	[°C]
U	U-value	[W/m²K]
Ue	Induced voltage	[V]
V	Volume	[m³]
y	Oversizing factor	[-]
η	Efficiency of the pump	[-]
v	Velocity	[m/s]
ψ	Linear heat loss	[W/mK]
ΔP	Pressure drop	[Pa]
ΔT	Temperature difference	[K]
ΔT_m	Mean logarithmic ΔT	[°C]
ρ	Density	[kg/m³]
τ	Time constant	[h]

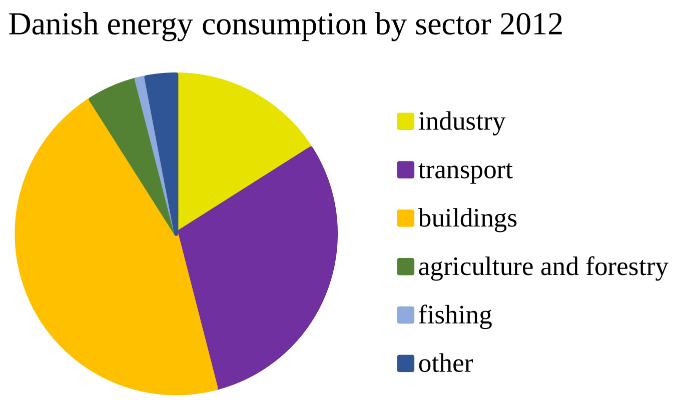
1 INTRODUCTION

The following Master Thesis report focuses on optimization of heating control systems in existing buildings and it is aiming to identify problems that are related to the heating system control with the purpose of reducing operational heating energy consumption.

The following chapter covers broad background of the problem, the hypothesis of the report (problem formulation), the importance of the control of heating systems, the approach to the problem and delimitation (boundary) of the project itself.

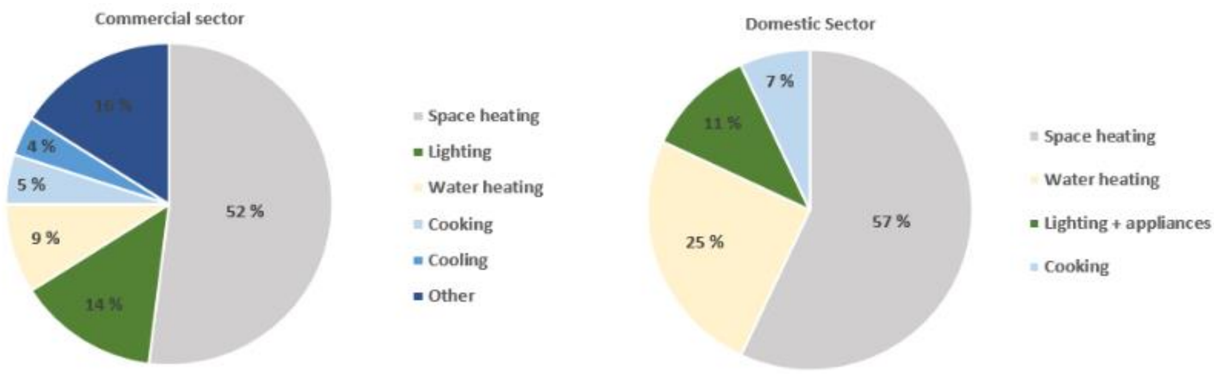
1.1 BACKGROUND

The building sector has a huge influence on the energy consumption of any country. According to the Nordic Energy Research, the total Danish building mass accounts for more than 40% of the country`s total energy consumption, as indicated in Graph 1.1.



Graph 1.1 Danish energy consumption by sector 2012, (Nordic Energy Research 2012)

For both commercial and residential buildings, not only in Denmark, but all over Europe, highest energy use is for space heating - Graph 1.2.



Graph 1.2 Energy distribution in commercial and domestic buildings (Illikainen & Sirviö 2015)

Currently, between 40% and 50% of Danish energy usage is wasted (Ministry of Foreign Affairs Denmark 2016), so efficient energy is something than can be introduced at all levels of society.

All these facts lead to the conclusion that reducing the energy waste is highly dependent on the efficiency of the heating systems – in both commercial and residential buildings. Optimizing the heating system includes many possibilities, having in mind the various ways buildings are heated nowadays.

"Different technologies are used for heating supply in Denmark. Some consumers use an individual oil boiler, gas boiler, biomass boiler or heating pump, but most consumers (over 60 %) receive their heating from the DH system…. Denmark has six large central DH areas with a total heating supply of 67 PJ in 2014, 56 % of the national DH supply. There are also around 400 small and medium-sized DH areas with an annual heating supply of approximately 53 PJ."

(Danish Energy Agency 2015)

Important factor for the efficiency of the district heating are the temperatures of the supply and return water. Low district heating temperatures are better mainly because they have lower heat loss from pipes. In Denmark in 2004 the conduction loss has been 19.95 %, and by 2014 it has been reduced to 17.38 %, which is equivalent to 150 million DKK. (Øllegaard Sørensen 2014) Currently the supply water of the district heating in most of the plants in Denmark has a temperature of 80°C, and after distribution it reaches the consumer at around 70°C. The required temperature drop from most of the DH centrals is 30°C. However, there is some variation according to the location.

In order to motivate the consumers to use efficiently the district heating network, municipalities are using different techniques. For example in Copenhagen, where the payment for DH is done according to energy consumption in kWh, the municipality is assigning bonuses or penalties to those who manage to return lower or higher water temperature than the assigned. In Aalborg the payment method is according to water consumption in m^3, because in this way the more the water is cooled by the consumer, the less he will need to pay.

At a building level the optimization of a heating system can include various possibilities. Such as zoned control of the temperatures, weather compensation according to outdoor temperatures or night setback of the heating system, which reduces the heat consumption when the building is not occupied. Therefore, these approaches for energy reduction are the best to be implemented in buildings with fixed time schedules in order to avoid discomfort of the occupants for example in commercial buildings, educational buildings. However, unlike most of the commercial buildings, in schools the occupancy time is often different from one classroom to another. Typically, in Denmark the school day starts at 08:00 and finishes at around 15:00, and the first three year groups usually finish earlier; a school year runs from August to June.

When discussing this issue with a Danish consultancy engineering company (MOE), it was mentioned that they are putting a lot of effort in trying to find the best solutions for their clients. It was mentioned that in many cases when they have been involved in renovation projects of office and school buildings it was difficult to identify what strategy is the best for the heating system, (meaning having centralized or decentralized control).

For example in school buildings many of the classrooms are set to have opening hours from 08:00-17:00. However, in reality they close between 13.00 and 17.00. Therefore having decentralized control system can contribute to energy savings compared to a centralized system where the heating will be working for the whole building even if only one room is occupied. Thus, the energy savings would be even larger with a decentralized control system.

1.2 PROBLEM FORMULATION AND RESEARCH QUESTIONS

The purpose of a good heating system is to provide the desired effect in terms of thermal comfort and economics. All heating systems are designed for the critical conditions of a specific climate; however, in reality those conditions rarely occur. Moreover, there will be a different demand on the system due to change in outdoor temperature and internal gains. Heating control is essential, and its aim is to provide the appropriate heating at all times without wasting energy.

In theory, an upgraded building envelope together with a well-designed heating system and a good control will minimize the heating requirements, which also will lead to energy savings. However, in practice there are more aspects regarding heating control that need to be considered.

The operation of the heating system is a very important aspect; it is not enough to own the most advanced components if there is lack of operation skills. Good or smart control systems have the potential of achieving energy savings but the way they are operated is of a great importance.

In many non-residential buildings, the temperature is lowered during unoccupied hours through a central reduction of the supply temperature to the radiators. This is known as an inexpensive method to obtain energy savings.

Some of the research questions are outlined as following:

- What are the methods used in the existing buildings aimed to reduce energy consumption for heating?
- What implies oversizing of radiators in terms of energy savings?
- How does setback strategy work for different building types according to their thermal mass and insulation level?
- How does the central reduction of supply temperature work in practice when applied in a school building with traditional TRVs?
- Does night-setback with central reduction of supply temperature result in energy savings when used with traditional thermostatic radiator valves, or do digital thermostats provide better performance of the system in terms of thermal comfort and energy use?

1.3 METHODOLOGY

This master thesis focuses on optimization of heating control systems in existing buildings and it is aiming to identify part of the problems that are related to the heating system control with the purpose of reducing energy costs. Research areas include zone control of the temperature by manual and automatic control, weather compensation, night setback of the heating system, with the aim of reducing the heat, thus energy consumption.

The master thesis project contains work of both theoretical and practical approaches therefore different methods are assessed. The methods used to address the research objectives of the master thesis are: literature review, filed tests, hand calculations and simulations.

The literature review used in the report indicates the studied work of different authors that were relevant for this particular project and acts as the basis for a fuller understanding of the context in which the research is conducted.

Theoretical investigations such as oversizing of the radiators and how this affects the performance of heating systems is performed throughout hand calculations. The influence of a setback in buildings with different thermal mass is approached both thorough literature review and simulations where simulation software IDA ICE and Simulink were used.

The primary research is done on a case study, where two types of zone temperature control are tested. The aim of carrying out a measurement campaign is to investigate the thermal comfort and energy consumption of the specified case study project and give suggestions and solutions for further improvements in terms of energy savings. Different strategies are implemented in the case study such as setback, decentralized control for heating through smart programmable thermostats. The energy performance and the thermal comfort of the case study are not handled as individual parameters, but as interconnected parts, which combined, will provide the best outcome in terms of comfort and energy consumption. The thermal comfort and energy usage in the case study is evaluated through both measurements and simulations. The simulation software IDA ICE is used for the evaluation of the indoor climate and energy use of the thermal zones, and the models are calibrated according to the conducted measurements.

The more detailed and specific methods applied in different investigations and analyses are presented in the respective sections of the master thesis report.

1.4 DELIMITATION

The following project emphases only buildings that are not permanently occupied, thus buildings in which the temperature must be lowered during unoccupied hours. A school building in Aalborg, Denmark is included as a case study in the project. The case study covers two rooms in the school; one room is used as reference room and the other as test room.

To be able to achieve the objectives of this project and to answer the questions stated in the problem formulation, the heating system and its control in the school are investigated in detail. The emphasis lays on analyses of thermal comfort and energy consumption. The operative temperature is the only parameter that is analysed when referring to thermal comfort.

The energy measurements performed in the case study have duration of two weeks, meaning that an annual energy consumption of the rooms is done throughout simulation program IDA ICE. The models for the simulations are calibrated according to measured data.

2 CONTROL OF HEATING SYSTEMS

"We need controls and control systems because, in our modern age of technology, they make our lives more convenient, comfortable, efficient and effective. A control enables equipment to operate effectively and sometimes gives the ability to change their actions as time goes on and conditions or occupancies change. Controls can be devices used to monitor the inputs and regulate the output of systems and equipment."

(Montgomery & McDowall 2009)

We use controls in our daily life at our homes, for instance, when we feel too cold or too warm we regulate the room thermostat; when we wash dishes, we regulate the desired water temperature by manually moving the faucet (valve); when it is getting too dark in the room we turn on the light, and so on. All these examples are representing closed loop manual controls. Manual because a person makes the action rather than a device (in case of automatic control), and close loop because there is a feedback from our action. People like the idea of having manual control of the devices that can affect their comfort. On the other hand, it will be almost impossible and very time consuming to control everything manually.

HVAC systems are designed for the critical conditions (in a specific climate), however in reality those conditions will happen rarely. Moreover, there will be a different demand on the system due to change in outdoor temperature and internal gains. This is the main reason why the need of control is essential to provide at all time the appropriate heating or cooling need without wasting unnecessary energy. In HVAC systems, automatic control eliminates the need of humans to permanently monitoring a process and therefore reducing labor costs and providing more consistence and improved performance.

HVAC control can be described as the starting, stopping or regulation of heating, ventilation and air-conditioning systems. The control can be manual or automatic. In case of automatic control, the device will imitate what a person would do at manual control. In the automatic control process a system variable is measured, the measured data is processed, and according to the processed data, an appropriate response is made. This can be for example when the temperature in the room becomes lower than what is desired a sensor will detect the difference between the measured and desired value and the valve will open and allow more flow to the radiator, achieving the desired set point. For most cases of HVAC systems, an automatic control is preferable because of more accuracy, safety reasons, economic aspects and the fact that nowadays it is almost impossible to have manual control on all the different parameters that can affect the users` comfort and energy usage in buildings.

"The ultimate aim of every HVAC system and its controls is to provide a comfortable environment suitable for the process that is occurring in the facility."

(Montgomery & McDowall 2009)

For instance, HVAC systems implemented in office buildings have the main purpose of providing good indoor air quality and thermal comfort for the users in order to be more productive. In hospitals, besides the precise temperature and humidity, the pressure control and the air quality is of a high importance. HVAC systems together with the control systems must regulate all these different parameters constantly in order to provide the desired environment.

Another aspect of the control systems is energy management. It is desired that HVAC systems perform as intended and provide the necessary output but in the most energy efficient way. Safety is also an important aspect of automatic control. An automatic system control should have the ability to stop the system when a risk of health and welfare of people is arising or in case of damaging the system itself.

This could include setting limitations to different types of controls, for example, overheating or freezing protection; in case of fire the ventilation must stop, preventing the fire to spread; limits for too high or too low pressure in ventilation and heating systems.

2.1 METHODS OF HEATING CONTROL

In the following subchapter centralized and decentralized temperature controls in buildings are discussed. The chapter includes general information about the two controls as well as their advantages and disadvantages.

The main difference between centralized and decentralized (zoned) temperature control is the thermostat that is controlling the output in the building. When the temperature control in the building is central, the signal for heating output of the system is maintained only through one thermostat, thus resulting in the same temperature in the whole building. In large buildings with centralized heating system control zoning is usually done by orientation (South/North).

On the other hand, zoned temperature control requires individual thermostats in all zones. In this way the temperatures in the zones can be maintained at different levels. Generally, the zoned control is more expensive due to the amount of thermostats required to complete the system. However, this accounts only for the initial investment of the system. Zoned temperature control is known to be more energy efficient solution due to the opportunity to decrease temperatures in parts of the building. Central temperature control will require heating up the whole building at the same level even if only one room is used.

In practice centralized temperature control is good for buildings such as offices, where is it expected that most occupants are present during fixed time of the day. School buildings are also good candidates for such temperature control. However, if a part of the building is expected to be used outside of occupied hours, centralized temperature control can cause excessive heat consumption because it requires turning on the heating system for the entire building. Therefore, implementing zone temperature control in such cases will result in energy savings. Residential buildings and houses can contribute a lot from zoned temperature control – it is possible to result not only in energy savings, but in better thermal comfort for the occupants.

To sum up:

- Centralized temperature control is a simple system, easy to install and maintain, can only provide the same temperature in the whole building or a large part of a building (for example one façade);
- Decentralized (zoned) temperature control requires more complex installation, has higher investment cost, has the possibility of maintaining different temperatures in the controlled zones, can result in energy savings and might increase the comfort level of the occupants.

2.1.1 CONTROL AND MONITORING DEVICES

"Sensors are used to measure the controlled variable. Without measurement, there can be no control. Sensors are also used for monitoring purposes to keep the operator informed about elements in the system that indicate proper (or improper) operation."

(Montgomery & McDowall 2009)

In radiator systems monitoring and measuring energy consumption is most often done at the building level. This is referred to as centralized heating system monitoring. The energy use of separate radiators can only be done by measuring both the temperature drop and the mass flow through the radiator – decentralized system monitoring.

2.1.1.1 Water flow meters

The following sub-chapter focuses on the different ways of measuring water flow in heating systems, which include the most commonly used meters: 1) differential pressure flow meters; 2) displacement meters and 3) passive flow meters.

1) The differential pressure flow meter measures the flow by correlating flow to differential pressure. This is one of the oldest techniques for measuring water flow and all devices using it are based on a form of Bernoulli`s equation:

$$\boldsymbol{v} = \boldsymbol{C} \cdot \sqrt{\frac{\mathbf{2} \cdot \boldsymbol{\Delta P}}{\boldsymbol{\rho}}} \tag{1}$$

Where v [m/s] is the velocity, C [dimensionless] is a constant, which is a function of the physical design of the meter, ΔP [Pa] is the measured pressure drop, and ρ [kg/m³] is the fluid density. (Montgomery & McDowall 2009)

Another example for a meter using differential pressure measurement is an orifice plate meter. The orifice plate meter consists of a flat plate with a circular hole in the middle as shown in figure Figure 2.1. The flow is calculated by measuring the pressure difference across the plate. Orifice meters are usually used to calibrate other devices, because the flow coefficient, C from equation (1), can be determined using the measured area of the pipe and the orifice opening. For most other devices this coefficient should be determined by experimentation using some other more accurate device.

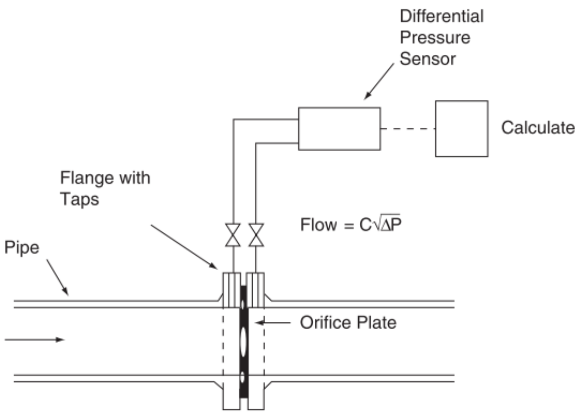


Figure 2.1 Orifice Plate flow meter, (Montgomery & McDowall 2009)

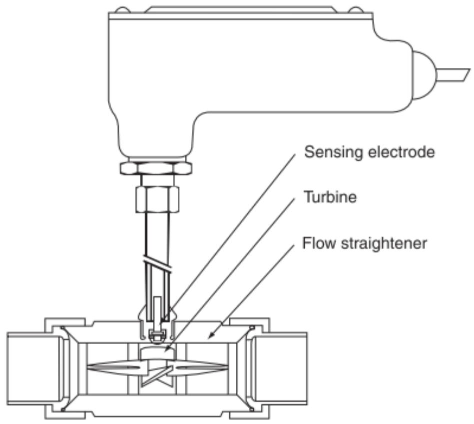


Figure 2.2 Inline Turbine flow meter, (Montgomery & McDowall 2009)

2) Displacement flow meters measure the flow by using the velocity of the water to displace or rotate a device, which is installed in the pipe. Example is a turbine meter, shown in Figure 2.2. Turbine measures the flow by counting the rate of rotations of a rotor, whose blades are parallel to the direction of the flow.

Another displacement method includes measuring flow by timing how long it takes for the fluid to fill up/out a container of known volume. This method is used primarily to calibrate other sensors.

3) Passive flow meters measure flow without placing any obstructions in the stream of the fluid. Therefore, they require less maintenance and don’t create additional pressure drops. There are three main types of passive flow meters:

- Doppler Effect ultrasonic meter (Figure 2.3) measures the Doppler shifts in frequency of the sound wave caused by the fluid flow.
- Time of flight ultrasonic meter (Figure 2.4) measures flow rate by detecting small differences in the time for sound waves to move through the fluid as fluid velocity varies.

(Montgomery & McDowall 2009)

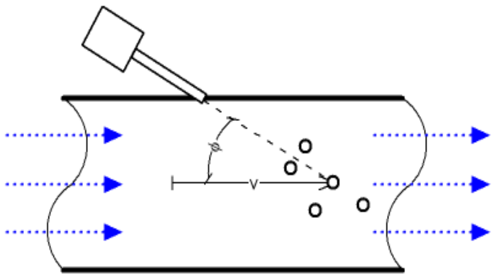


Figure 2.3 The Doppler effect ultrasonic flow meter, (Engineering ToolBox 2016)

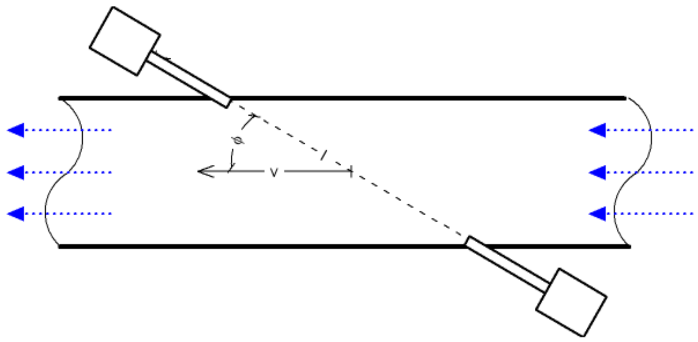


Figure 2.4 The time of flight ultrasonic flow meter, (Engineering ToolBox 2016)

- Magnetic flow meter measures the flow rate by magnetic induction caused by the moving fluid when exposed to a strong magnetic field. They consist of coils placed parallel to the flow, which are generating a magnetic field, and a set of electrodes in the sides of the pipe - Figure 2.5.

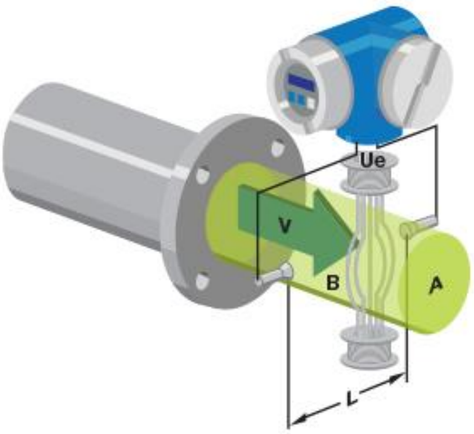


Figure 2.5 Magnetic flow meter, (Instrumentation tools 2016)

The magnetic flow meter is based on Faraday`s Law of Electromagnetic Induction, which states that a flow of conductive liquid through a magnetic field will cause a voltage signal proportional to the movement of the flowing fluid – when the fluid moves faster, more voltage is generated - equation (**2**). (Boyes 2009)

$$\boldsymbol{Ue = B \cdot L \cdot v} \tag{2}$$

Where *Ue* [V] is the induced voltage, *B* [Wb/m²] is the magnetic flux density/strength of the magnetic field (1 Wb/m² = 1 Tesla), *L* [m] is the length of the conductor (diameter of the pipe) and *v* [m/s] is the velocity of the flow.

The accuracy of flow meters in all cases depends on the producer. One should be careful when choosing a flow meter due to different range of the devices.

2.1.1.2 Temperature sensors

There are two ways of measuring water temperature in a pipe: by intrusion (having the sensor inside the pipe) or on the surface of the pipe.

In cases where penetration on the pipe is neither allowed nor desired the surface method is a good alternative. There are different ways of performing such measurements: by using thermocouple sensors, thermistors or RTD sensors (Resistance Temperature Detectors).

Thermocouple surface sensors are available in wire or foil. They are relatively cheap due to simple design, fast response, and ability to function at high temperatures.

RTD sensors, unlike thermocouples, do not require a reference point, (e.g. ice baths). The sensors have a very low thermal mass thereby providing an accurate surface temperature as well as a fast response time. RTD also changes resistance with temperature. Most metallic materials increase in resistance with increasing temperature; over limited ranges, this variation is linear for certain metals (e.g. platinum, copper, tungsten, nickel/ iron alloys). Platinum, for example, is linear within ±0.3% from –18 to 150°C. The RTD sensors are available for surface measurements and for immersion mounting. (ASHRAE 2009)

An important consideration when measuring water temperature on the surface of a pipe is that the recorded temperature by a sensor is not the flow temperature, which is in the pipe. There is temperature difference between the inner and outer surface of the pipe. The accuracy of a non-intrusive measurement is influenced by many variables like pipe wall thickness, process medium and its flow, process temperature, ambient conditions, direct radiation and the airflow around the sensor. Therefore, the sensor and surrounding surface should be insulated (also to prevent water build up between the pipe surface and the sensor). (Rosemount n.d.)

2.1.1.3 Thermostats

This subchapter describes historical development of thermostats, the latest inventions in this field, and gives a review of studies that were conducted on the topic of thermostats. Their user-friendliness and provided thermal comfort are also presented.

Brief history of thermostats

Oxford dictionary defines a thermostat as “a device that automatically regulates temperature, or that activates a device when the temperature reaches a certain point”. The word *thermostat* is derived from two Greek words *thermo* “heat” and *statos* “standing, stationary” (Harper 2016).

The development of thermostatic control dates back to 1620s, when a Dutch inventor Cornelis Drebbel created the first known feedback thermo-regulator to control the temperature of a chicken incubator (Tiere 1932). The first bimetal thermostat (that would bend as a result of increasing room temperature) was patented by Andrew Ure in 1830 (Mlsna 2016). In 1953 Honeywell produced the first device that we would recognize as a modern residential thermostat (Walker & Meier 2008), and it is still available today. Figure 2.6 presents the timeline of the history of thermostats; the past two centuries have brought several inventions that play an important role in the development of modern thermostatic control.

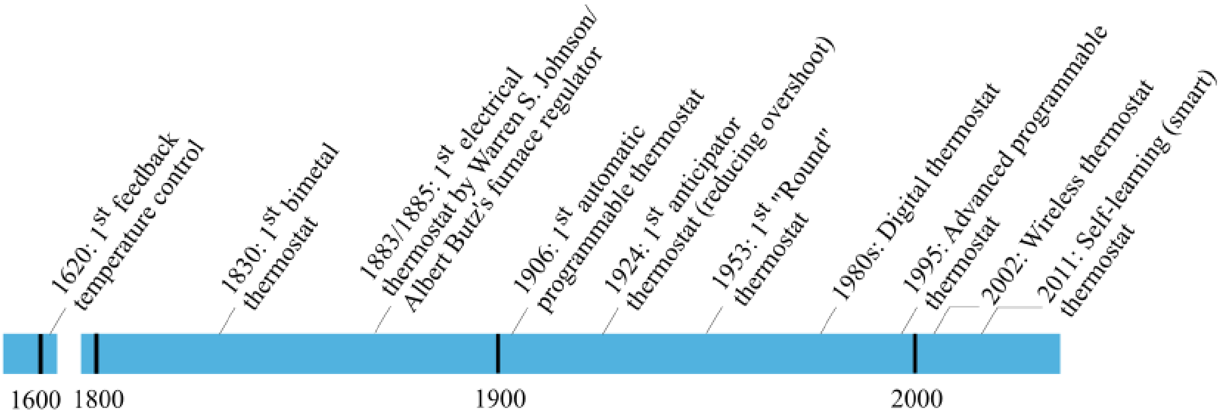


Figure 2.6 Timeline of history of thermostats, adapted from (Walker & Meier 2008) and (Peffer et al. 2011)

1990s in the history of thermostats present an advanced programmable thermostat (PT), which included multiple functions for HVAC control (temperature, ventilation, and dehumidification); moreover, programming for different schedules became available. The development of room thermostats continued with implementation of wireless control function in 2002 (National Trade Supply 2016). The most modern smart thermostats include self-learning function, which implies that a thermostat programs itself and adjusts to changes in users' behaviour.

Thermostats today – State of the art

The increasing interest in PTs resulted in rapid growth of various room temperature controls available on the market. Nevertheless, the efficient operation that is being promised by a producer is affected by the way the control system is being implemented and used. Factors influencing the operation of a thermostat are: placement of a sensor, measured variable, user awareness and behaviour.

When controlling the room temperature the most common control used in Denmark is the thermostatic radiator valves.

"A thermostatic valve is a self-acting automatic valve controlled by an expanding element. Depending on the difference between the temperature set point and the room temperature, the valve gradually opens or closes."

(Lauritsen 2015)

Thermostatic valves allow the achievement of the correct temperature in each room individually. With the correct settings of the system the flow and the differential pressure, the thermostatic valves compensate for a possible oversizing of the radiator and reduce the heat output when there is ''free heating'' (sun, equipment, people, etc.), in this way avoiding overheating and saving energy.

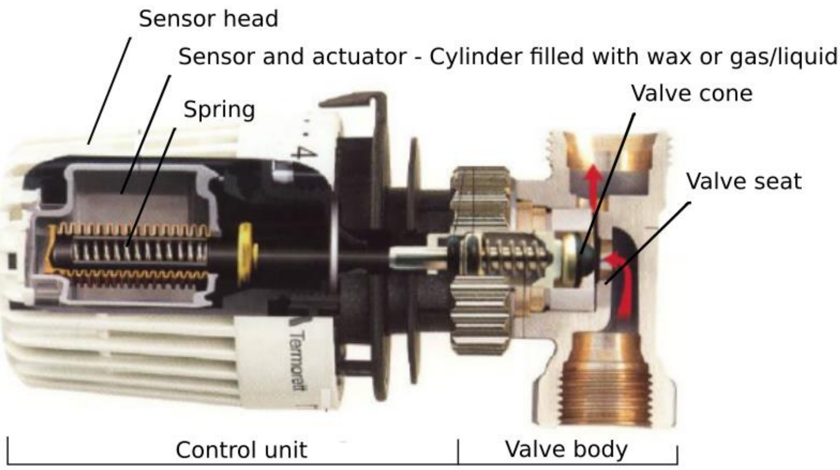


Figure 2.7 Section of a thermostatic radiator valve, photo taken from (Pomianowski 2015)

A thermostatic valve consists of two parts: the valve body and the control unit (Figure 2.7). The valve body can be found in different sizes and shapes. The most common control unit types are the ones with the build in sensor, or with a separate sensor connected with a capillary tube. Thermostatic valves are proportional controls that are regulating the heat supply in relation to the difference between the temperature set on the thermostat and the temperature detected by the sensor. In case of a too low sensed temperature in a room by the thermostat the valve will open more.

"The function of the thermostat is to measure the ambient temperature, compare this with the required temperature and correct the valve setting in accordance with the difference (Figure 2.8). *The European Standard EN215 requires that radiator thermostats meet various operating criteria."*

(Danfoss 2010)

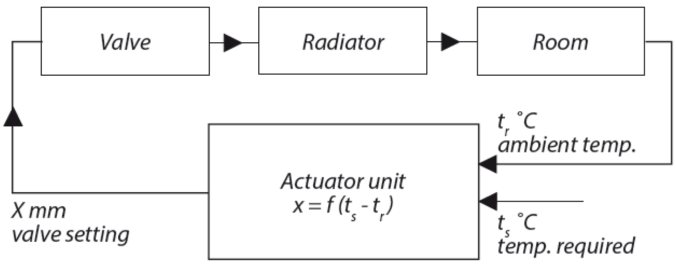


Figure 2.8 Operating principles of thermostats (Danfoss 2010)

The required room temperature is set by turning the setting dial. The temperature scales show the correlation between scale values and the room temperature.

"The temperature scales are stated according to European standards at Xp = 2°C. This means that the radiator thermostats close at a sensor temperature, which is 2 °C higher than stated on the temperature scales."

(Danfoss 2011)

Figure 2.9 presents an example of the temperature scale and the correlation between the values on the thermostat and room temperature (for guidance only). The thermostats have built-in sensors with frost protection; the temperature range is 5-26°C, and the possibility for limiting and locking the temperature set point. Note: the temperature values stated are for guidance only as the obtained room temperature will often be influenced by installation conditions.

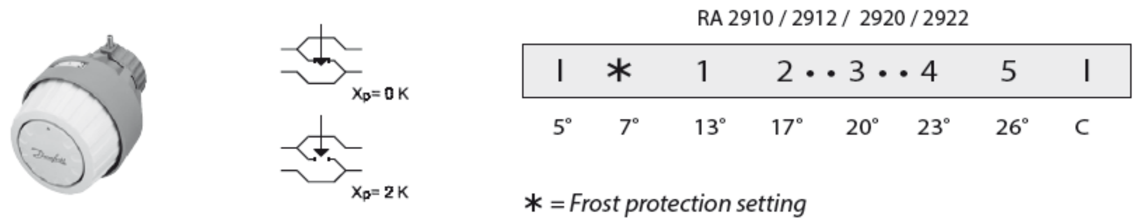


Figure 2.9 Example of thermostats with build in sensors, temperature range 5-26°C (Danfoss 2011)

In order for a sensor to measure a correct room temperature it should be fitted properly. Thermostatic radiator valves (TRVs) should be placed in a way that the measurements are not affected by hot radiator temperatures, i.e. the thermostat is not blocked by, for example, a curtain. In case of a remote controlled thermostat, it should be easily accessible and readable. Remote sensors for TRVs should be installed in situations when the valve is inaccessible for adjustment and air cannot freely circulate through the valve.

Considering what variable is measured by a thermostat is also important, as it may affect the way the thermostat is being operated. Most thermostats measure air temperature, and as it has been proven by P.O. Fanger (Fanger 1970) the thermal comfort of a person depends on several factors, including air and mean radiant temperature, relative humidity, air velocity, metabolic rate and clothing level. Thermostatic sensors that ignore the radiant temperature can lead to user misunderstanding of thermostat settings and consequently thermal discomfort. For example, a person next to a poorly insulated window will feel cold due to radiant heat exchange, and will want to increase the setting on a thermostat.

User awareness and behaviour are probably the least thought of, but one of the most influencing factors when it comes to efficient room temperature control. A study by (Peffer et al. 2011) through surveys about residential thermostats control in the U.S. showed that consumers do not universally understand the distinction between the types of thermostats even though manual and programmable thermostats have very different capabilities. By interviewing 27 office occupants in 13 Finnish buildings (Karjalainen & Koistinen 2007) found that the temperature controls were often not used in thermal discomfort, and that the main reason for many of the problems is that the systems are planned and constructed without a realistic view of their users, and that the end users are presumed to have knowledge they don't have.

Classification of thermostats that are used today is not universal, and as it was noted by (Peffer et al. 2011) this might be the reason for end users' misunderstanding of the heating controls. Terminology that is used to describe different types of thermostats can be confusing, especially if various names are used by different suppliers and technicians installing a system. The focus of recent research by (Wade et al. 2016) has been on the significant role that heating installers play in influencing the control products that are installed for end users. In this work it was observed that heating installers distinguish between mechanical, digital and smart heating controls, where the last option is suggested mainly to be suitable for only the most technologically competent of users. Table 2.1 gives an overview of room thermostatic controls available today.

	Mechanical	Digital	Smart
Thermostatic Radiator Valve	Built-in sensor / Remote sensor  		
Thermostat	**Electromechanical** 		

Table 2.1 Types of thermostatic control. Images are taken from a product catalogue by (Danfoss 2016)

According to some users of one of the popular line of home smart thermostats from NEST, the product fails to measure and control the room temperature and it does not provide the energy savings that was promised by the producer.

"*Nest's base and faceplate heat up, which causes Nest's temperature reading to be from two to ten degrees higher than the actual ambient temperature in the surrounding room. This defect prevents the thermostat from working properly. As a result, Nest users do not experience the advertised energy savings.*"

(Anon 2013a)

2.1.1.4 Balancing of radiator heating systems

In order to control a heating system efficiently, it is important that the system is balanced.

Balancing of a heating system is done to ensure that at all times there is correct amount of flow in all consumption points. In a heating system, risers, branches and the thermostatic radiator valves need to be balanced.

"In a two pipe system, with a control of temperature in each room, the flow will vary and thereby the available pressure, which in turn means that a pre-set adjustment will only function at full flow. At a decreasing flow the resistance decreases by the square of the flow change, and the exceeding differential pressure must be handled by the thermostatic valve. Imbalance and disturbing noises may arise."

(Danfoss 2000)

Automatic adjusting valves for differential pressure control can be used in order to maintain constant pressure at varying flows in a heating system. They sense the pressure in the supply and return in the riser via an impulse tube, and the possible pressure changes are transferred to a cone in the valve, and thus the differential pressure remains constant (Danfoss 2000).

DS 469 (Dansk standard 2013) demands automatic regulation with individual control of the heat supply to the needs of each zone. Regulation should ensure that the room gets the desired temperature and that there is a possibility of closing the heat supply when there is no need for heating. The requirement implies that the control's sensor must detect the room temperature and that the automation must adjust the heat supply in accordance with the measured room temperature.

When controlling the room temperature the most common control used in Denmark is the thermostatic valves on radiators (more in chapter *2.1.1.3 Thermostats*).

Thermostatic valves should be set at the desired room temperature, and the flow temperature at the valve should be high enough in order to achieve that particular room temperature. The presetting of thermostatic valves is done in order to obtain the design flow in each individual radiator.

Valves are dimensioned for the K_v values, which are calculated according to equation (3), and express water flow q [m^3/h] when pressure difference Δp over the valve is 1bar (100 kPa). The K_v value depends on the degree of the opening of the valve. When the valve is fully open the specific K_v is called K_{vs}.

$$\boldsymbol{K_v = \frac{q}{\sqrt{\Delta p}}} \tag{3}$$

The heat authority of the thermostatic valve needs to be minimum 1.0, which means that they need to have at least that heat amount available at the valve which is required to keep the temperature set on the thermostat. The valve authority S [-] is calculated with equation (**4**), and expresses the ratio between the pressure drop across the valve Δp_v [Pa] compared to the total pressure drop across the entire system Δp [Pa].

$$\boldsymbol{S = \frac{\Delta p_v}{\Delta p}} \tag{4}$$

2.1.1.5 Pump characteristic curves

This sub-chapter aims to provide information about characteristic curves of hydraulic centrifugal pumps (referred to as circulators or pumps), different types and uses of pump regulations, their advantages and disadvantages, as well as their influence on the control of heating systems in terms of night setback.

Pump characteristic (or performance) curves, also known as Q-H curves, show the relation between the flow (Q on the x-axis) and the head/pressure (H on the y-axis). The head of a pump describes the maximum differential pressure that it can handle. The slope of the curve is determined by the manufacturer’s design of the pump. A steep pump curve (high head at low flow) is achieved by an impeller with large diameter, while flat pump curve (lower head over a wide range of flows) can be provided by a small diameter impeller (Siegenthaler 2012). Pump characteristic curves are used for pump selection; there is a range of pump operations on the market to choose from, depending on the specific design of the heating system and the desired outcome. The following pump operation modes will be discussed in the chapter:

- Constant speed pump
- Constant differential pressure at the pump
- Constant pressure at the last valve at the end of the system
- Proportional differential pressure

Constant speed pump

Figure 2.10 presents the principle of a non-adjustable single speed circulator regulation. When a system characteristic curve changes, what is very common in heating systems (for example, thermostatic valve gets closed in one room), the differential pressure in the system changes according to the pump characteristic curve – the speed of the pump. In case of a fixed-speed pump, the pressure increases from nominal to maximum when flow decreases due to valve closure.

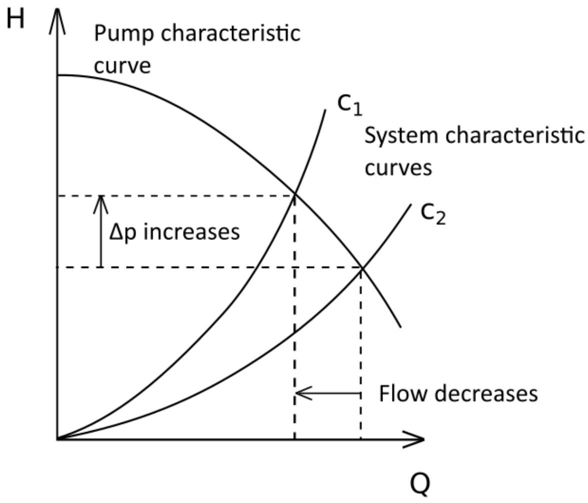


Figure 2.10 Pump with a constant speed regulation: less flow in the system creates higher differential pressure

To reduce the number of circulator models needed and still cover a wide range of performance requirements, most circulator manufacturers now offer wet rotor circulators capable of operating at three different speeds (Siegenthaler 2012). The speed setting is chosen manually, and afterwards the circulator works at constant speed, as shown in Figure 2.10.

Circulators with a fixed speed are not advised to be used in heating systems due to dynamic changes of the heat demand based on boundary conditions of indoor and outdoor temperatures, as well as manual adjustment of thermostatic valves. Non-adjustable pumps can be used in systems, where constant flow is desired and recommended.

Smart circulators

Smart circulators are the new generation electronically controlled pumps, which can adjust their speed according to the load in the system. The so-called self-regulating pumps switch from one speed to another as soon as the flow requirement in the system changes. The differential pressure can either be kept constant, or decrease with decreasing flow – constant or proportional pressure regulation. A smart circulator can therefore lower the running costs of the system: the power use of a pump is calculated from equation (**5**), where Δp is the pressure increase over a pump [Pa], q is the volume flow over the pump [m³/s], and η is the total efficiency of the pump [-], typically $0.8 < \eta < 0.95$ (Lauritsen 2015).

$$\boldsymbol{P = \frac{\Delta p \cdot q}{\eta}} \tag{5}$$

Constant differential pressure at the pump

Figure 2.11 shows the principle of a constant pressure pump regulation. With a pump set to constant pressure mode, pressure remains at the nominal level, despite variations in flow. When flow decreases, the pump automatically switches to a lower speed, while maintaining constant differential pressure.

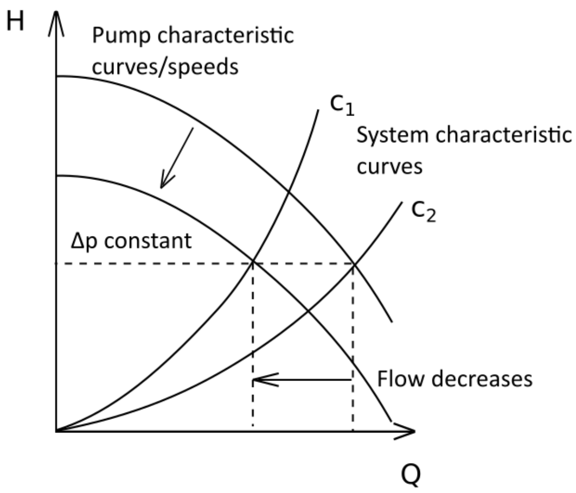


Figure 2.11 Pump with a constant pressure regulation: pressure is not increasing when the flow is decreasing

Constant differential pressure at the last consumer

Another principle for controlling the differential pressure provided by a pump is by having a constant differential pressure at the last branch/valve. When there is a large distance from the pump to the final consumer, the pressure can vary widely depending on the flow.

"*A constant differential pressure at the last consumer gives a lower available differential pressure at a decreasing consumption and at a flow of almost zero, the low differential pressure prevails throughout the whole system. The available differential pressure for valves and branches is determined at a maximum flow. At a maximum flow, the valves and the branches close to the pump will have a considerably higher differential pressure than which they are sized for.*"

(Danfoss 2000)

According to Danfoss, the largest cut in the operating costs for the pump is obtained when the differential pressure is kept constant at the last consumer (branch, valve).

Proportional differential pressure control mode

In case of proportional pressure control mode, the exact pressure requirements will be achieved regardless of the valve position.

