Accelerating the Dutch energy transition: Lowering operating temperatures of heat distribution systems in the built environment

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Executive summary

To achieve the 3,4 Mton CO_2e reduction target in the built environment stated in the Dutch climate agreement, far-reaching modifications are required. One being the replacement of gas-fired boilers in central heating systems by sustainable heat sources. When replacing the gas-fired boiler by heat pumps and low-temperature district heating, lower supply temperatures to and return temperatures from heat distribution systems are applied. Nowadays, it is generally believed that lower operating temperatures causes problems, because the conventional high-temperature radiators are unable to provide enough heat. Deltares and Berenschot question this assumption, since they believe that radiator systems in the Netherlands are overdimensioned. Together, both organizations formulated the following hypothesis: "the majority of the dwellings in the Netherlands are equipped with overdimensioned heat distribution systems". If the hypothesis is confirmed, this will save the Dutch society roughly 72.5 billion euro. Unfortunately, the lack of data inhibits the confirmation of this hypothesis. Deltares consequently initiated the development of a measuring campaign (=design project) to gather data.

The design of the measuring campaign contains three main components: heat loss of a dwelling, heat output of a heat distribution system and thermal comfort experienced by residents. By gathering data for each of the main components in 250 unique dwellings that a part of the Dutch dwelling stock, the hypothesis can be tested. A reliable cost-effective empirical method was found for each main component. The heat loss of a dwelling and heat output of a heat distribution system is measured by an energy meter, while the thermal comfort of residents is determined via a questionnaire. Based on data that is acquired by the measuring campaign, the heat loss at design conditions can be calculated. Furthermore the maximum heat output of the heat distribution system can be derived from the data. Based on the difference between these values, overdimensioned heat distribution system can be identified. Furthermore the lowest acceptable supply and return temperatures of the heat distribution system can be calculated. Since cleaning the data set and performing the data analysis can be time consuming in $\geq$ 250 dwelling, a code was written in R 3.5 that fully automates the process. This code will also become available in Python 3.6 in August.

Validation of the measuring campaign was performed by testing the code with data obtained from energy meters installed in two apartment complexes. Results showed that in at least one apartment complex lower supply and return temperatures can be applied throughout the year. Now that the measuring campaign has been developed and validated, the next step has to be initiated which is implementing the measuring campaign in a pilot case. If the measuring campaign also shows promising results during the pilot case, it can be rolled out on full scale. When this moment arises, a data set that is large enough to scientifically test the hypothesis of Deltares and Berenschot is obtained.

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Acronyms

ASHRAE		American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2e	-	Carbondioxide equivalent
CU	-	Consumption unit
EI		Energy index
HLC	$W \cdot K^{-1}$	Heat loss coefficient
LMTD	$^{\circ}C$	Logarithmic mean temperature difference
A	m^2	Surface area
$\dot{Q}_{convection}$	W	Heat transfer by convection
$\dot{Q}_{design,output}$	W	Heat output of a heat distribution system at design temperatures
$\dot{Q}_{gain,dwelling}$	W	Heat gains (convection and radiation)
$\dot{Q}_{HL,dwelling}$	W	Heat loss of a dwelling
$\dot{Q}_{HO,hds}$	W	Heat output of heat distribution system
$\dot{Q}_{output}$	W	Heat output of a heat distribution system at chosen temperatures
$\dot{Q}_{radiation}$	W	Heat transfer by radiation
$\dot{Q}_s$	W	Heat output radiator
$\dot{Q}_{T,dwelling}$	W	Heat transfer by transmission (conduction)
$\dot{Q}_{V,dwelling}$	W	Heat transfer by ventilation and air infiltration (convection)
T_s	$^{\circ}C$	Radiator supply temperature
T_r	$^{\circ}C$	Radiator return temperature
T_e	$^{\circ}C$	Exterior mean air temperature
T_i	$^{\circ}C$	Indoor mean air temperature
T_m	$^{\circ}C$	Logarithmic mean temperature difference
$T_m r$	$^{\circ}C$	Mean radiant temperature
T_o	$^{\circ}C$	Operative temperature
h	$W \cdot K \cdot m^2$	Coefficient of thermal transmittance
σ	$5.67{\cdot}10^{-8}\ W \cdot m^2 \cdot K^4$	Stefan-Boltzmann constant
ϵ	$-$	Emissity factor
ρ	$kg \cdot m^{-3}$	Density
ϕ_v	$m^3 \cdot s$	Volume metric flow rate
c_p	$kJ \cdot kg^{-1} \cdot K^{-1}$	Specific heat capacity at constant pressure
φ	$-$	Correction factor in theoretically radiator heat output
n	$-$	Radiator exponent

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1 Introduction

1.1 National climate agreement

The Dutch government has set out the objectives for the national climate agreement. By 2050, the greenhouse gas emissions should decrease by 95% compared to 1990 (SER 2018). In the period to 2050, a midterm goal of 49% greenhouse gas emission reduction has been set for the year 2030 (SER 2018). Authorities, companies and interested groups are meeting at five so-called climate sector tables to reach agreements that will result in at least 49% reduction in greenhouse gas emissions by 2030 (Ingenieur 2018). The five sector tables are Electricity, Built Environment, Industry, Agriculture & Land Use, and Mobility (SER 2018). To reach the 49% goal by 2030, the sector table Built Environment has to reduce CO_2equivalent-emissions (CO_2e) by 3,4 Mton in 2030 (SER 2018). Although several attempts to reduce the greenhouse gas emissions have been successful in the past, only reductions of greenhouse gases with the highest global warming potential, such as CH_4, N_2O, HFCs, PFCs, SF_6 and (NF_3)[3] were achieved (PBL 2018). Unfortunately, the CO_2 emissions increased by 1,6% from 1990 to 2016 (PBL 2018). Taking in consideration that CO_2 emissions account for 85% of the total CO_e emissions, a lot of progress has to be made to reach the (midterm) goal stated in the Dutch climate agreement (PBL 2018).

To achieve the 3,4 Mton CO_2e reduction target in the built environment far-reaching modifications are required (Schmidt et al. 2017). Frequently addressed modifications are (additional) insulation of buildings, replacing the windows and replacement of the gas-fired boiler in central heating systems by sustainable alternatives (Filippidou et al. 2016). Sustainable alternatives are defined as heat sources that do not directly rely on fossil fuels. Examples are heat pumps and low-temperature district heating networks that receive heat from geothermal, data centers or surface water. Replacing the windows and providing existing buildings with (additional) insulation started a few decades ago and becomes more and more popular because of its cost-effectiveness (PBL 2012, van den Brom et al. 2019). However, replacing the gas-fired boiler by sustainable alternatives progresses slowly (Itard & Meijer 2008).

Conventional gas-fired boilers are still the most commonly used source of heat production in Dutch dwellings (Eijdems et al. 1994, Itard & Meijer 2008). In combination with a heat distribution system heat can be provided and distributed among dwellings. Dwellings equipped with a conventional gas-fired boiler commonly operate their heat distribution systems with a 90/70°C, 80/60°C or 75/55°C supply and return temperature (ISSO 2001, Lauenburg 2016, Østergaard & Svendsen 2018*b*, Sarbu & Sebarchievici 2015). Sustainable heat sources, such as heat pumps, geothermal and solar collectors preferably operate heat distribution systems at supply and return temperatures of 55/35°C, 55/45°C, 50/35°C or 40/25°C (Jangsten et al. 2017, Nagy et al. 2014, Schmidt et al. 2017, Østergaard & Svendsen 2017). Figure 1 shows the difference in operating temperatures of conventional gas-fired boilers and sustainable heat sources. A commonly heard statement is that the change in operating temperatures causes thermal comfort problems, because the heat output of the heat distribution decreases.

A heat distribution system should be able to efficiently heat spaces. Therefore the heat distribution system

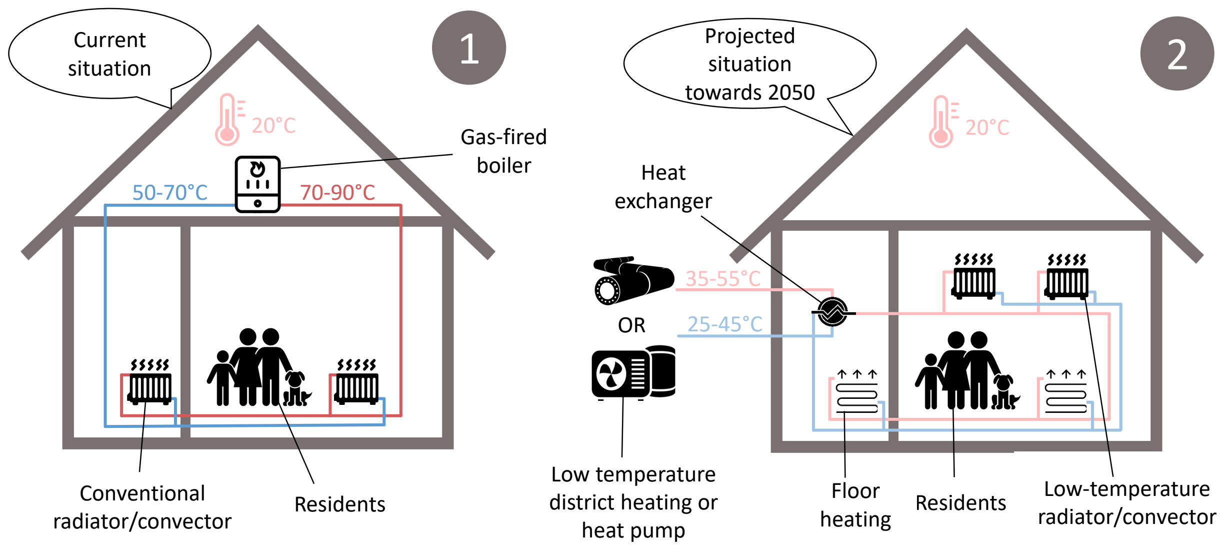

Figure 1. *Effect of different heat sources on the heat distribution system. Situation 1 shows the current situation, in which dwellings are equipped with traditional gas-fired boiler and regular heat distribution systems. Situation 2 illustrates the situation when gas-fired boiler is replaced by environmental friendly alternatives such as heat pumps and low-temperature district heating networks. In situation 2 the high-temperature heat distribution system is replaced by a low-temperature heat distribution system consists of floor heating and low-temperature radiators.*

is designed to have a certain theoretical heat output. Heat output calculations commonly start by determining the theoretical heat loss of a building at outdoor design temperatures (ISSO 2001, Jangsten et al. 2017). Based on the theoretical heat loss, the heat distribution system's minimum heat output is determined. Most heat distribution systems in the Dutch dwelling stock are designed with a >75/55°C supply and return temperature (Gvozdenovic et al. 2015). When replacing gas-fired boilers by environmental friendly alternatives, such as heat pumps and low-temperature district heating networks, it is generally believed that the lower water supply and return temperature causes problems for the heat distribution systems because the heat output decreases too much. This could result in insufficient heat output to heat the building, which includes that people will not be comfortable in that particular building. Obviously, this situation is undesirable and should be avoided. Therefore it is generally assumed that high-temperature heat distribution system should be replaced by a low-temperature heat distribution system in order to have sufficient heat output to heat a dwelling with sustainable heat sources. However, a hypothesis, formulated by Deltares and Berenschot, is that the majority of the dwellings in the Netherlands are equipped with over-dimensioned heat distribution systems, figure 2. Several reasons have been put forward why this hypothesis might hold:

- Common design methods are either based on rough rules of thumb or extreme design conditions (Østergaard & Svendsen 2018*a*).
- Over time existing buildings were retrofitted with energy saving alternatives, for example (additional) insulation and HR++/HR+++ glass. Therefore the heat loss of the building decreases, while the heat output of the heat distribution systems remained equal. (Østergaard & Svendsen 2016).
- The building standards concerning insulation changed over time, while the regulations involving heat

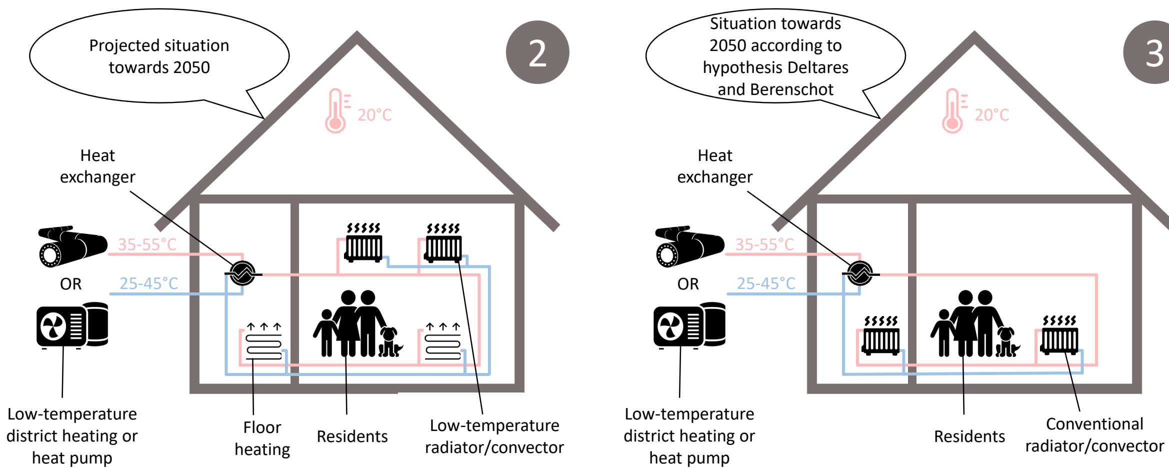

Figure 2. *Visualization of the hypothesis. Situation 2 shows the required adjustment of the heat distribution systems, when heat pumps, solar collectors or geothermal provide heat. Situation 3 shows the hypothesis of Deltares and Berenschot, which proposes that the current high-temperature heat distribution systems have enough heat output to heat spaces when heat pumps and low-temperature district heating networks provide heat.*

distribution system's heat output have not been adjusted.

Literature shows that heat distribution systems are over-dimensioned in some cases. Hasan et al. (2009) concluded that lower supply and return temperatures can be applied in heat distribution systems of modern Finnish buildings, because of oversized radiators and convectors were installed. In addition, Brand & Svendsen (2013), Harrestrup & Svendsen (2015), Wang et al. (2015) found that supply and return temperatures can be lowered if existing building were retrofitted with energy saving alternatives. Furthermore, Østergaard & Svendsen (2016) found that typical Danish single-family dwellings can be heated with 55/35°C supply and return temperature for the largest part of the year. In addition, in dwellings that went through reasonable energy renovations, the supply temperature could even be reduced below 50°C. This indicates that there is good reason to believe that heat distribution systems in Danish single-family might be over-dimensioned. It should be noted that Østergaard & Svendsen (2016) investigated dwellings connected to district heating networks.

1.2 Societal relevance

Literature strengthens the hypothesis to a high extend. Consequently, it is highly recommended to explore the hypothesis because it could save significant investments costs. According to the climate agreement approximately 7 million dwellings should be renovated to achieve the 2050 CO_2e reduction target (SER 2018). This includes that a large amount of households should replace their gas-fired boiler by a sustainable alternative. Currently, this would also incorporate adjustment of the high-temperature heat distribution system to a low-temperature heat distribution system. Research showed that installation of low-temperature heat distribution systems in a regular household on average costs €12.500 (RVO 2016). If the hypothesis is confirmed, this adjustment is not longer required, wherefore investment costs will decrease dramatically. When, for example, 5 million households do not have to replace their high-temperature heat distribution system, this will save €72.5 billion.

2 Problem analysis

This chapter addresses the main problem for which a solution has to be found during the design project. In addition, the main problem owner is identified in section 2.1 and a stakeholder power-interest grid is provided in section 2.2. Lastly, a problem definition is given in section 2.3 for which a possible solution is provided in section 2.4.

2.1 Problem owner analysis

Multiple problem owners can be identified on different levels. Consequently, the main problem owner depends on the scope of the problem. On a higher level the Dutch government or households can be assigned as problem owners. However, this project focuses on a lower level, namely determining what is needed to test the hypothesis formulated by Deltares and Berenschot. Therefore people within both organizations that are involved in this project can be identified as problem owners. As this project is primarily executed at Deltares, I. Pothof, the person who extensively participated in the formulation of the hypothesis is designated as main problem owner.

2.2 Stakeholder analysis

An extensive stakeholder analysis has been performed to indicate which parties and persons are interested in this project and to what extend they can affect the project. All identified stakeholders are divided over four quadrants of the power-interest grid, which defines four categories of stakeholders: Players, Subjects, Context setters and Crowd (Ackermann & Eden 2011).

- **Players** are interested stakeholders who also have a high degree of power.
- **Subjects** are also interested stakeholders, but have less influence.
- **Context setters** are not necessarily interested, but may have a high degree of power.
- **Crowd** do not exhibit interest and have no or a very low degree of power.

Deltares (in particular the hydrotechnology department)
The project is executed at Deltares, which is an independent institute for applied research in the field of water and subsurface. Currently, the hydrotechnology department is amongst others exploring the application of low-temperature district heating networks in the built environment. Therefore relevance with this project is high, considering that low-temperature district heating networks provide low supply and return temperatures. Confirmation of the hypothesis will lower the economic thresholds for low-temperature district heating networks, wherefore outcomes of this project could increase the interest in low-temperature district heating networks significantly. Lastly, the project owner is a Deltares employee, which includes that Deltares has a financial stake in the project.

Berenschot (in particular the Energy department)
The project idea was established during a work session in which both Deltares and Berenschot participated. The knowledge gained during the project is of importance for the Berenschot energy department, because the department is growing fast and wants to gain market share in the energy transition sector. By participating in projects that can have a substantial impact on the energy transition, Berenschot attempts to gain market share. Moreover, Berenschot is also financially involved in the project, by in kind contribution.

Cabinet Rutte III (in particular Eric Wiebes)
The climate agreement is one of the most important topics in Dutch politics at the moment. Especially to the minister of Economic Affairs and Climate Policy, since he is responsible for the climate agreement formulation. Considering that this project can to a large extent contribute to one of the goals present in the climate agreement, Eric Wiebes is solely interested in the outcome of this project. Eric Wiebes only wants to know if low supply and return temperatures can be applied in conventional heat distribution system, because this would save billions in investment costs. Although, the outcome is important to Eric Wiebes, his influence on the project is negligible.

Climate sector table built environment (in particular Diederik Samsom)
This sector table focuses on the CO_2e reduction in the built environment and advises Eric Wiebes how to achieve the proposed goal for the built environment in the climate agreement. Diederik Samsom is the chairman of the climate sector table built environment, which incorporates that he provides advise to Eric Wiebes. Since this project might give opportunities to reach the 3,4 Mton CO_2e reduction target for the built environment, Diederik Samsom will be interested in the outcomes. Also the influence of this stakeholder on the project in negligible.

NGOs focused on the environment
This stakeholder type includes many organizations, amongst others NVDE, Natuur&Milieu. Most of them pursue the establishment of a healthy and natural environment, where fossil fuels are not essential. Almost every initiative that reduces the emissions of GHGs is encouraged by these NGOs. Although, NGOs can not directly affect the project, they posses the power to promote or discourage projects via amongst others social media.

Installation companies (Feenstra, Breman, Schouten)
The involvement of these companies is crucial in the project. Their expertise is required to successfully executed the project. However, their interest in the outcome is limited. However, they might even be more interested in replacing conventional radiators with low-temperature radiators. In that case they would have an interest to falsify the hypothesis.

ISSO
ISSO sets the minimum requirements of amongst others heat distribution systems. Contractors are obligated to install new heat distribution systems according these minimum requirements. New technologies, methods or situations that are declared unsafe by ISSO will be prohibit. If lower supply and return temperatures are applied, ISSO should approve the new system operation configurations. Therefore ISSO exhibits a high degree of power on the project.

TKI Energy

The artifact developed during this design project will be operationalised in the data acquisition phase of a larger project. All the phases in the larger project are visualized in figure 4. Especially during the data acquisition phase at least € 500.000 is required of which majority will be come for subsidy (MMIP4) granted by the Top sector Energy. The larger project forms one theme in the subsidy application in which multiple companies and parties participate in a consortium. If TKI Energy does not grant the subsidy, none of the theme's will be executed. This includes that preceding phases of the larger project are superfluous.

Building owners & tenants

The proposed design of the artifact requires the participation of building owners and tenants. Data gathered from these participants is essential to test the hypothesis. Without the participants the to be designed artifact is worthless. Although the power of one building owner or tenant is negligible, the combined power of building owners and tenants is significant. However, taking into account the size of the Dutch dwelling stock, it is expected that enough participants will be found, wherefore the influence of building owners and tenants on the project is small.

District heating companies (Eneco, Nuon, Firan, Ennatuurlijk, etc.)

District heating companies have a high interest in this project, since it might result in new business opportunities for them. Because if the hypothesis is confirmed, the costs for low-temperature district heating reduces. Although, the interest of district heating companies the project is high, their influence is low.

Air/water heat pump suppliers (Techneco, Vaillant, Daikin, Itho, Nefit, etc.

Similar as for district heating companies, this project might result in new business opportunities for air/water heat pump suppliers. Again, confirmation of the hypothesis, lowers the heat pump installation costs. Although, the interest of district heating companies the project is high, their influence is low.

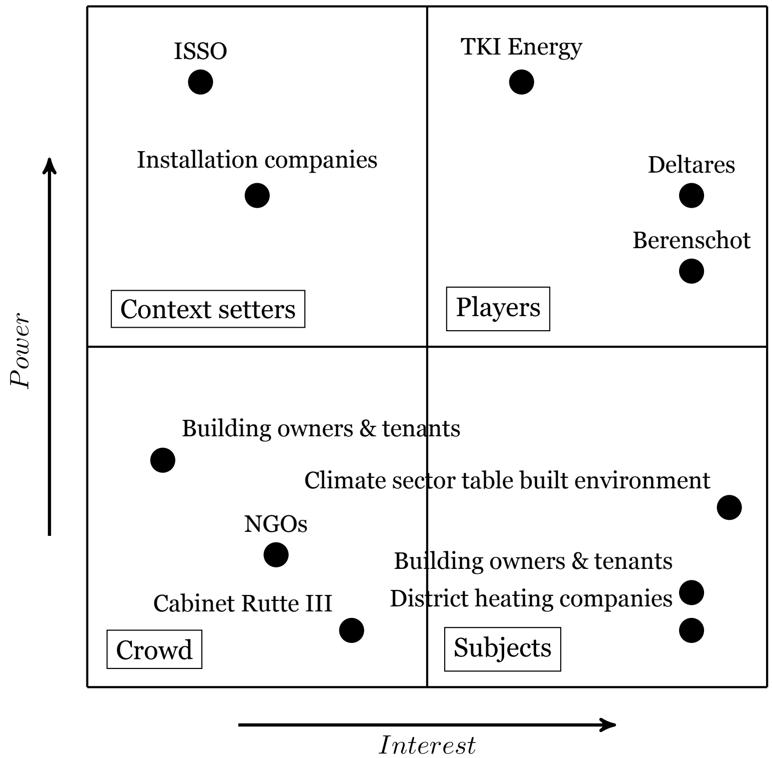

Figure 3. *Stakeholder analysis with a power-interest grid (Ackermann & Eden 2011)*

2.3 Problem definition

Although literature states that heat distribution systems in other countries are able to operate at lower supply and return temperatures, this does not imply that lowering supply and return temperatures is also feasible in Dutch dwellings. Consequently, the problem owner, I. Pothof wants to test the in section 1.1 stated hypothesis, because he wants to speed up the energy transition by amongst others lowering the economic threshold for low-temperature district heating networks. In order to test the hypothesis: *"majority of the dwellings in the Netherlands are equipped with over-dimensioned heat distribution systems"*, I. Pothof requires data concerning the heat output of heat distributions systems in and heat losses of Dutch dwellings. Currently, the absence of useful data makes it impossible to test the hypothesis, which includes that some kind of measuring campaign/program/instrument needs to be developed to acquire relevant data. Therefore the following problem definition is stated:

Problem definition: The lack of representative and reliable data about heat losses of dwellings, heat output of heat distribution systems and thermal comfort experienced by residents in those dwellings makes it impossible to test the hypothesis.

2.4 Proposed solution

Data is required to test the hypothesis. Therefore an artifact will be designed that is able to obtain data with which the hypothesis can be tested.

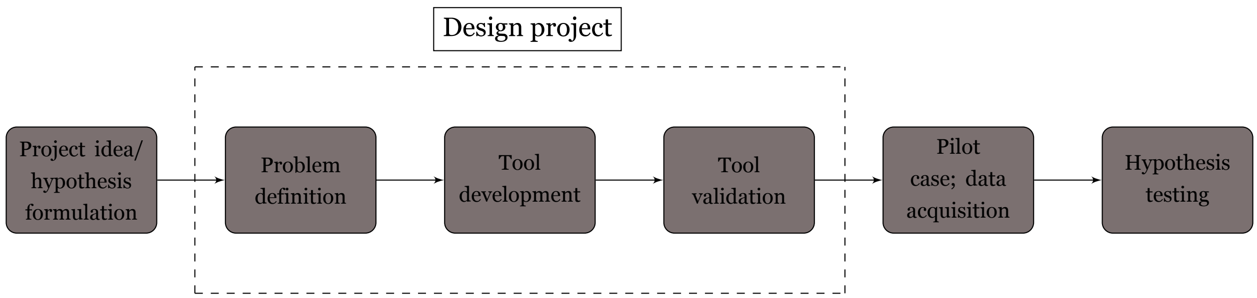

Figure 4. *Project phases of the larger project. This design project only focuses only the problem definition and artifact development, phase 2-4 respectively*

3 System description

This chapter provides an extensive system description in which the problem occurs. Section 3.1 gives a brief introduction to the system. Subsequently the system boundaries are identified in section 3.2. On the basis of these boundaries the system components are determined in section 3.3. To provide a simplistic overview of all system components and their relations, section 3.4 shows a schematic system description. Section 3.5 supplies additional information about the inputs to and outputs from the system, while the scope of the design project is discussed in section 3.6. Section 3.7 until section 3.9 focus on the research goal, research questions and artifact requirements.

3.1 General system description

The system under investigation is a heat distribution system in a Dutch dwelling and its interaction with the dwelling and residents, see figure 5. In this system people reside in a dwelling. To create a pleasant indoor climate for the residents, heat is supplied to a dwelling when outdoor conditions become cold and stormy. In the Netherlands this is often accomplished by a gas-fired boiler in combination with a hydronic heat distribution system (Eijdems et al. 1994). Commonly, the radiators and convectors of the hydronic heat distribution system are parallel connected (Eijdems et al. 1994).

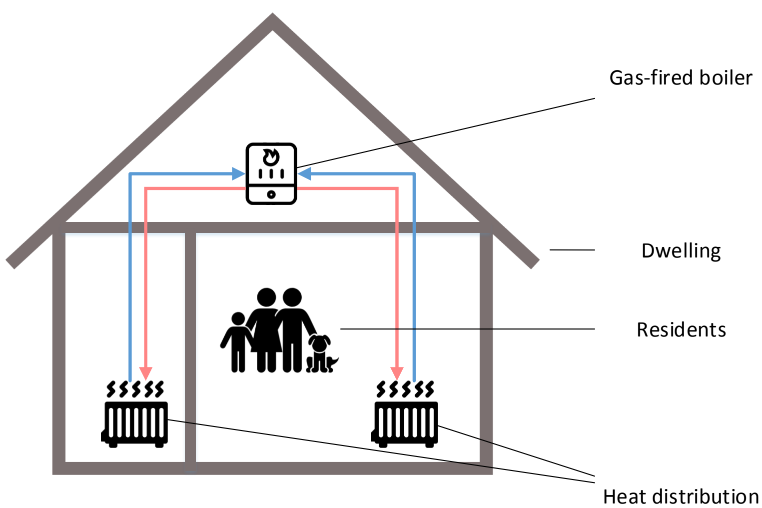

Figure 5. *The system under investigation.*

3.2 System boundaries

System boundaries have been defined in order to limit the complexity of the system. By using system boundaries one can easily determine what components are part of the system and what relations they have. The following system boundaries have been formulated:

- Only dwellings that are part of the Dutch housing stock are taken into account.
- Only dwellings that are representative for the Dutch housing stock are taken into account. Especially dwelling shape and construction year are of importance.
- Only dwellings that operate a conventional gas-fired boiler in combination with a conventional high-temperature hydronic heat distribution system are part of this research.
- Only dwellings that are inhabited are taken into account.
- Although the gas-fired boiler is physically located inside the dwelling, the boiler is not considered as a component in the system.
- Only the thermal comfort experience of residents is taken into account.

