FROM GAS TO GEOTHERMAL ENERGY
ADAPTATIONS AT BUILDING LEVEL FOR A LOWER TEMPERATURE IN THE HEATING NETWORK

Silvia Filgueira Luaces
MSc. Sustainable Energy Technology
Delft University of Technology

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ADAPTATIONS AT BUILDING LEVEL FOR A LOWER TEMPERATURE IN THE HEATING NETWORK

by

SILVIA FILGUEIRA LUACES

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Thesis committee:	Prof.dr. K. (Kornelis) Blok
	Dr.ir. S.C. Jansen
	Dr.ir. I.W.M. Pothof
External supervisor	P. (Peter) de Jong

TUDelft

Delft University of Technology

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The transition from fossil fuels to renewable energy sources brings along the reduction of the supply temperature of the distribution heating networks, because renewable energy sources usually provide heat at lower temperatures. This master thesis specifically focuses on the buildings because it is uncertain which adaptations are necessary to ensure thermal comfort when the supply temperature decreases. Especially in existing buildings, since they were originally designed for high operating temperatures. A case study was conducted by studying the performance of a non-residential building under different simulated scenarios to enable lower operating temperatures in the heating network.

The objectives of the research are two: 1) to develop of a protocol for data collection and selection of promising adaptations that facilitates a case study on this topic and 2) to compare the observed effects of the different possible adaptations on the required operating temperatures in this case study with the results of the few other studies available.

The most interesting results derived from the case study are that it is possible to lower the peak power, and thus the operating temperatures, in the current situation of the selected building, without any adaptation, from 78/70ºC to 63/55ºC. Assuming that the mass flow is decreased in order to achieve a bigger temperature difference between supply and return, operating temperatures can be 70/50ºC. Mass flow control through radiators should then be implemented in order to obtain the lowest possible return temperature for a given supply temperature. During the implementation phase of the geothermal project, the implications of this measure need to be studied.

When heat losses are small, smart settings in the building management system prove successful to lower the supply temperature further. In the controls and operation scenarios, adjusting the room temperature setpoints and the heating schedules enables even lower supply and return temperatures, 50/35ºC.

In old, poorly insulated buildings, minimal renovations in the buildings' envelope are crucial (and often sufficient) to enable low temperature heating. When the building without renovations was simulated, it was not possible to lower the operating temperatures; instead, the required temperature increased to 90/70ºC.

Changes in the energy system, such as the installation of radiators designed for lower temperature heating, also enable supply and return temperatures of 50/35ºC. The case study building has a ventilation system with heat recovery and pre-heating of air to 19ºC. A scenario is simulated with a system with only heat recovery. The ventilation air is introduced in the room at lower temperatures, and the heating system takes over the heat demand. For the same operating temperatures, 70/50ºC, the heat recovery scenario suffers a decrease in the thermal comfort. Seeing the effect of the heating through ventilation air in lowering the supply and return temperatures, a central ventilation system with heat recovery and pre-heating that can operate at low temperatures can represent a good alternative to other decentralised adaptations in the energy system, such as changing radiators.

The protocol for data collection and selection of promising adaptations created during this research facilitates the first stages of a case study, by providing an inventory of the main elements for the data collection and their implication in lowering the operating temperatures in the heating network. It also presents a list of possible adaptations to enable low temperature heating.

Future case studies could focus on fixing thresholds for the properties of the envelope that limit the lowering of the supply and return temperature. Further research could also continue exploring the optimisation of schedules and room temperature settings to lower the temperatures in the heating network even more, considering the possibility to use the thermal mass of the building as passive storage. Generalisations from case study findings are necessary to start developing one common standardised procedure, with recommended tools and guidelines for simulation as well as practical tests. The standard procedure at building level ought to be included as part of a holistic district level and building level approach in order to facilitate the transition to more efficient and sustainable heating networks.

FOREWORD

This research is a Sustainable Energy Technology master thesis. The master thesis is a 45 ECTS course, which corresponds to approximately a 7 to 8-month research period. The research was started in January 2019 and it was finished in November of the same year. The master program requires the focus of the thesis to lie on one or more sustainable energy technologies. A plan to implement geothermal heating in the campus of Delft University of Technology was being set up and this research studies how a part of the thermal energy system will need to be adapted, namely the faculty buildings.

The master thesis was supervised by three experts, all related to the university.

- **Kornelis Blok** is the main supervisor; he works as a professor at the faculty of Technology, Policy and Management at the department of Engineering Systems and Services. He conducts and supervises research in the field of energy transition and energy efficiency improvement. Thank you for the opportunity and guidance to set up this research. And the ever-calm tone of you voice.

- **Sabine Jansen** is the daily supervisor; she works as an assistant professor and researcher at the faculty of Architecture and the Built Environment, at the department of Architectural Engineering and Technology. Her focus is on the development and evaluation of sustainable heating solutions for the built environment, in relation to the required heat transition in the Netherlands. Thank you for facilitating my introduction to the building's sector and for offering a friendly and personal interaction.

- **Peter de Jong** is the external supervisor; he is the manager of the building system manager, controlling the heating network at the campus. He facilitates the contact with the Combined Heat and Power plant and Campus and Real Estate. Thank you for your determinism in finding out every single piece of information that I asked for. And for giving me extra permissions to building management systems and trusting I would not let the whole faculty freeze.

The thesis committee was formed by Kornelis Blok, Sabine Jansen and Ivo Pothof.

- **Ivo Pothof** was not directly involved in the supervision of the thesis, since one member of the thesis committee needs to be outside the research group. His area of expertise aligns well with the thesis topic. He is a part-time associate professor of Smart Thermal Grids and chair of the TU Delft Thermal Energy Platform.

1. INTRODUCTION

1.1. Background

The Netherlands (NL) is one of the countries that signed the Paris Agreement in 2015 (UNFCCC, 2015) and committed to reduce its greenhouse gas emissions over the coming decades, aiming to mitigate climate change. The steps on how to reduce its emissions are concretised further in national and regional agreements. The *Klimaatakkoord* (Rijksoverheid, 2019) (Dutch climate agreement), signed in 2019, aims to achieve a reduction of greenhouse gas emissions of 49% by 2030 compared to 1990.

According to the *Masterplan Aardwarmte in Nederland,* the Dutch geothermal energy masterplan (Energie Beheer Nederland B.V., 2018), approximately half of the heat demand comes from the built environment, which means that enabling a sustainable heat supply can help to significantly reduce the emissions . The masterplan proposes both individual and collective solutions. An example of individual solutions is the installation of heat pumps, moving from gas to electricity, whereas the collective solutions involve the connection of multiple buildings to a heating network powered by sustainable sources (sun, wind, biomass and geothermal energy). None of these sources can provide the total demand on its own, which means that a mix of sustainable sources is necessary for a rapid transition. Geothermal energy proves to be an essential technology, as it has the potential to supply 5% of the total heat demand by 2030 and 22% by 2050 (Energie Beheer Nederland B.V., 2018).

Delft University of Technology (TU Delft) constitutes an innovation niche in this transition towards sustainability, since it is a self-governing institute. In its Energy Efficiency Plan (EEP) (TU Delft, 2016), TU Delft defines its own goals in reducing energy consumption and improving its energy efficiency. The EEP is based on the national *Meerjarenafspraken energie-efficiëntie* (MJA3) (Ministerie van Economische Zaken en Klimaat, 2016), which is a long-term energy efficiency pact in which the university takes part. The ambitions defined for 2020 include a 50% reduction of carbon dioxide emissions compared to 2005 and a sustainable production of 25% of the energy used at the campus. As part of the EEP, the implementation of a geothermal energy source for district heating at the university is being researched.

The transition from fossil fuels to renewable energy sources brings along the reduction of the supply temperature of the distribution heating networks, because renewable energy sources usually provide heat at lower temperatures (H.Lund et al., 2010). The current natural gas-based system is a high temperature district heating system, designed for supply and return temperatures of 130 and 80ºC respectively. On the contrary, the temperature of the water extracted from the geothermal production well is expected to operate at a significantly lower supply temperature, approximately 80ºC (Ir. K.F. Haak, 2013).

As the system has to undergo a transformation to enable a lower temperature in the heating network, the TU Delft investigates limiting factors and crucial adaptations in the definition phase of the geothermal project. All the components of the district heating system need to be evaluated, which are the CHP plant, the distribution network, the heat exchangers and the buildings.

This master thesis specifically focuses on the buildings because it is uncertain which adaptations are necessary to ensure thermal comfort when the supply temperature decreases. Especially in existing buildings, since they were originally designed for high operating temperatures. A case study is carried out that deals with the adaptation of the existing buildings at the campus to lower temperatures in the heating network.

1.2. Problem statement and knowledge gaps

An initial literature search on this topic brings forward that it is possible to adapt existing buildings to lower temperature heating with little or even no adaptations, due to the fact that heating systems tend to be over-dimensioned. There are however important knowledge gaps found in the literature, which is understandable considering the emerging nature of the topic:

A gap in standardised approaches was identified. It is yet unknown how a building can be adapted in the most effective and efficient way. Researchers and institutions prepare their own guidelines and tools to set up and conduct projects to enable lower temperatures in a heating network, however, there are no general guidelines or procedures to be followed during simulations and practical tests in buildings.

A gap in experimental studies was found too. Only a small quantity of case studies has been done. Nevertheless, the findings of the available research are consistent: case studies confirm that simulations show which adaptations are necessary to enable a lower temperature in the heating network. More case studies can help confirm the effect of the different possible adaptations on the required operating temperatures.

1.3. Research questions

The main research question (RQ) and sub-questions derived from the knowledge gaps are presented below.

Main research question
What are the effects of different feasible adaptations in existing buildings on the required operating temperatures of the heating network?

Research sub-questions	
1.	**Which adaptations are possible at building level to enable a lower temperature in the heating network?**
2.	**How can a systematic collection of data and potential adaptations be made?**
3.	**How does the mass flow affect the supply and return temperature?**
4.	**How does lowering the supply temperature affect the building's thermal comfort when no adaptations are done?**
5.	**How does each of the possible adaptations affect the required supply temperature?**

1.4. Research methodology

The methodology followed in the research, as well as the structure of the report can be seen in the diagram presented in Figure 1. For an extended version, see APPENDIX A, in page 65. The methodology that comes after this introduction consisted of the following steps:

- **Literature review**: in chapter 2, related to research sub-question 1, a systematic review of the relevant research on this topic is performed in order to obtain an up-to-date overview of the knowledge about the possible adaptations and their impact.

- **Design of the data collection protocol**: in chapter 3, related to research sub-question 2, a protocol to collect data and give an indication of promising adaptations is developed. A first version of the protocol, based on the literature review, was created. Through a testing and improvement loop during the case study concerning this research, the final version was obtained.

- **Case study**: chapter 4 deals with questions 3 to 5. First, the developed protocol was followed in order to select the building for the case study, collect the necessary data and select promising adaptations. Next, the data validation for the simulation was done, the current situation of the building was validated with real measured data. After that, the considered adaptations to enable lower temperature in the selected building were modelled as different scenarios. Finally, the outputs of the simulated scenarios were analysed, and the results are presented.

- **Discussion and conclusions**: the evaluation of the outcomes of the research is presented at last.

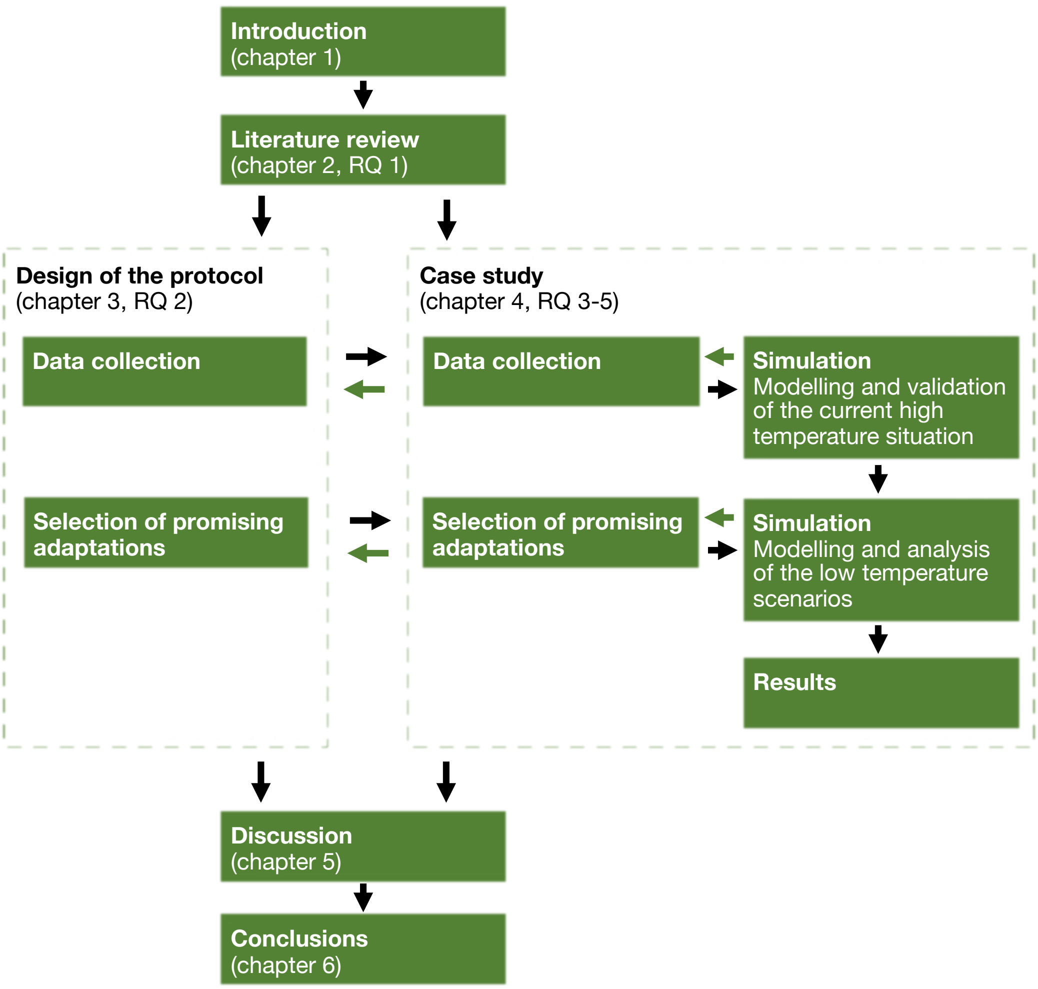

Figure 1. Research flow diagram. The methodology followed in the different steps of the research is presented in the diagram. The number of the chapter that deals with the specific steps is included. The order of the steps is indicated with arrows. The green arrows are feedback loops within the research.

2. LITERATURE REVIEW

Thermal energy systems used to be based on fossil fuels as the energy source and designed to work at high temperatures in the distribution network. For example, in The Netherlands, district heating networks heavily rely on gas and design operating temperatures are usually 90 and 70ºC for the supply and return temperatures respectively (Ir. K.F. Haak, 2013). The problems with conventional sources are their scarcity and the damaging effects to the environment. Therefore, it becomes imperative to transition to other energy sources, more renewable and sustainable, such as biomass, waste heat and geothermal energy. The change in primary energy sources means the whole system will have to adapt. There will be a decrease in the operating temperatures, because a system operating at lower temperatures is more efficient and because renewable energy sources usually provide heat at lower temperatures (H.Lund et al., 2010). The thermal comfort to the end-users, the occupants of the buildings, must not be compromised in the transition to lower temperature heating. There is uncertainty about which adaptations at building level are possible to ensure thermal comfort when the supply temperature drops, especially in existing buildings, originally designed for high operating temperatures (Lund et al., 2018).

The aim of this literature review is to provide an overview of the existing knowledge, by categorising the possible adaptations at building level to enable lower temperatures in heating networks. An overview of the steps followed is shown below in Figure 2. First, in section 2.1, the search terms and general definitions are given. Section 2.2 provides an overview of the available research on the topic. In section 2.3, a categorisation of the possible adaptations at building level to enable lower temperature heating is presented, and the literature is reviewed per category. Finally, in 2.4, the consulted literature can be found, and in 2.5, the conclusions of the review can be read.

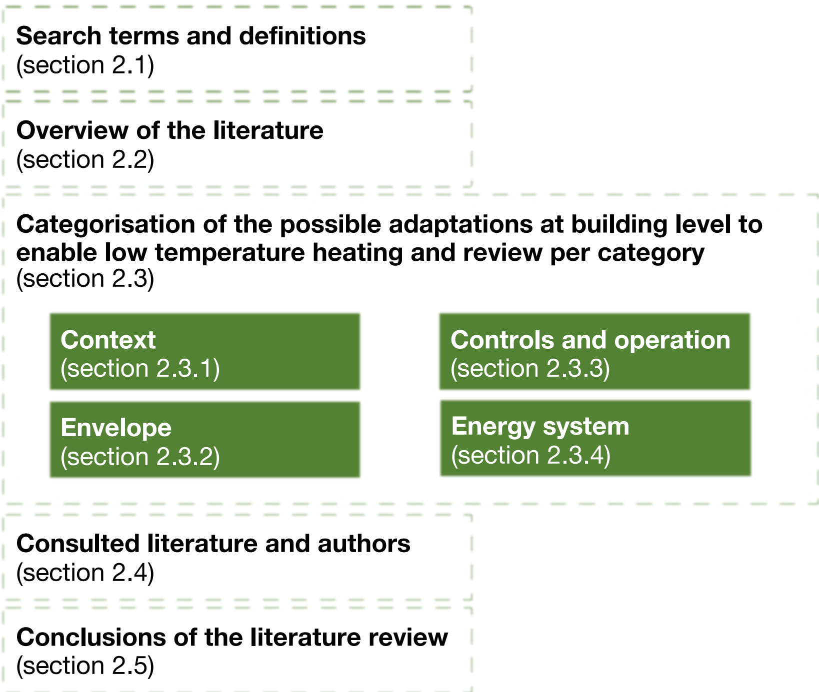

Figure 2. Overview of chapter 2. Literature review.

2.1. Search terms and definitions

Two initial search terms were defined, namely low temperature heating systems and adaptations of buildings. This study deals with analysing how a lower temperature in the distribution network will affect the buildings connected to it and their capacity to be heated up to a certain level of comfort. Literature covering one of the topics alone, regarding for example district heating systems at the conversion level or modernisation of buildings with the sole goal of saving energy, are not considered. More restrictive terms are however included at the building level, since there are studies that deal with some specific building component. Restrictive search terms included, among others, space heating, thermal energy storage and insulation measurements. In Table 1, the various keywords used in literature are gathered, together with the restrictive search terms. Even though this research is embedded in a project where temperature will go from high to medium temperature heating, the search is done for low temperature also, since medium temperatures are share the same focus: decreasing the operating temperatures.

Table 1. Literature review search terms.

Heating network	Building system	
	General terms	Restrictive terms
Low temperature heating	Adaptations	Building envelope
Medium temperature heating	Renovations	(Façade) insulation
Lower temperature heating	Retrofit	Smart controls
Low Temperature District Heating (LTDH)	Refurbishment	Thermal energy storage
4th Generation District Heating (4GDH)	Thermal modernisation	Passive storage
	Adaptations	Space heating
	Measures	Emission systems
		(Hydraulic) radiators

A few general definitions about the topic are introduced. **District heating (DH) systems** are defined by Kljajic et al. (2018) as

> *the heating system which supplies hot water or steam to the building thermal system from a heat generation system outside the building. The district heating system transmits heat through networks to a number of remote buildings. Ideally it is an energy infrastructure capable of integrating locally accessible shallow geothermal energy sources as well as clean and efficient energy technology into the building sector, delivering a year-round low-cost heating solution.*

The definition of **Low temperature district heating (LTDH)** varies, Tunzi et al. (2016) define it as

> *a system operating with supply temperature of 50-55ºC and return of 25-30ºC with the capability of increasing supply to 60-70ºC and return of 40ºC when necessary according to heat demand.*

4th generation district heating (4GDH) is a wider concept, defined by Lund et al. (2018) as

> *[a system that involves] balancing the energy supply with energy conservation and thus meeting the challenge of supplying increasingly more energy efficient buildings with space heating (SH) and domestic hot water (DHW), while reducing losses in district heating (DH) grids. Furthermore, 4GDH involves strategic and innovative planning and the integration of DH into the operation of smart energy systems.*

Based on the design temperatures, district heating networks are classified as in the table below. The classification is not strict and varies from different sources in literature, but it serves as an indication for the supply and return temperatures.

Table 2. Classification of district heating networks. Sources: (Dalla Rosa et al., 2012; Lund et al., 2014; Tunzi et al., 2018).

Type of district heating network	Supply / return temperatures (ºC)
High Temperature District Heating (HTDH)	130-90 / 70
Medium Temperature District Heating (MTDH)	80-55 / 45-40
Low Temperature District Heating (LTDH)	55-50 / 35-25
Ultra Low Temperature District Heating (ULTDH)	35 / 25

2.2. Overview of the literature

2.2.1. Review articles

The research topic has only been in the spotlight for a few years, so few review articles can be found. There are researchers who conduct a case study and also provide a review section in their papers.

In December 2018, present a complete review on the status of 4GDH. They identify five main elements of a 4GDH system, with its coupled abilities.

- Building systems: this element refers to the building level of a thermal energy system. It will need to have the ability to operate existing, renovated and new buildings with low temperature DH for space heating and DHW.
- Distribution systems: distribute heat in networks with low heat losses.
- Heat sources: recycle from low temperature sources and integrate renewable heat sources.
- Smart energy systems: through smart controls and operation, the heating network will be able to integrate fluctuating renewable energy sources and energy conservation.
- Planning and implementation: ensure sustainable planning, cost and incentive structures and strategic investments that lead to the development of future sustainable energy systems.

Though not too extensively, they collect the main research findings of the building systems, which is the focus of this study.

Schmidt (2018) and Schmidt et al. (2017) present and discuss the outputs of an IEA report on LTDH technologies. Space Heating (SH) control to ensure the design cooling (minimal temperature difference desired between the supply and return temperatures) is stressed to be a main factor in network performance. This means that measures should be installed to achieve the desired difference between supply and return temperatures for an efficient district heating system. Temperature and flow rate control of water through the emission system, mainly radiators, are encouraged to be studied further.

Jangsten et al. (2017) build up precisely on the aforementioned knowledge gap and collect literature available on previous studies at the same time as they monitor the temperatures in and out of radiators of a selected group of buildings. They find the difficulty of LT heating lies on achieving the desired return temperature. On top of smart control solutions, they suggest an increase in radiator surface.

Ovchinnikov et al. (2017) perform a comparative review of the literature about LT developments for SH. Tables presented specify simulation tools, emission system type and temperatures, envelope renovation and primary energy consumption of case studies regarding this topic. The conclusions are that low temperature heating can provide the same level of thermal comfort in existing buildings in case of minimal retrofitting of the envelope.

Paiho et al. (2019) connect both the elements planning and implementation and building systems in their review about procedures for energy refurbishment of buildings. To efficiently renovate building systems in relation to the DH system, a district level approach is necessary, since renovations alter the balance of the DH system significantly. That is why in the procedure developed during their project, two parts are included in their feasibility study step: energy performance of individual buildings and district scale potentials and solutions assessment. Municipalities are key decision-makers that will benefit from the availability of tools and methods with the following characteristics: uncomplicated gathering and input of the systems characteristics, combinations of solutions for DH and electricity network and attractive visual results. The inclusion of even rough estimates of unit costs for the analysed scenarios can further facilitate decisions.

2.2.2. Case study articles

A case study approach is the most common in the recent scientific research on this topic. Either simulations or practical tests are conducted. Simulations refer to modelling and dynamic calculations of the thermal performance of a building in a simulation tool and practical tests are physical adaptations made to a building to measure its thermal performance under low temperature heating. They are necessary to optimise the adaptation activities (Nagy et al., 2014). Cost analysis and environmental assessments are included in a few cases, as a way of facilitating the decision about which adaptation should be implemented in the case under study.

Simulations

Simulation tools that can model the thermal performance of buildings are used, such as EnergyPlus, IDA ICE, MATLAB, CityGML and TRNSYS. In some studies, a discrepancy between calculated performance and actual energy consumption of buildings is reported. The importance of the validation of the data with real measures of the heating demand is pinpointed (Francisco Pinto & Carrilho da Graça, 2018; Nagy et al., 2014; Tunzi et al., 2016). For realistic results in simulations, (D. Østergaard & Svendsen, 2017), (Lidberg et al., 2017) and (Brand & Svendsen, 2013) choose an operative temperature a bit higher than the usual indoor winter setpoint of 20°C. 21°C or 22°C prove to correlate better with occupants' behaviour and system control setpoints.

Practical tests

Current knowledge is mainly based on simulations. There are little measurements available on systems' temperatures in actual buildings and how the system design affects those temperatures (D. S. Østergaard & Svendsen, 2018). This poses a challenge when gathering data for validation of a simulation model. It also makes clear that there is a knowledge gap in experimental data. However, based on the available studies, there is a margin to reduce the operating temperature in existing buildings, since the experiments show that the original energy system in often over-dimensioned (D. S. Østergaard & Svendsen, 2018).

2.3. Categorisation of building system components relevant to enable low temperature heating and review per category

A categorisation of the relevant building components to adapt existing buildings to lower temperatures in the heating network was developed. The main findings from case study articles consulted are summarised and described within this categorisation, which is presented below.

CONTEXT

Building

Occupants

ENVELOPE

Walls, roof, ceiling, floor

Windows

Infiltration/Air tightness

CONTROLS AND OPERATION

Operating temperatures

Mass flow

Peak power

Schedules and room temperature setpoints

ENERGY SYSTEM

Ventilation

Emission heating system

DHW

Storage

Conversion/Substation

Figure 3. Categorisation of building system components relevant to enable low temperature heating.

2.3.1. Context

It is useful to have an idea of the context surrounding the building and its occupants. Year of construction, type of building and location are relevant information to consider when assessing the adaptation of the building. Occupants' schedules and behaviour ought to be taken into account too.

Building

Current research follows a building by building approach, individual assessments are done to optimise the heating system performance. It can be expected that when more results are available, extrapolations can be drawn and retrofit actions will be more standardised (Nagy et al., 2014).

The architecture is typical northern European, since locations are Denmark, Finland and Sweden, since this is where most recent studies took place (for a location overview, refer to Table 3 in page 20).

Since the research deals with building renovations, the objects of study are existing buildings, typically dating from 1850s to the late 1990s. The fact that a building has undergone some kind of refurbishment of the envelope or the heating system is key information. The improvement of the insulation or the radiators for example can lead to the system being over-dimensioned compared to its original design (D. S. Østergaard & Svendsen, 2016).

Most case studies simulate or measure the performance of thermal energy systems in residential buildings, either single-family houses or multi-story apartment blocks. Fewer studies include non-residential buildings. (Tunzi et al., 2018) look into improving thermal performance of different types of buildings in a farmland, mixing old and new built. (Mishra et al., 2019) investigate the management on the demand side of a university building, a multi-story office and teaching space. The concrete findings of these two studies are discussed in controls and operation. Apartment blocks and faculty buildings can be comparable in volume and centralised heating systems. Nevertheless, there are some significant differences to take into account. Room partitions can smaller in residential buildings, if compared to big laboratories or conference rooms. Occupants' schedules and behaviours differ; in apartments, occupants may have more freedom to change heating settings; faculty buildings are usually empty at nights. The share of DHW in heat consumption is higher in residential buildings.

Occupants

Internal gains are dependent on occupants' number and schedules (apart from electrical appliances and lighting), which is something to take into account for energy flow calculations (D. Østergaard & Svendsen, 2017). Occupants' accessibility to system operational settings and to open the windows and doors is of great importance, because occupants' behaviour can affect heating setpoints and natural ventilation. During practical tests, controls can perform poorly due to end-users' settings. Maintaining a good line of communication with the occupants of the buildings and offering technical support can prove useful. Malfunctioning of heating elements can be detected faster through end-user and supplier exchange of information (Tunzi et al., 2018).

2.3.2. Envelope

The envelope of a building is the homologous of the skin of a body, the outer layer of a system that is in contact with the outside. Heat transfers through the envelope, therefore a good insulation of the façade (external walls and windows), roof, ceilings and floors will prevent heat loss to the environment. Refurbishment of a buildings' envelope improves insulation, minimising heat loss through the buildings' envelope and leading to a decrease in heating demand. There is a high focus on energy savings in research, while few studies investigate how insulation measures can allow to lower the temperature in the heating network and thereby maximising the efficiency.

Walls, roof, ceilings and floors. Windows

There is a big potential for LTDH to be applied in existing buildings, recent literature shows that thermal comfort can be guaranteed when lowering the temperatures of operation even when minimal retrofit actions are taken.

(D. S. Østergaard & Svendsen, 2016) present tables with U-values for original, maintenance and renovation scenarios for different time periods. Renovations refer to roof, floor, wall and windows. General maintenance of Danish houses was found to decrease the U-value of the roof (from around 2 to under 1 W/m^{2}K) and windows (from 4 to under 3 W/m^{2}K). Thorough renovation of roof, floor and walls means a U-value of under 0.5 W/m^{2}K in almost all houses; which were divided depending on the time period they were constructed. For windows, U-value becomes lower than 1.5 W/m^{2}K after renovation. Upon their theoretical study they conclude that renovations in old houses cause radiator systems to be over-dimensioned by 20-50% compared to the original design. And even when only general maintenance was considered, there is a margin to lower the supply temperature.

(Brand & Svendsen, 2013) results show that without any renovations, the single-family houses studied can be heated with a DH mean supply temperature of 50ºC for 59% of the year. And after window replacement and attic insulation temperature stayed under 50ºC for 96.6%. These two measures proved to be the most effective: windows in the north and west façade were replaced with triple-glazing, reducing by 21% the heating demand and ceiling insulation lead to a 18% reduction.

(Nagy et al., 2014) plot possible supply temperature of a system as a function of typical retrofit measures. Findings are that supply temperature can be lowered, within comfort limits, from the original 55ºC to 45ºC in the baseline and first retrofit stage (window replacement and plaster insulation of the north, east and south external walls). When insulation is improved in the second retrofit stage (a thicker aerogel layer in all façades instead of plaster), supply can further decrease to 40ºC.

(Pavičević et al., 2017) include a cost analysis of refurbishment measures at neighbourhood level. They define various scenarios differing in the depth of the refurbishment and other upgrades in the space heating system. When left free to decide, the optimisation model chooses not to refurbish, because in that case heat prices lower compared to the current situation. Opting for renovation leads to similar heat prices than those of the current system. The authors argue that renovation should be taken into account anyway because the systems should be designed for the future heating demand. It is to be expected that envelope components will be changed when they reach the end of their lifetime.

Infiltration/Air tightness

Infiltration heat losses occur due to uncontrolled air leakage across the buildings' envelope. Air tightness of a building is a significant parameter to consider in cold climates and depends on temperature difference between outside and inside, wind conditions, building geometry and integrity of the envelope. Measures to improve the infiltration losses include renovations to the façade, replacement of windows or frames and upgrade of the ventilation system (Francisco Pinto & Carrilho da Graça, 2018).