"*This is because the pump contains an internal sensor that measures and controls the Δp, the difference between pressure (delivery) and suction (income), in order to meet the needs of different valves throughout the system.*"

(DeVoir n.d.)

Figure 2.12 shows the principle of a proportional pressure pump regulation. When flow decreases, so does the differential pressure.

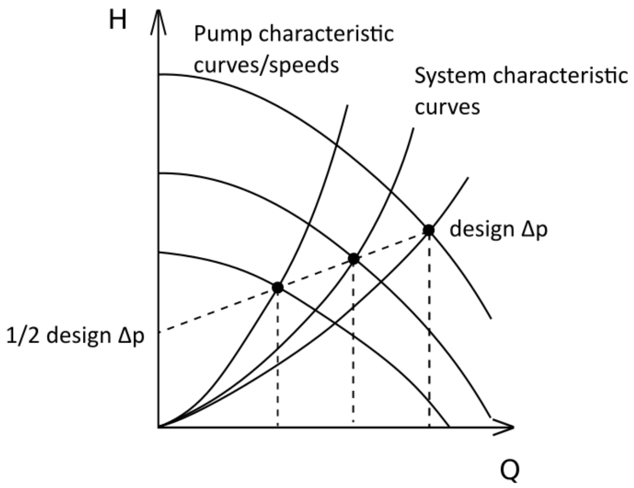


Figure 2.12 Pump with a proportional pressure regulation: pressure decreases with decreasing flow

A more sophisticated form of proportional pressure control was introduced and patented by Grundfos. They offer pumps with a unique auto adapt technology.

"When the flow is subsequently reduced, the auto adapt function ensures that the operating profile does not simply return to the original curve – it sets a new, lower pump speed that results in even greater energy savings."

(Grundfos 2016b)

2.1.2 CONTROL MODES

This subchapter aims to provide the reader with a brief theoretical description of control modes, describes the most common control mode used in HVAC and more specifically in heating systems. The literature used for the subchapter: (Montgomery & McDowall 2009), (Bhatia 2012), (ASHRAE 2009) and (CIBSE 2010).

In general there are two types of control: open loop and closed loop. Open loop control has no feedback, i.e. the controlled variable is not measured in order to monitor that the system works effectively. An example of such control system can be an outdoor temperature sensor (weather compensation) that is used to control the supply temperature (Figure 2.13). The sensor measures the outdoor temperature and sends a signal to the controller. The control system has no way of knowing if the desired internal temperature has been achieved.

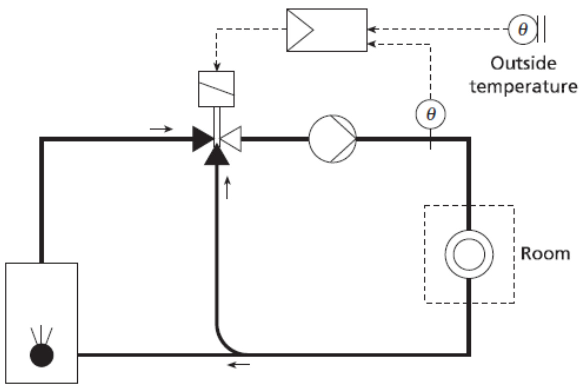


Figure 2.13 Weather compensation for controlling flow temperature (CIBSE 2010)

On the other hand, HVAC control systems are typically closed loop (block diagram in Figure 2.14), where the controlled variable is measured by a sensor, and the error between the desired set point and the measured variable is fed to the controller. The controller then makes a control decision and passes that on to the controlled device (actuator) and to the process plant.

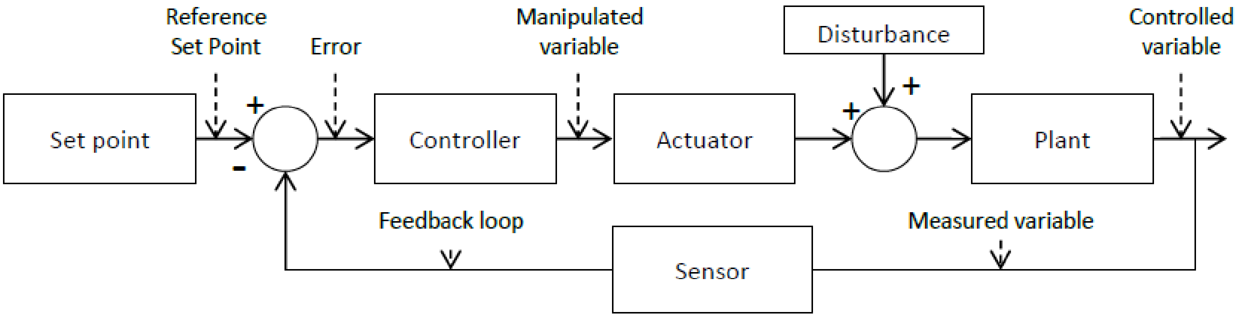


Figure 2.14 Block diagram of closed loop control

Generally control modes can be divided in three types: two-position, floating, and modulating control. Each type includes subcategories depending on algorithms (methods) used by the controller.

1) Two-position (on-off) is the simplest type of control. The controlled variable fluctuates as the controller responds with either maximum (on) or minimum (off) output.
2) Floating control is similar to two-position control, and requires a modulating controlled device. The controller is moving the controlled device towards open/closed position or leaving the device at its current position ("floating").

Table 2.2 gives an overview of two-position and floating control modes, their advantages and disadvantages, as well as examples of their implementation.

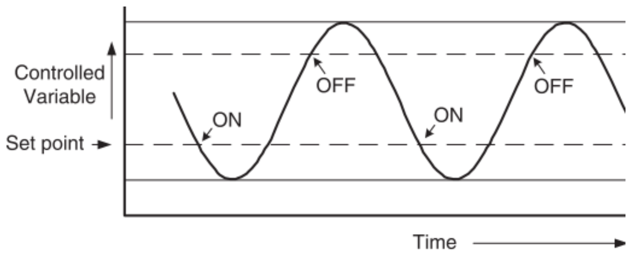
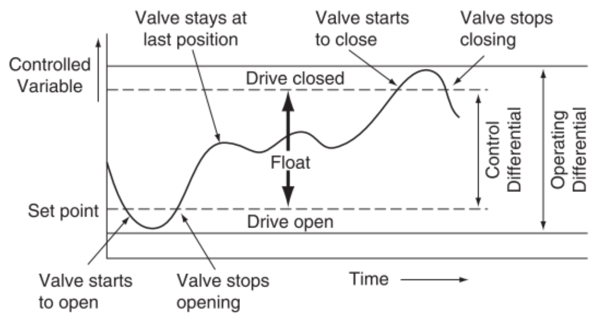
Two-position (on-off)	**Floating**
	
Advantages: simple and cheap	Advantages: can have smaller control differential than two-position without instability or excessive cycling
Disadvantages: set point is reached only for a few moments	Disadvantages: does not function well in systems with high time constant (overshooting/undershooting can occur)
Example: furnace, small AC unit, on-off pumps, valves and dampers	Example: motorized dampers and valves

Table 2.2 Examples of different control types (a). Illustrations' source: (Montgomery & McDowall 2009)

3) Modulating control includes different algorithms: proportional (P), proportional plus integral (PI), proportional-integral-derivative (PID), and others. Adaptive control, fuzzy logic, cascade control, etc. are not described in the report.

With proportional control the controlled device is positioned in proportion to the response to changes in controlled variable. Equation (5) mathematically describes the proportional controller, where the controller output V_p is a sum of offset adjustment parameter V_0 and proportional gain K_p multiplied with the error (or offset) e.

$$\boldsymbol{V_p = V_0 + K_p e} \tag{6}$$

Proportional plus integral control eliminates the offset by adding an integral component to the control action, as described by equation (7). The longer the error exists, the larger the integral term becomes in attempt to eliminate the error.

$$\boldsymbol{V_p = V_0 + K_p e + K_i \int e\,dt} \tag{7}$$

The proportioning action occurs within a proportional band (also referred to as throttling range, control differential) around the set point, outside which the controller acts as an on-off unit.
Proportional-integral-derivative control includes one more term, and the equation becomes:

$$\boldsymbol{V_p = V_0 + K_p e + K_i \int e\,dt + K_d \frac{de}{dt}} \tag{8}$$

Where, *de/dt* is time derivative of error. PID control results in a fast response, although the derivative term makes the controller more sensitive to noise, and tuning more difficult, therefore normally PID control is used when very dynamic behaviour is expected, which is normally not the case in HVAC applications. Figure 2.15 shows a block diagram of a PID-controller.

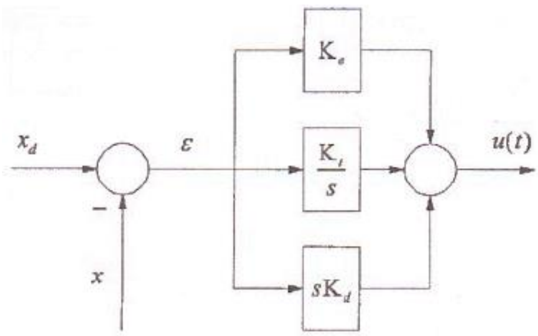
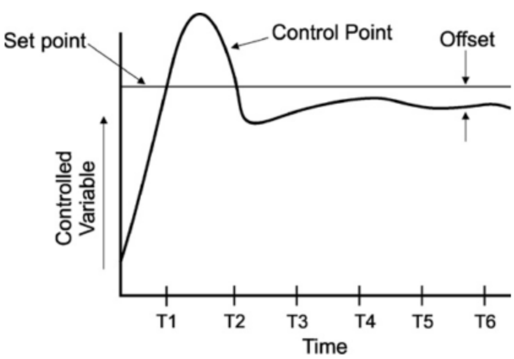
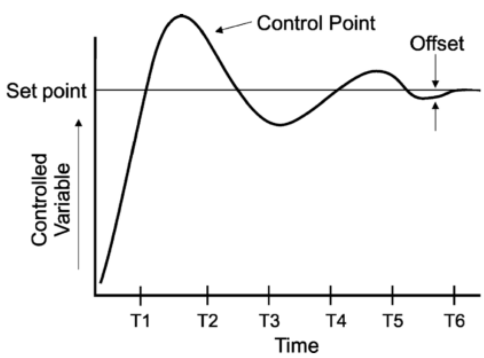


Figure 2.15 Block diagram of a classic PID controller (Manring 2005)

Table 2.3 gives an overview of P and PI control modes, their advantages and disadvantages, as well as examples of their implementation.

Modulating: Proportional (P)	**Modulating: Proportional Plus Integral (PI)**
	
Advantages: fast response	Advantages: fast response, eliminates offset

Modulating: Proportional (P)	Modulating: Proportional Plus Integral (PI)
Disadvantages: There is always an offset from the set point. The bigger the error from set point, the higher the controller output, and vice versa. This creates over-and undershoots. Offset can be decreased by increasing the gain, but then there is risk of oscillations.	Disadvantages: windup. In case the system is shut down, the controller will interpret that as an error over time, destabilizing the system once it is turn on again; solution: anti-windup.
Example: thermostatic radiator valves	Example: most HVAC systems

Table 2.3 Examples of different control types (b). Illustrations' source: (Montgomery & McDowall 2009)

Hydronic heating systems include multiple controlled devices, such as control valves, differential pressure control valves, shut-off valves, flow regulating valves, pumps. All of them require a type of control mode that will afterwards act together with the help of a central controller. Flow regulation at radiators is done by thermostats or thermostatic radiator valves (chapter *2.1.1.3 Thermostats*) – that can be described as modulating control. Simple bimetallic thermostats act as on-off control, most TRVs are proportional direct-acting controllers, and modern programmable thermostats are based on PI control.

2.2 WAYS TO SAVE ENERGY WITH HEATING CONTROL

This subchapter describes the two methods used to reduce energy consumption for heating: weather compensation and night setback. It gives an overview of what these strategies imply; where, how and why they are implemented.

Furthermore, an important aspect of thermal mass of a building when applying night setback is studied through literature review and simulations in IDA ICE software.

As a conclusion of the subchapter the reader is presented with information from the Danish Knowledge Centre for Energy Savings in Buildings regarding potential energy savings when implementing the discussed ways to optimize control of heating systems.

2.2.1 WEATHER COMPENSATION

Danish District Heating Association (Dansk Fjernvarme) supplies 62 % of Danish households (1.6 million) with district heating and cover around 52 % of space heating demand in all buildings (International District Energy Association 2016). As the weather changes frequently and it has the main impact on the indoor temperature of a building, there is a permanent need of heating control. Besides the thermostatic radiator valves, which are the most common type of heating control for buildings, there is another approach – the weather compensation, which is also widely implemented in buildings connected to district heating.

In a heating system, the flow temperature must be adjusted according to the outdoor temperature in order to achieve the desired room temperature. A more accurate control can be achieved if the system uses the weather compensation to predict the need of heat and adjust the flow temperature to compensate the future changes.

Weather Compensation in District Heating Systems

"Intelligent weather compensation performed by a correctly commissioned electronic heating controller optimizes the energy efficiency of a district heating system by reducing the return temperature. This creates energy savings of around 10-15% and longer system life."

(Uhd Noergaard 2016)

The optimum heat supply for a building is when the demand is met and nothing is in excess. An intelligent electronic controller for the weather compensation in the heating system can adjust the supply of heat needed to keep the desired room temperature by detecting changes in the weather conditions outside. This can lead to valuable way to improve the energy efficiency of the heating system. In reverse, a heating system without a weather compensator will only react on the current indoor temperature, and thus be likely to be in delay when changes occur outside. This negatively affects both user comfort and energy efficiency.

In a building without a weather compensator the flow temperature to the radiator is not adjusted automatically according to the changes in the outdoor temperature. When the outdoor temperature is decreasing, the room temperature will also decrease. The flow temperature will not be sufficiently high to compensate for the higher demand for heat, because the valve is at a static position (for example 10% open). If there is no weather compensator, the temperature is dependent on a room thermostat, which will only take effect after the inside of the building has become too cold (or too warm). This may result in discomfort for the users. Until this point, the user probably will turn on the thermostat even more thus wasting energy. With a weather compensator, the change in the system will happen as soon as there is a change in outdoor temperature.

The weather changes constantly and so does the heat load required to heat up the building, therefore the weather compensation is an important aspect.

How does it work?

A weather compensation unit consists of:

- Control unit
- Control motor control valve
- Sensor for outdoor temperature
- Sensor for flow temperature
- Sensor for return temperature (optional)
- Timer (optional)

(Danfoss 2000)

The control station adjusts the flow temperature in relation to the outdoor temperature. The weather compensation box gets its information regarding the outdoor temperature from a sensor placed on the north facade of the building. The outdoor sensor detects the temperature fall or increase as soon as it happens, and it sends this information to the control station. The heating curve that is implemented in the control box dictates the desired flow temperature at different outdoor temperatures. The measured value is compared to the desired value through a flow sensor, and if these two values do not correspond, the electronic controller adjusts the heat supply to the radiators (by opening or closing the control valve) to reflect the new conditions and to make sure that the desired room temperature is achieved and kept constant in the room.

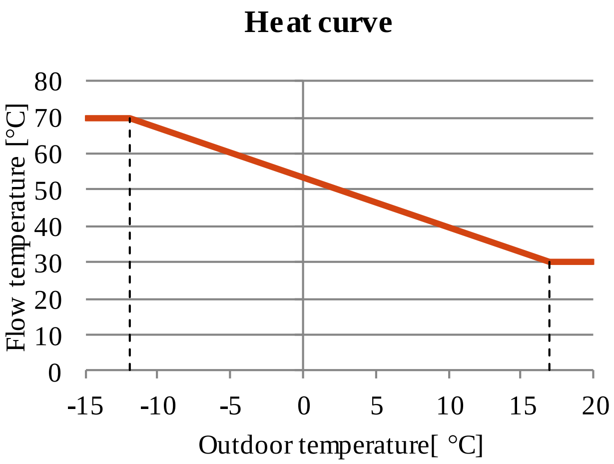
Heat curve

The controller determines the flow temperature related to the outdoor temperature. This relation is called the heat curve. The heat curve represents the desired flow temperature at different outdoor temperatures.

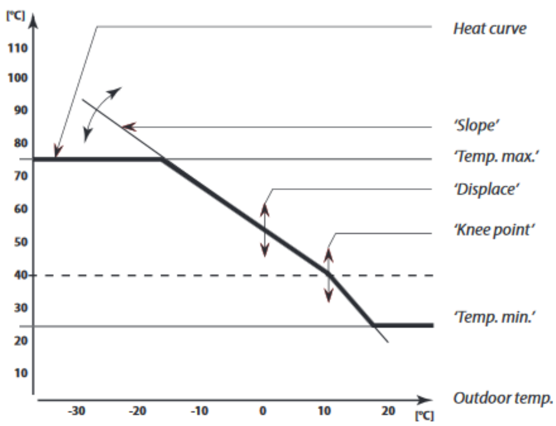
The heat curve is the most important setting for the weather compensation feature to operate optimally. The goal is to have as low slope as possible but at the same time to reach the desired room temperature and energy efficiency of the heating system. The initial slope of the curve depends on two factors: type of heating system and the heat demand.

The factor that affects the initial heat curve slope is the weather, which has the highest impact on the heat demand of the building. A low outdoor temperature will result in a higher flow temperature need and at a higher outdoor temperature a lower flow temperature is required in order to achieve the desired room temperature.

As an example, a simple heat curve (Graph 2.1) shows that at an outdoor temperature of 0 °C the desired flow temperature will be 55 °C. When outdoor temperature is higher than 17°C there is no need for heating anymore and the minimum flow temperature is 30°C. It should be mentioned that an assumption of 20 °C for room temperature is used for the curve; in case of higher desired room temperature the slope of the curve will change. When increasing the room temperature set point on the controller, it will have an influence on the calculated flow temperature, i.e. heat curve, no matter if a room temperature sensor is connected or not. However, if a room temperature setting was changed manually by turning up thermostats and not modifying the set point on the controller, then the flow will increase, chapter *2.3.2 Change in ambient temperatures*.



Graph 2.1 Simple heat curve. Supply temperature decreases proportionally to the outdoor temperature increase.



Graph 2.2 Parameters of a heat curve (Danfoss 2008)

Graph 2.2 shows another example of a heat curve, where different parameters are explained. In this example the heat curve bends and becomes steeper at a “knee point” of 40°C supply temperature, corresponding to approx. 10°C outside, meaning that at outdoor temperatures higher than 10°C the supply can be reduced at a higher rate.

The heat curve must be set in order to ensure that the flow temperature is high enough to achieve the desired room temperature at any outdoor condition, but at the same time not having a too high flow temperature and waste energy. In order to save energy the adjustment of the slope of the heating curve is of a great importance. In accordance to Danfoss the slope of the heating curve is typically high in buildings with high heat demand (poor insulated buildings, small radiators) and low slope in good insulated buildings with well-dimensioned radiators or in case of floor heating systems.

The heat curve slope needs to be set after the installation of the controller and regularly optimized especially when the temperature drops below 0 °C. According to Danfoss the initial heat curve slope should be changed by 0.1 at a time during a span period of one-two weeks, preferred in winter season because the impact will be higher.

Advantages of weather compensation are:

- Gradually feeding energy to the building
- Heat source running at a lower and more efficient rate
- Less heat loss from pipes, valves etc.
- Reduction of cycling (on /off), thus less premature failure
- Increase level of comfort (steady temperature)
- No need to turn of heating
- Potential saving up to 15%
- Increased value of the building

To summarize, weather compensation controls enable the system to respond to outside temperature changes and adjust the radiator output, to maintain a constant temperature indoors. Weather compensation facility should also contain a function that makes it possible to lower the room temperature at certain times, for example at night (setback). When a new desired room temperature will be defined, the controller will make a new calculation of the needed flow temperature. Some controllers have a function that helps avoid load peaks in the heat supply after a period with setback temperature. They gradually increase the desired flow temperature by allowing a valve to open gradually in a period of e.g. one hour before the room temperature set point changes to "day" or "comfort" setting.

2.2.2 NIGHT SETBACK

The following chapter aims to provide basic knowledge and understanding about setback temperatures, their advantages and disadvantages. The chapter also includes a summary of the most important considerations when applying setback temperatures.

A temperature setback is a simple strategy to save energy by reducing the heating or cooling system operation time. This is done by allowing the temperature in a building to drift to a lower (heating mode) or higher (cooling mode) temperature.

In Denmark the design of heating systems is done according to DS 469, where it is stated that:

"Heating systems in buildings with well-defined usage time, e.g. offices, shops, day care centers and schools must be fitted with timers that automatically stop or reduce heating outside its usage time. The timing can either be controlling the heat supply to the heaters or by controlling the individual heaters directly, for example by shutting off the heater, or by lowering room temperature set point outside of the usage time."

(Dansk standard 2013)

The comfort of occupants is of great importance when applying a setback temperature in a building. The best approach to implement a setback strategy is to allow lower temperature when there are no occupants. This can include daily schedules or schedules for vacant periods. A setback schedule works best for people with predictable work and sleep periods. If their schedule is completely irregular, setback will not be efficient in terms of comfort and energy savings. In case of commercial buildings the night-setback can be a good way to save energy for heating. It is very important to carefully plan the setback period in order to allow enough time for reaching desired temperature before the occupants arrive in the building.

Theoretically, any level of temperature setback, no matter if it is done manually or through a programmable thermostat, will result in energy savings. This is because the less the temperature difference between outdoor and indoor, the less the heat losses will be. The extent of savings that can be achieved is dependent on two parameters: the period of setback and the temperature. In theory the longer the setback time and the greater the setback temperature, the greater the savings. Though, in reality this may not always be the case – if the setback temperature during the night is too low, then in the morning a lot of energy will be used to heat up the building, and thereafter all the savings which are made during the setback time can be lost for preheating.

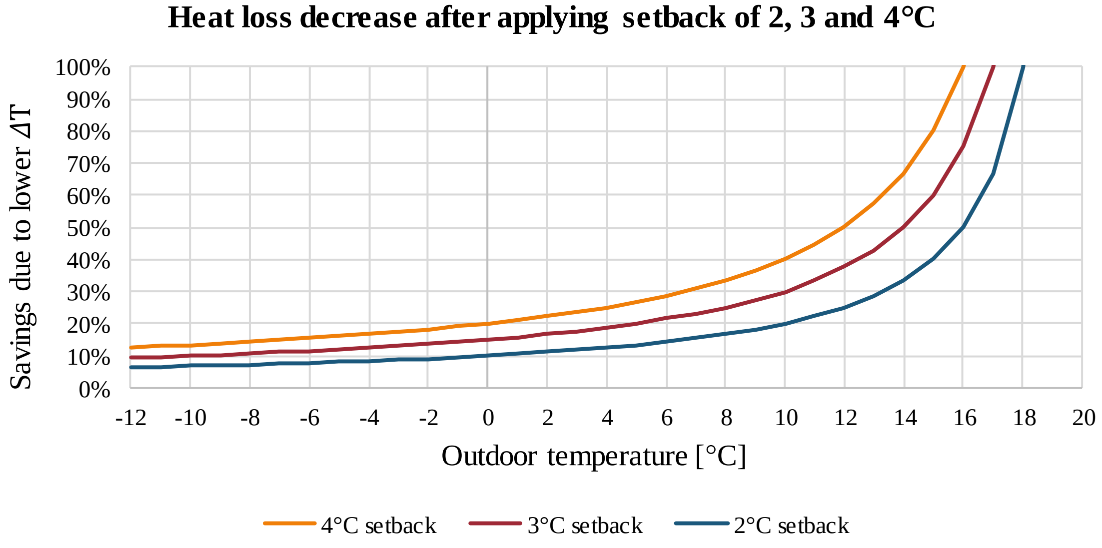
The influence of the temperature difference to the heat loss is expressed by equation (9).

$$\boldsymbol{Q = U \cdot A \cdot \Delta T} \tag{9}$$

Where Q [W] is the transmission heat loss, U [W/m²K] is the U-value of the component, A [m²] is the area of the component and ΔT [K] is the temperature difference between inside and outside.

If the U-value and the area are assumed as constant values, it can be concluded that the heat loss is proportional to the temperature difference and any reduction in heat loss can be counted as a saving. As an example, the effect of applying different setback temperatures to the heat loss is calculated in percentage and plotted on Graph 2.3. A ratio is made between the temperature differences after applying the setback and the original temperature difference (assuming indoor temperature T_{i0}=20°C in all cases). The saving can then be expressed as:

$$\frac{Q_x}{Q_0} = \frac{(T_{i,setback} - T_o)}{(T_{i0} - T_o)} \text{ and } Saving = \left(1 - \frac{(T_{i,setback} - T_o)}{(T_{i0} - T_o)}\right) \cdot 100\% \tag{10}$$



Graph 2.3 Effect of applying different setback temperatures to the heat loss

It can be read from the graph that, for example at 0°C outdoor temperature, having a setback with 2°C (20°C-18°C=2°C) will result in 10% savings; with 3°C – 15%; and with 4°C setback – 20%. An assumption is made for the calculation that the setback temperature is achieved.

However, aiming for bigger savings by allowing too low temperature may cause not only discomfort due to too high relative humidity (in Denmark the relative humidity in comfort range varies between 30 and 70%), but also moisture problems in the building envelope, especially during the winter period. (CEN 1998). The reason for this is that cold air can contain less moisture than warm air, which means that the relative humidity will rise as the air cools. Too high temperature drop can cause condensation on windows surfaces and building envelope components.

The effectiveness of a setback temperature also relies on the type of heating system. Setback of a system works better with systems which have low thermal inertia. Systems with high thermal inertia need longer period to respond (for example if there is large amount of water to be heated before releasing heat to the building). Therefore, systems connected to district heating are very suitable for applying setback. However, in the cases of underfloor heating it may not be a good idea due to the slow response time of the system. On the other hand, radiator systems with district connection are theoretically one of the best candidates for applying setback temperature due to their comparatively fast response time and low thermal inertia.

Summary of considerations when applying setback temperature:

- comfort of the occupants – fixed schedules;
- degree of setback temperature – RH, preheating time, comfort of the occupants;
- type of heating/cooling system – setback works well with systems with low thermal inertia and fast response time.

The control of setback temperature can be divided generally in two types: manual and automatic. Manual control implies changing the setting on a TRV every time a user wants to reduce the room temperature. In case of dwellings or domestic buildings such option can easily be applied, although in big buildings, such as offices and schools, the procedure can be tedious. The solution is the automatic control, which offers more flexibility and potentially improved comfort. In order to implement automatic control, thermostats should have programmable options, which will allow the building operator to vary the temperature set point automatically based on the building use. There are different types of thermostats that can help achieve the desired effect of setback, and they can be classified in three types:

- Electromechanical thermostats - use an electrical clock and a series of pins and levers to control temperature. This is usually the least expensive with ease of operation but have limited flexibility;
- Digital thermostats - offer more flexibility to tailor settings to differing schedules for different days of the week or up to 6 set points per day;
- Occupancy sensor thermostats - maintain the setback temperature until triggered by a person entering the controlled space. The trigger mechanism can be a switch, button, light, or motion sensor.

(Energy Star 2010)

More about thermostats in chapter *2.1.1.3 Thermostats.*

Night setback strategy with different pump operations

During a night setback, when the supply temperature is lowered, thermostatic valves will open when detecting a drop in room temperature. A 2^{nd} generation electronically controlled pump will misinterpret the temperature drop as an increased heat demand and it will speed up to compensate for it (Bidstrup 2002). There is an increase in mass flow and power consumption by the circulator, and the night setback of room temperatures is not achieved. To prevent this, a circulator must react to a drop in supply temperature and keep the flow at minimum.

"Some smart circulators also contain an internal temperature sensor that allows them to detect a sustained drop in water temperature associated with night-setback. When the circulator's firmware determines that night-setback is in effect, it automatically reduces the flow rate."

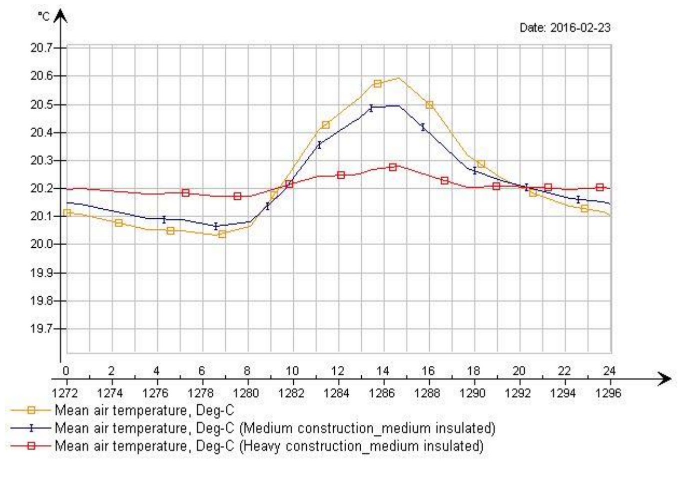
(Siegenthaler 2012)

The drop in supply temperature for night setback can vary form 10°-15°C, depending on the desired reduction in room temperatures. The new generation circulator pumps, detecting such temperature drop over a period of approx. two hours will automatically change to night setback. A speed-controlled pump, or a pump with proportional pressure control function, can handle varying load conditions and adjust to the demands of the system. When the pump is in constant-speed mode automatic night setback cannot be enabled (Grundfos 2016a).

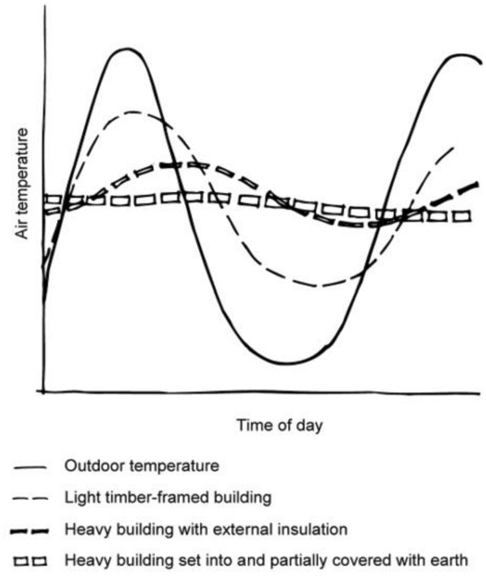
2.2.2.1 Setback influence on different building constructions

A consideration when applying setback temperature should be the comfort of the occupants and preheating time. This can vary greatly depending on the thermal mass of the building.

Thermal mass is the ability of a material to absorb and retain heat energy. Materials with high density require more energy to change their temperature (for example concrete, brick), and in reverse lightweight materials with low thermal mass, such as wood, require less energy. In a building with low thermal mass, heat that has entered the space will simply re-radiate back fast, making the space too hot with solar heat gain and too cold without it. Even though the thermal mass will not prevent the heat from escaping the room, it will help with slowing down the heat flow and create a better comfort for occupants (less fluctuations of indoor temperature). In Graph 2.4 can be seen the indoor temperature for tree different buildings for one day simulated in IDA ICE, the indoor temperature in the heavy building is fluctuating the least, in reverse to the light building(represented by yellow line) where the temperature fluctuates the most. Graph 2.5 presents another example of indoor temperature fluctuations in different type of buildings.



Graph 2.4 One day indoor temperature fluctuations from IDA ICE



Graph 2.5 Temperature fluctuations for different type of constructions (YourHome, 2013)

More about thermal mass in Appendix B.

Heat capacity and time constant

Heat capacities represent the ability of a building component to store energy from either side when the corresponding temperature varies periodically. Scientifically, thermal mass is equivalent to heat capacity, the ability of a body to store energy. It is typically referred to by the symbol *C* and measured in units of [J/K].Heat capacity is calculated as follows:

$$\mathbf{C} = \boldsymbol{m} \cdot \boldsymbol{Cp} \tag{11}$$

Where *m* is the mass of the body [kg] and C_p is the specific heat capacity [J/kg K].

The time constant is the result of the internal heat capacity of the building, divided by the average transmittance of the components that build up its thermal envelope. In other words, on one side this value depends on the amount of heat stored inside the building, and on the other, on how much it is insulated. The time constant is calculated for the building as a whole and not by individual components.

The time constant of a building is calculated as follows (S.Larsen 2008):

$$\boldsymbol{\tau} = \boldsymbol{A}\,[\boldsymbol{m}^2] \cdot \frac{\boldsymbol{C}\left[\frac{\boldsymbol{Wh}}{\boldsymbol{Km}^2}\right]}{\boldsymbol{H}\left[\frac{\boldsymbol{W}}{\boldsymbol{K}}\right]} = \frac{\boldsymbol{Cm}\left[\frac{\boldsymbol{J}}{\boldsymbol{K}}\right]\Big/\boldsymbol{3600}}{\boldsymbol{H}\left[\frac{\boldsymbol{W}}{\boldsymbol{K}}\right]} \tag{12}$$

Where $\boldsymbol{\tau}$ is the time constant in hours [h], *A* is the heated floor space of the building in, *Cm* is the building thermal capacity, and *H* is the building heat loss in [W/K]. The time constant is a measure of how quickly the interior of the building responds to a temperature differential between inside and outside. The longer the time constant of a building the longer the building will remain warm. A high time constant is especially good for buildings, which are permanently occupied such as residential buildings. The time constant is determined by the type of building structure. The higher the thermal constant of a building the longer will be the time to affect the indoor conditions of a room, regardless whether this change is caused by external condition or by the heating system.

In Denmark in order for a new building to get a building permit, it has to comply with regulations on maximum energy demand in kWh/m² per year. The calculation of building energy need is performed using software Be15 (Aggerholm & Grau 2008), where it is recommended to specify the building's heat capacity according to one of the four categories: extra light, medium light, medium heavy, and extra heavy. The values for the different categories are given in Wh/K·m², see Table 2.4.

DS/EN ISO 13790		Be15			
Class / units	**[kJ/K·m²]**	**Class / units**	**[Wh/K·m²]**	**[kJ/K·m²]**	**Description of internal construction**
Very light	80	Extra light	40	144	Light walls, floors and ceilings, e.g. skeleton with boards without any heavy structures
Light	110	Medium light	80	288	A few heavy structures, e.g. concrete slabs with wooden floor or light-weight concrete walls
Medium	165	Medium heavy	120	432	Several heavy structures, e.g. concrete slabs with clinker and brick or clinker concrete walls
Heavy	260	Extra heavy	160	576	Heavy walls, floors and ceilings of concrete, brick and clinkers
Very heavy	370				

Table 2.4 Thermal capacity of buildings according to different standards: (Dansk Standard, 2008) and (Aggerholm & Grau 2008)

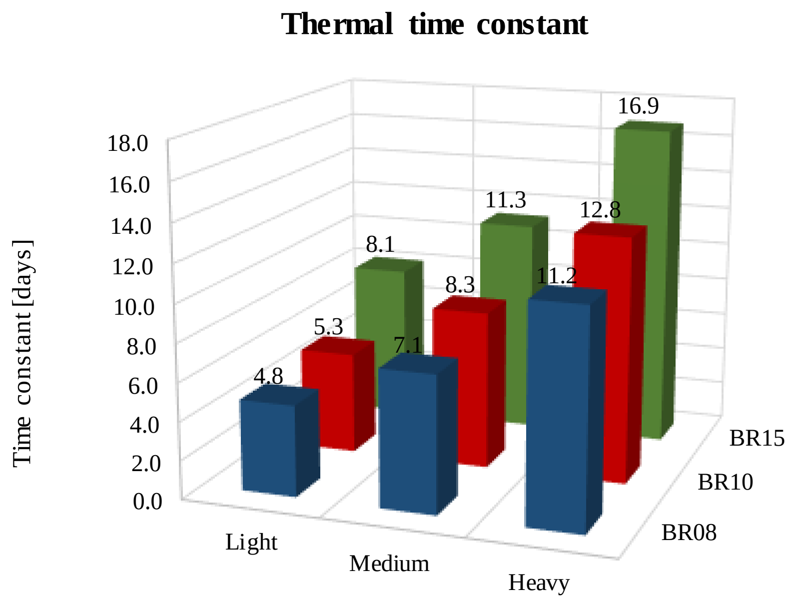
Comparing these values to the ones given in standard DS/EN ISO 13790 (Dansk Standard 2008), it is noticed that the thermal capacity used in Be15 is much larger. For example, medium light building in Be15 has a thermal capacity of 288 kJ/K·m², while a heavy building in DS/EN ISO 13790 corresponds to 260 kJ/K·m². Additionally, a study by (Olsen 2008) indicates that it can normally not be expected that a detailed calculation will provide a larger heat capacity than when the Danish tabulated values are used, and that there might be a need for assessment of the Danish tabulated values to check whether the level of heat capacity is appropriate. Therefore, further calculations and simulations will use the thermal capacity values given in DS/EN ISO 13790.

A simple calculation of the thermal time constant is performed for different combinations of construction (light, medium and heavy) and insulation levels (poor, medium, and super). The thermal time constant is defined as the ratio of a building`s thermal mass and overall heat loss and it is calculated with equation (12). The time constant is a measure of how quickly the interior of the building responds to a temperature differential between inside and outside.

Specific heat capacities for the components are used according to standard DS/EN ISO 13790 - Table 2.4. And heat transfer coefficients are calculated using minimum U-values according to BR08, BR10 and BR15 – Table 2.5. The area of the external wall is 11 m², and the window area is 3 m².

	External wall U-value [W/m²K]			**Window U-value [W/m²K]**	**Cm [kJ/K]**			**H=UA [W/K]**		
	Light	Medium	Heavy		Light	Medium	Heavy	Light	Medium	Heavy
BR08	0.2	0.2	0.2	1.5	2750	4125	6500	6.7	6.7	6.7
BR10	0.19	0.17	0.18	1.3	2750	4125	6500	5.99	5.77	5.88
BR15	0.11	0.14	0.16	0.9	2750	4125	6500	3.91	4.24	4.46

Table 2.5 Parameters used for time constant calculation



Graph 2.6 Thermal time constant for different buildings

Time to reach setback temperature in different buildings – hand calculation

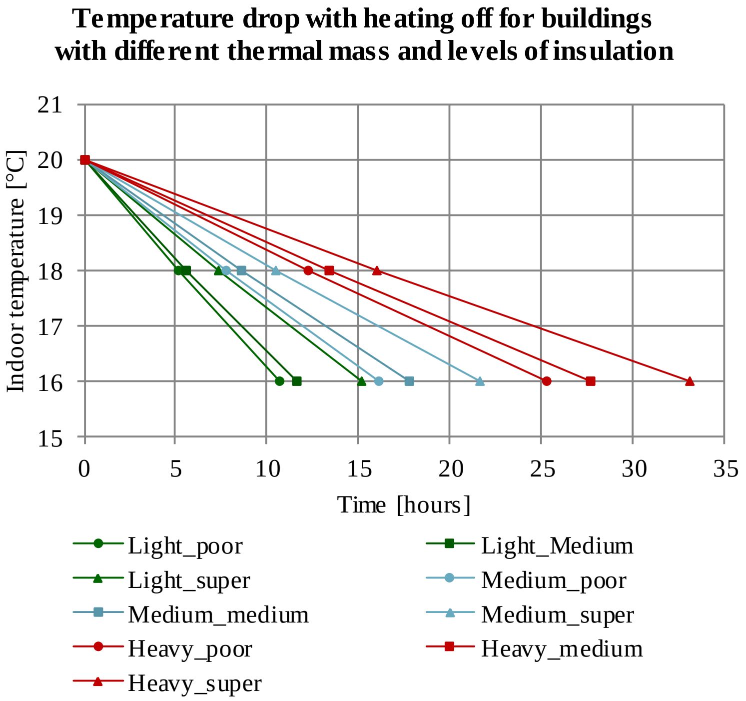
A simple calculation using equation (13) is done with the aim of estimating how different buildings react to a temperature drop depending on their thermal mass C [J/K] and overall heat transfer coefficient $H = UA$ [W/K]. The equation determines room temperature versus time, once heat output is turned off; the lower the ratio of heat loss divided by thermal mass, the slower the temperature will drop (Siegenthaler 2012).

$$\boldsymbol{T_r = T_o + (T_{ri} - T_o) \cdot e^{-\left(\frac{UA}{C}\right) \cdot t}} \tag{13}$$

The time t [h] for room air temperature to drop from initial condition T_{ri} to a setback point T_r is then

$$\boldsymbol{t = \frac{\ln\left(\frac{T_r - T_o}{T_{ri} - T_o}\right)}{-\left(\frac{UA \cdot 3600}{C}\right)}} \tag{14}$$

Outdoor temperature T_o is assumed at -12°C. Graph 2.7 presents the results of the calculation; it is shown that the light buildings (green lines) cool down faster than the heavy ones (red lines), for example it will take around 33 hours for the room temperature in a very well insulated heavy building to decrease from 20 to 16°C, while in a light building such step change will happen after only two-three hours. This suggests that setback strategy will create potential for energy savings in lighter buildings.



Graph 2.7 Time to reach setback temperature for buildings with different thermal mass and levels of insulation

2.2.2.2 IDA ICE Simulations

IDA Indoor Climate and Energy (IDA ICE) is a building simulation tool, which is used for studying energy consumption, indoor air quality and thermal comfort. In principle, any systems of any kind can be simulated with the aid of the general functionality of IDA ICE. Normally, the systems consists of a building with one or more zones, a primary system and one or more air-handling units. Weather data is provided by choosing a climate file, or by inputting a fixed value for the outdoor temperature for a 24-hour period Figure 2.16.

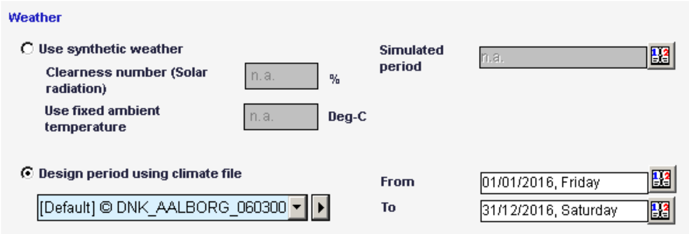


Figure 2.16 Weather input options

Predefined building components and other parameter objects can be loaded from a database.
The first version of IDA ICE was released in 1998 and the present version, 4.7, was released in February 2016. IDA ICE is commercially available and marketed by the Swedish company EQUA Simulation AB.

"The model library of IDA ICE was written in the Neutral Model Format (NMF). NMF is a program-independent language for modelling the dynamical systems by using differential-algebraic equations. IDA, on which IDA ICE is based, is a general-purpose simulation environment, which consists of the translator, solver, and modeller. The Division of Building Services Engineering, the Royal Institute of Technology in Stockholm (KTH), and the Swedish Institute of Applied Mathematics (ITM) have developed IDA. The mathematical models of the IDA ICE have been developed at the Royal Institute of Technology in Stockholm and at the Helsinki University of Technology."