3.3 System components

Based on the system boundaries, the components that are part of the system can be identified. The components are the heat distribution system, the dwelling and the residents. The heat distribution system is the most important component in the dwelling. Its main purpose is to distribute heat among a dwelling. The heat distribution system receives heat from the gas-fired boiler when the heat loss of a dwelling increases, because more heat has to be distributed among the dwelling to maintain a constant indoor temperature, i.e. pleasant indoor climate to the residents. Another component is the dwelling itself, in which people reside. The main function of a dwelling is to provide an enjoyable indoor climate for the residents. Although residents are a component in the system, they do not have an explicit function. Nevertheless, residents ultimately demand certain properties from the dwelling and heat distribution system in order to create a pleasant indoor climate for themselves. Since humans are very complex systems themselves, only the thermal comfort experience of humans/residents in their own dwellings is taken into account.

3.4 Schematic system description

In order to understand the relationship between all the system components, one should comprehend the energy balance between a dwelling's heat loss and the heat output of the heat distribution system. To maintain a constant indoor temperature i.e. pleasant indoor climate, the energy balance should be in equilibrium, see equation 3.1 (ISSO 2017). Here $\dot{Q}_{HL,dwelling}$ and $\dot{Q}_{HO,hds}$ denote the dwelling's heat loss and heat distribution system's heat output respectively. If the residents do not feel themselves comfortable, the dwelling's heat loss is larger than the heat output of the heat distribution system. Subsequently, additional heat should be supplied to the dwelling. This includes that the heat output of the heat distribution system should exceed the dwelling's heat loss.

$$\dot{Q}_{HL,dwelling} = \dot{Q}_{HO,hds} \tag{3.1}$$

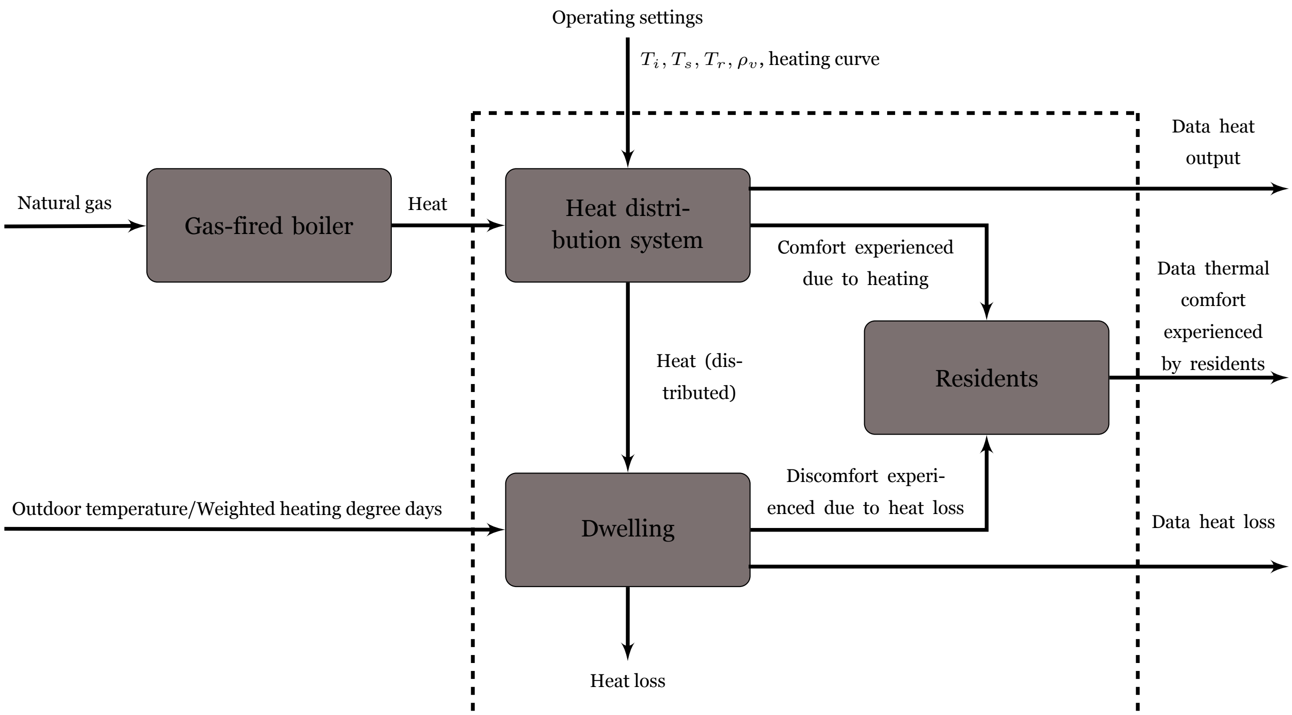

Figure 6. *Schematic representation of the system. The systems consists of 3 components: the heat distribution system, the residents and the dwelling. Operating settings, heat from the gas-fired boiler and outdoor temperature/weighted heating degree days are inputs, while data concerning the heat output of the heat distribution system, heat loss of a dwelling and thermal comfort experienced by residents are outputs. The scope of the project is enclosed by the dashed rectangle.*

3.5 System input and output

Figure 6 shows a schematic representation of the system under investigation. A heat distribution system is installed to maintain a pleasant indoor climate. Therefore the heat distribution system requires heat from the gas-fired boiler. Heat is generated in the gas-fired boiler by burning natural gas. However, since the gas-fired boiler is not part of the system under investigation, the heat generated by the boiler is the first input. The operating settings include amongst others the desired indoor temperature, the supply and return temperature of water going to and coming from the heat distribution system, the volumetric flow rate and of the heat distributing system determine the maximum heat output, hence the operating settings are also an input of the system. During cold and windy days, a dwelling's heat loss increases, wherefore additional heat has to be supplied in order to maintain the indoor climate at a comfortable 19-22°C (van der Linden et al. 2006, Taleghani et al. 2014). Jokisalo et al. (2009), Hens et al. (2010), Feist et al. (2005) state that the dwelling's heat loss is affected by transmission, air infiltration, ventilation and heat gains. All 3 types of heat loss are dependent on many variables Younes et al. (2012), ISSO (2017). To combine all these variables in to one simple parameter, the measure weighted heating degree days has been developed (Rovers 2013). When the amount of heating degree days increases, more heat has to be supplied to the dwelling. However, during the design of a dwelling the (design) outdoor temperature is applied instead of the weighted heating degree days. Consequently, weighted heating degree days or outdoor temperature is an input to the system.

The output of the system is related to the performance of the system and the level of thermal comfort experienced by the residents. The system's performance is dependent on energy balance, equation 3.1. Therefore data should be gathered to determine the system's performance, hence data about the heat output of a heat distribution system and heat loss of a dwellings are both outputs of the system. Furthermore, the thermal comfort experience by residents should be determined. This requires data acquisition, which is also an output of the system.

3.6 Scope

The project will primarily focus on what is required to design an artifact with which data can be acquired to test the hypothesis. The schematic representation in figure 6 demonstrates that data about the thermal comfort experience of residents, heat loss of dwellings and heat output of the heat distribution systems is essential. Residents, dwelling and the heat distribution system are therefore vital components in the system. Consequently, the scope of the project includes these components and their in- and outputs.

Besides relevant data to test the hypothesis, Deltares and Berenschot want to investigate to what temperature the supply and return temperature of the heat distribution systems in Dutch dwellings can be lowered without the loss of comfort. These two goals do not interfere with each other, because if it is known to what temperature the supply and return temperature of the heat distribution systems can be lowered, one can also test the hypothesis.

3.7 Research goal

The goal of this research should comply to the S.M.A.R.T. criteria, which stands for Specific, Measurable, Achievable, Relevant and Time-Based respectively, in order to be successful (Doran 1981, Bjerke & Renger 2017). The following research goal has been formulated:

An artifact that is able to determine to what temperature the supply and return temperature of heat distribution systems can be lowered in Dutch dwellings that operate a conventional gas-fired boiler in combination with a hydronic heat distribution system without the thermal comfort loss.

- **Specific:** The system boundaries are specific. Only representative Dutch dwellings with a conventional gas-fired boiler and a hydronic heat distribution system are taken into account.

- **Measurable:** The heat output of heat distribution system can be determined with several theoretical and experimental methods.

- **Achievable:** All knowledge required to develop the artifact is present, because of the collaboration between Deltares, Berenschot, TU Delft OTB and ISSO. Furthermore, data acquisition to test the hypothesis is not part of this project, wherefore the goal should be achievable within the limited amount of time.

- **Relevant:** Deltares and Berenschot are executing projects that make use of low supply and return temperatures in heat distribution systems. Examples are neighbourhoods in which heat is supplied via low-temperature district heating, decentralized heat pumps or geothermal. Furthermore the energy transition is currently a hot topic in the Netherlands. Now that the climate agreement is finalized, some concrete measures have to be taken in order to comply to target set for the built environment. Therefore developing this artifact is also relevant for the Dutch society.

- **Time-based:** The research should be conducted in 4 months, the amount of time granted for a IEM design project at the University of Groningen.

3.8 Research question

Specifying a proper research question will contribute the achievement of the research goal. Taking into account the problem stated in section 2.3 and the S.M.A.R.T goal stated in section 3.7, the following research question has been formulated:

What is required to determine to what temperature the supply and return temperature of heat distribution systems in existing Dutch dwellings can be lowered without losing thermal comfort?

3.8.1 Sub research questions

Sub research questions are formulated in order to divide the complexity of the research question over multiple knowledge and design questions.

Knowledge questions:

SQ1 *What is the effect of lower supply and return temperatures on the heat output of heat distribution systems?*

SQ2 *How can the heat loss of a Dutch dwelling be determined?*

SQ3 *How can the heat output of a heat distribution system be determined?*

SQ4 *What is the relation between the outdoor conditions and the heat loss of dwellings?*

SQ5 *How can the thermal comfort experience of residents be determined?*

SQ6 *What are the design conditions and are they representative for 2019?*

Design questions:

SQ7 *How to design an artifact that is able to determine the heat loss of a dwelling, the heat output of a heat distribution system and the thermal comfort experienced by residents at design conditions?*

SQ8 *How can the costs of the artifact be reduced without compromises on functionality?*

SQ9 *In what kind of dwellings should the artifact be operationalised in order to generate relevant data?*

3.9 Artifact's requirements

- The artifact shall produce reliable and uniform data.
- The artifact should be able to acquire all data within a time span of one winter.
- The artifact should be simple to install and user-friendly to operate.
- The artifact shall be able to determine to what temperature the supply and return temperature of heat distribution systems can be lowered.
- The artifact shall be able to determine the level of thermal comfort experienced by residents.
- The artifact should be applicable to all existing dwellings in the Netherlands.
- The artifact's costs should not exceed € 2000.

4 Research Design

To structure the artifact's design process, design science is applied. Since the view on design science methodology varies among researchers, section 4.1 concisely describes the different views and subsequently explains which view on design methodology is chosen. Furthermore, additional information about the operationalisation of the research questions is given in section 4.2. Lastly, the design project's planning is given in section 4.3

4.1 Design science

Hevner (2007), Alan et al. (2004), Wieringa (2014) are often cited in books and articles that discuss design science. Wieringa (2014) argues that design science research is curiosity-driven and fun-driven research and focuses on the investigation and design of artifacts in context. Wieringa (2014) defines two kinds of research problems in design science: to design an artifact to improve a problem context or to answer knowledge questions about the artifact in context. The first applies more to the artifact in this project than the latter. Hevner (2007) and Alan et al. (2004) agree with Simon (1996), who states that design science research is motivated by the desire to improve the environment by the introduction of new and innovative artifacts and the processes for building these artifacts. In addition, Alan et al. (2004) states that design science is active with respect to technology, engaging in the creation of technological artifacts that impact people and organizations by focusing on problem solving. Considering that this project aims to design an artifact that generates useful data which solves the problem of I. Pothof and thereby enhance the Dutch society, the approach of Alan et al. (2004) and Hevner (2007) seems more appropriate. Consequently, their design science methodology is applied in this design project.

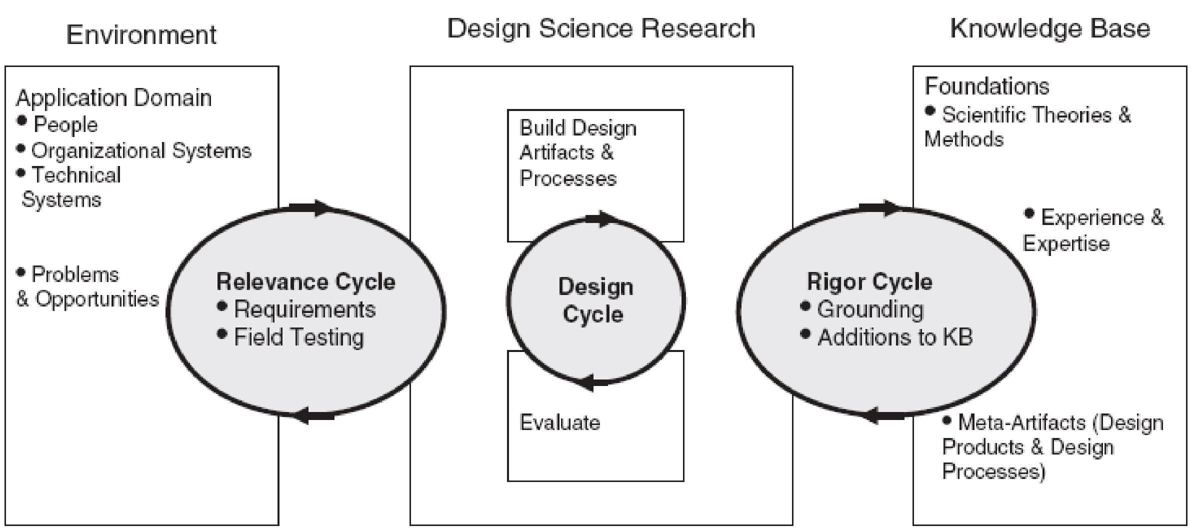

Figure 7. *Design science cycles (Hevner 2007)*

In the article of Hevner (2007) a framework is introduced that contains 3 inherent cycles. Figure 7 shows the framework including the relevance cycle, the rigor cycle and the design cycle. The relevance cycle initiates design science research by providing requirements for the project. In addition, the relevance cycle also defines acceptance criteria for evaluation of the proposed solutions. The rigor cycle connects the design science activities with the knowledge base of scientific foundations, experience and expertise which forms the foundations of the research project. In the design cycle the artifact is created that should meet the minimum requirements. The requirements are inputs from the relevance cycle, while the design and evaluation theories and methods are a product of the rigor cycle (Hevner 2007).

4.2 Research operationalisation

During the entire project the design science cycles of Hevner (2007) are used as guideline. The rigor cycle is applied to gather information to answer the knowledge questions. Based on the knowledge obtained from scientific literature and interviews with experts during the rigor cycle, the knowledge questions and design questions are answered. Subsequently, an artifact is designed on the basis of the knowledge obtained from the sub research question.

Knowledge questions:

SQ1 *What is the effect of lower supply and return temperatures on the heat output of heat distribution systems?*

Lowering the supply and return temperatures change the operating settings of heat distribution systems. Logically, this affects the heat output of the heat distribution system. Finding the dependency between the supply/return temperature and heat output is therefore important.

Methods and tools that are used:

1. Literature study to find the dependency.

SQ2 *How can the heat loss of a Dutch dwelling be determined?*

Heat loss is an important characteristic of a dwelling, because the minimum required heat output of a heat distribution system is dependent on the heat loss. Determining the heat loss of a dwelling is therefore necessary.

Methods and tools that are used:

1. Literature study to find methods and tools with which the heat loss of dwellings can be determined.
2. Interviews with experts from TU Delft OTB and ISSO to discuss and evaluate these methods.

SQ3 *How can the heat output of a heat distribution system be determined?*

Measuring methods and tools are needed determine the maximum heat output of heat distribution systems at varying supply and return temperatures.

Methods and tools that are used:

1. Literature study to find methods and tools with which the heat output of heat distribution systems can be determined.
2. Interviews with experts from ISSO to discuss and evaluate these methods.

SQ4 *What is the relation between the outdoor conditions and the heat loss of dwellings?*

During the year the weather conditions vary, while the ambient indoor air temperature remains almost equal. This dynamic weather behaviour affects the heat loss of a dwelling. Investigating the dependency is important to determine the heat loss of a dwelling during design conditions when empirical methods are applied.

Methods and tools that are used:

1. Literature study to find the dependency.
2. Statistical analysis with R to check the literature. Only if reliable data is available.

SQ5 *How can the thermal comfort experience of residents be determined?*

Lower supply and return temperatures, will change the way a heat distribution system operates. This can affect the thermal comfort of the residents. Consequently, it is important to measure the thermal comfort experienced by the residents.

Methods and tools that are used:

1. Interviews with experts from TU Delft OTB in order to define thermal comfort and find methods to quantify comfort.

SQ6 *What are the design conditions and are they representative for 2019?*

The heat loss at design conditions should be known to ensure that dwellings can be provided with enough heat during extreme weather conditions. Applying the correct design conditions is therefore critical.

Methods and tools that are used:

1. Interviews with experts from ISSO.
2. Statistical analyses with R to determine if the design conditions are representative for 2019.

Design questions:

SQ7 *How to design an artifact that is able to determine the heat loss of a dwelling, the heat output of a heat distribution system and the thermal comfort experienced by residents at design conditions?*

Combining the knowledge obtained from knowledge questions is essential when designing an artifact that is able to gather useful data to test the hypothesis. However, the data obtained with varying methods and tools should be compatible. Consequently, a proper artifact design is therefore required.

Methods and tools that are used:

1. Repetitive meetings with experts from Deltares to sharpen the artifact requirements.
2. Analytical hierarchy process (AHP) decision making tool is used to determine which methods are incorporated in the artifact.

SQ8 *How can the costs of the artifact be reduced without compromises on functionality?*

The costs of the artifact should be as low as possible, because the artifact will be operational in many dwellings. However, the artifact's functionality should not be affected by cost reductions.

1. Interviews with experts from Deltares are performed to determine what functions of the artifact are essential.

SQ9 *In what kind of dwellings should the artifact be operationalised in order to generate relevant data?*

The Dutch housing stock is very large and heterogeneous. Therefore an analysis is necessary to determine in what kind of the dwellings the artifact will be utilised to gather relevant data to test the hypothesis.

1. ARC GIS pro is used to assign a specific dwelling type to each dwelling registered in the Kadaster BAG data set.
2. Statistical analysis is performed with R in order to determine in what kind of dwellings and what building period the artifact should be operationalised.

4.3 Research planning

Figure 8. *Gantt chart of the project planning. The blue and orange diamonds indicate meetings and deadlines respectively.*

5 Literature study and interview results

In this chapter the knowledge questions will be answered by an extensive literature study in combination with relevant information obtained from interviews with experts. Summaries of all interviews are included in appendix A. First the effect of lower supply and return temperature is discussed in section 5.1. Subsequently the main components of the measuring campaign, heat loss of a dwelling, heat output of heat distribution systems and thermal comfort of residents, are investigated in section 5.2 until section 5.6. The findings in this chapter form the basis for the artifact's design, which is discussed in chapter 6.

5.1 Lowering the supply and return temperature of heat distribution systems

Changing the operating settings of heat distribution system, by lowering the supply and return temperature affects the heat output. It is important to understand why this happens, therefore this section will provide more in depth knowledge with which SQ1 can be answered.

What is the effect of lower supply and return temperatures on the heat output of heat distribution systems?

To understand why the heat output of a heat distribution systems decreases when supply and return temperatures are lowered, the equations for heat transfer by convection and radiation should be understood. Convection is the transfer of heat from one place to another by the movement of fluids or gases and is defined by equation 5.1. Here, h, A and T_m denote the heat transfer coefficient $[W \cdot m^{-2} \cdot K^{-1}]$, area $[m^2]$ and the logarithmic mean temperature difference (LMTD) $[°C]$ respectively. The logarithmic mean temperature difference is used to determine the temperature driving fore of heat transfer in flow systems (Agromayor et al. 2016). By calculating the temperature differences between the supply (T_s) and return temperature (T_r) of the heat distribution system and the mean indoor air temperature (T_i) in $[°C]$, the logarithmic mean temperature difference can be determined, which is shown by equation 5.2. Substituting equation 5.2 in equation 5.1 results in the full convection equation, demonstrated by equation 5.3.

$$\dot{Q}_{convection} = h \cdot A \cdot T_m \tag{5.1}$$

$$T_m = \frac{T_s - T_r}{ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \tag{5.2}$$

$$\dot{Q}_{convection} = h \cdot A \cdot \frac{T_s - T_r}{ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \tag{5.3}$$

Lower supply and return temperatures result in a lower LMTD. Consequently, the temperature driving force decreases, wherefore the heat transfer of convectors is reduced. In contrast to convectors which distribute heat mainly via convection, radiators emit the majority of the heat via radiation. Radiation heat transfer is the process by which the thermal energy is exchanged between two surfaces obeying the laws of electromagnetics (Rao 2011). Equation 5.4 describes heat transfer by radiation. Here, σ denotes the Stefan-Boltzmann constant $[5.67 \cdot 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}]$, while ϵ denotes the emissivities of the surfaces. Furthermore, surface areas are denoted by $A\ [m^2]$ and viewing factor is given by F. The viewing factor indicates the proportion of radiation which leaves surface 1 and strikes surface 2.

Similar to convectors, the heat output of radiators decreases when lower supply and return temperatures are used, because the difference between the arithmetic mean temperature of the radiator and the indoor mean air temperature decreases. Regardless of convectors or radiators are installed in a dwelling, one can generally say that the heat output of a heat distribution system decreases when lower supply and return temperatures are used as a result of a decreased LMTD.

$$\dot{Q}_{radiation} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{A_1 \cdot \epsilon_1} + \frac{1}{A_1 \cdot F_{1\rightarrow 2}} + \frac{1-\epsilon_2}{A_2 \cdot \epsilon_2}} = \frac{\sigma\left(\left(\frac{T_s+T_r}{2}\right)^4 - T_i^4\right)}{\frac{1-\epsilon_1}{A_{rad} \cdot \epsilon_1} + \frac{1}{A_{rad} \cdot F_{rad\rightarrow i}} + \frac{1-\epsilon_i}{A_i \cdot \epsilon_i}} \tag{5.4}$$

5.2 Heat loss of a dwelling

Apart from changes in heat output of heat distribution systems, the heat loss of dwellings also plays an important role in the artifact's design. Therefore this section will answer SQ2:

How can the heat loss of a dwelling be determined?

The heat loss of a dwelling can be determined theoretically or empirically. Commonly, the heat loss of a new dwelling is approximated theoretically during the design phase (ISSO 2017) via the ”building envelope” method. However, in existing dwellings the heat loss can also be determined empirically by several empirical methods. First the ”building envelope” method is discussed, followed by all identified empirical methods.

5.2.1 Theoretical heat loss of existing dwelling

Equation 5.5 shows the general equation used to theoretically determined a dwelling's heat loss in steady-state conditions. Here $\dot{Q}_{T,dwelling}$ denotes the dwelling's heat loss by transmission, $\dot{Q}_{V,dwelling}$ the heat loss by ventilation and air infiltration, while $\dot{Q}_{gain,dwelling}$ denotes the heat gains (Jokisalo et al. 2009, Hens et al. 2010, Feist et al. 2005).

$$\dot{Q}_{HL,dwelling} = \dot{Q}_{T,dwelling} + \dot{Q}_{V,dwelling} - \dot{Q}_{gain,dwelling} \tag{5.5}$$

Heat gains, heat loss by transmission and heat loss by ventilation and air infiltration are all dependent on many variables, including meteorological conditions, such as outdoor temperature, wind velocity, relative humidity and sun radiation (Jokisalo et al. 2009, Hens et al. 2010, Feist et al. 2005). In addition, internal heat gains caused by metabolism of humans, electronic devices and kitchen equipment add heat to dwellings and high indoor mean air temperatures contribute to higher heat losses. This complicates the heat loss calculation. Nevertheless, the ”building envelope” method has been developed to theoretically approximate the heat loss based on the dwelling characteristics. In the ”building envelope” method the heat loss of a dwelling follows from the heat loss by transmission and heat loss by ventilation and air infiltration reduced by the internal heat gains (ISSO 2017). Equation 5.6 describes this ”building envelope” method (ISSO 2017).

$$\dot{Q}_{HL,dwelling} = \sum_i (\dot{Q}_{T,ie} + \dot{Q}_{T,iae} + \dot{Q}_{T,iaBE} + \dot{Q}_{T,ig}) + \dot{Q}_{V,build} - \sum_i \dot{Q}_{gain,i} \tag{5.6}$$

$\dot{Q}_{T,ie}$	Heat loss by transmission to outdoor air	$[W]$
$\dot{Q}_{T,iae}$	Heat loss by transmission to unheated adjacent space	$[W]$
$\dot{Q}_{T,iaBE}$	Heat loss by transmission to adjacent buildings	$[W]$
$\dot{Q}_{T,ig}$	Heat loss by transmission to soil	$[W]$
$\dot{Q}_{V,build}$	Heat loss due to air infiltration and ventilation	$[W]$
$\dot{Q}_{gain,i}$	Heat gains	$[W]$

Heat loss by transmission

The heat loss by transmission for dwelling i can be determined by equation 5.7. Here, T_o and T_e denote the operative and outdoor temperature respectively.

$$\dot{Q}_{T,ix} = H_{T,ix} \cdot (T_o - T_e) \tag{5.7}$$

$H_{T,ix}$	Specific heat loss due to transmission	$[W \cdot K^{-1}]$
T_o	Operative temperature	$[^{\circ}C]$
T_e	Outdoor temperature	$[^{\circ}C]$

Heat loss by transmission to outdoor air is described by equation 5.8.

$$\sum_k H_{T,ie} = \sum_k (A_k \cdot (U_k + \delta U_{TB}) \cdot f_k) \tag{5.8}$$

A_k	Surface area external partition construction	$[m^2]$
U_k	Heat transfer coefficient of external partition construction	$[W \cdot m^{-2} \cdot K^{-1}]$
$\delta U_T B$	Premium for thermal bridges	$[W \cdot m^{-2} \cdot K^{-1}]$
f_k	Correction factor for heated surfaces or temperature gradients	$[-]$

Heat loss to adjacent unheated spaces is described by equation 5.9.

$$\sum_k H_{T,iae} = \sum_k (A_k \cdot U_k \cdot f_k) \tag{5.9}$$

A_k	Surface area of wall, floor or ceiling to unheated spaces	$[m^2]$
U_k	Heat transfer coefficient of partition construction	$[W \cdot m^2 \cdot K)]$
f_k	Correction factor for temperature difference outdoor temperature and unheated adjacent space temperature	$[-]$

Heat loss to adjacent buildings is described by equation 5.10.

$$\sum_k H_{T,iaBE} = c_z \cdot \sum_k (A_k \cdot U_k \cdot f_{ia,k}) \tag{5.10}$$

c_z	Correction factor for heat assurance adjacent building	$[-]$
A_k	Surface area of the partition construction that separates the buildings	$[m^2]$
U_k	Heat transfer coefficient of partition construction that separates the buildings	$[W \cdot m^{-2} \cdot K^{-1}]$
f_k	Correction factor for temperature difference outdoor temperature and adjacent building temperature	$[-]$

Heat loss to soil is described by equation 5.11.

$$\sum_k H_{T,ig} = 1.45 \cdot \sum_k (A_k \cdot U_{equiv,k} \cdot f_{gw} \cdot f_{ig,k}) \tag{5.11}$$

A_k	Surface area of construction that touched the soil	$[m^2]$
$U_{equiv,k}$	Equivalent heat transfer coefficient	$[W \cdot m^{-2} \cdot K^{-1}]$
f_{gw}	Correction factor for ground water	$[-]$
f_k	Correction factor for temperature difference outdoor temperature and average soil temperature	$[-]$

Heat loss by air infiltration and ventilation

Heat loss by air infiltration and ventilation is described by equation 5.12.

$$\dot{Q}_{V,build} = (H_i + H_v) \cdot (T_o - T_e) \tag{5.12}$$

H_i	Specific heat loss due to air infiltration	$[W \cdot K^{-1}]$
H_v	Specific heat loss due to ventilation	$[W \cdot K^{-1}]$
T_o	Operative temperature	$[^\circ C]$
T_e	Outdoor temperature	$[^\circ C]$

The specific heat loss due to air infiltration is described by equation 5.13.

$$H_i = 1200 \cdot q_i \cdot z \tag{5.13}$$

1200	Constant value $c_p \cdot \rho$	$[J \cdot m^{-3} \cdot K^{-1}]$
q_i	Volume metric flow rate air infiltration	$[m^3 \cdot s^{-1}]$
z	Air infiltration fraction depending on dwelling	$[^{\circ}C]$

The specific heat loss due to ventilation is described by equation 5.14.

$$H_v = 1200 \cdot q_v \cdot f_v \tag{5.14}$$

1200	Constant value $c_p \cdot \rho$	$[J \cdot m^{-3} \cdot K^{-1}]$
q_v	Volume metric flow rate ventilation	$[m^3 \cdot s^{-1}]$
f_v	Correction factor for higher inlet temperature than outdoor temperature	$[-]$

Heat gains

Equation 5.15 describes the total heat gains of a dwelling. Heat gains are caused by internal heat gains and heat added to a dwelling by the sun. Examples of internal heat gains are heat added by lamps, people, computers, ovens, fridges and freezers. Since the heat gains can vary considerably, the ”building envelope” method does not take heat gains into account when determining the heat loss of a building.

$$\sum_i \dot{Q}_{gain,i} = 0W \tag{5.15}$$

The ”building envelope” method is often applied when the power output of a gas-fired boiler needs to be determined (ISSO 2017). Considering that the operating settings also affect the required power output, some premiums are added to equation 5.6 (ISSO 2017). Firstly, a premium is added to compensate for operating restrictions such as lower temperatures during the night. Secondly, a premium is added to compensate for simultaneously occurring system losses. Examples are heat distributed by floor heating that is directly transferred to the soil and heat that is lost during transport in unheated spaces. Considering that premiums only compensate system losses or operating restrictions, they do not affect the heat loss of a dwelling. Therefore these premiums are not incorporated in equation 5.6. Full explanation about this method, including examples, is available in ISSO (2017).