2.3.3. Controls and operation

Both simulation and practical tests results show that proper system control leads to lower energy consumption and more efficiency.

Three elements are interconnected: operating temperatures (temperature difference between supply and return), mass flow through the radiators and peak power of the radiators (heat is calculated from the peak power delivered during a certain amount of time in the equation).

$$Q = \dot{m} \cdot Cp \cdot \Delta T$$

Equation 1. Q: heat, $\dot{m}$: mass flow, Cp: specific heat, ΔT: temperature difference.

The peak power available is directly related to the operating temperatures and the mass flow rate through the radiators. The flow rate and supply and return temperatures to radiators can be adjusted according to heating demand and radiators' requirements, through thermostatic radiator valves (TRVs). So was the case in the following studies: (D. S. Østergaard & Svendsen, 2018; Schmidt et al., 2017; Tunzi et al., 2016, 2018).

Lastly, the control and optimisation of heating schedules and temperature setpoints are dealt with.

Operating temperatures

The operating temperatures refer to the supply and return temperature between the heating network and the building systems. The current focus is to lower the temperatures.

(Nagy et al., 2014) study how much the supply temperature can be lowered in relation to the renovation state of a building's envelope (as already mentioned in the Envelope section). Findings are that supply temperature can be lowered, within comfort limits, from the original 55ºC to 45ºC in the baseline and first retrofit stage. When insulation is improved in the second retrofit stage, supply can further decrease to 40ºC.

(D. S. Østergaard & Svendsen, 2016) simulate Danish residential houses with original supply and return temperatures of 90/70ºC respectively. They found out that during most of the year thermal comfort can be provided at 55/35ºC and even below 50ºC when renovations are done. In a later practical test, (D. S. Østergaard & Svendsen, 2018) the results are validated. Temperatures of 55/30ºC were achieved when a few practical issues regarding occupants' behaviour, heating system design and system control were identified.

(Jangsten et al., 2017) point out the lack of statistics on supply and return temperatures of radiators in DHS. After conducting a practical test by monitoring radiator systems for a year, it was concluded that existing radiators in Swedish multi-family buildings can operate at typical LTDH supply temperatures. The challenge lies on getting the return temperature to be low enough for the DH systems to be efficient. In (Tunzi et al., 2016) study, a target return temperature of 25ºC is set and achieved through proper control of supply temperature, adjusting to demand and radiator's capacities.

For further consultation of case study results on operating temperatures, (Ovchinnikov et al., 2017) present in a review paper, a thorough overview.

Mass flow

It is of importance to know if there is a margin to lower the mass flow in the distribution lines of the heating system of the building. Lowering the mass flow increases the temperature difference between supply and return, which can be beneficial, because lower return temperatures are desired in order to increase the efficiency of the heat extraction from the water.

System control should set a maximum flow rate that ensures a pre-set return temperature measured by sensors at the radiators' secondary side (Schmidt et al., 2017).

Peak power

For a given supply temperature in the heating network, a decrease in the mass flow leads to a decrease in the power output that the system can deliver. Therefore, the understanding of how much the peak power can be lowered without compromising the thermal comfort of the building will give an indication of what the lowest achievable return temperature is.

It is often the case that the design temperature of the heating systems is that of the coldest day of the year, following the worst-case scenario design approach. This is an extreme condition, for the main part of the year the building will demand less energy and peak power than it was designed for. Which means that the capacity of the system is usually bigger than necessary for most part of the year. Sometimes systems are even over-dimensioned, size is more than enough for the coldest day of the year. This is especially the case if renovations have happened, decreasing the energy demand of the building (Lund et al., 2018).

(Brand & Svendsen, 2013) have looked into lowering operating temperatures of a DH system in order to make the over-dimensioned system more efficient. They analysed the reduction achieved after light building refurbishment and observed a 25% reduction in heat demand (kWh) and 20% reduction in peak heat output (kW). When updating a heating system, both the reduction in energy and power installed should be looked into to optimise energy savings, environmental impact and investment costs.

(Turski & Sekret, 2018) analyse to which extent peak heat output can be reduced. One alternative option is to control the supply temperature of the DH network and use the thermal mass of the buildings in the network to store heat. The heat stored can be used to compensate for the source heat output reduction. A maximum possible reduction of 14.8% was obtained with compensating periods of 1-2 days depending on the weather conditions.

(Difs et al., 2010) validate a software program that manages the heat stored in a building aiming to reduce peak load demand. They refer to this type of measure as heat load control. It results in a 7% annual reduction of the heat demand. No data is given about the consequent possibility to reduce the peak power.

Schedules and room temperature setpoints

(Mishra et al., 2019) state that demand side management (DSM) is not only interesting in electricity grids, but also in heat grids. They altered the inlet temperature of radiators and supply air temperature from air handling units based on dynamic pricing information. The measured temperatures in most of the rooms infrequently ventured out of the defined comfort limits. This would imply that the building's thermal mass, along with the price-based implementation of the algorithms, present avenues of energy flexibility.

(Foteinaki et al., 2018) experiment with using building management system controls to modulate the schedules and room temperature setpoint of the heating system in buildings and in that way storing heat in the thermal mass of the building. They play with 24ºC setpoint during storing periods and 20ºC when heat supply is curtailed or interrupted, and heat is released from the walls. More information of the optimisation of systems controls and operation for passive storage is found in the Storage category.

(Nagy et al., 2014) A comfort limit of 19.5ºC is stablished and a graph is presented with discomfort hours at different temperatures for baseline and two retrofit stages.

2.3.4. Energy system

Energy system of a building is composed by the physical installations for ventilation, (emission) heating system, domestic hot water (DHW) and storage. Different parts can be identified: the centralised machines that can usually be found in the basement of the building, the distribution lines and the decentralised emission devices, such as ventilation fans or emission heating radiators.

Ventilation system

Ventilation refers to air from the outside flowing into and out of the building through systems explicitly installed for this purpose. There are mainly three types of ventilation systems: natural through windows and grilles; mechanical supply or exhaust, for which a ventilator is needed; and mechanical ventilation with heat recovery (MVHR) (Bueren, 2012, pp. 113–174).

Energy flows through ventilation are calculated or estimated in most simulations. Some case studies (Francisco Pinto & Carrilho da Graça, 2018; Lidberg et al., 2017; Mishra et al., 2019) upgrade the ventilation system to mechanical and even MVHR to improve efficiency of the heating system. MVHR is particularly significant because it is part of the emission system of the building.

Emission heating system

(Jangsten et al., 2017) state that design emission system temperatures do not correlate well with operating temperatures of current space heating systems. This means that emission systems in existing buildings tend to be over-dimensioned due to safety margin or worst-case scenario design or due to building renovations over the years. The efficiency of the SH systems in existing buildings, and thus also that of the DH network they are connected to, is eligible to be improved. (D. S. Østergaard & Svendsen, 2016) calculated heating systems can be over-dimensioned by 20-50% when houses have gone through reasonable energy renovations.

There exist different types of heat emitters, designed to operate at different supply and return temperatures (Hesaraki et al., 2015; Ovchinnikov et al., 2017; Tunzi et al., 2016).

- The most commonly found in existing buildings are conventional panel radiators with one or more plates and none or few internal convection fins. Their design temperature is high (95/70ºC).

- The current tendency is to increase the number of plates and fins to favour convection and make it possible to operate at lower temperatures while keeping the heat output. This type of radiators is often simply referred to as low-temperature radiators. Ventilators can also be added to force convection in the so-called forced-convection radiators. Two types can be mentioned: ventilation, which combines ventilation supply system with heat emission system; and add-on fan, which incorporates an electrical fan. These various types of emission systems are designed for medium (55/45-40ºC) and low temperature (45/35-25ºC) heating.

- Modern systems install natural convection heat emitters, which are suitable for the lowest temperatures operation in the market (35/25ºC). It is the case of flat panel radiators: under-floor heating, ceiling heating and wall heating.

The power output of radiators is equal to the heat transfer coefficient multiplied by the surface area and the logarithmic temperature difference between supply and return. LTDH systems lower the supply temperature of the heating system, thus achieving a lower temperature difference. In order to maintain the power output of the system, either the heat transfer coefficient or the surface area of the heating system need to be improved (Ovchinnikov et al., 2017). There are several actions that may be taken when adapting existing heating systems to LTDH: change in radiator type, installing those more suitable for low temperature operation; installing more radiators or controlling the operation of the system.

(D. S. Østergaard & Svendsen, 2018) carry out a practical study in a building with different types of heat emitters (plane, panel, column and convector) and identify a problem common to other researchers (Jangsten et al., 2017; Schmidt et al., 2017; Tunzi et al., 2016): is it difficult to achieve the desired return temperature in the system. The reason is either that the power is not enough, if the supply and return temperatures are lowered to the desired point, or an imperfect hydraulic balancing and control of the TRVs, meaning that the speed of the water through the pipes is not optimal. They propose the replacement of critical malfunction valves and furthermore the development of new electronic type of valves; in order to better control the mass flow rate through the radiators.

Big attention has been made to emission systems in the buildings, a big share of existing buildings uses radiators. Changing ‘critical’ radiators, installing more or different type of radiators or improving valves operation play an important role in optimising the system. Even pipes configuration can be relevant, this is a point beyond the scope of this study. In general, research show that it is possible to lower operating temperatures of existing buildings by updating the heating system components. Efficient standardised strategies are yet to be found by performing simulations and practical tests in a more case to case basis for the time being. Flat panel radiator systems are commonly installed in new buildings, which makes them already suitable for lower temperature DH.

DHW

(Lund et al., 2018) explain requirements and challenges in the supply of domestic hot water with LTDH. Network requirement for DHW is a temperature higher than 55ºC for security measures, to ensure safety from Legionella contamination. SH and DHW networks usually share circulation lines, which is why when the supply temperature of the heating systems is below 55ºC, an additional boosting system is needed for the DHW circuit.

(Schmidt et al., 2017) also identify risk of Legionella at low temperatures as a barrier. Aiming for energy efficiency of the system, apart from hygiene and comfort; two DHW units are mainly used in LTDH, namely instantaneous heat exchanger and DH storage tank. The former has the lowest risk of Legionella. An alternative is having completely separate networks for SH and DHW, in which case the DHW unit can be an electrical boiler. Further analysis of literature can focus on what the most efficient strategy is regarding the connection of SH and DHW.

Storage

Physical storage, in forms of batteries for example, are not considered during this literature review. Passive storage of accumulated heat in the thermal mass of the building through system controls and operation strategies is the studied option.

(Foteinaki et al., 2018) conclude from their simulation study that buildings are robust and can be independent of heat supply for periods of 20-48 hours. Energy flexibility of buildings is then increased by using the thermal mass of the building as heat storage. Though this measure works when renovations in the heating system and envelope have been done and therefore heating demand of the building is low. It is also mostly significant when controlled and aggregated at district level.

(Mishra et al., 2019) analyse the effect of demand response (DR) actions to minimise price and energy use. Storing energy in a building's thermal mass proved to significantly increase the energy flexibility while maintaining the thermal comfort for the occupants.

(Turski & Sekret, 2018) propose passive thermal storage as an alternative solution that does not require expansion of the heating system to reduce the heat output of a DH system and save energy. Heat is stored by increasing the supply temperature when excess heat is available from renewable sources or when extreme low outdoor temperatures are forecasted. Periods of 1 or 2 days are considered for charging and discharging of heat store.

Conversion/substation

At a central level in the building, heat pump, heat exchangers and electrical boilers can be part of the heating systems. They can be connected to the ventilation system, emission system and DHW. They can also be used as storage. Heat exchangers can also separate the district heating network from the building distribution lines, in which case the supply and return temperatures can be referred to as primary or secondary, for the network and the building sides respectively. The analysis of adaptations regarding these centralised elements is beyond the scope of this literature study; future research is encouraged though.

2.4. Consulted literature and authors

In the table presented below, an overview is given of the consulted literature for this literature review. The topics from the category's division touched by the articles are indicated by a grey background. It is interesting to see the amount of papers which touch all different categories. The author and date of the article allow the reader to easily find the cited paper in the BIBLIOGRAPHY section of the thesis. The country where the study was done is also included in the table in order to provide better context about the locations because weather conditions are a boundary to the applicability of the observed results.

The work of authors like (D. S. Østergaard & Svendsen) and (Nagy et al.) are a reference to this research because the approach and goals of the research are very much in line. They conduct both simulations and practical tests in existing buildings and investigate the effect of different renovations in the envelope and energy system in the supply and return temperatures. (D. S. Østergaard & Svendsen) are also pioneers in not only studying the relation between heat demand and lower operating temperatures, but they connect it to the peak power demand. (Mishra et al.) and (Tunzi, Boukhanouf, Li, Svendsen, & Ianakiev) present very interesting research in non-residential buildings and the controls and operation adaptations. (Foteinaki et al.) are also a reference in this type of adaptations; in their case, both single family and multi-story apartment blocks are studied.

Table 3. Bibliography overview per category. The topics from the category's division touched by the articles are indicated by a grey background.

BIBLIOGRAPHY OVERVIEW			ENVELOPE						CONTROLS AND OPERATION				ENERGY SYSTEM	
Author	Date	Country	General	Windows	Roof Ceiling	Floor	Walls	Infiltration	Operating T	Mass flow	Peak power	Schedules Room T	Ventilation	Emission system
Brand	October 10, 2013	Denmark		■	■			■	■	■	■			■
Difs	August 1, 2010	Sweden			■						■	■		
Foteinaki	December 1, 2018	Denmark		■	■	■	■	■				■	■	■
Francisco Pinto	April 1, 2018	The Netherlands	■	■	■	■	■	■					■	
Hesaraki	December 15, 2015	Sweden Denmark							■				■	■
Himpe	November 1, 2015	Belgium												
Jangsten	October 15, 2017	Sweden	■						■					■
Kamaruzzaman	January 15, 2019	Malaysia	■						■					
Lidberg	May 1, 2017	Sweden	■					■	■				■	■
Lund	December 1, 2018	-												
Mishra	February 21, 2019	Finland		■	■	■	■		■			■	■	■
Mlecnik	2018	The Netherlands												
Nagy	October 15, 2014	Switzerland	■	■			■	■	■				■	■
Nord	May 15, 2018	Norway												■
Østergaard	June 1, 2017	Denmark	■	■	■	■	■	■	■				■	■
Østergaard	September 15, 2018	Denmark	■	■	■	■	■	■	■	■		■	■	■
Østergaard	August 15, 2016	Denmark	■	■	■	■	■		■	■	■			■
Ovchinnikov	February 1, 2017	Russia	■						■					■
Paiho	April 1, 2019	Finland	■	■			■		■					
Pavičević	October 15, 2017	Croatia		■			■		■					
Schmidt	June 1, 2017	-							■	■		■		■
Tunzi	October 15, 2016	Denmark UK	■						■			■		■
Tunzi	January 1, 2018	Denmark UK		■	■	■	■	■	■	■		■	■	■
Turski	November 15, 2018	Poland									■			

2.5. Conclusions of the literature review

There are few review papers about the adaptation of existing buildings to lower temperature heating, these present it however as an emerging topic with a big potential to increase the efficiency and sustainability in heating networks. There is for now a lack of standardised procedures and experimental base.

Even though the quantity of case studies is not high, the findings of the available research are consistent. Simulations and practical tests show similar results; therefore, simulations of individual buildings seem to be a realistic indication of the thermal performance of the buildings. For a good correlation, practical tests recommend the validation with measured real heat demand and a room temperature setpoint around 21-22ºC.

A categorisation of the different components of the building systems and their implication in lowering the operating temperature was done in order to provide an overview of the possible adaptations and facilitate further research.

Most research was done in northern Europe, in residential existing buildings dating from 1850s to the late 1990s. Only a few studies were found about non-residential buildings. Occupants' accessibility to system operational settings and to open the windows and doors is can affect heating setpoints and natural ventilation, so a line of communication with the end-users during practical tests is encouraged.

Insulation of the roof and external walls and replacement of windows are common retrofit actions, that decrease the heat loss and infiltration through the envelope. Minimal renovations leading to a U-value under

1 W/m^{2}K for walls and roof and under 2 W/m^{2}K for windows usually cause heating systems to be over-dimensioned by 20-50% compared to the original design. And thus, operating temperatures can be lowered.

Various studies show that it is possible to lower the supply temperature from the original 90ºC to 60-40ºC and the return temperature from 70ºC to 35-25ºC. The challenge lies in getting the return temperature to be low enough for the district heating systems to be efficient. The return temperature depends on the peak power needed for thermal comfort, the supply temperature considered and the mass flow through the radiators. Proper control of the hydraulic balance with thermostatic radiator valves (TRVs) can help optimize the return temperature.

There are few studies available which focus on optimising the temperature setpoints and schedules of the heating system in the buildings, both residential and non-residential buildings. They show positive results by adjusting schedules and room temperature setpoints and in that way storing heat in the thermal mass of the building (passive storage). This measure was only successful when minimal renovations had been done the buildings' envelope or energy system.

Renovations in the ventilation system, especially the installation of mechanical ventilation with heat recovery (MVHR) improve the efficiency of the energy system and can add to the over-dimensioning of the heating system. Case studies include different ventilation options in their renovation scenarios; however, no specific analysis was found on the relation between the upgrading of the ventilation and a building's flexibility to lower the operating temperatures.

Different types of emission heating systems exist, designed to operate at different supply and return temperatures. Most commonly, conventional panel radiators are found in existing buildings, designed for high temperatures (95/70ºC). Possible adaptations are installing more radiators or installing low temperature radiators, which give more power output. However, since the heating systems tend to be over-dimensioned, the required peak power in the building ought to be assessed in the first place.

To sum up, recent research shows that it is possible to lower the operating temperatures in heating networks by adapting existing buildings. In old, poorly insulated buildings, minimal renovations in the buildings' envelope are crucial (and often sufficient) to enable low temperature heating. When heat losses are small, smart settings in the building management system to use the thermal mass of the building as storage prove successful to lower the supply temperature further. Obtaining a low the return temperature to achieve the desired efficiency in the system is a challenge; required peak power, supply temperature considered and mass flow through the radiators can be optimized.

The categorization carried out during this literature review is useful to provide an up-to-date overview on the topic and furthermore, it facilitates the first stages of a case study, by providing an inventory of the main elements for the data collection.

3. DATA COLLECTION PROTOCOL

3.1. Overview

One of the knowledge gaps identified in the literature review is the lack of standardised approaches to adapt existing buildings to lower temperature heating. A proposition was made to develop a protocol to collect data and give an indication of promising adaptations and therefore facilitate further research.

The protocol aims to facilitate the process of assessment of necessary changes in an existing building by providing an overview of what data needs to be collected and where that information can be found. It also highlights the components that most probably will play a role, focusing the project during a simulation or practical test in a later stage. The full version of the protocol consists of an interactive Microsoft Excel file that can be filled in by the researcher in question. In Figure 4, the overview of the data protocol can be seen.

DATA COLLECTION PROTOCOL

Adapting existing buildings to a lower temperature in the heating network. A protocol for data collection and selection of promising adaptations

This protocol can be used to guide the first steps of a case study regarding the adaptation of an existing building to lower temperature heating. Please follow the steps below

1. SELECT APPROACH OF THE PROJECT: SIMULATION OR PRACTICAL TEST

2. SPECIFY THE ORIGINAL AND NEW OPERATING TEMPERATURES IN THE HEATING NETWORK

3. SELECT THE BUILDING

4. IDENTIFY THE DATA SOURCES

5. COLLECT THE DATA OF THE SELECTED BUILDING

6. SELECT PROMISING ADAPTATIONS

Read the list of promising adaptations proposed and the general considerations in which the protocol in based

LIST OF PROMISING ADAPTATIONS

GENERAL CONSIDERATIONS

Figure 4. Data collection protocol. Overview.

3.2. Step-by-step description

Below, the screenshots for the six steps to be followed are presented.

1. SELECT APPROACH OF THE PROJECT: SIMULATION OR PRACTICAL TEST

This tool is meant to help you in the first stages of your research project. It is designed for its use in a case study, specially for a simulation or a practical test. It has not yet been tested during a practical test. Other purposes might also benefit from its use, however no results can be guarateed.

What kind of project are you going to conduct?

		Select type
Case-study	**Simulation** Modelling and dynamic calculations of the thermal performance of a building in a simulation tool	
	Practical test Physical adaptation made to a building to measure its thermal performance under low temperature heating	
		Write down which one
Other research or project approach		

2. SPECIFY THE ORIGINAL AND NEW OPERATING TEMPERATURES IN THE HEATING NETWORK

What are the original design temperatures of the heating network in question? What are the new desired temperatures in the network?

		Note them down
Supply temperature (ºC)	Original	
	New	
Return temperature (ºC)	Original	
	New	

3. SELECT THE BUILDING

In this step you select the building to be studied. This protocol works for one building at a time. Here are the criteria to find the building that will probably be the limiting factor to lower the temperature. You might need to collect some data before you can decide which building to focus on, so the decision might be made during the first stages of the data collection.

Connection to the heating network

Identify all buildings connected to the same heating network. The supply temperature for all those buildings will be determined by the building that demands the highest temperature.

Data availability

Ideally, the building energy performance has been monitored and it is possible to compare measured supply temperature and heat demand of the buildings in the cluster. In case you will conduct a simulation, this information will be essential to validate your inputs, which can also be taken into account for building selection.

Context

Older buildings tend to demand the highest temperatures. Renovations both in the envelope and heating system usually lower the required temperature. Find out when the different buildings where built and whether they have been renovated. Real estate plans regarding the area should also be taken into account. Are there plans to renovate some buildings in the near future? Are there plans to demolish a building? You don't want to study how to adapt a building that will not be there when you get there.

Envelope insulation

Poorly insulated buildings have a higher heat loss, which means the heat demand is high. This usually means that the peak demand and the temperature supply will also be high. Single glazing of the windows and lack of insulation layers in theexternal walls might indicate that there are significant heat losses through the envelope.

Heating system

The heat emmission system has a big influence on the supply temperature demand. Single-plate radiators are not designed for low temperatures, radiators with more plates and fins will perform better. Panel radiators or underfloor heating, will have a better chance to work well at low temperatures. Take also a look at the ventilation system. Mechanical ventilation, specially with heat recovery, will have a big influence on lowering the required temperature and energy demand.

4. IDENTIFY THE DATA SOURCES

In this step the sources for the data collection will be identified. You need to know what kind of information you are looking for (see short description below: What am I looking for?). It is time then to find the involved stakeholders and building management systems (BMS) in your project. Below, a list of typical data sources is presented. Note that the information can be found in more than one source and for different projects, the same type of information might be held by different stakeholders. You may also take a look at the next step, where a complete list of data to gather is given.

What am I looking for?

Building surfaces: geometry and materials

Building energy balance regimes, schedules and settings

Weather data

Measured data over a period of time: heat demand, supply and return temperatures

Where can I find it?	Write down their names
Building real estate agency	
Centralised heat plant	
Previous research projects companies	
Building management system (BMS)	
Energy monitor system	
Meteorological institute	
Field research	
Scientific articles and books	
Simulation tool	

5. COLLECT THE DATA OF THE SELECTED BUILDING

Now you can go ahead and collect the data. Below you find a list with the basic categorisation of building components and relevant information about them. The information might be sub-divided up to three levels or a short description will be shown. This data will be necessary during the next stages of the case study. Please fill in the two colums on the right.

				White: describe the data **Yellow**: choose an option from (yes) or (no or limited) **Blue**: select type	Where did you find this data?
CONTEXT	Level 1	Level 2	Level 3		
Building	Type	Residential	Single-family house		
			Multi-story apartment block		
		Non-residential			
	Location				
	Year of construction				
	Year of refurbishment				
Occupants	Accessibility to system operational settings				
	Accessibility to open windows and doors				
	Internal gains	Number of people			
		Schedules			
		Electrical appliances			
		Lighting			

ENVELOPE					
Windows	Type	Single glazing			
		Double glazing			
		Triple glazing			
	Geometry	Area, orientation, frame to window ratio			
	U-value (W/m^2K)				
	g-value				
	Insulation	Poor	[1] U-value higher than 3 W/m^2K		
		Sufficient for low temperature	[1] U-value lower than 2 W/m^2K		
Walls, roof, ceiling, floor	Geometry	Length, height and depth, areas of building, orientation and relative location			
	Composition	Materials and thickness of the layers			
	U-value (W/m^2K)				
	R-value				
	Insulation	Poor	Cracks, unsealed frames [1] U-value higher than 1,5 W/m^2K		
		Sufficient for low temperature	No cracks, sealed frames [1] U-value lower than 1 W/m^2K		
Infiltration	Infiltration rate (airchange 1/h)	Difficult to find or calculate, usually taken from literature.			
	High	Old buildings, big cracks and openings in the buildings' envelope	[2] Infiltration rate higher than 0,6 airchange 1/h		
	Low	Well insulated or airtight buildings, no cracks or openings	[2] Infiltration rate higher between 0,15-0,25 airchange 1/h		

Source 1. (D. S. Østergaard & Svendsen, 2016). Source 2. (Lidberg et al., 2017)

CONTROLS AND OPERATION	Description		
Room temperature setpoint	[3] The best option is to find the setpoint and measures in the actual situation. In case that information is not available, a temperature setpoint for the simulations between 21 and 22ºC is an accurate guess. Winter and summer might have a different setpoint.		
Schedule heating system	Get the hourly schedule from the BMS or estimate it if it is not available.		
Temperature setpoint ventilation	Find out whether the ventilation supply to the rooms is pre-heated and to what temperature. This greatly influences the heat balance in the rooms.		
Schedule ventilation system	Get the hourly schedule from the BMS or estimate it if it is not available.		

MEASURED DATA			
Heat demand	The real data measured is the heat supply, which can be regarded as heat demand when there are no significant losses between supply and emission in the rooms. It is usuful to collect data for at least the winter period, or a whole year. Preferably you will have data over multiple years. It is a good way to validate the simulation outputs.		
Supply and return temperature	Even though the building was designed for a specific supply and return temperatures in the network, it doesn't always require the highest temperature to achieve the thermal comfort. Real temperatures required over a period of time can help during the building selection process, data validation and after a practical test to check whether temperature demand decreases after renovation.		

WEATHER DATA			
Average temperatures and solar radiation at the location	You can either use real weather data in the simulation or compare the predicted simulation file with real weather to validate it.		

Source 3. (Brand & Svendsen, 2013)

ENERGY SYSTEM					
Ventilation	Type	Natural			
		Mechanical	Supply		
			Exhaust		
			Supply-exhaust with heat recovery		
			Supply-exhaust with heat recovery and pre-heat air		
	Ventilation rate				
	Heat recovery efficiency				
	Humidity of the air supply				
Emission heating system	Type	Conventional panel radiators. Type (10-100) [4] High design T (95/70ºC)	Single plate		
			Multiple plates		
			No internal convection fins		
			Few internal convection fins		
		Forced convection radiators. [4] Medium (55/45-40ºC) and low design temperature (45/35-25ºC)	Booster		
			Add-on fan		
		Flat panel radiators or underfloor heating. 4 Low design temperature (35/25ºC)	Ceiling heating		
			Wall heating		
			Under floor heating		
	Thechnical specifications of the radiators	Power output			
		Dimentions			
	Number and location of radiators				
DHW production	Connected to space heating (SH)	[5] In the case the two systems are connected, when the supply temperature of the heating systems is below 55ºC, an additional boosting system is needed for the DHW circuit.			
	Seperate from SH				
Storage	Passive storage	Thermal mass of building used as storage			
	Other storage				
Conversion/Substation	Heat pump				
	Heat exchanger				
	Boiler				

Source 4. (Hesaraki et al., 2015; D. S. Østergaard & Svendsen, 2018; Ovchinnikov et al., 2017).

Source 5.(Brand & Svendsen, 2013; D. Østergaard & Svendsen, 2017; Schmidt et al., 2017)

6. SELECT PROMISING ADAPTATIONS

In this step you can select one or more possible adaptations to enable low temperature heating in the selected building. For simulations, it is easier to model multiple alternatives, so you might consider more than one adaptation. In a practical test, it is more common to choose one adaptation.

The first thing to consider is whether your building can operate at lower temperatures without any adaptation, since it is common that heating systems are over-dimensioned. Please read the general considerations for more information.

Possible adaptations
Full list of the possible adaptations ; in black the type of adaptation and in yellow the specific adaptation. The order to follow when considering which adaptation to choose is from the top to the bottom of the list.

Relevant data collected in step 5
Based on what you have filled in, it can be decided which adaptations are the most promising for the case under study. You must adjust the priority of the adaptations based on your case study, such as physical limitations, economic feasibility or convenience of installation.

DECREASE HEAT LOSSES	**ENVELOPE**			
Change windows	**Windows**	Poor	[1] U-value higher than 3 W/m²K	
		Sufficient for low temperature	[1] U-value lower than 2 W/m²K	
Add insulation layer to the walls, ceiling or floor	**Walls, roof, ceiling, floor**	Poor	Cracks, unsealed frames [1] U-value higher than 1,5 W/m²K	
		Sufficient for low temperature	No cracks, sealed frames [1] U-value lower than 1 W/m²K	
	ENERGY SYSTEM			
Install a ventilation system with heat recovery	**Ventilation**	Supply-exhaust with heat recovery		
SMART OPERATION OF THE HEATING SYSTEM	**CONTROLS AND OPERATION**			
Change the temperature setpoints to better match energy availability and decrease the maximum heating power necessary	**Room temperature setpoint**			
	Temperature setpoint ventilation			
Adjust the heating and ventilation weekly and hourly schedules	**Schedule heating system**			
	Schedule ventilation system			
INCREASE THE HEATING POWER AT LOWER TEMPERATURES	**ENERGY SYSTEM**			
Identify and repair malfunctions in the emission heating system				
Install a type of emission heating system designed for lower temperatures Changes can be made locally, by identifying critical radiators or locations where the heating power is not enough and changing those specific devices, or centrally, by improving the whole system.	**Emission heating system**	Conventional panel radiators. Type (10-100) [4] High design T (95/70°C)	Single plate	
			Multiple plates	
			No internal convection fins	
			Few internal convection fins	
		Forced convection radiators. [4] Medium (55/45-40°C) and low design temperature (45/35-25°C)	Booster	
			Add-on fan	
		Flat panel radiators or underfloor heating. 4 Low design temperature (35/25°C)	Ceiling heating	
			Wall heating	
			Under floor heating	
Install a ventilation system with pre-heating of the air supply, either locally or centrally A higher supply temperature of the ventilation in the room reduces the required heat supply from the radiators and thereby the necessary maximum power in the emission heating system. The temperature setpoint of the ventilation can then be optimised as a smart operation adaptation	**Ventilation**	Supply-exhaust with heat recovery and pre-heat air		

3.3. List of promising adaptations

The full list of possible adaptations to enable low temperature heating in existing buildings is presented in Figure 5. For simulations, it is easier to model multiple alternatives, so more than one adaptation might be considered. In a practical test, it is more common to choose one adaptation.