(Kalamees 2004)

IDA ICE is most recently validated according to ASHRAE 140, 2004; EN 15255, 2007; EN 15265, 2007; EN 13791; International Energy Agency SHC Task 34 and Techanical Memorandum 33 (TM33). There is also available validation upon request, according to sustainability shemes like LEED, BREEAM and DGNB. (EQUA 2016)
The IDA ICE dynamic multi-zone simulation is used in this project for study's of indoor comfort and energy usage in reference models and for the case study (Vester Mariendal School). The IDA ICE program is used for different tests for example to investigate the setback startegy in different buildings, to evaluate the thermal comfort, to investigate the energy consumption with & without setback.

The following part of the report includes the investigation of setback temperature in nine different zones. The investigations are performed throughout simulations in IDA ICE software. The weather file used in the simulations is from ASHRAE2013 for Aalborg location. By different zones, is meant different thermal mass of the construction with combination of different amount of insulation. The room model used in the simulations has the parameters as described in Table 2.6. More details about the parameters of the nine zones can be found in Appendix D.

A_f (floor area)	25 m²
A_w (window area)	3 m²
A_{wo} (wall area facing outside)	11 m²
H (room height)	2.8 m
V (room volume)	70 m³

Table 2.6 Room model parameters

All nine zones have each: one window and one external wall, while the other walls are defined as internal walls, and the floors and ceilings are defined as internal components/partitions. The thermal zones have the same internal dimensions 5m x 5m x 2.8m height. The window is facing South in all cases. The components are defined by using the requirements from the Danish Building Regulations

2008, 2010 and 2015, and the U-values are as indicated in Table 2.7. Note part of the construction components of the IDA ICE room model are adapted from (Le Dréau et al. 2013).

Building Regulations	External wall	Window
2008 (poor)	0.2	1.5
2010 (medium)	0.17	1.3
2015 (good)	0.14	0.9

Table 2.7 U-values of the components used in the simulations

Thereafter, the building thermal accumulation will vary according to the type of construction (light, medium, heavy), and the U-values and infiltration according to the insulation and airtightness.

For the simulations it is assumed that the rooms are not ventilated (except infiltration) and internal loads from people, lighting and equipment are disregarded. Note: even though the zones are built separately in different building bodies, the infiltration is applied only once at the building level when all nine buildings are created in the same file in IDA ICE.

The heat emission from the radiator in IDA ICE is calculated as:

$$\boldsymbol{P = K \cdot l \cdot dT^n} \tag{15}$$

Where l is device length and dT is the temperature difference between the mean surface temperature of the equipment and the air temperature (logarithmic mean temperature difference). K and n are constants characterizing a device of a certain height.

The alternative data input for the radiator was used in this case, meaning that the values for the design mass flow and K were calculated by the software based on the inputs of maximum power and design temperature conditions (70/40/20). The value for N (the exponent of power curve) is 1.3. Water radiator with Proportional (P) control is implemented in all the zones. The P-band for the proportional controller is set to 2 °C.

Following scenario it is assumed: all nine cases have same schedules for occupancy from 08 to 16 o'clock; the heating schedule starts 2 hours before the occupancy period (6 o'clock) and ends at 16 o'clock; heating set point during occupancy is 20°C and the setback set point is 16°C (Figure 2.17). The simulation is performed for one day with constant outdoor temperature of -12°C; all zones have same value for the maximum radiator output ; P control – operative temperature.

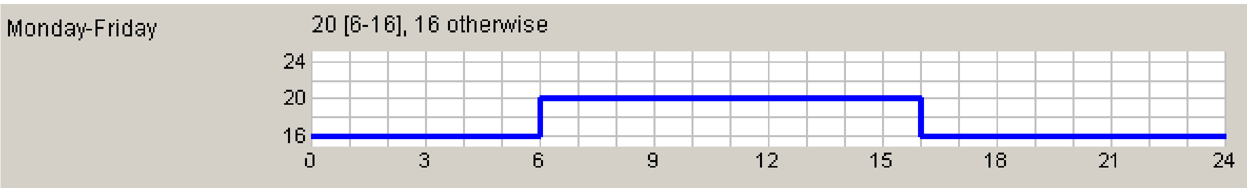
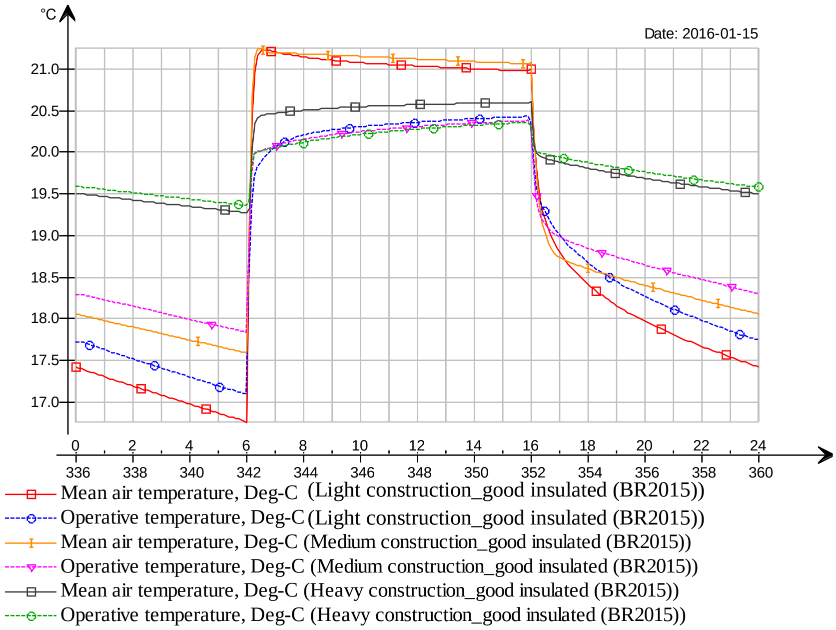


Figure 2.17 Heating schedule

The objective is to see how the different buildings react to the implemented setback. The results of the simulations in the graphs are presented by construction type (light, medium, heavy) and by having same insulation level, at first BR2015 than BR2010 and BR2008.

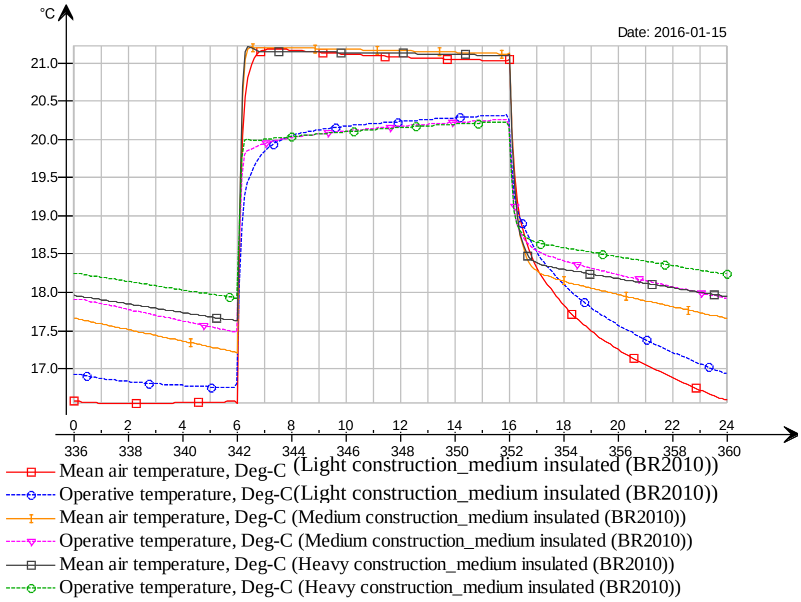
On Graph 2.8 the air and operative temperature for the light, medium and heavy constructions with insulation level according to BR2015 are plotted. First entries on the legend (red and blue) are for heavy construction, good insulated.



Graph 2.8 Indoor temperatures for light, medium, heavy buildings with insulation level (BR2015)

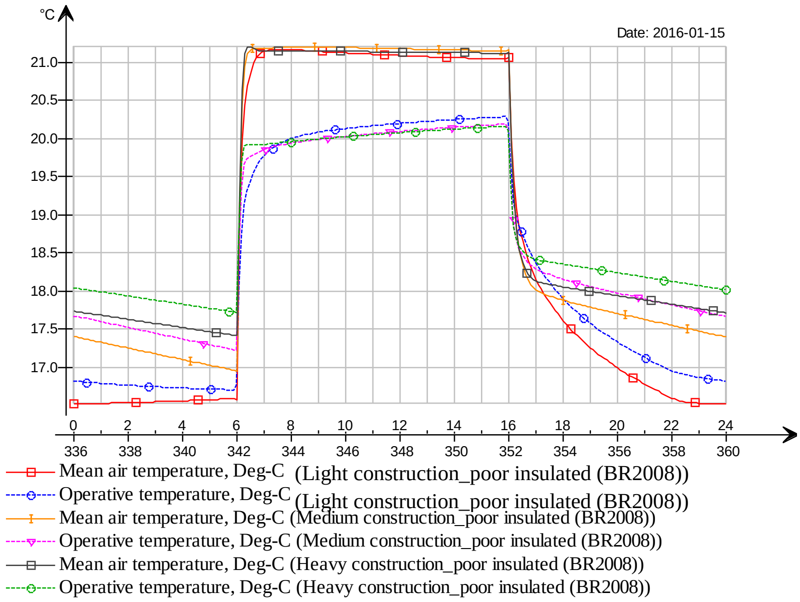
From Graph 2.8 it can be seen that in light, medium and heavy buildings insulated according to BR2015, the drop in temperature after 16 o'clock is different in the three building constructions. In the heavy building the temperature drops much slower compared to the other two buildings, this is due to the high heat accumulation that the heavy buildings contain, meaning that it will take a longer time before the room temperature will drop when the heat is partly or fully turned off. From the graph, it can also be seen that the temperature in the heavy building will never reach the night setback of 16°C. The operative temperature drops approximately 1°C for the entire period of 14 hours. The light building has a larger drop in temperature during the setback, the operative temperature drops to around 17°C. Note: the starting point in the three buildings is different because in every case the result is taken from the last point of that particular case, for example heavy building manages to drop to 19.5°C therefore this value is taken as an input. Note: as mentioned before the proportional band is set to 2K, which means in this case that the heating will be on when the temperature reaches 19°C and off when the temperature reaches 21°C during day set point 20°C; the reason for operative temperature being 20.4°C.

Same simulation is run for the light, medium and heavy buildings, this time with the insulation level according to BR2010. The simulation shows similar behaviour for all buildings to the one described before, only that this time the temperature drops slightly faster since the insulation level is lower. The operative temperature drops to 18°C in the heavy building and in the light building to16.7°C Graph 2.9.



Graph 2.9 Indoor temperatures for light, medium, heavy buildings with insulation level (BR2010)

A faster and larger temperature drop happens in buildings that are poorly insulated as shown in Graph 2.10; in this case, insulation level is defined according to BR2008. During the 14 hours of setback, the operative temperature drops 3.6 degrees in the light zone and 2.6 degrees in the heavy zone.



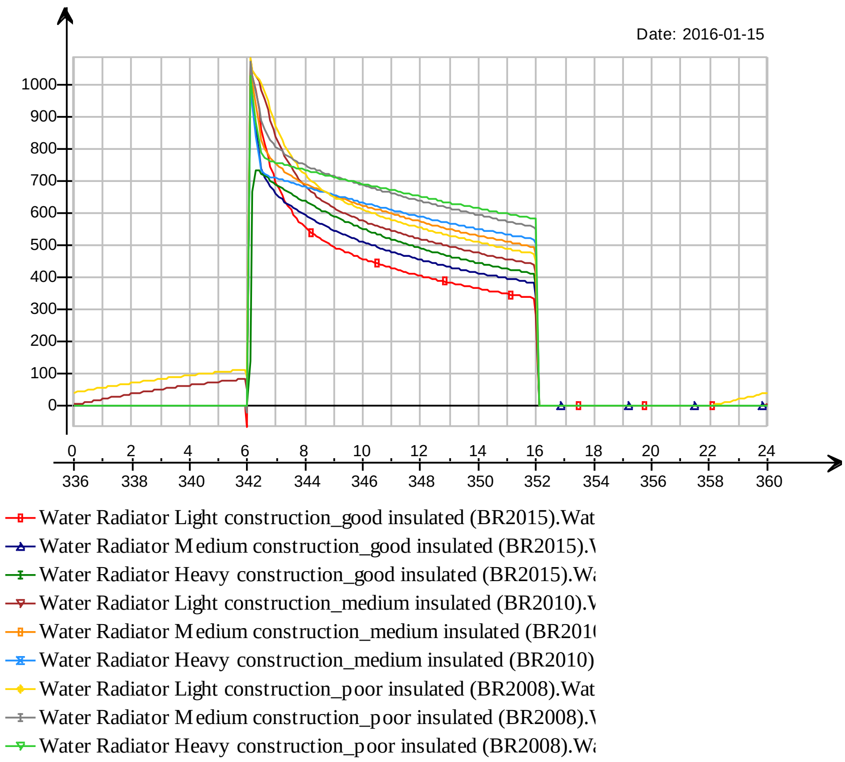
Graph 2.10 Indoor temperatures for light, medium, heavy buildings with insulation level (BR2008)

From the above presented graphs, it can also be seen how the profiles of operative temperature switch with the air temperature in all zones, after 16 o'clock when the heating is stopped or reduced until the day set point starts again. This is due to the fact that the air temperature becomes slightly lower after the heating is stopped, in comparison with the operative temperature which becomes slightly higher because of the warm surface temperatures. In all nine cases, the operative temperature is under comfort range during occupied hours (20°C).

From this simple simulation, it can be concluded that in case when the same setback is applied to the different buildings the temperature drop will not be the same due to different heat accumulation and insulation levels in the different buildings.

A setting-back of the temperature during a shorter or a longer period of time is sometimes applied in non-residential buildings in order to reduce the heat consumption during unoccupied hours. In order to achieve savings for the heat consumption the temperature is lowered in the room after occupied hours. An important consideration when doing this is to consider the preheating time after a setback, in order to make sure that a higher energy consumption will not occur. In consideration of the foregoing, the energy consumption for the day is presented in the following graph and table.

In Graph 2.11 and Table 2.8, the output of the radiator in watts for one day is displayed. As it can be seen in both the graph and the table, the only zones that use energy during the night setback are the light constructions with poor insulation, which start to use energy from around 22 o’clock when the operative temperature reached 16.5°C and the light construction with medium insulation at around 24 o’clock. The rest of the buildings do not use energy during the night setback, due to higher heat accumulation stored during the day, and good level of insulation, which prevents the heat loss.



Graph 2.11 Radiator output in watts for one day (at outdoor -12°C)

The highest heating consumption occurs in the three buildings (light, poor, medium_BR2008), when compared by insulation level and it is decreasing for the tree buildings insulated according to BR2010 and followed by the other tree cases respectively BR2015 (as shown in Graph 2.11). However, when looking at scenario with buildings insulated to BR2015 level, it can be seen that the heavy building uses the most heating when compared to the medium and the light from the same class of insulation level (grey cell in the table 5314 W). This can be explained by the fact that the heavy building needs more energy to heat up the temperature in the room compared to lighter buildings.

Hour	BR2015			BR2010			BR2008		
	Light	**Medium**	**Heavy**	**Light**	**Medium**	**Heavy**	**Light**	**Medium**	**Heavy**
	mean*h [W]								
1	0	0	0	12.29	0	0	49.05	0	0
2	0	0	0	29.34	0	0	64.15	0	0
3	0	0	0	44.59	0	0	77.29	0	0
4	0	0	0	57.65	0	0	89.3	0	0
5	0	0	0	69.37	0	0	100.1	0	0
6	-3.0	0	0	78.36	0	0	108.6	-1	0
7	825.1	745.1	617.5	923.3	821.7	749.8	942.6	865	794.3
8	616.5	624.6	663.8	752.6	719.6	696.2	786.9	775.8	747.5
9	523.5	570	613.8	648	673.1	670.5	683.4	732.4	724.7
10	476.7	529.1	571.4	595.7	640.3	645.9	631.3	701.8	703.1
11	443.6	495.7	535.5	560.7	612.3	622.1	595.9	675.1	682.5
12	416.8	467.8	504.9	532.7	586.4	600	567.3	650.7	662.5
13	394.1	444	478.7	508.6	562.3	579.5	542.6	627.9	642.9
14	374.4	423.6	456.1	486.5	540.5	560.5	520.5	606.1	624.4
15	357.2	405.7	436.5	466.5	520.6	542.9	499.9	585.4	607
16	339.4	387.8	417.2	447.2	501.6	525.9	480.2	566	590.7
17	14.14	16.98	18.61	20.48	23.77	25.27	22.46	27.59	29.11
18	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0.04	0	0
23	0	0	0	0	0	0	9.9	0	0
24	0	0	0	0.5874	0	0	30.89	0	0
mean	199.1	212.9	221.4	259.8	258.4	259.1	283.4	283.9	283.7
mean*24h	4778.2	5110.4	5314.1	6234.5	6202.1	6218.6	6802.3	6812.6	6808.7

Table 2.8 Hourly and total radiator output in watts for 1 day (at outdoor -12°C) with setback

Note: in Table 2.8 the time when the heating set point is 20°C is marked with red, and for the rest of the time the set point is 16°C.; the yellow cells in the table present the time when the heating was used in hourly mean value [W]. Note: this results applies only for one-day simulation at constant outdoor temperature of -12°C, for a long simulation period the results may be different, this investigation is done later in this chapter.

Since it is not of a statistical relevance to compare the same setback for different construction and insulation level among the different cases, a simulation with no setback is performed in order to be able to compare the energy results between having and not having a setback for all the nine cases. Table 2.9 outlines the total heat output of the radiator for a period of 24 hours, outdoor condition constant -12°C, for the nine cases with and without setback and the difference in energy consumption compared to the reference case with no setback. In all nine buildings, the heat output of the radiator is smaller when setback is applied, and the savings for light building constructions is the highest in all three insulation categories.

	BR2015			BR2010			BR2008		
	Light	Medium	Heavy	Light	Medium	Heavy	Light	Medium	Heavy
	mean*24h [W]								
No setback	5020.7	5297.5	5384.3	6632	6498.1	6506.1	7255.5	7192.2	7194.6
With setback	4778.2	5110.4	5314.1	6234.5	6202.1	6218.6	6802.3	6812.6	6808.7
Difference [%]	5%	4%	1%	6%	5%	4%	6%	5%	5%

Table 2.9 Total radiator output in [W] for 1 day (at outdoor -12°C) with/without setback

However, a setback for only one night will not give significant savings therefore longer setback periods should be investigated, for example for an entire year.

In Table 2.10 it can be seen the energy usage in kilowatts for one year (2016) with and without setback, and also the difference between in all nine case scenarios. The energy usage for space heating is lower in all nine zones when setback is applied. By insulation level, the highest savings are achieved in buildings insulated according to BR2008. Same as in the one-day simulation the light buildings from all three insulation levels have the highest percentage difference for the energy usage when the setback is applied.

	BR2015			BR2010			BR2008		
	Light	Medium	Heavy	Light	Medium	Heavy	Light	Medium	Heavy
mean*8784 h [kW]									
No setback	236	259	242	373	363	350	382	364	361
With setback	204	230	223	315	318	309	316	314	314
Difference [%]	13%	11%	8%	15%	13%	12%	17%	14%	13%

Table 2.10 Total radiator output in [kW] per year with/without setback

Further investigations can be considered for example choosing different degrees and periods for the setback in the nine cases. For example for the heavy buildings the heating can be stopped with one or two hours before the day ends since the heat accumulation of such buildings is quite high. However, this report does not cover further investigations for the nine buildings.

The above described investigations prove the statement mentioned in chapter *2.2.2 Night Setback* that the light building with poor insulation has the biggest potential for savings with the night setback(in this case 13%,15%,17%) because the temperature difference between outdoor and indoor is small, thus are the heat losses. With a higher thermal mass, the energy use for space heating is lower but the difference in having or not having a setback is smaller in comparison with the light and medium building.

2.2.3 POTENTIAL ENERGY SAVINGS

According to Knowledge Centre for Energy Savings in Buildings (in Danish: *Videncenter for energibesparelser i bygninger*) changing conventional thermostats to electronic ones in a building with district heating can save up to 279 kWh per radiator valve (Table 2.11).

Change	Heating form	
	District heating	Gas or oil
	Energy savings in kWh per radiator valve	
Manual to thremostat (TRV)	131	155
Manual to electronic	413	487
Thermostat (TRV) to electronic	279	329

Table 2.11 Energy savings when replacing radiator valve/thermostat (Videncenter for energibesparelser i bygninger (Knowledge Centre for Energy Savings in Buildings) 2015a)

By establishing weather compensation can result in energy bills per building being 790 kWh less per year; night-setback can save 395 kWh annually per building (Table 2.12).

Actions	Energy savings in kWh per year
Weather compensation	790
Night setback	395

Table 2.12 Energy savings by establishing weather compensation and night-setback (Videncenter for energibesparelser i bygninger (Knowledge Centre for Energy Savings in Buildings) 2015b)

Temperature difference Δt – bonus or penalty

For the District heating network to be run as efficiently as possible, it is important that there is a large temperature difference between the supplied district heating water, which the building receives, and its return. The return temperature should be as cold as possible. In Denmark, for example in Copenhagen area, there is a bonus for users, which make a good use of the district heating, and on the contrary, there is penalty for those, which do not. If the temperature difference is up to 5°C higher or lower than required, there will be no extra payment neither a bonus will be received. The economic benefits (”bonus”) are offered for those households, which return district water with the temperature difference more than 5 degrees compared to the average/required Δt of 33°C (in Copenhagen area). If for example the actual average Δt for a year is higher than 38°C then there will be a bonus or in reverse, there will be a penalty if Δt in average for the year will be under 28 °C. The bonus or the penalty is calculated per consumed MWh for each degree the Δt deviates from the requirement. (HOFOR 2016)

Calculation example:

Required ΔT 33°C, price including VAT 5.3 kr. (see Table 2.13) with an actual ΔT of 41°C and consumption of 21 MWh the difference will be :41-33=8°C, and the bonus for that year will be

8°C *21 MWh *5.3 kr. =890.4 kr. including VAT.

Required ΔT 33°C, actual ΔT of 26°C and consumption of 21 MWh the difference will be :33-26=7°C, and the penalty for that year will be

7°C *21 MWh *5.3 kr. =779.1 kr. including VAT.

The bonus or the penalty is stated in the year’s bill and is based on the last year consumption and mean ΔT for that year.

Price for District Heating 2016(København)		
Hot water	**Without VAT(kr.)**	**With VAT (kr.)**
Effect of payment (Kr. Per. KW)	159.82	199.78
Energy Price incl. taxes (Kr. per. MWh)	529.45	661.81
Correction for cooling - bonus / extra expense per degree (kr. per. MWh) *	4.24	5.30

Table 2.13 Price for district heating in Copenhagen (HOFOR 2016)

**) The adjustment is provided as 0.8% of the energy price. There are only calculated bonus / extra costs when the cooling differs by more than 5 degrees from the prescribed average cooling (cooling requirements) set to 33 degrees. For low temperature at Vesterbro is cooling requirement being set at 25 degrees*

From the above-described calculations, it can be concluded that, the lower the return temperature (high ΔT) the higher will be the bonus and the higher the return temperature (low ΔT) the bigger the penalty-in comparison with the required ΔT. Note the calculation for bonus and penalty applies to users of district heating in Copenhagen area.

In Table 2.14 it can be seen the difference between the prices per MWh for district heating for Aalborg and Copenhagen. The prices for district heating in Aalborg are much lower than the country's average, and in comparison with Copenhagen the price is 54 % lower. Note: there is a difference in price mentioned in Table 2.13 and the price in Table 2.14 for Copenhagen area, this is due to different sources used.

Since the prices in Copenhagen are significantly higher it is of a great importance to make a good use of the district heating meaning that the return temperature should be as low as possible in order to get the economic benefits (bonus).

District heating prices		
	Aalborg Municipality	Copenhagen area
Price per MWh	341 kr.	735 kr.
Heating price per year, standard apartment	6430 kr.	13472 kr.
Heating price per year, standard house	9337 kr.	16639 kr.

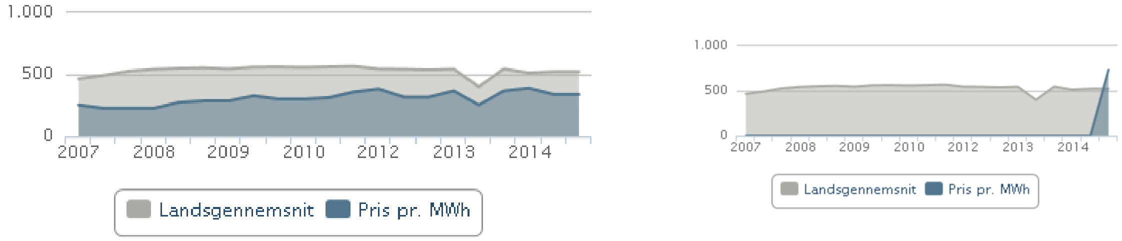
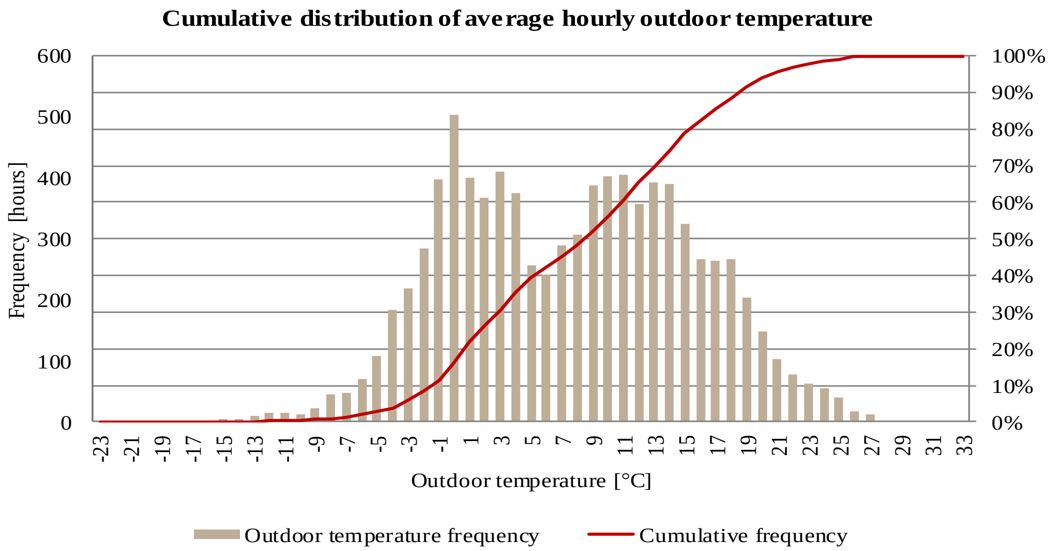


Table 2.14 District heating prices (BOLIUS 2016)

2.3 OVERSIZED RADIATORS

Radiators are dimensioned for the design heat loss of a room. Design heat loss of a room or a building consists of transmission, line, and ventilation losses, which in Denmark are calculated according to DS 418 (Dansk standard 2011). The standard specifies the design indoor temperature of 20°C and the design outdoor temperature of -12°C. However, such low outdoor temperature occurs for less than 0.1% of an average year in Denmark (based on Design Reference Year – DRY 2013), as can be seen in Graph 2.12. This implies that the radiators are normally over-dimensioned.



Graph 2.12 Cumulative curve for outdoor temperature in Denmark, from DRY 2013 in BSim

The design supply and return temperatures depend on the type of heat source. According to DS 469 (Dansk standard 2013), which is a mandatory standard for design of heating systems in Denmark, systems with condensing boilers or heat pumps, for example, must have maximum design supply temperature of 55°C, while design conditions for systems connected to district heating (DH) depend on the main district taps (Dansk standard 2013). Production sites of DH in Aalborg heat the water up to 75°C in summer and about 82-90°C in winter; a customer returns the water with a temperature of about 40°C (Aalborg Kommune 2016). According to Dansk Fjernvarme the heat loss from distribution pipes of all Denmark equals 17.38% (Øllegaard Sørensen 2014). Due to such heat loss in the district pipes the water reaches the customer at about 70°C, which gives the minimum required temperature drop of 30K. Since supply and return temperatures could have been different in the past, it can be expected that radiators in existing buildings are either under- or oversized, depending on the flow temperatures they were designed for.

Determining the size of radiators on the basis of internal room volumes was very popular in the past, because the differences in thermal-technical properties of the buildings were significantly smaller than nowadays (Korado 2016). Rule-of-thumb methods would often result in oversized radiators to avoid risk of a radiator not fulfilling the room heat loss.

The maximum heat output of a radiator available from a catalogue rarely equals to the design room heat loss that the radiator should cover. The choice is always made in favour of a radiator with a higher heat output. Furthermore, due to aesthetical considerations and to avoid cold downdraught, radiators are often chosen as wide as the windows. These design details can also lead to radiators being oversized.

When improving the building envelope during a renovation, transmission heat losses are reduced and the airtightness is increased, meaning that the necessary heating demand is lowered to comply with the toughening energy requirements. This, together with increasing internal gains from equipment, lighting, people, as well as increased solar gains due to new energy-efficient windows will make the existing heating system of a building largely oversized.

To sum up, the reasons for existing radiators being oversized can be:

- too low design outdoor temperatures;
- changes in the flow temperatures;
- sizing according to simple rules-of-thumb;
- intentional choice of bigger radiators due to product availability or aesthetics;
- reduction of necessary heat demand during a building renovation.

2.3.1 CONSEQUENCES OF OVERSIZED RADIATORS

A radiator output Q [W] can be calculated with equation (16), where $\dot{m}$ is the water mass flow [kg/s], C_p is the water specific heat capacity [J/kg K], and T_S-T_R is the temperature difference between the supply and return flows [K].

$$\boldsymbol{Q} = \dot{\mathrm{m}} \cdot \boldsymbol{C_p} \cdot (\boldsymbol{T_S} - \boldsymbol{T_R}) \tag{16}$$

In case of different flow temperatures the heat output of a radiator is calculated using equation (17) (Dansk standard 2013), where Q_0 is the nominal heat output (radiator output from the producer) [W], ΔT_{mx} and ΔT_{md} are the mean logarithmic temperature differences [°C], and n is the dimensionless radiator component/factor, typical value is 1.3.

$$\boldsymbol{Q} = \boldsymbol{Q_0} \cdot \left(\frac{\Delta \boldsymbol{T_m}}{\Delta \boldsymbol{T_{md}}}\right)^{\boldsymbol{n}} \tag{17}$$

The mean logarithmic temperature difference is determined by equation (18) with T_S, T_R, and T_i as supply, return, and internal temperatures [°C], respectively.

$$\Delta T_m = \frac{T_S - T_R}{ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \tag{18}$$

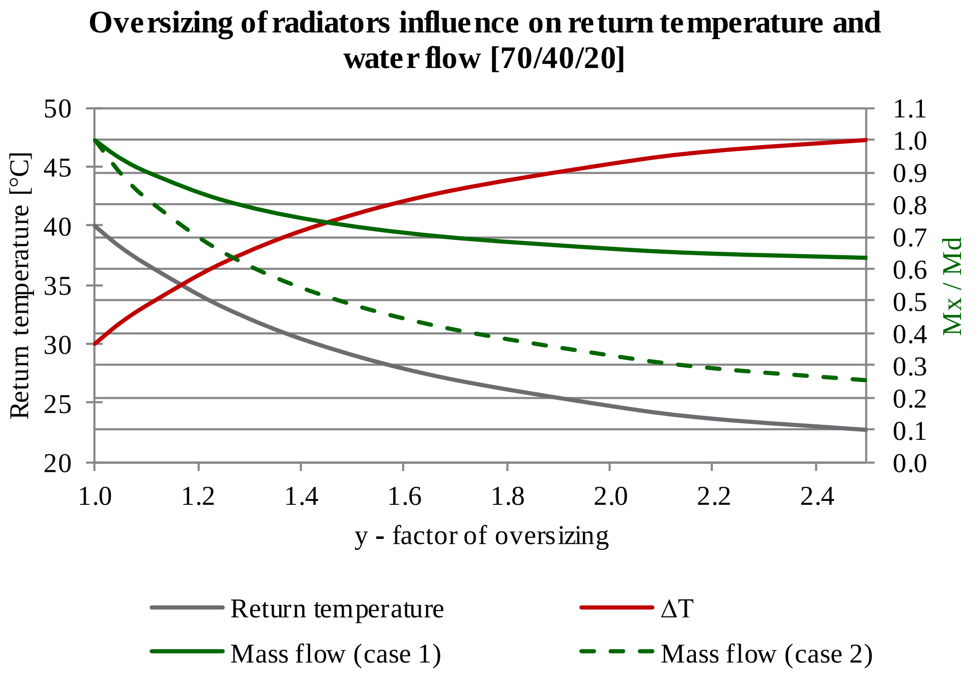
Combining equations (16), (17) and (18) we get:

$$Q = \dot{m} \cdot C_p \cdot (T_S - T_R) = Q_0 \cdot \left(\frac{T_s - T_R}{\ln\left(\frac{T_s - T_i}{T_R - T_i}\right)} \cdot \frac{1}{\Delta T_{md}} \right)^n \tag{19}$$

Where, ΔT_{md} is the mean logarithmic temperature difference at the design conditions (70/40/20) = 32.74°C. The effect of oversized radiators on the flow and the return temperature can therefore be studied theoretically using equation (19). First, the return temperature is found by iteration, and then it is used to calculate the mass flow.

In the investigation the oversizing factor (or in some cases under-sizing) "*y*" is determined by $Q_0 = Q \cdot y$, where the factor shows the relation between the nominal radiator output and the design room heat loss. The oversizing factor is equal to 1 when a radiator's size corresponds to the heat demand of a room; in case of y=1.5 there is an oversizing of 50%.

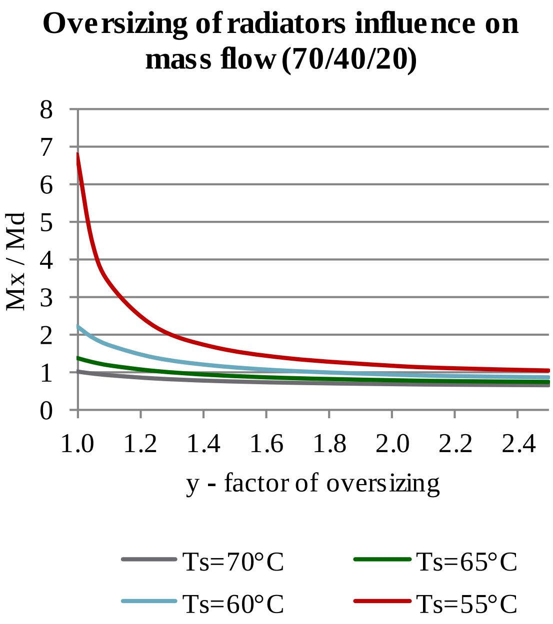
If we consider the design and actual supply, return and room temperatures to be the same as the design conditions of 70/40/20, oversized radiators will have lower necessary mass flow and higher temperature difference. The higher the degree of oversizing, the higher the ΔT can be obtained, and the lower the flow is needed. This is illustrated on Graph 2.13.



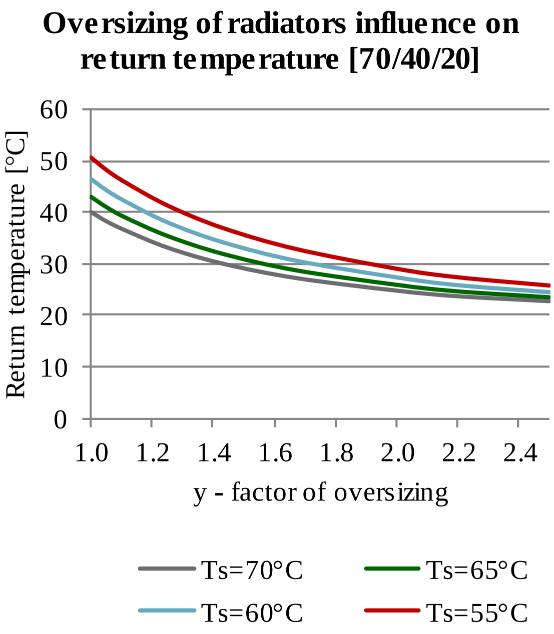
Graph 2.13 The effect of oversized radiators with the same design and actual conditions of 70/40/20

The results for mass flow are presented as a fraction of the design flow (Mx / Md). There are two cases presented for the mass flow calculation: case 1 and case 2. Case 1 on Graph 2.13 represents the flow for initially oversized radiators (radiator design heat output is increased), while case 2 (dashed line) shows the flow in the event of decreased dimensioning heat loss – when a radiator becomes oversized after a building's envelope was improved; the Mx / Md fraction in case 2 is thus smaller.

The results presented on the Graph 2.13 are only true if an oversized radiator is working at the design conditions. However, if a radiator was designed for temperatures of 70/40/20, afterwards supplying it with a lower temperature will result in higher flow and lower ΔT in order to keep the necessary heating output. Moreover, the higher the percentage of oversizing, the less the influence of different supply temperatures – if a radiator is 2.5 times bigger than needed, the required mass flow and return temperatures become very similar regardless of the supply temperature. This can be seen on Graph 2.14 and Graph 2.15.



Graph 2.14 Mass flow at different supply temperatures depending on the percentage of oversizing



Graph 2.15 Return temperature at different supply temperatures depending on the percentage of oversizing

A conclusion can be drawn that in case of changing the supply temperature to lower than the design one it is beneficial to have oversized radiators. This is due to the fact that oversized radiators are able to cover the heat demand with lower supply temperatures. However, the percentage of oversizing has a big influence on the required mass flow: for example, if the oversizing is only 10% (y=1.1) the mass flow needs to be ≈3 times larger with T_S of 55°C compared to T_S of 70°C.

Increasing the mass flow in an existing system can be problematic due to increased pressure drop and risk of noise. The resistance varies by the square of the flow change (Danfoss 2000), so there is a possibility that pumps would have to be changed to new ones when the necessary flow is increased. In case of unchanged mass flow, the room/building dimensioning heat loss needs to be reduced. The same factor "*y*" as for oversizing is now used to express the part of the heat demand that can be covered by existing radiators and changed supply temperature (different from the design conditions), while still keeping the mass flow constant. Several design supply and return temperatures, presented in Table 2.15, were assumed for this calculation.

Design T_S/T_R	
70/40°C	Common Danish practice nowadays
90/70°C	Were used for older houses, DS/EN 442
80/40°C	Common for DH before the mid-1990s

Table 2.15 Design supply and return temperatures that were used in Denmark (Ljunggren & Wollerstrand 2006)

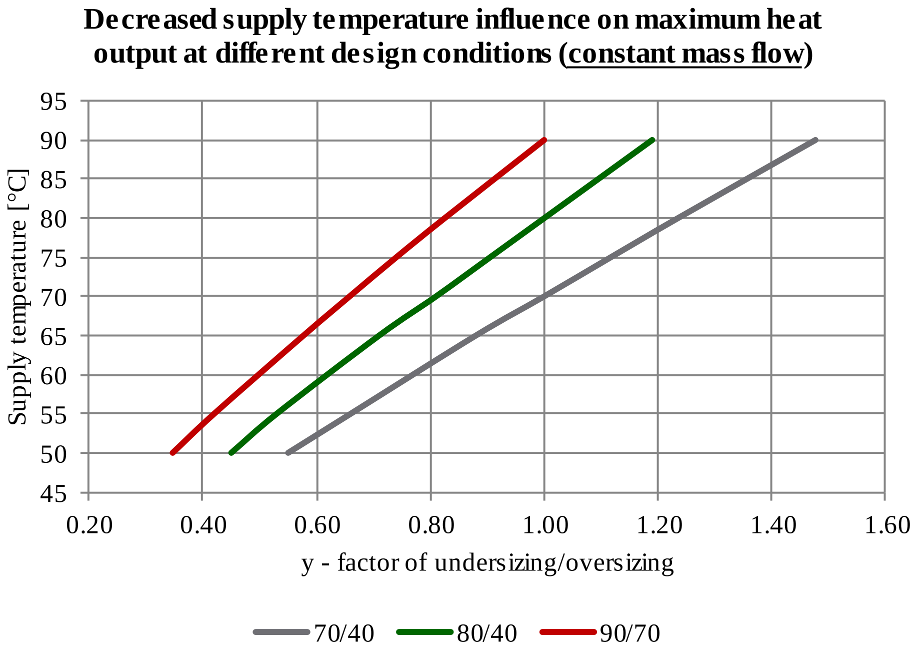
If we set a random condition (x) with relation to dimensioning condition (d) the following can be written:

$$\frac{Q_x}{Q_d} = \left(\frac{\Delta T_{mx}}{\Delta T_{md}}\right)^n = \frac{m_x}{m_d}\frac{\Delta T_x}{\Delta T_d} = y \tag{20}$$

Assuming the same mass flow, the relation m_x/m_d in the equation (20) will be 1, and then by rewriting the equation (the process is described in 5), factor "*y*" is found by:

$$y = \frac{T_s - T_i}{\Delta T_d}\left(1 - \exp\left(-\frac{\Delta T_d}{\Delta T_{md}} y^{1-\frac{1}{n}}\right)\right) \tag{21}$$

Graph 2.16 shows how much of the heat demand can be covered by existing radiators that had various dimensioning conditions (Table 2.15) with unchanged water flow at different supply temperatures.



Graph 2.16 Decreased supply temperature influence on heat output at different design conditions (mass flow kept constant)

From the graph it is clear that the radiators that were designed for higher supply/return temperatures can only cover a part of a room's heat demand, if the water mass flow is to be unchanged. For example, a radiator that was designed for T_S/T_R=80/40°C will only cover ≈60% of the necessary heat demand when supplied with 60°C. This means that for these conditions the dimensioning room heat loss should be reduced by 40% (by insulating and air tightening the construction).

2.3.2 CHANGE IN AMBIENT TEMPERATURES

Furthermore, calculations are made concerning the change of mass flow according to different indoor temperatures. For the calculation change is made in the indoor temperature, while keeping the outdoor at -12°C. The calculation is done for two scenarios: 1) considering design conditions of 70/40/20 and 2) considering different design conditions including 70/40/20; 65/35/20; 60/30/20 and 55/25/20.

For both cases in order to calculate how much the water flow changes, relation is made between the random (x) condition and the dimensioning (d) condition. Following equation (20), the relation is expressed by equation (22).

$$\frac{Qx}{Qd} = (\frac{\Delta Tmx}{\Delta Tmd})^n = \frac{Mx \cdot \Delta Tx}{Md \cdot \Delta Td} = \frac{Tix - Tux}{Tid - Tud} \quad (22)$$

By rewriting the equation (22) is obtained equation (23), which aims to find the mean logarithmic temperature difference.

$$\frac{\Delta Tmx}{\Delta Tmd} = \sqrt[n]{\frac{Tix - Tux}{Tid - Tud}} \; and \; \Delta Tmx = \sqrt[n]{\frac{Tix - Tux}{Tid - Tud}} \cdot \Delta Tmd \quad (23)$$

Thereafter, the temperature drop through the system is calculated using equation (24), which origins from the basic definitive equation of mean logarithmic temperature difference (equation (18)).