The ”building envelope” method can only be applied to entire buildings. However, when determining the minimum required heat output of radiators and convectors, the theoretical heat loss per space is often used (ISSO 2017). Small adjustments to the ”building envelope” method enables it to also apply the method to individual spaces. Although the approach remains similar, more details are added in order to differentiate between the type of spaces in a dwelling. For example a bathroom will have other characteristics than an unheated cellar. Equation 5.16 shows the general equation used to theoretically determine the heat loss of space i. The theoretical heat loss per space is required to determine the minimum heat output of radiators and convectors in a specific space. Therefore a premium $[\dot{Q_{hu,i}}]$ is added to equation 5.16 to compensate for operating restrictions. Addition of the premium results in equation 5.17. Again, this premium does not contribute to the heat loss of a specific space. The premium is only added to equation 5.16 to ensure that the radiators and convectors in space i have sufficient heat output. Full details about theoretical heat loss determination of individual spaces are provided in ISSO (2017).

$$\dot{Q}_{HL,i} = \dot{Q}_{T,i} + \dot{Q}_{V,i} - \dot{Q}_{gain,i} \tag{5.16}$$

$\dot{Q}_{T,i}$	Heat loss by transmission of space i	$[W]$
$\dot{Q}_{V,i}$	Heat loss due to air infiltration and ventilation of space i	$[W]$
$\dot{Q}_{gain,i}$	Heat gains of space i	$[W]$

$$\dot{Q}_{HL,i} = \dot{Q}_{T,i} + \dot{Q}_{V,i} + \dot{Q_{hu,i}} - \dot{Q}_{gain,i} \tag{5.17}$$

5.2.2 Empirical heat loss determination

In existing dwellings the heat loss can also be determined empirically by a co-heating test (Bauwens & Roels 2014). The aim of the co-heating test is to find the heat loss coefficient (HLC) of the dwelling, which is the rate of heat loss in Watts per Kelvin of temperature differential between the indoor and outdoor temperature (Farmer et al. 2016). In order to determine the HLC a heat balance is required, which is shown by equation 3.1. By maintaining a constant indoor air temperature the heat balance is kept in equilibrium. At equilibrium conditions, the heat input equals the heat loss of the dwelling. By measuring the heat input and outdoor temperature the HLC can be determined, taking into account that the indoor temperature is already known, because it should be kept constant during the measurements.

The co-heating test is quasi-stationary heating experiment (Bauwens & Roels 2014). During this test a dwelling is heated by the building's own services and electrical heaters with known efficiency. Hence the name co-heating (Bauwens & Roels 2014). Although standard procedures for this test have not been established yet, a commonly used indoor air temperature is 25°C (Johnston et al. 2013). When steady-state conditions are reached, i.e. a constant indoor air temperature is maintained, the co-heating test is started. From that point heat is only supplied by electrical heaters. In order to maintain a homogeneous temperature in the dwelling, all internal doors should be fully opened. Furthermore, ventilators are used to create air circulation, which promotes a homogeneous temperature distribution inside the dwelling. By measuring the amount of heat supplied by the electrical heaters, the heat loss of the dwelling can be determined, since the heat output of the heaters is equal to the dwelling's heat loss.

To simplify procedures, Farmer et al. (2016) developed the integrated co-heating test. This test only makes use of a dwelling's central heating system to add heat. Electrical heaters and fans are not required, hence the total heating input should be determined by measuring the heating output of the central heating system. Since the measurements take place in an empty dwelling, the gas consumption can be directly related to the amount of heat supplied to the dwelling. Only the efficiency of the gas-fired boiler causes deviations in the correlation.

Both the co-heating and integrated co-heating test require an empty house, which is not convenient when residents are present. Therefore the gas meter method can also be applied in dwellings where people reside during the test (Summerfield et al. 2015). Although this method is simple and cost-effective, it involves inaccuracies, because the efficiency of the gas-fired boiler fluctuates when varying return temperatures are used. Furthermore, the gas consumption can not directly be related to space heating. When people reside in a dwelling, gas is also used to cook and to heat up tap water. To eliminate these inaccuracies, Farmer et al. (2016) proposed to measure the amount of energy that is supplied to and returned form the heat distribution system, with an energy meter. This method is called the energy meter method. The total amount of heat supplied to a dwelling can be determined according equation 5.18.

$$\dot{Q} = \rho \cdot c_p \cdot \phi_v \cdot (T_s - T_r) \tag{5.18}$$

ρ	Density	$[kg \cdot m^{-3}]$
ϕ_v	Volume metric flow rate	$[m^3 \cdot s]$
c_p	Specific heat capacity at constant pressure	$[kJ \cdot kg^{-1} \cdot K^{-1}]$
T_s	Heat distribution system supply temperature	$[K]$
T_r	Heat distribution system return temperature	$[K]$

Independently of the used method, measurements should be taken over a long period of time to diminish the thermal mass charging and discharging effect (Bauwens & Roels 2014). Especially in "heavy" buildings, this effect can lead to inaccuracies (Bauwens & Roels 2014). Nonetheless, the results can also be affected by dynamic weather conditions, such as sun radiation and wind (Bauwens & Roels 2014). Monitoring the weather conditions is therefore recommended. However, this involves additional costs because extra equipment is required.

5.3 Heat output of heat distribution systems

This section will answer SQ3: *How can the heat output of a heat distribution system be determined?*

Similar to the heat loss of dwellings, the heat output of heat distribution systems can be determined theoretically and empirically. Theoretical approaches are often applied during the design phase of the heat distribution system or when the operating settings are changed (ISSO 2017), while empirical methods are frequently used to divide the energy costs in apartment complexes that are supplied with heat from one central gas-fired boiler or district heating (Saba et al. 2017, Ecothermo 2019).

5.3.1 Theoretical heat output of existing heat distribution systems

Equations 5.19 and 5.20 show how the minimum heat output of non-normalized heat distribution systems with radiators or convectors can be determined theoretically during a dwelling's design phase. The first step in both equations is the determination of a dwelling's heat loss. For example with the "building envelope" method. Subsequently multiple correction factors are applied to correct for deviations from the normalized situation. The correction factors dependent on the characteristics of the dwelling.

Although the heat distribution system's heat output might exceed the dwelling's heat loss, this does not guarantee that all spaces in that dwellings are provided with sufficient heat. The heat output of all radiators and convectors in the system should therefore be proportionally divided over all spaces in the dwelling. A more sophisticated approach is to determine the heat loss of space i in a dwelling and subsequently apply equations 5.19 and 5.20 in which $\dot{Q}_{HL,dwelling}$ is replaced by $\dot{Q}_{HL,space,i}$.

$$\dot{Q}_s \geq \dot{Q}_{HL,dwelling} \cdot \varphi_v \cdot \varphi_w \cdot \varphi_e \cdot \varphi_o \tag{5.19}$$

$\dot{Q}_s$	Heat output radiator	$[W]$
$\dot{Q}_{HL,dwelling}$	Theoretically determined heat loss dwelling	$[W]$
φ_v	Correction factor for absorbing exterior wall	$[-]$
φ_w	Correction factor for casing and deviant placement (for example: in front of a window or windowsill)	$[-]$
φ_e	Correction factor for emission factor surface radiator	$[-]$
φ_o	Correction factor for overtemperature	$[-]$

$$\dot{Q}_s \geq \dot{Q}_{HL,dwelling} \cdot \varphi_w \cdot \varphi_h \cdot \varphi_o \tag{5.20}$$

$\dot{Q}_s$	Heat output convector	$[W]$
$\dot{Q}_{HL,dwelling}$	Theoretically determined heat loss dwelling	$[W]$
φ_w	Correction factor for placement under windowsill, alcove or something that increase the air resistance	$[-]$
φ_h	Correction factor for height casing	$[-]$
φ_o	Correction factor for overtemperature	$[-]$

In existing dwellings, the heat distribution system is already installed, which incorporates that the theoretical heat output at design conditions is known. Lowering the supply and return temperature of the heat distribution systems changes the design conditions, because the LMTD is changed. With the help of a radiator chart the new heat output can be determined when lower supply and return temperatures are applied. Figure 9 shows a radiator chart of radiator or convector that has normalized operating conditions of 75/65/20°C. The numbers denote the supply, return and operative temperature respectively. Since the radiator chart is applicable to radiators and convectors, it can also be used to determine the new heat output of the entire heat distribution system if the radiators and convectors have similar normalized operating conditions. If the radiator chart method is applied to the whole system, one prerequisite is that the heat distribution system is perfectly balanced, such that every radiator or convector in the system operates with similar supply and return temperatures.

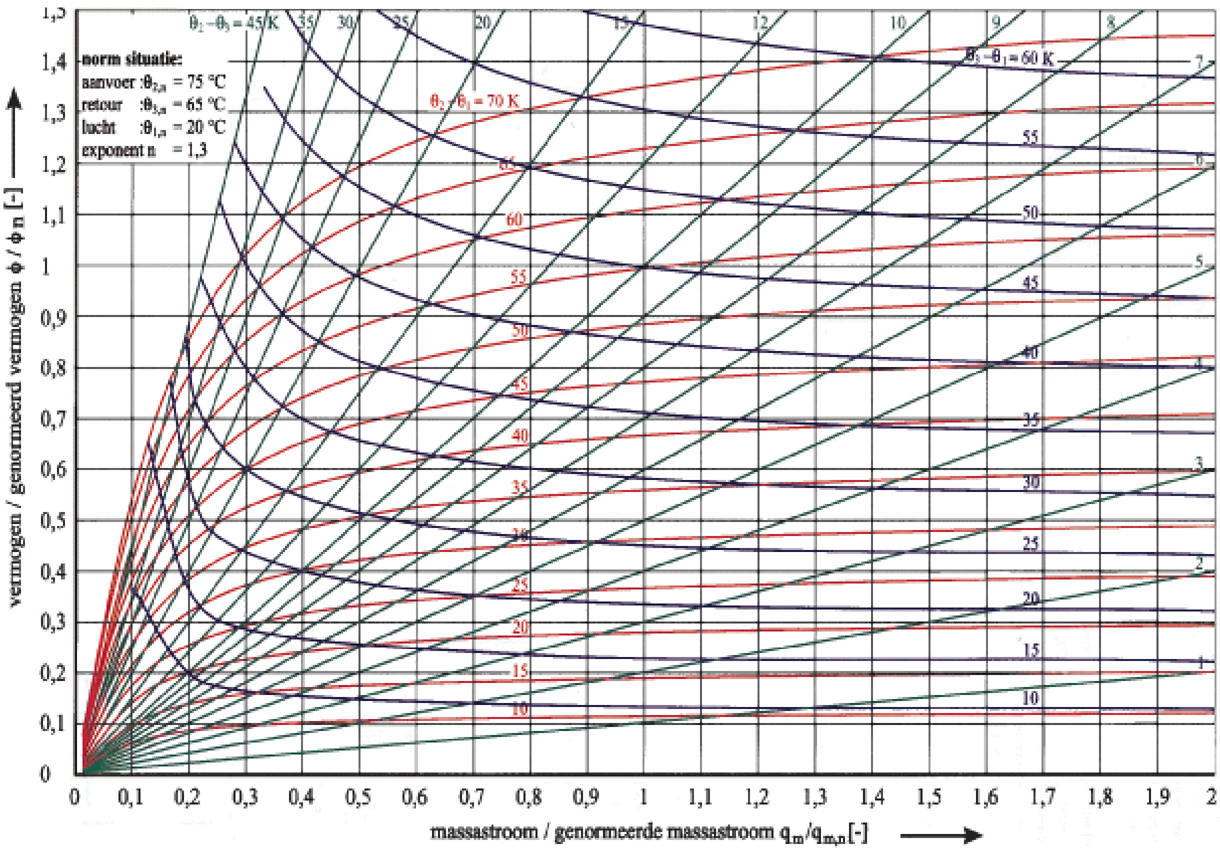

Figure 9. *Radiator chart. Normalized operating conditions in this chart are 75/65/20°C. The first two numbers denote the supply and return temperature, while the last number indicates the operative temperature of space i. If new operating conditions are applied, the correction factor for temperature gradient can be determined by finding the junction of the red and green lines on the y-axis. The required red line can be found by calculating the difference between the supply and operative temperature. The required green line can be found by calculating the difference between the supply and return temperature. For example 55/45/20°C, results in a correct factor of 0,51. This includes that the heat output of a normalized 75/65/20°C radiator/convector decreases by a factor* $\frac{1}{0{,}51}$ *when 55/45/20°C are applied.*

Although using radiator charts is a cost-effective method to theoretically determine the heat output of radiators and convectors, it requires a different chart for every radiator that has divergent normalized operating conditions (ISSO 2001). A more general method that is applicable to all radiators and convectors was developed by Danish Building Research Institute (2000). This method uses the normalized heat output of a radiator, $\dot{Q}_{design,output}$, at normalized operating conditions, which is known because manufacturers supply them normally. This also holds for the radiator exponent n, which is a characteristic that depends on the design of the radiator and indicates the change in heat output of a radiator when the actual conditions, in terms of supply, return and indoor temperature, differ from standard conditions, i.e. the values that were used to define a radiator's nominal heating capacity. When non-normalized operating conditions are applied, the new heat output can be determined by equation 5.21. Here, the $T_m, design$ can be calculated because the normalized conditions are known and T_m can be determined on the basis of the new defined operating settings. Substituting all value into equation 5.21 emanates in the new heat output of the radiator Østergaard & Svendsen (2018*a*).

$$\dot{Q}_{output} = \dot{Q}_{design,output} \cdot \left(\frac{T_m}{T_{m,norm}} \right)^n \tag{5.21}$$

5.3.2 Empirical heat output of existing heat distribution systems

Over the years several methods to measure the heat output of heat distribution systems have been developed. These methods can be divided over two categories. The first category contains all methods that are able to determine the heat output of a single radiator or convector, while the second category consists of methods that determine the heat output of the entire system.

A method to determine the heat output of a single radiator or convector is to measure the heat output with heat allocators over a period of time. Two types of heat allocators exist, electronic and evaporation heat allocators (Ista 2019). The first measures the difference between the radiator surface temperature and the ambient air temperature, while the latter measures the amount of liquid evaporated from one or two special tubes placed in the measuring instrument (Ista 2019). By dividing the total amount of heat distributed by the time the radiator needed to emit the heat, the heat output can be determined. During the measuring period the operating setting must remain as constant as possible. Both types, however, calculate the amount of heat emitted in predefined ”consumption units” (CU). Therefore the total heat input of the heat distribution must be known. By dividing the total heat input by the ”consumption units” of radiator or convector x and time t the heat output of each specific radiator or convector can be determined. This is illustrated by equation 5.22.

$$\dot{Q}_{radiator,x} = \frac{\int_0^t \dot{Q}(t)\,\mathrm{d}t}{\left(\frac{CU_x}{CU_{total}}\right) \cdot t} \tag{5.22}$$

A more reliable method is to measure the volumetric flow rate in combination with the supply and return temperature just after the gas-fired boiler, with an energy meter. This method is similar to the approach described in section 5.2.2. Unfortunately, this method is only cost-effective when the heat output of the entire heat distribution is determined. When one wants to apply this method to a single radiator or convector, an energy meter is required for every single radiator or convector in a dwelling, which becomes an expensive operation.

5.4 Influence of the outdoor conditions on the heat loss of dwellings

Determining the heat loss of a dwelling is crucial in this project. The total heat loss is the sum of heat loss by transmission, ventilation and air infiltration reduced by the heat gains (Jokisalo et al. 2009, Hens et al. 2010, Feist et al. 2005). Low outdoor temperatures result in high transmission losses, see equation 5.7. High wind velocities result in higher air infiltration rates, which consequently increases the total heat loss. Sun radiation can lead to significant heat gains, especially if large glass surfaces are present in dwellings. Understanding the relation between the dynamic outdoor conditions and heat of a dwelling is important to determine the heat loss at design conditions, therefore this section will answer SQ4:

What is the relation between the outdoor conditions and the heat loss of dwellings?

Summerfield et al. (2015), Johnston et al. (2013), Lowe et al. (2007) explored the dependency between the outdoor conditions and a dwelling's heat loss. They found a relationship via linear regression of heat delivered to a dwelling and the temperature difference between the indoor air temperature and mean outdoor temperature. In the study of Lowe et al. (2007) the delivered heat was corrected for solar gains, before the regression was performed. Furthermore, Lowe et al. (2007) used the co-heating method to determine the heat loss, which is in steady-state conditions equal to the heat loss (Johnston et al. 2013). Summerfield et al. (2015), Johnston et al. (2013) used metered energy input to a dwelling, which includes that other heat sources also contributed to the heat input. The data metered energy input was not corrected for these indirect heat gains. As a result, the study of Summerfield et al. (2015) and Johnston et al. (2013) were less accurate than the study of Lowe et al. (2007).

Generally, the outdoor air temperature is considered to be the most important weather variable when determining a dwelling's heat loss experimentally (ISSO 2017). Therefore in most studies the outdoor temperature is monitored, while other variable such as sun radiation and wind velocities are measured to improve the accuracy of the heat loss determination (Lowe et al. 2007, Summerfield et al. 2015, Johnston et al. 2013). Multiple studies found a linear dependency between the heat loss of a dwelling and the outdoor air temperature (Summerfield et al. 2015, Johnston et al. 2013, Lowe et al. 2007). This dependency is useful when the heat loss during extreme design conditions needs to be determined. Especially, because extreme weather conditions, i.e. heavy frost temperatures occur seldom in the Netherlands. When an empirical method is used to the determine a dwelling's heat loss, the linear relationship between the outdoor temperature and heat loss of a dwelling can be used to calculate the heat loss at very low temperatures. Low temperatures do therefore not have to occur when measurements take place.

5.5 Thermal comfort experienced by residents

The reason to install a heat distribution system in dwellings is to facilitate comfort to the residents. Especially during colder periods heat has to be supplied in order to maintain an agreeable indoor temperature. However, simply supplying extra heat to a dwelling will not necessarily increase the thermal comfort level, because thermal comfort is defined as a collection of six variables (Fanger et al. 1970). Lowering the supply and return temperature might affect the thermal comfort of residents. Therefore the effects should be well understood to guarantee that residents will experience a similar thermal comfort sensation at lower operating temperatures. Consequently, this section will answer SQ4:

How can the thermal comfort experience of residents be determined?

The predicted mean vote (PMV)/predicted percentage of dissatisfaction (PPD) model developed by Fanger et al. (1970) stands amongst the most recognized thermal comfort models (Humphreys & Nicol 2002, Hamdi et al. 1999). The model was developed based on the principles of heat balance and experimental data collected from a very large heterogeneous group of people in a controlled climate chamber under steady-state conditions (Fanger et al. 1970). Based on the collected data Fanger et al. (1970) constructed the PMV/PPD model, which indicates the average level of comfort experienced by people at certain indoor conditions and the percentage of people that will be dissatisfied at those conditions (Fanger et al. 1970).

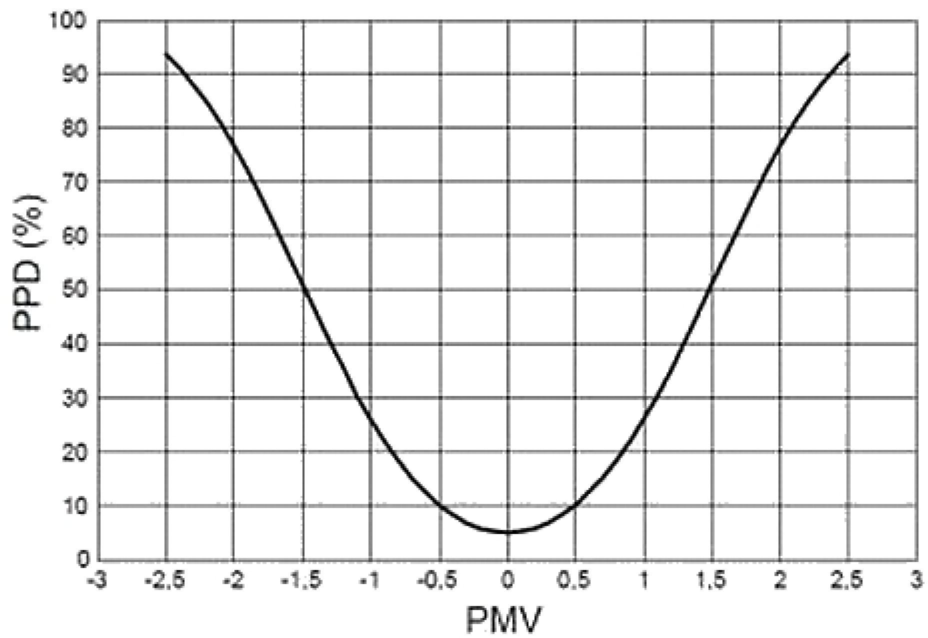

Figure 10. *The Predicting Mean Vote/Percentage of People Dissatisfied chart developed by Fanger et al. (1970). The x axis indicates the perception of the temperature and goes from cold (-3) to hot (+3), while the y axis shows the percentage of people that will be dissatisfied at that perception of temperature (Ohm 2019).*

However, the De Dear & Brager (1998) and Nicol & Humphreys (2002) criticized the model of Fanger et al. (1970), because it is unable to cope with a dynamic environment. Therefore an adaptive model was developed based on hundreds of field studies with the idea that residents dynamically interact with their environment by means of clothing, operable windows, fans, personal heaters, and sun shades (De Dear & Brager 1998, Nicol & Humphreys 2002). De Dear & Brager (1998) state that contextual factors and past thermal history are believed to modify expectations and thermal preferences, wherefore thermal satisfaction is also achieved through appropriate adaptation to the indoor climatic environment.

Although the models differ from each other, both are based on six primary factors with can be divided over two categories: personal factors and environmental factors. Personal factors are characteristics of the occupants and include the metabolic rate and clothing level of a person. Environmental factors are the air temperature, mean radiant temperature, relative air velocity and relative humidity (Nicol & Humphreys 2002, Nicol 2004). On the basis of these factor the PMV and PPD can be calculated and the level of thermal comfort can be predicted (ASHRAE 2017).

The steady-state PMV/PPD of Fanger et al. (1970) is incorporated in ISO (2005), which is used to determine the indoor design temperatures of space in dwellings (ISSO 2017), despite the criticism of other scientists (De Dear & Brager 1998, Nicol & Humphreys 2002). By rearranging the PMV equation, one can determine the required indoor design temperature by chosing a PMV value, which can be obtained from figure 10. Based on ISO (2005) four scenario's are distinguished, which define the input variables for the rearranged PMV equation. In these scenarios the personal factors vary, while the environmental factors remain equal. Table 1 provides the corresponding values and required indoor design temperature for each scenario.

Table 1: *Indoor design temperature based on four scenarios defined in ISSO (2017). The first scenario resembles relatively low activity in which residents remain primarily seated with some activity of the arms (metabolic rate equals 1,7). The second and fourth scenario simulates a seated activity (metabolic rate equals 1,2) and scenario 3 resembles a resting situation (metabolic rate equals 1). The difference between scenario 2 and 4 is caused by the difference in clothing level.*

Factor		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Metabolic rate	[-]	1,7	1,2	1	1,2
Clothing level	[clo]	0,8	0,9	0,9	0,7
Relative humidity	[%]	40	40	40	40
Relative air velocity	$[m \cdot s^{-1}]$	0,1	0,1	0,1	0,1
PMV-value	[-]	0[a]	-0,5[b]	-0,5[b]	-0,4[b]
Operative temperature	**[°C]**	**20**	**20**	**22**	**22**

a thermally neutral
b slightly cold

Table 1 indicates that an operative temperature between 20 and 22°C is acceptable and will provide comfort to residents in varying situations. More activity results in higher metabolism, wherefore lower operative temperatures are required and on the other hand, lower activity and clothing levels result in higher required operative temperatures. The operative temperature is combination of the mean air temperature and mean radiant temperature, see equation 5.23. The value of a is dependent on the indoor air velocity. Since this parameter is difficult to determine, a value of 0,5 is often applied, wherefore the operative temperature is the arithmetic mean of the mean air temperature and mean radiant temperature ISSO (2017). This results in equation 5.24. Although an operative temperature between 20 and 22°C provides comfort, not all spaces in a dwelling require such high temperatures (ISSO 2017). This holds for amongst others storage facilities and toilets. Appendix B provides an overview of the operative temperatures that are deemed appropriate for each space.

$$T_o = a \cdot T_i + (1 - a) \cdot T_{mr} \tag{5.23}$$

$$T_o = \frac{T_i + T_{mr}}{2} \tag{5.24}$$

Since thermal comfort is a combination of six primary factors, simply measuring the indoor air temperature will not be sufficient to determine the effect of lower supply and return temperature on the thermal comfort level of resident. Other factors should be measured as well. Personal factors, such as the metabolic rate and clothing level of a person, are not directly affected by lower supply and return temperatures. This also holds for the relative humidity and relative indoor air velocity[1]. The air temperature and mean radiant temperature are directly affected. Measuring these factors, i.e. operative temperature is essential to precisely determine the effect of lower supply and return temperatures on the thermal comfort of residents.