The first thing to consider is whether the building under study can operate at lower temperatures without any adaptation, since it is common that heating systems are over-dimensioned.

The order to follow when considering which adaptation to choose is from the top to the bottom of the list. The priority of the adaptations must be defined and adjusted based on the concrete case study, considering for instance physical limitations, economic feasibility or convenience of installation.

LIST OF PROMISING ADAPTATIONS
DECREASE THE HEAT LOSSES
Change windows
Add insulation layer to the walls, ceiling or floor
Install a ventilation system with heat recovery
SMART OPERATION OF THE HEATING SYSTEM
Change the temperature setpoints to better match energy availability and decrease the maximum heating power necessary
Adjust the heating and ventilation weekly and hourly schedules
INCREASE THE HEATING POWER AT LOWER TEMPERATURES
Identify and repair malfunctions in the emission heating system
Install a type of emission heating system designed for lower temperatures Changes can be made locally, by identifying critical radiators or locations where the heating power is not enough and changing those specific devices, or centrally, by improving the whole system.
Install a ventilation system with pre-heating of the air supply, either locally or centrally A higher supply temperature of the ventilation in the room reduces the required heat supply from the radiators and thereby the necessary maximum power in the emission heating system. The temperature setpoint of the ventilation can then be optimised as a smart operation adaptation

Figure 5. Data collection protocol. Full list of promising adaptations in existing buildings to enable low temperature heating.

3.4. General considerations

The general considerations and difficulties when adapting buildings to lower temperature heating are written below. Please note that these are the same as the conclusions drawn from the literature review performed during this research, since the development of the protocol was derived from it.

GENERAL CONSIDERATIONS	
Review	There are few review papers about the adaptation of existing buildings to lower temperature heating, these present it however as an emerging topic with a big potential to increase the efficiency and sustainability in heating networks. There is for now a lack of standardised procedures and experimental base.
Case studies Simulations and practical tests	Even though the quantity of case studies is not high, the findings of the available research are consistent. Simulations and practical tests show similar results; therefore, simulations of individual buildings seem to be a realistic indication of the thermal performance of the buildings. For a good correlation, practical tests recommend the validation with measured real heat demand and a room temperature setpoint around 21-22ºC.
Categorisation	A categorisation of the different components of the building systems and their implication in lowering the operating temperature was done in order to provide an overview of the possible adaptations and facilitate further research.
Context Building and occupants	Most research was done in north Europe, in residential existing buildings dating from 1850s to the late 1990s. Almost no studies found about non-residential buildings. Occupants' accessibility to system operational settings and to open the windows and doors is can affect heating setpoints and natural ventilation, so a line of communication with the end-users during practical tests is encouraged.
Envelope	Insulation of the roof and external walls and replacement of windows are common retrofit actions, that decrease the heat loss and infiltration through the envelope. Buildings renovations leading to a U-value under 1 W/m2K for walls and roof and under 2 W/m2K for windows usually cause heating systems to be over-dimensioned by 20-50% compared to the original design. And thus, operating temperatures can be lowered.
Controls and operation	Various studies could lower the supply temperature from the original 90ºC to 60-40ºC and return temperature from 70ºC to 35-25ºC. The challenge lies on getting the return temperature to be low enough for the district heating systems to be efficient. Return temperature depends on the peak power needed for thermal comfort, the supply temperature considered and the mass flow through the radiators. Proper control of the hydraulic balance with thermostatic radiator valves (TRVs) can help optimize the return temperature. There are few studies available which focus on optimising the temperature setpoints and schedules of the heating system in the buildings, both residential and non-residential buildings. They show positive results by adjusting schedules and room temperature setpoints and in that way storing heat in the thermal mass of the building (passive storage). This measure was only successful when minimal renovations had been done the buildings' envelope or energy system.
Energy system	Renovations in the ventilation system, especially the installation of mechanical ventilation with heat recovery (MVHR) improve the efficiency of the energy system and can add to the over-dimensioning of the heating system. Case studies include different ventilation options in their renovation scenarios; however, no specific analysis was found on the relation between the upgrading of the ventilation and a building's flexibility to lower the operating temperatures. Different types of emission heating systems exist, designed to operate at different supply and return temperatures. Most commonly, conventional panel radiators are found in existing buildings, designed for high temperatures (95/70ºC). Possible adaptations are installing more radiators or installing low temperature radiators, which give more power output. However, since the heating systems tend to be over-dimensioned, the required peak power in the building ought to be assessed in the first place.
Summary	To sum up, recent research shows that it is possible to lower the operating temperatures in heating networks by adapting existing buildings. In old, poorly insulated buildings, minimal renovations in the buildings' envelope are crucial (and often sufficient) to enable low temperature heating. When heat losses are small, smart settings in the building management system to use the thermal mass of the building as storage prove successful to lower the supply temperature further. Obtaining a low the return temperature to achieve the desired efficiency in the system is a challenge; required peak power, supply temperature considered and mass flow through the radiators can be optimized.
Conclusion	The categorization carried out during this literature review, that concluded into this protocol, is useful to provide an up-to-date overview on the topic and furthermore, it facilitates the first stages of a case study, by providing an inventory of the main elements for the data collection.

4. CASE STUDY

In this chapter, the case study conducted in this research is explained in detail. Section 4.1 deals with the data collection and selection of promising adaptations. Section 4.2 introduces the modelling of the current situation of the selected building and its validation with real measured data. Next, in section 0, the modelling and analysis of the low temperature scenarios are explained. Lastly, the results of the simulated scenarios are presented in section 4.4.

4.1. Data collection and selection of promising adaptations

This section describes the first stages of the case study, concerning the data collection and the selection of promising adaptations that are needed for the simulation. The process is presented in a logical, linear way, following the steps proposed in the final version of the protocol for data collection, which was presented in chapter 3.

1. SELECT APPROACH OF THE PROJECT: SIMULATION OR PRACTICAL TEST

The first step is to decide what kind of a project or research is being conducted. This research follows a case-study approach. The main methodology is a simulation, used to answer the research questions.

2. SPECIFY THE ORIGINAL AND NEW OPERATING TEMPERATURES IN THE HEATING NETWORK

In the next step, a look is taken at the original and new design temperatures of the heating network. In this project, the heating network was originally design for a supply temperature of 130ºC and a return temperature of 80ºC. The new supply temperature that the geothermal source is expected to deliver is 80ºC, measured at the primary side of the buildings. This means before the heat from the network is transferred into the buildings by the heat exchangers. There are heat exchangers in most faculty buildings. Another supply temperature is considered in this research, measured on the secondary side of the heat exchangers in the building. The performance and possible renovation of the heat exchangers is not a question brought onto this case study. This decision was made early on during the data collection process, based on site-specific data, namely that the heat exchangers at the selected building are being changed for new more efficient ones later during this year. It is to be noted that during the application of protocol, information about the heat exchanger is gathered in the data collection step. The new design return temperature of the heating network is 55ºC. It is desired that this temperature is as low as possible for the system to extract sufficient heat and thus have a high efficiency.

The heating network will change from a High Temperature District Heating (HTDH) network of supply and return temperatures 130 and 80ºC to a Medium Temperature District Heating (MTDH) network of 80 and 55ºC. The secondary side temperatures, after the new heat exchanger installed, are 78 and 53ºC. This research deals with the temperatures at the secondary side (see schema in Figure 6 below).

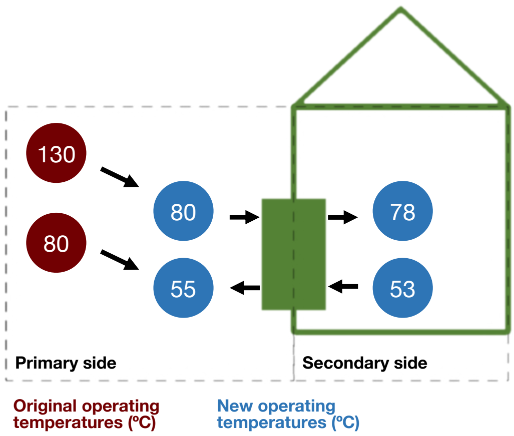

Figure 6. Schema of the original and new operating temperatures of the heating network at the primary and secondary sides of the heat exchangers.

3. SELECT THE BUILDING

In a district heating network, there are multiple buildings connected. Even if those buildings could operate at different temperatures because of their unique characteristics, the supply temperature in the network will need to be the highest temperature demanded. The selection of one building to focus the research on is the next step. The protocol provides the researcher with general criteria to select the building that will probably be the limiting factor to lowering the temperature in the heating network. These criteria can be found in section 3.2, under step 3. The selection of the building is done during the first stage of the research, before the simulation can be started, but it overlaps with data collection for some time, since the selection depends on some basic information about the network and the buildings.

The Aerospace Engineering (AE) faculty, building number 62, was selected for the case study. The argumentations for every criterion that led to the selection of this faculty are described below:

- Connection to heating network: the heating network is composed of four clusters, north 1 and 2 and south 1 and 2. A number of faculty buildings are connected to each cluster. The building that demands the higher temperature per cluster will define the supply temperature demand for that whole cluster. AE is connected to cluster south 2. A list of all buildings at the campus and if they were or not connected to the heating network was the first step in building selection.

- Data availability: heat demand and operation temperatures are measured for AE. Buildings for which no real measured data was available were not considered anymore as a possibility.

- Context: construction year is 1962, so the building is relatively old. The envelope, namely external walls and windows were renovated in the beginning of 2000 (Jeroen Sap et al., 2014). New construction buildings were not considered anymore as a target. Other buildings classified as a monument, such as the Aula Conference Centre or with uncertain real state plans to tear them down, as is the case of Electric Engineering, Mathematics and Computer Science (EEMCS); were also scratched from the list. The opinion of the Campus and Real State employees about the alignment of the remaining buildings with the geothermal project was also taken into account.

- Envelope insulation: the renovation around the year 2000 of the envelope added an external insulating layer to the façade and double glass windows were installed. Envelope insulation was checked in different buildings so a decision could be made based on an overview of the buildings in the campus. For the AE faculty the envelope in not the main issue why the building demands a high supply temperature for heating (Jeroen Sap et al., 2014).

- Heating system: consists mostly of conventional radiators designed to operate at high temperatures. Some floor heating also is installed. Furthermore, the ventilation system pre-heats the outside air with both a heat recovery system and a heating system. The first look at the heating system suggests that improvements could lower the supply temperature demand and heat demand of the building.

Figure 7. Image of the Aerospace Engineering (AE) faculty building and its surroundings.

Because of all the arguments presented above, AE faculty is selected for this case-study (Figure 7). Other buildings that were interesting to study in the future were noted and the geothermal energy project was informed of which ones they were. In Appendix A, in page 65, a table is shown with the buildings considered and their characteristics.

4. IDENTIFY THE DATA SOURCES

In the next step the data sources are to be identified. The protocol provides a basic list of what data is relevant to conduct the research and a general list on what kind of sources (stakeholders, documents, systems and literature) might be in possession of that information. The relevant data are building surfaces (geometry and materials), building energy balances, regimes, schedules and settings, weather data and measured data over a period of time (heat demand and supply and return temperatures). A more detailed list of necessary data is presented in the next section, linked to which data was found via which source. The protocol suggests taking a look at the next step from the beginning and completing these two steps in parallel. Figure 8 below summarises the data sources used for the data collection during this research project.

Building real state agency	Campus and Real State
Centralised heat plant	TU Delft CHP plant
Previous research projects companies	Deerns
Building system manager	Honeywell
Energy monitor system	ERBIS
Meteorological institute	Royal Netherlands Meteorological Institute (KNMI)
Field research	Building visit and observation
Scientific articles and books	Bibliography
Simulation tool	TRaNsient System Simulation (TRNSYS)

Figure 8. Data collection sources. Type on the left and specific case study source on the right.

5. COLLECT THE DATA OF THE SELECTED BUILDING

The collected data is filled in this step. The protocol ensures that all relevant data is collected by providing a basic inventory of what to collect and a check column where a short comment is added when data is collected. Moreover, it facilitates an overview of where a concrete dataset was found that can serve for future individual projects within the same heating network. See the tables of the collected data in Appendix C, in page 69.

6. SELECT PROMISING ADAPTATIONS

From the comparison of the data collected from the AE faculty with list of promising adaptations, a number of low temperature scenarios will be defined in section 4.3.1. The adaptations chosen are the following:

- **Envelope**: the insulation is sufficient for low temperature. It is decided to take a step back and model scenarios where either the windows, the external walls or both had not been renovated.
- **Controls and operation**: the schedules and temperature setpoints are adjusted to the working hours of the faculty, so there is room to extend the schedule and play with the setpoints to study how these changes affect the required operating temperatures.
- **Energy system**: the ventilation air is already pre-heated; it can be studied how the operating temperatures are affected in the case where the supply air is not pre-heated. The conventional single-plate radiators, originally designed for high temperature operation, might be a critical component. The installation of new radiators can be studied.

4.2. SIMULATION. Modelling and validation of the current high temperature situation

The goal of the validation process is to define a system which represents reality in a fair way; in order to being able to trust outcomes of imagined scenarios in the next phase. It is an iterative process in which simulation outputs are compared to real measured data available from information manager systems. The result of the validation process is the current high temperature situation checked out.

In Figure 9, an overview of this section is presented, which is structured as follows; first (4.2.1), the simulation tool and outputs obtained from a simulated model are introduced. The next section, 4.2.2, describes data inputted to model the current high temperature situation of the selected building. Section 4.2.3 explains which real measured data is used for the validation and how it was processed in order to obtain comparable data with the simulation output. In the last section, 4.2.4, the points of validation are shown.

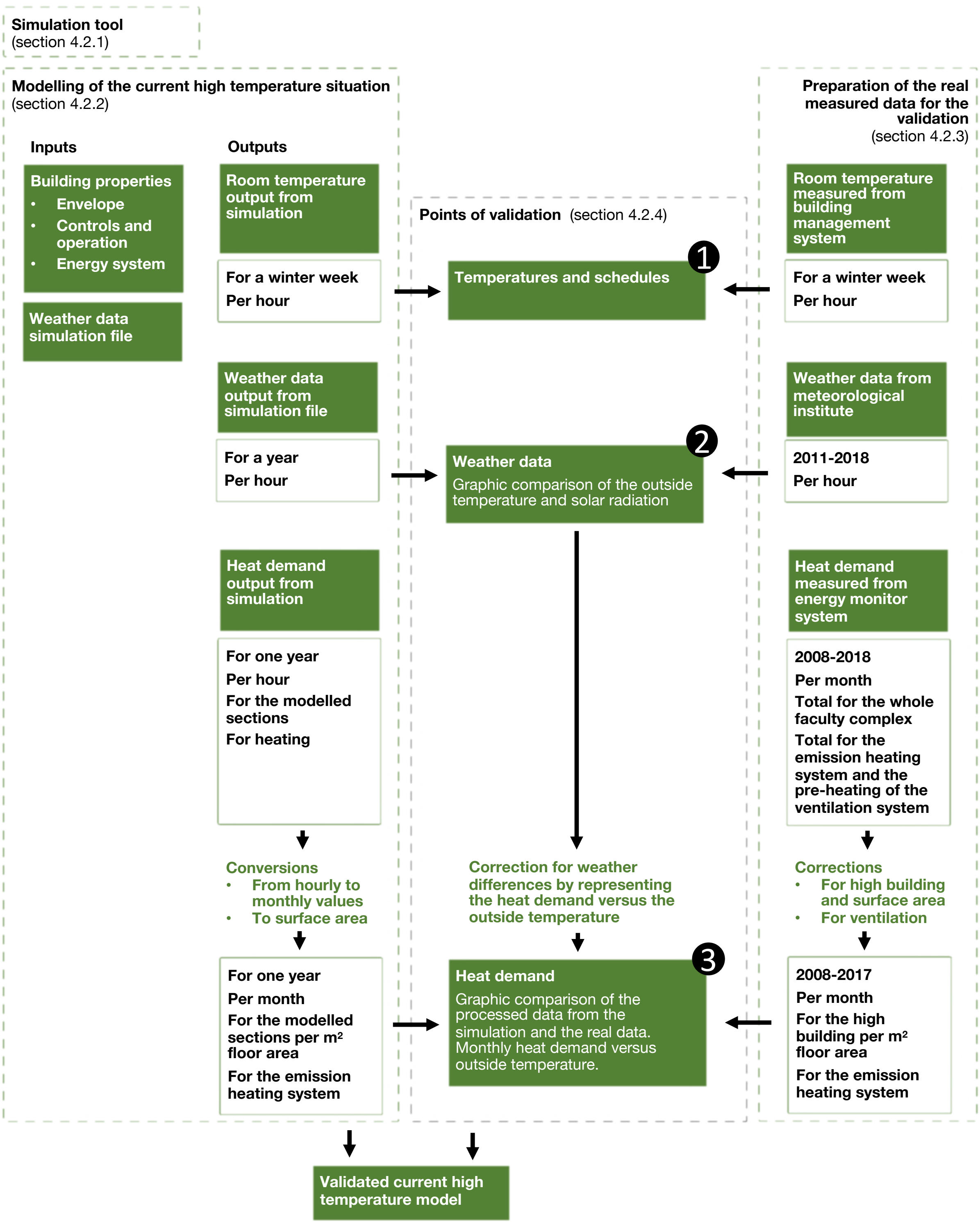

Figure 9. Overview of section 4.2: Modelling and validation of the current high temperature situation.

4.2.1. Simulation tool

The site-specific data gathered for the data collection is built in a simulation tool, TRNSYS (TRaNsient System Simulation program) and further analysed in a spreadsheet processor, Microsoft Excel. A simple model can be simulated in two packages of TRNSYS, namely Simulation Studio and TRNBuild. The model in Simulation Studio consists basically of a weather input, a building file (type 56) and an output file (type 65b). See Figure 10.

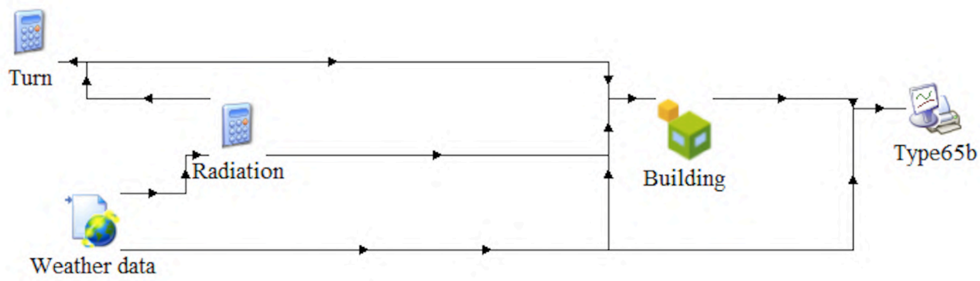

Figure 10. Simulation studio. Data validation set-up.

The program generates an input summary file and an output file. It runs for a year, 8760 hours, and it is set to give the hourly temperatures and heat demand of the different sections modelled. Outputs from the simulation in TRNSYS are the following:

- Time and date: they connect all other outputs, the simulation runs for a whole year, and hourly results are outputted.
- Heat demand: the raw output is in kilojoules per hour (kJ/h), for a year, per hour. Every section simulated gives its own output.
- Temperatures: outside temperature from the weather input file and room temperatures for each section simulated. For a year, per hour. The units are degree Celsius (ºC).

The raw outputs are then processed and analysed in Microsoft Excel to make different data sets comparable. The formula below (Equation 2) represents an overview of the thermal energy flows in a building.

$$Qbalance = Qtransmision + Qinfiltration + Qventilation + Qsolar + Qinternal\ gains$$

Equation 2. Thermal energy flows in a building. $Q_{balance}$: heating/cooling demand. Q_x: energy flow through transmission, infiltration, ventilation, solar radiation and internal gains.

The balance heat can be defined as cooling demand when positive, and heating demand when negative (Bueren, 2012). The energy demanded during 1h and expressed in Wh is identical to the (average) power during this hour. Therefore, the energy flows during 1 h are defined as follows:

$$\frac{Qheating\ [Wh]}{1\ [h]} = Pheating\ [Wh/h]$$

Equation 3. $Q_{heating}$: heat demand for 1 h. $P_{heating}$: (average) heating power during 1 h.

For this research, the heat (or power) demand output, together with the air temperature in the room and outside temperatures, are going to be the main performance indicators of the simulated models.

4.2.2. Modelling of the current high temperature situation

The inputs in the simulation tool will be the weather data and all the building properties collected during the data collection phase. After the description of the inputs, the different sections of the building that were modelled are explained. The outputs of running the simulated model are the general outputs described in the simulation tool section right above.

Weather data

The weather file (.tm2) from Schiphol-Amsterdam is used to simulate weather conditions. The location of the buildings is relatively close to that of the input file. Delft is located 45 km away from Schiphol in a straight line and they do not differ greatly in terms of climate conditions. Nevertheless, the simulated weather needs to be validated.

Building properties

Building properties are divided into surfaces, energy system and controls and operation. A summary of the inputs is presented in Table 4. It provides the most relevant inputs, the ones that are eligible to adaptations in future scenarios. In Appendix D, in page 71, extensive tables can be found for the building properties, for each level of the simulation.

- Surfaces correspond to the external and internal walls, ground, floors, ceilings and roof, as well as the windows. Since no internal walls or ceilings are modelled, surfaces are referred to as envelope. Data such as their geometry, materials, thickness, thermal transmittance (U-value) and R-value among others are to be inputted in TRNBuild. The envelope of the building is well insulated compared to the original construction; it was renovated in the early 2000s. The external walls present with no cracks, sealed frames and a low U-value and they are composed by three layers: brick, insulation and plaster. The windows have double glazing (Jeroen Sap et al., 2014).

- In the energy system, the ventilation type is supply-exhaust with heat recovery and pre-heated air, so the building is well equipped in terms of ventilation. The emission heating system is provided with type 10 conventional panel radiators, with a high design temperature (90/70ºC), single plate and no internal convection fins. Two radiators of 10x400x1400cm^3 are placed in each room in the building. The emission system was originally designed for high temperatures in the heating network and has not been upgraded. The heating and cooling are initially set to have unlimited power (maximum theoretical power output installed), in order to get the heat demand output out of the simulation and compared it to the real heat demand.

- Controls and operation refer to the temperature and schedule setpoints of the different energy flows in the building; these are infiltration, ventilation, heating, cooling and gains. The relevant controls and operation are the room temperature, schedule of the emission heating system and temperature and schedule of the ventilation system. Currently, room temperature is set to 21,2 degrees. Schedule of the emission heating system is Monday to Friday, 4-19 h and Saturday to Sunday, 9-15 h. Temperature setpoint of ventilation is 19ºC and schedule is Monday to Friday 6-22 h, which corresponds almost to the working hours of the building, namely Monday to Friday, 8-22 h.

Table 4. Inputs of the model of the current high temperature situation (CURRENT HT)

INPUTS			
			HT CURRENT
CONTROLS AND OPERATION			
Room temperature setpoint		ºC	21,2
Schedule heating system			Mon-Fri, 4-19 h Sat-Sun, 9-15 h
Temperature setpoint ventilation		ºC	19
Schedule ventilation system			Mon-Fri, 6-22 h
ENERGY SYSTEM			
Ventilation	Type		Supply-exhaust with heat recovery and pre-heated air
	Mass flow rate (per room)	kg/h	250
Emission heating system	Type		Conventional panel radiators. High design T (90/70ºC) Single plate No internal convection fins
	Type (10-100)		10
	Dimentions		10x400x1400
	Radiators (per room)		2
ENVELOPE			
Outwall	Insulation		Good No cracks, sealed frames, low U-value, high R-value
	Composition	m	Brick 0,200 Insulation 0,100 Plaster 0,015 0,315 m
	U-value	W/m^2K	0,344
	R-value	m^2K/W	2,734
Windows	Type		Double glazing
	u-value	W/m^2K	1,4
	g-value	%/100	0,589
Infiltration	Low		No cracks or openings in the buildings envelope
	Infiltration rate	airchange 1/h	0,25

Modelled sections

The Aerospace Engineering faculty consists of two buildings located in the south of the TU Delft campus, connected to cluster south 2; one is called the old building (high building plus low building) and the other is the new building (see Figure 11). They have mainly lecture and study rooms and offices. The high building is the one chosen to proceed with the study.

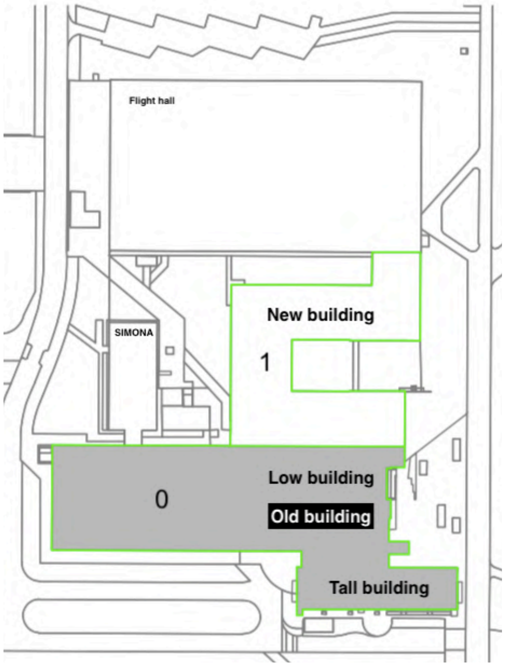

Figure 11. Aerospace Engineering faculty building. Left: high building.
Right: schema faculty buildings: old building (low and tall/high), new building and Simona.

The behaviour of the simulation and the system is studied at different levels, for which different sections are modelled in the TRNBuild package. These are a representative floor and a slice (cross section) of the high building from the AE faculty complex (see Figure 12). The final output after the validation is the simulated current situation of the level slice (cross-section) of the high building. It is proposed that the limitation to lower the temperature in the network lies at room level. In other words, if a representative room in the building can be heated at a certain temperature, it is assumed that the whole building will be ready to operate at such temperature. This is especially applicable in an office building like this one, where all floors have a similar layout: small offices on both sides with a corridor in the middle. The slice section is chosen because it is the most complete possible at room level, since it is composed by two rooms (one on the east, ROOM E, and one on the west, ROOM W) and a part of the corridor. That way the east-west differences in performance can be observed. The building does not have rooms strictly facing north or south, the staircases and the bathrooms are located there. Low temperature radiators are located in the staircases, that is why these spaces are considered to be well heated as they are, and the limit to lower the temperature not to lie there.

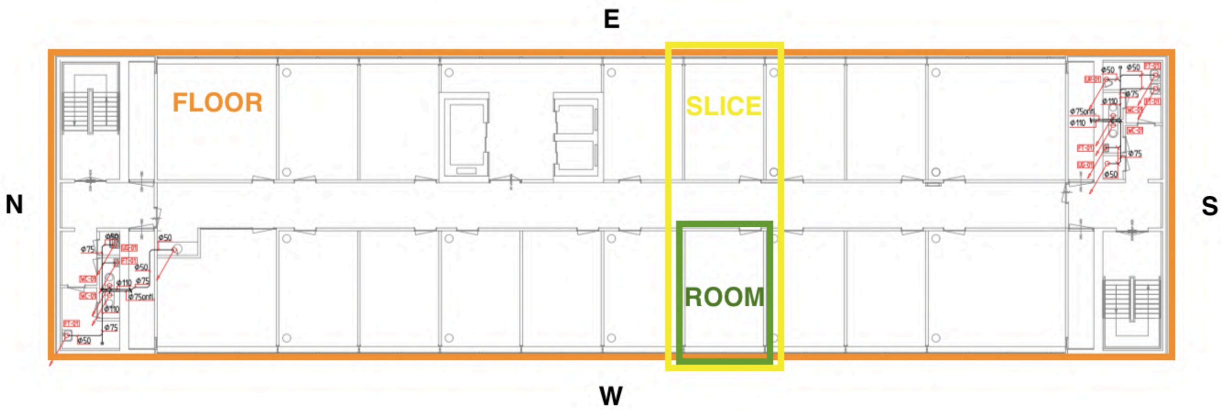

Figure 12. Modelled sections. Floor and slice (cross-section composed by west and east room and a part of the corridor).

The whole building blocks for the high building, low building, new building and SIMONA building are also simulated with two intentions. Firstly, it serves as a comparison between building level and floor or room level. And secondly, the different heat demand of each building in the complex can be used to correct the real measured heat demand. The reason why this is necessary can be read in detail in section Correction for high building and surface area, in page 40.

4.2.3. Preparation of the real measured data used for validation

The temperatures and schedules for a first internal check of the model are downloaded from the building management system. Real measured weather data is obtained from the meteorological institute. The main point of validation will check that the heat demand output from the simulation corresponds well to the real heat supply measured in the energy monitor system. The processing of the real measured data, especially that of the heat demand, in order the make it comparable to the outputs from the simulated model is described in this section.

Temperatures and schedules

A random period in winter and another in spring are downloaded with ventilation temperatures to be used for the ventilation correction of the real data from the high building. Springtime when heat recovery is on and heating if off is used to find the efficiency of the heat recovery. Wintertime when both systems are on is used to find a formula for heat recovery temperature. GBS data is also downloaded for a random winter period, for a week, with the room temperatures to check schedules and temperature setpoint in point of validation 1, and used in general as input data.

Weather data

Real data is collected from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) corresponding to hourly temperature and solar radiation in Rotterdam (10 km away from Delft) over the past decade (from 2011 to 2018).

Heat demand

Heat supply data used for the validation is measured from how much warm water is delivered from the CHP plant in the campus and stored at ERBIS energy monitor system. Heat supply can be regarded as heat demand, since no significant losses occur between supply and emission in the rooms. Figure 13 gives an overview of the characteristics of the data before and after its processing to make it comparable to the simulated heat demand.