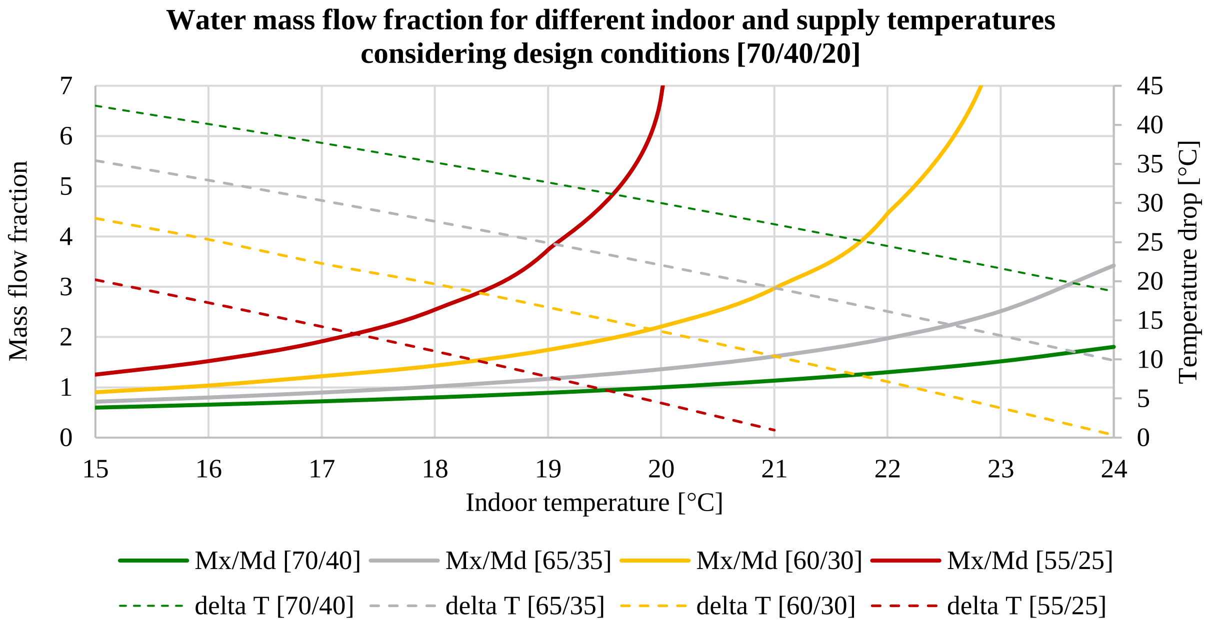
$$\Delta Tmx = \frac{\Delta Tx}{\log_e \frac{Ts - Tix}{Ts - \Delta Tx - Tix}} \; and \; \Delta Tx = (Ts - Tix) \cdot (1 - e^{\frac{-\Delta Tx}{\Delta Tmx}}) \quad (24)$$

At last, in order to find the relation between the necessary and the dimensioning mass flow, equation (22) is rewritten, and equation (25) is obtained.

$$\frac{Mx \cdot \Delta Tx}{Md \cdot \Delta Td} = \frac{Tix - Tux}{Tid - Tud} \; and \; \frac{Mx}{Md} = \frac{Tix - Tux}{Tid - Tud} \cdot \frac{\Delta Td}{\Delta Tx} \quad (25)$$

1) This calculation shows the influence of the indoor temperature on the mass flow, while design conditions are assumed at 70/40/20. In other words the calculation expresses how much the water flow at different indoor temperature will change if the supply temperature is reduced. In this way the mean logarithmic temperature difference is the same for all cases (32.74°C, corresponding to conditions 70/40/20).

The results from the calculation are plotted in Graph 2.17, where "Mx/Md" represents the fraction of the design mass flow required to maintain the indoor temperature at certain degree. The dashed lines in the graph represent the temperature drops for the different supply temperatures.

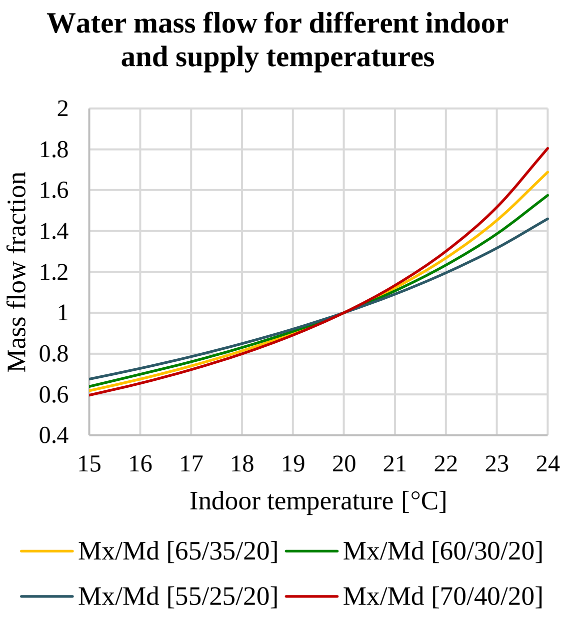


Graph 2.17 Water mass flow fraction for different indoor and supply temperatures considering design conditions [70/40/20]

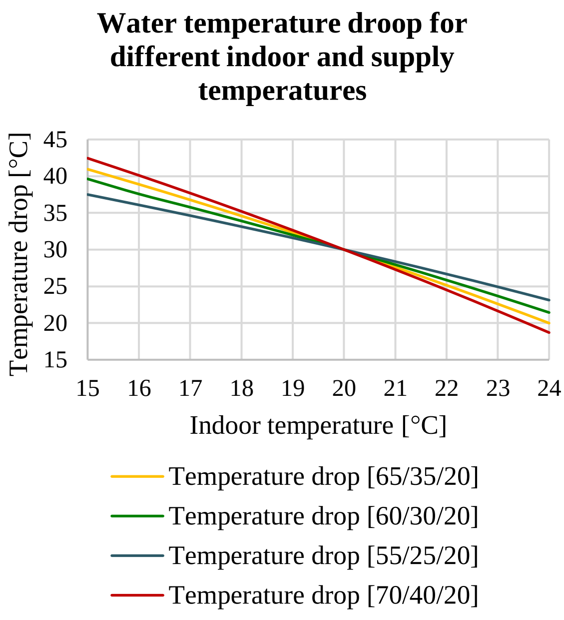
Graph 2.17 indicates that the lower the supply temperature, the higher the mass flow and the lower the temperature drop. It is interesting to point out that when reducing the supply temperature to 55°C, the highest indoor temperature that can be achieved is 20°C (taking into account dimensioning conditions with indoor-outdoor temperature difference of 32°C). This finding can be related to the night-setback strategy with centralized reduction of supply water temperature. Based on the degree of setback a controller should be able to calculate the minimum supply temperature that will reduce the room temperature to the setback temperature. In this way it can be assured that the setback temperature will never be exceeded no matter the valve position (the amount of mass flow).

2) This calculation shows the influence of the indoor temperature on the mass flow for different design conditions, including 70/40/20; 65/35/20; 60/30/20 and 55/25/20. The calculation expresses how much the water flow at different indoor temperature will change if the supply temperature is kept as designed. In this way the mean logarithmic temperature difference is different for each design condition.

The results from the calculation are plotted in Graph 2.18 and Graph 2.19 , where "Mx/Md" represents the fraction of the design mass flow required to maintain the indoor temperature at certain degree. The numbers in square brackets represent the design condition for each case.



Graph 2.18 Water mass flow for different indoor and supply temperatures

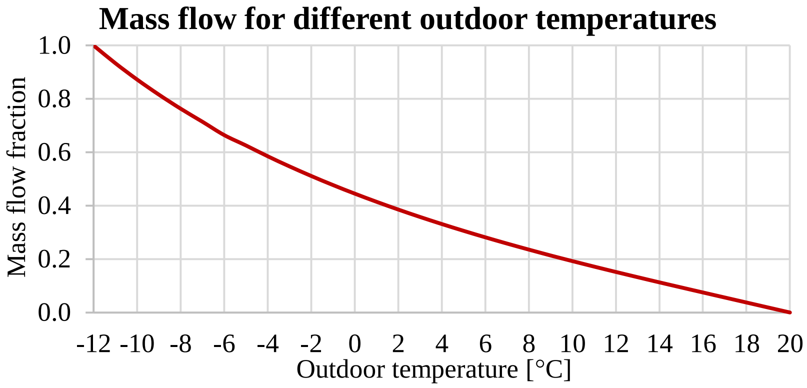


Graph 2.19 Water temperature droop for different indoor and supply temperatures

It should be noted that both calculations take into consideration constant outdoor temperature of -12°C, and by increasing the indoor temperature the indoor-outdoor temperature difference rises. This means that at higher than 20°C indoor, the temperature difference will exceed 32°C, which in reality is not likely to occur.

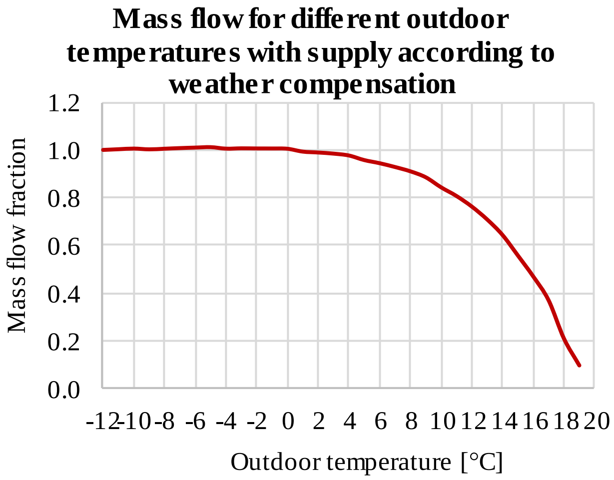
Investigations of the water mass flow for different supply temperatures and indoor temperatures when having fixed return temperature are also performed, the graphs can be found in Appendix E.

A change in outdoor temperature with a constant indoor temperature of 20°C will affect the mass flow by the same principle as described above, since the parameter that has influence on the necessary mass flow is the temperature difference between indoor and outdoor conditions. A calculation with outdoor temperature range from -12°C to 20°C was done using equation (25) to find the fraction of necessary and design mass flow at different outdoor temperatures, and the results are presented in Graph 2.20

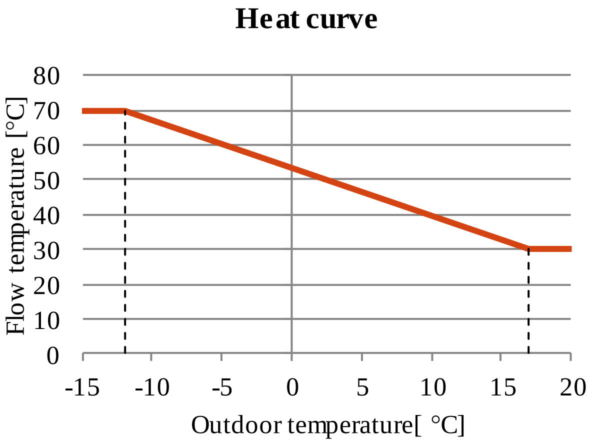


Graph 2.20 Mass flow fraction depending on outdoor temperature

The graph shows that the mass flow decreases when outdoor temperature increases. It should be noted that an assumption of constant supply water temperature of 70°C was used in the calculation. In a system with weather compensation the supply temperature is regulated according to outdoor temperature (chapter *2.2.1 Weather compensation*). By using the same calculation (equations (24) and (25)) and changing supply temperature according to a linear heat curve (Graph 2.22), the necessary mass flow is found to be constant with outdoor temperatures from -12 to 0°C - Graph 2.21.



Graph 2.21 Mass flow fraction depending on outdoor temperature; applied supply temperature reduction according to weather compensation



Graph 2.22 Simple heat curve. Supply temperature decreases proportionally to the outdoor temperature increase

According to the calculation the necessary mass flow is lower when the outdoor temperature is higher than 0°C. This means that the slope of the heat curve can be adjusted if the aim is to keep constant mass flow in the system.

2.4 PART CONCLUSION

The first part of the project included theoretical investigations. It is aimed to give knowledge about the different aspects of the control of the heating system and how they work. It contains description of different ways of monitoring energy use of a radiator system. Furthermore, the method, range and accuracy of different water flow sensors were described in order to select the most suitable method and meter for the measurement campaign. Ultrasound energy metering, based on the “time of flight” effect was chosen due to the good accuracy and the non-intrusive installation.

Furthermore, the theoretical part included a description and analyses of how different pump operation modes perform when setback strategy is applied to the system. It was concluded that smart pumps with auto adapt mode would have the best performance due to their integrated temperature sensor, which goes automatically in night mode if it senses significant drop in the supply temperature.

Brief history describing the development of thermostats and different types of thermostatic valves were studied to acquire an understanding of how TRVs perform. Additionally, the theoretical part of the report aims to inform the reader about different types of controllers, their advantages and disadvantages, as well as the applications they are most suitable for.

Moreover, the theory chapter gives understanding and knowledge about different ways of saving energy with heating control. These methods include weather compensation, setback strategies and the influence of oversized radiators on the system.

From the literature review and building simulations it was clear that when applying setback strategy, the thermal mass and insulation level of the building should be taken into consideration. It is also of great importance that the reduction of heating energy consumption of the building by lowering the indoor temperature should not compromise the comfort of the occupants in the building. The potential for energy savings with night setback strategy is higher in poorly insulated buildings, and in buildings with low thermal mass.

Oversizing of radiators was investigated both theoretically and analytically. The calculations that were performed included the influence of oversizing on the mass flow and temperature drop for different design conditions, as well as different supply temperatures used in the system. An important aspect to mention is that oversizing of radiators allows a lower supply temperature to achieve the desired set point. Change of ambient temperatures to a different degree than the design conditions and its influence on the mass flow was also studied.

Part of the theoretical background included so far in the report is further used in the case study of the project, where the project research questions are studied practically.

3 CASE STUDY

In this chapter a process for case study choice, description of the case study building and measurement campaign, the methods and equipment used, and the discussion of results are included. A brief description of a measurement campaign is provided below as an introduction.

Background

The following paragraph outlines two school buildings in Denmark, which chose to implement programmable thermostats from Salus Controls for individual control of the heating in the rooms; same provider is used in our case study building.

Salus iT600 heating control for radiator system was chosen by EnergiMidt to be implemented in two schools in Denmark, in order to reduce the energy consumption for heating. The schools are Ferslev and Vester Hassing. Each school has about 80 rooms which are divided into six zones. The rooms are individually controlled and have one up to six radiators, which are controlled by the wireless room thermostat. The system controls and monitors both the rooms and common areas in the schools. The technical service leader can use an Android or Apple device to monitor or to change the settings. The temperature in the rooms can also be individually controlled by use of the room thermostat.

The schools have great focus on energy consumption and just the possibility of installing individual room control without the need to pull cables or wires around the entire school has made it economically feasible to upgrade their heating systems. With the ability to monitor the system from a smartphone, tablet or PC, the flexibility is great and allows to quickly change the time or temperature, even when the service manager is not at the school. Service leaders have expressed great satisfaction with a significantly improved overview of the school's heating system, as well as the ability to customize individual areas to their specific heat demand. (Salus 2015)

Introduction

The measurement campaign is carried out in a school building in Aalborg, Denmark, with the aim of evaluating the operation of the existing heating control system and comparing it to a new control type. The evaluation of heating system controls operation is based on two factors: energy consumption and provided thermal comfort. The main focus area is to study the difference between digital and traditional thermostatic radiator valves when implementing the night-setback strategy. The main research question is:

<u>“Does night-setback with central reduction of supply temperature result in energy savings when used with ordinary manual thermostatic radiator valves, or do digital thermostats provide better performance of the system in terms of thermal comfort and energy use?”</u>

The measurements will be conducted simultaneously in two rooms for the two types of TRVs. One room will serve as a test room, where the new programmable thermostats will be installed, and the other room will be a reference room, with the existing TRVs. The energy consumption used for room heating will be measured separately for each of the two rooms, by using an energy meter, which combines flow and temperature measurements. The two temperature sensors measure the difference between the supply and return temperatures of the monitored flow, resulting in energy measurement (equation (16)). Thermal environment is evaluated by logging operative temperature. The measurement results can then be used for several purposes described below:

- By analysing the night setback strategy it can be observed how much time it will take until the room temperature reaches the day set point. In this way it can be investigated if there is risk of thermal discomfort when night setback is applied. Additionally, the optimum temperature set point for night setback can be studied.

- By measuring the energy consumption and indoor temperature the oversizing of the radiators can also be investigated. In this way it can be considered if the supply temperature can be further decreased at the central level.
- By comparing the measurements in the two rooms, it can be studied if programmable thermostats perform better in terms of thermal comfort and energy use compared to traditional TRVs, and what would be the payback time for the investment.
- By analysing the measurements it can also be discovered if there are any failures in the heating system.

The measurements are further used to calibrate the model built in a simulation program IDA ICE and to analyse the yearly energy consumption results.

3.1 CHOICE OF A BUILDING

For the purpose of this project, buildings which are not always occupied such as schools, offices, were considered, as in non-residential buildings it is a common practice that the room temperature is lowered during unoccupied times at a central level by decreasing water supply temperature to the radiators.

For the scope of this project the heating in the building must be controlled centrally (i.e. by use of ECL) and to have/give the possibility of installing a decentralized control in at least one of the rooms. In order to perform the necessary tests there should be at least two rooms in the building, which are identical. The rooms, which are used in the case study, should have same size, orientation, occupied time, amount of windows, same heat loss, internal gains and heat output by the radiators.

In order to find a suitable case study building for this master thesis, few buildings and their heating systems were assessed. All visited school buildings are located in Aalborg Municipality and they are connected to District Heating, and heated by radiators. The mentioned buildings were built and renovated between 1959 and 2006. In the following paragraphs it is outlined what was found and observed during these school visits concerning the heating system, their control and operation.

The gathered information is obtained by questioning the employees in charge of the schools. The main problem noticed, by far is the fact that they do not have a full understanding of how the heating systems are controlled and how to operate them. In general, it was observed that they do not know what type of components exist in the building, as well as their function and adaption, all that leading to an inflexible communication.

Unfortunately, many of the answers were lacking consistency, were ambiguous/ misleading and some of the questions remained unanswered. In many of the discussions, they were unsure on some of the facts, leading to a big confusion.

Overall, it seemed as if the personnel had minimum training in the field, they are used to do things as in old times and they are not updated with the changes. They have limited skills in operating the control systems. The efforts in decreasing the energy consumption for heating are minimal.

For a better overview, part of the gathered information is summarized in Table 3.1.

Info	School			
	1	**2**	**3**	**4**
Build in	1959	1972	1985	1969
CTS	✓	✓✗	✗	✓
ECL	✗	✗	✓	✓
Weather compensation	✓	✗	✗	✓
Limit on radiators	✗	✓	✗	✗
Night setback	✗	✓	✓	✓
Room temperature control	TRV	TRV	TRV	TRV
Availability of 2 identical rooms	✓	✓	✗	✓

Table 3.1 Summarized information about schools

Furthermore, it was decided to have/use as a case study school number four mentioned in the above table (Vester Mariendal School), since the heating in the building is controlled centrally, has the type of control which we are interested in (ECL), gives the possibility to implement the new control type in one of the rooms and has two identical rooms that can be used for the investigations. In the next subchapter, the description of the case study building is presented.

3.2 BUILDING DESCRIPTION

Vester Mariendal school is located in the South-West part of Aalborg and it was built in 1969. Since then the school went through different changes several times. Extensions were built, adding extra classrooms, rooms for therapy, hall and child care (DUS). The last major renovation was held in 1995 and since then it was partly renovated in 2010. The total area of the school is 11 079 m^2.

There is a block dedicated to the special needs classes for children with disabilities and specific learning difficulties. Currently the school holds approximately 500 students, divided in 31 classes from kindergarten level to 9th grade. The total staff working in the school is 80 people.

Figure 3.1 Vester Mariendal school area (http://www.vmarieskole.dk/Faelles/Skoleporten/Skolen%203.jpg), and top view (Udviklings- og investeringsplan for Aalborg kommunes skoler)

The building layout is structured as eight interconnected blocks. The architecture of the school is dominated by two major wings, oriented to the East and West, connected in the middle by a third wing. Partly under the connecting block and under the entire East wing there is a basement floor, the rest of the building is carried out only at a ground floor level. Figure 3.2 and Figure 3.3 illustrate the ground floor and basement layout. The ground floor has a total area of 8497 m^2 and the basement is 2582 m^2.

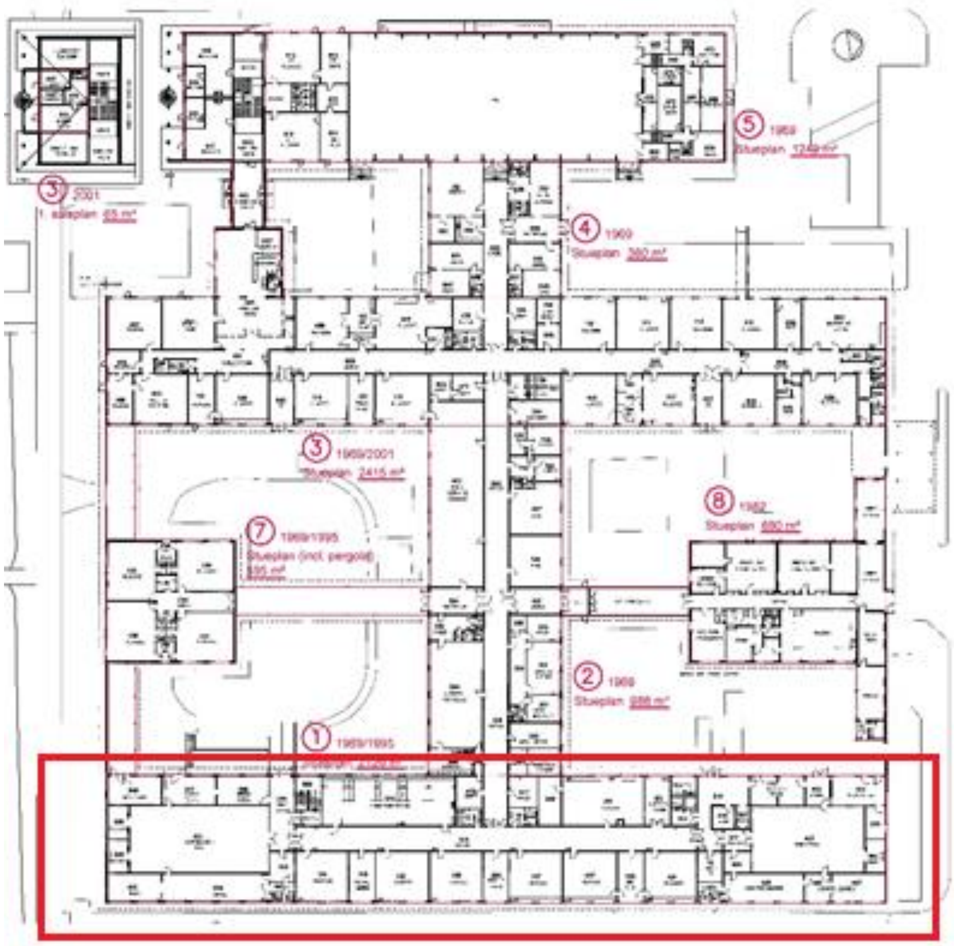


Figure 3.2 Ground floor plan view

On the ground floor of the East wing are located classrooms, group rooms, rooms for special classes, two sport halls, the support center and several administration rooms. In the basement are positioned the biology, physics and chemistry labs, wood workshop, classrooms, several depot rooms, technical room and a large hall room used as recreational area.

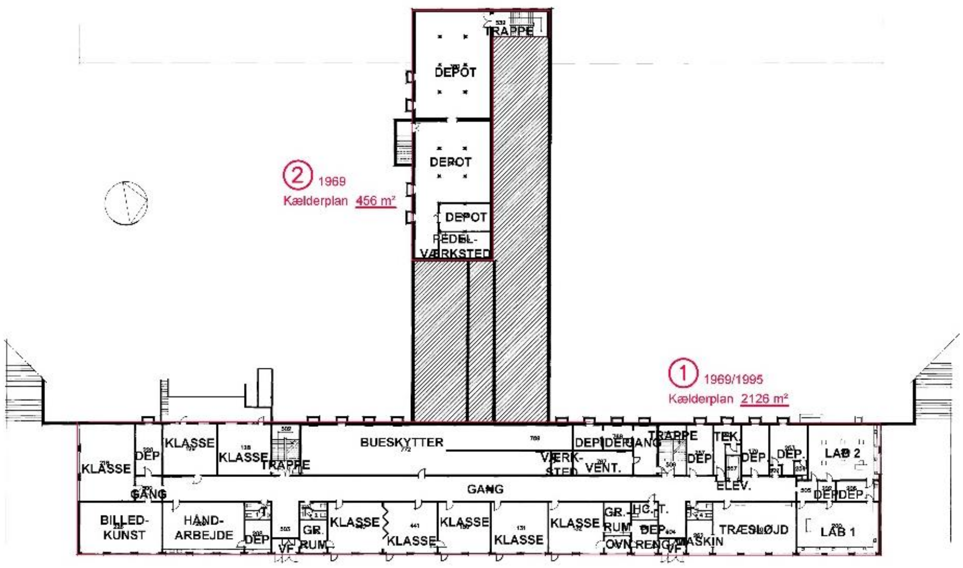


Figure 3.3 Basement plan view

Construction components

As mentioned before the building went through several renovations since it was built in 1969, resulting in different construction components in different parts of the building along the years. In the following description, the construction components are described for the East Block.

The block is carried out as a medium heavy construction with concrete walls and floors, and light wooden roof. The internal partition walls are 150 mm concrete. The bearing part of the partition floor between the basement and the ground floor is carried out as 180 mm reinforced concrete hollow core deck. The floor covering type varies in the different parts of the building, between vinyl tiles and linoleum. The roof is built at 30˚ pitch with wooden trusses and corrugated sheets. The U-values of the different structures are presented in Table 3.2, for calculation refer to Appendix E.

External wall construction	**U-value [W/m²K]**
60 mm reinforced concrete 75 mm insulation 25 mm ventilation gap 30 mm concrete	0.44
Roof construction	**U-value [W/m²K]**
13 mm gypsum board 34/50 mm wooden laths 28/34 mm wooden battens 2x50 mm insulation Corrugated sheets on battens	0.33
Window	2.30

Table 3.2 U-values for different building components

Building ventilation system

The East wing is equipped with two different ventilation systems (Figure 3.4). On the ground floor there is an old ventilation system from the 60's. The unit is operating only as an extraction system on a 3-hour daily schedule. The hallway is not ventilated; there is extraction only in the occupied rooms and in the gyms. The newer ventilation system, which was established during the partial renovation in

2008, is supplying and extracting air in the basement with the same 3-hour working schedule: for one hour at 9, 11 and 13 o’clock. The hallways are not ventilated.

Figure 3.4 Ventilation system in the basement (left) and on the ground floor (right)

3.2.1 BUILDING HEATING SYSTEM

The school is connected directly (without heat exchanger) to the local District heating system. The heating distribution system in the building is carried out as a two-pipe system made out of steel. The classrooms are heated by water radiators (two in each classroom) and the room temperature is controlled by thermostatic valves. The pipe system is a reverse return system, where the supply and the return water flows in the same direction (Figure 3.5). The radiators are section radiators placed under the windows in the classrooms. The main hallways and depot rooms are also heated.

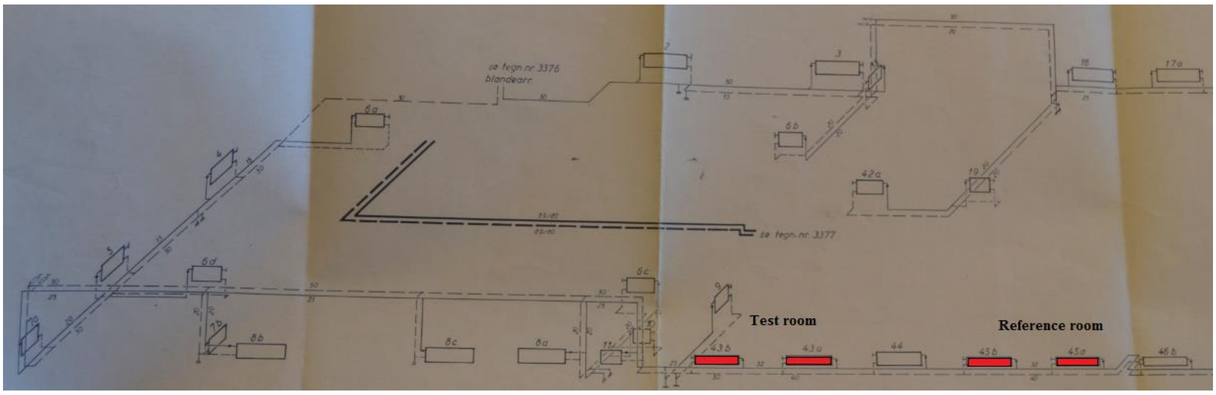


Figure 3.5 Distribution pipes: reverse return heating system

The main distribution pipes on the west facade of the ground floor are led through the ceiling and along the facade to each room. On the east facade they go along the external wall at floor level. The technical room, with all the main connections, is placed on the ground floor level. The heating on the ground floor is controlled at central level with ECL control. The connection to the district for the ground floor of the East block is as shown in Figure 3.6.

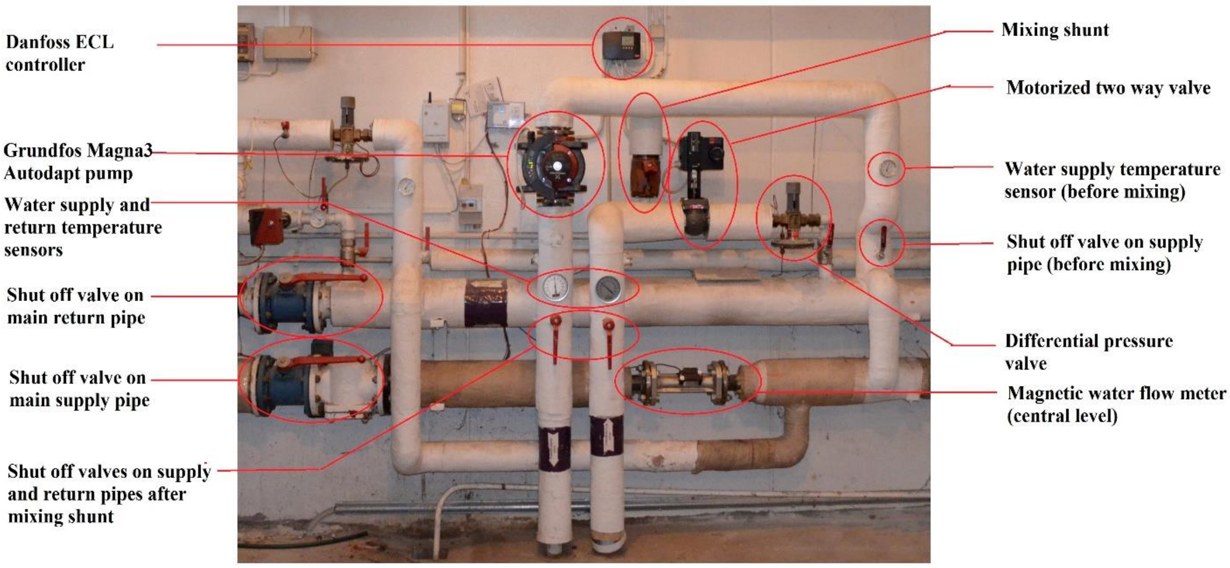


Figure 3.6 District heating connection for the ground floor of the East block

For efficient use of the water there is a mixing shunt for each separate connection. The ECL controller is connected to the pump, to the pressure regulator (actuator), water temperature sensors and to the weather compensation station. Monitoring of the used heating energy is done on a central level. Schematic diagram of the particular connection is shown in Figure 3.7.

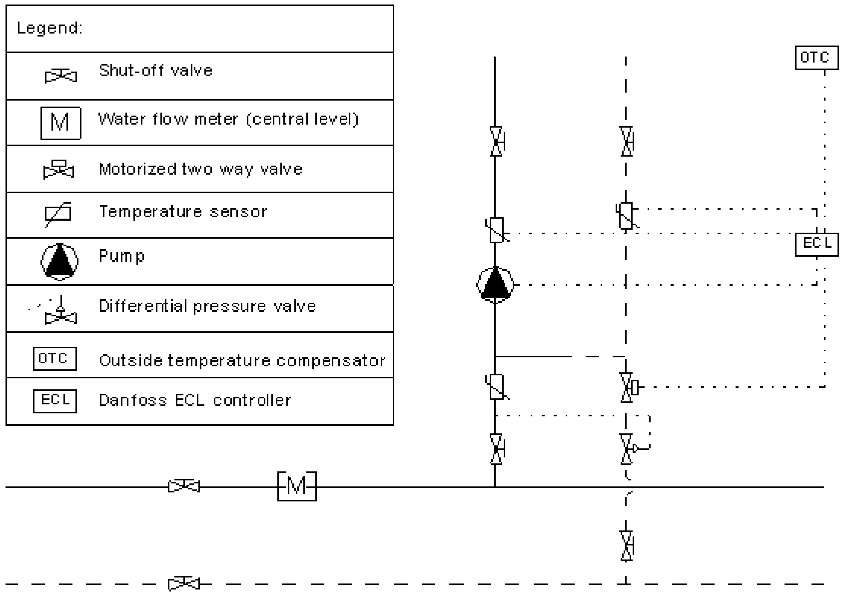


Figure 3.7 Schematic diagram of district heating connection for ground floor of the East block

The differential pressure valve is connected to both supply and return pipe, the purpose of it to maintain constant pressure at all times over the two way motorized valve, which opening and closing according to a signal given by the ECL controller.

3.2.1.1 Circulation pump

Producer of the circulation pump is Grundfoss and the type of pump is Magna 32-120 f. The pump has a maximum operation range of the head of 12 meters and maximum flow of 25 m³/h. The Grunfoss Magna pump can be set to the control mode which is most suitable for the individual system. The possible control modes include Auto adapt (factory setting), proportional pressure and constant pressure. Each of the control modes can be combined with automatic night-time duty, where the pump automatically changes over to night-time duty when the build-in sensor registers a flow-pipe temperature drop of more than 10-15°C within approximately 2 hours. Changes over to normal duty takes place when the temperature has increased by approximately 10°C.

The control mode Auto adapt continuously adapts the pump performance. The set point of the pump has been factory set at 6 meter for Magna 32-120 f. This setting cannon be changes manually. When the pump registers a lower pressure on the max curve, A_2, the Auto adapt automatically selects a corresponding lower control curve, H_{set2}, thus reducing the energy consumption – Figure 3.8.

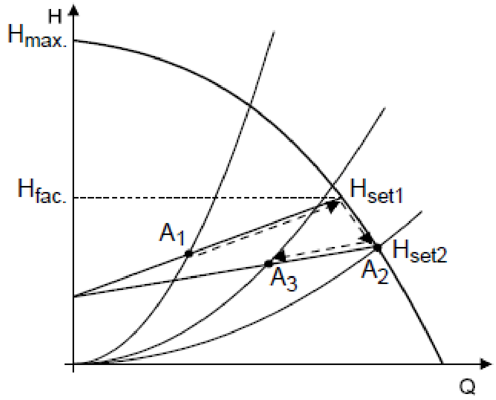
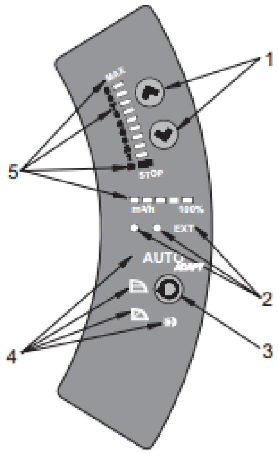


Figure 3.8 Auto adapt mode of the circulation pump, (Grundfos 2016b)

Where A_1 is the original duty point, A_2 is lower registered pressure on the max curve, A_3 is new duty point after Auto adapt control, H_{fac} is the factory set point, H_{set1} is the original set point and H_{set2} is the new set point after auto adapt control.

The control panel on the pump control box/terminal incorporates the basic functions for readings and settings as indicated in Figure 3.9.



Pos.	Description
1	Buttons for setting of head
2	• Indicator lights for operating and fault indication and • symbol for indication of external control
3	Button for selection of control mode: *AUTOADAPT*, proportional pressure, constant pressure and automatic night-time duty
4	Light symbols for indication of control mode and night-time duty
5	Light fields for indication of head, flow and operating mode

Figure 3.9 Magna 32-120 f control panel, (Grundfos 2016b)

The pump in the Vester Mariendal school is currently set to Auto adapt mode, which is assumed to be with a factory setting of the head of 6 meters. There is no indication on the control panel of the pump that the night-time duty is activated – Figure 3.10.

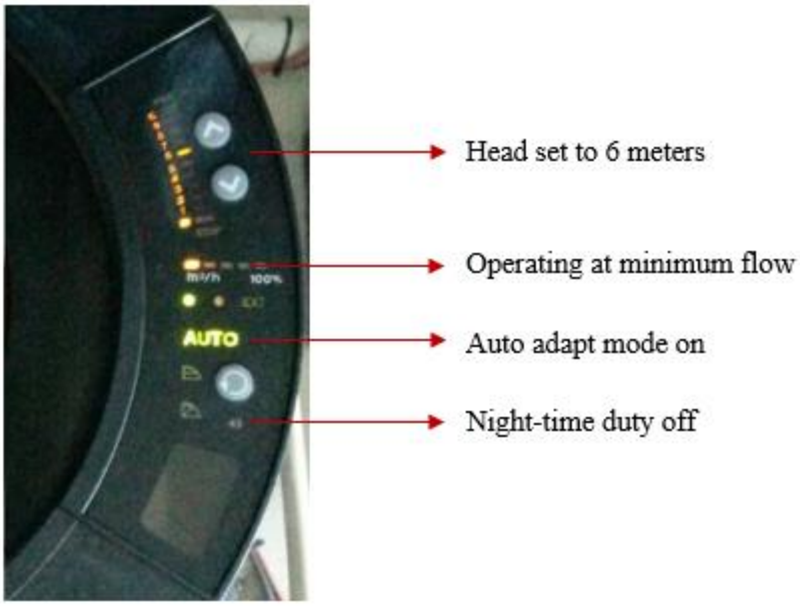


Figure 3.10 Picture of the control panel of the pump

3.2.1.2 ECL Controller

In the following subchapter a short description of the Danfoss ECL control is included. The ECL controller is used for automatic temperature control of heating systems and it is frequently met in buildings in Denmark. Information regarding the ECL is composed based on Danfoss ECL data specifications.

The ECL control provides the possibility of adjusting the room and hot water temperatures based on the user settings that are implemented in the controller. The controller is designed for a wide range of heating systems with different capacities and configurations.

The shown diagram in Figure 3.11 is a simplified schematic of how an ECL control is connected to a heating system. Note: the outlined diagram also resembles the connection that the project case study Vester Mariendal School has; more about the heating system schematic of the school in chapter *3.2.1. Building heating system.*

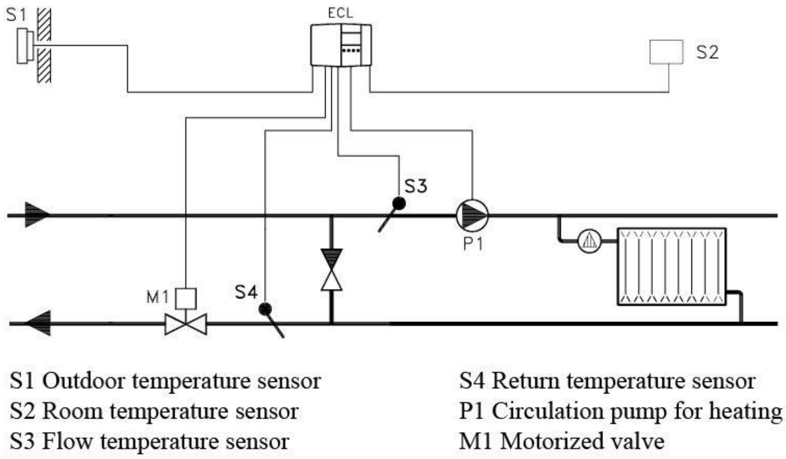


Figure 3.11 Heating system- connection to ECL (Danfoss n.d.)

The outdoor temperature sensor is usually installed on the north facade of the building due to less possibility of direct solar radiation. The system can operate either with or without room temperature sensor.

Users have the possibility to adjust the factory settings, which are implemented in the control system. Settings such as supply and return temperature of the water in the system (min. and max. limit), desired room temperature, schedules for day and night, PI regulation, the heating curve. Desired temperature can be controlled only if a room sensor is installed. If no sensor is installed, the desired temperature is only an expression for a possible obtainable room temperature, meaning that the room temperature is controlled by radiator thermostats/valves. The day plan can consist of up to three comfort periods per day. The weather compensation is a facility, which enables the controller to consider outdoor weather conditions for heat control. Weather compensation is based on the user-defined heat curve, which determines the flow temperature at varying outdoor temperatures.

There is also a possibility to set the flow temperature reference to increase slowly after a setback period in order to avoid load peaks in the supply network, this will cause the valve to open slowly.

There are three different options for the permanent display: A-for room temperature (if there is a room sensor), B-for system information and C-for today's schedule. Figure 3.12 presents a print screen of the ECL controller where it can be seen that the time bar is continuous because the schedule comes from the CTS, the controller is in automatic mode (the clock symbol) and the white arrow indicates the present state (comfort period). Figure 3.13 presents an example of the ECL display.

Figure 3.12 ECL on Vester Mariendal school

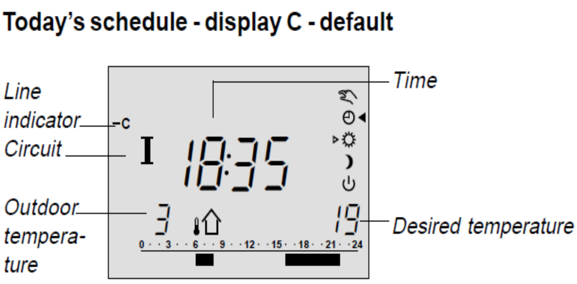


Figure 3.13 Display C example from (Danfoss n.d.)