An alternative approach is to use a questionnaire, which is according to ASHRAE (2017) an acceptable way of assessing comfort conditions. Since thermal comfort also consists of personal factors, which vary among humans, a qualitative approach might also be suitable. Although a questionnaire does not generate quantitative data, it tells whether residents experience thermal comfort or not. Moreover, a questionnaire is cost-effective because no expensive equipment is required. Nevertheless, the addition of quantitative data would improve the reliability of the method. Combining a questionnaire with equipment that can measure the operative temperature or at least the indoor air temperature would be optimal. The design of the questionnaire has to be straight-forward and user-friendly. Several thermal comfort surveys have been developed over the years, one of them being the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standard field questionnaire and protocol (De Dear & Brager 2001). This standard requires that thermal comfort questionnaires include the seven-point sensation scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot) developed by (Fanger et al. 1970) is used (De Dear & Brager 2001).

A project similar to this design project, called ”warm in de wijk”, was executed by the municipality of The Hague last winter. During this project the supply and return temperatures of heat distribution systems in dwellings located in the ”Vruchtenbuurt” were lowered to 70°C. Subsequently, participants rated the thermal comfort experience on a four-point sensation scale (warm, pleasant, cold, very cold). Furthermore, the participants rated the level of satisfaction on a five-point scale (very positive, slightly positive, neutral, slightly negative, very negative). Considering the resemblance with this project, the results from the ”warm in de wijk” project are used as input for the design of a thermal comfort survey. Nevertheless, the ASHRAE survey served as main guideline for the questionnaire’s design. Appendix C shows the proposed questionnaire design.

5.6 Design conditions

To ensure that the heat output of heat distribution systems always exceeds the heat loss of a dwelling, extreme design conditions have been established in the past (ISSO 2017). However, due to global warming the climate in the Netherlands has changed (Van Vliet et al. 2002). The standardized design conditions might therefore be too extreme. Therefore this section investigates the climate change and the frequency of extreme weather conditions occurrence in the Netherlands, resulting in an answer to SQ6:

This section will answer SQ6: *What are the design conditions and are they representative for 2019?*

In dwellings, the standardized operative temperature is 20 or 22°C and the standardized outdoor mean air

[1]The relative humidity and relative indoor air velocity are not directly affected by lower supply and return temperatures. However, lower supply and return temperatures directly affect the air temperature, which subsequently can effect the air velocity and relative humidity, because of less convection. This effect is assumed to be negligible

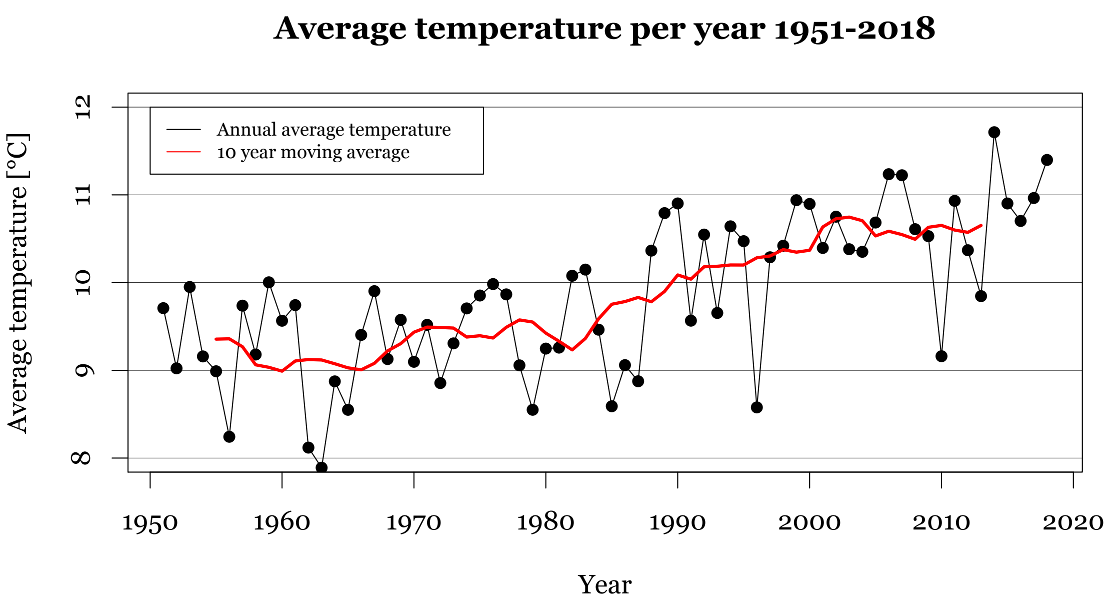

Figure 11. *Annual average temperature 1951-2018 in De Bilt, the Netherlands.*

temperature -10°C (ISSO 2017). Detailed heat loss calculations sometimes also incorporate a wind velocity of 5 $m \cdot s^{-1}$ (ISSO 2006). These design conditions are extreme and will not occur frequently.

As a result of global warming the average global temperature increased by approximately 0.6 °C over the last 100 years and is projected to rise rapidly (Houghton et al. 2001). This has affected the climate around the world (Meehl et al. 2000, Trenberth 2011, Alexander et al. 2006). Although the effects vary across the world, global warming especially led to milder winters in western Europe (Beukema 1992, Vogelsang & Franses 2005, Van Oldenborgh et al. 2015). These effects were clearly noticeable in the Netherlands, where the last two decades of the 20th century have been exceptionally warm (Van Vliet et al. 2002). The 11 warmest years of the 20th century all occurred in the last 20 years (Van Vliet et al. 2002).

To check these findings, historical data from the KNMI was analysed. Figure 11 shows the trend in average annual temperature and the 10 year moving average from 1951-2018 in De Bilt, the Netherlands. The findings correspond with the findings of Van Vliet et al. (2002). However, more interesting is that the period from 2000-2018 was even warmer than 1980 until 2000. The average annual temperature from 2000-2018 was 10.64±0.57°C, while in the period 1981-1999 average temperature equaled 9.93±0.78°C. Except from 2010 and 2013, the period 2000-2018 was extremely warm.

Although the average annual temperature increases rapidly, this does not exclude that extreme weather conditions do not occur anymore. The frequency of extreme weather conditions should be investigated to determine if the current design conditions are still representative for 2019. Table 2 shows all weather stations in the Netherlands that collected climate data from 1951 up to and including 2018. Two columns are specified in table 2 that group that filter the data on specific criteria. The third column indicates the amount of hours

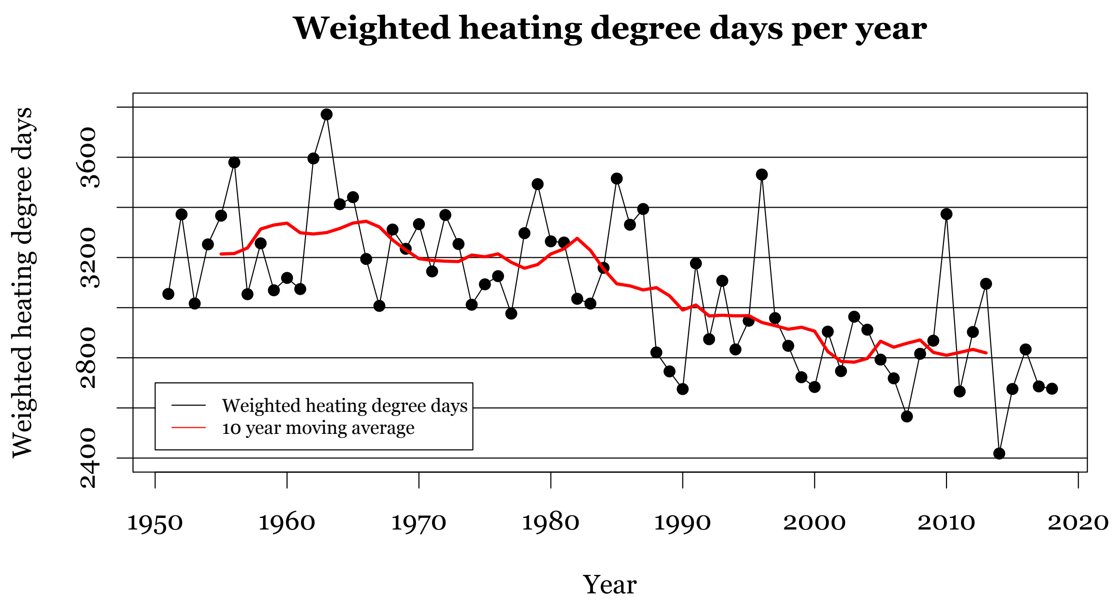

Figure 12. *Weighted heating degree days 1951-2018 in De Bilt, the Netherlands.*

in the period 1951 up to an including 2018 in which the average hourly outdoor air temperature and wind velocity was exceeding -10°C and 5 $m \cdot s^{-1}$ respectively for each weather station. In column four only one criterion was used, namely an average hourly temperature of <-10°C.

In order to determine if extreme weather conditions occur frequently, the weather stations with the most reliable data had to be found. Although all weather stations started to measure climate characteristics in 1951, some weather stations did not collect data every hour. Only the data from weather stations located in De Bilt, Vlissingen, Maastricht and Eelde did not contain missing values. Consequently, the data from these weather stations was investigated. As table 2 shows, multiple criteria can be used to filter the data set. Considering that the outdoor temperature was deemed to be the most important variable, only this variable (temperature <-10°C) was further explored.

Table 2: *Hourly temperature and wind velocity data from all weather stations in the Netherlands from 1951-2018. The period 1951-2018 contains 590.088 hours. Three filters have been defined, which results in 3 subset of the initial data set. The first group contains the total amount of hours in which the average hourly temperature was <-10°C & wind velocity >5 $m \cdot s^{-1}$ per weather station. The second group contains the total amount of hours per weather station in with the average hourly temperature was <-10°C. The third group contains the total amount of hours per weather station in with the average hourly temperature was <-10°C between 06:00 and 23:00, i.e. night was not included.*

Weather station	**location**	**Requirements**					
		Temperature <-10°C & wind velocity >5 $m \cdot s^{-1}$		Temperature <-10°C		Temperature <-10°C between 06:00-23:00	
		Hours	% of total	Hours	% of total	Hours	% of total
210	Valkenburg*	90	0,015	649	0,110	264	0,045
235	De Kooy*	67	0,011	282	0,048	128	0,022
240	Schiphol*	93	0,016	679	0,115	270	0,046
260	De Bilt	222	0,038	1106	0,187	451	0,076
265	Soesterberg*	81	0,014	1461	0,248	598	0,101
270	Leeuwarden*	80	0,014	1203	0,204	533	0,090
275	Deelen*	257	0,044	1599	0,271	715	0,121
280	Eelde	292	0,049	1792	0,304	790	0,134
290	Twenthe*	139	0,024	1943	0,329	828	0,140
310	Vlissingen	113	0,019	234	0,040	100	0,017
344	Rotterdam*	79	0,013	612	0,104	233	0,039
350	Gilze-Rijen*	140	0,024	1425	0,241	607	0,103
370	Eindhoven*	132	0,022	1310	0,222	568	0,096
375	Volkel*	139	0,024	1481	0,251	663	0,112
380	Maastricht	417	0,071	1533	0,260	706	0,120

*Missing data points. Not all temperatures and wind velocities were logged at these weather stations.

Figure 13 shows the amount of hours per year from 1951 up to and including 2018 in which the average hourly temperature was below -10 °C for weather stations located in De Bilt, Vlissingen, Eelde and Maastricht. A clear difference is visible between the weather stations located in Vlissingen and Eelde. Vlissingen is close to the North sea, wherefore the weather station encountered very mild weather conditions (Kottek et al. 2006). Eelde is located approximately 250 km north of Vlissingen, which resulted in lower temperatures. This does not hold for Maastricht, which is located south of Vlissingen. Maastricht, however, is located more landward than Vlissingen wherefore the weather conditions are less mild.

At all four weather stations the amount of hours in which average hourly temperature was below -10°C decreased in the period 1951-2018. Furthermore these ”cold” hours occurred less frequently, but did not completely vanish. In Vlissingen temperatures below -10°C occurred seldom in the past 68 years. Nevertheless, the historical data indicates that heavy frost temperatures were reached until 2000. After the turn of the millennium, not one hour was registered where the temperature in Vlissingen was below -10°C. At weather station Eelde, where much lower temperatures occur, a similar trend is visible. 248 hours below -10°C were registered in the 50s, 492 hours in the 60s, 241 hours in the 70s, 441 hours in the 80s, 188 hours in the 90s, 30 hours in the 00s and 70 hours until 2019. In short, extreme weather conditions occur less frequently than in the past, wherefore the need to incorporate extreme weather conditions during the design phase of a dwelling is less important.

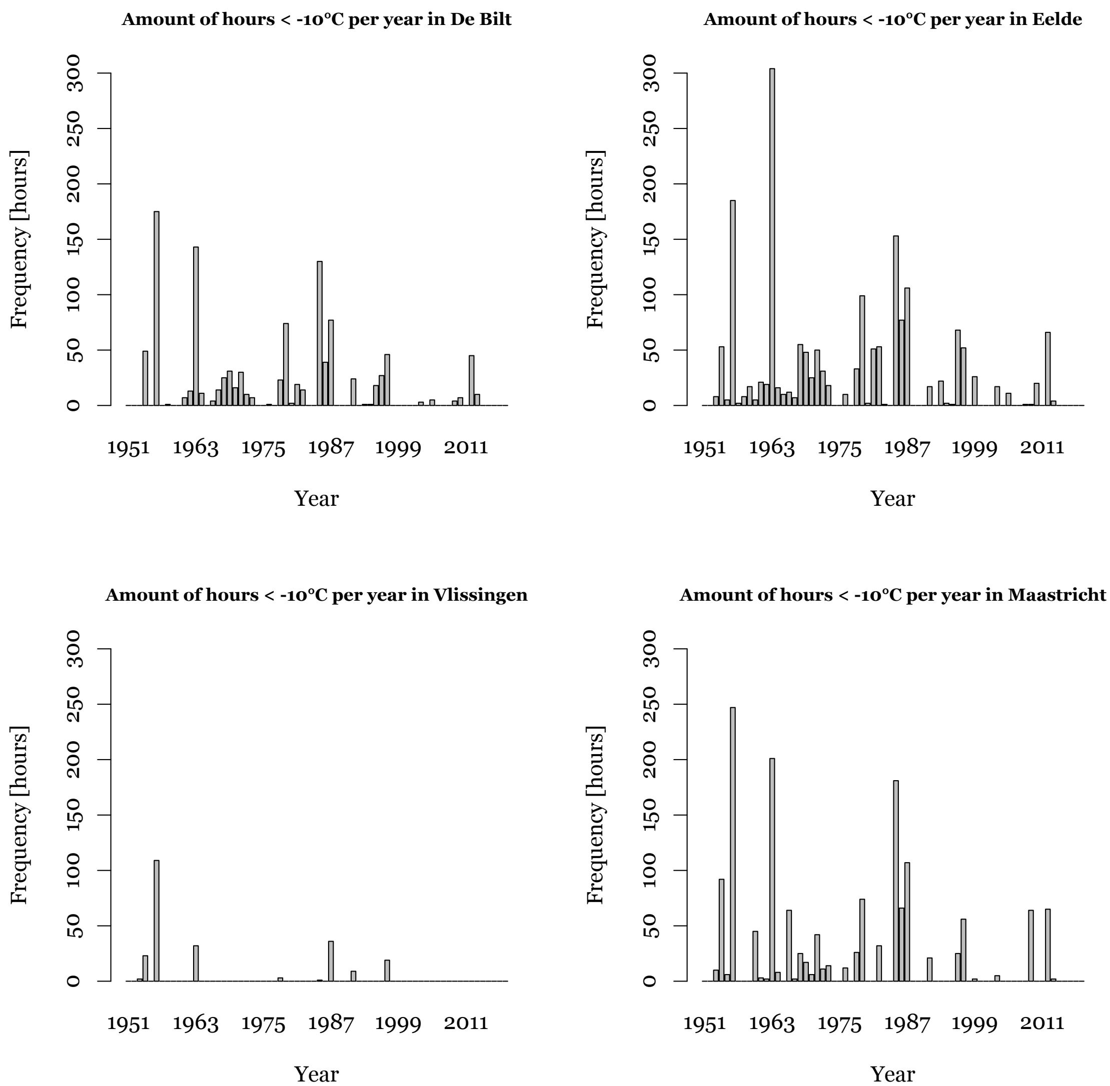

Figure 13. *The amount of hours per year from 1951 up to and including 2018 in which the average hourly temperature was below -10 °C for weather stations located in De Bilt, Vlissingen, Eelde and Maastricht*

The thermal mass of a building affects its heat loss gradient[2]. ”Thermally heavy” buildings are able to store heat for a long period of time. When ”thermally heavy” building need to be heated, a lot of heat has to be provided. This does not hold for ”thermally light” buildings, which heat up relatively quickly. This effect also works the other way around, which means that ”thermally heavy” buildings are less prone to short periods of heavy frost temperatures. Therefore daily average temperatures are more interesting than hourly average temperatures. Consequently, a similar analysis is executed for daily average temperatures. The results are shown in table 3 and figure 14.

[2]More information about thermal mass of buildings in provided in chapters 6 and 7

Table 3: *Average daily temperature data from all weather stations in the Netherlands from 1951-2018. The period 1951-2018 contains 24.837 days. Three filters have been defined, which results in 3 subset of the initial data set. The first group contains the total amount of days in which the average daily temperature was <-10°C per weather station. The second group contains the total amount of days per weather station in with the average daily temperature was <-7°C. The third group contains the total amount of days per weather station in with the average daily temperature was <-5°C.*

Weather station	**location**	**Requirements**					
		Temperature <-10°C		Temperature <-7°C		Temperature <-5°C	
		Days	% of total	Days	% of total	Days	% of total
210	Valkenburg*	8	0,032	77	0,310	205	0,825
235	De Kooy*	6	0,024	58	0,234	172	0,693
240	Schiphol*	14	0,056	86	0,346	226	0,910
260	De Bilt	25	0,101	125	0,503	268	1,078
265	Soesterberg*	32	0,129	128	0,515	277	1,116
270	Leeuwarden*	34	0,137	130	0,523	303	1,220
275	Deelen*	44	0,177	159	0,640	309	1,244
280	Eelde	42	0,169	175	0,705	391	1,574
290	Twenthe*	55	0,221	188	0,757	363	1,461
310	Vlissingen	3	0,012	36	0,145	96	0,387
344	Rotterdam*	12	0,048	66	0,266	176	0,709
350	Gilze-Rijen*	35	0,141	131	0,527	263	1,059
370	Eindhoven*	32	0,129	121	0,487	250	1,007
375	Volkel*	31	0,125	147	0,592	299	1,204
380	Maastricht	48	0,193	152	0,612	293	1,180

*Missing data points. Not all temperatures and wind velocities were logged at these weather stations.

A similar trend is visible when daily average temperatures are used in the analysis. Since 2000, only one day occurred in De Bilt that had an average temperature below -10°C. This also holds for Eelde. In Maastricht two days with an average daily temperature below -10°C were measured since 2000, while in Vlissingen zero days were measured that meet this criterion. Nevertheless, almost all dwellings in the Netherlands are design at a -10°C outdoor temperature. Consequently, this also holds for the heat output of the heat distribution systems, because the minimum heat output is determined by the heat loss of dwellings at design conditions. This indicates that heat distribution system are almost always overdimensioned. Especially in coastal areas, where design conditions are very rare.

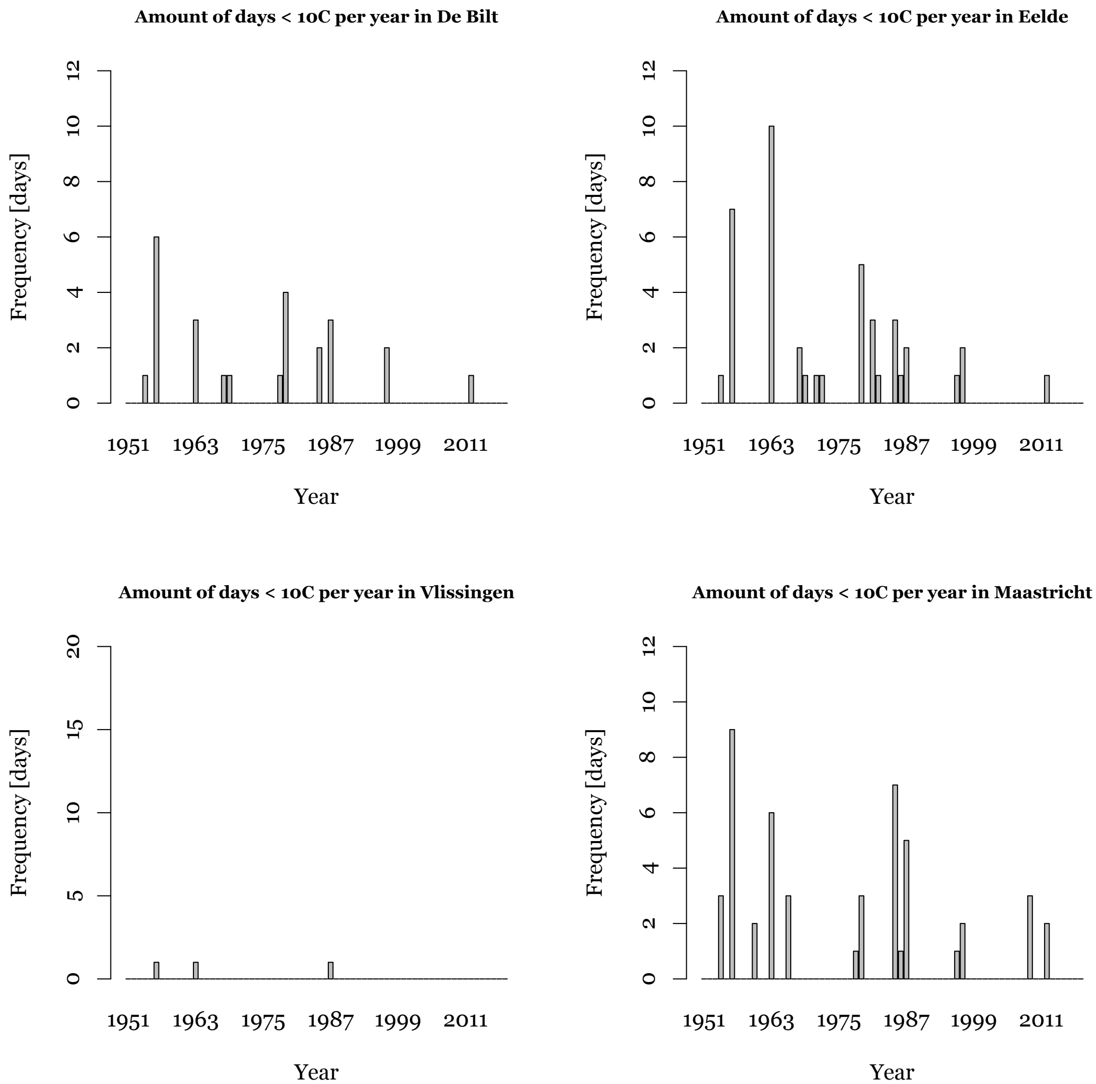

Figure 14. *The amount of days per year from 1951 up to and including 2018 in which the average daily temperature was below -10 °C for weather stations located in De Bilt, Vlissingen, Eelde and Maastricht*

6 Artifact design

In this chapter an artifact is designed that is able to collect representative and reliable data with which the hypothesis of Deltares and Berenschot can be tested. Three topics are addressed in this chapter. Firstly, all methods are evaluated in section 6.1. Subsequently, a method is chosen for each of the artifact's main components in section 6.2. This section also describes the operationalisation procedure. Lastly, the Dutch dwelling stock is divided over a framework of categories in section 6.3, which is important for the operationalisation phase.

6.1 Methods evaluation

As described in section 3.4 the artifact has to produce relevant data for each of the three main components. The components are the heat loss of a dwelling, the heat output of a heat distribution system and the thermal comfort experienced by the residents. In chapter 5, several methods are explicated for each component. Six methods are differentiated that can be used to the determine the heat loss of a dwelling. These methods are the "schil method" applied to the whole dwelling, the "building envelope" method applied to each space in a dwelling, the co-heating method, the integrated co-heating method, the energy meter method and gas meter method. Three methods have been distinguished which are able to determine the heat output of a heat distribution system. These methods are the radiator chart method, heat allocator method and energy meter method. Lastly, four methods are identified which are able to determine the thermal comfort experience of residents. These four methods are a questionnaire, indoor comfort measuring method, indoor operative temperature measuring method and indoor air temperature measuring method. Table 4 summarizes all methods per component.

Table 4: *Overview method for each of the artifact's main components. The bold methods are selected. These methods will be included in the artifact's final design.*

Heat loss dwelling	Heat output heat distribution system	Thermal comfort
Schil method applied to whole building	Radiator chart	**Questionnaire**
Schil method applied to each space	Heat allocator	Indoor comfort measuring
Co-heating method	**Energy meter**	Operative temperature measuring
Integrated co-heating method		Indoor air temperature measuring
Energy meter		
Gas meter		

The artifact only contains one method per component, hence the most convenient methods should be chosen. Therefore, all advantages and disadvantages of each method should be known to properly evaluate them. When all pro and cons for each method are summarized SQ7 can be answered:

SQ7 *How to design an artifact that is able to determine the heat loss of dwelling, the heat output of a heat distribution system and the thermal comfort experienced by residents at design conditions?*

The artifact will be applied in a large amount of dwellings, consequently, the costs should be kept as low as possible. By adding a price quotation or estimation to each method SQ8 can be answered and the most cost-effective methods can be chosen.

SQ8 *How can the costs of the artifact be reduced without compromises on functionality?*

The ”building envelope” method uses a theoretical approach. This incorporates that the heat loss of a dwelling is determined by dwelling characteristics and mathematical equations (ISSO 2017). Although the method is fast and accurate in new buildings, it is less suitable in older buildings. New buildings have well documented characteristics and did not change much compared to their original designs. However, older buildings are mostly renovated over time, wherefore the building characteristics have changed (RVO 2011). Commonly these renovations are not documented very well, which includes that the dwellings characteristics have to be determined experimentally by an expert. This expert needs approximately 0,5-1 day to determine the heat loss of dwelling via the ”building envelope” method. An expert can easily cost €100 per hour, wherefore this method costs >€400 per dwelling according to appendix A.4. In addition, experimental estimation of the building characteristics involves an error margin according appendix A.4. Consequently, the ”building envelope” method will be less accurate in older buildings. However, in contrast to empirical methods the ”building envelope” method is not sensitive to internal and external heat gains which can lead to underestimation of the heat loss (ISSO 2017). Examples of internal heat gains are the metabolism of humans, wherefore heat is emitted to the ambient air. Electronic devices such as computers, television, fridges, freezers and kitchen equipment also emit heat. Sun radiation is the main source of the external gains. Especially during summer periods the solar heat gains can be substantial (ISSO 2017). Lastly, the ”Building envelope method” is very fast compared to experimental methods”.

The ”building envelope” method can also be applied on individual spaces. Although the process remains similar, it takes more time to determine the heat loss of every individual space, because internal heat losses to other spaces should also be determined. Considering that some extra time is required for this method, costs will exceed the costs for the ”building envelope” method applied to the whole building. Costs are estimated to be >€500 per dwelling. Although this method is able to determine the heat loss per space, it still faces the same disadvantages. The total costs for the ”building envelope” method in general, vary as a result of dwellings type and size. Larger detached dwelling require more time than small apartments. If several dwellings of the exact same type, shape and building year are measured the ”building envelope” method can be very cost-effective because the heat loss of only one dwelling has to be determined.