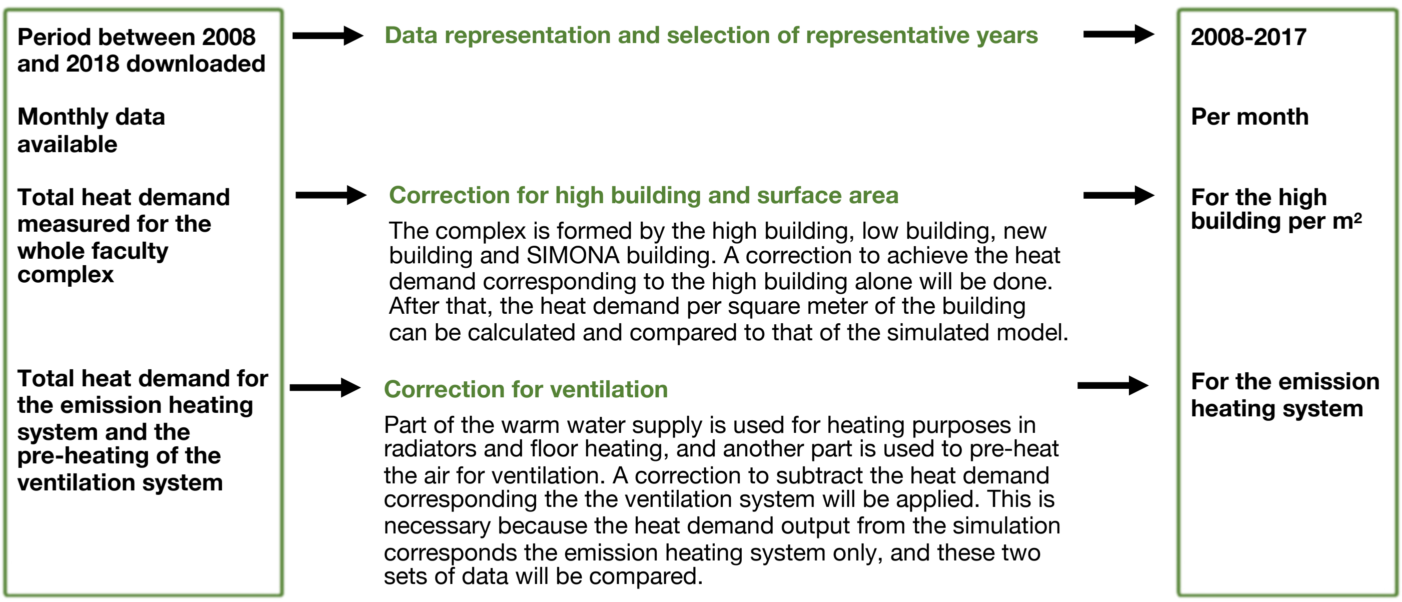

Figure 13. Overview of the preparation of the real measured heat demand for the validation.

Data representation and selection of representative years

First, the monthly heat supply from the period between 2008 and 2018 is represented in a graph (Figure 14). The year 2018 is excluded because of the noticeable lower heat demand that is not accurately explained either by weather conditions or changes in the heating system or the building. Furthermore, in December 2018 the smart meters of the building were changed and updated, so data from December could not be used anyway.

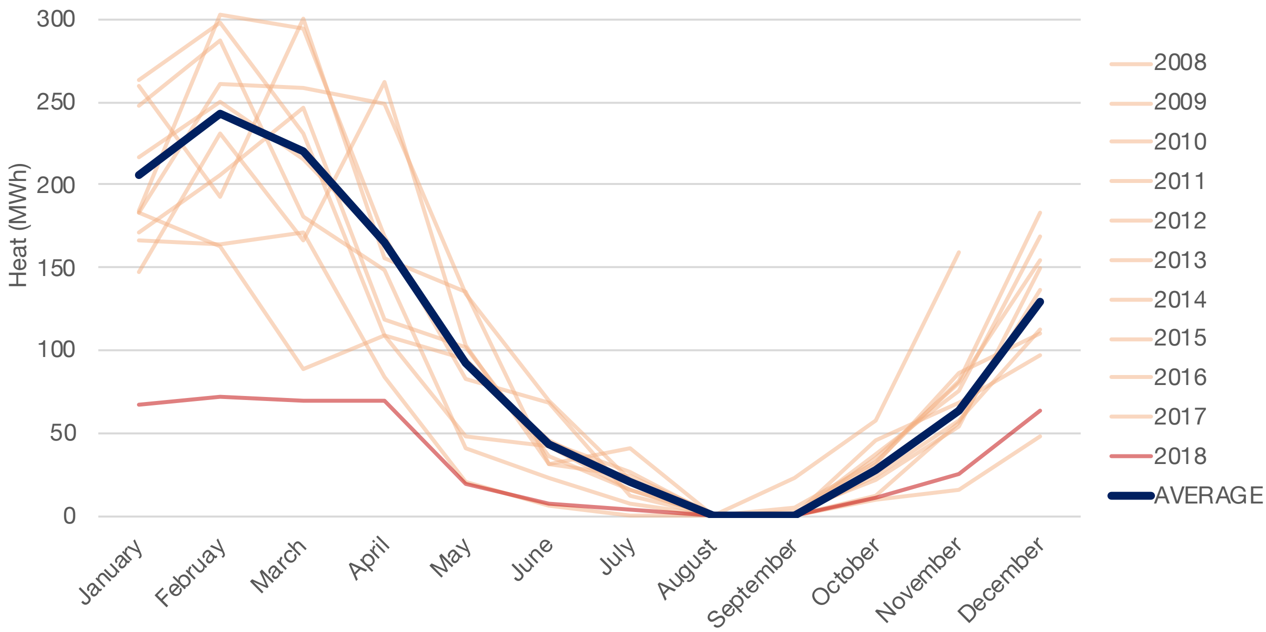

Figure 14. Monthly heat demand from ERBIS for the AE faculty complex for the period of 2008-2018 and the average.

Correction for high building and surface area

The available real data correspond not only to the selected building for this case study, but to the total of the buildings of the complex: the high building, low building, new building and SIMONA building. It is to be expected that the heat demand is not equally divided throughout the four buildings, since their geometry and other building properties differ significantly. The following steps are followed to achieve the heat demand of the high building:

- **Simulation of a simple model of the four buildings**: each building's properties are inputted to the simulation and a simulated heat demand per building is obtained. The simulated heat output cannot be compared to the real measured one, because of the fact that the measured data corresponds to heat for both heating and ventilation properties. Nevertheless, the relative heat demand consumed by each different building is assumed to be similar to that of the real data.
- **Calculation of heat demand corresponding to the high building based on the simulation**: the simulated monthly heat demand per building is compared and the percentage of the total heat demand corresponding to the high building is obtained.
- **Extraction of the high building consumption from the real measured heat demand**: once the percentage corresponding to the heat demand of the high building is obtained from the simulation, that same percentage is used to calculate the heat demand corresponding to the high building from the real data.

The simulated model is done at the slice level (two representative rooms and part of the corridor). In order to compare the simulation outputs with the real measured data, the heat demand per floor area (m^2) needs to be calculated. The heat demand obtained that corresponds to the high building is divided by the floor area of the high building to achieve the average heat demand per square meter that can be used for the validation (once the correction for the ventilation is applied).

Correction for ventilation

A part of the warm water supply from the CHP plant to the AE faculty is used for the emission heating system (radiators and floor heating) and another part is used to pre-heat the air in the ventilation system.

Only the total heat demand for both the emission heating system and the ventilation system is measured in the energy monitor system. In order to compare the real heat demand with the output from the simulated model in the validation, the heat demand corresponding to only the emission heating system is necessary. Therefore, the heat demand for the pre-heating of the ventilation air will be calculated and subtracted from the measured total heat demand.

The characteristics of the system are shown in Figure 15. A mechanical ventilation system with heat recovery and pre-heating of air is installed. There are two air handling units (AHU) located in the basement of the high building that provide ventilation air for the north and south sides. In a typical winter day, outside air enters the unit and is heated at the heat recovery part (a twin coil system). If the temperature after heat recovery is not enough, the air is heated up to 19°C in the heating part of the AHU, which uses warm water from the CHP plant. The air is then distributed into the rooms in the building. Since the temperature of the room is about 21°C, the air returning from the ventilation is usually at a higher temperature and heat can be recovered from it. So, the return air goes through the heat recovery system before being ejected to the outside.

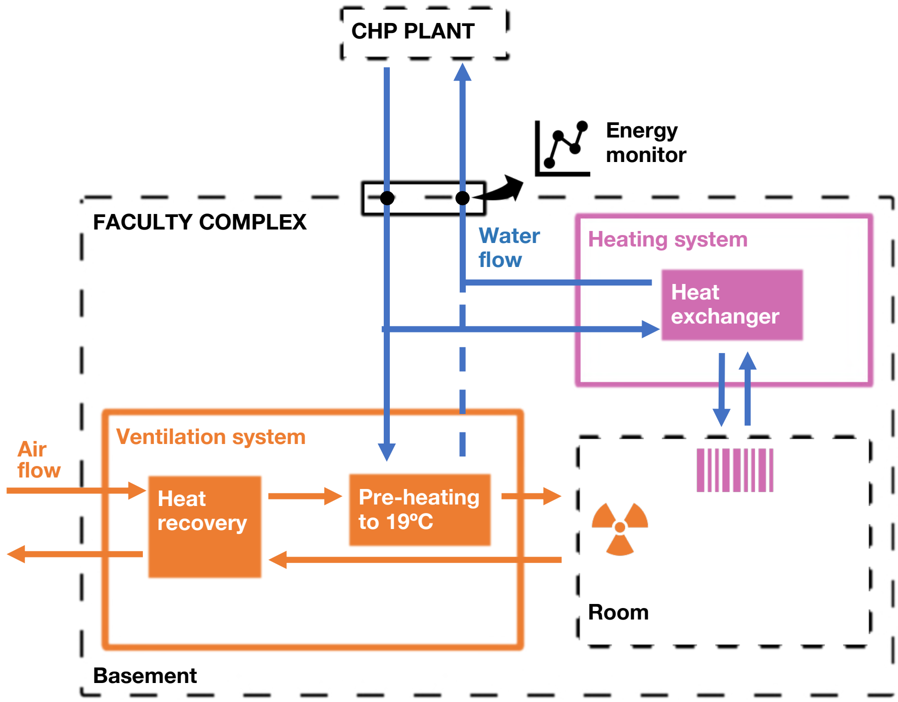

Figure 15. Schema of the warm water delivered to the faculty complex for the emission heating system and ventilation system.

The heat contained in the air flow can be calculated and it will be the equal to the heat supplied by the water flow for ventilation, since for a heat exchanger using fluid A and B, the following is true (Equation 4).

$$Q_A = \dot{m}_A \cdot Cp_A \cdot \Delta T_A = Q_B = \dot{m}_B \cdot Cp_B \cdot \Delta T_B$$

Equation 4. Derived from Equation 1. Heat from fluid A equals heat from fluid B in a heat exchanger.

The necessary values are the ventilation mass flow for the building and the temperature difference, namely ventilation temperature setpoint (19°C) minus the temperature after heat recovery. The air mass flows for the building, floors and rooms, as well as the temperature of the outside air, air supply and return air are available. However, the temperature after the heat recovery system is not a value that is measured. It can be calculated based on the efficiency of the heat recovery system using Equation 5.

$$\eta = \frac{T_{after\ heat\ recovery} - T_{outside}}{T_{return\ air\ from\ ventilation} - T_{outside}}$$

Equation 5. η: efficiency of the heat recovery (%/100). T: temperature (ºC).

A problem is encountered because neither the efficiency, nor the temperature after the heat recovery are known. The heat recovery temperature is obtained following the steps below:

- **Calculation of the efficiency of the system at a certain outside temperature**: finding those tiny moments of time when the heat recovery system is on, but the heating part is off. In that case the temperature after the heat recovery will be the same as the air supply temperature. The efficiency of the system can be found at a certain temperature. Temperature data from these specific moments is downloaded from the energy monitor system.
- **Extrapolation of the efficiency of the system to a bigger range of outside temperatures**: based on literature, (Choi et al., 2018), a formula is defined that connects the efficiency of the system to the outside temperature.
- **Calculation of the temperature after heat recovery based on the outside temperature**: with the efficiency formula, another formula is defined that calculates the temperature after heat recovery from the outside temperature, based on temperatures extracted for a period of three winter months from the energy monitor system.

The heat recovery temperature can now be obtained from the outside temperature. The heat necessary for ventilation in the high building for month of a year can then be calculated by substituting all the values in Equation 4.

Final corrected results

After the correction to achieve the heat demand for the high building, we obtained the monthly heat demand of the high building corresponding to the emission heating system and the ventilation system. The monthly heat demand corresponding to the pre-heating of the ventilation air has just been found and can be subtracted. Therefore, the monthly heat demand for the high building corresponding to only the emission heating system is finally found. It is these values that can be compared to the simulated ones in the validation.

4.2.4. Points of validation

The three graphical arguments to validate the data are presented below. Namely temperatures and schedules, weather and the heat demand. By these, the simulated current high temperature situation of the building is validated, meaning that it is considered realistic and ready to serve as a reference for the imagined future scenarios in the next phase of the case study.

1. Temperatures and schedules

Simulation outputs room and outside temperature are represented for every hour of a winter week (second week of February). The graph is compared to the real measured data available from the building management system. This allows for an internal check that the temperature setpoints and schedules form the expected pattern.

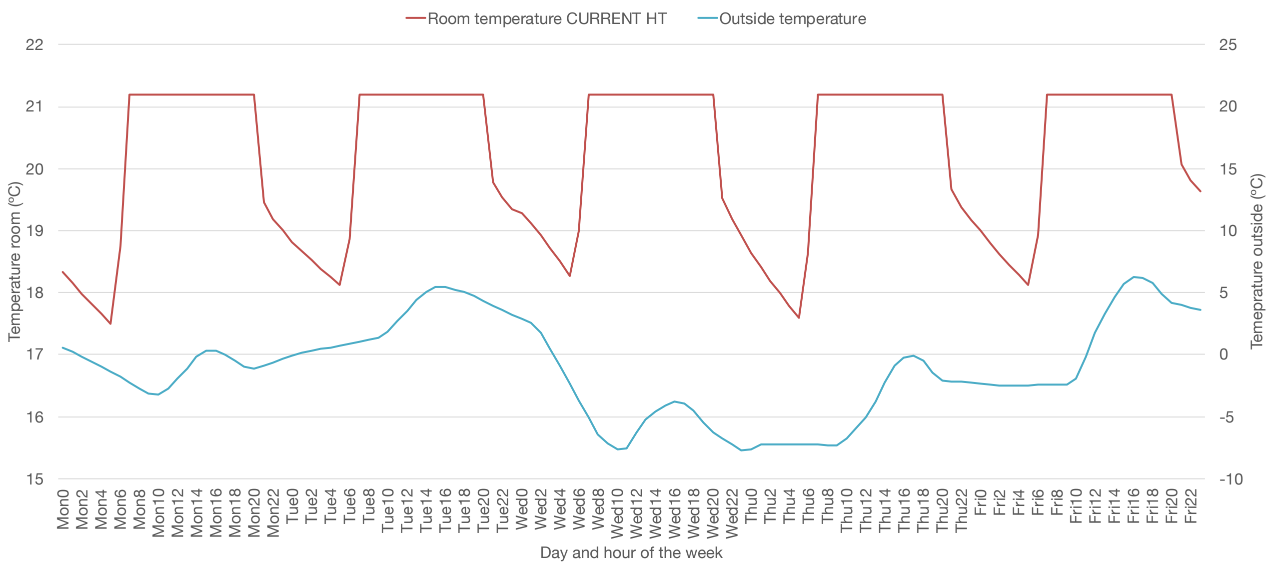

Figure 16. Point of validation 1: Temperatures and schedules. Simulation outputs room and outside temperature are represented for every hour of a winter week (second week of February). The graph is compared to the real measured data available from the building management system in order the check that the room temperature and schedules are correct.

2. Weather data

The graphs below, Figure 17 and Figure 18, compare the temperatures and solar radiation from TRNSYS and KNMI. The simulation file proves to be slightly different from the collected data. An overall lower temperature and solar radiation is found for TRNSYS. A slightly bigger difference is observed in January and December. This lower tendency would imply a higher heat demand output from the simulation than in reality, and it might give an even higher difference around the beginning and end of the year. This comparison brings awareness to the possible influence of the weather file in the heat demand output. For this reason, it is decided to represent the heat demand versus the outside temperature. The simulated heat demand will be plotted versus the simulated weather data and the measured heat demand versus the real meteorological data.

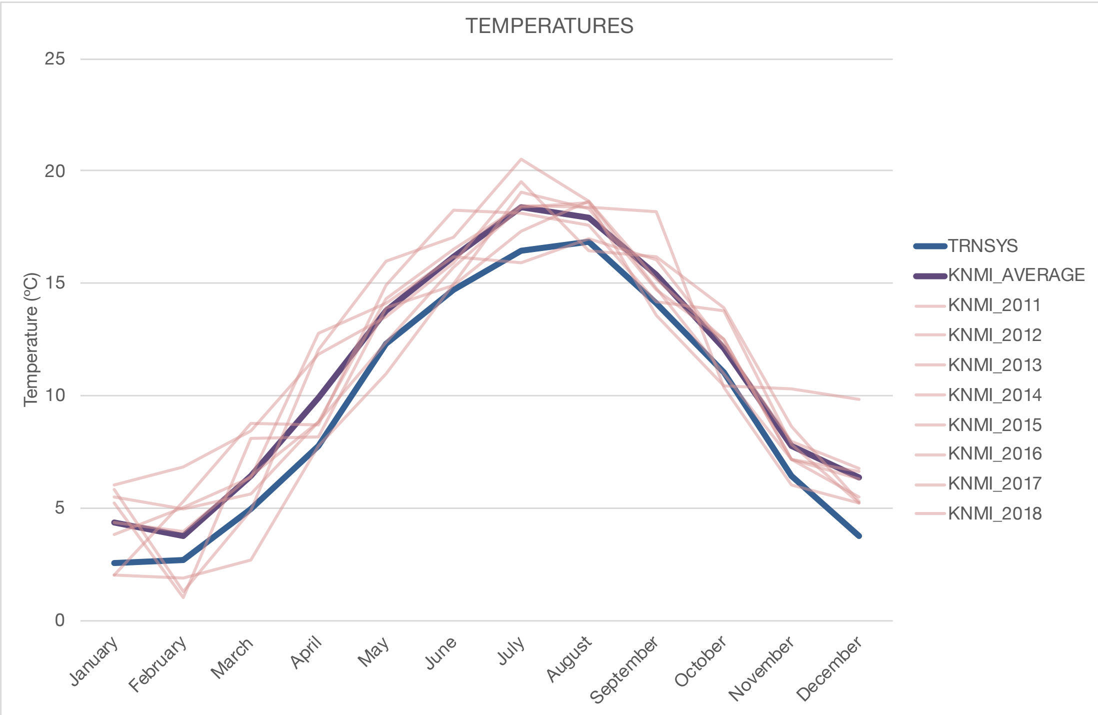

Figure 17. Data validation. Comparison KNMI vs TRNSYS weather data. Temperatures.

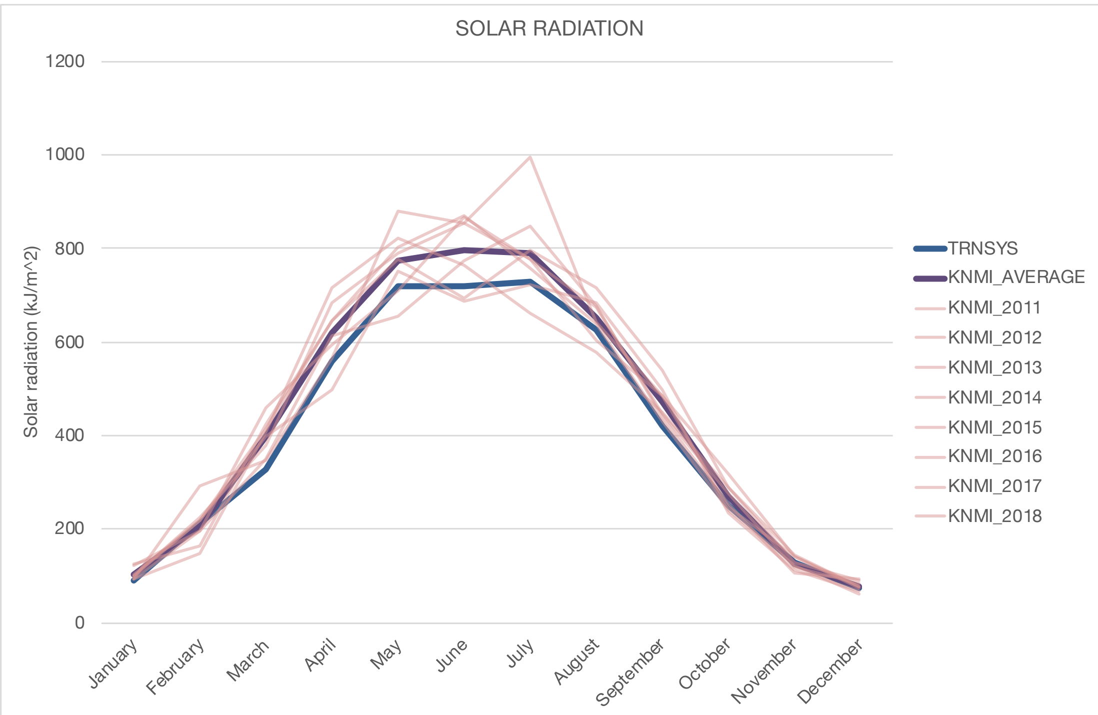

Figure 18. Data validation. Comparison KNMI vs TRNSYS weather data. Solar radiation.

3. Heat demand

The graph for validating the heat demand (Figure 19) shows both the simulated and measured monthly heat demand versus the monthly average outside temperature.

The outputs for the different levels simulated are presented. The main output is the slice section, which will be the one used in the validated model. The floor and single room levels are also shown in the graph, to indicate that the heat demand per floor area of the different levels compare well to each other, and thus also to the whole building block.

Individual points correspond the heat demand per month. The simulated values correspond to the months of one year and the measured ones to monthly values between the period between 2008 and 2017. They are plotted against the average outside temperature, in order to correct for the slight difference in weather files, as explained in the point of validation of the weather. Trendlines adjust well to a second order polynomial line.

The slice gives a lower heat demand compared to the whole building. This can be explained by the fact that the slice has fewer external walls than the simulated block building and because it is more detailed, the corridor part in between the rooms is well insulated and has a lower heating demand, which decreases the overall demand per m^2 for the slice. The differences make sense and are in line with the assumptions. The modelled current high temperature is considered validated.

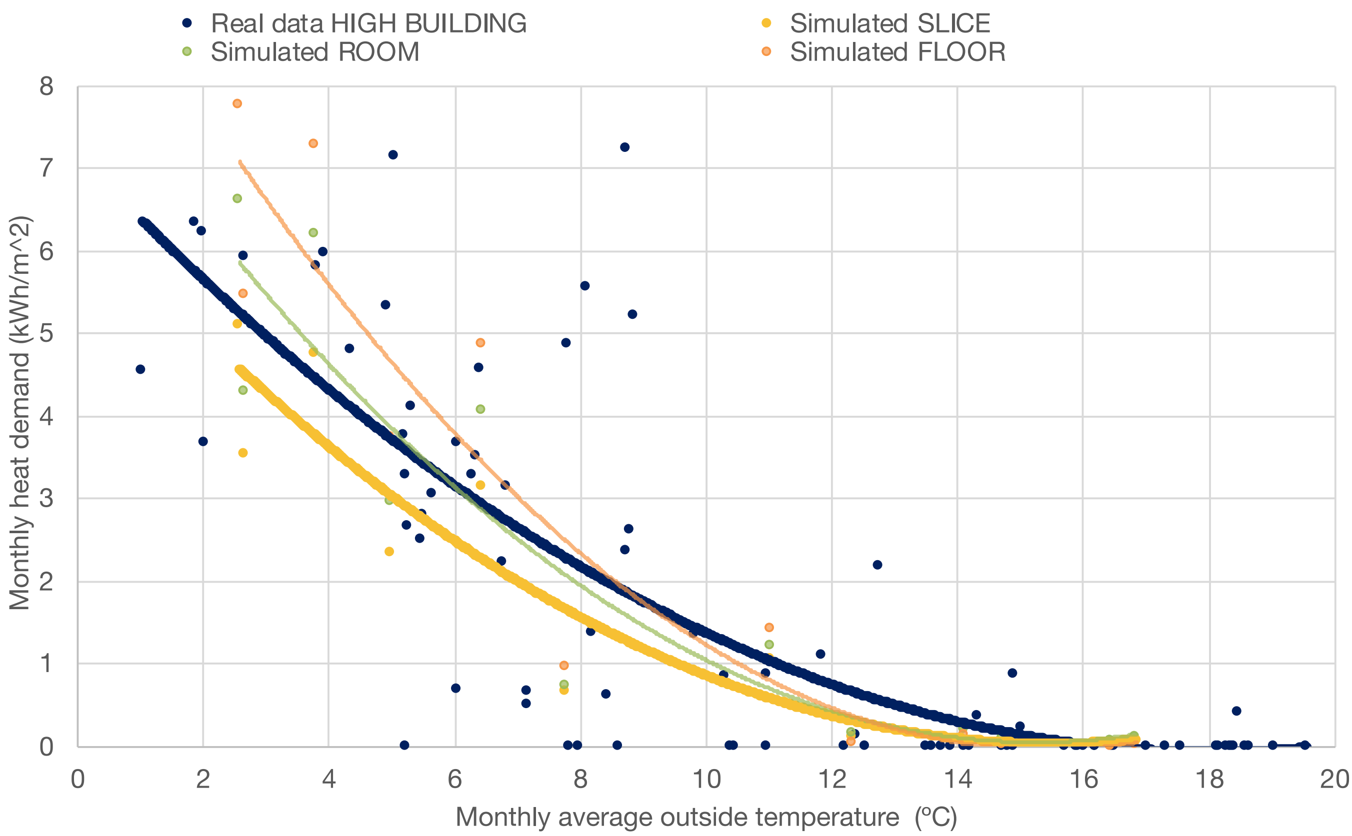

Figure 19. Graphic comparison of the simulated and (corrected) real measured heat demand. FLOOR, ROOM and SLICE are the simulated sections and HIGH BUILDING corresponds to the measured data in the case study building.

4.3. SIMULATION. Modelling and analysis of the low temperature scenarios

The steps to obtain the results per scenario are explained in this section (see Figure 20). First, multiple scenarios are modelled in the simulation tool TRNSYS, based on the selected promising adaptations at building level to enable lower operating temperatures (see step 6 in section 4.1). Then, the available peak power corresponding to an assumed temperature difference between supply and return temperatures is calculated. Next, each modelled scenario is simulated with the calculated available peak power. The raw output data is analysed in the spreadsheet processor Microsoft Excel in order to check the thermal comfort in the building for that given peak power. The available peak power is adjusted until the thermal comfort in the building is just achieved. Then, the lowest required peak power and related operating temperatures are defined per scenario.

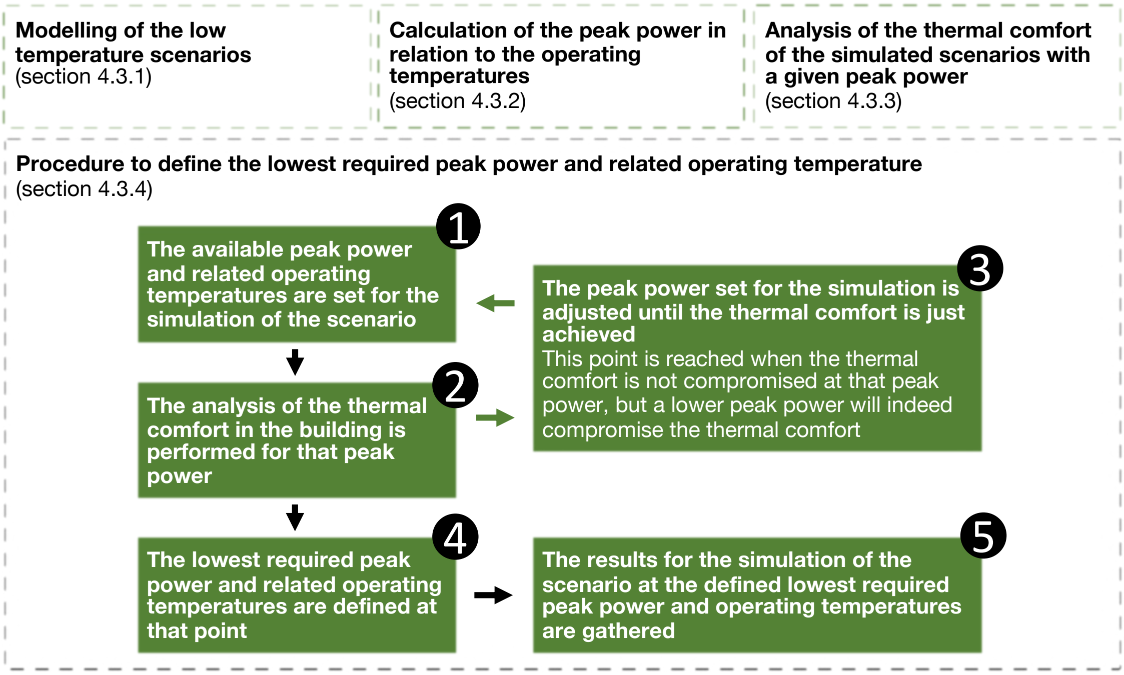

Figure 20. Overview of section 4.3: Modelling and analysis of the low temperature scenarios.

4.3.1. Modelling of the low temperature scenarios

During the data collection and validation phases, the envelope, the energy system and the controls and operation of the current system were defined. The properties of the current situation of the building simulated during the validation phase, are used as reference for the scenarios. In every different scenario, a new adaptation to lower temperature heating is proposed.

Including the high temperature current system, 11 scenarios in total are simulated. All other scenarios are named with low temperature (LT) because it is studied how much the temperature can be lowered. One scenario corresponds to that in which the operating temperatures are lowered, but no extra measures are taken. Three scenarios are proposed with different changes in the envelope of the building. Four scenarios deal specifically with changes in the controls and operation. And two more incorporate adaptations on the energy system. An overview is shown below in Figure 21, and a short description of their characteristics can be found right after. A more visual version is presented in Table 5 and Table 6.

Scenario	Category
HT CURRENT	
LT NO CHANGES	
LT POOR INSULATION + EXTENDED SCHEDULE ALL NIGHT 18ºC	**ENVELOPE**
LT POOR INSULATION WINDOWS + EXTENDED SCHEDULE ALL NIGHT 18ºC	
LT POOR INSULATION WALLS + EXTENDED SCHEDULE ALL NIGHT 15ºC	
LT EXTENDED SCHEDULE 2h	**CONTROLS AND OPERATION**
LT EXTENDED SCHEDULE ALL NIGHT 20ºC	
LT VENTILATION 21ºC	
LT VENTILATION 21ºC + EXTENDED SCHEDULE 2h	
LT VENTILATION Theat_recovery + EXTENDED SCHEDULE 1h	**ENERGY SYSTEM**
LT NEW RADIATORS	

Figure 21. Scenarios under envelope, controls and operation and energy system categorisation. This division indicates the focus of each scenario and not necessarily that the only changes applied are in that category.

HT CURRENT

The high temperature current situation was presented in the Building properties, section Building properties, page 36.

LT NO CHANGES

In the case of this scenario, only the maximum power output of the emission heating system is affected, since it is the intention to assess if the current system can already be operated with lower temperatures in the heating network. The possibility to lower the temperatures in the network without any additional adaptations would mean that the current system is over-dimensioned.