The controller can be set to five different modes as it can be seen in Figure 3.14. The state indicator shows the actual mode of the controller during automatic operation. The automatic controller mode is typically selected. The manual mode is selected only at maintenance and service. The desired temperature is controlled according to the implemented day plan with automatic changeover to/from comfort and reduced temperature periods (night setback).

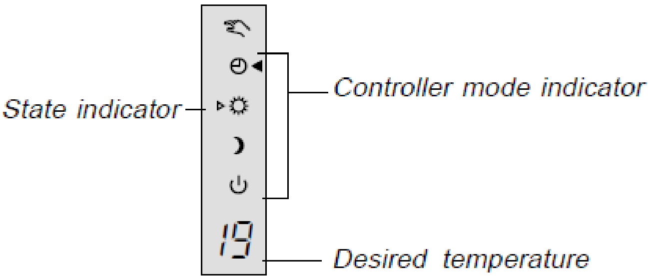


Figure 3.14 Controller modes (Danfoss n.d.)

From the settings in the ECL controller in Vester Mariendal School it was found that the slope of the heating curve is set to 1.5 in, the outdoor temperature limit at which the heating will be shut off is 18°C, the return temperature set point is 40°C. The day mode schedule starts at 06:00 and ends at 20:00 and the "desired temperature" is 25°C, the controller uses this value in the calculation of the supply temperature. However, this does not mean that the temperature in the rooms will be 25°C, because at the room level the temperature can be controlled by using the thermostatic radiator valves. The night mode starts at 20:00 and finishes at 06:00 and during this period the "desired temperature" is 16°C. More about the settings included in the ECL can be found in Appendix G.

Table 3.3.summarizes a few observations of the different parameters from the ECL controller. The parameters include supply and return temperature, outdoor temperature, time, desired temperature and mode of the pump.

Date	Day of the week	Time	"Desired T°C"	Outdoor T°C	Supply T°C	Return T°C	Pump
17/11/2016	Thursday	15:53	25°C	7°C	60°C	42°C	ON AUTO
24/11/2016	Thursday	18:12	25°C	7°C	63°C	43°C	ON AUTO
04/12/2016	Sunday	12:43	16°C	7°C	28°C	23°C	ON AUTO
07/12/2016	Wednesday	20:15	16°C	10°C	52°C	40°C	OFF
08/12/2016	Thursday	19:15	25°C	9°C	57°C	41°C	ON AUTO
		19:57	16°C	9°C	56°C	40°C	ON AUTO
		20:06	16°C	9°C	40°C	40°C	ON AUTO
		20:36	16°C	8°C	37°C	37°C	ON AUTO
09/12/2016	Friday	20:43	16°C	9°C	58°C	46°C	OFF
20/12/2016	Tuesday	17:46	25°C	5°C	63°C	42°C	ON AUTO
21/12/2016	Wednesday	20:57	16°C	7°C	33°C	33°C	ON AUTO
28/12/2016	Wednesday	14:15	25°C	7°C	61°C	42°C	ON AUTO
29/12/2016	Thursday	14:33	25°C	8°C	59°C	38°C	ON AUTO
01/01/2017	Sunday	16:17	16°C	5°C	31°C	29°C	ON AUTO
02/01/2017	Monday	16:58	25°C	2°C	65°C	43°C	ON AUTO

Table 3.3 Parameters observations from ECL

3.3 MEASUREMENT CAMPAIGN

This subchapter describes the process of preparation for the measurement campaign. It includes measurement set-up analysis, choice of the test and reference room in the case study building, and the description of equipment used for the case study.

The period of the energy measurement campaign is from 21.12.16 - 08.01.17. During this period, the settings on the central ECL controller remain unchanged.

Several investigations are made in the reference room, where the different TRV positions are tested. TRVs in the test room are programmed to have a day set point of 20°C (during occupied hours), and 18°C during night (night setback). The aim is to investigate the amount of savings when having programmable TRVs with a night setback. An assumption is made, that the regular TRVs in the reference room are not adjusted after the occupancy period – a scenario when people forget to turn down the TRVs for the night.

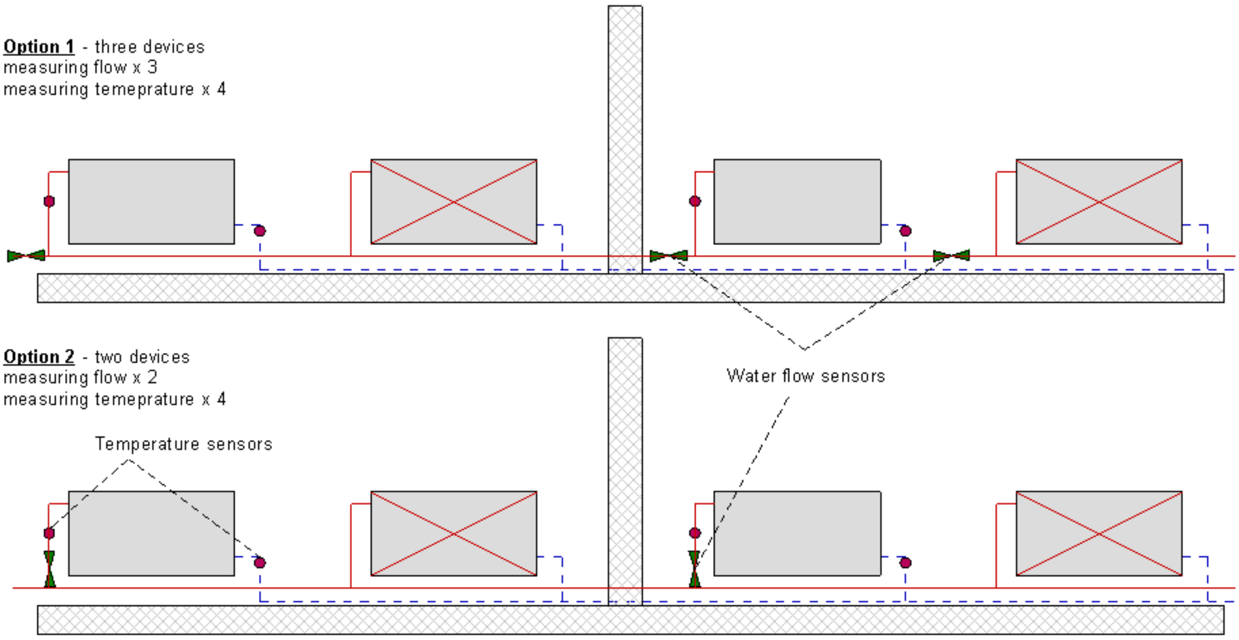
Since the period of measurements happens to be during the holiday period, the internal loads from people, lighting and equipment will not be present in the rooms of interest. Therefore, the measurement results will not be affected by these factors. Solar radiation, on the other hand, will contribute to internal heat loads of both rooms. For rooms with the same orientation, glazing area and type it can be assumed that the solar gains are the same.

3.3.1 SET-UP ANALYSIS

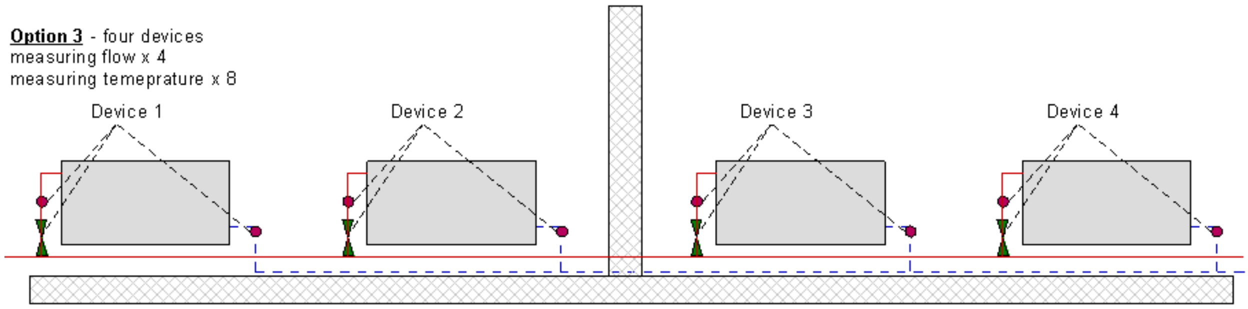
Energy meters

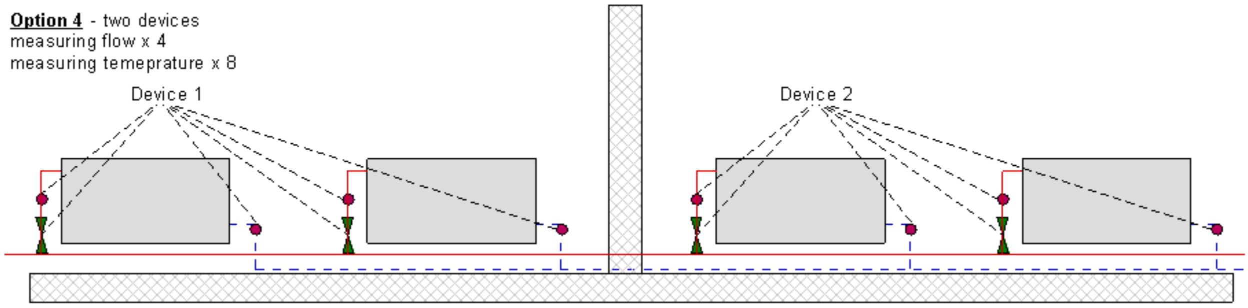
Several options for measurement set-ups were considered. Initially a possibility of measuring flow and temperatures separately was thought about. Using flow meters and temperature sensors separately complicates logging of the results and the set-up itself. Considering different possibilities for temperature measurement (chapter *2.1.1.2 Temperature sensors*), the simplest and most suitable to use in this case study would be thermocouples, however, the set-up would require a reference point (ice bath). Therefore, using a meter that would combine both flow and temperature measurements was in preference.

Measurement set-up analysis included a few possibilities depending on the amount of devices used. The following options were considered during the concept phase:



The first two options included the necessity to turn off one radiator in each room, leaving only one of them working. Depending on the energy meter specifications, namely the pipe size range for flow measurements, the set-up could include three (Option 1) or two energy meters (Option 2). In the first case the flow is measured on the main supply pipe, and then by subtraction the flow to each of the radiators can be found; and in the second option the flow is measured on a branch pipe to the radiator. Due to one radiator being turned off both options could compromise the thermal comfort in the rooms, and furthermore lead to false conclusions drawn from the measurement campaign. Therefore, further possibilities were analysed.





Options 3 and 4 would give the energy measurements of each radiator separately; the difference between them is in the amounts of devices used. There are devices that allow more than one connection of flow and temperature sensors to be connected to it. However, the price of such two devices (Option 4) is not much less than the price for four separate devices (Option 3), moreover four different devices allow more flexibility for further use by the university. All things considered, the final energy meter set-up is chosen to be as illustrated in figure for Option 3.

Amount and placement of operative temperature sensors

Thermal comfort measurements include air and mean radiant temperature, relative humidity, air velocity (draft) and vertical temperature gradient. In this study, however, only operative temperature measurements are used with the aim of determining if the heating system and its controls work as they were intended to and provide good indoor thermal comfort. Furthermore, measuring the indoor temperature can answer questions concerning high heat consumption due to inadequate insulation, unwanted air circulation or high indoor temperatures (IC-Meter 2016) - Figure 3.15.

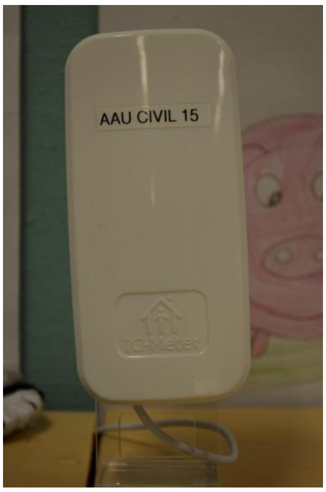


Figure 3.15 IC-Meter

When measuring operative temperature in a room, one needs to consider a proper placement of sensors. Various standards provide guidelines to measurements of operative temperature. The height for temperature sensor placement depends on the type of the room that is being investigated. DS/EN ISO 7726 (Dansk Standard 2001) recommends that the measuring heights for the physical quantities of an environment are: ankle level (0.1 m), abdomen level (1.1 m) and head level (1.7 m). In case of classrooms, where people are normally seated, these levels are 0.1, 0.6 and 1.1 m, respectively. Sensors should not be exposed to direct solar radiation; the minimum distance to a window/radiator should be 1.5 m, and min. 0.5 m to a corner. The placement of sensors is illustrated in Figure 3.16.

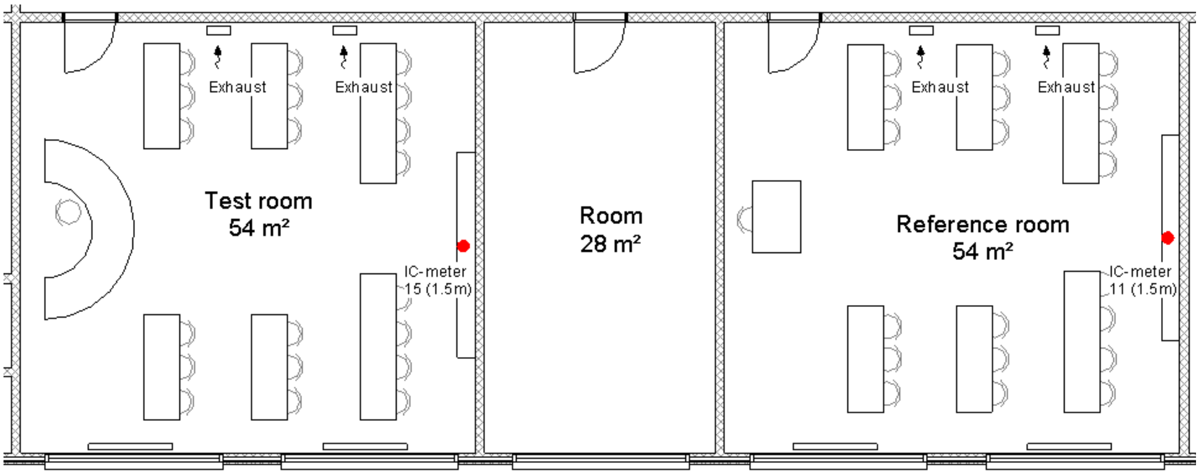


Figure 3.16 Placement of Indoor Comfort sensors

3.3.2 Room description

In order to be able to compare the results for the energy consumption with the existing TRVs and the new programmable TRVs, two identical rooms are used in the investigations (Figure 3.17). By identical rooms it is meant that the rooms should have same size, orientation, occupied time, amount of windows, same heat loss, internal gains and heat output by the radiators. In those two rooms, different control strategies are applied. In one of the rooms the heating is controlled by the existing manual thermostatic valves while in the other room by digital control.

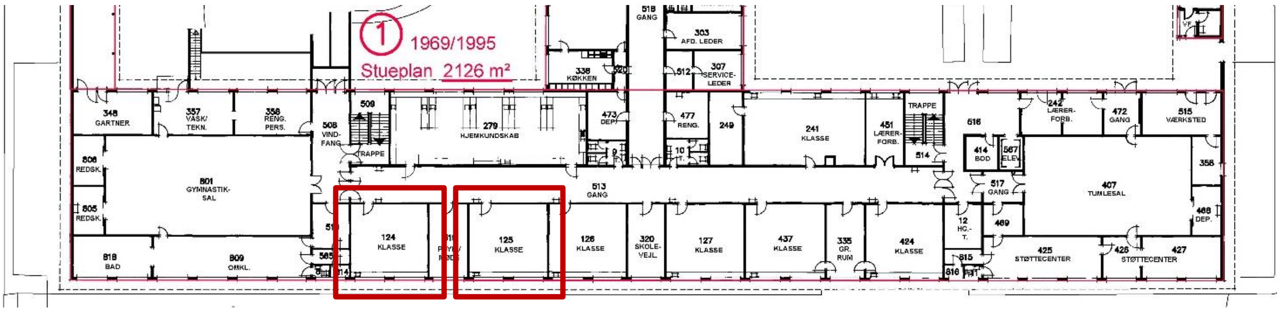


Figure 3.17 Rooms location

Classrooms are located on the ground floor; they both have an area of 54 m^2 and are East oriented. Both of the classrooms have two iron radiators with a maximum output of 1331 W each. Table 3.4 presents the heat losses of the room due to transmission, line and ventilation (including infiltration). The calculation was based on the design indoor and outdoor temperatures of 20 and -12°C, respectively.

	Area [m²] / length [m]	U-value [W/m²K]	Loss [W]
External wall	12.2	0.44	172.7
Window	12.5	2.30	918.9
Roof	54	0.33	571.7
Line loss	20.3	0.08	51.9
Total transmission			1715.0
Ventilation	0.5	ach	947.5
Room total heat loss			**2663**

Table 3.4 Heat losses of the test room

Figure 3.18 illustrates the plan drawing, where the location and sizes of radiators are indicated; and Figure 3.19 shows the 3D drawing of the test room.

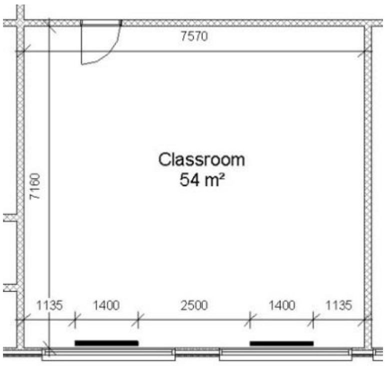


Figure 3.18 Plan drawing / photo of the classroom

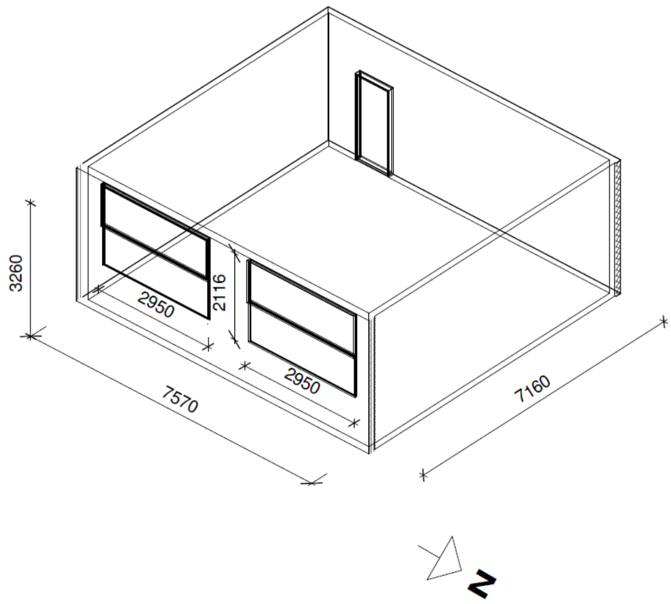


Figure 3.19 Test room sizes

3.3.3 CHOICE OF EQUIPMENT

3.3.3.1 Energy meters

Various flow meters types have a certain velocity range conditions under which they perform In order to make sure that the selected equipment can be used for the needed measurements, a simple calculation is made to estimate the water flow velocity in the radiator pipes.

The branch pipes to radiators were measured to have an external diameter of ≈ 20.3 mm and circular length of ≈65 mm. According to (Lauritsen 2009) the nominal (or internal) diameter of 15 mm for threaded steel pipes corresponds to minimum 21 and maximum 21.8 mm external diameter; the thickness of the pipe is 2.65 mm for medium heavy and 3.25 mm for heavy pipes. It is worth bearing in mind that wall thicknesses come within a specified tolerance, depending on the engineering standard used – a typical wall thickness tolerance is 12.5% (Anon n.d.). It is assumed that the wall thickness of the pipes for installing energy meters is 2.65 mm, see Figure 3.20.

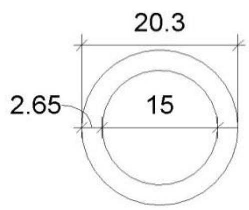
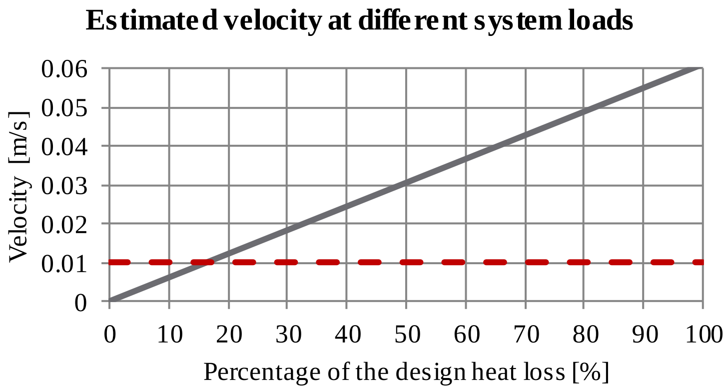


Figure 3.20 Pipe dimensions for the test

Based on the heat loss calculation for one classroom at the design conditions (Table 3.4) and the measured pipe size of DN 15 mm, the calculated velocities at different system loads are presented in Graph 3.1. The calculation can be found in Appendix H. Note: Only half of the heating need is taken into consideration in the calculation because the estimated velocity is needed to be determined per radiator.



Graph 3.1 Estimated velocity at different system loads

The graph shows that at loads higher than 18% (that corresponds to an approx. outdoor temperature of 14°C) the velocity in the pipes will be above 0.01 m/s – that is normally the minimum required velocity in order for the energy meter to be able to measure the flow.

In order to measure the output of the radiators, water flow and temperature of the supply and return water will be measured by use of “KAT flow 100” meter - Figure 3.21.

Figure 3.21 KAT flow 100

The meter is a clamp-on ultrasonic flow transmitter, which measures water flow by using the ultrasonic transit time principle (chapter *2.1.1.1 Water flow meters*).

"This involves sending and receiving ultrasonic pulses from a pair of sensors and examining the time difference in the signal. The signals are generated by a clamp-on transducers that are mounted externally on the surface of the pipe. The flowing liquid causes time difference in the ultrasonic signals which are then evaluated by the flow meter to produce an accurate flow measurement."

(Katronic 2014)

The flow meter can operate on various pipe materials and diameters over a range from 10 mm to 6500 mm. The accuracy varies between ±1 and 3% of the measured value. If the meter is process calibrated the accuracy can be increased up to ±0.5% of the measured value.

PT100 clamp-on sensors (Figure 3.22) are used for supply and return temperature measurements. The sensor has a four-wire connection, two to carry the current, and two to sense voltage across the sensor element (Figure 3.23). Such four terminal sensing, i.e. separation of voltage and current electrodes, eliminates the influence of the resistance in lead wires on the sensor reading, increasing the accuracy of the measurement. Summary of specifications of the PT100 sensor used in the case study is in Table 3.5.

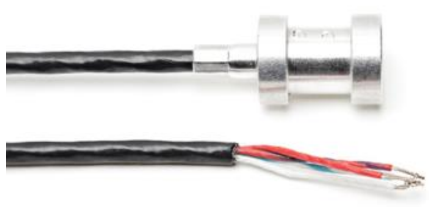


Figure 3.22 PT100 with wired cable connection (Katronic 2014)

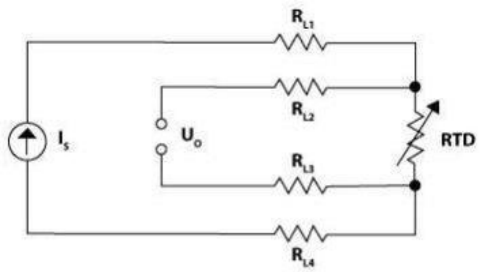


Figure 3.23 4-wire configuration (Innovative Sensor Technology, 2010)

Temperature sensor PT100					
Parameter	**condition**	**min**	**typical**	**max**	**Units**
Accuracy T	Class A	-	±0.15+0.002│T│	-	°C
Accuracy ΔT	Corresponding to EN 1434-1	-	≤0.1 (3K<ΔT<6K)	-	K
Measurement range	-	-30	-	80	°C
Response time	-	-	50	-	S

Table 3.5 Technical data for clamp-on temperature sensor PT100 (Katronic 2014)

Katdata software by Katronic Technologies is the tool for extracting the data logged by the energy meter. There is a possibility to log 100 000 data points, and one can choose up to 10 parameters to be logged. The parameters with multiple options for units to choose from include: volumetric flow rate, flow velocity, mass flow rate, volume, mass, heat flow, heat quantity and temperature. The logging interval is also defined by the user. For the case study the following parameters are chosen to be logged with an interval of 300 s (5 min): volumetric flow rate [m^3/h], heat flow [W], heat quantity [kWh], supply and return temperatures [°C].

3.3.3.2 Indoor Climate Meters

Indoor Climate Meter (IC-Meter) is a new plug and play concept that focuses on indoor climate and energy. The IC- Meter equipment is a smart "cloud" based IT solution and a web/smartphone. IC-Meter measures and visualizes indoor climate in a room or a building. The concept includes a data measurement device, a server and website with APP client for mobile units (IOS/Android). The meter device delivers accurate information for temperature, humidity and CO_2 concentration. Every five minutes the measurements are uploaded to the server, via the client's own Wi-Fi/Internet. (IC-Meter 2016). The temperature sensor specification is outlined in Table 3.6.

Temperature sensor Sensirion SHT21					
Parameter	**condition**	**Min**	**typical**	**max**	**Units**
Resolution	14 bit	-	0.01	-	°C
Accuracy tolerance	typical	-	±0.3	-	°C
Repeatability	-	-	±0.1	-	°C
Operating range	-	-40	-	125	°C
Response time	τ 63%	5	-	30	s
Long term drift	-	-	<0.04	-	°C/yr

Table 3.6 Technical data for temperature sensor in the IC-Meter (Sensirion 2011)

3.3.3.3 Programmable thermostats

Digital thermostats provide the possibility of allowing temperatures settings for two, four, or six periods each day, and usually allow each period to be set to a unique temperature. More-sophisticated thermostats may have a weekday schedule and a separate weekend schedule (so-called 5/2 setting). Digital thermostats can provide individual room control from phone, tablet and PC. The thermostats can be remotely controlled from a mobile app for example, in this way the temperature in the room can be controlled even when no occupant is present.

In the following subchapter, a short introduction/description of a digital thermostat (VS20WRF) and radiator valve (TRV10RFM) from Salus Controls is made.

With Salus iT600 control of radiator system - Figure 3.24, Figure 3.25, Figure 3.26 , it is possible to build a wireless system that is battery operated. The system consists of a wireless TRV mounted on the radiator valve and a room thermostat.

Figure 3.24 Salus TRV

Figure 3.25 Programmable room thermostat – Salus

Figure 3.26 Window sensor - Salus

The system can be controlled either locally from the room thermostat, or it can be connected via the internet to a smartphone, tablet or computer.

The VS20 digital thermostat may be used for controlling a heating zone with up to six TRV’s per thermostat. It can also be connected to windows and doors sensors and smart plugs. The units are wireless connected and they give the possibility to insert both time and the temperature for each room in use. Each room can have up to six settings per day and it can be set to 5/2 week control, each day individual or all days alike. It is also possible to set it to an extended operation period, vacation or frost protection.

Features of (VS20):

- Three adjustable temperature settings including night setback
- Party and holiday modes
- Temporary and permanent overrides
- External sensor options including cylinder thermostat when configured as a hot water timer
- Default heating/cooling program
- Memory backup (settings don’t need to be reset in the event of power loss)
- Heating/cooling changeover when used with KL10RF

The wireless radiator controller (TRV10RFM) is a battery-powered, mini-size TRV using wireless communication. The features of TRV10RFM are outlined in Table 3.7.

Model	TRV10RFM
Type	Hydraulic Radiator Valve DC Motor M30 x 1.5
Valve adaption	Automatic
Power source	2x AA batteries
Control method	Modulating
Communication	2.4GHz ZigBee wireless
Operating temperature	0 to 50 ℃

Table 3.7 Features of TRV10RFM

Note: For the above specifications, Salus Controls web page was used. (Salus Controls 2016)

3.3.4 ENERGY METERS INSTALLATION

The following content describes the installation of the energy meters "KAT flow 100", in the case study building, and some of the aspects that should be considered when using this particular equipment. Note: The energy meters were not tested in the laboratory in a controlled environment due to time constrains of the project and late delivery of the equipment.

In order to exclude any errors occurring in the measurements the correct positioning of the sensor is an essential condition, for the sound signal to be received under optimal conditions and evaluated correctly. There is no standard solution for the positioning of the transducer, because of the variety of applications and the different factors influencing the measurements. The correct positioning will be influenced by: diameter, material, wall thickness, general condition of the pipe, the medium in the pipe. Additionally the external and internal pipe corrosion, solid particles in the medium strongly contribute to signal attenuation. Another important aspect to consider is the sufficient "straight pipe length" in order to obtain accurate measurements. The recommended distances from the disturbance sources are illustrated in Figure 3.27. More information can be found in the operating instructions manual (Katronic Technologies 2016).

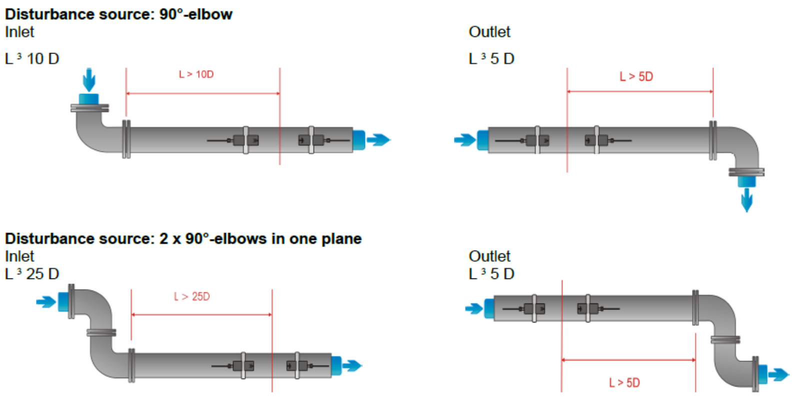


Figure 3.27 Recommended distances from disturbance sources (Katronic Technologies 2016)

The energy meters were installed in the reference and test rooms on 21.12.2016. Figure 3.28 presents the installation of one energy meter (same procedure is followed for the three other energy meters). Each installation includes two flow sensors, two temperature sensors and one meter, which is powered supply connected.

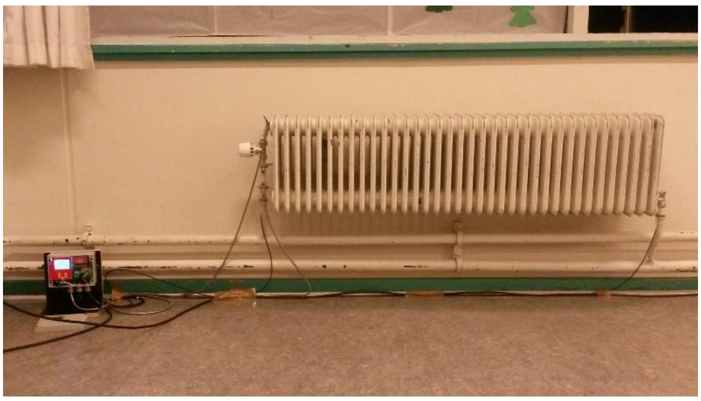


Figure 3.28 Energy meter installation

There are two options for mounting configuration: Reflection Mode and the Diagonal Mode. The Diagonal mode is often used for large pipes, while the Reflection Mode is used for small pipes. Additional variation of the Reflection and the Diagonal mode are possible by changing the passes through the pipe. For very small pipes, sensor mounting configurations such as 4 passes are used.

The clamp-on flow sensors are mounted with tension straps, vertically on the supply pipe as indicated on Figure 3.29. The mounting configuration in this case is Reflection Mode (same side of the pipe), the ultrasonic signal passes four times through the water (4 signal passes). The distance between the sensors is automatically calculated by the flow meter based on the parameter entries for the pipe (outside diameter, wall thickness, medium, process temperature, sensor type, and number of signal passes).

Figure 3.29 Clamp-on flow sensors

Figure 3.30 Temperature sensor

For a good acoustical contact between the pipe and the flow sensors, a bead of acoustic coupling gel was applied. Each transducer has an engraving on the top, the mounting is correct when the engravings form an arrow Figure 3.29 (the arrow indicates the direction of the flow). In Figure 3.30 an example of mounted temperature senor is presented. Note: the flow sensors are very sensitive therefore, it should be ensured that the sensors are pressed firmly onto the pipe and that there is no air pockets between the sensor surface and the wall pipe.

Figure 3.31 presents the display of the meter showing the adjustment of the sensor location. The upper bar presents the signal-to-noise and the lower bar the quality. The bars should be of identical length and the circle between the two bars should be positioned in the middle.

Figure 3.31 Sensor positioning screen

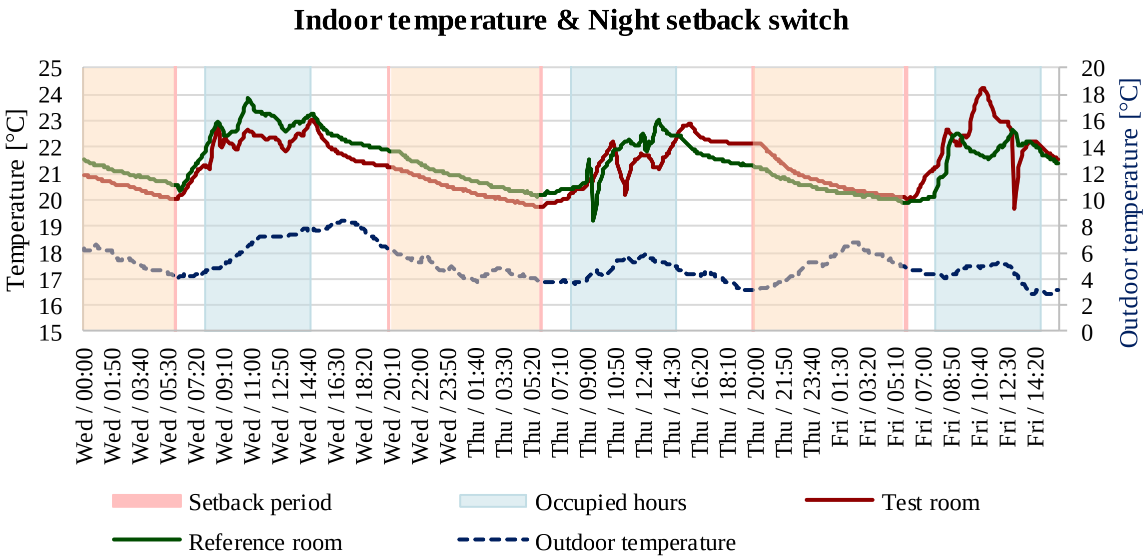
The energy meter is switched on by connecting the power supply to the instrument, when the external supply is disconnected the energy meter will switch off. The logged data can be exported using the KatData software and a USB cable.

3.4 Measurement data analyses

3.4.1 Current thermal comfort

Analyses of thermal comfort in the reference room and in the test room are included in the following subchapter. This is done in order to see if there is setback applied in the rooms, what are the temperature set points for day, night and weekend, and if the rooms have similar condition in terms of thermal comfort. Note: When referred to time, 24 hour format is used.

The IC-meters were installed in both rooms on Tuesday 15th of November at around 15 o'clock. The Graph 3.2 shows the outdoor temperature and the indoor temperature in the two rooms for a period of three days. The conditions regarding the temperature in the two identical rooms are similar: the slopes of the temperature increase at the start of the day, and decrease after the occupancy time is finished, and have the same tendency, meaning that both rooms react to the change in boundary conditions in the same way. In the reference room, the temperature it is slightly higher on Wednesday and Thursday, than in the room, which will be used as the test room (the room with the programmable TRV's). During the occupied hours the temperature is around 22-23°C and after the occupied hours it drops to around 20°C.It can be seen that at after 15 o'clock when the children leave the classrooms the temperature starts to drop slowly when there are no more internal gains. The position of the thermostat after occupied hours it is unknown.



Graph 3.2 Indoor temperature for three days 16-18/November

*Note: The orange filled area marked in the graph illustrates the setback period, which starts at 20 and finishes at 06 o'clock

From the same graph, it can be observed that there is a steeper drop in temperature around 20:30 and a raise in temperature each morning at around 6:30 in both of the rooms (marked with the vertical line). This is due to the setback applied at the central level by the ECL controller. The schedule that the system follows is input in CTS, from which all heating connections and ventilation are controlled. CTS system is sending a signal to the ECL to reduce supply temperature as soon as it is time for setback. In this case the period is between 20:00 and 06:00 o`clock. The CTS schedule can be found in Appendix I. However, the operative temperature in the room does not change immediately, from Graph 3.2 and the CTS schedule it can be estimated that there are 30 min response time, which can be explained by the location of the room, the type of radiator and the thermal mass of the building.

Programmable thermostats

On Friday afternoon the 18th of November, the programmable TRV's and the thermostat where installed in the test room. The current schedule applied is presented in Table 3.8. Note: different settings for time and degree of setback were investigated before, the observations can be found in Appendix J.

Day	Hour	Degree [°C]
Monday	06:00 – 14:00	20
	14:00 – 06:00	18
Tuesday to Friday	07:00 – 14:00	20
	14:00 – 06:00	18
Saturday & Sunday	All time	18

Table 3.8 Schedule for the thermostat in the test room

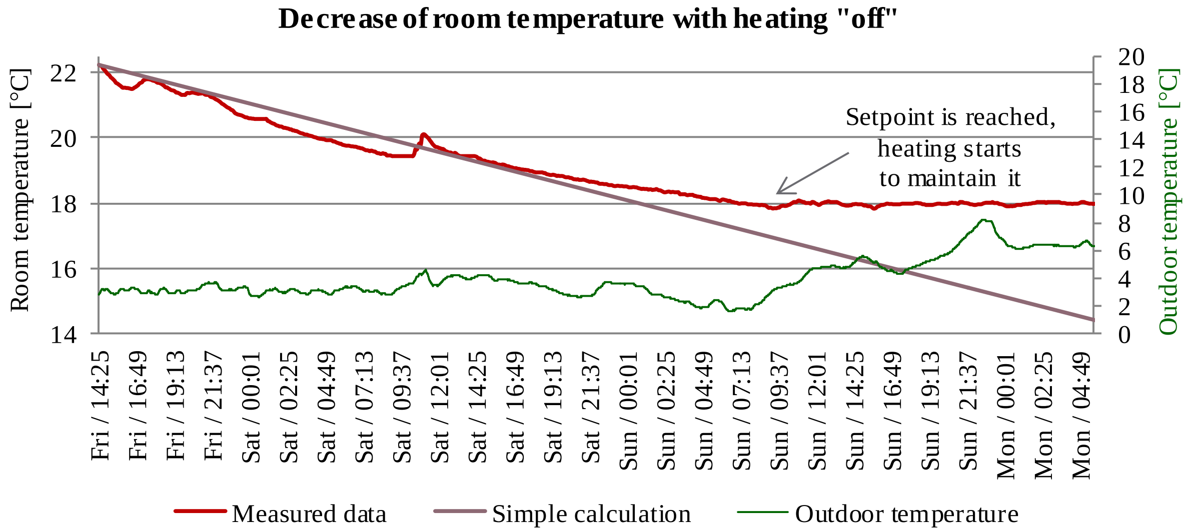
The sensor in the TRV needs approximately 2 days to self-calibrate during that time the feedback of room temperature is done by the sensor integrated in the TRV. Afterwards, when the calibration is finished, the room thermostat on the wall is measuring the operative temperature that is wirelessly communicating with the TRV.

Regarding the temperature setback during the weekend in the test room, by analyzing the IC-Meter measurements it was observed that the temperature in the test room reached the weekend setback of 18°C after around 40 hours, at around 7 o'clock in the morning on Sunday. A simple calculation using equation (13), where thermal mass C [J/K] and overall heat transfer coefficient $H = UA$ [W/K] of the case study room is taken (for the calculation of both values used refer to Appendix E and Appendix K). The equation determines room temperature versus time, once heat output is turned off.

$$\boldsymbol{T_r = T_o + (T_{ri} - T_o) \cdot e^{-\left(\frac{UA}{C}\right)\cdot t}} \tag{26}$$

The time t [h] for room temperature to drop from initial condition T_{ri} to a setback point T_r is then

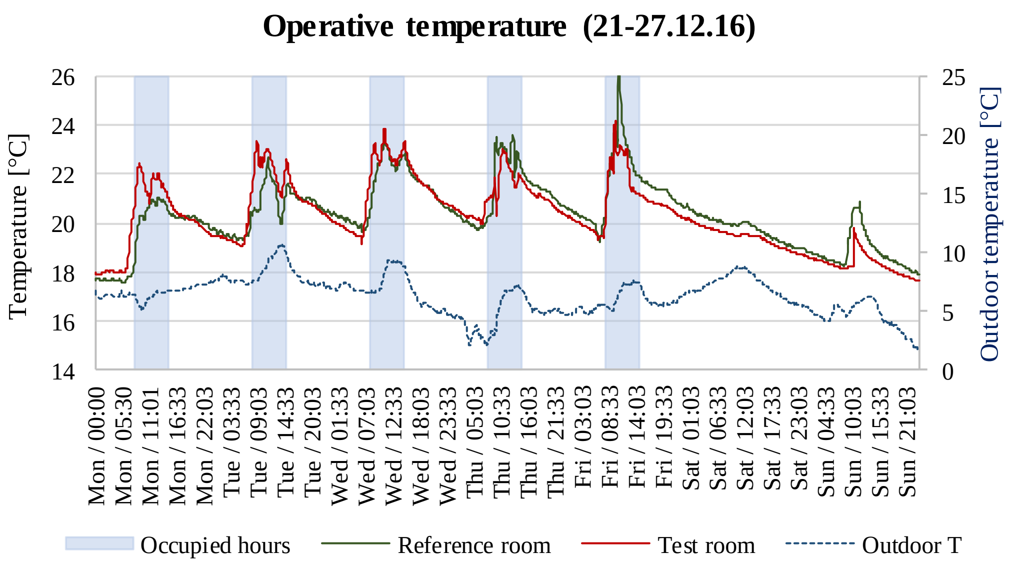
$$\boldsymbol{t = \frac{\ln\left(\frac{T_r - T_o}{T_{ri} - T_o}\right)}{-\left(\frac{UA \cdot 3600}{C}\right)}} \tag{27}$$



Graph 3.3 Decrease of room temperature in the weekend, heating "off"

A simple calculation using equation (27) shows a similar result for the decrease of room temperature, Graph 3.3. The time scale on Graph 3.3 starts from Friday afternoon, when the kids leave the school, and finishes on early Monday morning. Note: for the calculation the average outdoor temperature of 3.5°C was used. For the results of the simulation refer to Appendix L.