Since several studies have shown that the actual energy performance of buildings can differ significantly from its designed value, the scientific co-heating method was designed (Bauwens & Roels 2014). The co-heating method applies an empirical approach which can cope with the energy renovation problem in dwellings. This method results in precise measurements in renovated buildings. Unfortunately, this method is not practical because dwellings need to be empty when measurements take place. Measurements commonly last two weeks (Butler & Dengel 2013, Stafford et al. 2014). Moreover, the costs are relatively high because labor is required to set up and remove test equipment and data loggers. Half a day per visit is not unrealistic (Butler & Dengel 2013, Stafford et al. 2014). Furthermore, the cost of instrument hire or depreciation should be added, the cost of electrically heating the building needs to be covered and the costs of data analysis could also be taken into account (Butler & Dengel 2013). Consequently, applying the co-heating method is estimated to cost €2.000 per dwelling.

The integrated co-heating test is less expensive than the standard co-heating test, because the electrical heaters and fans are not needed (Farmer et al. 2016). This results in an estimated cost reduction of approximately € 500, wherefore the costs of the co-heating test are estimated to amount € 1.500 per dwelling. Unfortunately the test produces less accurate measurements and still requires an empty house (Farmer et al. 2016). Considering that residents should be able to reside in their dwelling during the measurements, the co-heating and integrated co-heating method do not seem to be suitable for the artifact's design. Moreover, costs are 3 times the costs of the "building envelope" method, wherefore a major part of the artifact's design budget is consumed.

The energy and gas meter methods are both experimental methods that use the total energy input in a dwelling to determine the heat loss. Both methods are less accurate than the (integrated) co-heating test, but allow the residents to stay at home. Due to internal and external heat gains the heat loss of a dwelling can be underestimated according to interview A.1. When the energy meter method is chosen, equipment is needed to perform measurements. Total costs, which include the purchasing and installation costs of an energy meter and data analysis are estimated at € 300 per dwelling. Equipment is not always required when the gas meter method is applied, because gas meters are already installed in Dutch dwellings. However, these meters are often analogue gas meters which are not able to log data (Van Aubel & Poll 2019). Only dwellings equipped with smart meters are able to log data.

In 2014 the Dutch government decided to go ahead with the roll out of smart meters to every home (Kamp 2014). By the end of 2016 approximately 3 million were equipped with smart meters that monitored the gas and electricity consumption at 10-s intervals (RVO 2018). Because data collection can take up to 24 hours, energy receive much less fine-grained data (15 minutes instead of 10 seconds (Van Aubel & Poll 2019). Using smart meters is a very cost-effective method, because only data analysis costs, estimated at € 50 per dwelling, have to be incurred. Nevertheless, gas meter measurements can be highly inaccurate, because the efficiency of the gas-fired boiler is unknown and a certain percentage of the total gas consumption is used for cooking and hot water.

Several methods can be applied to determine the heat output of a heat distribution system. The radiator chart method developed by ISSO (2001) is simple and accurate. Furthermore costs are low (€ 50-100 per dwelling), because equipment is not required. However, the radiator characteristics and design settings should be known upfront (ISSO 2001). Especially in older buildings with outdated radiators, this might cause problems.

The heat allocator and energy meter method both use experimental approaches. Heat allocator are devices placed on a radiator or convector to measure the amount of heat emitted by every single radiator or convector. Normally, heat allocators are used to divide the heating costs among residents that live in apartment complexes in which heat is generated centrally. At steady-state operating conditions the heat output of a radiator can be determined by dividing the total heat output by the time in which the heat was emitted. Although this method is fast and relatively cheap >€ 30 per radiator, it is highly inaccurate. Firstly, because steady-state operating conditions are uncommon in central heating system and secondly because the heat allocators are not accurate themselves. The inaccuracy is caused because heat allocators do not measure the fundamental physical parameters (radiator inlet and outlet temperature + volumetric flow rate), but measure radiator surface and ambient air temperature at a specific point in time (Saba et al. 2017, Ecothermo 2019). Furthermore, temperature sensors connected to a data logger should be added to the heat allocators to determine to which temperatures the radiator can be lowered. Costs will consequently be multiplied by at least a factor two. Considering that the accuracy of the heat allocators is poor and costs increase by addition of the temperature sensors, the heat allocator method does not seem appropriate for the artifact's design.

Another experimental way to determine the heat output of heat distribution system is to apply energy meters. By continuously monitoring the volumetric flow rate, inlet and outlet temperature, the total heat output of a radiator can be determined precisely. However, much equipment is needed when the energy meter method is applied to every single radiator (€ 250 per radiator in a dwelling, hence the costs will be high. The method can also be applied to the whole heat distribution system, by monitoring the variables just after the heat source. This approach is significantly cheaper (€ 300), but unable to determine the heat output of a single radiator. Depending on the method chosen to determine a dwelling's heat loss, costs can be even further reduced. If the energy meter method is used to determine the heat loss of dwelling, no equipment is needed to determine the heat output of the entire heat distribution system, because it is already installed.

The most cost-effective method to measure thermal comfort is a questionnaire, because it is fast and does not require equipment to obtain data. Costs are estimated at € 50 per dwelling, which are mainly caused by communication and data processing. A questionnaire unfortunately results in qualitative data. Hence, measuring thermal comfort is preferable since quantitative data is obtained. Although measuring instruments exist that are able to measure all thermal comfort parameters, these instruments are not suitable for the artifact due to the exorbitant costs. According to a quotation of Delta OHM costs are approximately € 3000 per space, wherefore it exceeds the artifact's budget. Obtaining data with thermal comfort measuring instruments is therefore not cost-effective.

Measuring only a few of thermal comfort parameters, such as radiant and/or indoor air temperature would be a solution to lower the costs. The most important thermal comfort parameters are the indoor air and radiant temperature. On the basis of these parameters the operative temperature can be calculated. The operative temperature is often used in heat loss calculations and gives an accurate indication of thermal comfort (ISSO 2017). Although measuring air and radiant temperature is cheaper than measuring all thermal comfort parameters, costs are still substantial, € 1.000 per space according a quotation of Delta Ohm. This is mainly caused by the radiant temperature measuring equipment. Measuring only the air temperature is more cost-effective (€ 100 per space) but produces less reliable data, because the operative temperature can not longer be determined. Connecting a data logger to the thermostat is even slightly cheaper. Albeit, not all thermostats are able to transfer data to a logger.

6.2 Method selection

The main problem during the artifact design is to find the optimum between accuracy and cost-effectiveness. On the one hand, the artifact should produce reliable data to test the hypothesis. Accurate methods are therefore required. On the other hand, the artifact should be operationalised in a considerable amount of dwellings to produce a representative data set. This implies that the costs for the artifact should be kept as low as possible.

The analytic hierarchy process (AHP) multi-criteria decision making instrument was used to select a method for each the artifact's main components. The AHP considers a set of evaluation criteria, and a set of alternative options among which the best decision is to be made. Via pairwise comparisons of the criteria by a decision maker, the AHP generates weights for each evaluation criterion. A higher weight resembles higher importance. In addition to the fixed criteria, the AHP assigns a score to each option according to the decision maker's pairwise comparisons of the options based on that criterion. Again, the higher the score, the better the performance. Finally, the AHP combines all option scores and criteria weights, which results in a global score. The global score is obtained by the weighted sum of the scores obtained with respect to all criteria. This results in a ranking in which the method with the highest global score is the preferred method of choice.

Four general criteria were defined on which the methods were evaluated. These criteria are:

- **Accuracy:** the ability of the method to produce accurate measurements. This also includes the capability of measuring the heat loss or thermal comfort per space and the heat output per radiator. High accuracy is preferred.
- **Costs:** Costs should be kept as low as possible. The lower the costs, the better.
- **Applicability:** It should be possible to use the method in a variety of situations. For example in old (renovated) and relative new dwellings or when residents are present. The more versatile the method, the better.
- **Subjected to season:** The possibility to apply the method throughout the year. Not necessarily during winter conditions. Again, the more versatile the method, the better.

Table 5: *Analytic hierarchy process decision matrix. High scores indicate suitable methods that can be applied in the artifact's design.*

Criteria	**Weight**	**Dwelling heat loss determination**						**Heat output radiator**			**Thermal comfort**			
		"Building envelope" method	"Building envelope" method per space	Co-heating method	Integrated co-heating method	Energy meter method	Gas meter method	Radiator chart	Heat allocators	Energy meter method	Questionnaire	Measuring indoor climate temperature	Measuring operative temperature	Measuring indoor air temperature
Precision	0,46	0,16	0,27	0,29	0,15	0,10	0,02	0,47	0,07	0,47	0,04	0,56	0,27	0,13
Costs	0,33	0,14	0,07	0,03	0,12	0,18	0,46	0,66	0,16	0,19	0,57	0,04	0,14	0,25
Applicability	0,16	0,07	0,07	0,03	0,03	0,40	0,40	0,07	0,47	0,47	0,25	0,25	0,25	0,25
Subjected to season	0,05	0,41	0,41	0,05	0,05	0,05	0,05	0,60	0,20	0,20	0,25	0,25	0,25	0,25
Score		**0,15**	**0,18**	**0,15**	**0,12**	**0,17**	**0,23**	**0,47**	**0,17**	**0,36**	**0,26**	**0,32**	**0,22**	**0,19**
Preference I. Pothof		0,00	0,00	0,10	0,10	0,10	0,10	0,00	0,10	0,10	0,10	0,10	0,10	0,10
Total score		**0,15**	**0,18**	**0,25**	**0,22**	**0,27**	**0,33**	**0,47**	**0,27**	**0,46**	**0,36**	**0,42**	**0,32**	**0,29**

First the set of evaluation criteria was assessed via pairwise comparison. Precision (0,46) turned out to be the most important evaluation criterion, followed by costs (0,33) and applicability (0,16). Seasonal dependency (0,05) was not considered to be very important. The scores of all evaluation criteria add up to one. Subsequently all methods related to each main component were pairwise evaluated based on the weighted evaluation criteria. This resulted in a global score for each method.

Based on the global scores in table 5 and preferences of I. Pothof a method is chosen for each of the artifact's main components. I. Pothof prefers experimental methods over theoretical methods, because several studies on closely related topics have already used theoretically methods. However, data obtained with experimental methods is often not available. Moreover, I. Pothof wants to generate a large data set that can also be used for other purposes than solely testing the hypothesis. Therefore an additional "bonus" is added to the scores in table 5 to indicate the preferences of I. Pothof.

The co-heating, energy meter and gas meter method generated the highest scores. The co-heating method is not selected due to its exorbitant costs. Although the gas meter method scores higher than the energy meter method, it is not favourable, because the score on precision is very poor compared to the other methods. The high total score of the gas meter method was caused by high scores on costs and applicability. Finally, the energy meter method remains. Even though it does not have the highest score in table 5, the method is experimental and more reliable than the gas meter method. Consequently, this method is chosen to determine the heat loss of dwellings.

Two of the three possible methods to determine the heat output of heat distribution system produced high scores. These are the radiator chart and the energy meter method. The first is a theoretical method and the latter an experimental method. Therefore the energy meter method is preferred over the radiator chart method. In addition, the difference in scores of both methods is mainly caused by the large discrepancy in costs. However, this discrepancy is nullified due to the fact that the required equipment is already installed, because similar equipment is needed to determine a dwelling's heat loss with the energy meter method. Although the radiator chart scored higher than the energy meter method in table 5, the energy meter method was chosen over the radiator chart because of the above standing reasoning.

Four methods were identified that could be used to determine the thermal comfort experience of residents. A questionnaire that generates qualitative data and three methods that produce quantitative data by taking measurements. Although I. Pothof prefers quantitative data, a qualitative questionnaire is chosen over a quantitative method. Cost-effectiveness is the main reason to select a questionnaire. The costs to determine the thermal comfort temperature of one specific space are exorbitant. Only measuring the operative temperature is cheaper, but also consumes a large fraction of the artifact's budget. Moreover, these methods only gather data of one single space. Therefore costs will increase by a multiple of the previous mentioned amount if data of all spaces in a dwelling must be acquired.

In short, the artifact main pillars are determination of a dwelling's heat loss, the heat output of the heat distribution system in that particular dwelling and the thermal comfort experienced by the residents. The dwelling's heat loss will be determined by the energy meter method. This also holds for the heat output of the heat distribution system. To keep the costs of the artifact within budget, the thermal comfort of the residents will be determined via a questionnaire. All advantages and disadvantages of the chosen methods are summarized in table 6. In addition, the artifact will be called "measuring campaign" as of now.

Table 6: *Advantages and disadvantages of the chosen methods incorporated in the measuring campaign.*

	Advantages	**Disadvantages**
Heat loss Energy meter	Complies to the preferences of I. Pothof, i.e. experimental approach	Not applicable to individual spaces
	Can be applied when residents are present	Not suitable in seasons other than winter
	Cost-effective	Requires a considerable amount of time to acquire data
Heat output Energy meter	Complies to the preferences of I. Pothof, i.e. experimental approach	Only applicable to individual radiator and convectors at high costs
	Cost-effective since similar equipment is used for the heat loss determination	Slower than theoretical methods
	Can be applied when residents are present	
Thermal comfort Questionnaire	Captures the thermal sensation of the residents	Results in qualitative data
	Cost-effective	Subjective

6.2.1 Measuring campaign operationalisation phases

The measuring campaign operationalisation consists of four main phases: preparation, executing, resetting and test phase. These phases will be executed sequentially, because the subsequent phases can only be initiated when previous phases are completed.

1. **Preparation phase.** During the preparation phase a heating, ventilation and air conditioning (HVAC) technician will install an energy meter just after the gas-fired boiler, connect a data logger to the thermostat and install an outdoor thermometer with data logger. The latter is optional, because data from a nearby KNMI weather station can also be used. Nevertheless measuring the outdoor temperature near the dwelling is more precise. Furthermore, the heat distribution system will be balanced

by the HVAC technician in order to guarantee maximum heat output at variable supply and return temperatures. An initial report will be formulated that summarizes the dwellings characteristics, heat distribution system configuration and households composition. An example of this report is available in appendix D.

2. **Execution phase.** When the preparation phase has ended, data acquisition will start. This phase can only be initiated during colder periods, because a large temperature differential between the in- and outdoor air temperature is required. In eight consecutive weeks data will be acquired by the energy meter and data loggers every minute.

3. **Resetting phase.** With the data acquired during the execution phase, the new operating settings can be determined. First the heat loss is determined at outdoor design conditions that are deemed acceptable. Secondly, the maximum heat output of the heat distribution system is determined at standard operating settings. Subsequently the required maximum heat output of a heat distribution system is adjusted to the heat loss determined in the first step of the resetting phase. On the basis of this new heat output the new operating settings, including the new supply and return temperatures can be determined. Again, a HVAC technician will visit the dwelling to lower the supply temperature from the gas-fired boiler to the heat distribution system.

4. **Test phase.** During this phase the new operating settings will be tested, which results in a different heating regime. The new heating regime might affect the thermal comfort experience of the residents. In order to determine if the change in thermal comfort is acceptable for the residents, they will continue their regular life in a similar manner as they did during the executing phase. They will evaluate the performance of the heat distribution system by completing a questionnaire. In the case that residents experience thermal discomfort during the test phase, they can contact the project supervisor.

Considering that the measuring campaign will be operationalised in many dwellings and produces a large chunk of data per dwelling, the time to clean and process the data set is substantial. An R 3.5 code has been written that also becomes in python 3.6 in August. The code is able to determine the heat loss and maximum heat output of the heat distribution system based on the data obtained from the energy meter. When these parameters are known, the new operating setting, i.e. new supply and return temperatures can be determined according equation 5.21. In short, the code automates phase 3: the resetting phase, except for the HVAC technician that still has to adjust the supply temperature manually.

6.3 Measuring campaign in operationalisation

The measuring campaign can not be implemented in every dwelling. Therefore a representative part of the Dutch Dwelling stock should be analysed. The dwelling stock in the Netherlands consists of many different dwelling types (Yücel 2013). Trying to capture the diversity in its full scale may yield too much variation which makes operationalisation complex. On the other hand, assuming that the Dutch housing stock is homogeneous might result in overlooking important details. Therefore this section will answer SQ9, which explores the dwelling types that are representative for the Dutch dwelling stock.

SQ9 *In what kind of dwellings should the artifact be operationalised in order to generate relevant data?*

A framework has been designed that divides the Dutch dwelling stock over five dwelling types and three building periods. Based on the RVO (2011) ”voorbeeldwoningen” document five dwellings types have been distinguished, which are: detached dwellings, semi-detached dwellings, corner dwellings, terraced dwellings and apartments. Figure 15 shows examples of the five dwelling types. Furthermore, three building periods have been defined based on economic events and changes in building standards over the years. The first building period includes all dwellings until 1974. The main reason for choosing this period is the oil crisis in 1973, since adding insulation to dwellings before the oil crisis was not economically feasible according to Smeds (2004), Verbeeck & Hens (2005), A.C. van der Linden (2015) and the interview in appendix A.2. In addition, buildings constructed well before 1974 do often not contain a cavity wall according to interview in appendix A.2. The second period contains all dwellings build between 1974 and 1991. Although a part of the Dutch dwelling stock was provided with insulation after 1973, the quality of the insulation material is often inferior compared to materials that are currently available (Abu-Jdayil et al. 2019). The last period contains all dwellings build after 1991. This period was selected, because the first building standards were set by the Dutch government in 1992 according to the interview in appendix A.2.

Figure 15. *Examples of the distinguished dwelling types*

BAG (Basisregistratie Adressen en Gebouwen) data has been imported in ARC GIS pro to assign one of the five dwelling types to each dwelling in the Netherlands. This was performed by using an algorithm that first determines if a building is a dwelling on basis of the building classification and subsequently determines the number of neighbours for each dwelling based on the geometrical coordinates. The number of neighbours eventually determine the type of dwelling according the following rules:

- **Detached dwelling:** A dwelling without neighbours is denoted as detached dwelling.
- **Semi-detached dwelling:** Two dwellings that both have only one neighbour are both semi-detached dwellings.
- **Corner dwelling:** A dwelling that is attached to one neighbour that has two neighbours must be a corner dwelling.
- **Terraced dwelling:** A dwelling that is attached to two other dwellings.
- **Apartments:** If multiple dwellings are located in one building.

This analyses resulted in a data set which contained all dwellings and their building year in the Netherlands.

Subsequently R was utilized to distribute the dwellings over the framework. Table 7 shows the dwelling distribution in the Netherlands. Although table 7 gives a representative overview of the Dutch dwelling stock, the amount of corner dwelling and detached dwelling is too high. This is caused by the fact that buildings with another classification than residential are filtered from the data set. Consequently, dwellings that are in reality connected to a store/shop/workplace/etc. are considered as corner dwellings or detached dwellings.

Table 7: *Dwelling distribution in the Netherlands. Dwellings are divided over 5 dwellings types and 3 building periods. Dwelling types: detached dwellings, semi-detached dwellings, corner dwellings, terraced dwellings and apartments. Building periods: before 1974, 1974–1991, after 1991.*

Building period	Detached dwelling	Semi-detached dwelling	Corner dwelling	Terraced dwelling	Apartment
After 1991	3,6%	2,0%	2,7%	7,1%	5,5 %
1974–1991	2,5%	1,6%	4,3%	9,5%	6,3 %
Before 1974	7,3%	4,9%	6,0%	12,6%	24,1%

The measuring campaign should be operationalised in many dwellings to obtain a data set that is large enough to scientifically test the hypothesis. The more dwellings, the better. However the larger project discussed in 4 is also limited by a budget, wherefore only a certain amount of dwellings can be measured. A trade-off between the sample size and the measuring campaign's budget per is unavoidable. With equation 6.1 the minimum sample size can be determined in large categorical populations (Cochran 2007). Here, n_o denotes the number of samples required. t denotes the abscissa of the normal curve that cuts off an area α at the tails ($1 - \alpha$ equals the desired confidence level). The selected α is 0.05 per tail, which results in a confidence interval of 0.9. p denotes the estimation of variance and can be found by $p = 1 - q$, where q denotes the proportion of the population which has the attribute in question. The proportion is unknown, because the effect of dwelling types is not clear. Consequently, the maximum amount of variance is chosen (0.25) by letting $q = 0,5$. Lastly, d stands for the acceptable margin of error (Cochran 2007), which is set at 5%.

$$n_o \geq \frac{t^2 \cdot p \cdot q}{d^2} \geq \frac{0,9^2 \cdot 0.5 \cdot 0.5}{0,05^2} \geq 250,2 \geq 251 \tag{6.1}$$

Based on the above defined confidence interval and acceptable margin of error, 251 dwellings need to be measured in order to acquire a data set large enough to test the hypothesis. However, it is not possible to take 251 random dwellings from the Dutch dwelling stock. First of all, because homeowners should participate in the project, wherefore they agree to the fact that data about their energy consumption behaviour is used. Secondly, the Dutch dwelling stock in not equally divided over all dwelling types and construction periods. This is illustrated by table 7. Now that the minimum sample is known, a proportional stratified sample of the Dutch dwelling stock can be taken. With proportionate stratification, the sample size of each stratum is proportionate to the population size of the stratum. By taking the number of samples shown in table 8 as a bare minimum the hypothesis can be scientifically tested.

Table 8: *Strata sample size when taking into account the 80% most occurring dwelling types.*

Building period	Detached dwelling	Semi-detached dwelling	Corner dwelling	Terraced dwelling	Apartment
After 1991	9	12	7	18	14
1974–1991	6	5	11	24	16
Before 1974	18	4	15	32	60

7 measuring campaign validation

In this chapter the designed measuring campaign is validated to ensure that it is able to acquire data that can be used to test the hypothesis. First, a short introduction to the case study is given. Subsequently, the energy meter method, which is used to determine the heat loss of dwellings and the heat output of heat distribution systems, is validated in section 7.2 and 7.3. In section 7.4 it is demonstrated that the new supply and return temperatures can be calculated based on outcomes of the previous sections. Lastly, the questionnaire, used to thermal comfort experience of residence, is validated in section 7.5.

7.1 Case study

A case study is performed to validate the measuring campaign. Data of two apartment complexes located in Leiden has been obtained from Delft municipality. In both apartment complexes an energy meter was installed that measured the average hourly energy input from 2010-2018. A front view of each building is shown in figure 16. Apartment complex WH Leiden consists of 31 identical apartments. Building OSG Leiden is larger and contains 100 identical apartments. Although the exact construction year is unknown, both apartment complexes were probably built between 1960 and 1980.

Besides energy meter data, the average hourly outdoor temperatures were obtained from KNMI weather stations Valkenburg and Voorschoten. Weather station Valkenburg was closed in 2016 to make space for other buildings. Consequently, the KNMI opened weather station Voorschoten to replace weather station Valkenburg (KNMI 2014). Both weather stations are located near Leiden. To generate a temperature data set that is representative for outdoor temperature of apartment complexes WH and OSG Leiden in the period 2010-2018, data from weather station Valkenburg from 2010 until 2016 was combined with data from weather station Voorschoten 2016 until 2019.

(a) *Apartment complex WH Leiden* ***(b)*** *Apartment complex OSG Leiden*

Figure 16. *Front view of both apartment complexes in Leiden*

7.2 Heat loss

First the heat loss of both apartment complexes was determined by a linear regression of the average daily energy consumption and amount of weighted heating degree days per day or indoor-outdoor air temperature differential. Figures 17 and 19 show the regression plots of building WH and OSG Leiden when the average daily energy consumption is plotted against the indoor-outdoor air temperature differential. To determine the indoor-outdoor air temperature differential, an average indoor air temperature of 20°C was assumed (ISSO 2017). By subtracting the outdoor air temperatures obtained from the KNMI weather stations from the assumed indoor air temperature the hourly indoor-outdoor air temperature differential can be determined. Subsequently the 24 hour mean was calculated to determine the daily indoor-outdoor air temperature differential.

The linear regressions, shown by figure 17 and 19 both result in reasonable R^2-values, which indicates the goodness-of-fit by determining the percentage of variance that can be explained. A high R^2-value is not necessarily good, therefore 95% prediction intervals have been added. A prediction interval is an estimated interval in which observations will fall, with a certain probability based on what has already been observed. Although figure 17 and 19 show decent linear regressions, some unexpected values were visible in the plots. Some data points indicate heat output to the apartment complexes, when the outdoor temperature exceeds the assumed indoor temperature of 20°C. This results in an indoor-outdoor temperature differential below 0°C. A possible cause is that the residents prefer higher indoor temperatures, for example 22°c instead of 20°C. A second plausible explanation is the effect of thermal mass. Although outdoor temperatures might have increased a rapidly that day, the building heated up at a slower rate, wherefore the heat had to be supplied. Another clear difference that is illustrated by both figures is the disparity in insulation. OSG Leiden needs less energy to heat the apartments than WH Leiden. Furthermore, less heat is required in the spring and summer months which is also a sign of better insulation. Nevertheless, the OSG Leiden building contains three times a much apartments as WH Leiden, wherefore the building volume to building envelope ratio is higher.

Figures 18 and 20 show the linear regression of building WH and OSG Leiden when the average daily energy consumption is plotted against the amount of weighted heating degree days. A heating degree day is a measurement designed to quantify the demand for energy needed to heat a building. It is the number of degrees that a day's average temperature is below 18°C, which is the temperature below which buildings need to be heated. By subtracting the hourly outdoor air temperature from the KNMI weather stations from the standardized 18°C, the heating degree hours are determined. When the average outdoor temperature at a random hour equals 10°C, this results in 8 heating degree hours. However, during the winter periods the heat gains by sun radiation are lower than during the summer. Furthermore the heat loss by air infiltration increases, because the higher wind velocities occur more frequently during the winter. To compensate for these differences the heating degree hours in the November, December, January and February are multiplied by a factor 1,1 and in April, May, June, July, August, September by a factor 0,8. In March and October the heat degree hours are not adjusted. To calculate the weighted heating degree days, the 24 hour mean was calculated from the weighted heating degree hours.

Linear regression of the average daily energy consumption and weighted heating degree days showed slightly better correlations than energy input and indoor-outdoor temperature differential, especially in figure 20. This does not hold for figure 18. Despite a R^2-value of 0,87, the figure seems to have a more logarithmic curve. Nevertheless, the first was deemed more accurate than indoor-outdoor temperature differential, because corrections for sun radiation and wind velocity were applied. Therefore regression results from figures 18 and 20 are applied in subsequent steps.