ENVELOPE

It is interesting to study what would happen if the envelope of the building had not been renovated, because this might be the case in other faculty buildings. Three extreme cases of poor insulation are presented. A problem was encountered during the simulation, so a comment needs to be added in this methodology section: additional controls and operation measures were taken to make sure that the building is maintained at a minimal temperature during the night, because due to the poor insulation, it cooled down fast and thermal comfort could not be achieved.

CONTROLS AND OPERATION

In the two extended schedule scenarios, the influence of control and operation measures are studied. Especifically, the extension of the emission heating system schedule and the temperature setpoin of the room. The intention is to analyse whether smarter controls can enable lower temperatures in the heating network.

Two scenarios consider changes in the settings of the ventilation. The AE faculty has pre-heated air ventilation, up to 19ºC. The ventilation air is heated up with the water from the heating network, just as the emission system. Based on the temperatures extracted from the building management system, the temperatures required to heat up the ventilation air do not usually exceed 50ºC; therefore, for simplication, it is considered that the decrease in the supply and return temperatures will not affect the functioning of the pre-heating in the ventilation.

ENERGY SYSTEM

The ventilation scenario looks at the building when the ventilation is supply-exhaust with heat recovery, but no pre-heating. This might be the case in other office buildings, so it is an interesting scenario to consider.

It means the ventilation air is not set to a fixed temperature, but the air is supplied to the room at the temperature achieved after the heat recovery.

The new radiators scenario proposes to substitute the current high temperature radiators (two per room) with medium temperature radiators (one per room), with a higher power output when operating at the same temperatures. The new radiators are type 22, a conventional panel radiator, medium design temperatures (75/65ºC), multiple plates, a few internal convection fins. The dimensions stay the same. Medium temperatures radiators and not lower temperature radiators are chosen because the power delivered by them is already enough to lower the temperatures in the heating network to the lowest considered, namely 50ºC for supply. It is an example of the impact of the installation of new radiators.

Table 5. Scenarios inputs. Current, no changes and envelope. Controls and operation and envelope changes in the scenarios, with respect to the current situation, are highlighted in grey.

INPUTS					**ENVELOPE**		
			HT CURRENT	**LT NO CHANGES**	**LT POOR INSULATION** + EXTENDED SCHEDULE ALL NIGHT 18ºC	**LT POOR INSULATION WINDOWS** + EXTENDED SCHEDULE ALL NIGHT 18ºC	**LT POOR INSULATION WALLS** + EXTENDED SCHEDULE ALL NIGHT 15ºC
CONTROLS AND OPERATION							
Room temperature setpoint		ºC	21,2	-	Mon-Fri, 4-19 h, 21,2 Mon-Fri, 20-3 h, 18 Sat-Sun, 0-24 h, 18	Mon-Fri, 4-19 h, 21,2 Mon-Fri, 20-3 h, 18 Sat-Sun, 0-24 h, 18	Mon-Fri, 4-19 h, 21,2 Mon-Fri, 20-3 h, 15 Sat-Sun, 0-24 h, 15
Schedule heating system			Mon-Fri, 4-19 h Sat-Sun, 9-15 h	-	24/7	24/7	24/7
Temperature setpoint ventilation		ºC	19	-	-	-	-
Schedule ventilation system			Mon-Fri, 6-22 h	-	-	-	-
ENVELOPE							
Outwall	Insulation		Good No cracks, sealed frames, low U-value, high R-value	-	Poor Cracks, unsealed frames, high U-value, low R-value	-	Poor Cracks, unsealed frames, high U-value, low R-value
	Composition	m	Brick 0,200 Insulation 0,100 Plaster 0,015 0,315 m	-	Brick 0,200 Insulation 0,050 Plaster 0,015 0,265 m	-	Brick 0,200 Insulation 0,050 Plaster 0,015 0,265 m
	U-value	W/m^2K	0,344	-	0,604	-	0,604
	R-value	m^2K/W	2,734		1,482		1,482
Windows	Type		Double glazing	-	Single glazing	Single glazing	-
	u-value	W/m^2K	1,4	-	5,68	5,68	-
	g-value	%/100	0,589	-	0.855	0.855	-
Infiltration	Low		No cracks or openings in the buildings envelope	-	-	-	-
	Infiltration rate	airchange 1/h	0,25	-	-	-	-

Table 6. Scenarios inputs. Controls and operation and energy system. Controls and operation and energy system changes in the scenarios, with respect to the current situation, are highlighted in colour.

INPUTS				**CONTROLS AND OPERATION**				**ENERGY SYSTEM**	
			HT CURRENT	**LT EXTENDED SCHEDULE 2h**	**LT EXTENDED SCHEDULE ALL NIGHT 20ºC**	**LT VENTILATION 21ºC**	**LT VENTILATION 21ºC + EXTENDED SCHEDULE 2h**	**LT VENTILATION Theat_recovery +** EXTENDED SCHEDULE 1h	**LT NEW RADIATORS**
CONTROLS AND OPERATION									
Room temperature setpoint		ºC	21,2	-	Mon-Fri, 4-19 h, 21,2 Mon-Fri, 20-3 h, 20 Sat-Sun, 0-24 h, 20	-	-	-	-
Schedule heating system			Mon-Fri, 4-19 h Sat-Sun, 9-15 h	Mon, 0-19 h Tue-Fri, 2-19 h Sat-Sun, 9-15 h	24/7	-	Mon, 0-19 h Tue-Fri, 2-19 h Sat-Sun, 9-15 h	Mon-Fri, 4-20 h Sat-Sun, 9-15 h	-
Temperature setpoint ventilation		ºC	19	-	-	21	21	Toutside + HeatRecovery	-
Schedule ventilation system			Mon-Fri, 6-22 h	-	-	-	-	-	-
ENERGY SYSTEM									
Ventilation	Type		Supply-exhaust with heat recovery and pre-heated air	-	-	-	-	Supply-exhaust with heat recovery	-
	Mass flow rate (per room)	kg/h	250	-	-	-	-	-	-
Emission heating system	Type		Conventional panel radiators. High design T (90/70°C) Single plate No internal convection fins	-	-	-	-	-	Conventional panel radiators. Medium design T (75/65°C) Multiple plates A few internal convection fins
	Type (10-100)		10	-	-	-	-	-	22
	Dimentions		10x400x1400	-	-	-	-	-	-
	Radiators (per room)		2	-	-	-	-	-	1

4.3.2. Calculation of the peak power in relation to the operating temperatures

The heating power of radiators at different temperatures can be calculated with Equation 6 and Equation 7. They are proposed by Danish researchers in the field of low temperature heating as a good method to calculate the peak power available as a function of the new operating temperatures in the heating network from the original operating temperatures (D. S. Østergaard & Svendsen, 2016).

$$\phi = \left(\frac{\Delta T}{\Delta T_0}\right)^n \cdot \phi_0$$

Equation 6. ϕ: radiator heating power at the new temperature set, ΔT: logarithmic mean temperature difference at the new temperature set, ΔT_0: logarithmic mean temperature difference at the original temperature set. ϕ_0: radiator design heating power at the original temperature set, n: radiator exponent (standard value is 1.3).

$$\Delta T = \frac{T_{supply} - T_{return}}{\ln \frac{T_{supply} - T_{room}}{T_{return} - T_{room}}}$$

Equation 7. ΔT: logarithmic mean temperature difference. T: temperature.

Every peak power available can be achieved by different sets of supply and return temperatures with the same logarithmic mean temperature difference. In the results of this case study, the required peak power for a given scenario is related to two sets of supply and return temperatures:

- $\boldsymbol{Typical\ (Tsupply - Treturn) = 20ºC}$: a 20ºC typical supply and return temperature difference. Heating networks are typically designed for a temperature difference of 20ºC between supply and return temperature. A system with such a drop ensures a good efficiency in extracting the heat from the distribution lines.

- $\boldsymbol{Current\ (Tsupply - Treturn) = 8ºC}$**:** an 8ºC current supply and return temperature difference. While validating the current system, the real operating temperatures were downloaded from the building management system. The current temperature difference is calculated based on real data for a range of temperatures between 85-45ºC for the supply and 77-37ºC for the return. The current temperature drop of the system is 8ºC, which means the mass flow is relatively high.

It is relevant for the geothermal project which is the lowest return temperature that can be achieved in a given low temperature scenario. The lowest possible peak power is defined for each scenario, and for that peak power, a lower return temperature is achieved with the design temperature set than with the current one. However, in order to achieve the lower return temperature corresponding to the typical temperature difference, the current system would have to undergo physical changes to decrease the mass flow. It is therefore of importance to know which return temperature can be achieved with and without changing the system, so that an informed decision can be made during the practical implementation of the project.

Example of a calculation: the maximum peak power for one of the radiators in the building at the design temperatures of 90/70ºC is 611W. The new temperature sets are 60/40ºC for the typical temperature difference set and 53/45ºC for the current one. Both these sets of temperatures correspond to a heating power of 222W.

4.3.3. Analysis of the thermal comfort of the simulated scenarios with a given peak power

The simulation outputs for each scenario for a given available peak power are then processed and the analysis provides the graphs explained below:

- Winter week pattern. Graph representing a close view of the behaviour of the temperature of the air in the east room from the slice section. Room temperature for the different operating temperatures is shown together with the outside temperature for every hour of the second week of February.

- Discomfort hours during working hours. Room temperature below 19,5ºC is considered uncomfortable. This graph presents the number of discomfort hours in a year, at every hour of a working day. Working days for this office building are Monday to Friday from 8-22 h. It can be seen in the graph at which hour of the day the building cannot reach the comfort temperature and how many hours in a year this occurs in the current situation compared to a given low temperature scenario.

- Discomfort hours per month. This graph presents the number of discomfort hours in a year, per month. It helps to see in which months of the year might the thermal comfort be compromised by a limited peak power in the heating system.

- Heat demand per month. This shows how the adaptations taken up in the scenarios will influence the heat demand per month in the building, at the level of the section slice.

The graphs deriving from this analysis, per scenario, can be consulted in Appendix E, in page 76.

4.3.4. Procedure to define the lowest required peak power and related operating temperatures

The procedure to define the lowest required peak power of a modelled low temperature scenario is the following (see also schema in Figure 20):

1. The available peak power and related operating temperatures are set for the simulation of the scenario.
2. The analysis of the thermal comfort in the building is performed for that peak power.
3. The peak power set for the simulation is adjusted (by repeating steps 1 and 2) until the thermal comfort is just achieved. This point is reached when the thermal comfort is not compromised at that peak power, but a lower peak power will indeed compromise the thermal comfort.
4. The lowest required peak power and related operating temperatures are defined at that point.
5. The results for the simulation of the scenario at the defined lowest required peak power and operating temperatures are gathered.

The final results of the different scenarios are presented and compared in the next section, RESULTS.

4.4. RESULTS

The results of the case study conducted are presented in this section. The first section, 4.4.1, presents a graph which makes a comparison of the heat demand and thermal comfort obtained for every scenario's results. Next, a graphic overview of the most important results, lowest required peak power and related operating temperatures, is shown in section 4.4.2. Lastly, a description of the results per scenario is given in section 4.4.3.

4.4.1. Overview of the heat demand and discomfort hours of the scenarios

The heat demand and thermal comfort achieved for every scenario at the defined lowest required peak power and operating temperatures are gathered. These values are presented in the graph below (Figure 22):

- **Heat demand for a year** (kWh/m^2): the heat demand (shown with grey bars) of the current situation of the building is low; the building is well insulated. An increase in the heat demand is observed for the scenarios under the envelope adaptation, which is expected because a worse insulation of the windows and external walls was modelled.
- **Discomfort hours under 19,5 and 19ºC during working hours for a year** (number of hours): the thermal comfort is showed with blue bars. In the current situation, the number of discomfort hours under 19,5ºC is 9 hours. For all the scenarios, it is kept under 30 hours, and it is considered that the thermal comfort is achieved (except for the LT POOR INSULATION). Comments per scenario can be read in section 4.4.3 for a better understanding on why it is considered that the peak power and operating temperatures can be defined that low, even if the number of discomfort hours is higher than in the current situation.

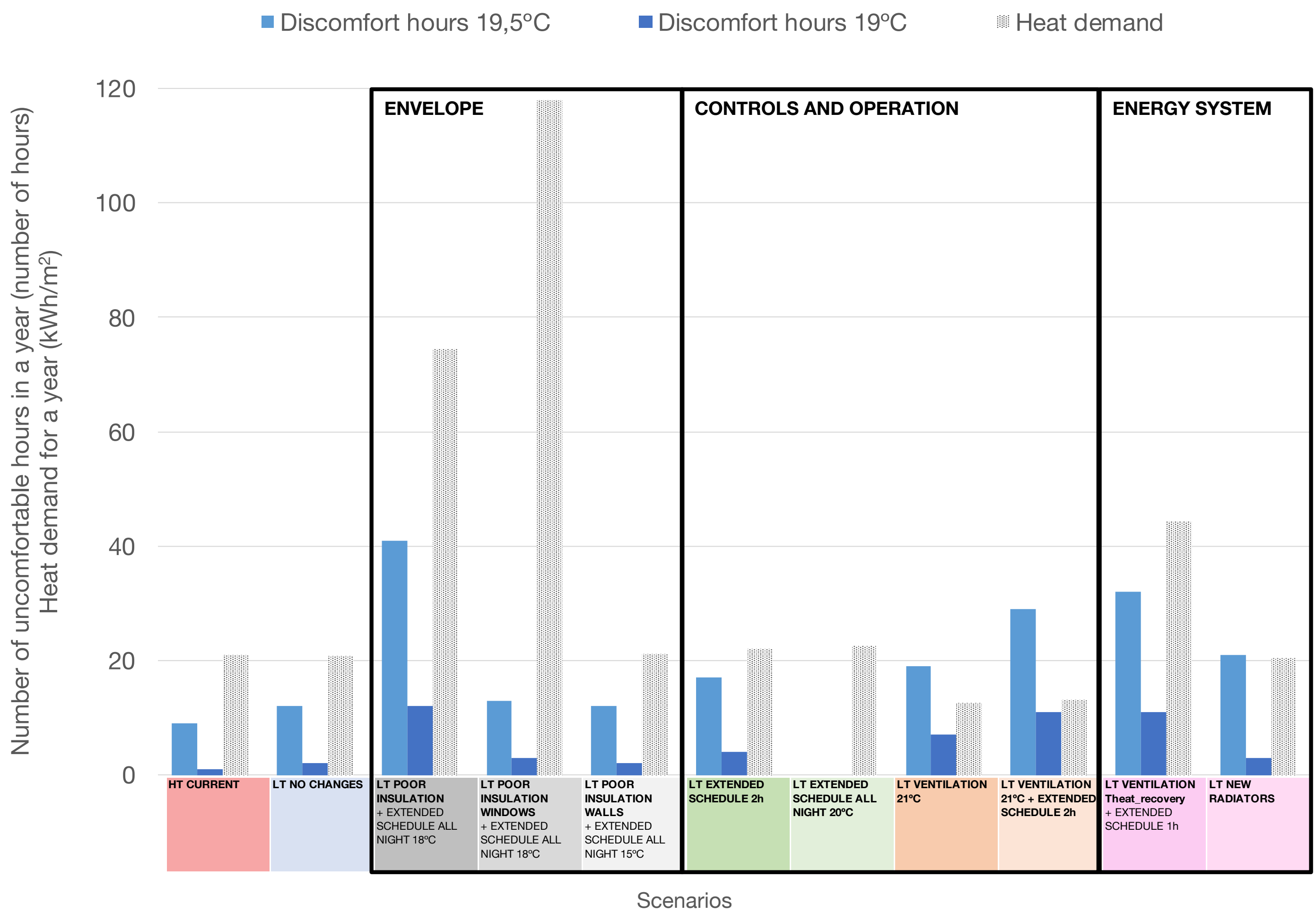

Figure 22. Scenarios comparison. Discomfort hours and heat demand for a year per scenario at the defined lowest required peak power and related operating temperatures.

4.4.2. Overview of the lowest required peak power and operating temperatures of the scenarios

The main result of the scenarios is the defined lowest required peak power and related operating temperatures that are enabled by the simulated adaptations. The following values are represented in Figure 23, a graphic overview of the results:

- **Lowest required peak power per radiator and per room** (W).
- **Lowest possible operating temperatures** (at both the $typical\ Tsupply - Treturn = 20ºC$ and $current\ Tsupply - Treturn = 8ºC$) (°C).

The most interesting results are that it is possible to lower the peak power, and thus the operating temperatures, in the current situation, without any adaptation, to 70/50°C. In the controls and operation scenarios, adjusting the room temperature setpoints and the heating schedules enables even lower supply and return temperatures, 50/35°C. When the renovations to the building's envelope are reversed in the envelope scenarios, it is not possible to lower the operating temperatures, which increase to 90/70°C. Changes in the energy system, such as the installation of radiators designed for lower temperature heating, also enable supply and return temperatures of 50/35°C.

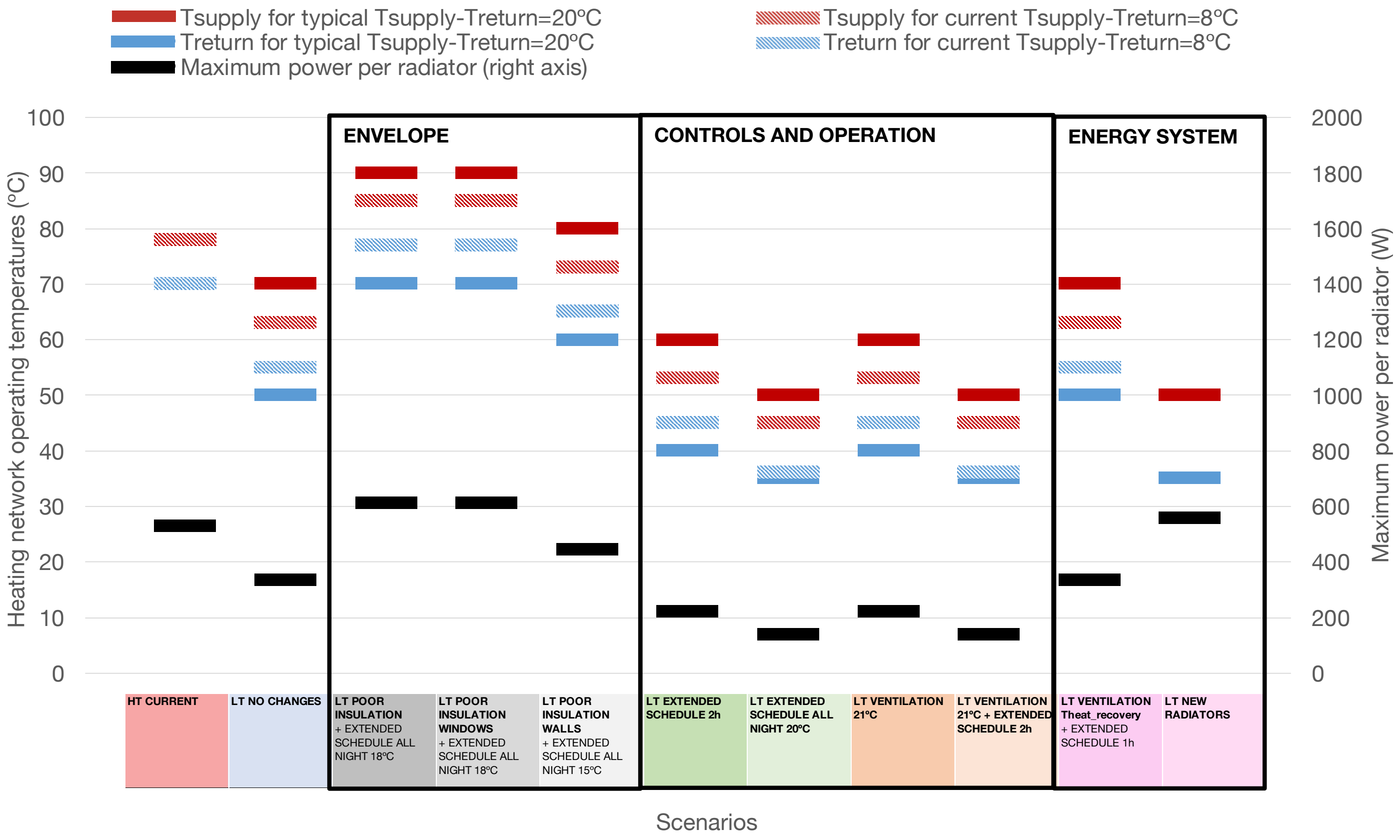

Figure 23. Scenarios comparison. Lowest possible operating temperatures on the secondary side of the heating network (left axis) and lowest required peak power (right axis) enabled by the adaptations simulated in the scenarios.

4.4.3. Description of the results per scenario

HT CURRENT

The peak power needed by the current system is 528 W per radiator, which corresponds to 86% of the expected installed power for the design temperatures of 90/70°C. Previous renovations in the envelope of the building and/or an over-dimensioning in the original design may be the reason why less power is required than installed. The system works with a supply temperature of 78°C and a return temperature of 70°C.

LT NO CHANGES

The low temperature scenario, with no adaptations of any kind, can work at lower operating temperatures than the current situation. Operating at supply temperature of 63°C and return of 55°C is possible, without changing the current supply and return temperature difference. If measures are taken to decrease the mass flow to that corresponding to a 20ºC temperature difference, operation temperatures can be 70 and 50ºC. The heat demand is the same as in the current situation and the thermal comfort is not compromised.

ENVELOPE

LT POOR INSULATION + EXTENDED SCHEDULE ALL NIGHT 18ºC

The maximum theoretical operating temperatures are necessary, 90/70ºC. The heat demand of the building rises tremendously. The thermal comfort is not covered at certain moments during the winter season.

LT POOR INSULATION WINDOWS + EXTENDED SCHEDULE ALL NIGHT 18ºC

The maximum required operating temperatures and corresponding mass flows are the same as in the complete poor insulation. The heat demand of the building rises to 117,9 kWh/m^2. However, the thermal comfort of the building is kept.

LT POOR INSULATION WALLS + EXTENDED SCHEDULE ALL NIGHT 15ºC

The operating temperatures can be lower than the theoretical design temperature, namely 80/60ºC. The heat demand of the building remains similar to the current situation.

CONTROLS AND OPERATION

LT EXTENDED SCHEDULE 2h

The operating temperatures can be as low as 60/40ºC. If the current supply and return temperature difference is considered, the temperatures are 53/45ºC. The heat demand of the building remains similar to the current situation and the number of discomfort hours in a year increases only slightly.

LT EXTENDED SCHEDULE ALL NIGHT 20ºC

The operating temperatures can be as low as 50/35ºC. The heat demand of the building is only a bit higher than in the current situation. The number of discomfort hours in a year is 0 hours under 19,5ºC and 0 hours under 19ºC, which is better than the current situation. The room temperature setpoint of 20ºC, workdays and weekends, day and night, is reached.

LT VENTILATION 21ºC

LT VENTILATION 21ºC + EXTENDED SCHEDULE 2h

For the two ventilation scenarios above, the operating temperatures can lower down to 60/40ºC and 50/35ºC respectively. The heat demand of the building decreases, which simply means that a higher percentage of the heat demand is covered by the ventilation pre-heating instead of the emission system. The thermal comfort of the building is affected; however, the operating temperatures are proposed to be that low because it is known that the building can for the most part be comfortably warm, and that extra measures in the heating schedule and temperature setpoints can cover the deficiencies of these concrete moments. It is observed that specially after the weekend, when the heating system was off, the comfort is compromised.

ENERGY SYSTEM

LT VENTILATION Theat_recovery + EXTENDED SCHEDULE 1h

Operating temperatures can only be lowered to 70/50ºC. The heat demand of the building increases, this only means that a lower percentage of the heat demand is covered by the ventilation compared to the emission heating system. Just as in the other ventilation scenarios, the thermal comfort of the building is slightly affected.

LT NEW RADIATORS

Operating temperatures can be lowered down to 50/35ºC. Since the water runs through a new radiator system, with a higher surface for heat delivery, the mass flow through a radiator is higher than in the previous scenarios where these temperatures were chosen. The heat demand of the building is virtually the same as in the current scenario. There is a small loss in thermal comfort, but since the second threshold of 19 degrees is good, and the possibility of extra adaptations is open, the decision remains to propose the mentioned operating temperatures.

5. DISCUSSION

The evaluation of the outcomes of the research is presented in this chapter. First, the interpretation of the results, per research sub-questions, is found in section 5.1. After that, the implications of the research, compared to other authors' findings, is found in section 5.2, to answer the main research question. Then, the limitations of this research are listed in section 5.3. Lastly, the recommendations for further research and practical implementation of the geothermal project, are to be found in section 0.

5.1. Interpretations and research sub-questions

1. Which adaptations are possible at building level to enable a lower temperature in the heating network?

The components of a building system relevant to enable low temperature heating were divided in three main categories (presented in Figure 3, in page 14): envelope, controls and operation and energy system. The envelope category is composed by the walls, roof, ceilings, floors and windows. The materials, thickness, insulation and infiltration through these surfaces are key elements to take into account. Controls and operation include temperature setpoints and schedules of the different installations of the energy system. The emission heating system and ventilation mainly form the energy system category. Storage, DHW production and other substation devices are also included in the energy system. Lastly, the context of the building ought to be considered too: the building type and year of construction and the occupants' schedules and accessibility to the building's operation and state.

2. How can a systematic collection of data and potential adaptations be made?

Deriving from the literature review performed for this research and from the case study, the main elements to consider were collected and are part of the resulting protocol for data collection and selection of promising adaptations. The protocol consists of six guided steps: 1) select approach of the project (simulation or practical test), 2) specify the original and new operating temperatures in the heating network, 3) select the case study building, 4) identify the data sources, 5) collect the data of the selected building and 6) select promising adaptations. An extensive table with the relevant data to be collected and a complete list of possible adaptations to consider in order to prepare a building to function at lower temperatures in the distribution network proved to be of use in the early stages of the project. The complete list of adaptations (previously presented in section 3.3, in page 29) is divided into three categories, namely the decrease of the heat losses, the smart operation of the heating system and the increase of the heating power at lower temperatures; in order of priority.

3. How does the mass flow affect the supply and return temperature?

The optimisation of the system is an interaction between four points: required peak power, desired return temperature, maximum supply temperature considered and mass flow lower and upper limits. It is of importance to know if there is a margin to lower the mass flow in the distribution lines of the heating system of the building. Lowering the mass flow increases the temperature difference between supply and return, which can be beneficial, because lower return temperatures are desired in order to increase the efficiency of the heat extracted from the water. However, for a given supply temperature in the heating network, a decrease in the mass flow leads to a decrease in the power output that the system can deliver. Therefore, the understanding of how much the peak power can be lowered without compromising the thermal comfort of the building will give an indication of what the lowest achievable return temperature is.

Here is an example of how the mass flow relates to the peak power and operating temperatures. Based on Equation 1, an indicative mass flow is obtained. The peak power delivered at 70/50ºC for the typical temperature difference set and 63/55ºC for the current one in the case study building is the same: 333 $W/radiator$. The mass flow for the 70/50ºC operating temperatures is 15 kg/h. The mass flow obtained for the current situation of the building is 37 kg/h. Measures to slow down the mass flow from 37 to 15 kg/h and work at 70/50ºC instead of 63/55ºC with the same peak power, will therefore extend the temperature difference from 8 to 20ºC. The maximum return temperature experiences then a 5ºC decrease; however, the supply temperature is increased.

Practical implementation of a reduction in the mass flow usually implies an initial investment in water pumps that can regulate the flow down in the distribution pipes from the heating system central installation through the emission system in the building.

4. How does lowering the supply temperature affect the building's thermal comfort when no adaptations are done?

Lowering the supply temperature leads to lower peak power and there comes a point when the thermal comfort of the building will be jeopardised. However, in the line of the initial hypothesis it is observed that in the building concerning this case study, there is a margin to lower the supply and return temperatures with no negative effect in the thermal comfort of the building. These results build on existing evidence that the heating systems are often over-dimensioned. Also, later renovations of the façade can contribute to lowering the peak power required by the system.

This research found that there is a margin to lower the peak power of the heating system in the simulated building without compromising the thermal comfort. Therefore, it is possible to lower the mass flow and obtain a lower return temperature. The required peak power can be lowered from 528 to 333 $W/radiator$ without any adaptations to the building. The related operating temperatures can be lowered from the current 78/70ºC to 63/55ºC without any adaptation. If the mass flow is slowed down to around half the current flow, 70/50ºC temperatures in the heating network can be achieved. With further controls and operation measures, thermal comfort can be extended to operation temperatures as low as 50/35ºC. It is the same case when the emission heating system is renovated.

The building is currently using a maximum temperature of around 80ºC, which is lower than the design temperature, but higher than what is necessary. The operation temperatures in the heating network can be lowered, also depending on the requirements of other buildings that share the district network.

5. How does each of the possible adaptations affect the required supply temperature?

5.A. How does the insulation of the façade affect the required supply temperature?

The case study building is well insulated, so three scenarios were defined in which the insulation of the façade was downgraded. The thickness of the insulation material in the external walls of the building was cut to half and the windows have single instead of double glazing. U-value of the external walls changed from 0,34 to 0,60 W/m^{2}K, which is expected to still be sufficient for low temperature heating. That of the windows, changed from 1,4 to 5,68 W/m^{2}K. These circumstances were studied both combined and separately.

As expected, the heat demand of the building increased, due to bigger heat losses through the envelope of the building. The increase was significantly high, up to five times the current heat demand in the windows scenario (117,9 compared to 21,0 kWh/m^2). A reasonable explanation is that the increase in the U-value from double to single glazing is significantly high; also, in this particular building, the ratio window and external wall surface is high.

The operating temperatures required in the poor insulation scenarios are the original high temperature for the windows scenario (90/70ºC) and a slightly lower temperature for the external walls scenario (80/60ºC). In contrast, with the good insulation from the current building, temperatures of 70/50ºC can be achieved.

The influence of the insulation of the façade on the required peak power and operating temperatures of the heating system is evident, and especially the glazing surfaces may have a relevant impact in the heat loss, increasing the heat demand.

5.B. How does the extension of the heating schedule affect the required supply temperature?

Office buildings usually have a heating schedule that matches the working hours of the occupants. In the current situation of the case study building, the heating schedule is 4-19 h, Monday to Friday, and 9-15 h, in the weekends. The room temperature setpoint is 21ºC. In that sense, there is a significant freedom to play around, extending the heating schedule and managing the temperature setpoints.

An all-night all-week heating schedule is introduced, maintaining the temperature above 20ºC in the rooms. Results of the research show that it is possible to lower the operating temperatures from 70/50ºC to 50/35ºC. This corresponds to a drop in the peak power from 333 to 139 W, with no negative effect whatsoever on the thermal comfort. It is worth mentioning that the heating demand does not increase excessively; from 21,0 to 22,5 kWh/m^2 per year.