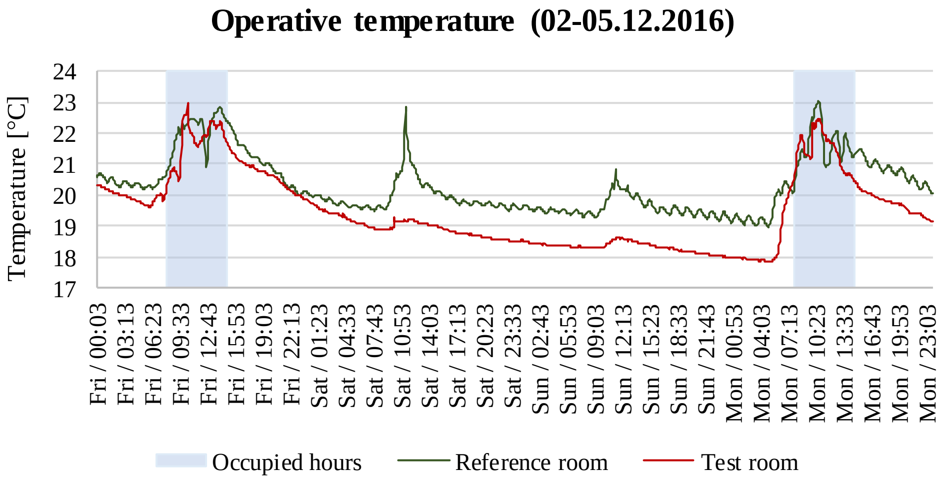
In Graph 3.4 are plotted the operative temperature in the test and reference rooms and simultaneously the outdoor temperature for 1 week period. The programmable thermostats in the test room have the settings according to the schedule described in Table 3.8 applied from 23 November. The existing TRVs in the reference room are controlled by the users according to their wishes. It can be observed that the ordinary thermostats and the programmable thermostats provide similar thermal comfort. The central control from the ECL has a night setback starting at 20:00. This implies reduction of supply temperature at the central level. Both test and reference room react to the central setback in a similar way. Due to high internal loads during the day and thermal accumulation in the construction, the measured operative temperature does not go below 19°C during weekdays. These observations suggest that the heating is off in both rooms for the time of setback.



Graph 3.4 Operative temperature in the test and reference rooms (21-27.11.2016)

Due to different time schedules of the rooms (thus different time and amount of hours that the room is occupied), the operative temperature is rising to different levels during the day. Exception is Wednesday when the internal loads, as well as losses from natural ventilation (opening windows) for the two rooms are exactly the same. Due to direct solar radiation on the sensor Friday noon the operative temperature in the reference room is registered at more than 26°C. Due to the same reason there is a peak of 21°C on Sunday noon.

Further, the setback temperature during the second weekend of the measurement period is investigated. The idea is to evaluate if the thermal comfort on Monday morning will be acceptable if during the weekend the setback temperature is reduced to 18°C.



Graph 3.5 Operative temperature in the test and reference rooms

From Graph 3.5 it can be seen that Monday morning the temperature in the test room is able to reach 20°C, thus not compromising the thermal comfort in the classroom (the settings on the programmable thermostats can be found in Table 3.8). It is also observed that the programmable thermostats in the test room provide more stable thermal environment, compared to the traditional TRVs in the reference room, where there are continuous fluctuations of the operative temperature. This is because the thermostats were left on an open position, so the TRVs are still trying to maintain the set point by opening and closing, thus the temperature fluctuates.

All the above-mentioned observations are made in order to find the proper time period and degree of the setback in order to reduce the heat consumption during unoccupied hours. An important consideration when doing this is to consider the preheating time after a setback, in order to make sure that a higher energy consumption will not occur. The energy consumption for heating of the two rooms will be later investigated, when the flow meters and temperature sensors are installed on the radiators. The aforementioned changes to the temperature set point, heating hours, start of preheating time will be further investigated/evaluated in order to find an optimal solution.

3.4.2 Energy consumption

This subchapter contains analyses of measurements including energy use, water flow, supply and return temperatures at radiators, and the operative temperature in the two rooms in Vester Mariendal School. The test room has Salus Controls programmable TRVs installed, and the reference room has traditional TRVs. Various investigations are performed, throughout which the two strategies for room temperature control are analyzed. The aim is to prove that, by implementing a setback strategy at the room level will result in lower energy consumption.

3.4.2.1 TRV set points in the reference room

With the aim of determining the operative temperature that corresponds to the set point on the TRV, different positions on existing TRVs in the reference room were tested, and water flow and operative temperature were monitored in the room. The TRV positions represent the following temperatures according to valve specification - Figure 3.32. Since the producer does not specify if the set point should represent air or operative temperature, it is assumed that the provided guidelines describe operative temperatures, referred to as room temperatures.

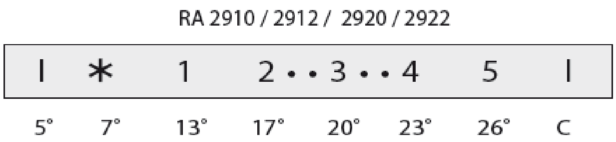
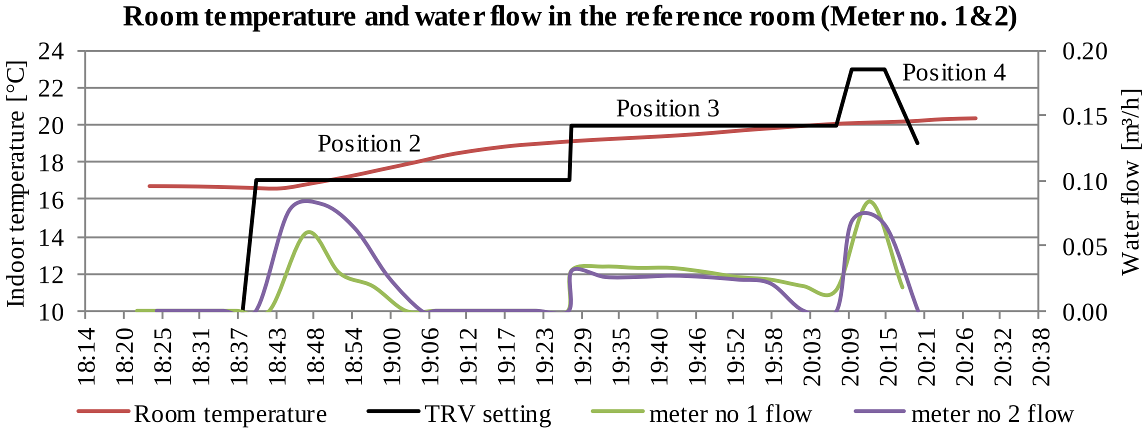


Figure 3.32 Thermostat positions and corresponding room temperatures (Danfoss 2011)

Before the test, the room is being cooled down by opening windows for about an hour to bring the room temperature from 19 to 16.5°C. Thereafter, both radiator valves are being turned up to position 2 (17°C); when the flow to both radiators stops, the recorded operative temperature should represent the set point of the TRV for that position. The same process is repeated for TRV position 3 and 4, however the test was stopped before reaching 23°C (position 4) due to the night mode switch at the central level. The water flow and operative temperature measurements that were recorded during the test are illustrated in Graph 3.6.



Graph 3.6 Testing the setpoints of the existing TRVs in the reference room

The first observation is that meter number 1 and 2, representing the two radiators in the room, do not show the exact same flows over the whole period of the test. The reason for this could lie in the position of the radiators: the air temperature that is recorded by TRVs can, for example, be affected by a possibly leaky window above one of the radiators. Another reason can be difference in the return temperatures: the flow through one radiator is smaller due to higher temperature drop, but the resulting heat output of both radiators could be the same. This reason is further analysed, see *3.4.2.1 Supply and return temperature comparison for radiators in the reference room.*

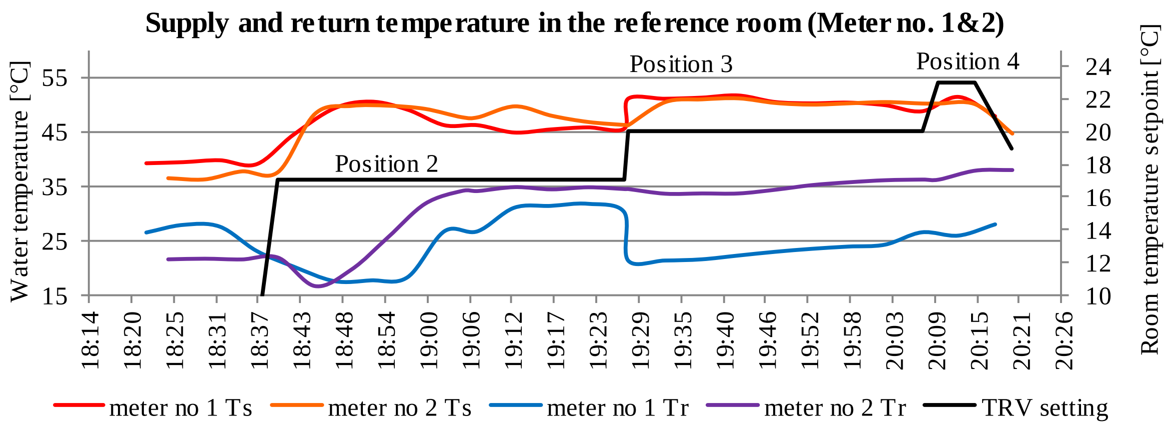
Secondly, the water flow measurements show that both valves react to a change in set point, and that different positions result in different amount of flow – the valves are working proportionally, depending on the error - difference between the sensed temperature and the set point. Therefore, the change to position 2 right after the air was cooled down by opening windows gives a higher flow than the change to position 3 and 4 afterwards.

Furthermore, proportional control results in an offset from the set point. How big of an offset there is for the different set points cannot be determined based on this test, since the TRVs were not left on the same position for a longer period of time. Moreover, dynamic weather conditions are changing the heat loss of the room, and steady state for determining the offset can only be assumed for a period of time when the outdoor temperature is constant.

It is also observed that both valves start closing at the time when the room temperature approaches the set point. After the valve is completely closed the temperature continues to rise due to the heat release from the radiator.

3.4.2.1 Supply and return temperature comparison for radiators in the reference room

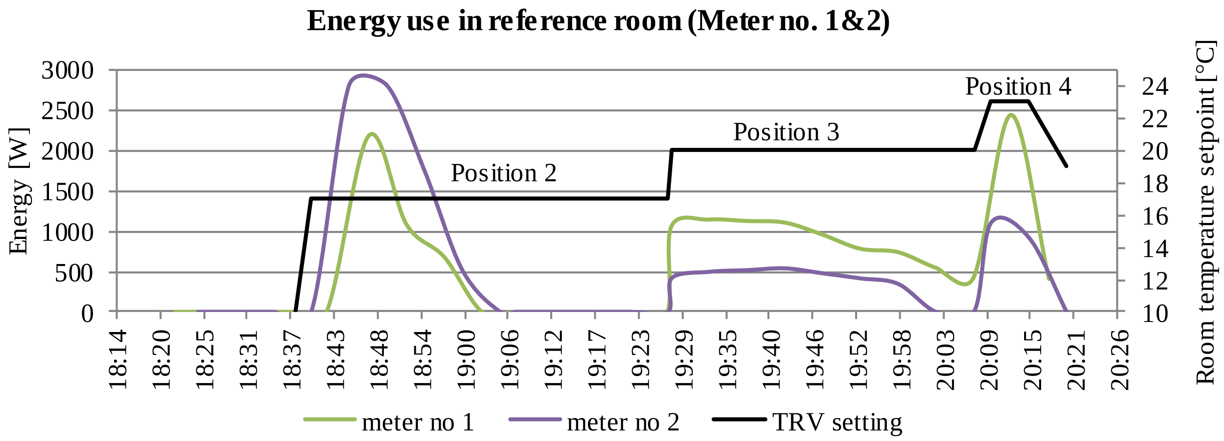
In order to see if the flow is different on the two radiators because of different return temperatures Graph 3.7 is plotted.



Graph 3.7 Testing TRV positions in the reference room: resulting supply and return temperatures

From Graph 3.7 it can be seen that turning up the radiator to position 2 shows an increase in supply temperature measurement – the water in the radiator pipe receives hot supply water flow from the main pipe. After increasing the set point to 17°C, a sudden drop in the return temperature occurs – the sensor records the temperature of the cooled water that was staying in the radiator. Afterwards the supply temperature stays fairly constant for both radiators, but the return temperature gradually increases. The low return temperature and the increase of mass flow and supply temperature results in peak values for the energy output of the radiators, which is illustrated on Graph 3.8.

The return temperature of the first energy meter is always lower than the second one on Graph 3.7. An observation is made that a difference of about 10 degrees between the return temperatures happens at around 19:30 – 20:00, when the TRVs are on position 3, and the water flow at both valves is the same (Graph 3.6). In Graph 3.8 the energy output of both radiators in the reference room is plotted.



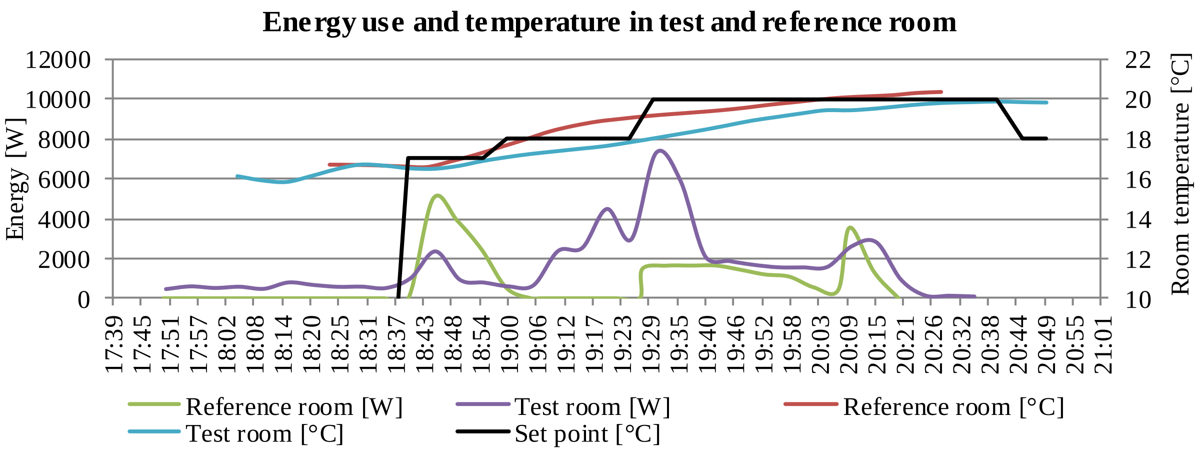
Graph 3.8 Resulting energy use of the two radiators in the reference room

Even though the flow is similar for both radiators, meter no. 1 records a lower return temperature, thus resulting in higher energy consumption for the first radiator during the time TRVs are on position 3.

3.4.2.1 Comparison of water flow and energy use in the two rooms

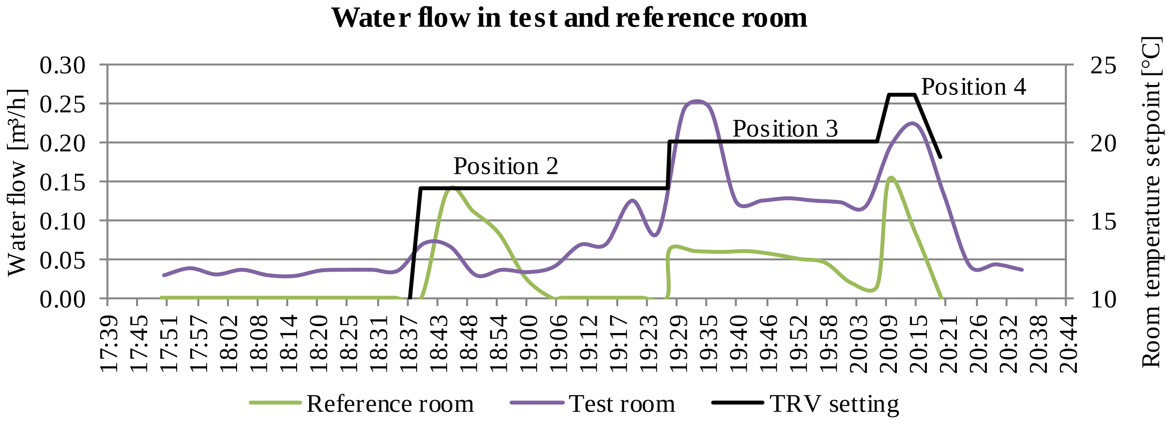
If the radiators in both rooms release the same amount of heat under similar conditions, the rooms can be considered identical. Therefore, such parameters as energy output to radiators [W] and operative temperature [°C] in both rooms are compared and plotted on Graph 3.9.

The test was performed simultaneously with the test described above (*3.4.2.1 TRV set points in the reference room*). The settings on programmable TRVs in the test room are being controlled by increasing set points on the thermostat through Salus online dashboard, trying to keep both rooms at the same operative temperature.



Graph 3.9 Resulting energy use of both meters, and operative temperature in test and reference room

Graph 3.9 shows that the heat output of radiators in the two rooms is different. From the measurements, it was observed that different flow is provided by the radiator valves in the two rooms, and that the flow and the resulting heat output have the same tendency. This can be seen on Graph 3.9 and Graph 3.10.



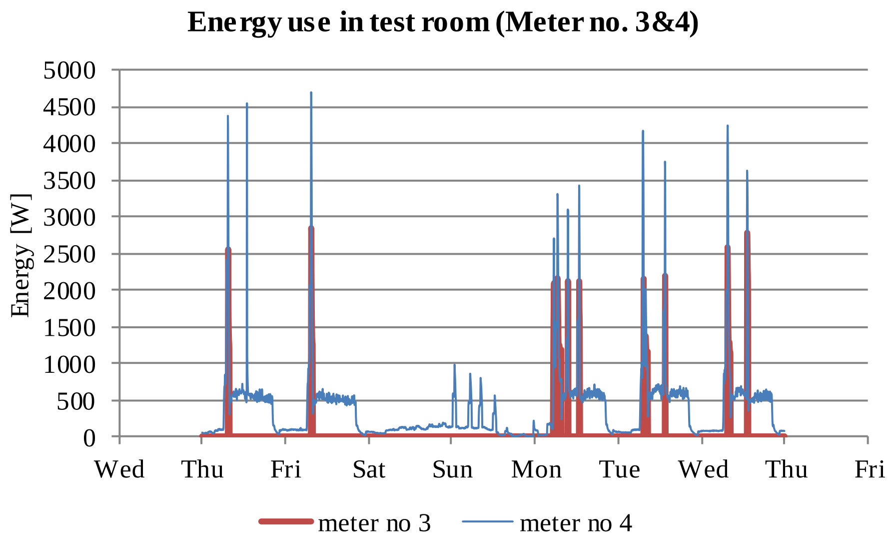
Graph 3.10 Resulting water flow of both meters in test and reference room

From Graph 3.9 it can be seen that the radiators in the reference room have a higher output during the first set point change (from closed to 17°C). This is due to the fact that the cold air sensed by the TRVs in the reference room gives a higher error from the set point, and the valve opens more. On the other hand, in the test room the operative temperature sensor controlling the programmable TRVs gives a signal to increase the flow slightly, as the sensed temperature is only 0.5 degrees lower than the set point.

Such differences in the room temperature control explain the fast increase of operative temperature in the reference room, as well as the increase of energy use in the test room during the second set point change to 18 and then 20°C. The measurements suggest that programmable thermostats with a remote room temperature sensor combined with a PI-controller provide a very precise temperature control.

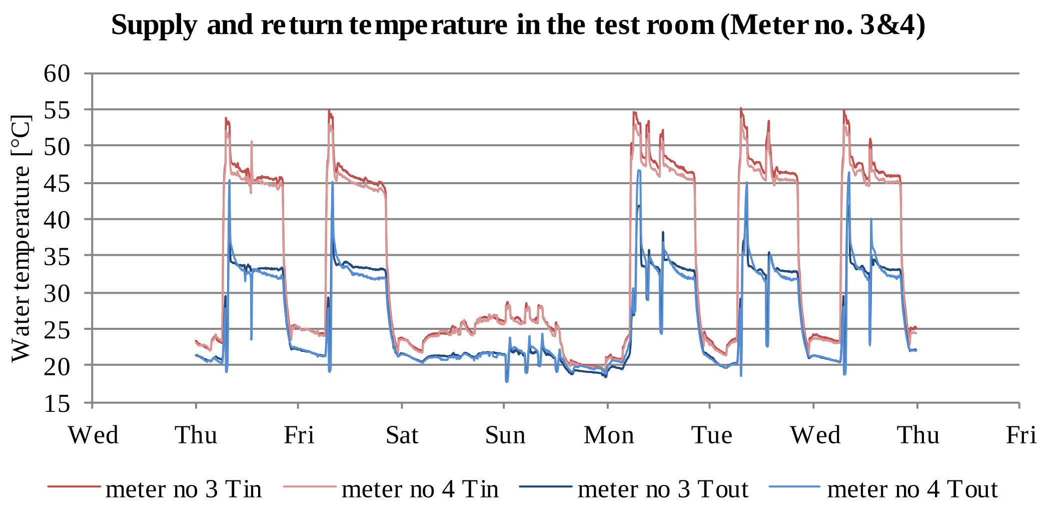
3.4.2.2 Leaking radiator valve in the test room

For a period of one week (22 to 29 of December), the energy use in the test room measured with the energy meter number 3 and 4 is displayed in Graph 3.11 . From the graph, it can be seen that the output of the two radiators in the room is different, one of the radiator always has output compared to the other.



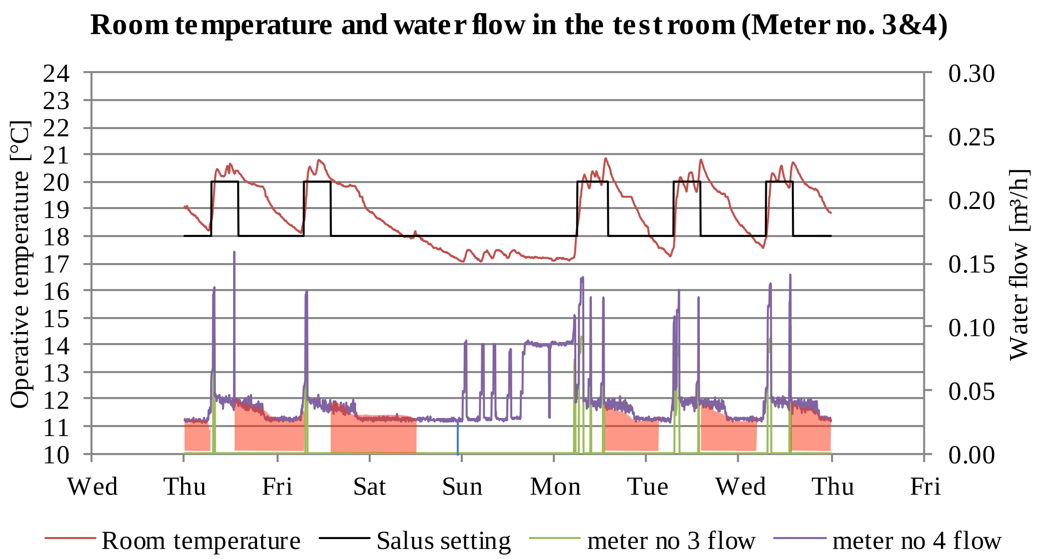
Graph 3.11 Energy use of the two radiators in the test room over a period of one week

The supply and return temperatures of the water are also displayed in order to see if both of the radiators are performing under same conditions. From Graph 3.12 it can be seen that the supply and return temperatures of the water are similar for both radiators.



Graph 3.12 Supply and return temperatures in the test room over a period of one week

In order to find if this is a failure of the energy meter or that the valve or the gland seal inside the valve are damaged, the temperature set point and the actual room temperature are plotted. The idea is that when the set point of the room temperature is reached the valve should close. Graph 3.13 presents the set point in test room, which is 20°C during occupied time and 18°C during the setback, the actual room temperature measured with the IC meter and the water flow measured by the energy meters. One of the valves (meter no 3 - green line) is opening only when there is need for heating and it does close completely when the temperature set point is reached , the other valve represented by the purple line on the graph shows that it never closes fully which results in permanent flow passing through it. Therefore, it was checked if the installation of the TRV was done correctly, and it was observed that the thermostat and the valve body are mounted properly, and that the problem is the gland seal, which does not move to the end of the valve and still letting flow passing through.



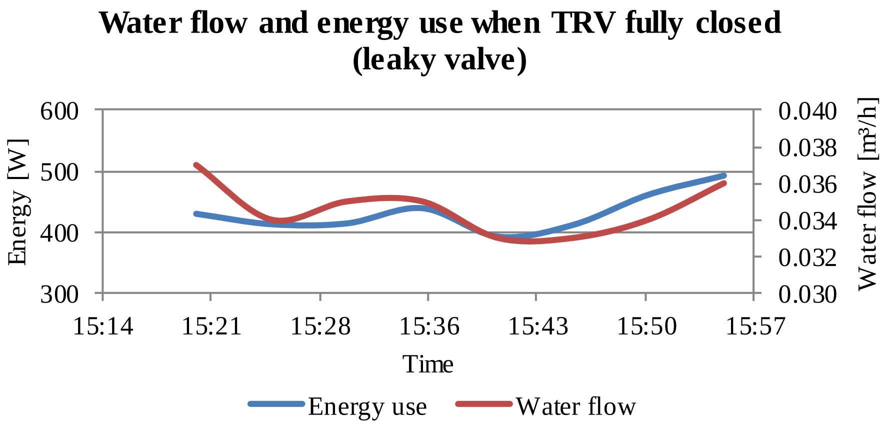
Graph 3.13 Room temperature and water flow in the test room

Note: The red filled area marked in the graph illustrates the "energy waste" by the leaky valve

During the setback one of the valves (green line) is always closed, even in the weekend and for short time in the mornings when the room temperature is actually bellow the set point. In reverse, the 'leaky valve' allows the flow to pass, moreover the increase in water flow during the weekend is recorded by the energy meter. The room temperature is below the set point from Saturday to Monday morning – this can be explained by the fact that the supply water temperature is reduced at the central level in the ECL. Therefore, even though the broken valve allows the flow to pass, the temperature of the supply water is very low (around 25°C) as it can be seen in Graph 3.12 making it insufficient to reach the room set point temperature.

The estimation of how much energy is wasted due to this failure of the gland seal is hard to be made, because the radiator that always receives flow affects the heat released by the radiator with properly working valve. The waste can be counted only when the temperature set point is reached but the radiator still provides flow, as it can be seen in Graph 3.13, the filled area marked with red.

A test was made on 3rd of January, by opening the windows in the test room, (where there are window sensors installed) in this way both of the TRVs were switched off automatically, for a period of 40 minutes.



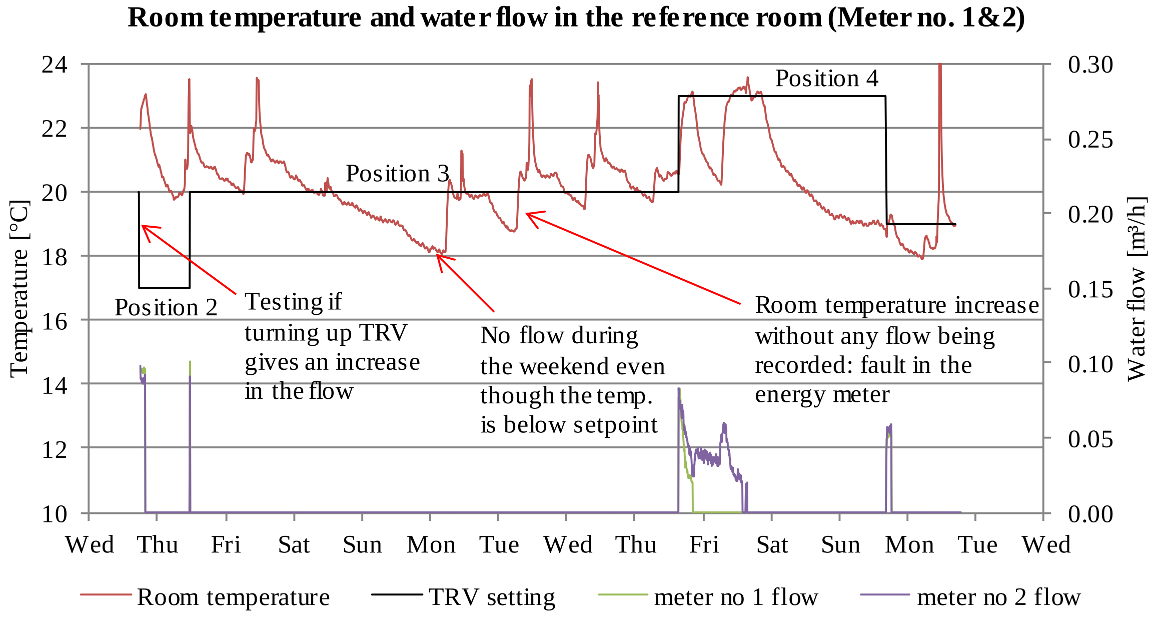
Graph 3.14 Water flow and energy use, leaky valve (window open)

Graph 3.14 presents the flow and the energy use for approximately 40 minutes. During this time, the not properly working vale lets flow passing through even though the valve it is fully closed. Total amount of flow that was passing through during this time is 0.18m^3. During this 40 minutes period a waste of energy of 0.295kWh was recorded.

3.4.2.3 Flow in the reference room during the night

The hypothesis of this project problem is based on the idea that if traditional TRVs are not regulated for the night setback after occupancy time, there will be flow during the night, as the thermostats will try to keep the set point that the TRV is left on.

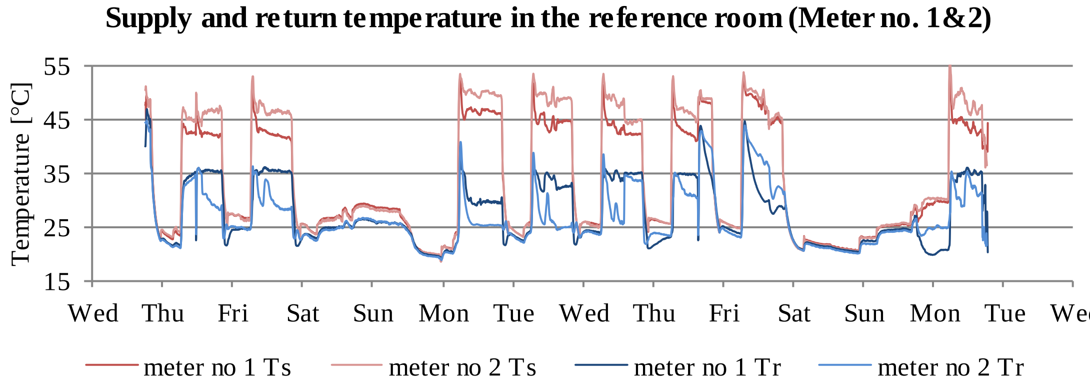
In order to test how the TRVs in the reference room perform, several positions were tested for a longer period of time. Graph 3.15 shows the measurement results.



Graph 3.15 Testing different positions on TRVs in the reference room over a longer period of time

Graph 3.15 shows the measurements of water flow to the two radiators and the operative temperature, and Graph 3.16 presents the supply and return temperatures to radiators in the reference room over the period of approx. two weeks (21.12.16-02.01.17). Note: the peaks of room temperature to ≈24°C are due to solar radiation.

On Wednesday evening, when the energy meters were installed, the reaction of the flow meter was tested by turning up the radiator valves, and it was proved that the increase of the set point results in the flow increase. From Graph 3.16 it is visible that there is a night setback on a central level: the supply temperature drops and becomes almost as low as the return temperature – around 25°C.



Graph 3.16 Supply and return temperature measurements over two weeks in the reference room

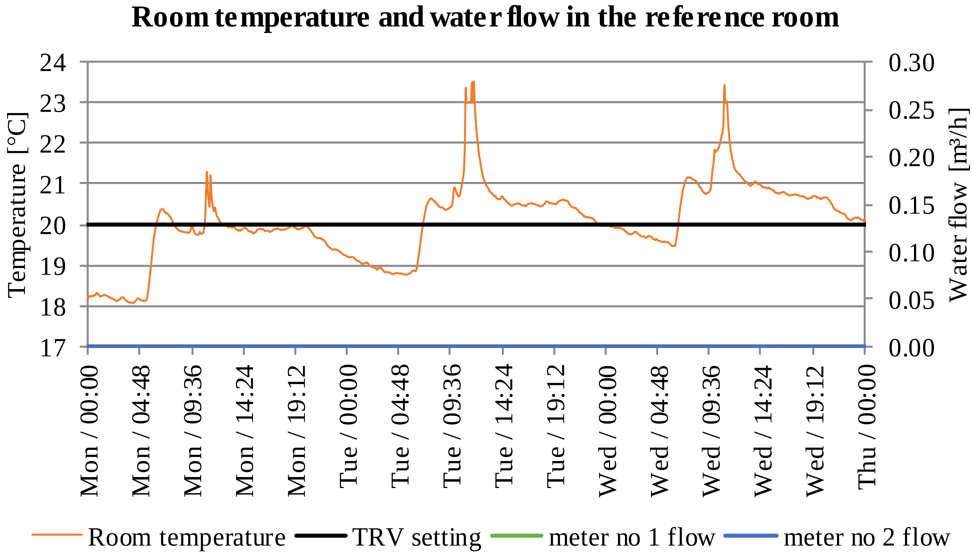
During the first night of measurements, when the TRVs were left on position 2 (corresponding to 17°C), there was no flow detected. This is due to the room temperature being above the set point. After increasing to position 3 on the TRVs (20°C), there was an increase in flow detected by the energy meter, but only for a very short period. However, no flow was recorded during the whole week with TRVs left on position 3. From the measurements of the IC-meter during that period it is visible that the room temperature was increasing without any flow being recorded. This issue will be analyzed further in chapter *3.4.2.4 Undetected flow*.

The only period of time with the recorded flow during the night was when the TRVs were left on position 4 (corresponding to 23°C). It was also observed that after extracting the data and resetting the meters, they were able to record the flow again, even though before they were showing 0 m³/h. Such recording can be seen during the last change of TRVs position, where flow was recorded when the set point was changed from 23 to 19°C.

After these observations the location of ultrasound flow sensors was checked and adjusted in order to improve the signal strength and quality and to avoid the faults in further measurement data. The location of supply and return temperature sensors were adjusted, as the measurements from Graph 3.16 show that one of the sensors was located too close to the main distribution pipe, and was recording a higher temperature.

3.4.2.4 Undetected flow

From the measurements, it was observed that there are periods of time when the measured flow of the radiators is 0, while at the same time the indoor temperature raises. Example of such case is illustrated in Graph 3.17. Note: The high peaks in operative temperature occur due to direct solar radiation on the IC-meter (east orientation of the room). However, the peaks occur for a very short period and do not influence the rest of the measurement, therefore they can be disregarded.



Graph 3.17 Room temperature and water flow in the reference room (26-28.12.2016)

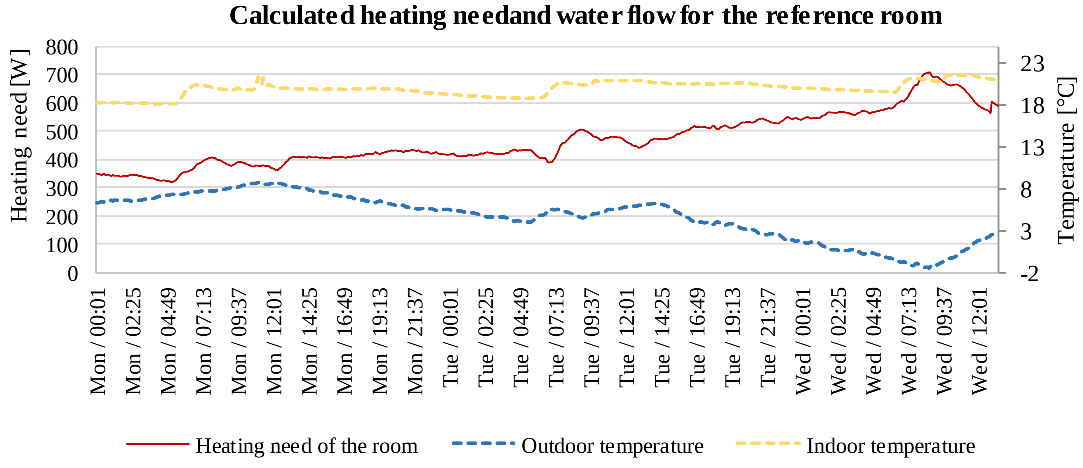
In order to investigate if the increase of room temperature is due to the radiator output not being detected by the energy meters, the heat demand of the room and the corresponding water flow is calculated for the three days.

A steady state heat loss calculation is performed for every five minutes using the measured data of the indoor and outdoor temperatures. For the simplification only the transmission losses through external wall and windows are taken into consideration. The parameters of these components are as described in Table 3.9.

	U-value [W/m²K]	Area [m²]	UA [W/K]
Wall	0.34	12.2	4.15
Window	2.3	12.4	28.52

Table 3.9 Parameters of external wall and window

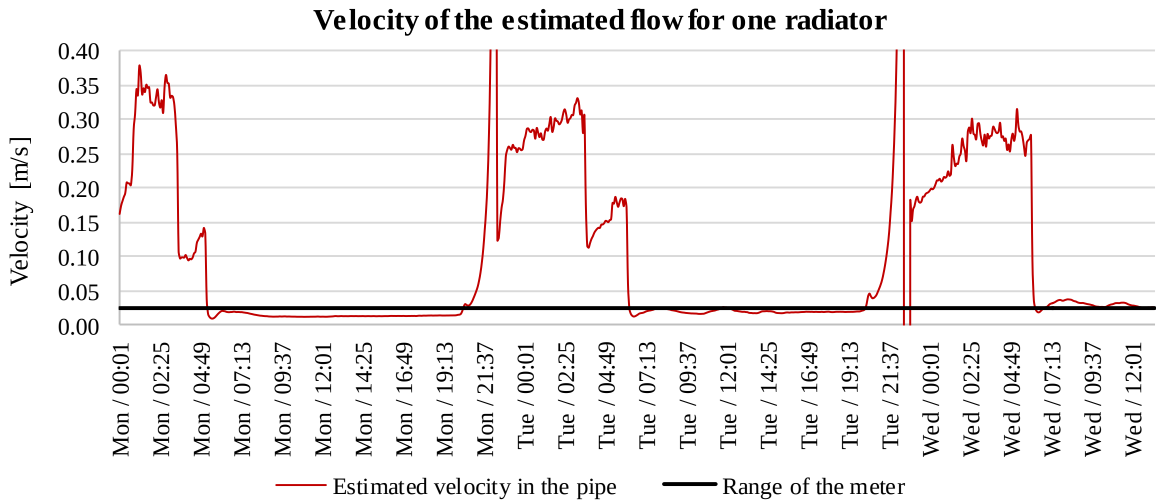
The result of the calculation is plotted in Graph 3.18. Note: the calculated heat demand is for the whole room.



Graph 3.18 Calculated heating need for the test room over the period of three days

The KATflow energy meters by specification have a minimum velocity of 0.01 m/s required to detect the flow. However, after talking with a contact person from the company it was mentioned that with flow below 0.025 m/s the meters can already have difficulties in measuring.

For the estimation of possibly not detected flow the average measurements of supply and return temperatures are used, and the water specific heat capacity of 4186 J/kg K and the density of 980 kg/m³ are assumed. Thereafter the velocity is estimated according to the water flow and the internal cross-area of the pipe (0.00177 m²). Calculation results are plotted in Graph 3.19. The velocity peaks that are not visible on the full scale of the graph are occurring during the setback switch on the central level, when the supply and return temperatures have a difference of less than1K. The velocity drop below 0 m/s is a result of the return temperature being higher than the supply.



Graph 3.19 Velocity of the undetected flow

Graph 3.19 shows that the estimated velocity in a pipe is above the minimum range of the energy meter during the nights, when the room temperature was measured to be below the set point. Based on the calculation it can be assumed that the reason of having 0 m³/h from the energy meter recordings is due to a fault in the sensors. Therefore, we contacted Katflow to require more information about the problem. They explained that the meter could be recording only zeroes, because after some period with no flow, the ultrasound signal is trapped in the wall of the pipe, without passing through the liquid itself – as shown with red in Figure 3.33.

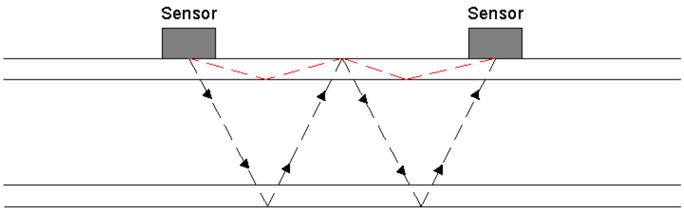
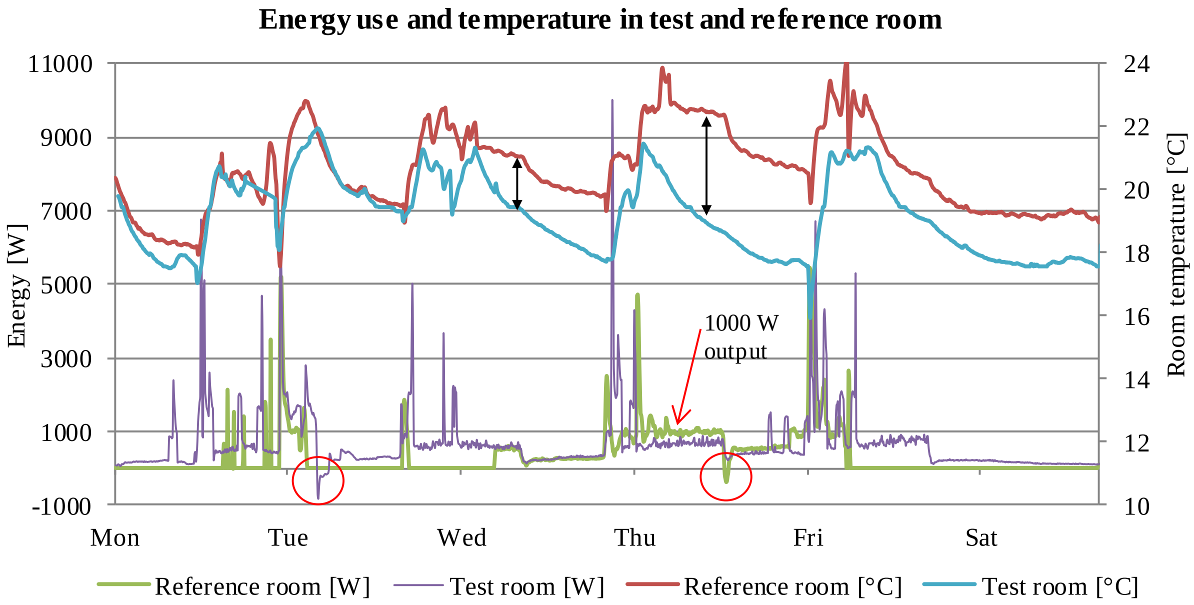


Figure 3.33 4 sound passes - reflection mode

General solution of the problem could be the reduction of sound signal passes to minimum (e.g.1 pass – diagonal mode), even though such mode is only recommended for large pipes. Nevertheless, the 1 pass mode solution was applied and verified and it resulted in high error, namely the flow was being recorded with a closed TRV. Therefore, the location of the ultrasound sensors was switched back to the original mode with 4 passes. The problem of the meter not recording any flow was found not to be permanent, as after the meter is resumed it is easier for the sensors to start detecting the flow.