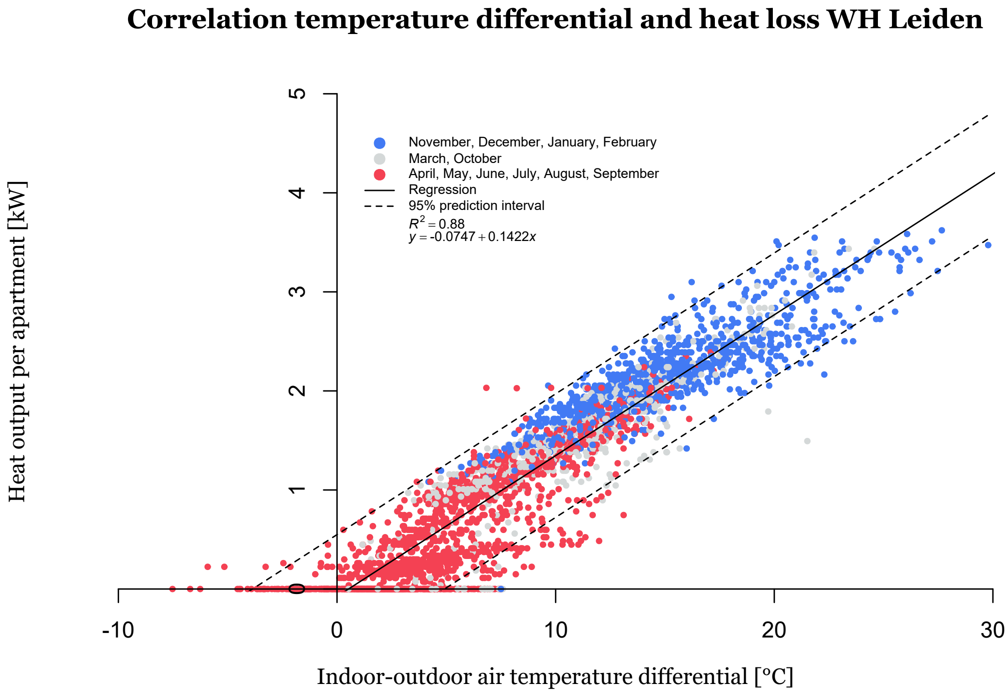

Figure 17. *Heat loss of a dwelling (type: apartment) as a function of the difference between the indoor and outdoor air temperature. The apartment complex WH Leiden consists of 31 apartments.*

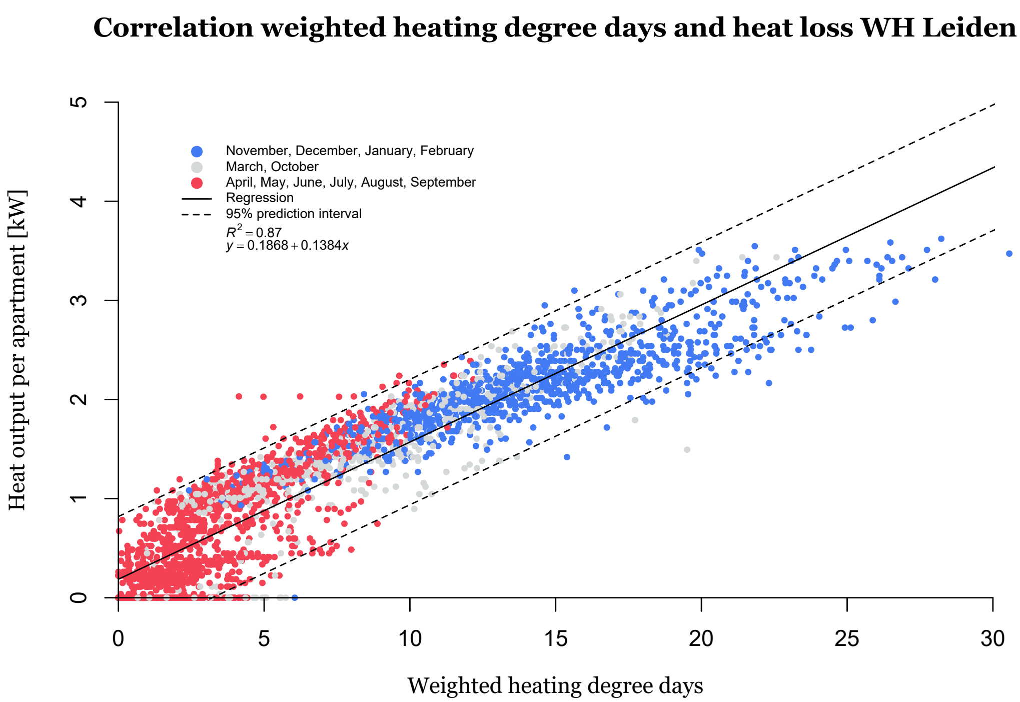

Figure 18. *Heat loss of a dwelling (type: apartment) as a function of the amount of weighted heating degree days. The apartment complex WH Leiden consists of 31 apartments.*

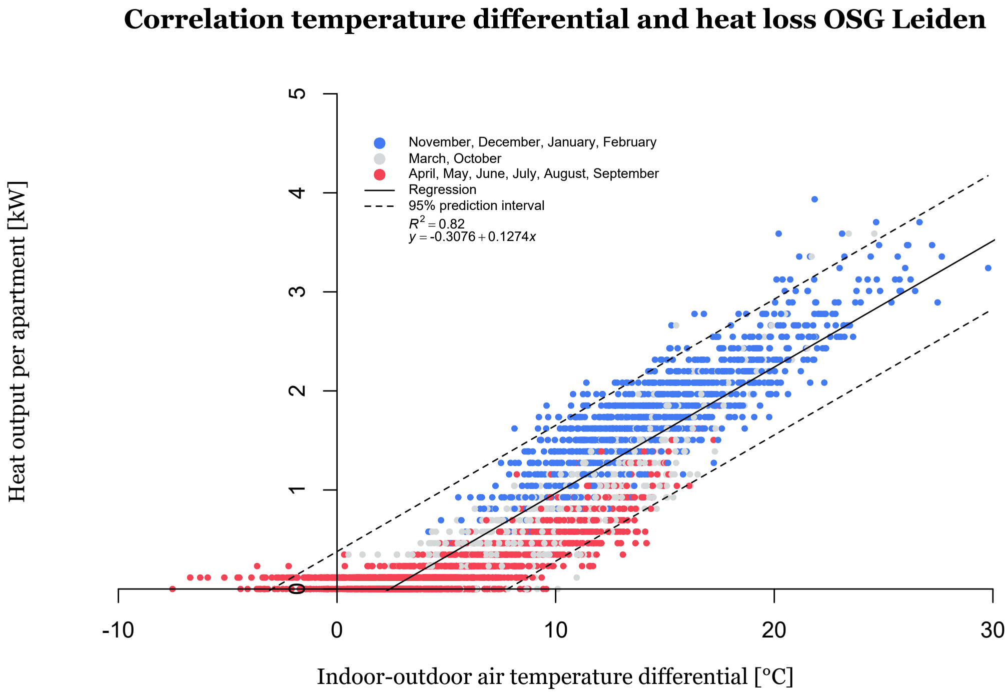

Figure 19. *Heat loss of a dwelling (type: apartment) as a function of the difference between the indoor and outdoor air temperature. The apartment complex OSG Leiden consists of 100 apartments.*

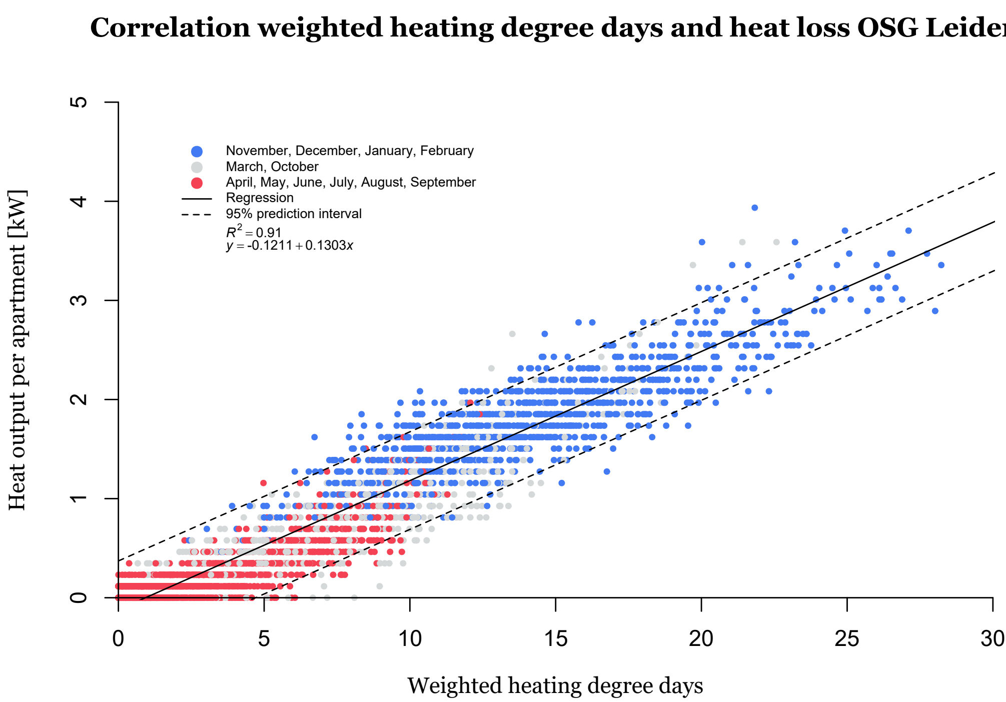

Figure 20. *Heat loss of a dwelling (type: apartment) as a function of the amount of weighted heating degree days. The apartment complex OSG Leiden consists of 100 apartments.*

7.3 Heat output

The maximum heat output of the heat distribution system was determined with the energy metered method. Since the energy meters in both apartment complexes monitored the amount of energy that was distributed in the apartment complexes every hour, an average heat output per hour could be calculated. Maximum heat output will only occur when much heat has to be provided to the building in a short amount of time. Naturally, this occurs at temperatures far below zero. Figures 21 and 22 show the average hourly heat output of the heat distribution systems of both apartment complexes during the last heavy frost period in the Netherlands. This period occurred from 30th of January 2012 until 13th of February 2012. The average, minimum and maximum temperature in this period equaled -4,4°C, -15,9°C and 4,8°C respectively. Converting these temperatures to weighted heating degree hours results in 24,6, 37,3 and 14,5 respectively. Furthermore, the coldest day in the period 2010-2018, was the 4th of February 2012, with an average temperature of -9,8°C equaling 30.6 weighted heating degree days. During this heavy frost period, the maximum measured heat output per apartment complex WH Leiden and OSG Leiden equaled 4,5 and 5,6 kW respectively. Remarkably, maximum heat output only occurred a fraction of the time, which indicates that more heat could be supplied to the apartment complexes.

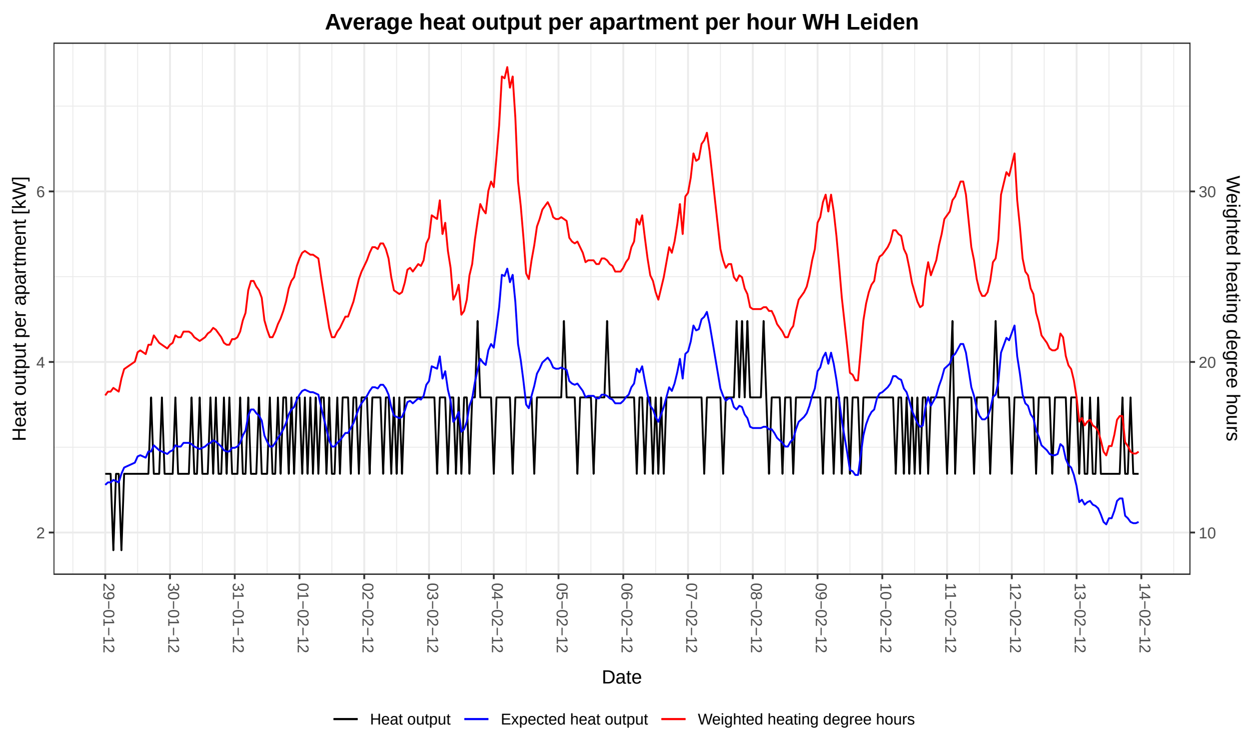

Figure 21. *Heat output of apartment complex WH Leiden during the heavy frost period in 2012*

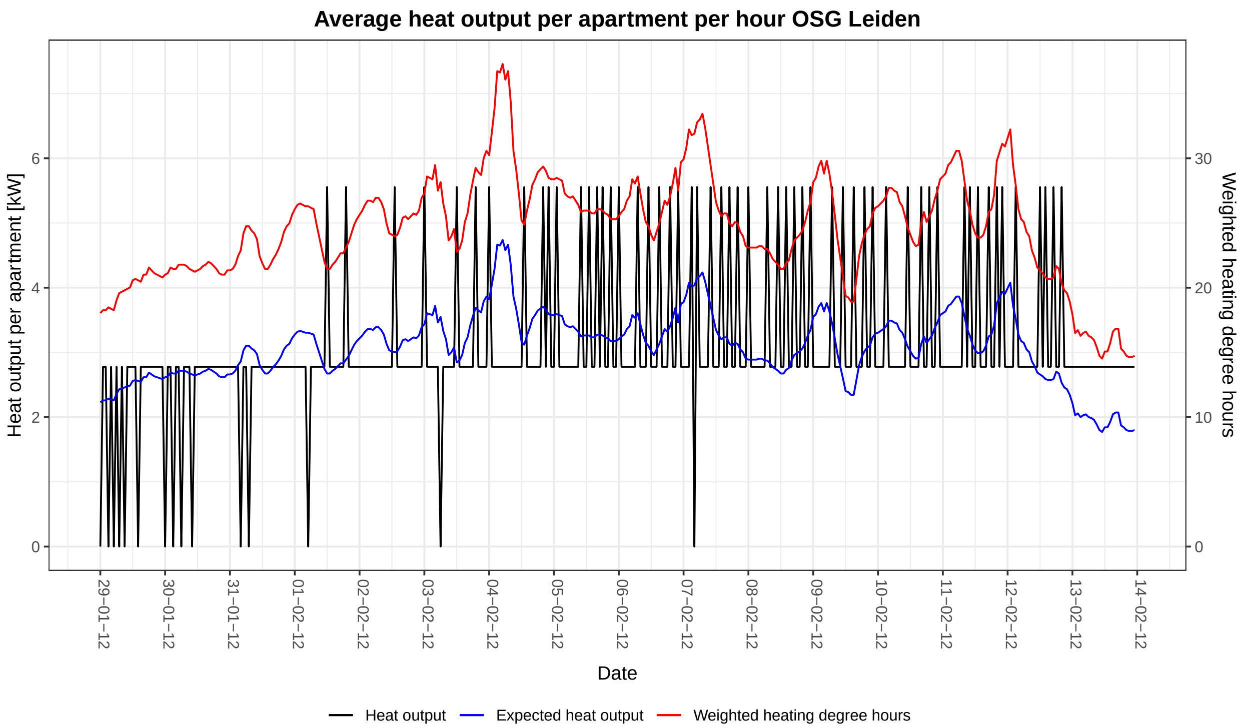

Figure 22. *Heat output of apartment complex OSG Leiden during the heavy frost period in 2012*

This presumes that the heat distribution systems in both apartment complexes can withstand even more extreme weather conditions or that lower operating supply and return temperatures can be applied. During the heavy frost period of 2012, the average amount of heating degree hours amounted 24,6, which equals a heat loss of 3,6 kW for an apartment in building WH Leiden. In an apartment located in building OSG Leiden this amounts to a heat loss of 3,1 kW. Considering that the maximum heat output of both heat distribution systems is 4,5 and 5,6 kW respectively, both heat distribution systems are able to provide enough heat to the apartments. Even at common design outdoor conditions, -10°C (ISSO 2017) which is equal to 30,8 weighted heating degree days during the winter, both heat distribution systems have enough heat output. At 30,8 weighted heating degree days building WH Leiden has an average heat loss of 4,4 kW per apartment and OSG Leiden in 3,9 kW at design conditions. For building OSG Leiden this implies that supply and return temperatures of heat distribution systems can be lowered when the outdoor temperature is -10°C. This is shown in figure 24, which contains the regression plot and the maximum heat output of the heat distribution system. Lowering the temperature in building WH Leiden is not possible at design conditions, because the maximum heat output of the heat distribution system and the buildings heat loss are almost equal.

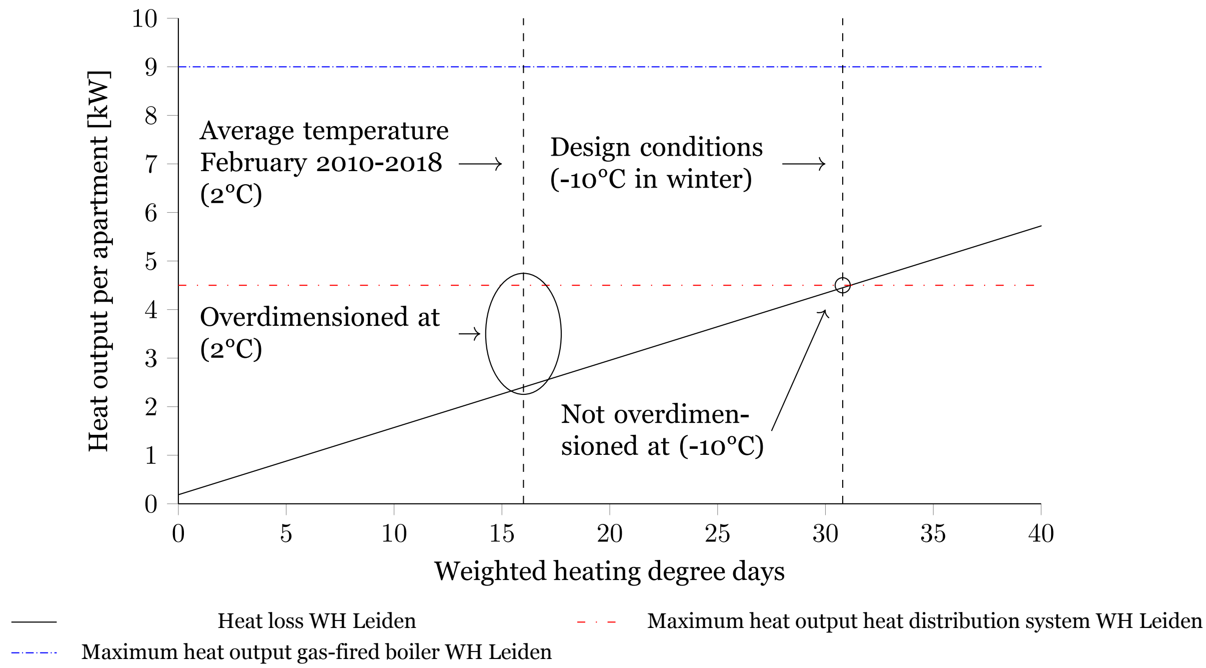

Figure 23. *Maximum heat output of heat distribution systems in WH Leiden*

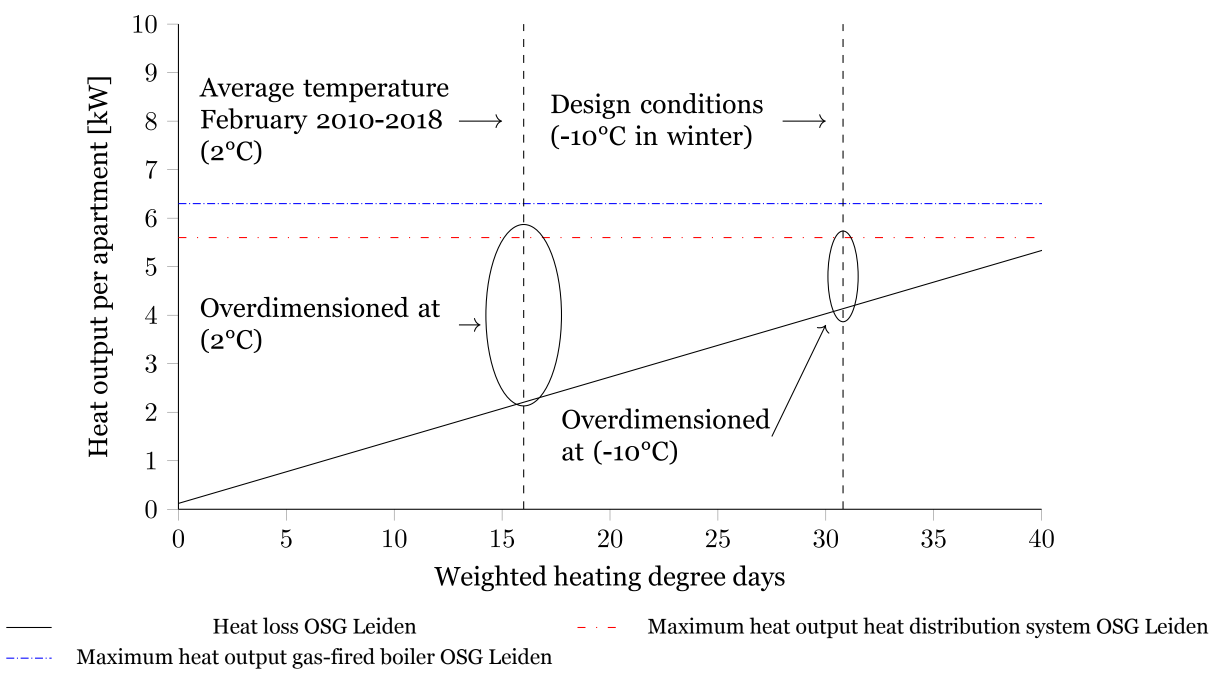

Figure 24. *Maximum heat output of heat distribution systems in OSG Leiden*

7.4 New operating conditions

Based on the previous analysis the new operating conditions can be determined. To both buildings most heat was supplied at 06:00 as a result of night temperature reduction, consequently this time of day was used to determine the new operating settings. In apartment complex WH Leiden the heat distribution system regularly operated at maximum heat output (4,5 kW) at 06:00 with average supply and return temperatures of 79,3°C and 68,6°C respectively. Assuming design conditions (-10°C), results in a heat loss of 4,4 kW per apartment. By rearranging equation 5.21 into equation 7.1 and substituting the measured values of apartment WH complex Leiden into the equation, the new minimum LMTD over the heat distribution can be calculated. Based on this value the supply and return temperatures of the heat distribution can be chosen. Table 9 shows all possible supply and return temperature combinations that result in a LMTD of $\sim$ 54 °C. Considering that multiple combinations are possible, others restrictions have to be defined. A reasonable temperature difference between the supply and return temperature is essential, therefore the minimum temperature difference is defined as the standard supply and return temperature difference multiplied by the ratio between $\dot{Q}_{output}$ and $\dot{Q}_{design,output}$. Furthermore, the lowest acceptable supply temperature should be used. Due to both restrictions only one combination of supply and return temperatures remains that results in a LMTD of $\sim$ 54 °C. For apartment complex WH Leiden the minimum supply and return temperature are 80°C and 69°C respectively, which is a logical result considering that the heat loss approximately equals the maximum heat output of the heat distribution system at design conditions. The pink highlighted cells in table 9 indicate this combination.

$$T_m = T_{m,norm} \cdot \left(\frac{\dot{Q}_{output}}{\dot{Q}_{design,output}} \right)^{\left(\frac{1}{n}\right)} \tag{7.1}$$

$$53,8°C = \frac{79,3°C - 68,6°C}{ln\left(\frac{79,3°C - 20°C}{68,6°C - 20°C}\right)} \cdot \left(\frac{4,4\ kW}{4,5\ kW} \right)^{\left(\frac{1}{1,3}\right)} \tag{7.2}$$

Heavy frost conditions occur very seldom in the Netherlands. Lowering the heat supply and return temperatures of heat distribution system is therefore almost always possible throughout the year. The average amount of weighted heating degree days in the month February from 2010-2018 is 16. Applying the same approach, with different inputs, for example a heat loss of 2,4 kW per apartment (average temperature in February 2010-2018), results in a new LMTD of 34°C. The combination with the lowest possible supply and return temperature is 57°C and 51°C respectively, shown by the purple highlighted cell in table 9. This includes that during mild winter conditions, the supply and return temperature of the heat distribution system in apartment complex WH Leiden can be significantly lowered.