When a high peak power is available, the building can rely on a steep increase in temperature when needed. Perhaps no smart algorithm to adjust the peak load to the temperature setpoint and outside temperature is required then. However, a smart operation of the heating system, such as avoiding the peak by not letting the thermal mass cool off, might allow to lower the required peak power and related operating temperatures and let the system work more efficiently. The insulation of the building is presumed to be of primary importance, since all-night schedules would lead to a high increase in energy demand if the heat losses through the envelope are high.

5.C. How does the temperature setpoint of the ventilation affect the required supply temperature?

Ventilation systems can supply air to the rooms at the outside temperature or already pre-heated, either by heat recovery alone or by pre-heating the air to a set temperature. The building of this research is provided with a ventilation system with heat recovery and pre-heating, set to a constant 19ºC. The heating of the ventilation air occurs through a heat exchange with water from the same distribution network as the heating system. The process of heating of the outside air to the set temperature is assumed to not be affected by a decrease in the operating temperatures; judging by the building management system, the ventilation system is ready for low temperature heating.

One scenario studied contemplates a situation where a bigger part of the heating demand is covered by the ventilation system: the air is preheated to 21ºC. Results show that the temperatures in the network can then be lowered down to 60/40ºC with only a small decrease in the thermal comfort (10 hours more of discomfort hours under 19,5ºC in a year, compared to the current scenario). When, in addition, an extended heating schedule is considered, the number of discomfort hours goes down, and temperatures of 50/35ºC can be reached.

In another scenario, a system with only heat recovery is studied. The ventilation air is introduced in the room at lower temperatures, and the heating system takes over the heat demand. For the same operating temperatures, 70/50ºC, the heat recovery scenario suffers a decrease in the thermal comfort: there is a jump from 12 to 32 discomfort hours per year under 19,5ºC. It is presumed that this effect can be counteracted with adjustments in controls and operations; nevertheless, the influence of the temperature setpoint of the ventilation system is noticeable.

Seeing the effect of the heating through ventilation air in lowering the supply and return temperatures in the district network, a central ventilation system with heat recovery and pre-heating that can operate at low temperatures can represent a good alternative to other decentralised adaptations in the energy system, such as changing radiators. The investment or the difficulty of one solution compared to another can help deciding.

5.D. How does the installation of lower temperature radiators affect the required supply temperature?

In the new radiators scenario, the two conventional high temperature radiators per room are replaced by one radiator designed for medium temperatures. The operating temperatures proposed for this new scenario are 50/35ºC. The discomfort time at those temperatures is somewhat higher than in the current situation, 21 hours compared to 9 hours in a year. In combination with small measures in operation and controls, these discomfort hours could be reduced while keeping these low temperatures.

The power delivered by low-temperature radiators is even higher, due to a higher heating surface area. This means that other upgrades in the energy system, like low temperature flat panel radiators or underfloor heating, will result in an immediate possibility to lower the operation temperatures. However, the investment costs and the effort and time required by such decentralised renovations should be taken into consideration and balanced against less invasive solutions first.

5.2. Implications and main research question

What are the effects of different feasible renovations in existing buildings on the required operating temperatures of the heating system?

This research adds to the observed lack of knowledge about potential measures to enable low temperature heating in existing buildings by providing a standardised procedure to identify potential solutions, and by providing more insight in the effect of the different solutions.

The results of the case study conducted are in line with the findings of similar research (Nagy et al., 2014; D. S. Østergaard & Svendsen, 2016), namely that it is possible to lower the heating network operating temperatures significantly by adapting existing buildings. The simulation performed was validated with real measured data. After some struggle separating the measured heat demand corresponding to the emission heating system from that of the ventilation system, the energy flows simulated were found to match those of the building sufficiently. As suggested by Brand & Svendsen (2013) and Francisco Pinto & Carrilho da Graça (2018), real data was helpful to get a realistic output and overcome unknown data. Room temperature data was also available, and the average was 21.2ºC, which agrees with the reported range of 21-22ºC for accuracy with occupants' requirements for thermal comfort.

This research was located in The Netherlands, such as most previous studies, in northern Europe. The case study building dates from the 1960s and the envelope was refurbished in the early 2000s. It is a non-residential building; the adaptation to low temperatures has barely been researched before in this type of buildings. The extension of the heating schedule (from working hours to all-night all-week) and room temperature setpoints (night setpoint of 20ºC) led to the possibility of lowering the operating temperatures from 70/50ºC to 50/35ºC. Mishra et al. (2019) also found flexibility in the energy performance of non-residential building when controls and operation strategies were implemented. Foteinaki et al. (2018) go a step further in adjusting the schedules and temperature setpoints. They studied the possibility of using the thermal mass of the building for passive storage of heat by elevating the temperature setpoint up to 24ºC during high energy availability periods, and decreasing it back to 20ºC during low energy availability periods, during which the heat stored in the thermal mass was released to the rooms. They efficiently manage the fluctuations in peak power available and heat demand. This suggests that in this case study building, further adjustments could lead to enabling even lower operating temperatures. Nevertheless, since the temperature setpoints are increased, it becomes important to establish not only the thermal comfort limit for underheating, but also for overheating.

Foteinaki et al. (2018) state that thermal storage is less effective when the building envelope insulation is poor. The envelope scenarios of this case study reached the same conclusions. Poor insulation was simulated, going from a U-value for windows from 1,4 to 5,6 W/m^{2}K. Operating temperatures could not be lowered more than 90/70ºC, with a night setpoint of 18ºC, in comparison to the 70/50ºC current state reference. D. S. Østergaard & Svendsen (2016) confirm these findings; original windows with U-values higher than 4 W/m^{2}K in old houses were pinpointed to be a key renovation to lower the heat demand as well as the operating temperatures in the heating network.

When heat losses through the envelope are low and a smart operation of the heating system is implemented, renovations in the energy system can be considered to enable even lower operating temperatures. A few studies (Brand & Svendsen, 2013; Hesaraki et al., 2015; Jangsten et al., 2017; D. Østergaard & Svendsen, 2017; Ovchinnikov et al., 2017) focus on the effect of renovations on the emission heating system, such as the installation of low-temperature radiators. The ventilation system can be improved by installing a system with heat recovery and furthermore with pre-heating of the supply air. Seeing the effect in the case study building of the pre-heating of the ventilation air in lowering operating temperatures, a central ventilation system with heat recovery and pre-heating that can operate at low temperatures can represent a good alternative to other decentralised adaptations in the energy system, such as changing radiators. Specific studies about the effects of adaptations in the ventilation system on the supply and return temperatures have not been found in literature.

The renovations of the envelope and the heating system of a building, together with a probable over-estimation of the heating power needed in the original design; lead to an over-dimensioning of the system (Jangsten et al., 2017). In the case study building, after renovation of the façade and ventilation system, results show that 55% of the theoretical power output of the conventional high temperature radiators is enough to keep the thermal comfort. When controls and operation adaptations are considered, even 23% of the original power is sufficient. These results add to the studies of Brand & Svendsen (2013), who compared the effect of renovations on the peak power and heat demand. They analysed the reduction achieved after light building refurbishment and observed a 25% reduction in heat demand and 20% reduction in peak heat output. In this research, the heat demand is maintained the same, since no renovations were studied because the building envelope had already been renovated. It was found that the heating system was over-dimensioned. This opens a margin to lower the peak power and related supply temperature, and to optimise the return temperature by adjusting the mass flow through the radiators. Also according to research (D. S. Østergaard & Svendsen, 2018) the current mass flow can be reduced in order to increase the temperature difference between the supply and return. The practical implications of this measure are discussed in the recommendations section.

This research agrees with recent research that it is possible to lower the operating temperatures in heating networks by adapting existing buildings. In old, poorly insulated buildings, minimal renovations in the buildings' envelope are crucial (and often sufficient) to enable low temperature heating. When heat losses are small, smart settings in the building management system to use the thermal mass of the building as storage prove successful to lower the supply temperature further. This research finds a margin to lower the required peak power; mass flow control through radiators ought to be implemented in order to obtain the lowest possible return temperature for a given supply temperature.

Judging from the similar findings from previous and current research, more standardised procedures can be implemented in the practise, in accordance to Paiho et al. (2019) as well. The developed data collection protocol provides an up-to-date overview on the topic and furthermore, it facilitates the first stages of a case study, by providing an inventory of the main elements for the data collection and their implication in lowering the operating temperatures in the heating network.

5.3. Limitations

The results presented in this report are subject to a number of limitations and uncertainties, listed below:

- Only the building level was analysed. The district level, interactions between different buildings, distribution network or energy sources were not contemplated.

- The building investigated was a university faculty building. It is possible to draw general conclusions about office buildings and multi-story apartment blocks, because of the similarity in the geometry of these types of buildings. However, the specific behaviour of other case study buildings ought to be analysed independently.

- Original building properties may differ slightly from the simulation because of the lack of some data. For example, the materials of walls are based on the R-value provided by a previous research; no specification on the composition of the layers could be found.

- The simulation model was done at slice (cross-section) level, containing two rooms and part of the corridor. During the validation phase, the assumption was made that the heat demand was equally distributed throughout the building floor area. The heat demand corresponding to the whole faculty building was slightly higher than that of the slice section. The slice represents most of the offices in the building; however, it should be taken into account that critical locations within the building might be missed, such as corner rooms or the top floor, where more walls are external. This was noted during the validation and can be accounted for when practical measures are implemented.

- The correlation between the results of the simulated scenarios and the implementation of the studied adaptations is not yet confirmed with practical tests. Nevertheless, the accessibility to real measured data made it possible to validate and trust the simulated models.

5.4. Recommendations

Recommendations for future scientific studies and the practical implementation of the results of this case study are presented in this section.

Further research

Future case studies could focus on fixing thresholds for the properties of the envelope (such as U-value of external walls and windows) that limit the lowering of the supply and return temperature, since it was found in this research and previous research that the insulation of the envelope is usually the main limiting factor.

Further research could also continue exploring the optimisation of schedules and room temperature settings to increment the possibility of lowering the temperature in the heating network. The use of the mass of the building as thermal storage can be a good option, however the specifics of the operation of the system to optimise the storage while keeping the thermal comfort are not clear. The upper and lower room temperature setpoint, as well as the duration and timing of the different setpoints should be studied further.

More case studies that investigate the possibility to reduce the required peak power and related operating temperatures and the effect of different adaptations in existing buildings will allow researchers to make generalisations. From those findings, it is possible to start developing one common standardised procedure, with recommended tools and guidelines for simulation as well as practical tests. The procedure should be improved with more case study results and possibly more and more concise possible adaptations. Lastly, the standard procedure at building level ought to be included as part of a holistic district level and building level approach in order to facilitate the transition to more efficient and sustainable heating networks.

Practical implementation of geothermal project

The results from the simulated low temperature no changes scenario show that it is possible to lower the operating temperatures from 78/70ºC to 63/55ºC without any changes in the building system.

An extension of the heating schedule from the current Monday to Friday, 4-19 h to a new schedule (Monday, 0-19 h; Tuesday to Friday, 2-19 h) allows for a further decrease in the supply return temperatures to 53/45ºC.

With an all-night scenario (Monday to Friday from 4-19 h with a temperature setpoint of 21,2ºC and the rest of the time 20ºC) temperatures can be as low as 45/36ºC.

The controls and operation adaptations to extend the heating schedule are especially interesting in this case study because the energy source to be implemented is a geothermal source. The production and injection wells will work continuously, therefore, an even distribution of the heating demand throughout the day and night times fits well with the operation of the heat extraction. Furthermore, the decrease in the necessary peak power with these scenarios, may allow the connection of more buildings to the network, if all of them are working under an optimized peak power.

It is recommended to reduce the mass flow in order to increase the supply and return temperatures difference, and thus improving the efficiency of the system. Simple calculations based on Equation 1 lead to the following: a reduction to half of the current mass flow, will lead to a temperature difference of about

20ºC. So, for the no-changes scenario, 70/50ºC, for the extended schedule, 60/40ºC and for the all-night schedule, 50/35ºC. Bigger differences could be achieved, getting closer to the desired 78/53ºC on the secondary side (or 80/55ºC on the primary side), since there is a big margin to lower the peak power. Physical limits to lower the flow rate through the pipelines should be studied. The next step is to investigate the concrete mass flows that will be implemented on a more technical level. Investments in pumps that can regulate the mass flow to the desired optimal return temperature are necessary.

A table is shown below with these three recommended scenarios and the possible design supply and return temperatures difference depending on the indicative calculation of the mass flow.

Table 7. Low temperature scenarios recommended for the geothermal project and the results per scenario.

SCENARIOS AND OUTPUTS					CONTROLS AND OPERATION	
			HT CURRENT	LT NO CHANGES	LT EXTENDED SCHEDULE 2h	LT EXTENDED SCHEDULE ALL NIGHT 20ºC
Heat demand (for a year)		kWh/m^2	21,0	20,8	22,0	22,5
Discomfort hours 19,5ºC (for a year)		Number of hours	9	12	17	0
Discomfort hours 19ºC (for a year)		Number of hours	1	2	4	0
Maximum power (per radiator)		W	528	333	222	139
Maximum power (per room)		W	0	667	444	278
Extended T_{supply}-T_{return} = 25ºC	Supply temperature	ºC	-	**73**	**63**	**55**
	Return temperature	ºC	-	**48**	**38**	**30**
	Mass flow	kg/h	-	12	8	5
Typical T_{supply}-T_{return} = 20ºC	Supply temperature	ºC	-	**70**	**60**	**52**
	Return temperature	ºC	-	**50**	**40**	**32**
	Mass flow	kg/h	-	15	10	6
Current T_{supply}-T_{return} = 10ºC	Supply temperature	ºC	**78**	**63**	**53**	**45**
	Return temperature	ºC	**70**	**55**	**45**	**36**
	Mass flow	kg/h	56	37	25	13

6. CONCLUSIONS

The transition from fossil fuels to renewable energy sources, brings along the reduction of the operating temperatures of the distribution heating networks. A case study was conducted by studying the performance of a non-residential building under different simulated scenarios to enable lower operating temperatures in the heating network.

The findings of this research agree with recent research that it is possible to lower the operating temperatures in heating networks by adapting existing buildings. The most interesting results derived from the case study are that it is possible to lower the peak power, and thus the operating temperatures, in the current situation of the selected building, without any adaptation, from 78/70°C to 63/55°C. Assuming that the mass flow is decreased in order to achieve a bigger temperature difference between supply and return, operating temperatures can be 70/50°C. Mass flow control through radiators should then be implemented in order to obtain the lowest possible return temperature for a given supply temperature. During the implementation phase of the geothermal project, the implications of this measure need to be studied.

When heat losses are small, smart settings in the building management system (adjustments in the heating schedule and temperature setpoints) prove successful to lower the supply temperature further. In the controls and operation scenarios, adjusting the room temperature setpoints and the heating schedules enables even lower supply and return temperatures, 50/35°C.

In old, poorly insulated buildings, minimal renovations in the buildings' envelope are crucial (and often sufficient) to enable low temperature heating. When the building without renovations was simulated, it was not possible to lower the operating temperatures; instead, the required temperature increased to 90/70°C.

Changes in the energy system, such as the installation of radiators designed for lower temperature heating, also enable supply and return temperatures of 50/35°C. The case study building has a ventilation system with heat recovery and pre-heating of air to 19°C. A scenario is simulated with a system with only heat recovery. The ventilation air is introduced in the room at lower temperatures, and the heating system takes over the heat demand. For the same operating temperatures, 70/50°C, the heat recovery scenario suffers a decrease in the thermal comfort. Seeing the effect of the heating through ventilation air in lowering the supply and return temperatures, a central ventilation system with heat recovery and pre-heating that can operate at low temperatures can represent a good alternative to other decentralised adaptations in the energy system, such as changing radiators.

The protocol for data collection and selection of promising adaptations created during this research facilitates the first stages of a case study, by providing an inventory of the main elements for the data collection and their implication in lowering the operating temperatures in the heating network. It also presents a list of possible adaptations to enable low temperature heating.

Future case studies could focus on fixing thresholds for the properties of the envelope that limit the lowering of the supply and return temperature. Further research could also continue exploring the optimisation of schedules and room temperature settings to lower the temperatures in the heating network even more, considering the possibility to use the thermal mass of the building as passive storage. Generalisations from case study findings are necessary to start developing one common standardised procedure, with recommended tools and guidelines for simulation as well as practical tests. The standard procedure at building level ought to be included as part of a holistic district level and building level approach in order to facilitate the transition to more efficient and sustainable heating networks.

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APPENDIX

A. RESEARCH FLOW DIAGRAMS

B. DATA OF THE BUILDINGS CONNECTED TO THE HEATING NETWORK

C. COLLECTED DATA

1. **Context and envelope**
2. **Energy system and parameters**

D. INPUTS SIMULATION

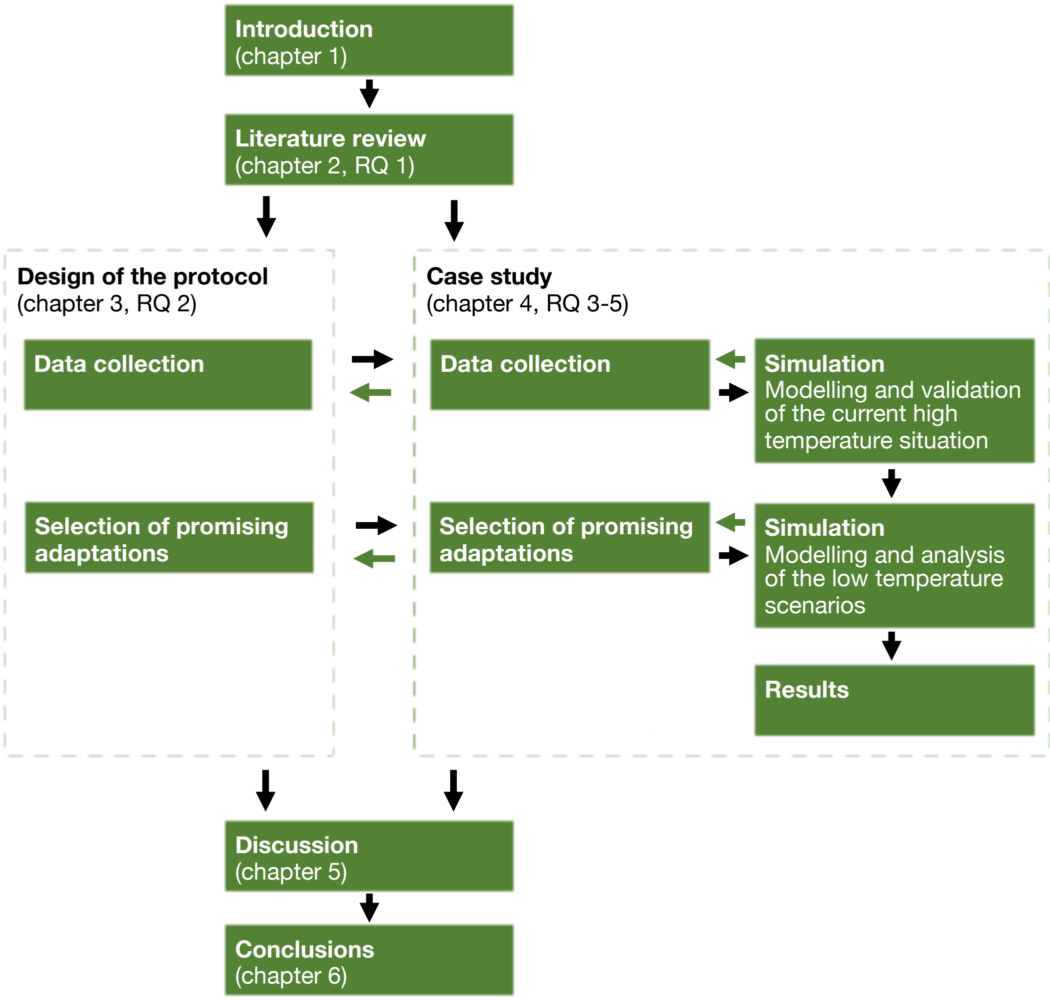
1. **Manager types**
2. **Buildings' surfaces**
3. **Buildings' controls and operation**
4. **Sections' surfaces**
5. **Sections' controls and operation**

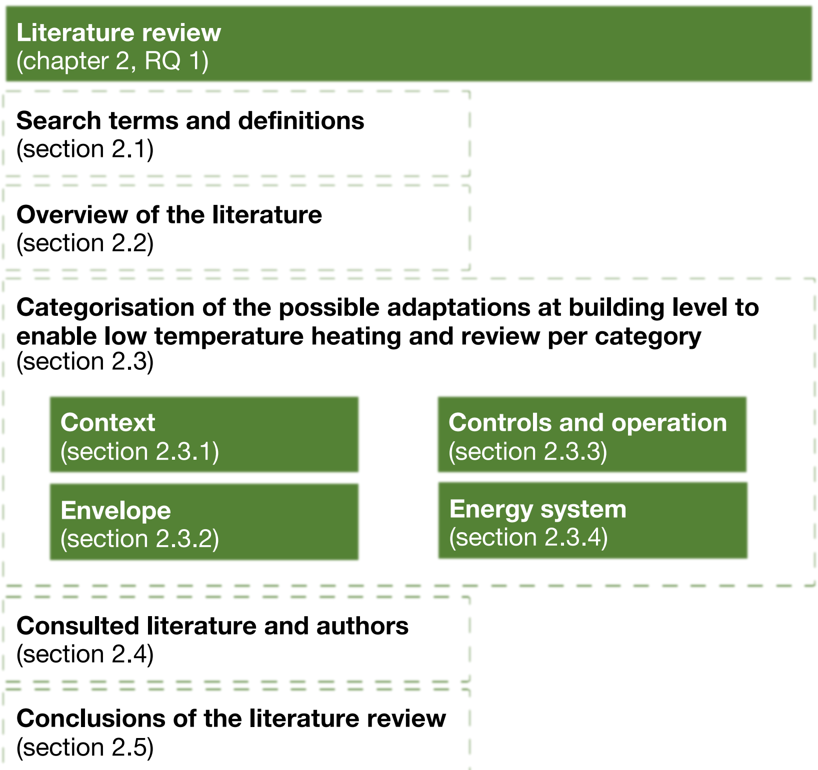
E. GRAPHS OF THE ANALYSIS OF THE SCENARIOS

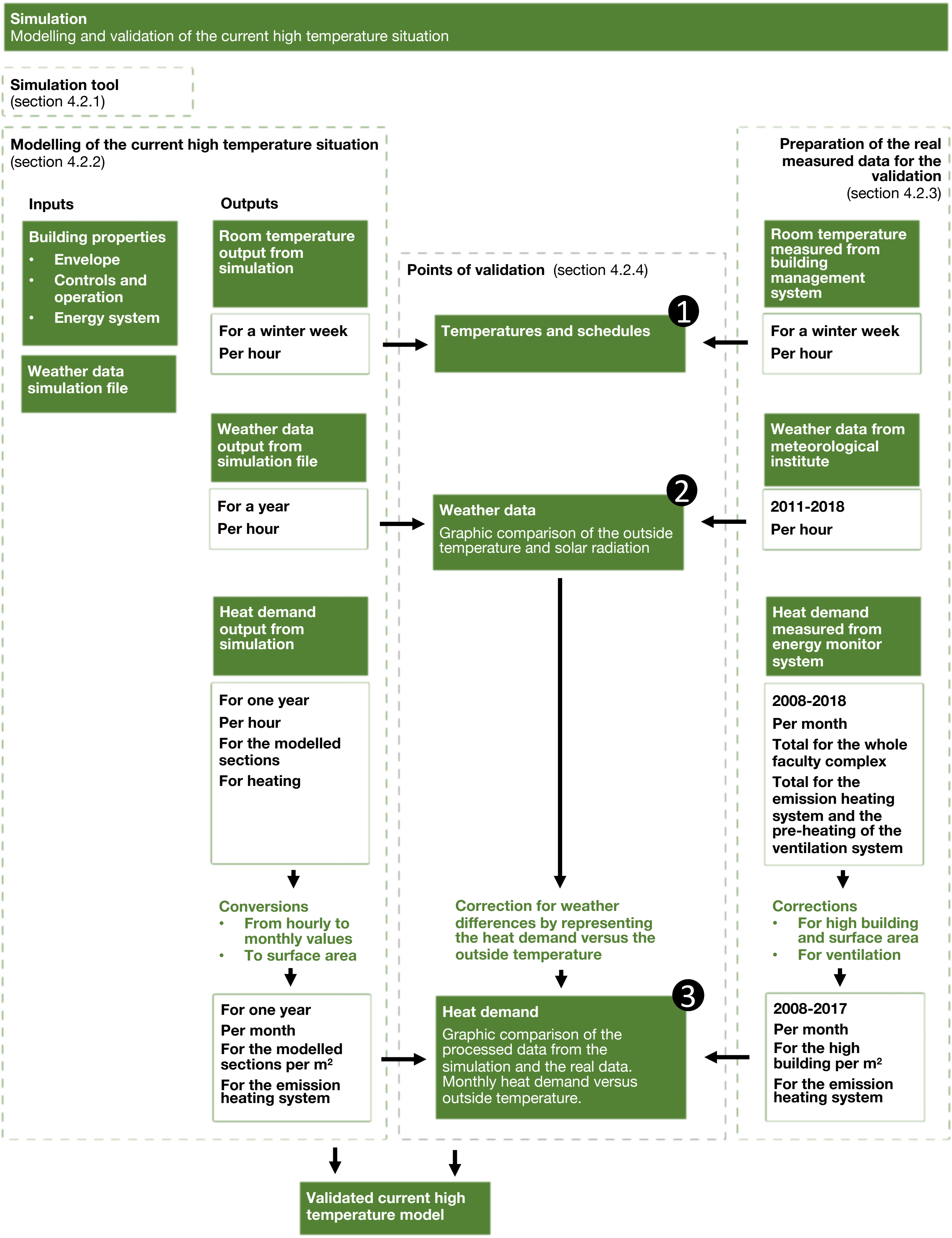
F. TABLES WITH THE RESULTS PER SCENARIO

1. **Theoretical, current, no changes and envelope**
2. **Controls and operation and energy system**

A. RESEARCH FLOW DIAGRAMS






Simulation
Modelling and validation of the current high temperature situation
Simulation tool
(section 4.2.1)
Modelling of the current high temperature situation
(section 4.2.2)
Inputs
Outputs
Building properties
• Envelope
• Controls and operation
• Energy system
Weather data simulation file
Room temperature output from simulation
For a winter week
Per hour
Weather data output from simulation file
For a year
Per hour
Heat demand output from simulation
For one year
Per hour
For the modelled sections
For heating
Conversions
• From hourly to monthly values
• To surface area
For one year
Per month
For the modelled sections per m²
For the emission heating system
Points of validation (section 4.2.4)
1
Temperatures and schedules
2
Weather data
Graphic comparison of the outside temperature and solar radiation
Correction for weather differences by representing the heat demand versus the outside temperature
3
Heat demand
Graphic comparison of the processed data from the simulation and the real data. Monthly heat demand versus outside temperature.
Preparation of the real measured data for the validation
(section 4.2.3)
Room temperature measured from building management system
For a winter week
Per hour
Weather data from meteorological institute
2011-2018
Per hour
Heat demand measured from energy monitor system
2008-2018
Per month
Total for the whole faculty complex
Total for the emission heating system and the pre-heating of the ventilation system
Corrections
• For high building and surface area
• For ventilation
2008-2017
Per month
For the high building per m²
For the emission heating system
Validated current high temperature model

Simulation
Modelling and analysis of the low temperature scenarios
(section 4.3)

Modelling of the low temperature scenarios
(section 4.3.1)

Calculation of the peak power in relation to the operating temperatures
(section 4.3.2)

Analysis of the thermal comfort of the simulated scenarios with a given peak power
(section 4.3.3)

Procedure to define the lowest required peak power and related operating temperature
(section 4.3.4)

1. **The available peak power and related operating temperatures are set for the simulation of the scenario**
2. **The analysis of the thermal comfort in the building is performed for that peak power**
3. **The peak power set for the simulation is adjusted until the thermal comfort is just achieved**
   This point is reached when the thermal comfort is not compromised at that peak power, but a lower peak power will indeed compromise the thermal comfort
4. **The lowest required peak power and related operating temperatures are defined at that point**
5. **The results for the simulation of the scenario at the defined lowest required peak power and operating temperatures are gathered**

B. DATA OF THE BUILDINGS CONNECTED TO THE HEATING NETWORK

Buildings TU Delft				Energy monitor			
Number	Subscript	Name	GBS	Gross floor area (m2)	Data available	Heating system	Cooling system
3		Science Centre	J	13100	Yes	Gas boilers	No
5		RoboValley	S	13700	Yes	Gas boilers	Electric (air treatment system)
5		RoboHouse	S	13700	Yes	Gas boilers	Electric (air treatment system)
6		Botanical Garden	S				
8		Architecture and the Built Environment (Arch)	S	47100	Yes	TU Delft heating network	Electric (air treatment system)
12		Chemical Engineering	J	28100	Yes	TU Delft heating network	Electric (air treatment system)
20		Aula Conference Centre	H	14100	Yes		
21		TU Delft Library	J	15100	Yes	Heat pumps from an underground heat and cold storage system	Heat pumps from an underground heat and cold storage system
21		University Corporate Office, department: Communication	J				
22		Applied Physics (AP)	J/S	43100	Yes	B-5 own gas boilers	Electric (air treatment system)
23		Civil Engineering and Geosciences (CEG)	H	66600	Yes	TU Delft heating network	Electric (air treatment system)
23		University Corporate Office, departments: Finance, Human Resources and Legal Services	H	66600	Yes	TU Delft heating network	Electric (air treatment system)
26		Blockchain, Delft Enterprises, M2I	J		Yes		
26		Valorisation Centre	J				
26		Bouwcampus	J				
26	b	Workcouncil, unions, student councils	J				
28		Mathematics & Computer Science (EEMCS)	J		Yes		
30		International Child Center	J	9300	Yes		
30	a	University Corporate Office, department: Education & Student Affairs	J				
30	b	University Corporate Office, department: Campus and Real Estate	J				
31		Technology, Policy and Management (TPM)	S	12400	Yes	TU Delft heating network	Electric (air treatment system)
32		Industrial Design Engineering (IDE)	J	34300	Yes	TU Delft heating network	Electric (air treatment system)
32		NewMedia Centre	J				
32		University Corporate Office, department: ICT & FM	J				
32	a	Teaching lab	J				
33	a	Pulse	J		Not yet	Heat pumps from an underground heat and cold storage system	Heat pumps from an underground heat and cold storage system
33	b	Coffee & Bikes	J				
34		Mechanical, Maritime and Materials Engineering (3mE)	J	47600	Yes	Mainly TU Delft heating network	Electric (air treatment system)
34		University Corporate Office, department: Strategic Development	J				
34	a	Executive Board / Supervisory Board	J				
34	b	Process & Energy Laboratory	J				
35		Education Building 35	J	5200	Yes		
36		Electric Engineering (EEMCS)	J	67900	Yes	TU Delft heating network	Electric (air treatment system)
36		University Corporate Office, department: Electronic and Mechanical Support Division	J				
37	38	X (former Sports & Culture)	J	11600	Yes	TU Delft heating network	Electric (air treatment system)
45		Low-speed Wind Tunnel Laboratory	H	3900	Yes		
46		TNO	H				
58		Applied Sciences (AP South Building)	H	32000	Yes	Heat pumps from an underground heat and cold storage system	Heat pumps from an underground heat and cold storage system
60		Logistics and Environment	S				
62		Aerospace Engineering (AE)	H	21100	Yes		
66		The Fellowship	J	4800	Yes		
67		Industrial Catalysis Lab	J				