3.4.2.5 Comparison of energy use during user control of TRVs and automatic control

This analysis presents a comparison of energy use in the test and reference room during a period of time, when the rooms are occupied, and the users can control the TRV positions in the reference room. The programmable TRVs in the test room are working according to the same schedule as before, with 20°C set point during the day, and having night setback to 18°C.



Graph 3.20 Energy use and operative temperature in the two rooms from 02.01.17 – 07.01.17

Graph 3.20 shows the energy use in the test and reference room, and the respective operative temperatures. The positions of the TRVs in the reference room are unknown for this period. The aim of this test is to have a more or less realistic situation in the reference room, where people had a possibility to regulate thermostats according to their desired thermal comfort.

The drops of energy use down to minus values, marked with red circles in Graph 3.20, happens due to reduction of supply temperature at the central level. During the first half an hour of the night setback period, the supply temperature becomes lower than the return – the supply is lowered by the ECL controller, but the return temperature gets warmed up by the heat stored in the iron radiators, causing such negative measurement of the energy used by the radiator.

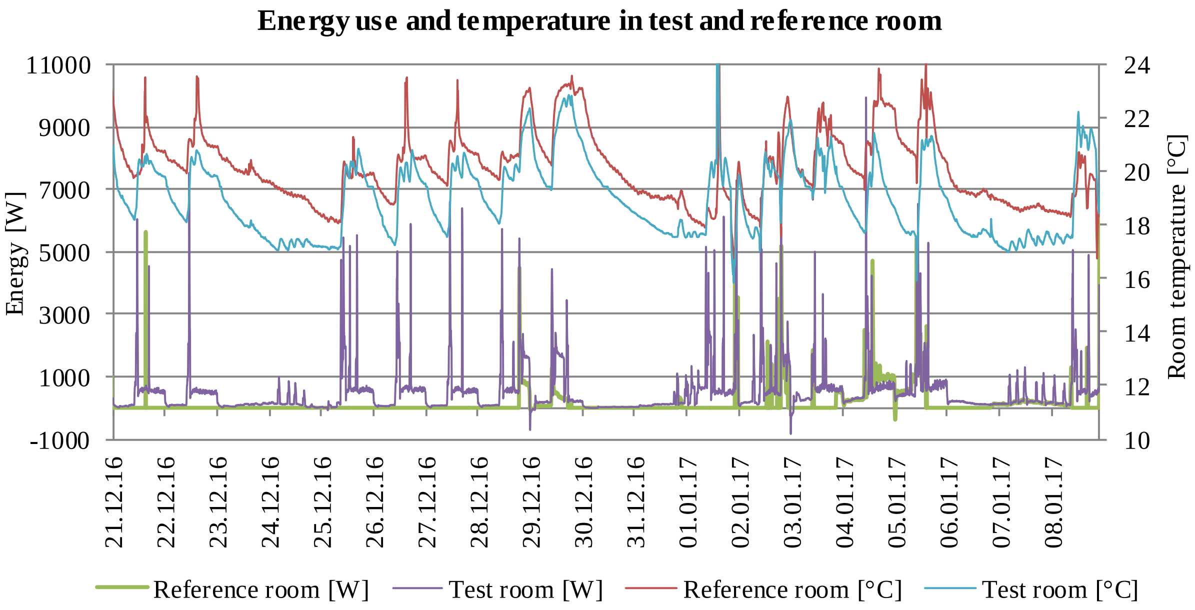
The preliminary analysis of thermal comfort in both rooms (chapter *3.4.1 Current thermal comfort*) showed that the two rooms have little difference in operative temperature. However, choosing the night setback to start from 14 o'clock and to finish at 6/7 in the morning in the test room, resulted in reduced temperature during both day and night, meanwhile in the reference room the users were controlling the TRVs. It is visible from Graph 3.20 that the test room temperature is generally lower. As it was discussed previously in the report, reduction of indoor temperature contributes to reduction of heat losses, and thus energy consumption.

The fact that TRVs were controlled by the user and were left on a higher position after occupied hours can be seen from indoor temperature measurements on Wednesday. The decrease of room temperature on Wednesday evening starts from the same point of ≈22°C in both rooms. However, the reference room temperature stays 1.5°C higher due to TRVs not being changed to a lower set point. The same situation is observed during Thursday evening, where the measured output in the reference room is around 1000W.

3.5 Evaluation of the results and discussion

This part conclusion includes a summary of the tests performed during the measurement campaign. The evaluation of the results will also discuss the energy meters' limitations, which were discovered, as well as the challenges that were faced during the process of the case study.

Graph 3.21 presents the measured data for energy use and operative temperature in the test and reference rooms over the whole period of the measurement campaign that lasted almost three weeks, from 21st of December to 8th of January.



Graph 3.21 Collected data during the period of measurement campaign (21.12.16 - 08.01.17)

The aim of the energy measurement monitoring was to prove that the installation of programmable thermostats and application of night setback strategy will reduce the energy consumption compared to the traditional TRVs. This hypothesis was based on both the literature review and theoretical calculations. Moreover, during the preliminary visits to the case study building it was observed that the existing TRVs were normally left on a high position, and were not turned off for the night time.

Nevertheless, the expected results cannot be reflected from the measurements. The measurements of energy use for the two rooms should not be used for drawing trustworthy conclusions due to a few reasons.

First of all, the energy meters that were used in the case study were unable to detect the flow over a long period of time, while the calculations and operative temperature measurements suggest that there was heat release from the radiators. This implies that the energy meters should be tested in a controlled environment in order to be able to conclude on the reason for such error.

Secondly, one of the valves in the test room was leaking, therefore a large part of the recorded energy use by the radiator should not be considered as the actual energy need for that room. The programmable TRVs were closed when the room temperature set point was reached, which was also verified by the tests performed.

Finally, the case study building had a central night setback from the ECL controller, which reduced the supply temperature to around 25°C. The measurements of supply and return temperatures showed that during the nights and weekends the temperature drop on the radiators is only 2-5K.

Even though both of the rooms are located in the same block, meaning that they have same setback schedule which is applied from the central level, the idea was to see how much energy can be saved by starting an earlier setback at the room level. Therefore, the automatic control for heating was implemented in the test room, where a setback at the room level was programed to start from 14:00 o’clock.

Thermal comfort and energy consumption should always be analysed as interconnected aspects. A reason for not changing the time of the setback for the entire block is that when referred to school buildings it is difficult to take such actions without compromising the thermal comfort of the occupants. The actions that are taken at the central level will influence the entire school block, meaning that if, for example, the setback is chosen to start at 15:00 – usually the time when the classes are finished, then it may happen that the rest of the rooms are still occupied and they will be affected by the changes. This leads us back to one of the points discussed in the background of this project regarding decentralized or centralized control strategy for heating systems in non-residential buildings.

All things considered, the measurement campaign carried out in the frame of the project case study showed potential in the implementation decentralized room temperature control and night setback strategy. Elimination of the problems discovered during the case study, and further tests of the equipment used are believed to yield more reliable results.

3.6 BUILDING SIMULATION

The two rooms that are used as reference and test room for the case study project are modelled in IDA ICE, with the purpose of analysing if the simulation can provide similar indoor thermal comfort and energy consumption when compared to the measurement results. Throughout the calibration of the two models it can be evaluated if the comparison between the programmable and traditional TRVs can be performed by using the simulation software.

3.6.1 BUILDING MODELLING IN IDA ICE

3.6.1.1 Model description

The two rooms representing the test and reference room in the case study are East oriented and have internal dimensions of 7.16 m x 7.57 m x 3.26 m height, a summary of the room parameters is presented in Table 3.10. Each room has two windows with the dimensions of (2.95m x 2.12m). The percentage of glazed area compared to the external wall is approximately 50%. The total window area is 23% of the total floor area. A U-value of 2.3 W/ m².K is used for the windows.

A_f (floor area)	54.2 m²
A_w (window area)	12.48 m²
A_{wo} (wall area facing outside)	12.19 m²
H (room height)	3.26 m
V (room volume)	176.7 m³

Table 3.10 Room parameters

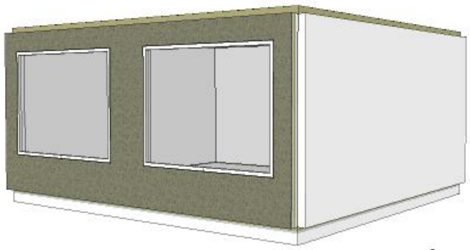


Figure 3.34 3D IDA ICE room model

The two rooms have each one wall facing outdoor, while the other walls are internal walls, and the floors/ceilings are defined as internal partitions. The description of the different construction components of the two rooms are defined as it is presented in Table 3.11.

Component	Materials	Thickness [mm]
External wall	Concrete 60 mm Insulation 75 mm Air gap 25 mm Concrete 30 mm	190
Internal wall	Concrete	150
Floor	Floor coating 0.16 mm Concrete 70 mm Insulation 30 mm Concrete 180 mm	281.6
Horizontal ceiling	Gypsum board 0.13 mm Wooden laths 0.30 mm Wooden battens 0.50 mm Insulation 100 mm	193

Table 3.11 Construction components

The ventilation (only extraction) and infiltration are defined according to the measurements/calculations performed on 2nd semester in the school. A value of 0.59 l/s/m² for extraction, and 3.3 l/s/m^2 (at Δp 50 Pa) for infiltration is input in the model. Occupancy per classroom is set to 21 persons, and the schedule is set from 8 to 15 o'clock.

Design temperatures for the radiator in IDA ICE are defined as 70/40/20 and the maximum power input is set according to the heat losses that were calculated (Table 3.4). Both the reference and the test room have each two radiators. In the reference room, the controller type is defined as P and for the test room PI, since this room has programmable TRVs.

In order to be able to compare the results for the energy consumption between the 2 rooms the intention/objective is to leave the reference room exactly as it is with no setback at the room level during the weekdays; and for the test room to implement the different settings and schedules for setback as it was already investigated throughout Salus control (chapter *3.4.1 Current thermal comfort*).

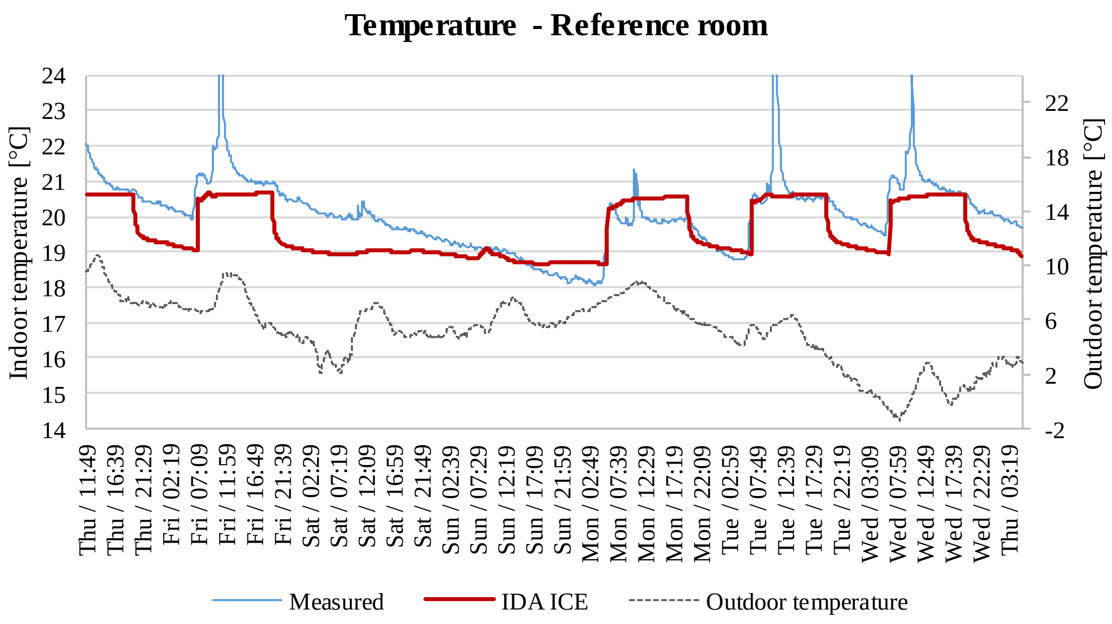
3.6.1.2 Model calibration

In order to be able to accurately predict the energy and thermal comfort of the rooms, the simulation models in IDA ICE are calibrated according to the measured data. In order to give reasonable prediction of the performance of the building it is of a great importance that the created model is as accurate as possible. An important variable to start with is the energy used in the zones. During the calibration process, energy use and the resulting temperatures in the rooms were evaluated simultaneously, however, in the following subchapter the calibration according to the operative temperature in the room is described first.

Calibration for a period without occupancy

The model is first validated according to one week of measurement data (operative temperature and energy use) from 22nd to 29th December. Since this is holyday period, the internal gains from people, lighting and equipment are neglected. The model is considered valid when the simulated parameters are within the same range of fluctuations and repeat the same profile as the measurement data.

Both measured and simulated operative temperatures, as well as outdoor temperature, are plotted in Graph 3.22. During this vacation period, the radiators in the reference room were left on position 3, which corresponds, to approximately 20 °C.

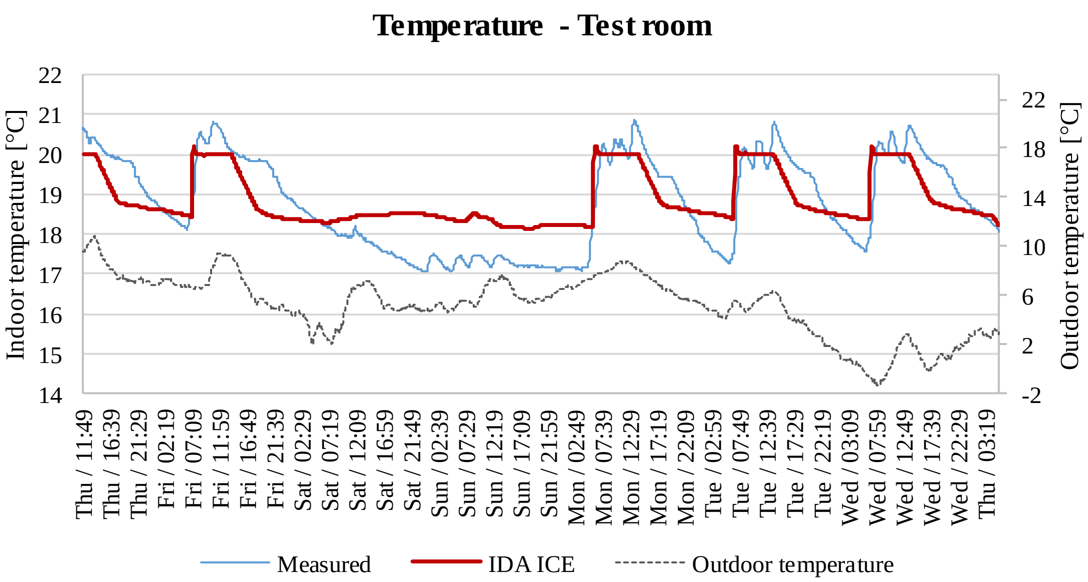


Graph 3.22 Temperature in the reference room without people, equipment and lighting loads

From the measured data, it can be observed that there is a drop in indoor temperature every day from 20:00 to 07:00. The temperature drop occurs due to low supply temperature from the central distribution, meaning that even though the TRV position 3 remains unchanged during day and night the supply temperature becomes so low that it is not enough to keep the room set point. As it can be seen from Graph 3.22, the simulated operative temperature during the day is around 20.8 °C, and at the night time it drops to 19 °C.

It should be noted that the high peaks in the measured operative temperature are due to direct solar radiation on the IC- meter. The peaks are occurring only for a short period, therefore are neglected in the simulation. Another noticeable fact from the graph is that the simulated temperature drops much faster in the beginning, when the setback starts. This is most obvious during the weekend when Friday at 20:00 the temperature drops from 20.8 °C to 19 °C almost immediately. However, by the end of the weekend, the simulated temperature is higher than the measured. During the weekdays, the decrease of the simulated temperature is faster compared to the measurements.

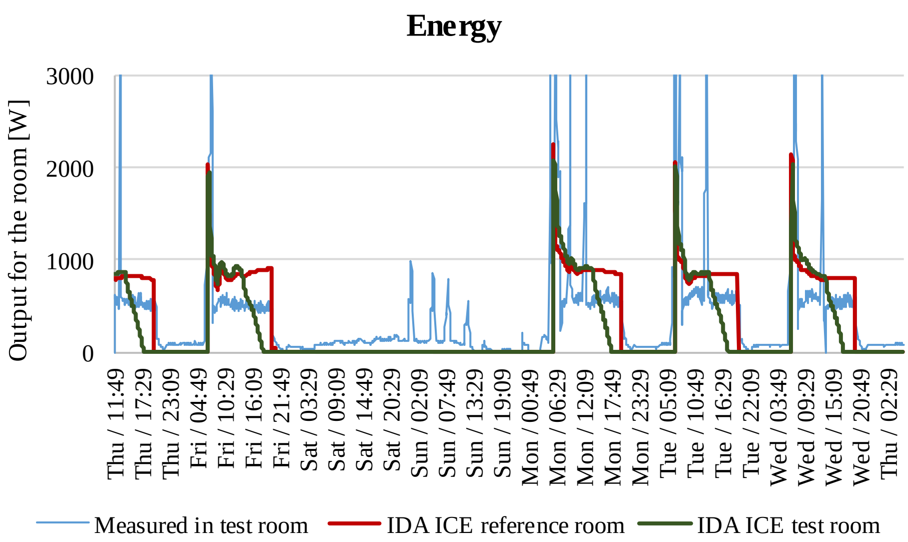
Same procedure for calibration is performed for the test room. The heating schedule for programmable thermostats from Salus has the set point of 20 °C during the day (07:00 to 14:00), and for the night setback (14:00 – 07:00) it is lowered to 18 °C. The measured and simulated operative temperatures, as well as the outdoor temperature for that period are plotted in Graph 3.23.



Graph 3.23 Temperature in the test room without people, equipment and lighting loads

The rooms have different heating schedules applied in the simulations. In the reference room the heating is scheduled until 20:00 (when the setback starts from the central level) and in the test room until 14:00. Another difference is the type of the heating controller. In the reference room with traditional thermostats the controller is P (proportional) and controller variable is the air temperature, while in the test room, with the programmable thermostats, the controller is PI (proportional integral) and the controller variable is the operative temperature.

The energy use of the two rooms is plotted in Graph 3.24. Both rooms are in this case compared to the energy measurements in the test room, because during that period there were no recorded values by the energy meters in the reference room.

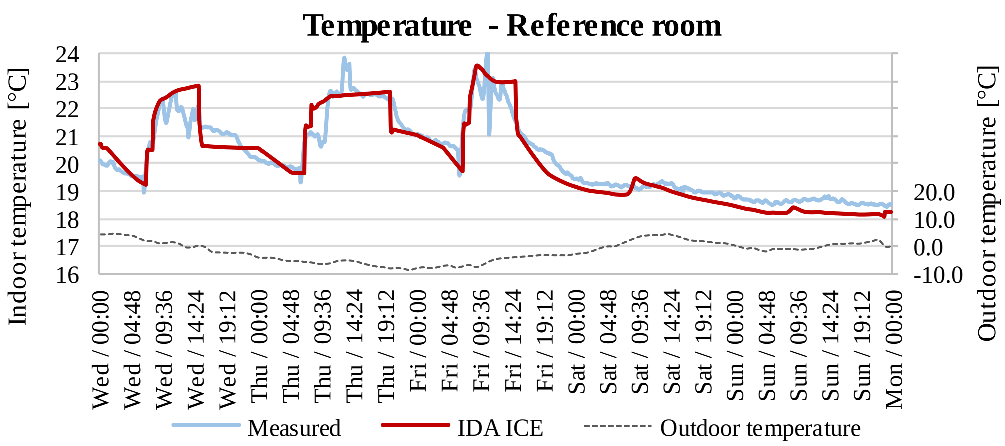


Graph 3.24 Energy use without people, lighting and equipment loads

As it can be seen from Graph 3.24, there are very high peaks in the energy consumption in the measured data. Graph 3.24 range finishes at 3000 W, but the measured peaks continue to 7000 W. Those high values are assumed to be the result of measurements with very low return temperature. When the radiator is not working for some time (during the night), the first measurement in the morning (5 min average) will include a period when the supply temperature and the mass flow are high, because the night setback is finished, but the return temperature is very low because the water has stayed and cooled down in the radiator during the night. However, the simulation shows lower peak values, because of a limitation in the software: the supply and return temperatures for a radiator are input as constants in IDA ICE.

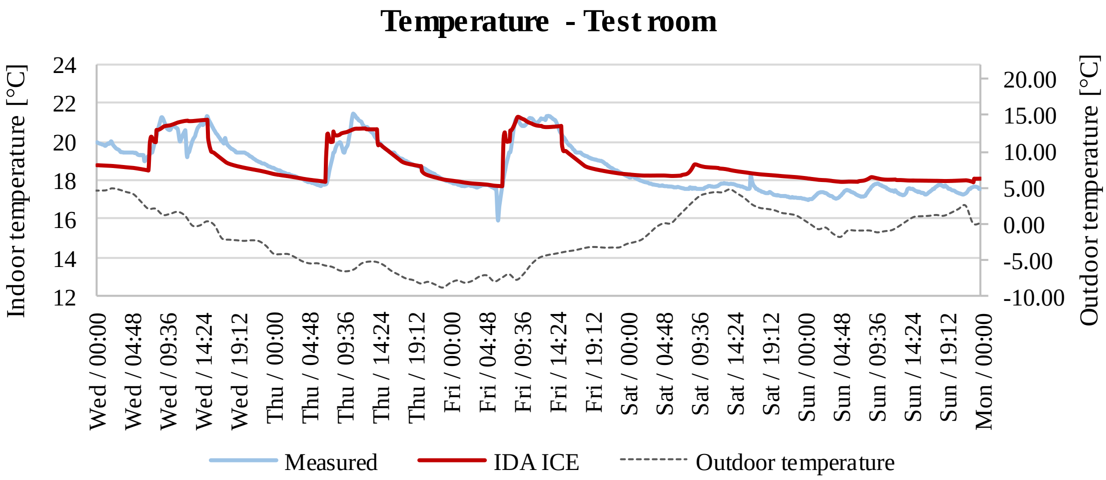
Calibration for a period with occupancy

Next, the model is calibrated according to measurements during an occupied period, when the students are present in the rooms from 08:00 to 15:00 from Monday to Friday. The chosen period is from 4nd to 8th of January.



Graph 3.25 Temperature in the reference room with people, equipment and lighting loads

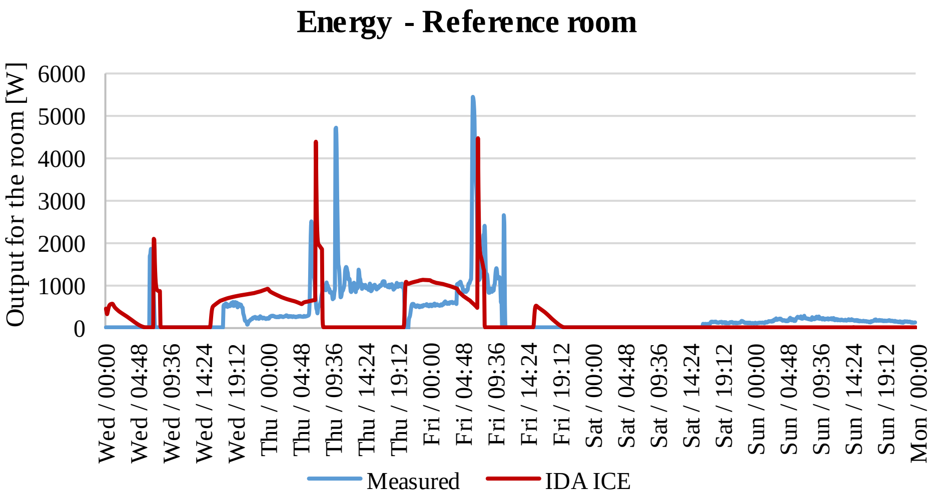
The measurements during the days with people load show frequent fluctuations of room temperature, which can occur due to several reasons, such as: internal loads from people, heat losses due to ventilation by opening windows, or changes in TRV positions by the users. From Graph 3.25 it is clear that when the students leave at 14:00, the operative temperature has a sudden drop (equipment and lighting have the same schedule as occupancy), and after that it slowly decreases up to 20:00. At that time the central setback starts and the drop of room temperature is more significant due to decreased supply water temperature.



Graph 3.26 Temperature in the test room with people, equipment and lighting loads

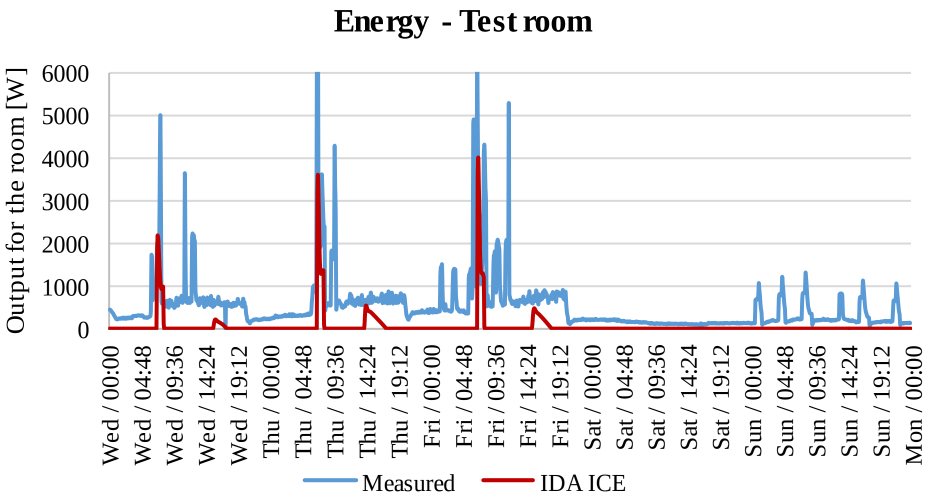
Graph 3.26 shows the calibrated results for the simulation of the operative temperature in the test room. Generally, for the week the temperature in the reference room is higher, and there can be several reasons for that. The amount of internal loads can be different, and the control of the TRVs is done by the users, while in the test room there is a fixed schedule for heating.

Graph 3.27 and Graph 3.28 present the comparison between the measured and the simulated energy consumption in the reference and test rooms during the days with people load.



Graph 3.27 Energy use in the reference room with people, lighting and equipment loads

The curves of measured and simulated energy consumption do not have the same tendency, when compared for every day individually. However, the sum of the energy consumption for the period resulted in only 3% difference between the measured and simulated results. Therefore, the simulation final results are concluded to be reliable, even though the distribution of used energy during this period is different.



Graph 3.28 Energy use in the test room with people, lighting and equipment loads

Overall, it is concluded that after calibrating both models of the test and reference rooms, the difference between the measured and simulated data, including operative temperature and energy consumption, is acceptable for performing further simulations. However, several limitations of the simulation should be considered.

Building simulation models cannot represent the real life situation entirely. An example is that in IDA ICE the supply and return temperatures are input as constant values and reduction of the supply temperature due to both weather compensation and central night setback could not be simulated.

Another aspect of the particular case is the leaky valve in the test room, which has an influence on the overall energy consumption for the room. This gives a high uncertainty for the calibration itself. For getting more precise results from the calibration it is a good idea to replace the valve body of the radiator in the test room. Eliminating the problems that were faced during the measurement campaign and continuing measurements for a longer period will provide more data that can be used for further calibration and use of the built model.

4 CONCLUSION

This master thesis report includes analyses of *Optimization of heating control in existing buildings* and aimed to identify problems that are related to the heating system control with the purpose of reducing operational heating energy consumption.

The theoretical part of the report aimed to provide background information necessary to be able to answer the questions stated in the problem formulation. Reduction of the energy consumption for heating in existing buildings includes various possibilities. The topics discussed in the hereby report include weather compensation according to outdoor temperature, night setback strategy, consequences of oversized radiators, as well as zoned temperature control.

One of the research questions was "How does setback strategy work for different building types according to their thermal mass and insulation level?" The performance will depend on the type of building in terms of thermal mass and insulation level. The aspect of different building constructions is described in the theoretical part of the report, where simulations are made in order to investigate the performance in terms of thermal comfort and energy usage for the different construction types. Throughout the performed simulations, poorly insulated buildings and building with low thermal mass resulted in having the highest potential for energy savings when night setback strategy was applied.

Lowering the water supply temperature on a central level in a building is a must in non-residential buildings in Denmark. However, theoretically in a building with traditional TRVs this strategy can lead to unnecessary energy consumption when not regulated accordingly. Moreover, changes to the heating system controls on a central level affect the whole building part that is supplied by that system. One of the solutions to this problem is the use of programmable thermostats for zoned temperature control.

Practical approach to the problem included a case study. Four school buildings in Aalborg, Denmark, were considered for the case study. During the visits, it was discovered that not all school buildings have the night setback strategy applied. Challenges were also faced concerning the understanding of the heating controls applied in specific buildings, as it was found to be very different from building to building. Even in the chosen case study building two different control methods were used in a combination.

In order to answer the research questions of the project, "How does the central reduction of supply temperature work in practice when applied in a school building with traditional TRVs?" and "Does night-setback with central reduction of supply temperature result in energy savings when used with traditional thermostatic radiator valves, or do digital thermostats provide better performance of the system in terms of thermal comfort and energy use?", several tests were performed on the case study building.

The aim of the tests and energy measurement monitoring was to prove that the installation of programmable thermostats and application of night setback strategy at the room level would reduce the energy consumption compared to the traditional TRVs. This hypothesis was based on both the literature review and theoretical calculations. In order to evaluate the performance of programmable and traditional TRVs, they were compared by measuring the energy consumption at the room level, as well as the provided thermal comfort. Nevertheless, the result of the conducted measurements was contradicting with the theory due to errors in the energy meters recordings and a leaky valve in one of the rooms.

Although the investigations performed during the project showed potential in the implementation of night setback strategy through the use of programmable thermostats, from the data collected it was not possible to determine if the change to digital control of room temperature results in energy savings. Further studies are therefore necessary to be able to conclude on the actual reduction in the energy consumption for heating when such optimization strategy is applied in existing buildings.

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Appendix A CALCULATION FOR OVERSIZING FACTOR Y

The following heat balance should always be satisfied:

$$Q = \dot{m}C_p(T_S - T_R) = Q_0\left(\frac{\Delta T_{mx}}{\Delta T_{md}}\right)^n = B_u(T_i - T_u)$$

where B_u is a specific heat loss of a room. If we set a random condition (x) in relation to dimensioning condition (d) the following can be written:

$$\frac{Q_x}{Q_d} = \left(\frac{\Delta T_{mx}}{\Delta T_{md}}\right)^n = \frac{m_x}{m_d}\frac{\Delta T_x}{\Delta T_d} = \frac{T_{ix} - T_{ux}}{T_{id} - T_{ud}} = y$$

where "y" is the factor showing a relation between the actual and the design condition. In case of constant mass flow, after transformation we get:

$$\Delta T_x = y\Delta T_d$$

$$\Delta T_{mx} = y^{\frac{1}{n}}\Delta T_{md}$$

Mean temperature difference is calculated according to:

$$\Delta T_{mx} = \frac{\Delta T_x}{ln\left(\frac{T_S - T_i}{T_S - \Delta T_x - T_i}\right)}$$

By substitution it is obtained that:

$$y^{\frac{1}{n}}\Delta T_{md} = \frac{y\Delta T_d}{ln\left(\frac{T_S - T_i}{T_S - y\Delta T_d - T_i}\right)}$$

Modifying the equation further:

$$ln\left(\frac{T_S - T_i}{T_S - y\Delta T_d - T_i}\right) = \frac{y\Delta T_d}{y^{\frac{1}{n}}\Delta T_{md}}$$

$$\frac{T_S - T_i}{T_S - y\Delta T_d - T_i} = exp\left(\frac{y\Delta T_d}{y^{\frac{1}{n}}\Delta T_{md}}\right)$$

$$T_S - y\Delta T_d - T_i = \frac{T_S - T_i}{exp\left(\frac{y\Delta T_d}{y^{\frac{1}{n}}\Delta T_{md}}\right)}$$

$$y = \frac{T_S - T_i}{\Delta T_d} - \frac{T_S - T_i}{exp\left(\frac{y\Delta T_d}{y^{\frac{1}{n}}\Delta T_{md}}\right)\Delta T_d}$$

The formula used for finding factor "y" by iteration becomes:

$$y = \frac{T_S - T_i}{\Delta T_d}\left(1 - exp\left(-\frac{\Delta T_d}{\Delta T_{md}}y^{1-\frac{1}{n}}\right)\right)$$

Appendix B THERMAL MASS

How thermal mass works

The active thermal capacity of the building is the heat accumulation capacity corresponding to the heat that is stored and emitted off during a 24-hour fluctuation. The inner structures of walls, ceiling and floor, are important to the thermal capacity of the building, while windows, doors and furniture are of minor importance. The mass of the building that is effective in terms of time constant it is the one from inside usually first 100 mm or before it reaches the insulation layer (Dansk Standard 2008), (CEN 2006).

When outdoor temperature fluctuates during the day, a high thermal mass will help keeping the indoor temperature relatively constant. The thermal mass will absorb the heat energy when the surrounding temperatures are higher than the mass, and will give the energy back when the surroundings get colder. Thermal mass acts as a thermal battery. Thermal mass can be heated up passively by solar radiation during the day or additionally by internal heating systems and at night the heat is released back into the room Figure 5.1.

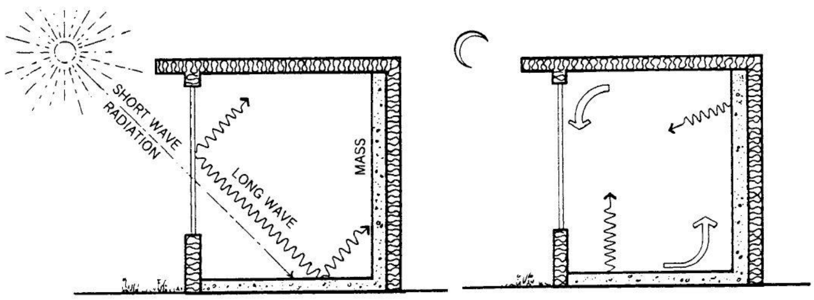


Figure 5.1 Solar radiation, heat storage principle, (Lechner 2015)

Despite the properties of storing heat, thermal mass is not a substitute for insulation. Thermal mass absorbs and releases heat, while insulation prevents heat energy from flowing into or out of the building. A high mass building needs to gain or lose a large amount of energy to change its internal temperature, while a lightweight building needs only a small energy gain or loss to change the temperature.

The thermal mass performance is determined by the density, thermal conductivity and thermal lag. The higher the density of a material the higher its thermal mass. For example, concrete has high thermal mass, aerated concrete blocks have moderate to low thermal mass, and insulation has almost none.

Thermal mass should be able to absorb and re-emit close to its full heat storage capacity in a single diurnal cycle. If the conductivity of a material is too low, the passive heating can discharge from the building before being stored. If conductivity is too high, the absorbed heat is released before it is most needed during the night. Brick and concrete have high density and are reasonably good conductors.

Appropriate thermal lag - the rate at which heat is absorbed and re-released by uninsulated material is referred to as thermal lag. Lag is dependent on conductivity, thickness, insulation levels and temperature differences either side of the wall. Consideration of lag times is important when designing thermal mass, especially with thick uninsulated external wall.

(YourHome, 2013)

Where to locate thermal mass - A good thermal mass practice for external walls will be to have the heavy component (ex. concrete, brick) on the inside and the insulation on the outside. If for example the insulation is placed on the inside and bricks on the outside, the mass of the brick will not contribute to thermal storage because it is insulated from the inside. The proper location of the thermal mass depends on the energy consumption of the building used for heating and cooling. In cases where the most energy is used at wintertime for heating, it will be good to locate thermal mass in areas that receive direct sunlight or radiant heat from heaters.

If the energy required for both heating and cooling is large, locating the thermal mass inside the building on the ground floor will be ideal for summer and winter efficiency. The ideal and most convenient location for thermal mass is the floor, because it receives the most direct sunlight.

If the summer cooling has the greatest energy consumption, is recommended to protect the thermal mass from summer sun with shading and insulation and allow cool night breezes and air currents to pass over the thermal mass, taking out all the stored energy. (YourHome, 2013)

Where not to locate thermal mass - *Avoid use in rooms and buildings with poor insulation from external temperature extremes and rooms with minimal exposure to winter sun or cooling summer breezes. Thermal mass can increase energy use when used in rooms where auxiliary heating or cooling is the only means of adjusting the temperature because it slows the response times.* (YourHome, 2013)

However, thermally conductive materials can be highly desirable inside a space. They will quickly transfer any heat build-up away from a surface struck by sunlight, deeper into the material, which both stores and evenly distributes the heat within the space. Whereas in less conductive materials, the surface will heat up more where the sun light strikes, while other parts of the space may be cold. For example, with a concrete floor the heat will be conducted and spread relatively even across the entire floor and in case of wooden floor the heat will not be distributed well because the wood it does not conduct heat well.

In direct gain storage, thin mass is more effective than thick mass. The most effective thickness in masonry materials is the first 100mm. Thicknesses beyond 150mm are usually unhelpful as the heat is simply carried away from the surface and lost. The most effective thickness in wood is the first 25mm. High thermal mass materials conduct a significant proportion of incoming thermal energy deep into the material. This means that instead of the first couple of millimetres of a wall heating up 5–10 degrees, the entire wall heats up only 1–2 degrees. The material then re-radiates heat at a lower temperature, but re-radiates it for a longer period of time.

(AUTODESK 2015)

The term active thermal capacity, which is the actual thermal capacity multiplied by the utilization of the thermal capacity. The amount of useful thermal storage is calculated by multiplying the VHC (volumetric heat capacity, kJ/m^{3}K by the total accessible volume of the material, i.e. the volume of material that has its surface exposed to a source of heating or cooling. (YourHome, 2013) For example, it takes 2060 kJ of energy to raise the temperature of one cubic meter of concrete by one degree.

The utilization of the thermal capacity is less for concrete than for materials with a smaller density. The reason can be explained by the reduction of the amount of heat transferred due to the surface resistance and the thermal conductivity of the material. The utilization of the thermal capacity must from an overall point of view be considered to be more dependent on the thickness of the material than the characteristics of the material. Therefore, the heat accumulation per surface area must be regarded as the most important parameter to consider, when the performance in relation to heat accumulation of a construction is evaluated.(Olsen 2008)

Appendix C TIME TO REACH SETBACK – SIMULINK

Modelling a reference room in Simulink – one node model

The following simulation is made in order to investigate how different types of buildings react to setback temperature. By different types of buildings in this case is meant different thermal mass of the construction with combination of different amount of insulation. Reference room is used in the simulation with parameters as described in Table 5.1.

A_f (floor area) [m²]	25
A_t (total area facing outside)[m²]	81
A_w (window area)[m²]	3
A_{wo} (wall area facing outside)[m²]	53
H(room height)[m]	2.8
V(room volume)[m³]	70

Table 5.1 Room parameters

Nine scenarios will be compared, with different parameters as indicated in Table 5.2. The thermal capacity of a building is considered for three different cases with combination of three different insulation levels. Thereafter, the building accumulation will vary according to the construction (light, medium, heavy), and the U-values and infiltration according to the insulation and airtightness (poor, medium, super).

	Parameter	Light	Medium	Heavy
Poor Insulated	Thermal mass C_m [kJ/K.m²$_{floor}$]	101	216	312
	U-value [W/m².K]	1	1	1
	Infiltration [h^{-1}]	0.15	0.15	0.15
	Line loss (7m) [W/m. K]	0.25	0.25	0.25
Medium Insulated	Thermal mass C_m [kJ/K.m²$_{floor}$]	101	216	312
	U-value [W/m².K]	0.8	0.8	0.8
	Infiltration [h^{-1}]	0.12	0.12	0.12
	Line loss (7m) [W/m. K]	0.1	0.1	0.1
Super Insulated	Thermal mass C_m [kJ/K.m²$_{floor}$]	101	216	312
	U-value [W/m².K]	0.6	0.6	0.6
	Infiltration [h^{-1}]	0.08	0.08	0.08
	Line loss (7m) [W/m. K]	0.03	0.03	0.03

Table 5.2 Simulation scenarios

For thermal mass of the building default values are taken from EN ISO 13790 – "Energy performance of buildings – Calculation of energy use for space heating and cooling", (Dansk Standard 2008). Infiltration values are according to Danish Building Regulations 2010 (The Danish Government 2010) as follows 1, 1.5 and 2 l/s/m² of floor area at pressure difference of 50 Pa, and expressed in the table as air change rate according to the volume of the room. Line losses are according to DS 418 –

"Calculation of heat loss from buildings" (Dansk standard 2011). Average U-value of the external components is calculated according to (Dansk standard 2011), including the components` area ratio - wall and window. It is assumed for the simulation that the investigated room has only one wall facing outdoors. The specific U-values are assumed as indicated in Table 5.3.