At OSG Leiden the maximum measured heat output of the heat distribution system was 5,6 kW, while the heat loss equals 3.9 kW at design conditions. Unfortunately the average hourly supply and return temperature of building OSG Leiden were unreliable. Consequently, a supply and return temperature of 80°C and 70°C respectively were assumed. Following the same procedure resulted in a LMTD of 42°C, with a new supply

Table 9: *LMTD table used to determine new operating settings. The pink and purple highlighted cells indicate the supply and return temperature combinations for apartment complex WH Leiden when design conditions (-10°C) and average February temperatures 2010-2018 (2°C are used to determine the heat loss. The orange and red highlighted cells indicate the combinations for apartment complex OSG Leiden at similar conditions.*

Tm tsupply	treturn 90	89	88	87	86	85	84	83	82	81	80	79	78	77	76	75	74	73	72	71	70	69	68	67	66	65	64	63	62	61	60	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	37	36	35	34	33	32	31	30
90		69	69	68	68	67	67	66	66	65	65	64	64	63	63	62	62	61	61	60	59	59	58	58	57	57	56	55	55	54	54	53	52	52	51	50	50	49	49	48	47	47	46	45	44	44	43	42	41	41	40	39	38	37	37	36	35	34	33	32	31
89			68	68	67	67	66	66	65	65	64	64	63	63	62	62	61	61	60	60	59	58	58	57	57	56	56	55	54	54	53	53	52	51	51	50	49	49	48	47	47	46	45	45	44	43	43	42	41	40	40	39	38	37	36	35	34	34	33	32	31
88				67	67	66	66	65	65	64	64	63	63	62	62	61	61	60	60	59	59	58	57	57	56	56	55	55	54	53	53	52	52	51	50	50	49	48	48	47	46	46	45	44	44	43	42	42	41	40	39	38	38	37	36	35	34	33	32	31	30
87					66	66	65	65	64	64	63	63	62	62	61	61	60	60	59	59	58	58	57	56	56	55	55	54	54	53	52	52	51	51	50	49	49	48	47	47	46	45	45	44	43	43	42	41	40	40	39	38	37	36	36	35	34	33	32	31	30
86						65	65	64	64	63	63	62	62	61	61	60	60	59	59	58	58	57	57	56	55	55	54	54	53	53	52	51	51	50	49	49	48	48	47	46	46	45	44	44	43	42	42	41	40	39	39	38	37	36	35	34	34	33	32	31	30
85							64	64	63	63	62	62	61	61	60	60	59	59	58	58	57	57	56	56	55	54	54	53	53	52	51	51	50	50	49	48	48	47	47	46	45	45	44	43	43	42	41	40	40	39	38	37	37	36	35	34	33	32	31	30	29
84								63	63	62	62	61	61	60	60	59	59	58	58	57	57	56	56	55	55	54	53	53	52	52	51	50	50	49	49	48	47	47	46	46	45	44	44	43	42	41	41	40	39	39	38	37	36	35	35	34	33	32	31	30	29
83									62	62	61	61	60	60	59	59	58	58	57	57	56	56	55	55	54	53	53	52	52	51	51	50	49	49	48	48	47	46	46	45	44	44	43	42	42	41	40	40	39	38	37	37	36	35	34	33	33	32	31	30	29
82										61	61	60	60	59	59	58	58	57	57	56	56	55	55	54	54	53	52	52	51	51	50	50	49	48	48	47	47	46	45	45	44	43	43	42	41	41	40	39	39	38	37	36	36	35	34	33	32	31	30	29	29
81											60	60	59	59	58	58	57	57	56	56	55	55	54	54	53	53	52	51	51	50	50	49	49	48	47	47	46	46	45	44	44	43	42	42	41	40	40	39	38	38	37	36	35	34	34	33	32	31	30	29	28
80												59	59	58	58	57	57	56	56	55	55	54	54	53	53	52	52	51	50	50	49	49	48	48	47	46	46	45	45	44	43	43	42	41	41	40	39	39	38	37	36	36	35	34	33	32	32	31	30	29	28
79													58	58	57	57	56	56	55	55	54	54	53	53	52	52	51	51	50	49	49	48	48	47	47	46	45	45	44	44	43	42	42	41	40	40	39	38	38	37	36	35	35	34	33	32	31	30	30	29	28
78														57	57	56	56	55	55	54	54	53	53	52	52	51	51	50	50	49	48	48	47	47	46	46	45	44	44	43	42	42	41	41	40	39	39	38	37	36	36	35	34	33	33	32	31	30	29	28	27
77															56	56	55	55	54	54	53	53	52	52	51	51	50	50	49	49	48	47	47	46	46	45	45	44	43	43	42	41	41	40	39	39	38	37	37	36	35	35	34	33	32	31	31	30	29	28	27
76																55	55	54	54	53	53	52	52	51	51	50	50	49	49	48	48	47	46	46	45	45	44	43	43	42	42	41	40	40	39	38	38	37	36	36	35	34	33	33	32	31	30	29	29	28	27
75																	54	54	53	53	52	52	51	51	50	50	49	49	48	48	47	47	46	45	45	44	44	43	42	42	41	41	40	39	39	38	37	37	36	35	35	34	33	32	32	31	30	29	28	27	26
74																		53	53	52	52	51	51	50	50	49	49	48	48	47	47	46	46	45	44	44	43	43	42	41	41	40	40	39	38	38	37	36	36	35	34	34	33	32	31	30	30	29	28	27	26
73																			52	52	51	51	50	50	49	49	48	48	47	47	46	46	45	45	44	43	43	42	42	41	40	40	39	39	38	37	37	36	35	35	34	33	32	32	31	30	29	28	28	27	26
72																				51	51	50	50	49	49	48	48	47	47	46	46	45	45	44	44	43	42	42	41	41	40	39	39	38	38	37	36	36	35	34	33	33	32	31	31	30	29	28	27	26	25
71																					50	50	49	49	48	48	47	47	46	46	45	45	44	44	43	42	42	41	41	40	40	39	38	38	37	36	36	35	34	34	33	32	32	31	30	29	29	28	27	26	25
70																						49	49	48	48	47	47	46	46	45	45	44	44	43	43	42	41	41	40	40	39	39	38	37	37	36	35	35	34	33	33	32	31	31	30	29	28	27	27	26	25
69																							48	48	47	47	46	46	45	45	44	44	43	43	42	42	41	40	40	39	39	38	38	37	36	36	35	34	34	33	32	32	31	30	29	29	28	27	26	25	25
68																								47	47	46	46	45	45	44	44	43	43	42	42	41	41	40	39	39	38	38	37	36	36	35	35	34	33	33	32	31	31	30	29	28	28	27	26	25	24
67																									46	46	45	45	44	44	43	43	42	42	41	41	40	40	39	38	38	37	37	36	35	35	34	34	33	32	32	31	30	30	29	28	27	26	26	25	24
66																										45	45	44	44	43	43	42	42	41	41	40	40	39	39	38	37	37	36	36	35	34	34	33	33	32	31	31	30	29	28	28	27	26	25	24	24
65																											44	44	43	43	42	42	41	41	40	40	39	39	38	38	37	36	36	35	35	34	33	33	32	31	31	30	29	29	28	27	27	26	25	24	23
64																												43	43	42	42	41	41	40	40	39	39	38	38	37	37	36	35	35	34	34	33	32	32	31	30	30	29	28	28	27	26	25	25	24	23
63																													42	42	41	41	40	40	39	39	38	38	37	37	36	36	35	34	34	33	33	32	31	31	30	29	29	28	27	27	26	25	24	23	23
62																														41	41	40	40	39	39	38	38	37	37	36	36	35	35	34	33	33	32	32	31	30	30	29	28	28	27	26	25	25	24	23	22
61																															40	40	39	39	38	38	37	37	36	36	35	35	34	34	33	32	32	31	31	30	29	29	28	27	27	26	25	24	24	23	22
60																																39	39	38	38	37	37	36	36	35	35	34	34	33	32	32	31	31	30	29	29	28	28	27	26	25	25	24	23	22	22
59																																	38	38	37	37	36	36	35	35	34	34	33	33	32	31	31	30	30	29	28	28	27	26	26	25	24	24	23	22	21
58																																		37	37	36	36	35	35	34	34	33	33	32	32	31	30	30	29	29	28	27	27	26	25	25	24	23	23	22	21
57																																			36	36	35	35	34	34	33	33	32	32	31	31	30	29	29	28	28	27	26	26	25	24	24	23	22	21	21
56																																				35	35	34	34	33	33	32	32	31	31	30	30	29	28	28	27	27	26	25	25	24	23	23	22	21	20
55																																					34	34	33	33	32	32	31	31	30	30	29	29	28	27	27	26	26	25	24	24	23	22	21	21	20
54																																						33	33	32	32	31	31	30	30	29	29	28	28	27	26	26	25	25	24	23	23	22	21	20	20
53																																							32	32	31	31	30	30	29	29	28	28	27	27	26	25	25	24	23	23	22	21	21	20	19
52																																								31	31	30	30	29	29	28	28	27	27	26	26	25	24	24	23	22	22	21	20	20	19
51																																									30	30	29	29	28	28	27	27	26	26	25	25	24	23	23	22	21	21	20	19	19
50																																										29	29	28	28	27	27	26	26	25	25	24	23	23	22	22	21	20	20	19	18
49																																											28	28	27	27	26	26	25	25	24	24	23	22	22	21	21	20	19	19	18
48																																												27	27	26	26	25	25	24	24	23	23	22	21	21	20	20	19	18	17
47																																													26	26	25	25	24	24	23	23	22	22	21	20	20	19	18	18	17
46																																														25	25	24	24	23	23	22	22	21	21	20	19	19	18	17	17
45																																															24	24	23	23	22	22	21	21	20	20	19	18	18	17	16
44																																																23	23	22	22	21	21	20	20	19	19	18	17	17	16
43																																																	22	22	21	21	20	20	19	19	18	18	17	16	16
42																																																		21	21	20	20	19	19	18	18	17	16	16	15
41																																																			20	20	19	19	18	18	17	17	16	15	15
40																																																				19	19	18	18	17	17	16	16	15	14
39																																																					18	18	17	17	16	16	15	15	14
38																																																						17	17	16	16	15	15	14	14
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31																																																													10

temperature of 66°C and return temperature of 59°C. The orange highlighted cells in table 9 indicate this combination. During mild winter conditions the temperatures can even be further reduced because the heat loss per apartment decreases to 2,0 kW. Again, by applying the same method this results in LMTD of 25°C, with new a supply and return temperature of 47°C and 43°C respectively, shown by red highlighted cells in table 9.

Building WH Leiden contains 31 apartments, while OSG Leiden consists of 100 apartments. Therefore the data sets are only representative for the entire building and not necessarily for each individual apartment in that building. Apartments located at the side of the building, top or bottom floor are more prone to heat loss than apartments located in the middle of the building. If the heat output of the heat distribution system is equally divided over all apartments, the temperature can not be lowered as much as calculated, because apartments that have a higher heat loss will not be able to distribute enough heat in the apartment. In other dwelling types the effect of thermal mass will not be as influential as in apartment complexes. Since, the total mass of a detached dwelling is significantly smaller than an apartment complex containing over 100 dwellings and its building volume to building envelope ratio is also smaller, detached dwellings loss heat faster than apartment complexes. When the heat loss exceeds the heat output of the heat distribution system for a considerable amount of time, apartment complexes can therefore cope more easily with this problem than other dwelling types.

7.5 Questionnaire

Residents will evaluate the new heat distribution system's operating conditions with the help of a questionnaire. A questionnaire should be validated in order to obtain relevant, consistent and reliable data. A drafted questionnaire can be validated theoretically or empirically. When a theoretical approach is applied, this is called transitional validity (Parsian & Dunning 2009). Two sub types of validity belong to transitional validity, namely face validity and content validity (Parsian & Dunning 2009). Empirical approaches make use of other surveys in the form of a field test (Bolarinwa et al. 2015). This examines how well a given measure relates to one or more external criteria, based on empirical constructs. Empirical validity can either be criterion-related or construct based (Engel & Schutt 2012).

Unfortunately, empirical validation methods can only be used when the measuring campaign is operationalised. Validating the questionnaire upfront is therefore only possible via face validation or content validation. Face validity is established when an expert on the research subject reviewing the questionnaire concludes that the questionnaire measures the characteristic of interest (Bölenius et al. 2012). Content validity applies to the degree to which the questionnaire fully assesses or measures the construct of interest (Sangoseni et al. 2013, DeVon et al. 2007). A content valid questionnaire is typically achieved by a rational analysis of the questionnaire by expert raters (Sangoseni et al. 2013, DeVon et al. 2007). Raters review all questionnaire items for readability, clarity and comprehensiveness (Sangoseni et al. 2013). Unfortunately, both validation methods are deemed highly subjective, because the approach is casual and soft (Engel & Schutt 2012).

Nonetheless, the proposed questionnaire was face-validated by people who executed the "warm in the wijk" project in The Hague and by I. Pothof. A general conclusion was drawn. The questionnaire is rather simple, wherefore it lacks precision. A survey, which is completed on a daily basis or that contains more in depth questions, would generate more valuable data. However, this requires a more extensive survey, which requires more input and time from the residents. When the questionnaire is too demanding, people might cease completing the survey, which must be avoided at all times. Despite of its simplicity the questionnaire able to efficiently gather sufficient data about the thermal comfort experience of residents, which ultimately is the reason for choosing a questionnaire.

Ideally, the questionnaire would also be validated with empirical methods. These methods are divided over two categories criterion-related or construct based validation. Criterion-related validity determines the relationship of scores in a test to a specific criterion (DeVon et al. 2007, Strauss & Smith 2009, Ong 2012), while construct validity is the degree to which an instrument measures the trait or theoretical construct that it is intended to measure (Ong 2012, Liang et al. 2014). Since, all rating questions in the survey design are similar to the ratings of the ASHRAE 55 standard, one could argue that the criterion-related validity for the questionnaire design corresponds to the criterion-related validity of the ASHRAE 55 standard. Similar reasoning also applies to construct validity. Since the ASHRAE developed a thermal comfort standard that ensures that thermal sensation is measured, one could argue that this project's questionnaire is construct valid considering that that similar survey questions are used. Consequently, the validity of the project's survey actually depends on the ASHRAE 55 standard's validity.

Although numerous studies have used the ASHRAE 55 standard to evaluate thermal sensation because of its simplicity (Wong et al. 2002, Kwok & Chun 2003, De Dear & Brager 2001, Jason & Jones 2019, ter Mors et al. 2011), some researchers criticize the standard. Humphreys & Hancock (2007) showed that sensations expressed on the ASHRAE scale can multiple meanings, encompassing psychological factors such as a motivation to express (dis)satisfaction with the situation or mood. This leads to the question how strongly the ASHRAE scale is affected by factors concerning the overall context rather than the actual thermal conditions (Schweiker et al. 2017). Nevertheless, the ASHRAE 55 standard is the most used approach for thermal comfort surveys, despite some uncertainty caused by humans that complete the questionnaire. Moreover, since there is not a better alternative, the ASHRAE 55 standard can be considered as golden standard (Haddad et al. 2012). Taken into account that this project's questionnaire was face-validated and uses questions similar to the ASHRAE 55 standard, the design is considered valid.

8 Discussion

The validation step showed that the proposed measuring campaign is able to gather relevant and reliable data in a cost-effective manner. Nevertheless, there are some imperfections in the design of the measuring campaign and the way it is validated. In section 8.1 to 8.6 all imperfections of the measuring campaign are discussed.

8.1 Bottlenecks are not identified

The measuring campaign is only able to determine the heat loss of an entire dwelling or building. This incorporates that the heat loss of each individual space is unknown. A similar problem holds for the determination of the heat distribution system's heat output. Considering that the energy meter is installed after the heat source, only the heat output of the entire heat distribution system can be determined. Consequently, it might be possible that the heat loss of a specific space exceeds the heat output of the radiators in that space when the supply and return temperature are lowered. As a result the residents will experience thermal discomfort in that space.

To avoid a situation as described above, the bottleneck in the dwelling should be determined. A bottleneck is created by a space in a dwelling in which the ratio between the heat output of the heat distribution system and the heat loss in a certain space is equal or smaller than one. Although the energy meter method remains similar, more equipment is needed to determine the heat loss and heat output of the heat distribution system per space, since at every radiator or convector an energy meter should be installed. Therefore the costs will increase by a multiple of the number of radiators and convectors. Naturally, such an approach is not cost-effective. Theoretical methods, such as the ”building envelope” method per space and radiator chart method do not face this problem and are consequently more cost-effective. However, theoretical methods do not comply to the desire of I. Pothof to use an experimental approach. Therefore combining the ”building envelope” per space method with the energy meter method would be optimal, since this combination enables experimental data acquisition and is able to find bottlenecks.

8.2 Balancing the heat distribution system

A well functioning heat distribution system is crucial in all situations. Especially, when the supply and return temperature is lowered, because less heat can be provided in an equal amount of time. However, in many dwellings and buildings the heat distribution system does not operate as desired. Some radiators and convectors are provided with too much heat, while others do not receive enough heat. Radiators and convectors that are closely located from the heat source often receive too much heat, while radiators and convectors located further away receive too little heat. By balancing the heat distribution system, heat can be proportionally divided over all radiators and convectors in the system. This will reduce the chance that residence will experience thermal discomfort in certain spaces, because all radiators and convectors are supplied with an equal amount of heat, proportional to the design heat output. Furthermore, the efficiency of the entire central heating system increases, resulting in less gas consumption. Consequently, balancing your heat distribution system is recommended at all times.

Most spaces in a dwelling or building have a well designed heat distribution system. This includes that the heat output of all radiators and convectors in a space exceeds the heat loss of that space. When the heat distribution system is properly balanced, the heat output - heat loss ratio is larger than one. Applying lower supply and return temperatures is in such case often possible. Only if the heat output of the radiators and convectors in one specific space was not sufficient during the dwelling design, heat distribution system balancing will not solve the problem. Such situations sometimes occur when dwellings are modified, because too little heat output is installed.

8.3 Design conditions

Another important aspect that should be addressed are the design conditions. Although multiple design conditions are defined, i.e. combinations of mean outdoor air temperatures and wind velocities, the most commonly used design condition is -10°C. These design conditions seldom occur in the Netherlands and if they occur they do not last long. Even though one can not exclude the occurrence of heavy frost temperatures, it is an evident fact that winters are milder and extremely cold temperatures occur less frequently. However, changing the design conditions is not recommended, since heavy frost temperatures can still occur. Nevertheless, the supply and return temperatures can be lowered in many situations. Mainly, because the winters tend to become milder, wherefore design conditions are not reached. Throughout the year, the heat loss of dwelling's is therefore merely a fraction of the maximum heat output of the heat distribution system, even when the operating settings are changed to a lower supply and return temperature.

8.4 Night temperature reduction

Lowering the supply and return temperature of heat distribution systems changes the heating regime of a heat distribution system. Due to lower supply and return temperatures the maximum heat output decreases. Consequently, heat has to be supplied over a longer period of time in order to add an equivalent amount of heat. As a result, heat will be gradually provided to a dwelling. This is in contrast with conventional operating settings, which mostly operate via a "hit-and-run" regime. Figures 21 and 22 both illustrate the "heat-and-run regime". Many peaks are visual, which indicate the on-off/"hit-and-run" heating regime. In addition, most households apply night temperature reduction currently. This includes that during the day the indoor air temperature is kept constant at 20-22°C and at night the temperature settings are lowered by approximately 4-6°C. Naturally, the indoor air temperature decreases gradually during the night. The gradient is dependent on the insulation of the dwelling. Commonly, the indoor air temperature is between 16 and 18°C in the morning. Residents expect a well heated dwelling in the morning, which includes that a large amount of heat has to be provided to the dwelling in a short period of time. When the heat output of the heat distribution system is lowered, this in not possible anymore, because the heat output of the heat distribution system decreases. Consequently, the difference between the day and night temperature settings should be reduced. Informing the residents/participants during the operationalisation phase is therefore absolutely crucial. Furthermore, the total energy consumption might be a fraction higher, because of higher indoor air temperatures during the night. A small compensation for the higher energy expense should therefore be reserved in the measuring campaign budget.

In general, night temperature reduction is applied to reduce heating costs and because people prefer lower temperatures during the night. Many people will argue that higher temperatures during the night will increase heating costs. Especially, in badly insulated dwelling this argument is true. However, this measuring campaign is designed to lower the threshold for sustainable heat sources, such as heat pumps and geothermal. Using more energy to heat a dwelling is not problematic as long as the energy is sustainable and affordable for the consumers. The lower the supply and return temperature of heat distribution system, the more efficient the sustainable heat sources. This especially holds for heat pumps. Consequently, a high efficiency may outweigh the smaller difference between night and day temperatures.

8.5 Validation

During the validation phase a data set was obtained that contained the average hourly energy input of the gas-fired boiler to the heat distribution system of apartment complex WH and OSG Leiden. The average hourly energy input of apartment complex WH Leiden contained data that was rounded to one decimal, while the data from OSG Leiden did not contain decimals. Figures 21 and 22 demonstrate the rounding. Especially for OSG Leiden this might have had a significant influence on the regression. Considering that the measured average hourly energy input can very significantly. For example, when the energy meter logger registered an average energy input of 2 GJ/hour, the value can vary between 1,5 and 2,4 GJ/hour, because of rounding. For WH Leiden this impact is much smaller, because the data is rounded to one decimal.

Thermal mass has a significant effect on the heat loss. ”Thermally heavy” buildings, i.e. buildings with a large amount of thermal mass, will heat up and cool down slowly. ”Thermally lighter” buildings are not able to retain heat for a long period of time. However, they heat up much faster than ”thermally heavy” buildings. This phenomenon can affect the results of the measuring campaign. Due to the lack of data, the measuring campaign was only validate with data of apartment complex. Its performance in smaller buildings, such as detached dwellings, is currently unknown. Validating the measuring campaign with data obtained from smaller buildings is consequently crucial.

8.6 Thermal comfort sensation questionnaire

Thermal comfort sensation is evaluated by a questionnaire. The questionnaire should be completed on a frequent basis and should address all six factors of thermal comfort. Unfortunately, this is very demanding, wherefore participants are likely to cease completing the survey or tend to give identical answers (Dillman et al. 1993, Burchell & Marsh 1992). Therefore the questionnaire design should be in balance, which includes that the questionnaire contains enough in-depth questions, but remains user-friendly and does not take a lot of time to complete. A solution would be to digitize the questionnaire and make it available as mobile application.

Although the questionnaire's design is considered valid, an insurmountable problem that arises when using a questionnaire, is the population size. Normally, a survey is spread among a large group of people that are subjected to the same influences. This is not case in the measuring campaign. Only people that reside in the same dwelling are subjected to the same influences. Other people that participate in the measuring campaign are subjected to influences of the dwelling in which they reside. Consequently, the sample size is very small, i.e. equal to the number of residents. This makes it impossible to determine if other people would also experience thermal comfort in that specific dwelling. Nonetheless, the questionnaire gives an reasonably accurate estimation of thermal comfort sensation, which is sufficient for this research. When one wants to obtain more reliable data, the survey should be complete by more people that are subjected to the same influences or be combined with equipment that measures physical parameters, such as mean air and mean radiant temperature.

9 Conclusion

Replacement of conventional gas-fired boilers by sustainable alternatives progresses slowly as a result of high investment costs and long payback periods. A substantial part of the investment costs are caused by converting the high-temperature heat distribution system to a low-temperature heat distribution system, which is currently deemed necessary. Deltares and Berenschot question this assumption and formulated the following hypothesis: ”The majority of the dwellings in the Netherlands are equipped with over-dimensioned heat distribution systems”. To test the hypothesis, Deltares needs relevant data that is currently lacking. Consequently, Deltares initiated this design project with the goal to develop a measuring campaign.

In a short period of time a measuring campaign has been developed that enables data acquisition in a cost-effective manner. By only focusing on the core characteristics of heat distribution systems, the estimated costs of the measuring campaign have been kept relative low. Although the design of the measuring campaign would have been more convenient when theoretical method were applied, the preference of problem owner, I. Pothof, and the fact that only limited amounts of experimental data are available, let to the incorporation of empirical methods in the measuring campaign’s design.

The final design consists of three main components: the heat loss of dwellings, the heat output of heat distribution systems and the thermal comfort sensation of residents. For the first two components quantitative data is acquired by an energy meter, while a questionnaire is used to determine the thermal comfort sensation of residents. The measuring campaign will be operationalised in four phases. The preparation phase, in which the dwelling is evaluated, the heat distribution system is balanced and the energy meter is installed. The execution phase in which data is acquired. The resetting phase in which the obtained data is cleaned and analysed. Based on the analysis results, the heat distribution system is evaluated. If the system is overdimensioned, the new supply and return temperatures can be calculated. Subsequently, a HVAC technician adjusts the operating settings of gas-fired boiler to the new calculated values, which will be tested on thermal comfort during the evaluation phase.

Validation proved that the measuring campaign acquires relevant data that can be used to determine if heat distribution systems are overdimensioned. However, the impact on the thermal comfort of residents when lower operating temperatures are applied is still unknown, because although lower operating temperatures are theoretically feasible in the apartment complexes, the operating settings have not been adjusted and the thermal comfort of residents was not evaluated yet. Considering that empirical testing can produce a different outcome than what is excepted upfront according theory, it is strongly recommended to validate the measuring campaign twice via a pilot case.

10 Design recommendations

Although the measuring campaign has been validated, it is recommended to test the measuring campaign in a pilot case before the measuring campaign is rolled out on full scale. Ideally, this pilot case would contain five different types of dwellings such that every dwelling type defined in the framework will be tested at least once. Although scientific literature in combination with knowledge from experts is used during the measuring campaign's design, this will not guarantee a flawless operation procedure. For example, the time a HVAC technician needs to balance a heat distribution system is estimated at 0,5 day. However, this is an estimated average, which can vary significantly depending on the amount of radiators and convectors installed in the dwelling, the complexity of the heat distribution system and its current state. A similar situation can occur during the resetting phase, where technicians reduce the supply temperature coming from the gas-fired boiler. Although the HVAC technicians are well trained and able to cope with different gas-fired boiler types, the time it takes to adjust the boiler can vary. Therefore it is strongly recommend to strictly follow the measuring campaign procedures in order to find possible deficiencies and points of improvement.

A simple questionnaire has been designed to determine the thermal comfort of residents. To obtain valuable and reliable data, the user-friendliness of questionnaire should be as high as possible. A design improvement would therefore be to digitize the questionnaire and make it available as mobile phone application. This technology enables residents to complete the survey at any time and location, wherefore the threshold to complete the survey is lowered. However, important is to keep an eye on the length of the questionnaire, since mobile web surveys have a 2,8 times higher break-off risk than PC web surveys (Couper et al. 2017).

Before the measuring campaign can be operationalised, participants need to be found. This can be accomplished via municipal authorities and housing corporations that are willing to contribute to the energy transition. Commonly the participants that are found via this route are tenants. Regularly, this does not hold for people that reside in (semi-)detached dwellings. Therefore another route has to be found to also involve house owners. Again, this can be achieved via municipal authorities. However, other initiatives should also be explored. For example, the establishment of a website where people that consider participating can find information about the goal of the project, the methods used, data handling, the influence of their thermal comfort, how they can subscribe, etc. Projects comparable with the design project all have such websites, which is found very useful by participants since it shows transparency. In addition, multiple routes have to be established via which a large participant pool can be created. From that pool participants will be picked to participate in the measuring campaign. Important is to guarantee diversity in the pool of possible participants.

Another important issue that should be taken care of during the measuring campaign is the coordination of the project and the communication with the participants. It is highly recommended to appoint a project coordinator that supervises all phases of the measuring campaign. In addition, the project coordinator is responsible for the communication with the participants. If participants have questions, complaints or desire feedback, they can directly contact the project coordinator. Since a code has been written that fully automates the data cleaning and required calculations, the data analysis is straight-forward and can also be executed by the project coordinator.

Nowadays, big data is a hot topic, but apart from all opportunities that arise from gathering data, some related hazards are unavoidable. Considering that data from people is gathered, the data should be handled carefully and stored in a save environment. Furthermore, data may only be distributed when approved by the project coordinator or Deltares.

References

Abu-Jdayil, B., Mourad, A.-H., Hittini, W., Hassan, M. & Hameedi, S. (2019), 'Traditional, state-of-the-art and renewable thermal building insulation materials: An overview', *Construction and Building Materials* **214**, 709–735.

A.C. van der Linden, E. v. (2015), 'Feiten en fabels na-isoleren van spouwmuren'.

Ackermann, F. & Eden, C. (2011), 'Strategic management of stakeholders: Theory and practice', *Long range planning* **44**(3), 179–196.

Agromayor, R., Cabaleiro, D., Pardinas, A., Vallejo, J., Fernandez-Seara, J. & Lugo, L. (2016), 'Heat transfer performance of functionalized graphene nanoplatelet aqueous nanofluids', *Materials* **9**(6), 455.

Alan, R. H., March, S. T., Park, J. & Ram, S. (2004), 'Design science in information systems research', *MIS quarterly* **28**(1), 75–105.

Alexander, L., Zhang, X., Peterson, T., Caesar, J., Gleason, B., Klein Tank, A., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F. et al. (2006), 'Global observed changes in daily climate extremes of temperature and precipitation', *Journal of Geophysical Research: Atmospheres* **111**(D5).

ASHRAE (2017), 'Standard 55-2017: Thermal environmental conditions for human occupancy', *American Society of heating, Refridgerating and Airconditioning Engineers: Atlanta* .

Bauwens, G. & Roels, S. (2014), 'Co-heating test: A state-of-the-art', *Energy and Buildings* **82**, 163–172.

Beukema, J. (1992), 'Expected changes in the wadden sea benthos in a warmer world: lessons from periods with mild winters', *Netherlands journal of sea research* **30**, 73–79.

Bjerke, M. B. & Renger, R. (2017), 'Being smart about writing smart objectives', *Evaluation and program planning* **61**, 125–127.

Bolarinwa, O. A. et al. (2015), 'Principles and methods of validity and reliability testing of questionnaires used in social and health science researches', *Nigerian Postgraduate Medical Journal* **22**(4), 195.

Bölenius, K., Brulin, C., Grankvist, K., Lindkvist, M. & Söderberg, J. (2012), 'A content validated questionnaire for assessment of self reported venous blood sampling practices', *BMC research notes* **5**(1), 39.

Brand, M. & Svendsen, S. (2013), 'Renewable-based low-temperature district heating for existing buildings in various stages of refurbishment', *Energy* **62**, 311–319.

Burchell, B. & Marsh, C. (1992), 'The effect of questionnaire length on survey response', *Quality and quantity* **26**(3), 233–244.

Butler, D. & Dengel, A. (2013), 'Review of co-heating test methodologies', *NHBC Foundation: Knowlhill, UK* .

Cochran, W. G. (2007), *Sampling techniques*, John Wiley & Sons.

Couper, M. P., Antoun, C. & Mavletova, A. (2017), 'Mobile web surveys', *Total survey error in practice* pp. 133–154.

Danish Building Research Institute (2000), 'Varmeanlæg med vand som medium [hydraulic heating systems]'.

De Dear, R. & Brager, G. S. (1998), 'Developing an adaptive model of thermal comfort and preference'.

De Dear, R. & Brager, G. S. (2001), 'The adaptive model of thermal comfort and energy conservation in the built environment', *International journal of biometeorology* **45**(2), 100–108.

DeVon, H. A., Block, M. E., Moyle-Wright, P., Ernst, D. M., Hayden, S. J., Lazzara, D. J., Savoy, S. M. & Kostas-Polston, E. (2007), 'A psychometric toolbox for testing validity and reliability', *Journal of Nursing scholarship* **39**(2), 155–164.

Dillman, D. A., Sinclair, M. D. & Clark, J. R. (1993), 'Effects of questionnaire length, respondent-friendly design, and a difficult question on response rates for occupant-addressed census mail surveys', *Public opinion quarterly* **57**(3), 289–304.