C. COLLECTED DATA

1. Context and envelope

CONTEXT	Level 1	Level 2	Level 3		
Building	Type	Residential	Single-family house		Campus and Real State
			Multi-story appratment block		
		Non-residential		✓	
	Location			Delft	Campus and Real State
	Year of construction			1965	Campus and Real State
	Year of refurbishment			Early 2000s	Deerns
Occupants	Accessibility to system operational settings			No or limited	Building visit and observation
	Accessibility to open windows and doors			Yes	Building visit and observation
	Internal gains	Number of people		Estimation, educated guess	Building visit and observation
		Schedules		Workdays Monday to Friday 8-22 h	Deerns
		Electrical appliances		Estimation, educated guess	Building visit and observation
		Lighting		Estimation, educated guess	Building visit and observation

ENVELOPE					
Walls, roof, ceiling, floor	Geometry	Length, height and depth, areas of building, orientation and relative location		Building plans	Campus and Real State
	Composition	Materials and thickness of the layers		Building documentation	Deerns
	U-value			From R-values	Deerns
	R-value			Report and R-values	Deerns
	Insulation	Bad	Cracks, unsealed frames, high U-value, low R-value		Deerns
		Good	No cracks, sealed frames, low U-value, high R-value	✓	
Windows	Type	Single glass			Deerns
		Double glass		✓	
		Triple glass			
	Geometry	Area, orientation		Yes	Campus and Real State
	u-value			1,8	Deerns
	g-value			Yes	Deerns
	Frame to glass ratio			Yes	Deerns
Infiltration	High	Big cracks and openings in the buildings' envelope			Bibliography
	Low	No cracks and openings in the buildings envelope		✓	
	Infiltration rate (airchange 1/h)	Difficult to find or calculate, usually taken from literature. Typical values: badly insulated (>0,6 0 airchange 1/h), well insulated (0,15-0,25 airchange 1/h)		0,25 estimated	Bibliography

2. Energy system and parameters

ENERGY SYSTEM					
Ventilation	Type	Natural			Honeywell
		Mechanical	Supply		
			Exhaust		
			Supply-exhaust with heat recovery		
			Supply-exhaust with heat recovery and pre-heat air	✓	
	Ventilation rate			Found in plans and compared to typical rates	Campus and Real State
	Heat recovery efficiency			Not found, calculated from measured temperatures	Honeywell
	Humidity			Estimated	Bibliography
	Temperture setpoint			19ºC	Honeywell
	Schedule			Mon-Fri, 6-22 h	Honeywell
Emission heating system	Type	Conventional panel radiators. High design T (95/70ºC)	Single plate	✓	Campus and Real State
			Multiple plates	✓	
			No internal convection fins	✓	
			Few internal convetion fins	✓	
		Forced convection radiators. Medium (55/45-40ºC) and low design temperature (45/35-25ºC)	Ventilation		
			Add-on fan		
		Flat panel heating. Low design temperature (35/25ºC)	Ceiling		
			Under floor heating	✓	
			Wall heating		
	Type (10-100)			10	Campus and Real State
	Power output			602 Wh per radiator	Bibliography
	Dimentions			10x400x1400	Campus and Real State
	Schedule			Mon-Fri, 4-19 h Sat-Sun, 9-15 h	Honeywell
	Number and location of radiators			2 per room	Campus and Real State
DHW	Connected to space heating				Campus and Real State
	Seperate from space heating			✓	
Storage	Passive storage	Thermal mass of building used as storage		No or limited	Campus and Real State
	Other storage				
Conversion/Substation	Heat pump			No or limited	
	Heat exchanger			Yes	
	Boiler				

CONTROLS AND OPERATION	Description		
Room temperature setpoint	For simulations, even if the temperature is set to 20ºC, 21 or 22 degrees is a more accurate guess. Winter and summer might have a different setpoint	21,2	Honeywell
Other relevant operation setpoints	Think of special settings, schedules, temperatures, air flows, holidays	Almost no special schedules for holidays	TU Delft CHP plant

MEASURED DATA			
Heat demand	Thermal energy demand of the building. It is usuful to collect data for at least the winter period, or a whole year. Preferably you will have data over multiple years. It is a good way to validate the simulation outputs.	Lots of data available per month for decades	TU Delft CHP plant
Peak power demand		Calculated from temperatues	Bibliography
Supply and return temperature demand	Even though the building was designed for a specific supply and return temperatures in the network, it doesn't always requires the highest temperature to achieve the thermal confort. Real temperatures required over a period of time can help during the building selection process, data validation and after a practical test to check if temperature demand decreases after renovation.	Design temperatures known, actual operating temperatures measured and available	Honeywell

WEATHER DATA			
Average temperatures and solar radiation at the location	You can either use real weather data in the simulation or check the predictive simulation file agaist real weather to validate it.	Simulation file compared to actual data	Royal Netherlands Meteorological Institute

D. INPUTS SIMULATION

1. Manager types

MANAGER TYPES

Window	
Name	DOUBLE
area frame/window	0,2
u-value (W/m^2K)	1,4
g-value (%/100)	0,589

Layer								
Name	BRICK	CONCRETE	GYPSUM	INSUL	PLASTER	FLOOR	SILENCE	STONE
Type	massive	massive	massive	massive	massive	massive	massive	massive
Conductivity	3,2 kJ/hmK	7,56 kJ/hmK	0,756 kJ/hmK	0,144 kJ/hmK	5 kJ/hmK	0,252 kJ/hmK	0,18 kJ/hmK	5 kJ/hmK
Capacity	1 kJ/kgK	0,8 kJ/kgK	1 kJ/kgK	0,8 kJ/kgK	1 kJ/kgK	1 kJ/kgK	1,44 kJ/kgK	1 kJ/kgK
Density	1800 kg/m^3	2400 kg/m^3	1200 kg/m^3	40 kg/m^3	2000 kg/m^3	800 kg/m^3	80 kg/m^3	2000 kg/m^3

Wall					
Name	GROUND	INTFLOOR	INTWALL	OUTWALL	ROOF
Layer	FLOOR	FLOOR	GYPSUM	BRICK	CONCRETE
Thickness (m)	0,005	0,005	0,012	0,200	0,240
	STONE	STONE	INSUL	INSUL	INSUL
	0,060	0,060	0,050	0,100	0,160
	SILENCE	SILENCE	GYPSUM	PLASTER	
	0,040	0,040	0,012	0,015	
	CONCRETE	CONCRETE			
	0,240	0,240			
	INSUL				
	0,080				
Total thickness (m)	0,425	0,345	0,074	0,315	0,400
U-value (W/m^2K)	0,313	0,834	0,652	0,344	0,233
R-value (m^2K/W)	3,022	1,026	1,360	2,734	4,119

Infiltration		
Name	INFIL_BIG	INFIL_SMALL
Airchange of	constant	constant
	0,6 1/h	0,25 1/h

Ventilation							
Name	VENT_FLOOR	VENT_ROOM_W	VENT_ROOM_E	VENT_HIGH	VENT_LOW	VENT_NEW	VENT_SIMONA
Airflow	mass flow rate	mass flow rate	mass flow rate	mass flow rate	mass flow rate	mass flow rate	mass flow rate
	schedule	schedule	schedule	schedule	schedule	schedule	schedule
	VENT	VENT	VENT	VENT	VENT	VENT	VENT
	5258*VENT kg/h	279*VENT kg/h	229*VENT kg/h	75298*VENT kg/h	12280*VENT kg/h	7826*VENT kg/h	2061*VENT kg/h
Temperature of	other	other	other	other	other	other	other
	19 ºC	19 ºC	19 ºC	19 ºC	19 ºC	19 ºC	19 ºC
Humidity of airflow	relative	relative	relative	relative	relative	relative	relative
	outside	outside	outside	outside	outside	outside	outside

Heating	
Name	HEAT_UNLIMITED
Room temperature control	constant
	21 ºC
Heating power	limited
	schedule
	RAD
	50000000*RAD kJ/h
Radiative part	constant
	0,3%/100
Humidification	off

Cooling	
Name	COOL_UNLIMITED
Room temperature control	constant
	21 ºC
Cooling power	limited
	schedule
	RAD
	50000000*RAD kJ/h
Dehumidification	off

Schedule								
Name	WORKDAYS	WEEKEND	WEEK	VENT_WORKDAYS	VENT	RAD_WORKDAYS	RAD_WEEKEND	RAD
Type	daily	daily	weekly	daily	weekly	daily	daily	weekly
From/Until/Value	00:00-06:00/0	00:00-01:00/0		00:00-06:00/0		00:00-04:00/0	00:00-09:00/0	
	06:00-18:00/1	01:00-24:00/0		06:00-22:00/1		04:00-19:00/1	09:00-15:00/1	
	18:00-24:00/0			22:00-24:00/0		19:00-24:00/0	15:00-24:00/0	
Monday			WORKDAYS		VENT_WORKDAYS			RAD_WORKDAYS
Tuesday			WORKDAYS		VENT_WORKDAYS			RAD_WORKDAYS
Wednesday			WORKDAYS		VENT_WORKDAYS			RAD_WORKDAYS
Thursday			WORKDAYS		VENT_WORKDAYS			RAD_WORKDAYS
Friday			WORKDAYS		VENT_WORKDAYS			RAD_WORKDAYS
Saturday			WEEKEND		WEEKEND			RAD_WEEKEND
Sunday			WEEKEND		WEEKEND			RAD_WEEKEND

2. Buildings' surfaces

BUILDING SURFACES				
	AREA (m^2)	TYPE	CATEGORY	ORIENTATION
HIGH	**19220,16**			
WALLS				
N	603,00	OUTWALL	EXTERNAL	N_180_90
S	603,00	OUTWALL	EXTERNAL	S_0_90
E	2225,70	OUTWALL	EXTERNAL	E_270_90
W	2225,70	OUTWALL	EXTERNAL	W_90_90
FLOOR	18557,39	INTFLOOR	BOUNDARY	
GROUND	662,76	GROUND	EXTERNAL	H_0_0
ROOF	662,76	ROOF	EXTERNAL	H_0_0
WINDOWS		DOUBLE	EXTERNAL	
N	160,80			N_180_90
S	160,80			S_0_90
E	1424,45			E_270_90
W	1424,45			W_90_90
LOW	**2616,90**			
WALLS				
N	85,80			
S	85,80			
E	274,50			
W	274,50			
GROUND	2616,90	GROUND	EXTERNAL	H_0_0
ROOF	2616,90	ROOF	EXTERNAL	H_0_0
WINDOWS		DOUBLE	EXTERNAL	
N	54,91			N_180_90
S	54,91			S_0_90
E	175,68			E_270_90
W	175,68			W_90_90
NEW	**1811,84**			
WALLS				
N	262,20	OUTWALL	EXTERNAL	N_180_90
S	262,20	OUTWALL	EXTERNAL	S_0_90
E	441,60	OUTWALL	EXTERNAL	E_270_90
W	441,60	OUTWALL	EXTERNAL	W_90_90
FLOOR	905,92	INTFLOOR	BOUNDARY	
GROUND	905,92	GROUND	EXTERNAL	H_0_0
ROOF	905,92	ROOF	EXTERNAL	H_0_0
WINDOWS		DOUBLE	EXTERNAL	
N	167,81			N_180_90
S	167,81			S_0_90
E	282,62			E_270_90
W	282,62			W_90_90
SIMONA	**476,85**			
WALLS				
N	95,37	OUTWALL	EXTERNAL	N_180_90
S	95,37	OUTWALL	EXTERNAL	S_0_90
E	45,00	OUTWALL	EXTERNAL	E_270_90
W	45,00	OUTWALL	EXTERNAL	W_90_90
GROUND	476,85	GROUND	EXTERNAL	H_0_0
ROOF	476,85	ROOF	EXTERNAL	H_0_0
WINDOWS		DOUBLE	EXTERNAL	
N	61,04			N_180_90
S	61,04			S_0_90
E	28,80			E_270_90
W	28,80			W_90_90
COMPLEX	**24125,75**			

3. Buildings' controls and operation

REGIME	INFILTRATION	VENTILATION	HEATING	COOLING	GAINS			COMFORT	HUMIDITY MODEL	INITIAL VALUES
HIGH_BUILDING	on INFIL_SMALL	VENT_HIGH	on HEAT_UNLIMITED	on COOL_UNLIMITED	Persons on ISO 7730 Seated, very light work schedule WEEK 140*WEEK people	Computer on 140W PC with monitor schedule WEEK 140 computers	Artificial lighting on related floor area 15000 m^2 heat gain 5 W/m^2 schedule WEEK	off	Simple humidity model	Zone temperature 20ºC Relative humidity 50%
LOW_BUILDING	on INFIL_SMALL	VENT_LOW	on HEAT_UNLIMITED	on COOL_UNLIMITED	Persons on ISO 7730 Seated, very light work schedule WEEK 30*WEEK people	Computer on 140W PC with monitor schedule WEEK 30 computers	Artificial lighting on related floor area 2500 m^2 heat gain 5 W/m^2 schedule WEEK	off	Simple humidity model	Zone temperature 20ºC Relative humidity 50%
NEW_BUILDING	on INFIL_SMALL	VENT_NEW	on HEAT_UNLIMITED	on COOL_UNLIMITED	Persons on ISO 7730 Seated, very light work schedule WEEK 30*WEEK people	Computer on 140W PC with monitor schedule WEEK 30 computers	Artificial lighting on related floor area 1800 m^2 heat gain 5 W/m^2 schedule WEEK	off	Simple humidity model	Zone temperature 20ºC Relative humidity 50%
SIMONA	on INFIL_SMALL	VENT_SIMONA	on HEAT_UNLIMITED	on COOL_UNLIMITED	Persons on ISO 7730 Seated, very light work schedule WEEK 10*WEEK people	Computer on 140W PC with monitor schedule WEEK 10 computers	Artificial lighting on related floor area 400 m^2 heat gain 5 W/m^2 schedule WEEK	off	Simple humidity model	Zone temperature 20ºC Relative humidity 50%

4. Sections' surfaces

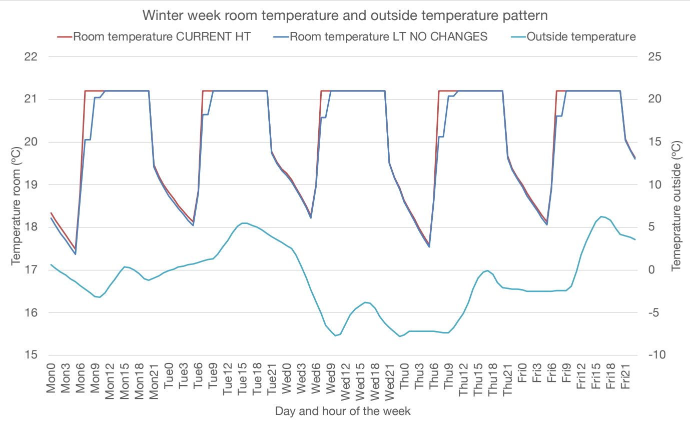
BUILDING SURFACES				
	AREA (m^2)	TYPE	CATEGORY	ORIENTATION
FLOOR				
WALLS				
N	40,20	OUTWALL	EXTERNAL	N_180_90
S	40,20	OUTWALL	EXTERNAL	S_0_90
E	148,38	OUTWALL	EXTERNAL	E_270_90
W	148,38	OUTWALL	EXTERNAL	W_90_90
FLOOR	1325,53	INTFLOOR	BOUNDARY	
WINDOWS		DOUBLE	EXTERNAL	
N	10,72			N_180_90
S	10,72			S_0_90
E	94,96			E_270_90
W	94,96			W_90_90
ROOM				
WALLS				
N	15,18	INTWALL	BOUNDARY	
S	15,18	INTWALL	BOUNDARY	
E	10,80	INTWALL	BOUNDARY	
W	10,80	OUTWALL	EXTERNAL	W_90_90
FLOOR	36,43	INTFLOOR	BOUNDARY	
WINDOWS		DOUBLE	EXTERNAL	
W	7,83			W_90_90
SLICE				
ROOM_W				
WALLS				
N	15,18	INTWALL	BOUNDARY	
S	15,18	INTWALL	BOUNDARY	
E	10,80	INTWALL	ADJACENT	CORRIDOR
W	10,80	OUTWALL	EXTERNAL	W_90_90
FLOOR	36,43	INTFLOOR	BOUNDARY	
WINDOWS		DOUBLE	EXTERNAL	
N	-			
ROOM_E				
WALLS				
N	15,18	INTWALL	BOUNDARY	
S	15,18	INTWALL	BOUNDARY	
E	10,80	OUTWALL	EXTERNAL	E_270_90
W	10,80	INTWALL	ADJACENT	CORRIDOR
FLOOR	36,43	INTFLOOR	BOUNDARY	
WINDOWS		DOUBLE	EXTERNAL	
N	-			
W	-			
CORRIDOR				
WALLS				
N	9,84	INTWALL	BOUNDARY	
S	9,84	INTWALL	BOUNDARY	
E	10,80	INTWALL	ADJACENT	ROOM_E
W	10,80	INTWALL	ADJACENT	ROOM_W
FLOOR	23,62	INTFLOOR	BOUNDARY	

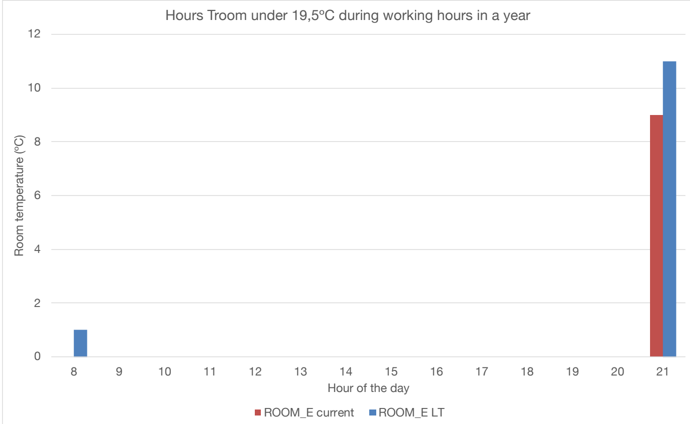
5. Sections' controls and operation

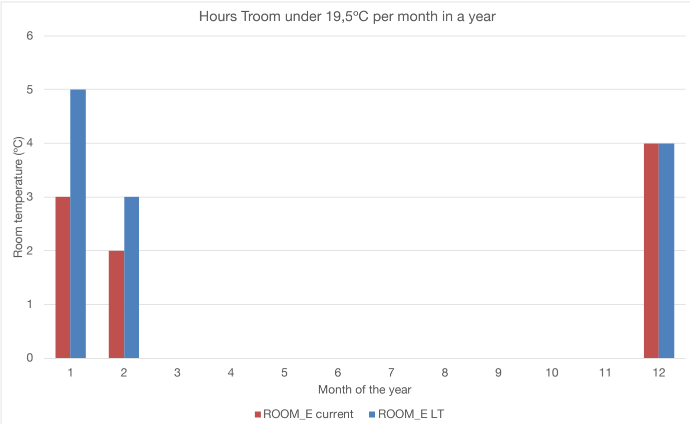
REGIME	INFILTRATION	VENTILATION	HEATING	COOLING	GAINS			COMFORT	HUMIDITY MODEL	INITIAL VALUES
FLOOR	on INFIL_SMALL	VENT_FLOOR	on HEAT_UNLIMITED	on COOL_UNLIMITED	Persons on ISO 7730 Seated, very light work schedule WEEK 15*WEEK people	Computer on 140W PC with monitor schedule WEEK 10 computers	Artificial lighting on related floor area 600 m^2 heat gain 5 W/m^2 schedule WEEK	off	Simple humidity model	Zone temperature 20ºC Relative humidity 50%
ROOM	on INFIL_SMALL	VENT_ROOM_W	on HEAT_UNLIMITED	on COOL_UNLIMITED	Persons on ISO 7730 Seated, very light work schedule WEEK 1*WEEK people	Computer on 140W PC with monitor schedule WEEK 1 computers	Artificial lighting on related floor area 18 m^2 heat gain 5 W/m^2 schedule WEEK	off	Simple humidity model	Zone temperature 20ºC Relative humidity 50%
SLICE										
ROOM_W	on INFIL_SMALL	VENT_ROOM_W	on HEAT_UNLIMITED	on COOL_UNLIMITED	Persons on ISO 7730 Seated, very light work schedule WEEK 1*WEEK people	Computer on 140W PC with monitor schedule WEEK 1 computers	Artificial lighting on related floor area 18 m^2 heat gain 5 W/m^2 schedule WEEK	off	Simple humidity model	Zone temperature 20ºC Relative humidity 50%
ROOM_E	on INFIL_SMALL	VENT_ROOM_E	on HEAT_UNLIMITED	on COOL_UNLIMITED	Persons on ISO 7730 Seated, very light work schedule WEEK 1*WEEK people	Computer on 140W PC with monitor schedule WEEK 1 computers	Artificial lighting on related floor area 18 m^2 heat gain 5 W/m^2 schedule WEEK	off	Simple humidity model	Zone temperature 20ºC Relative humidity 50%
CORRIDOR	on INFIL_BIG	off	on HEAT_UNLIMITED	on COOL_UNLIMITED	Persons off	Computer off	Artificial lighting on related floor area 4 m^2 heat gain 5 W/m^2 schedule WEEK	off	Simple humidity model	Zone temperature 20ºC Relative humidity 50%

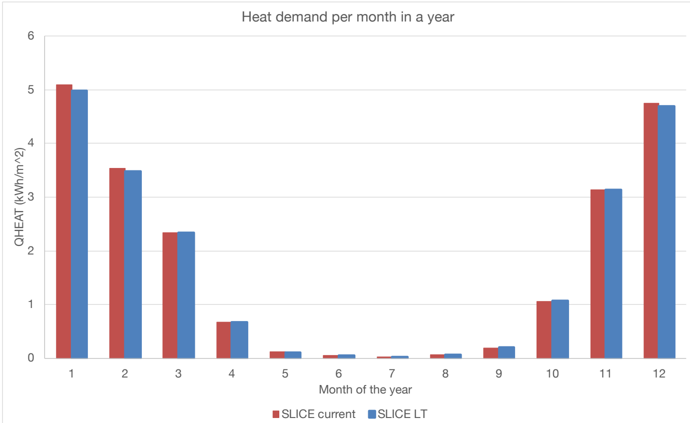
E. GRAPHS OF THE ANALYSIS OF THE SCENARIOS