Building period	Floor	Wall	Ceiling	Window
1973-1978 (poor)	0.19	0.49	0.54	2.8
1979-1998 (medium)	0.19	0.34	0.19	2.7
1999-2006 (super)	0.19	0.30	0.17	1.6

Table 5.3 Default U-values according to year of construction, (Kim B. Wittchen & Jesper Kragh 2012)

For the simulation it is assumed that the room is not ventilated and all internal loads are disregarded. In order to compare the pre-heating time and energy use of the room, it should be considered that the need for heating in the different scenarios will be different, since it will vary with the transmission heat loss and the infiltration heat loss. Therefore, the maximum capacity of a heater will be different depending on the airtightness and insulation of the building. The heat loss calculation includes transmission loss (equation (28)), line loss around the window (equation (**29**)) and infiltration loss (equation (**30**)).

$$Qt = \Delta T \cdot U \cdot A \tag{28}$$

$$Ql = \Delta T \cdot \psi \ \cdot L \tag{29}$$

$$Qinf = \frac{ACH \cdot V_{room} \cdot \rho_{air} \cdot C_{p\,air}}{3600} \tag{30}$$

Where, ΔT is the temperature difference [K], U is the U-value [W/m²K], A is area [m²], ψ is line loss [W/m.K], L is the length of the line loss [7m], ACH is the air change rate due to infiltration [h^{-1}], V_{room} is the volume of the room [70m³], ρ_{air} is the density of air [1.204 kg/m³], $C_{p\,air}$ is the heat capacity of the air [1005 J/kg.K].

The calculation is made in design conditions, assuming temperature difference of 32°C (20-(-12)).The resulted heat demand is indicated in Table 5.4.

Heat loss [W]	Poor insulated	Medium Insulated	Super Insulated
Transmission loss	448	358.4	268.8
Line loss around window	56	22.4	6.72
Infiltration loss	112.9	90.3	60.2
Total heat demand	616.9	471.1	335.8

Table 5.4 Heat loss according to amount of insulation

Assuming a simple first order model, the heat balance of the room is written as follows:

$$\begin{aligned} C_m\, A_f \frac{\partial \theta_{room}(t)}{\partial t} &= Q_{heater}(t) + U\, A_{tot}\big(\theta_{ambient}(t) - \theta_{room}(t)\big) \\ &+ \frac{ACR \cdot V_{room} \cdot \rho_{air} \cdot C_{p\,air}}{3600}\big(\theta_{ambient}(t) - \theta_{room}(t)\big) \end{aligned} \tag{31}$$

This is equivalent to:

$$C_m\,A_f\frac{\partial\theta_{room}(t)}{\partial t} = Q_{heater}(t) + UA_{equiv}\left(\theta_{ambient}(t) - \theta_{room}(t)\right) \tag{32}$$

Where,

$$UA_{equiv} = U\,A_{tot} + \frac{ACR \cdot V_{room} \cdot \rho_{air} \cdot C_{p\,air}}{3600} \tag{33}$$

Transfer functions were made for the formulation described above, and a Simulink model was established according to them. Laplace transform for the heat balance of the room is as follows:

$$\frac{C_m\,A_f}{UA_{equiv}}\,s\,\theta_{room}(s) + \theta_{room}(s) = \frac{Q_{heater}(s)}{UA_{equiv}} + \theta_{ambient}(s) \tag{34}$$

And expressing room temperature results in:

$$\theta_{room}(s) = \frac{1}{\frac{C_m A_f}{UA_{equiv}}s + 1} \cdot \left[\frac{1}{UA_{equiv}} \cdot Q_{heater}(s) + \theta_{ambient}(s)\right] \tag{35}$$

The following model is established in Simulink, Figure 5.2. The same model is applied for all the nine cases and the results are plotted simultaneously in order to understand the difference.

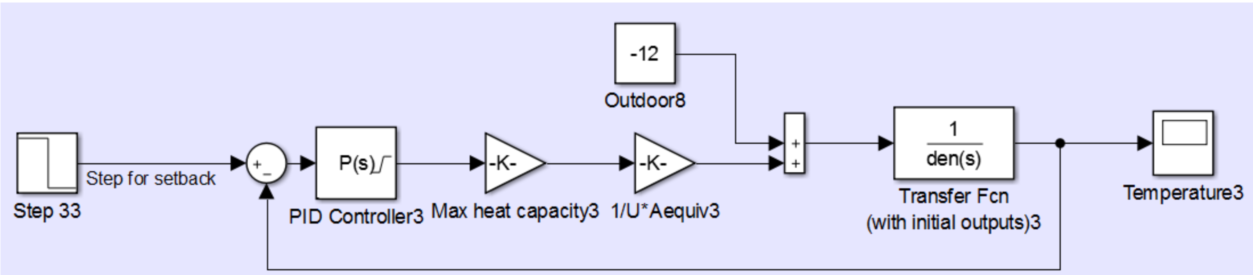
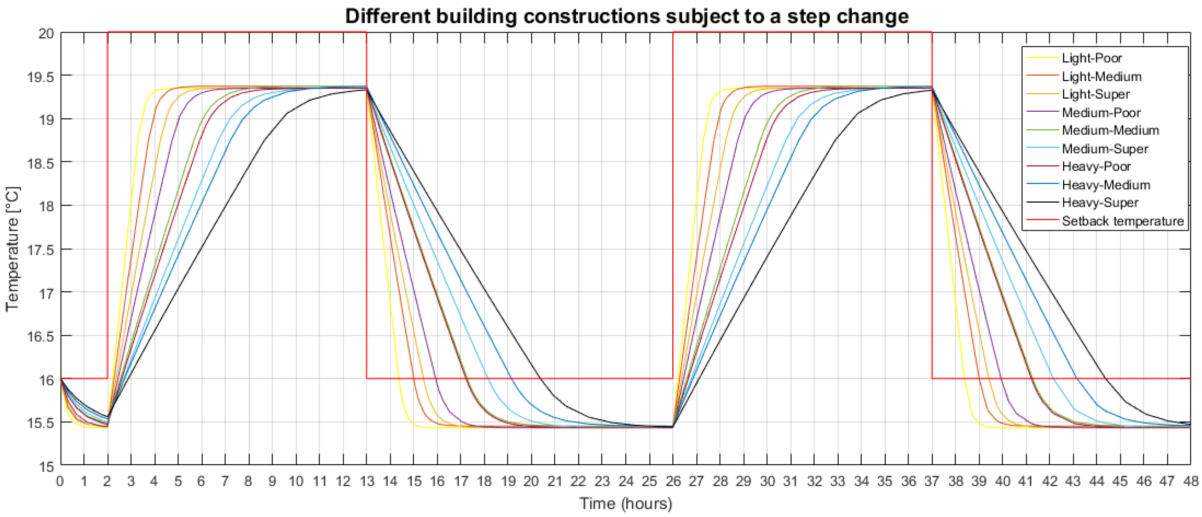


Figure 5.2 Simulink model

The simple one node model, where the heat accumulation of a building/room is equal to the sum of heater output and the heat loss by transmission and ventilation, has inaccuracy in predicting the time for reaching a set point in a step change. This is due to a single output of room temperature, which combines air and mean radiant temperature. It means that in the simulation the heater will stay "on" until not only the air, but also the thermal mass reaches the set point. Therefore, energy consumption is not investigated for this model. In order to get a more accurate result, a two node model should be used, where the feedback for the controller is from the air temperature. Such setup is similar to the way a thermostat works, since a radiator output (in case of TRVs – flow) is regulated based on air temperature.

Time to reach setback – tests in Simulink

A test for the time to reach setback was performed for the 9 cases of constructions and insulation types. Outdoor temperature in the simulation is assumed to be constant at -12°C. The simulation is done for a period of two days in order to achieve the same starting point for all the cases. The controller of the heater is assumed to have a proportional operation. Setback period is 11 hours. Results are plotted in Graph 5.1.



Graph 5.1 Buildings with different construction subject to a setback, temperature

It is clear from the graph that there is constant offset of the temperature. This offset is main characteristic of the proportional controller (as describer in chapter *2.1.2 Control modes*). The light building cases are heating faster and cooling down faster, but at the same time need higher amount of energy to maintain the temperature at certain point due to lower accumulation and higher losses. However, if the building has heavy construction and it is well insulated, it is possible during the setback time that the temperature will not drop to the set point (in the case it drops from 19.4°C to 15.4°C for 10.1h). It should be noted that the current model is facing outside with four walls and a roof, thus the cool down time is shorter compared to a zone that faces outside with only one wall. Therefore, during most of the setback time (or even all), the heating system will be off, while in lighter construction where the temperature drop happens faster, the heating system will need to work in order to maintain the setback temperature. However, a consideration about the setback period always should be made, because if the temperature in a heavy building drops very low, then it may compromise the thermal comfort during the occupied hours due to the long pre-heating time required.

From Graph 5.1 is extracted the time that is needed in each case for the temperature to drop to the set point after the occupied time. The time is indicated in Table 5.5.

	Light Construction	**Medium Construction**	**Heavy Construction**
Poor Insulated	1.9h	4.1h	6h
Medium Insulate	2.9h	5.9h	8.8h
Super Insulated	3.3h	7.2h	10.1h

Table 5.5 Time the building cools to setback temperature

Appendix D IDA ICE ROOM MODELPARAMETERS

BR 08

External wall [m²] 11

		U-value [W/m² K]	Rho [kg/m³]	Lambda [W/mK]	Cp [J/kg K]	Thickness [m]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm
Light	Gypsum board, 13mm	0.11	900	0.25	1000	0.013	0.143	129	128700	**153343** **[J/K]**
	Insulation , 180 mm		25	0.04	1030	0.18	1.98	50	50985	
	Outer bricks, 108mm		1700	0.77	800	0.108	1.188	2020	1615680	
Medium	Internal plastering, 13mm	0.14	900	0.25	1000	0.013	0.143	129	128700	**1430220** **[J/K]**
	Inner bricks, 108mm		1700	0.56	800	0.108	1.188	2020	1615680	
	Insulation, 170 mm		25	0.04	1030	0.17	1.188	30	30591	
	Outer bricks, 108mm		1700	0.77	800	0.108	1.188	2020	1615680	
Heavy	Internal plastering, 13mm	0.16	900	0.25	1000	0.013	0.143	129	128700	**2234100** **[J/K]**
	Medium density concrete, 100 mm		2200	1.65	1000	0.1	1.1	2420	2420000	
	Insulation, 170 mm		25	0.038	1030	0.17	1.87	47	48152.5	
	Outer brick, 108mm		1700	0.77	800	0.108	1.188	2020	1615680	

Floor and ceiling [m²] 50

		U-value [W/m² K]	Rho [kg/m³]	Lambda [W/mK]	Cp [J/kg K]	Thickness [m]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm
Light	Tiles, 25mm	0.22	400	0.07	1500	0.025	1.25	500	750000	**1727250** **[J/K]**
	Concrete screed, 15mm		1200	1.15	1000	0.015	0.75	900	900000	
	Insulation, 80 mm		25	0.04	1030	0.08	4	100	103000	
	Concrete, 85mm		1800	2	1000	0.85	42.5	76500	76500000	
Medium	Concrete screed, 15mm	0.15	1200	1.15	1000	0.015	0.75	900	900000	**8619313** **[J/K]**
	Concrete medium density, 70mm		2200	1.7	1000	0.07	3.5	7700	7700000	
	Insulation, 180 mm		25	0.04	1030	0.18	9	225	231750	
	Plasterboard, 12.5mm		900	0.25	1000	0.0125	0.625	562.5	562500	
Heavy	Concrete screed, 15mm	3.3	1200	1.15	1000	0.015	0.75	900	900000	**10250000** **[J/K]**
	Concrete medium density, 170 mm		2200	1.65	1000	0.17	8.5	18700	18700000	
	Plasterboard, 12.5mm		900	0.25	1000	0.0125	0.625	562.5	562500	

	Internal walls [m²]	42								
Light		U-value [W/m²K]	Rho [kg/m³]	Lambda [W/mK]	Cp [J/kg K]	Thickness [m]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm
	Gypsumboard, 13mm		900	0.25	1000	0.013	0.546	491.4	491400	
	Insulation, 50 mm	0.44	25	0.038	1030	0.05	2.1	52.5	54075	**1036875**
	Gypsumboard, 13mm		900	0.25	1000	0.013	0.546	491.4	491400	**[J/K]**
Medium	Gypsumboard, 13mm		900	0.25	1000	0.013	0.546	491.4	491400	
	Light weight concrete, 120 mm	3.2	2200	1.65	1000	0.12	5.04	11088	11088000	**8530200**
	Gypsumboard, 13mm		900	0.25	1000	0.013	0.546	491.4	491400	**[J/K]**
Heavy	Gypsumboard, 13mm		900	0.25	1000	0.013	0.546	491.4	491400	
	Light weight concrete, 120 mm	3	2200	1.65	1000	0.12	5.04	11088	11088000	**8530200**
	Gypsumboard, 13mm		900	0.25	1000	0.013	0.546	491.4	491400	**[J/K]**

BR 10

External wall

		U-value [W/m²K]	Rho [kg/m³]	Lambda [W/mK]	Cp [J/kgK]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm
Light	Gypsumboard, 13mm		900	0.25	1000	0.143	129	128700	
	Insulation ,200mm	0.19	25	0.04	1030	2.2	55	56650	**153343**
	Outer bricks, 108mm		1700	0.77	800	1.188	2020	1615680	**[J/K]**
Medium	Internal plastering, 13mm		900	0.25	1000	0.143	129	128700	
	Inner bricks, 108mm	0.17	1700	0.56	800	1.188	2020	1615680	
	Insulation, 200mm		25	0.038	1030	2.2	55	2	**1430220**
	Outer bricks, 108mm		1700	0.77	800	1.188	2020	1615680	**[J/K]**
Heavy	Internal plastering, 13mm		900	0.25	1000	0.143	129	128700	
	Medium density concrete, 120mm	0.18	2200	1.65	1000	1.32	2904	2904000	
	Insolation, 200mm		25	0.038	1030	2.2	55	56650	**2234100**
	Outer brick, 108mm		1700	0.77	800	1.188	2020	1615680	**[J/K]**

Storey partition									
Light		U-value [W/m²K]	Rho [kg/m³]	Lambda [W/mK]	Cp [J/kgK]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm
	Tiles, 25mm	0.31	400	0.07	1500	1.25	500	750000	**1727250 [J/K]**
	Concrete screed, 15mm		1200	1.15	1000	0.75	900	900000	
	Insulation, 100mm		25	0.04	1030	5	125	128750	
	Concrete, 100mm		2400	2	1000	5	12000	12000000	
Medium	Concrete screed, 15mm	0.19	200	1.15	1000	0.75	150	150000	**8412875 [J/K]**
	Concrete medium density, 75mm		2200	1.7	1000	3.75	8250	8250000	
	Insulation, 200mm		25	0.04	1030	10	250	257500	
	Plasterboard, 12.5mm		900	0.25	1000	0.625	562.5	562500	
Heavy	Concrete screed, 15mm	3.08	1200	1.15	1000	0.75	900	900000	**10250000 [J/K]**
	Concrete medium density, 150mm		2200	1.65	1000	7.5	16500	16500000	
	Plasterboard, 12.5mm		900	0.25	1000	0.625	562.5	562500	

Internal walls									
Light		U-value [W/m²K]	Rho [kg/m³]	Lambda [W/mK]	Cp [J/kgK]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm
	Gypsumboard, 13mm	0.44	900	0.25	1000	0.546	491.4	491400	**1026113 [J/K]**
	Insulation, 75mm		25	0.038	1030	3.15	78.75	81112.5	
	Gypsumboard, 13mm		900	0.25	1000	0.546	491.4	491400	
Medium	Gypsumboard, 13mm	3	900	0.25	1000	0.546	491.4	491400	**8530200 [J/K]**
	Light weight concrete, 100mm		2200	1.65	1000	4.2	9240	9240000	
	Gypsumboard, 13mm		900	0.25	1000	0.546	491.4	491400	
Heavy	Gypsumboard, 13mm	3	900	0.25	1000	0.546	491.4	491400	**8530200 [J/K]**
	Light weight concrete, 100mm		2200	1.65	1000	4.2	9240	9240000	
	Gypsumboard, 13mm		900	0.25	1000	0.546	491.4	491400	

BR 15

External wall

		U-value [W/m²K]	Rho [kg/m³]	Lambda [W/mK]	Cp [J/kgK]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm
Light	Gypsumboard, 13mm	0.11	900	0.25	1000	0.143	129	128700	**153343** **[J/K]**
	Insulation , 350mm		25	0.04	1030	3.85	96	99137.5	
	Outer bricks, 108mm		1700	0.77	800	1.188	2020	1615680	
Medium	Internal plastering, 13mm	0.14	900	0.25	1000	0.143	129	128700	**1430220** **[J/K]**
	Inner bricks, 108mm		1700	0.56	800	1.188	2020	1615680	
	Insulation, 250mm		25	0.04	1030	2.75	69	70812.5	
	Outer bricks, 108mm		1700	0.77	800	1.188	2020	1615680	
Heavy	Internal plastering, 13mm	0.16	900	0.25	1000	0.143	129	128700	**2234100** **[J/K]**
	Medium density concrete, 100mm		2200	1.65	1000	1.1	2420	2420000	
	Insolation, 220mm		25	0.038	1030	2.42	61	62315	
	Outer brick, 108mm		1700	0.77	800	1.188	2020	1615680	

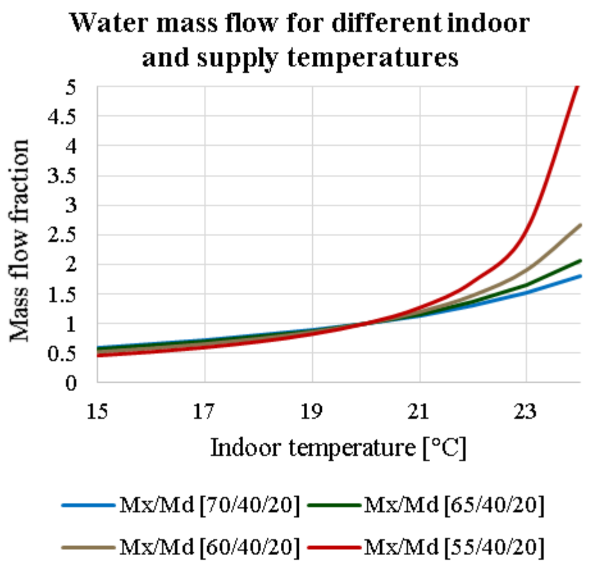
Storey partition

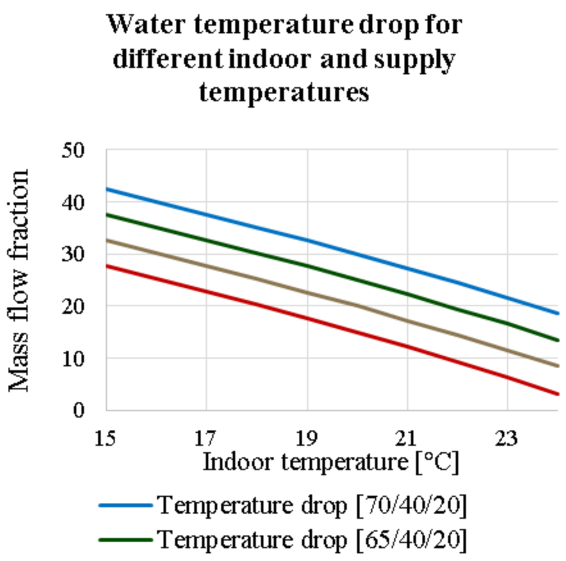
		U-value [W/m²K]	Rho [kg/m³]	Lambda [W/mK]	Cp [J/kgK]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm
Light	Tiles, 25mm	0.22	400	0.07	1500	1.25	500	750000	**1727250** **[J/K]**
	Concrete screed, 15mm		1200	1.15	1000	0.75	900	900000	
	Insulation, 150mm		25	0.04	1030	7.5	187.5	193125	
	Concrete, 85mm		1800	2	1000	4.25	7650	7650000	
Medium	Concrete screed, 15mm	0.15	1200	1.15	1000	0.75	900	900000	**8709438** **[J/K]**
	Concrete medium density, 70mm		2200	1.7	1000	3.5	7700	7700000	
	Insulation, 250mm		25	0.04	1030	12.5	312.5	321875	
	Plasterboard, 12.5mm		900	0.25	1000	0.625	562.5	562500	
Heavy	Concrete screed, 15mm	3.3	1200	1.15	1000	0.75	900	900000	**10250000** **[J/K]**
	Concrete medium density, 110mm		2200	1.65	1000	5.5	12100	12100000	
	Plasterboard, 12.5mm		900	0.25	1000	0.625	562.5	562500	

Internal walls										
		U-value [W/m²K]	Rho [kg/m³]	Lambda [W/mK]	Cp [J/kgK]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm
Light	Gypsumboard, 13mm		900	0.25	1000	0.546	491.4	491400	
	Insulation, 75mm	0.44	25	0.038	1030	3.15	78.75	81112.5	**1026113**
	Gypsumboard, 13mm		900	0.25	1000	0.546	491.4	491400	**[J/K]**
Medium	Gypsumboard, 13mm		900	0.25	1000	0.546	491.4	491400	
	Light weight concrete, 60mm	3.2	2200	1.65	1000	2.52	5544	5544000	**6526800**
	Gypsumboard, 13mm		900	0.25	1000	0.546	491.4	491400	**[J/K]**
Heavy	Gypsumboard, 13mm		900	0.25	1000	0.546	491.4	491400	
	Light weight concrete, 90mm	3	2200	1.65	1000	3.78	8316	8316000	**8530200**
	Gypsumboard, 13mm		900	0.25	1000	0.546	491.4	491400	**[J/K]**

Appendix E WATER MASS FLOW WITH FIXED RETURN

This Appendix refers to the analytical investigation performed in *2.3.2 Change in ambient temperatures*.





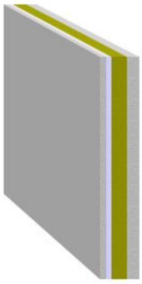
The graphs presented above are the result of the calculation, where the return temperature is fixed at 40°C. Therefore, when decreasing the supply temperature the temperature drop decreases, and the lower the supply temperature the higher the mass flow will be.

Appendix F U-VALUE CALCULATION - CASE STUDY

Constructions and their U-values:

Roof/horizontal ceiling	d [m]	λ [W/mK]	R [m^2K/W]
Rsi			0.10
Gypsum board	0.013	0.25	0.05
Wooden laths	0.003	0.12	0.03
Wooden battens	0.005	0.12	0.04
Insulation	0.10	0.039	2.56
Corrugated sheets on battens			0.20
Rso			0.04
	0.121	ΣR =	3.02
		U [W/m^2K]=	**0.33**

External wall	d[m]	λ [W/mK]	R [m^2K/W]
Rsi			0.13
Reinforced Concrete	0.060	2.44	0.02
Insulation	0.075	0.039	1.92
Ventilation gap	0.025	0.19	0.13
Concrete	0.030	2.44	0.01
Rso			0.04
	0.19	ΣR =	2.26
		U [W/m^2K]=	**0.44**



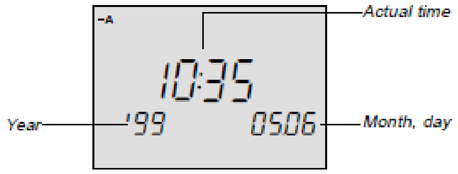
Heat transfer coefficient of the room:

	U	A	UA [W/K]
External wall	0.44	12.2	5.4
Window	2.30	12.5	28.7
Roof	0.33	54.0	17.8
Line loss	0.08	20.3	1.6
Ventilation loss (only infiltration of 0.27 h^{-1})			16.0
Total UA			**69.51**

Appendix G EXISTING SETTINGS ON THE ECL

Note: On the left side the images are from Danfoss guide, on the right side the pictures represents the settings on the ECL at the school.

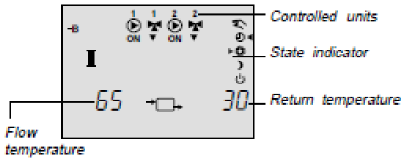
Go to line A.



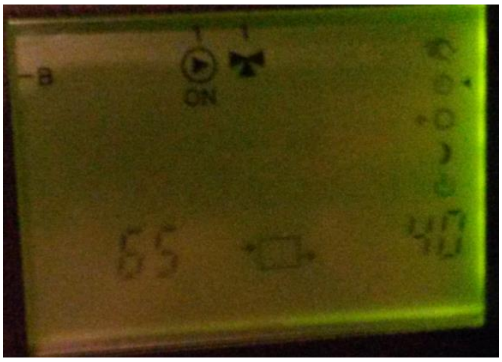
Line A – Setting the time

Line B – Heating system information

Go to line B.

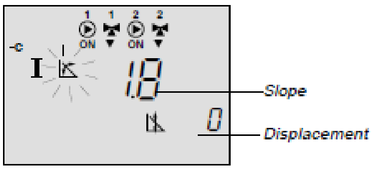


Push the shift button to see:
- the calculated flow temperature
- the return temperature set points



Line C - Heat curve

Go to line C.
The symbol for the slope of the heat curve will flash.

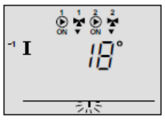


Slope		
Circuit	Setting range	Factory setting
I/II	0.2 ... 3.4	1.8

Line 1 - Heating cut out

1 Limit for heating cut-out		
Circuit	*Setting range*	*Factory setting*
I/II	10 ... 30 °C	18 °C

Go to line 1.

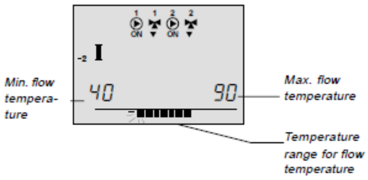


Set the outdoor temperature limit at which you want the heating system to stop.

Line 2 – Min/Max supply temperature

2 Flow temperature min., max. limits		
Circuit	*Setting range*	*Factory setting*
I/II	10 ... 110 °C	min. 40 °C max. 90 °C

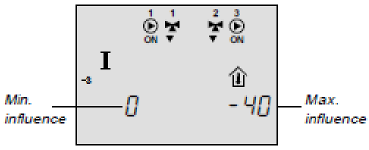
Go to line 2.

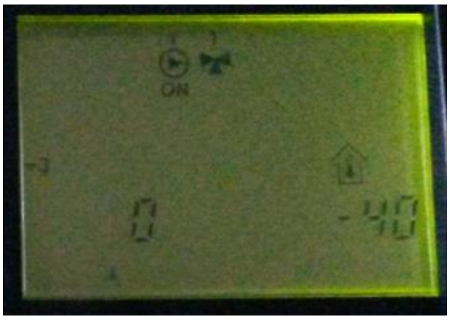


Line 3 – Min/Max room temperature influence

3 Room temperature influence		
Circuit	*Setting range*	*Factory setting*
I/II	0 ... 99/-99 ... 0	min. 0 max. -40

Go to line 3.

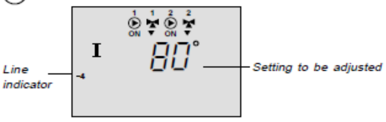




Line 4 – Proportional band (setting the PI regulation)

4 Proportional band		
Circuit	*Setting range*	*Factory setting*
I/II	1 ... 250 K	80 K

Go to line 4.



Set the proportional band.
A higher value will result in a stable, but slow regulation of the flow temperature.

Line 5- Integration time constant

5 Integration time constant		
Circuit	*Setting range*	*Factory setting*
I/II	5 ... 999 sec.	30 sec.

Go to line 5.

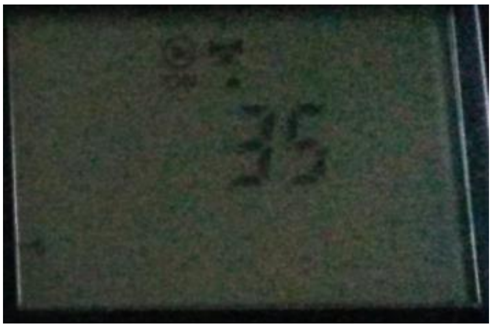
Set a high integration time constant to obtain a slow but stable reaction to deviations.
A low integration time constant will make the controller react fast but with less stability.

Line 6 – Running time of the motorized valve

6 Running time of the motorized valve		
Circuit	*Setting range*	*Factory setting*
I/II	5 ... 250 sec.	35 sec.

Go to line 6.

Set the running time of the motorized valve according to the example on the opposite page.
This is the time it takes the valve to move from closed to fully open position.



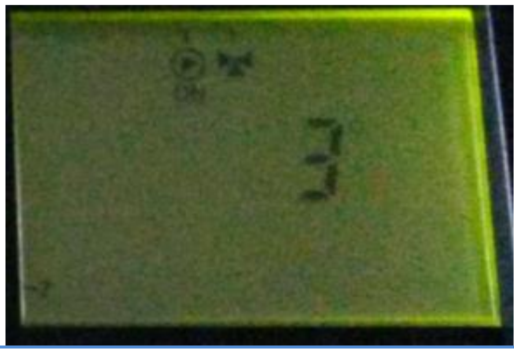
Line 7 – Neutral zone

7 Neutral zone		
Circuit	*Setting range*	*Factory setting*
I/II	0 ... 9 K	3 K

Go to line 7.

Set the neutral zone to a high value if you can accept a high variation in flow temperature.
When the actual flow temperature is within the neutral zone, the controller does not activate the motorized valve.

Note! The valve is symmetrically around the flow reference value.



Appendix H CALCULATION OF VELOCITIES IN A PIPE

The calculation is based on the design conditions of 70/40/20 with outdoor temperature of -12°C.

Room heat loss		2663	[W]
One radiator output (design)	Q	1331	[W]
Indoor temperature		20	[°C]
Outdoor temperature		-12	[°C]
Water density	ρ	980	[kg/m³]
Water specific heat capacity	C_p	4200	[J/kgK]
Pipe internal diameter (DN15)		0.015	[m]
Pipe cross sectional area	A	0.000176715	[m²]

- Volume flow calculation:

$$q = \frac{Q}{\rho \cdot C_p \cdot (T_s - T_r)}$$

- Velocity calculation:

$$v = \frac{q}{A}$$

- Velocity in a pipe at different loads:

Percentage of design heat loss (for 1 radiator)	Necessary radiator output [W]	Velocity, [m/s]
0%		0
20%	266	0.0122
30%	399.4	0.0183
40%	532.5	0.0244
50%	665.6	0.0305
100%	1331	0.0610

Appendix I CTS SCHEDULE

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00							
01:00							
02:00							
03:00							
04:00							
05:00	05:00						
06:00		06:00				06:00	
07:00							
08:00							
09:00							
10:00							
11:00							
12:00							
13:00							
14:00							
15:00							
16:00							
17:00							
						18:00	
18:00							
19:00							
	20:00	20:00					
20:00							
21:00							
22:00							
23:00							

Appendix J INVESTIGATION OF THERMAL COMFORT

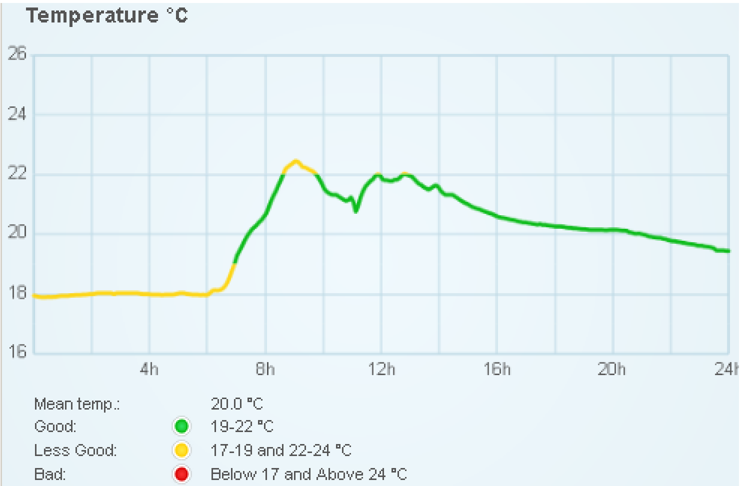
The preheating time after the weekend setback is investigated for Monday, and for a weekday (Tuesday).

For Monday 21 of November, the day temperature set point in the test room was set to 21°C and the starting hour was set to 4 o'clock in the morning, Table 5.6.

Day	Hour	Degree [°C]	Results
Monday	04:00	21	Even though the preheating was set for 4 o'clock only at 6 o'clock the temperature started to increase because there is a setback at the central level on the ECL which is scheduled from 6 o'clock.
	14:30	18	
Tuesday to Friday	06:00	21	Preheating from 6=>having 21°C at 08 o'clock
	14:30	18	
Saturday & Sunday		18	At Sunday around 5 o'clock the temperature reaches 18°C

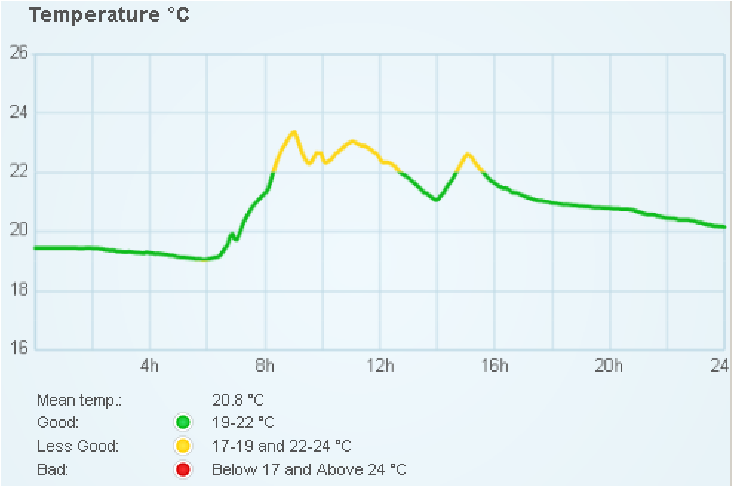
Table 5.6 Optimized schedule for the thermostat in the test room (settings valid until 23 November)

Although the heating was scheduled to start at 4 o'clock from Graph 5.2 it can be observed that no change in temperature occurred around this hour. This occurs due to the weekend setback at the central level on the ECL were a desired room temperature of 16 is set until 6 o'clock. From the same graph, it can be seen that only at around 6 o'clock the temperature in the room starts to increase, at 08 reaching 21°C. Since the desired temperature is reached quite fast after the weekend setback, it is decided to start the preheating on Monday with two hours before occupancy arrival instead of four, meaning form 6 o'clock.



Graph 5.2 Temperature in the test room on Monday/21November

Regarding the thermal comfort during the weekdays with the settings mentioned in Table 5.6 the operative temperature for 24 hours is displayed in Graph 5.3. From the graph, it can be seen that the temperature during occupied hours fluctuates between 21-23 °C, and after the occupied hours (15 o'clock), the temperature drops to approximately 19 °C.



Graph 5.3 Temperature in the test room on Tuesday/22November

Appendix K THERMAL MASS CALCULATION FOR CASE STUDY ROOM

External wall

area [m²]	24.7									
	U-value [W/m²K]	Rho [kg/m³]	Cp [J/kgK]	Thick [m]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm	Cm for first 50mm	Cm for first 10mm
Reinforced Concrete	0.44	2300	1000	0.060	1.48	3406	3405592	**3507266**	**2837993**	**567599**
Insulation		100	1030	0.075	1.85	185	190639			
Ventilation gap		0	0	0.025	0.62	0	0			
Reinforced Concrete		2300	1000	0.030	0.74	1703	1702796			
							5299026			

Roof

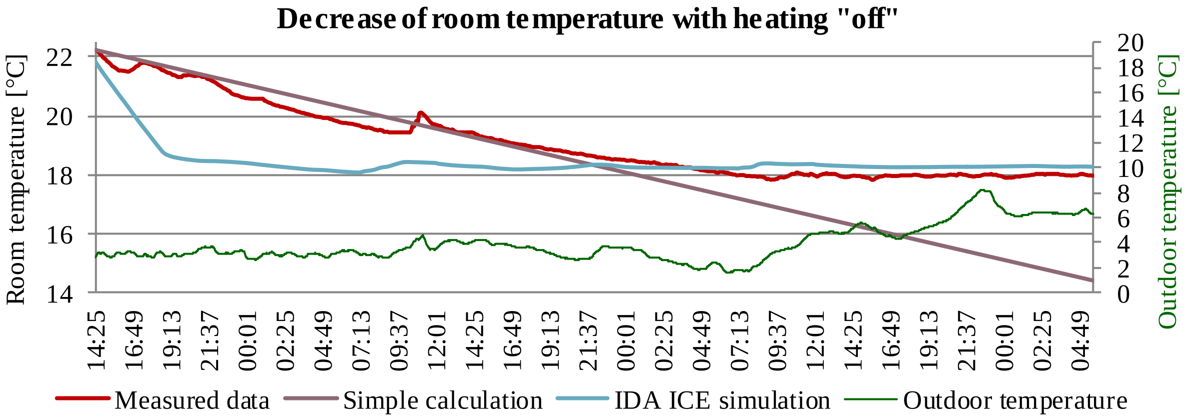
area [m²]	54.0									
	U-value [W/m²K]	Rho [kg/m³]	Cp [J/kgK]	Thickness [m]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm	Cm for first 50mm	Cm for first 10mm
Gypsum board	0.33	900	1000	0.013	0.70	632	631800	**3981294**	**3703194**	**486000**
Wooden laths				0.003	0.16	0	0			
Wooden battens		450	1600	0.005	3.98	1791	2865600			
Insulation		100	1030	0.100	5.40	540	556200			
							4053600			

Internal walls and floors

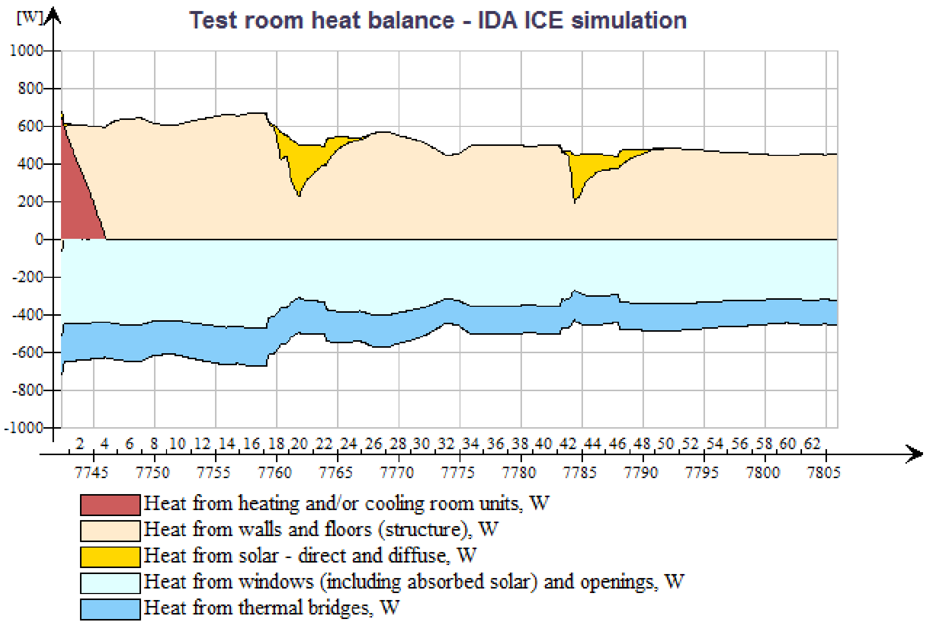
area [m²]	113.0									
	U-value [W/m²K]	Rho [kg/m³] or [kg/m²]	Cp [J/kgK]	Thickness [m]	V [m³]	m [kg]	Cm [J/K]	Cm for first 100mm	Cm for first 50mm	Cm for first 10mm
Reinforced concrete	2.63	2300	1000	0.150	16.95	38985	38985000	**25990000**	**12995000**	**2599000**
						Totals:	**48337626**	**33478560**	**19536187**	**3166599**

Appendix L TIME TO REACH SETBACK (IDA ICE)

This Appendix refers to the measurements and calculation performed in Analysis of current thermal comfort chapter, regarding the time needed for the room temperature to decrease to the night set point of 18°C. A simulation in IDA ICE was performed for the same weekend in order to compare the results to the measured and calculated values.



The simulation shows that there is a very fast drop of operative temperature during the first hour after the heating is turned off. However, the temperature for the rest of the weekend drops very slowly, and stabilizes at around 18°C. In order to find out if this occurs due to internal gains in the simulation, a heat balance from IDA ICE is analyzed (see graph below).

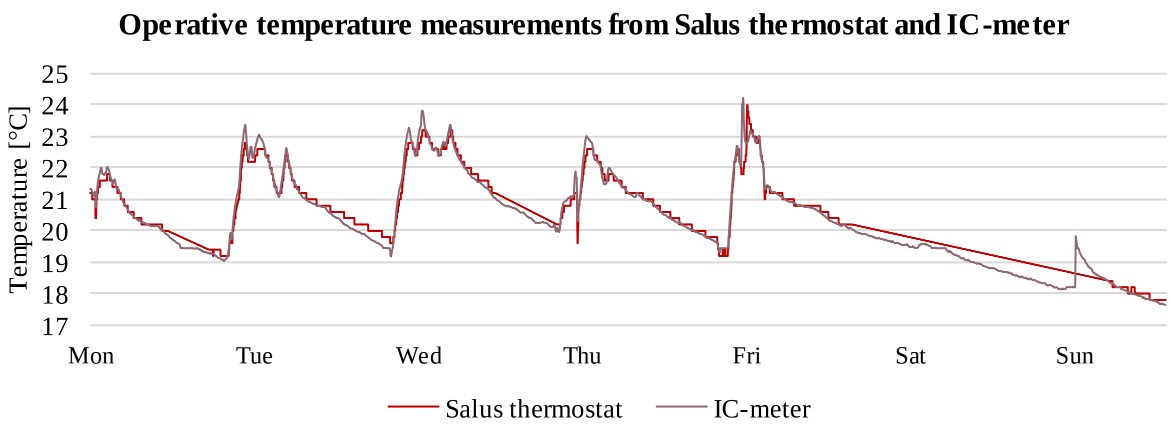


The heat balance from the simulation shows that there was no heating during the whole period, when the room temperature was kept at 18°C. Nevertheless, there are other internal gains that can contribute to the room temperature being so stable over the weekend. The heat accumulated in the internal thermal mass of the room accounts for around 450W according to the simulation; solar gains occur during both days of the weekend.

Appendix M SALUS TRV DATA

Salus Controls has a possibility to log data from the installed TRVs that includes thermostat set point, measured room temperature, and the percentage of valve opening. The logged information is provided as an average per minute.

Firstly, the room temperature logged by Salus is compared to the temperature logged by IC-meter in order to see if both devices provide similar reading. The graph shows a week of operative temperature measurements from both Salus thermostat and IC-meter. As it can be seen, both measuring devices show identical readings of operative temperature in the test room.



Secondly, the information logged by Salus Controls is analysed graphically with the aim of understanding the operation of the TRVs. The graph below shows operative temperature, thermostat set point and the percentage of valve opening in the test room for the period of one week. It should be noted that there are two TRVs installed in the room, and their opening percentages are exactly the same, since they both are controlled by one room thermostat.