Doran, G. T. (1981), 'There's a smart way to write management's goals and objectives', *Management review* **70**(11), 35–36.

Ecothermo (2019), 'Heat cost allocator drawbacks'.
URL: *http://www.ecothermo.it/heat-cost-allocator-drawbacks/*

Eijdems, H., Boerstra, A. & Op 't Veld, P. (1994), Low temperature heating systems: Impact on iaq, thermal comfort and energy consumption, *in* 'Proceedings, Healthy Building', Vol. 94.

Engel, R. J. & Schutt, R. K. (2012), *The practice of research in social work*, Sage Publications.

Fanger, P. O. et al. (1970), 'Thermal comfort. analysis and applications in environmental engineering.', *Thermal comfort. Analysis and applications in environmental engineering.* .

Farmer, D., Johnston, D. & Miles-Shenton, D. (2016), 'Obtaining the heat loss coefficient of a dwelling using its heating system (integrated coheating)', *Energy and Buildings* **117**, 1–10.

Feist, W., Schnieders, J., Dorer, V. & Haas, A. (2005), 'Re-inventing air heating: Convenient and comfortable within the frame of the passive house concept', *Energy and buildings* **37**(11), 1186–1203.

Filippidou, F., Nieboer, N. & Visscher, H. (2016), 'Energy efficiency measures implemented in the dutch non-profit housing sector', *Energy and Buildings* **132**, 107–116.

Gvozdenovic, K., Maassen, W. & Zeiler, W. (2015), Towards nearly zero-energy buildings in 2020 in the netherlands, *in* 'Renewable Energy in the Service of Mankind Vol I', Springer, pp. 455–464.

Haddad, S., King, S., Osmond, P. & Heidari, S. (2012), Questionnaire design to determine children's thermal sensation, preference and acceptability in the classroom, *in* 'Proceedings-28th International PLEA Conference on Sustainable Architecture+ Urban Design: Opportunities, Limits and Needs-Towards an Environmentally Responsible Architecture'.

Hamdi, M., Lachiver, G. & Michaud, F. (1999), 'A new predictive thermal sensation index of human response', *Energy and Buildings* **29**(2), 167–178.

Harrestrup, M. & Svendsen, S. (2015), 'Changes in heat load profile of typical danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating', *International Journal of Sustainable Energy* **34**(3–4), 232–247.

Hasan, A., Kurnitski, J. & Jokiranta, K. (2009), 'A combined low temperature water heating system consisting of radiators and floor heating', *Energy and Buildings* **41**(5), 470–479.

Hens, H., Parijs, W. & Deurinck, M. (2010), 'Energy consumption for heating and rebound effects', *Energy and buildings* **42**(1), 105–110.

Hevner, A. R. (2007), 'A three cycle view of design science research', *Scandinavian journal of information systems* **19**(2), 4.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K. & Johnson, C. (2001), *Climate change 2001: the scientific basis*, The Press Syndicate of the University of Cambridge.

Humphreys, M. A. & Hancock, M. (2007), 'Do people like to feel 'neutral'?: Exploring the variation of the desired thermal sensation on the ashrae scale', *Energy and buildings* **39**(7), 867–874.

Humphreys, M. A. & Nicol, J. F. (2002), 'The validity of iso-pmv for predicting comfort votes in every-day thermal environments', *Energy and buildings* **34**(6), 667–684.

Ingenieur, D. (2018), 'Main concepts of dutch climate agreement announced'.
URL: *https://www.deingenieur.nl/artikel/main-concepts-of-dutch-climate-agreement-announced*

ISO (2005), *NEN-EN-ISO 7730:2015 Ergonomics of the Thermal Environment: Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*, International standards, ISO.

ISSO (2001), 'Vermogen van radiatoren en convectoren in praktijksituaties'.

ISSO (2006), 'Kleintje individuele centrale verwarmingsinstallaties in woningen'.

ISSO (2017), 'Warmteverliesberekening voor woningen en woongebouwen'.

Ista (2019), 'Faq'.
URL: *https://www.ista.com/be/nl/infotheek/vaakgestelde-vragen-faq/*

Itard, L. & Meijer, F. (2008), *Towards a Sustainable Northern European Housing Stock: Figures, Facts, and Future*, Vol. 22, Ios Press.

Jangsten, M., Kensby, J., Dalenbäck, J.-O. & Trüschel, A. (2017), 'Survey of radiator temperatures in buildings supplied by district heating', *Energy* **137**, 292–301.

Jason, M. & Jones, P. (2019), 'Evaluation of thermal comfort in building transitional spaces - field studies in cardiff, uk', *Building and Environment* **156**, 191–202.

Johnston, D., Miles-Shenton, D., Farmer, D. & Wingfield, J. (2013), 'Whole house heat loss test method (coheating)'.

Jokisalo, J., Kurnitski, J., Korpi, M., Kalamees, T. & Vinha, J. (2009), 'Building leakage, infiltration, and energy performance analyses for finnish detached houses', *Building and Environment* **44**(2), 377–387.

Kamp, H. (2014), 'Besluit grootschalige uitrol slimme meters'.

KNMI (2014), 'Knmi-weerstation in voorschoten'.
URL: *https://www.knmi.nl/over-het-knmi/nieuws/knmi-weerstation-in-voorschoten*

Kottek, M., Grieser, J., Beck, C., Rudolf, B. & Rubel, F. (2006), 'World map of the köppen-geiger climate classification updated', *Meteorologische Zeitschrift* **15**(3), 259–263.

Kwok, A. G. & Chun, C. (2003), 'Thermal comfort in japanese schools', *Solar Energy* **74**(3), 245–252.

Lauenburg, P. (2016), Temperature optimization in district heating systems, *in* 'Advanced District Heating and Cooling (DHC) Systems', Elsevier, pp. 223–240.

Liang, Y., Lau, P. W., Huang, W. Y., Maddison, R. & Baranowski, T. (2014), 'Validity and reliability of questionnaires measuring physical activity self-efficacy, enjoyment, social support among hong kong chinese children', *Preventive medicine reports* **1**, 48–52.

Lowe, R., Wingfield, J., Bell, M. & Bell, J. (2007), 'Evidence for heat losses via party wall cavities in masonry construction', *Building Services Engineering Research and Technology* **28**(2), 161–181.

Meehl, G. A., Zwiers, F., Evans, J., Knutson, T., Mearns, L. & Whetton, P. (2000), 'Trends in extreme weather and climate events: issues related to modeling extremes in projections of future climate change', *Bulletin of the American Meteorological Society* **81**(3), 427–436.

Nagy, Z., Rossi, D., Hersberger, C., Irigoyen, S. D., Miller, C. & Schlueter, A. (2014), 'Balancing envelope and heating system parameters for zero emissions retrofit using building sensor data', *Applied energy* **131**, 56–66.

Nicol, F. (2004), 'Adaptive thermal comfort standards in the hot–humid tropics', *Energy and buildings* **36**(7), 628–637.

Nicol, J. F. & Humphreys, M. A. (2002), 'Adaptive thermal comfort and sustainable thermal standards for buildings', *Energy and buildings* **34**(6), 563–572.

Ohm, D. (2019), 'Comfortindices pmv and ppd - iso7730 (fanger method)'.
URL: *https://www.deltaohminternational.com/comfortindices-pmv-and-ppd-iso7730-fanger-method*

Ong, S. F. (2012), 'Constructing a survey questionnaire to collect data on service quality of business academics'.

Østergaard, D. S. & Svendsen, S. (2016), 'Theoretical overview of heating power and necessary heating supply temperatures in typical danish single-family houses from the 1900s', *Energy and Buildings* **126**, 375–383.

Østergaard, D. S. & Svendsen, S. (2018*a*), 'Are typical radiators over-dimensioned? an analysis of radiator dimensions in 1645 danish houses', *Energy and Buildings* **178**, 206–215.

Østergaard, D. S. & Svendsen, S. (2018*b*), 'Experience from a practical test of low-temperature district heating for space heating in five danish single-family houses from the 1930s', *Energy* **159**, 569–578.

Østergaard, D. & Svendsen, S. (2017), 'Space heating with ultra-low-temperature district heating–a case study of four single-family houses from the 1980s', *Energy Procedia* **116**, 226–235.

Parsian, N. & Dunning, T. (2009), 'Developing and validating a questionnaire to measure spirituality: A psychometric process', *Global journal of health science* **1**(1), 2–11.

PBL (2012), 'Naar een duurzamere warmtevoorziening van de gebouwde omgeving in 2050'.
URL: *https://www.pbl.nl/publicaties/2012/naar-een-duurzamere-warmtevoorziening-van-de-gebouwde-omgeving-in-2050*

PBL (2018), '2020 doelstelling niet-emissiehandelssectoren ruim haalbaar'.
URL: *https://themasites.pbl.nl/balansvandeleefomgeving/jaargang-2018/themas/energie-klimaat-lucht/emissies-broeikasgassen*

Rao, S. S. (2011), Chapter 13 - formulation and solution procedure, *in* S. S. Rao, ed., 'The Finite Element Method in Engineering', fifth edition edn, Butterworth-Heinemann, pp. 473 – 487.

Rovers, T. (2013), Energiegebruik in het twentebad, Master's thesis, University of Twente.

RVO (2011), 'Voorbeeldwoningen 2011'.

RVO (2016), 'Actualisatie investeringskosten maatregelen epa-maatwerk-advies bestaande woningbouw'.

RVO (2018), 'Marktbarometer aanbieding slimme meters'.

Saba, F., Fernicola, V., Masoero, M. & Abramo, S. (2017), 'Experimental analysis of a heat cost allocation method for apartment buildings', *Buildings* **7**(1), 20.

Sangoseni, O., Hellman, M. & Hill, C. (2013), 'Development and validation of a questionnaire to assess the effect of online learning on behaviors, attitudes, and clinical practices of physical therapists in the united states regarding evidenced-based clinical practice', *Internet Journal of Allied Health Sciences and Practice* **11**(2), 7.

Sarbu, I. & Sebarchievici, C. (2015), 'A study of the performances of low-temperature heating systems', *Energy Efficiency* **8**(3), 609–627.

Schmidt, D., Kallert, A., Blesl, M., Svendsen, S., Li, H., Nord, N. & Sipilä, K. (2017), 'Low temperature district heating for future energy systems', *Energy Procedia* **116**, 26–38.

Schweiker, M., Fuchs, X., Becker, S., Shukuya, M., Dovjak, M., Hawighorst, M. & Kolarik, J. (2017), 'Challenging the assumptions for thermal sensation scales', *Building Research & Information* **45**(5), 572–589.

SER (2018), 'Voorstel voor hoofdlijnen van het klimaatakkoord'.

Simon, H. A. (1996), *The sciences of the artificial*, MIT press.

Smeds, J. (2004), 'Energy aspects in swedish building legislation of the 20th century concerning dwellings', *Division of Energy and Builing Design. Lund Institute of Technology, Sweden. 7pp* .

Stafford, A., Johnston, D., Miles-Shenton, D., Farmer, D., Brooke-Peat, M. & Gorse, C. (2014), 'Adding value and meaning to coheating tests', *Structural Survey* **32**(4), 331–342.

Strauss, M. E. & Smith, G. T. (2009), 'Construct validity: Advances in theory and methodology', *Annual review of clinical psychology* **5**, 1–25.

Summerfield, A., Oreszczyn, T., Palmer, J., Hamilton, I. & Lowe, R. (2015), 'Comparison of empirical and modelled energy performance across age-bands of three-bedroom dwellings in the uk', *Energy and Buildings* **109**, 328–333.

Taleghani, M., Tenpierik, M. & van den Dobbelsteen, A. (2014), 'Energy performance and thermal comfort of courtyard/atrium dwellings in the netherlands in the light of climate change', *Renewable Energy* **63**, 486–497.

ter Mors, S., Hensen, J. L., Loomans, M. G. & Boerstra, A. C. (2011), 'Adaptive thermal comfort in primary school classrooms: Creating and validating pmv-based comfort charts', *Building and Environment* **46**(12), 2454–2461.

Trenberth, K. E. (2011), 'Changes in precipitation with climate change', *Climate Research* **47**(1-2), 123–138.

Van Aubel, P. & Poll, E. (2019), 'Smart metering in the netherlands: what, how, and why', *International Journal of Electrical Power & Energy Systems* **109**, 719–725.

van den Brom, P., Meijer, A. & Visscher, H. (2019), 'Actual energy saving effects of thermal renovations in dwellings—longitudinal data analysis including building and occupant characteristics', *Energy and Buildings* **182**, 251–263.

van der Linden, A., Boerstra, A. C., Raue, A. K., Kurvers, S. R. & De Dear, R. (2006), 'Adaptive temperature limits: A new guideline in the netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate', *Energy and buildings* **38**(1), 8–17.

Van Oldenborgh, G. J., Haarsma, R., De Vries, H. & Allen, M. R. (2015), 'Cold extremes in north america vs. mild weather in europe: The winter of 2013–14 in the context of a warming world', *Bulletin of the American Meteorological Society* **96**(5), 707–714.

Van Vliet, A. J., Overeem, A., De Groot, R. S., Jacobs, A. F. & Spieksma, F. T. (2002), 'The influence of temperature and climate change on the timing of pollen release in the netherlands', *International Journal of Climatology* **22**(14), 1757–1767.

Verbeeck, G. & Hens, H. (2005), 'Energy savings in retrofitted dwellings: economically viable?', *Energy and buildings* **37**(7), 747–754.

Vogelsang, T. J. & Franses, P. H. (2005), 'Are winters getting warmer?', *Environmental Modelling & Software* **20**(11), 1449–1455.

Wang, Q., Ploskić, A. & Holmberg, S. (2015), 'Retrofitting with low-temperature heating to achieve energy-demand savings and thermal comfort', *Energy and Buildings* **109**, 217–229.

Wieringa, R. J. (2014), *Design science methodology for information systems and software engineering*, Springer.

Wong, N., Feriadi, H., Lim, P., Tham, K., Sekhar, C. & Cheong, K. (2002), 'Thermal comfort evaluation of naturally ventilated public housing in singapore', *Building and Environment* **37**(12), 1267–1277.

Younes, C., Shdid, C. A. & Bitsuamlak, G. (2012), 'Air infiltration through building envelopes: A review', *Journal of Building physics* **35**(3), 267–302.

Yücel, G. (2013), 'Extent of inertia caused by the existing building stock against an energy transition in the netherlands', *Energy and Buildings* **56**, 134–145.

Appendices

A Interview summaries

A.1 Laure Itard - TU Delft OTB 8 April 2019

About L. Itard
Professor at TU Delft, specialised in the built environment. Published many papers concerning heat consumption of households, energy index labels of Dutch dwellings, comfort experience of residents in buildings and other related topics.

How can the heat loss of dwelling be determined?
Normally, the heat loss is theoretically determined during the design phase of a dwelling. This can be achieved with several methods, one being the ”building envelope” method from ISSO.

Can the heat loss be determined empirically?
This should be possible, but it is uncommon.

What do you think of an empirical method that uses the energy balance and natural gas consumption related to space heating to determine the heat loss of dwelling? (If the indoor temperature of a building is constant, the heat loss of a building is equal to heat output of the heat distribution system. Thus if the energy input of the heat distribution system is known, the heat loss of a building can be determined when the indoor temperature is constant.)
This is possible. However, internal heating gains might affect the results. To minimize the internal heat gains, the measurements should be executed at night and when the minimum amount of residents is represent. Determining the heat loss of a dwelling empirically may therefore involve a significant error margin.

Does this also apply to existing dwellings?
Yes, however is it very complicated to theoretically calculate the heat loss of an existing dwelling. Especially in dwellings that have been renovated several times, because new construction methods and building materials have been used. Usually, the modifications are not documented, wherefore crucial information concerning the building materials is lacking.

How can comfort be measured?
Comfort is a combination of temperature, ventilation and humidity. In order to maintain adequate CO_2, O_2 concentrations the ventilation rate should be controlled. Humidity can be controlled, but this is not required by building standards. However, it is important to control the indoor temperature. During the summer the temperature in the dwelling should not be too high, while during the winter heat should be supplied by the central heating system. When heat is supplied by the central heating system, the air temperature is often measured. However, a comfortable air temperature does not necessarily result in a high comfort level. In addition to the air temperature, the temperature of surfaces (commonly the walls) should be measured,

because these walls emit heat via radiation. An often heard complaint is that the indoor air temperature is 21°C, but the residents do not feel themselves comfortable. This is caused by too low radiant temperatures i.e. the surfaces of the space in which the radiator is placed do not emit enough heat.

A.2 J. de Leeuw - ISSO 17 April 2019

About J. de Leeuw
J. de Leeuw is project manager/specialist at ISSO. His expertise includes indoor climate (regulation systems) in buildings.

How did historical changes in building standards affect the heat loss of dwellings?
Several events in the past indirectly affected the ”energy-index” (EI) of buildings. During the early 60s, the obligation of the cavity walls in new buildings led to a reduction in energy consumption. However, the main reason to introduce the cavity wall was to stop internal penetrating damp. In the early 70s, people started to insulated their cavity walls in order to reduce their gas expenses. This was a result of higher gas and oil prices during the oil crisis in 1973. Until 1992, no building standards were defined for the heat loss of dwellings. From 1992, new buildings were required to have a minimum Rc-value of 2,5 and in 2012 a RC-value of 3,5 $m^2 \cdot K \cdot W^{-1}$.

How did historical changes in building standards affect the minimum heat output of heat distribution systems?
There are no building standards that set minimum requirements for the heat output of heat distribution systems. There are only rules of thumb. Currently, the heat output of heat distribution systems is dependent on the heat loss of buildings. If the heat output of a heat distributions well exceeds the heat loss of the dwelling at design conditions, the heat output is sufficient. Therefore there is no need to develop building standards for heat distribution systems.

How to determine the heat loss of dwellings?
ISSO publication 51 describes a method that can be used to theoretically determine the heat loss. This method is also applicable on existing buildings in which adjustments have been made. One requirement is well documented data about the building characteristics when buildings are adjusted. His collegue: Harry van Weele, knowns more about these methods.

How to determine the heat output of radiators empirically?
Measuring the heat output of heat distribution systems by measuring the volumetric flow of the system in combination with the supply and return temperature should give an accurate indication of the amount of energy distributed in a dwelling. Dividing the total energy input by the amount of time in which the heat is supplied, should result in average heat output of the heat distribution system. However, one concern is that the heat is not equally distributed among the dwelling. Some spaces in the dwelling might be very comfortable or even too hot, while others are too cold.

Design conditions
ISSO uses -10°C as design conditions. Wind velocity, humidity and sun radiation are not taken into account. In earlier publications ISSO sometimes used -7°C and a certain wind velocity. However, this corresponds (with a small error margin) to -10°C without a the wind velocity factor. For simplicity ISSO decided to use -10°C as design conditions. Currently, a common indoor temperature is approximately 20°C. In well isolated buildings, the heat loss is very small, wherefore people tend to use higher indoor temperatures. For example

22°C.

Is heat distribution systems balancing required?
In approximately 90% of the buildings in the Netherlands, the heat distribution systems do not operate efficiently. This is commonly caused by unbalanced heat distribution systems. When heat distribution systems are modified, the systems are often not balanced, because extra costs are charged by installation companies. As a result the heat output decreases dramatically. Therefore it is important to have a well functioning and balanced heat distribution system when measuring the maximum heat output by empirical methods. Otherwise the measures will not be representative.

What is required to create well functioning heat distribution systems?
First, the entire heat distribution system should be balanced. This incorporates that several adjustments have to be done to the heat distribution system to enable balancing. The number of adjustments dependents on the state of the heat distribution system. Subsequently the system should be balanced. Secondly, a minimum temperature difference between the supply and return temperature of approximately 15°C is required. This only holds for high-temperature heat distribution systems. Low-temperature heat distribution system can operate with smaller temperature differences.

How much does it cost to balance a heat distribution system in a regular Dutch dwelling?
2 people require approximately one day to install all required components and to balance the system. All radiators and convectors should be equipped with dynamic valves.

What kind of hydronic heat distribution systems are present in the Netherlands? series, parallel or series-parallel?
Most system are connected via a series-parallel circuit.

A.3 Person X - Company X 25 April 2019

About Person X
Person X is a heat distribution system balancing specialist with 20 years of experience. He balanced systems in several building varying from single family dwellings to large university buildings.

How important is CV tuning i.e. heat distribution balancing?
The majority of the heat distribution systems in the Netherlands are not properly balanced. This results in thermal discomfort and higher gas consumption. Before 1980, static balancing of the heat distribution system was mandatory. After 1980, this was not mandatory anymore. In addition, new and cheaper valves (RAFN replaced RAN) inhibited the possibility to balance heat distribution systems. In new buildings (built after 2000-2010), approximately 80% of the buildings are equipped with mechanisms that allow balancing.

How much many hours do you need to properly balance a heat distribution system?
Approximately 3 to 7 hours for regular dwellings. This depends on the dwelling's size and amount of radiators.

Do you need additional materials, such as valves, in order to balance the heat distribution system?
Only tools are required to adjusted the valves. However, some radiators and convectors do not have features that allow balancing. Therefore valves or similar mechanisms have to be installed before heat distribution balancing can take place.

What is your opinion about dynamic valves that automatically balance the heat distribution system?
Dynamic valves are expensive and not required to balance a heat distribution statically. Especially in combination with other radiator values, the dynamic valves to not operate correctly. Moreover, many heat distribution system operate with a regular pump that maintain a constant volumetric flow rate. Dynamic valves are therefore not required.

Is the volumetric flow rate affected when lower supply and return temperatures are applied?
This depends on the type of pump in the gas-fired boiler. Normally, pumps operate at a constant speed. However, new central heating systems are equipped with a modulating pump that is able to operate at varying speeds. As result the volumetric flow is affected when varying pump speeds are applied.

Do you think it is possible to use lower supply and return temperatures in existing heat distribution systems?
Applying lower temperatures is in almost all dwellings possible. However, this depends on the desired supply and return temperature. 70/50/20°C does not cause problems. Lower operating setting, such as 55/45/20°C will probably not be possible. Another important aspect is the composition of the heat distribution system. Radiators can operate at lower supply and return temperatures than convectors. The heat output of convectors is negligible at temperature <55°C.

A.4 Harry van Weele - ISSO 25 April 2019

About H. van Weele
Harry van Weele is employeed at ISSO for over 35 years and currently works as project manager. He was amongst others involved in several publications that describe standards to determine the theoretical heat loss of buildings.

How would you determine the heat loss of existing dwellings? Theoretically or experimentally?
Theoretically is often the most reliable and cost-effective approach. Experimental approaches are exposed to external and internal factors that can affect the measurements. Examples are internal heat gains and outdoor conditions.

Although a theoretical approach is straight-forward, it also faces difficulties when existing dwellings have been renovated over time. For example, when additional insulation is added to a dwelling. Is it in those case still possible to apply a theoretical approach?
Although certain situations make matters more complicated to apply a theoretical approach, it is still possible. Via a survey, in which experts gather important data about the construction/insulation materials, is required. On the basis of this data calculations can be performed that approximate the dwelling's heat loss.

What are the disadvantages of a theoretical approach?
On major disadvantage is the determination of the heat loss caused by air infiltration. Although some rules of thumb have been established over the years, the rate of air infiltration can deviate significantly as result of renovations, adjustments to the dwellings and the residents.

What design conditions are currently used?
Nowadays, the design conditions are -10°C and 5 $m \cdot s^{-1}$ wind.

In ISSO publication 51 only -10°C is used as design condition. The wind speed is not taken into account. How is this possible?
For many basic calculations only the outdoor temperature is used. In more complex (computer based) calculations, the wind speed is incorporated.

What does it cost to theoretically determine the heat loss of a regular single family dwelling?
Depending on the person/company that performs the heat loss determination it will approximately costs 0.5-1 day of work. Furthermore, the size, shape and condition of the dwelling can affect the costs.

B Operative temperatures per space

Type of space	Design operative temperature [°C]
Living spaces (living room, kitchen, bedrooms)	22/20
Living area	22/20
Bathroom	22
Hallways, stairs	20/18
Technical area	15
Storage facilities	15

* Higher operative temperatures might be applied in buildings designed with a specific purpose. For example nursing and retirement homes.

C Thermal comfort questionnaire

Project number: ____________________

1. **Age of residents?**
   - ☐ <25
   - ☐ 25 – 45
   - ☐ 46 – 70
   - ☐ >70

2. **Which of the following do you personally adjust or control in your space?**
   - ☐ Window blinds or shades
   - ☐ Room air-conditioning unit
   - ☐ Door to interior space
   - ☐ Door to exterior space
   - ☐ Adjustable air vent in wall or ceiling
   - ☐ Adjustable floor vent (diffuser)
   - ☐ Thermostat
   - ☐ Operable window
   - ☐ Other ____________________

3. **How satisfied are your with the temperature in your dwelling?**

   ☺ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☹

Please respond to the following questions based on your overall or average experience in the past X period of time

4. **If discomfort is experienced in the past week, please indicate in which spaces discomfort was experienced:**
   - ☐ Living room
   - ☐ Kitchen
   - ☐ Bedroom(s)
   - ☐ Bathroom(s)
   - ☐ Toilet(s)
   - ☐ Hallways, stairs
   - ☐ Storage facilities
   - ☐ Other: ____________________

5. **If discomfort is experienced in the past week, how would you describe the source of this discomfort?**
   - ☐ Humidity too high (damp)
   - ☐ Humidity too low (dry)
   - ☐ Air movement too high
   - ☐ Air movement too low
   - ☐ Incoming sun
   - ☐ Heat from equipment/machines
   - ☐ Drafts from windows
   - ☐ Drafts from vents
   - ☐ Heating system does not respond quickly enough to thermostat
   - ☐ Hot/cold surrounding surfaces (ceiling/walls/floor/windows)
   - ☐ Other: ____________________

6. **If you are dissatisfied with the temperature in your dwelling, which of the following contribute to your dissatisfaction:**
   - ☐ Always too hot
   - ☐ Often too hot
   - ☐ Occasionally too hot
   - ☐ Occasionally too cold
   - ☐ Often too cold
   - ☐ Always too cold

7. **If you are dissatisfied with the temperature in your dwelling, when is this often a problem (check all that apply:**
   - ☐ Morning (before 11:00)
   - ☐ Midday (11:00–14:00)
   - ☐ Afternoon (14:00–17:00)
   - ☐ Evening (after 17:00)
   - ☐ Weekends/holidays
   - ☐ Monday mornings
   - ☐ No particular time
   - ☐ Always
   - ☐ Other: ______________________________

D Dwelling evaluation form

Project number: ____________________
Project date: ____________________

Number of residents: ____________________
Dwelling building year: ____________________

Energy renovations	Yes	No	Additional information
Wall insulation	☐	☐	____________
Roof/Ceiling insulation	☐	☐	____________
Floor insulation	☐	☐	____________
Glass replacement	☐	☐	____________
Air leakage prevention	☐	☐	____________
Ventilation heat recovery	☐	☐	____________

Space: ________	Covered	(re)painted	Behind furniture	Other:
Radiator/convector 1	☐	☐	☐	____________
Radiator/convector 2	☐	☐	☐	____________
Radiator/convector 3	☐	☐	☐	____________
Radiator/convector 4	☐	☐	☐	____________

Space: ________	Covered	(re)painted	Behind furniture	Other:
Radiator/convector 1	☐	☐	☐	____________
Radiator/convector 2	☐	☐	☐	____________
Radiator/convector 3	☐	☐	☐	____________
Radiator/convector 4	☐	☐	☐	____________

Space: ________	Covered	(re)painted	Behind furniture	Other:
Radiator/convector 1	☐	☐	☐	____________
Radiator/convector 2	☐	☐	☐	____________
Radiator/convector 3	☐	☐	☐	____________
Radiator/convector 4	☐	☐	☐	____________

Space: ________	Covered	(re)painted	Behind furniture	Other:
Radiator/convector 1	☐	☐	☐	____________
Radiator/convector 2	☐	☐	☐	____________
Radiator/convector 3	☐	☐	☐	____________
Radiator/convector 4	☐	☐	☐	____________