LT NO CHANGES

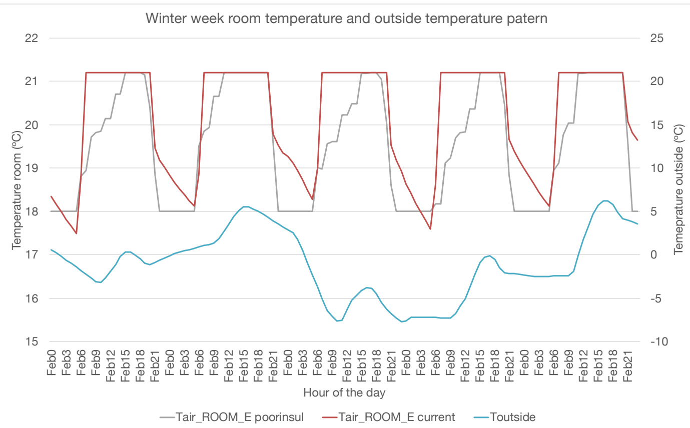


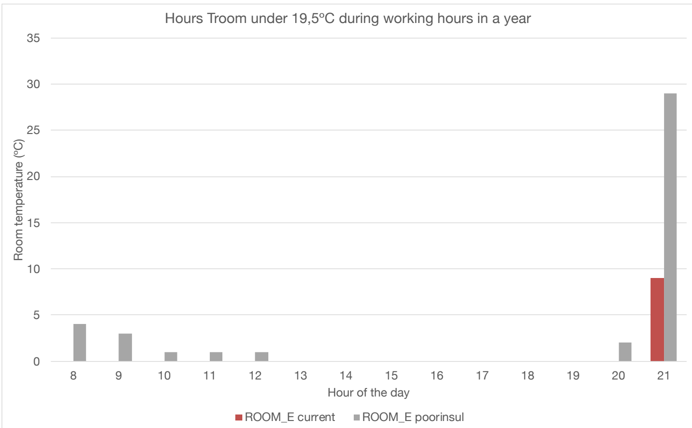


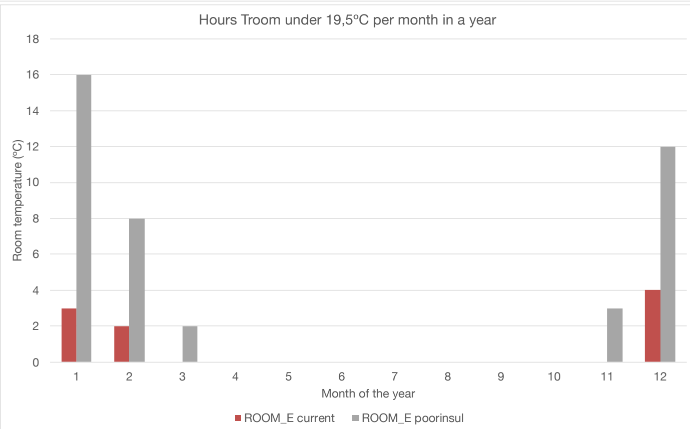


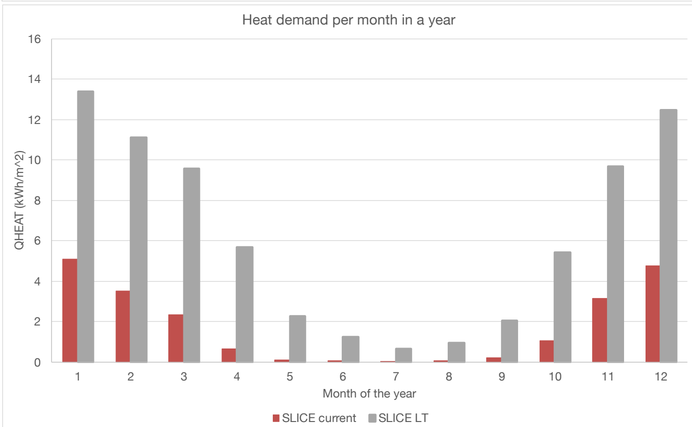


LT POOR INSULATION + EXTENDED SCHEDULE ALL NIGHT 18ºC

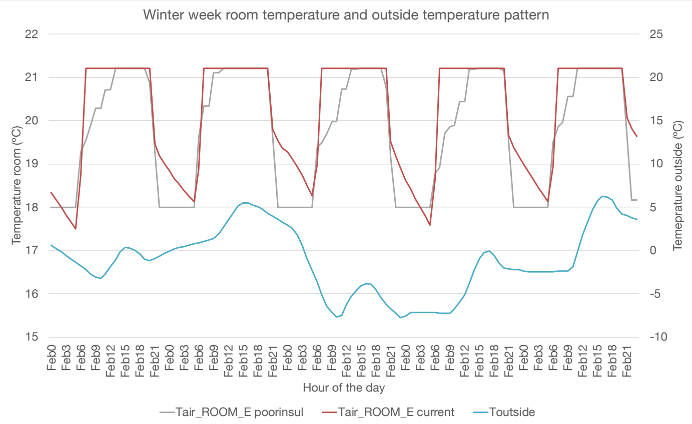


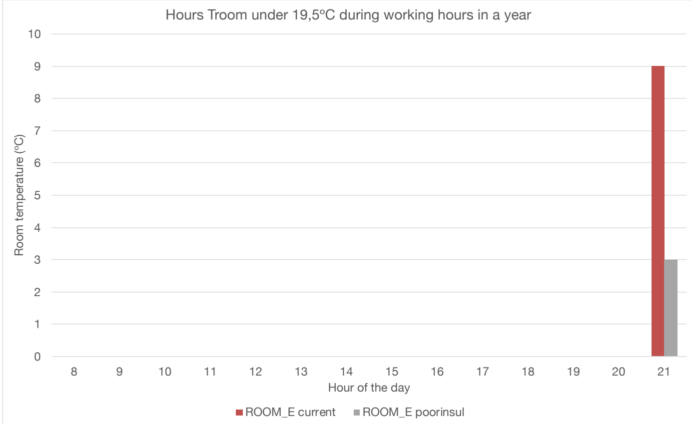


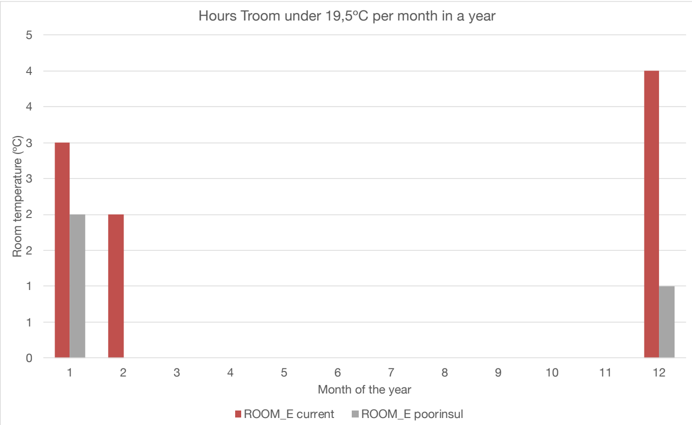


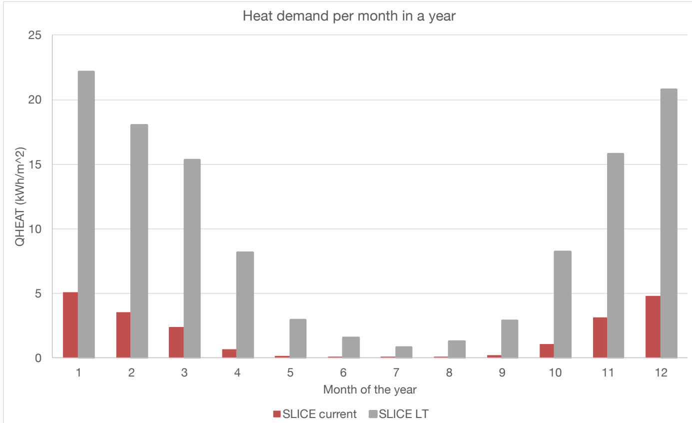


LT POOR INSULATION WINDOWS + EXTENDED SCHEDULE ALL NIGHT 18ºC

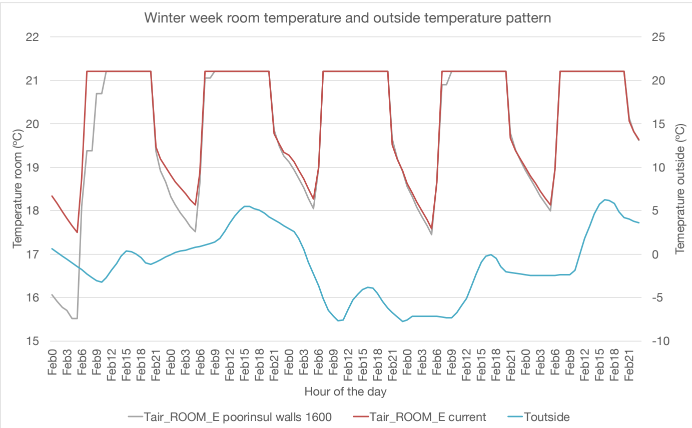


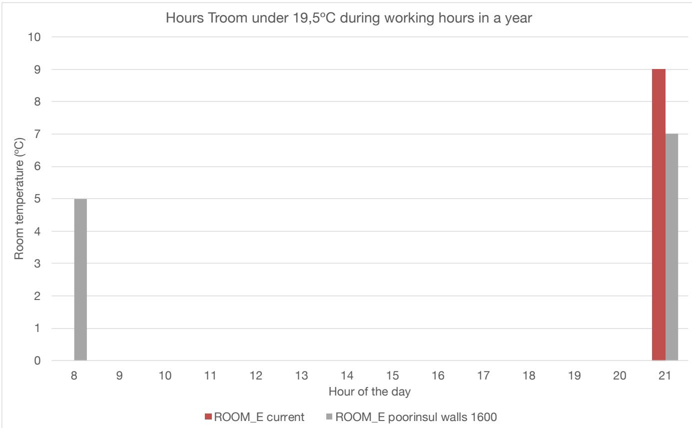


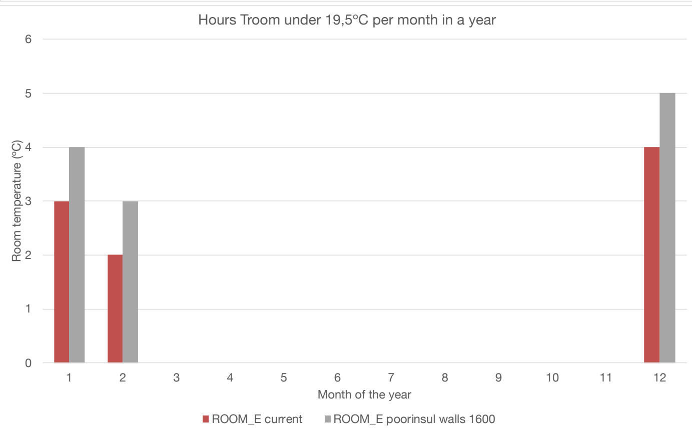


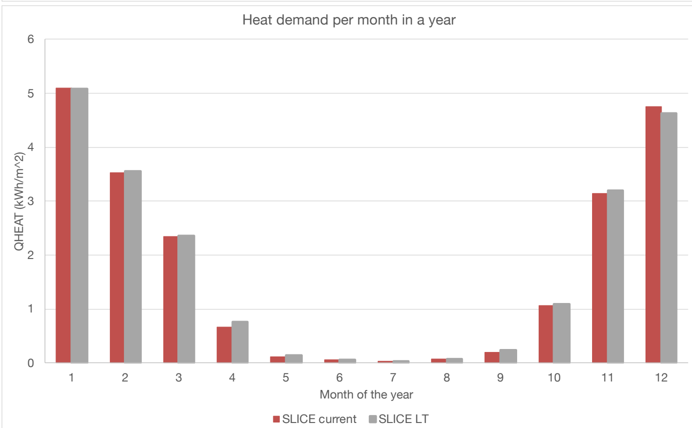


LT POOR INSULATION WALLS + EXTENDED SCHEDULE ALL NIGHT 15ºC

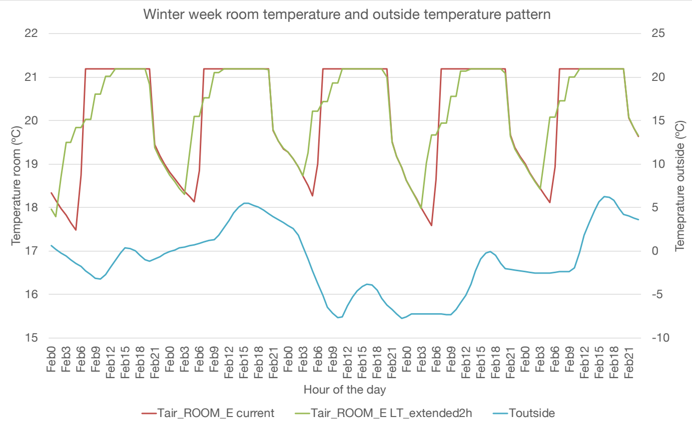


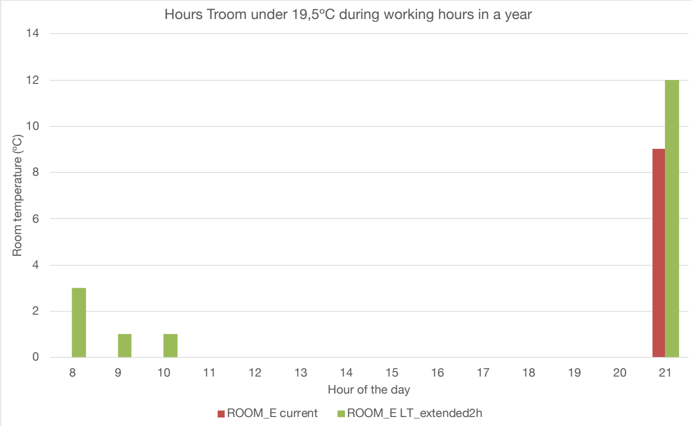


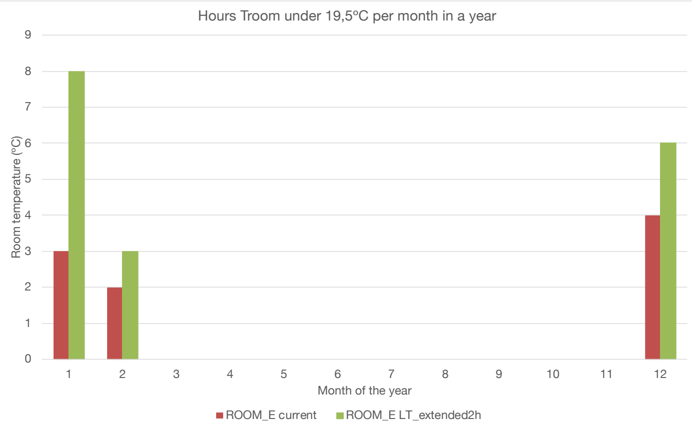


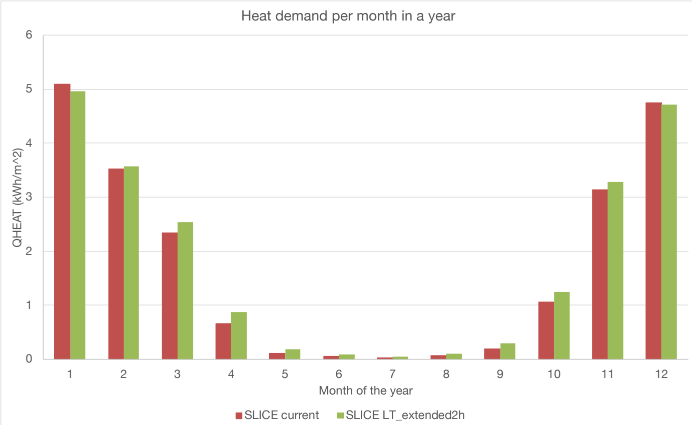


LT EXTENDED SCHEDULE 2h

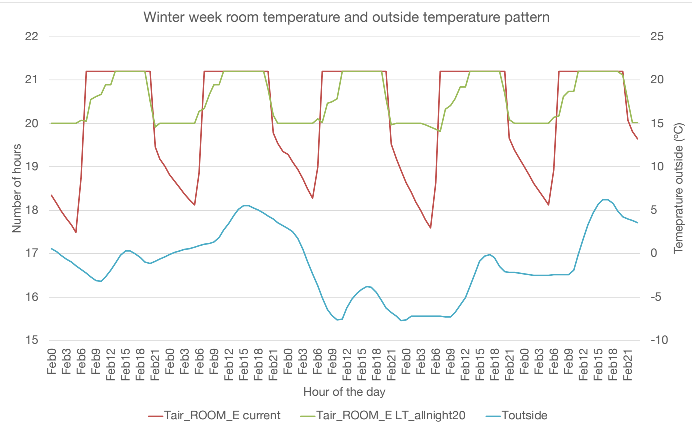


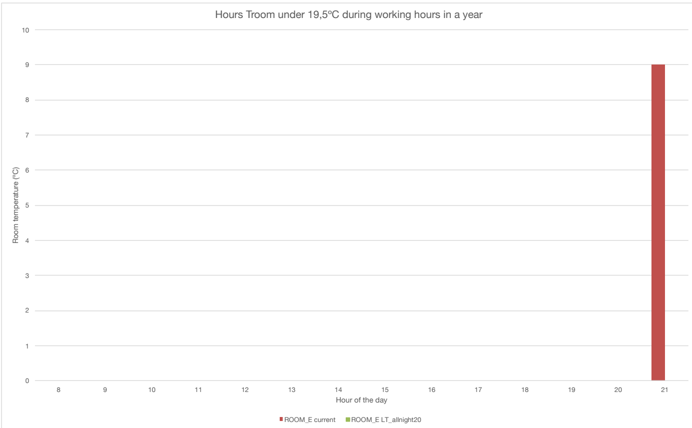


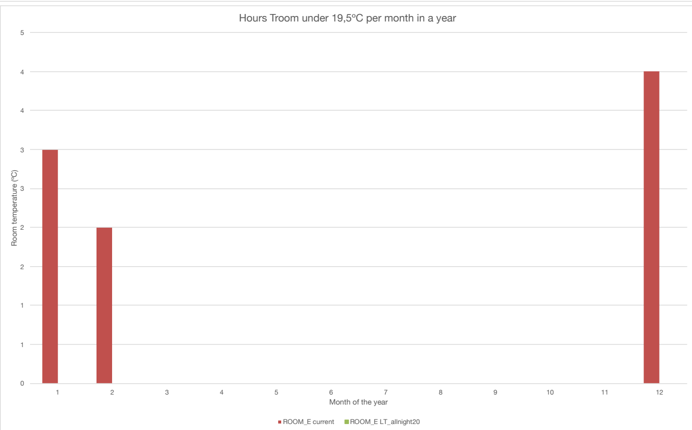


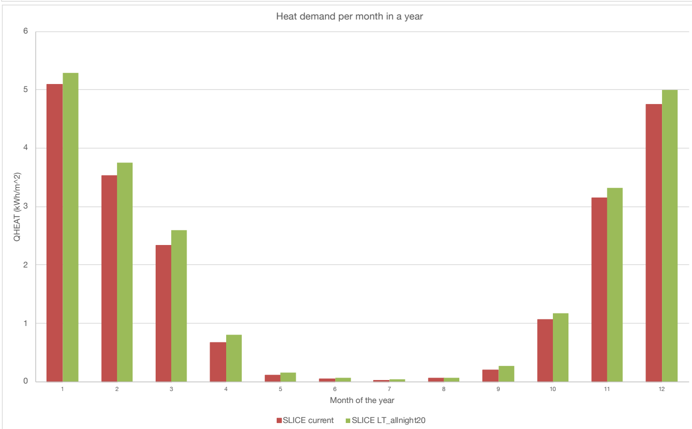


LT EXTENDED SCHEDULE ALL NIGHT 20ºC

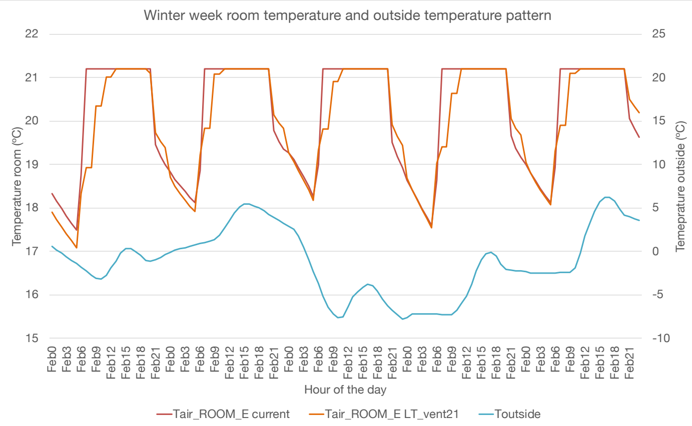


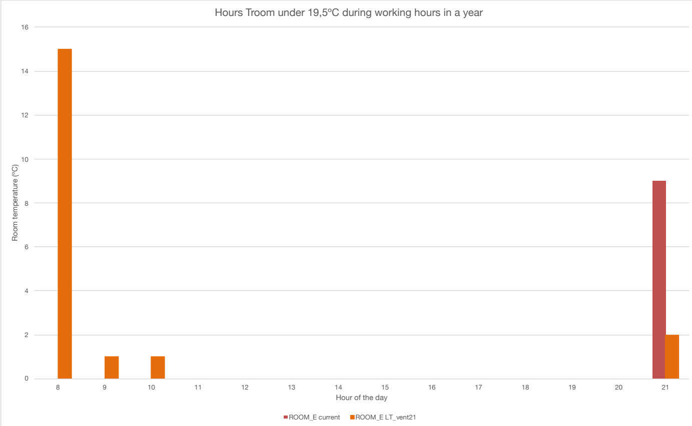


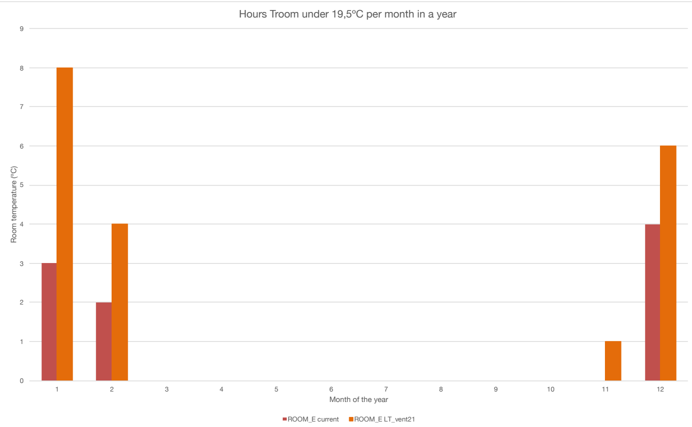


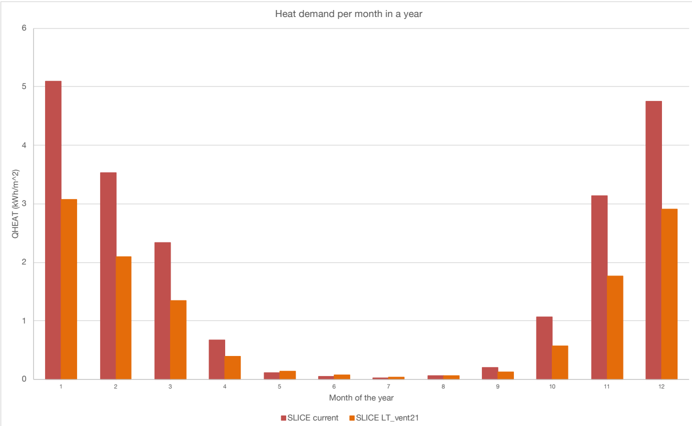


LT VENTILATION 21°C

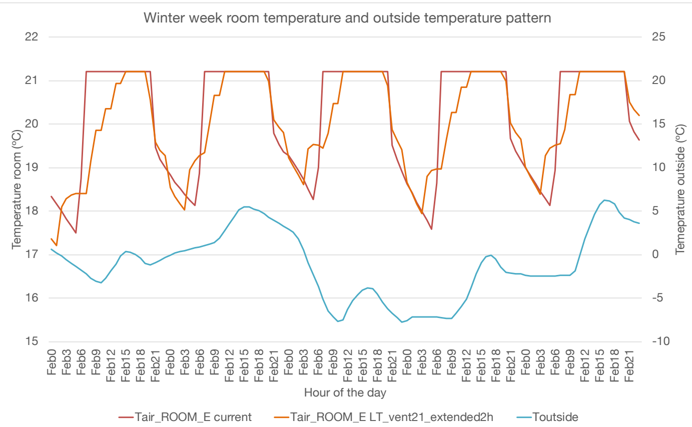


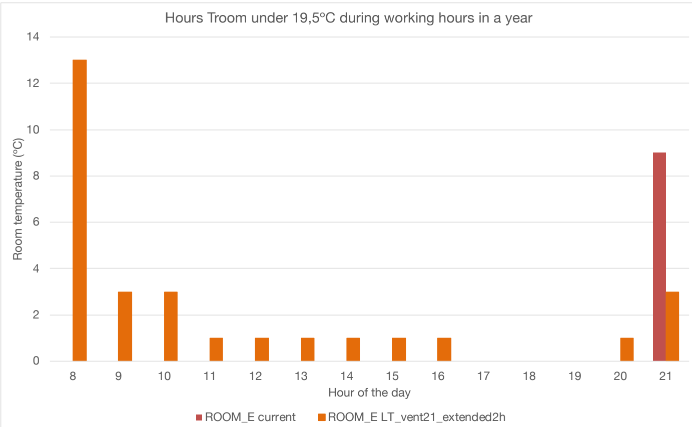


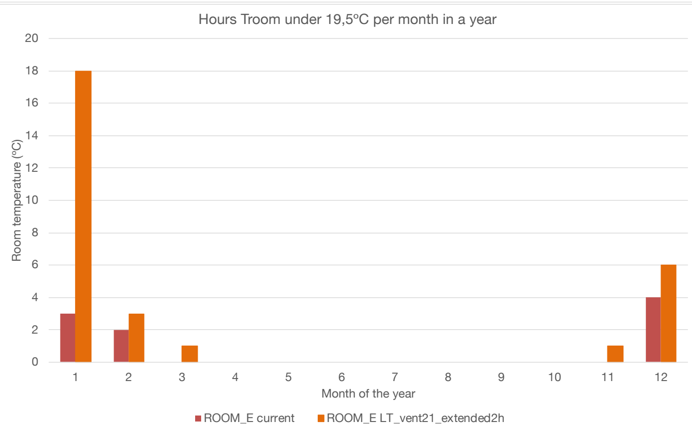


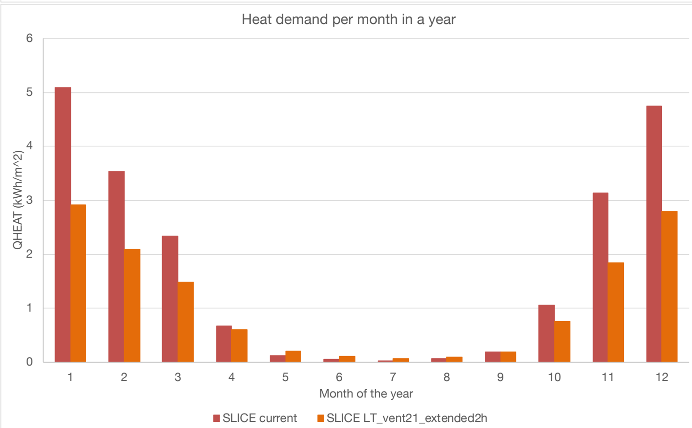


LT VENTILATION 21°C + EXTENDED SCHEDULE 2h

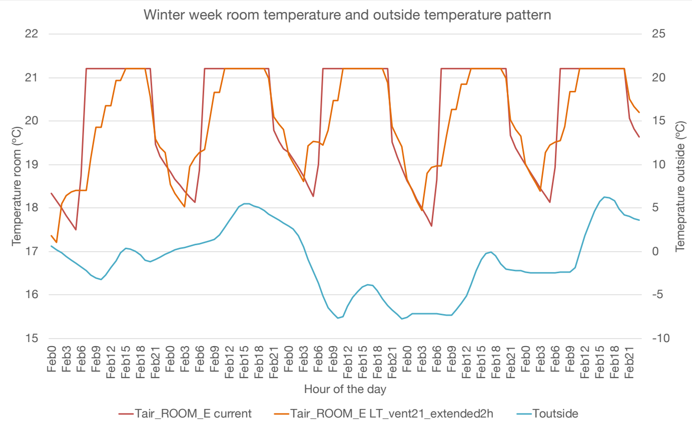


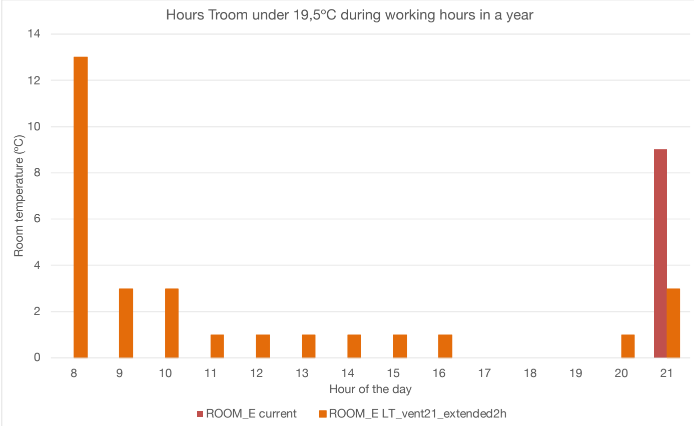


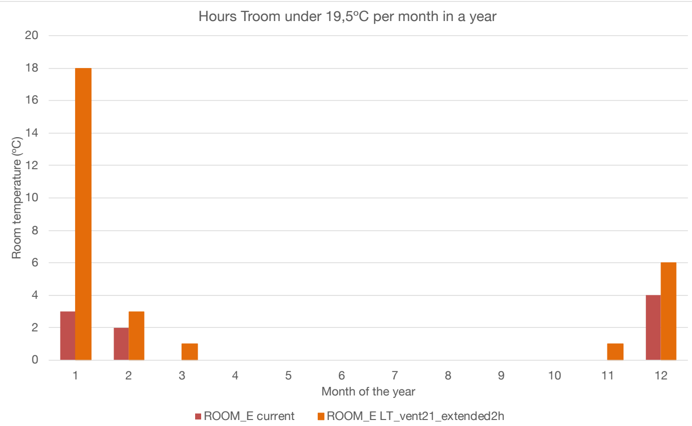


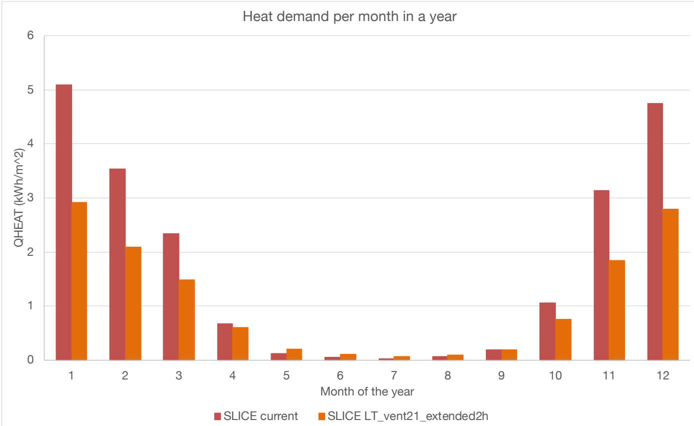


LT VENTILATION Theat_recovery + EXTENDED SCHEDULE 1h

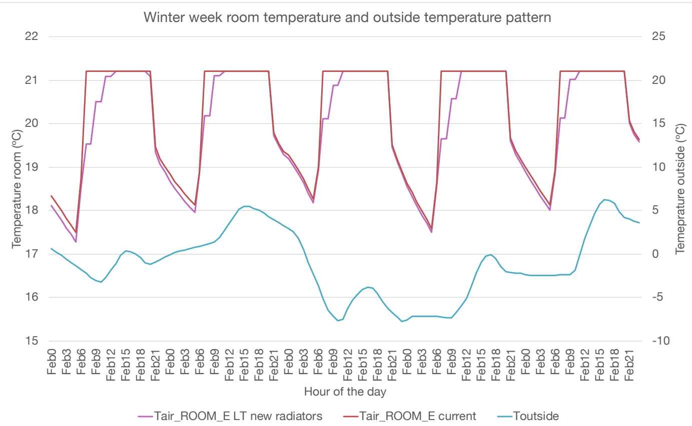


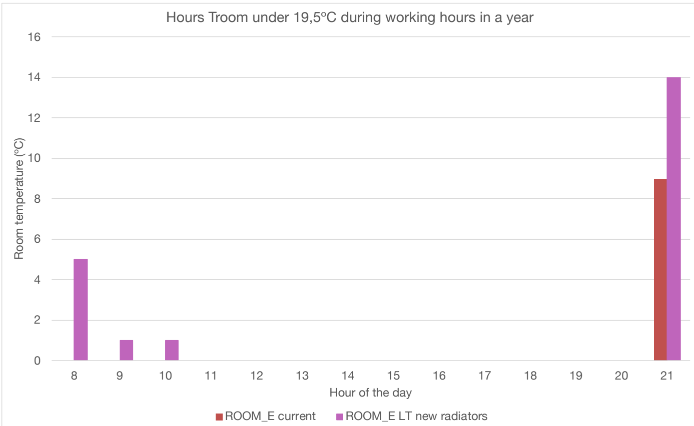


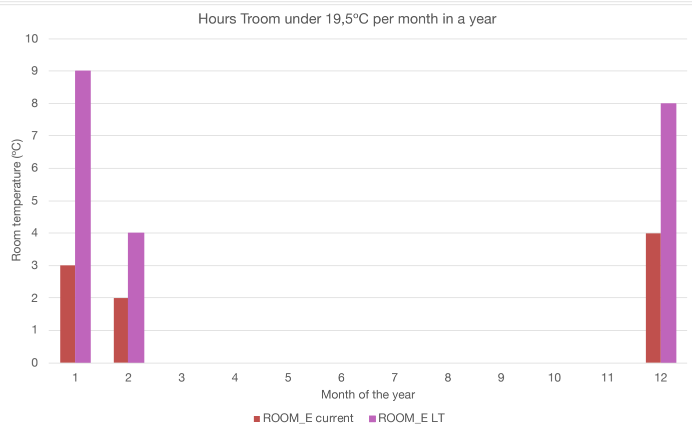


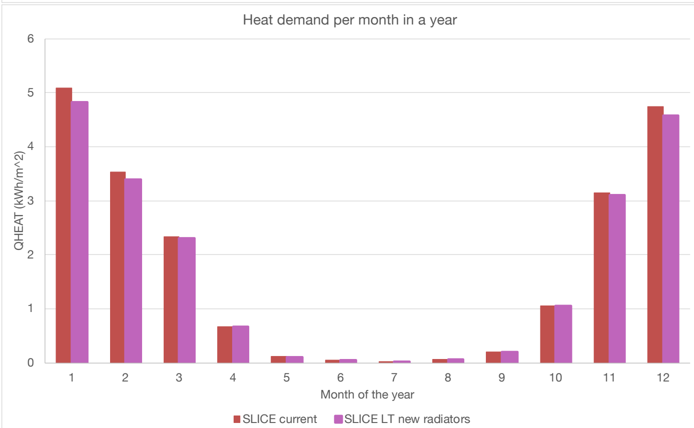


LT NEW RADIATORS









F. TABLES WITH THE RESULTS PER SCENARIO

1. Theoretical, current, no changes and envelope

The lowest supply and return temperatures possible for each scenario are highlighted in squares.

SCENARIOS AND OUTPUTS						ENVELOPE		
			HT THEORETICAL	HT CURRENT	LT NO CHANGES	LT POOR INSULATION + EXTENDED SCHEDULE ALL NIGHT 18ºC	LT POOR INSULATION WINDOWS + EXTENDED SCHEDULE ALL NIGHT 18ºC	LT POOR INSULATION WALLS + EXTENDED SCHEDULE ALL NIGHT 15ºC
Heat demand (for a year)		kWh/m^2		21,0	20,8	74,5	117,9	21,2
Discomfort hours 19,5ºC (for a year)		Number of hours		9	12	41	13	12
Discomfort hours 19ºC (for a year)		Number of hours		1	2	12	3	2
Maximum power (per radiator)		W	611	528	333	611	611	444
Maximum power (per room)		W	1222	1056	667	1222	1222	889
Design temperature difference (deltaT 20ºC) *15ºc for new radiators scenario	**Supply temperature**	ºC	**90**	-	**70**	**90**	**90**	**80**
	Return temperature	ºC	**70**	-	**50**	**70**	**70**	**60**
	Mass flow	kg/h	21	-	15	21	21	20
Current temperature difference (deltaT around 10ºC)	**Supply temperature**	ºC	-	**78**	**63**	**85**	**85**	**73**
	Return temperature	ºC	-	**70**	**55**	**77**	**77**	**65**
	Mass flow	kg/h	-	56	37	67	67	50

2. Controls and operation and energy system

The lowest supply and return temperatures possible for each scenario are highlighted in squares.

SCENARIOS AND OUTPUTS			CONTROLS AND OPERATION				ENERGY SYSTEM	
			LT EXTENDED SCHEDULE 2h	LT EXTENDED SCHEDULE ALL NIGHT 20ºC	LT VENTILATION 21ºC	LT VENTILATION 21ºC + EXTENDED SCHEDULE 2h	LT VENTILATION Theat_recovery + EXTENDED SCHEDULE 1h	LT NEW RADIATORS
Heat demand (for a year)		kWh/m^2	22,0	22,5	12,6	13,2	44,3	20,4
Discomfort hours 19,5ºC (for a year)		Number of hours	17	0	19	29	32	21
Discomfort hours 19ºC (for a year)		Number of hours	4	0	7	11	11	3
Maximum power (per radiator)		W	222	139	222	139	333	556
Maximum power (per room)		W	444	278	444	278	667	556
Design temperature difference (deltaT 20ºC) *15ºc for new radiators scenario	**Supply temperature**	ºC	**60**	**50**	**60**	**50**	**70**	**50**
	Return temperature	ºC	**40**	**35**	**40**	**35**	**50**	**35**
	Mass flow	kg/h	10	9	10	9	15	30
Current temperature difference (deltaT around 10ºC)	**Supply temperature**	ºC	**53**	**45**	**53**	**45**	**63**	-
	Return temperature	ºC	**45**	**36**	**45**	**36**	**55**	-
	Mass flow	kg/h	25	13	25	13	37	-