Facade renovations of dwellings for high comfort with low temperature heating

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MSc Thesis

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Faculty of Civil Engineering & Geosciences

Façade renovations of dwellings for high comfort with low temperature heating

By
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in partial fulfilment of the requirements for the degree of

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Preface

This thesis will conclude two years of studying towards the MSc degree in Civil Engineering at the TU Delft. It has been a great experience where I learned a great deal about Building Physics. I have become very passionate about this topic and look forward to the next steps in this field.

First of all I would like to thank all members of my graduation committee. As chair of the committee Laure Itard has been of great importance with her in-depth knowledge and expertise regarding energy in buildings and renovations. Laure helped shape the research proposal from the first meeting and has offered excellent guidance throughout the process. From the Civil Engineering faculty, Roel Schipper has been a great support. Already at the first day of starting the Building Engineering program at the CEG faculty, Roel has been involved with both practical study related issues as well as in-depth technical guidance. His input is greatly appreciated and helped shape this study to what is now. As daily supervisor, Paula van den Brom has been a major support in the process of writing this thesis. Through a vast amount of (online) meetings and email chains, Paula has been the main point of contact where she always managed to offer tremendous guidance. Paula has been a consistent source of exceptional know-how of the topics at hand, which she was always prepared to share with great enthusiasm.

Secondly, I would also like to thank my family. The continuous support of my parents, Mascha and Ruud, is greatly appreciated. Their involvement, both practical and emotional, has been a huge help throughout my time as a student for which I am extremely grateful. Also my brother Philip, has been a great support in the process. I would also like to thank my girlfriend, Olivia, for her care and support throughout the process of writing this thesis. I am very excited to see what future steps hold in store for us.

Lastly, many thanks to my friends who have all shown great support. Terence, Joey, Aljosja, Jeroen, Coen, David and Alex have all been their consistently throughout my time as a student. Also Marc-Vincent has been a great help and motivation. Marvin and Rafael, who were going through the same graduation process, have been a great support and motivation. Also my fellow members of U-BASE Board 6 have been a huge support. Working together with them, whilst many of us were graduating at the same time, has been a pleasure.

Abstract

Especially in colder climates, like The Netherlands, a large quantity of non-renewable energy is used for space heating by burning natural gas. To meet climate goals, natural gas should be replaced with renewable sources. Reducing the total energy demand for space heating and lowering the design water temperature in a heating system enable more renewable energy production alternatives for space heating. So high temperature heating (HTH) systems need to be replaced with low temperature (LTH) alternatives to get dwellings through the energy transition.

Despite the indisputable advantages of LTH, it also comes with risks. One risk is that heating elements need to become exceedingly large to ensure sufficient heating capacities. Insufficient capacities may adversely affect indoor thermal comfort. To mitigate this effect, extra measures should be taken in the façade, ground floor and roof to reduce infiltration and increase insulation. In order to introduce these measures a renovation should be carried out. This study will focus on façade renovations.

For the assessment of comfort levels when changing to LTH, this research presents a case study into a typical Dutch terraced dwelling. This case study was carried out through simulations in TRNSYS 17. This is a validated program simulating energy flows in transient systems. Although TRNSYS 17 has built-in comfort calculation options, these were not deemed sufficiently transparent in their workings for this study. Furthermore, calculations of view-factors, mean radiant temperatures (MRT) and the predicted mean vote (PMV) showed deviations from standards NEN-EN ISO 7726 and 7730. Therefore a workaround is presented which calculates comfort levels closer in line with standards.

Two façade options were investigated for 1 HTH and 3 LTH systems. The HTH model was calibrated to match measured air and surface temperatures of a test dwelling. LTH was then simulated while keeping the current radiators, which showed that diminished capacities significantly reduce comfort and façade renovations cannot realistically mitigate this. This option is not possible when changing to LTH in dwellings in general. Then a system with specialized LTH radiators was investigated, with capacities determined through ISSO 51. This still showed a high peak of discomfort at current insulation levels. Comfort levels were improved significantly after a renovation to match the new ‘Target Values’ (‘Streefwaarden’) for insulation and an ‘excellent’ qualification for infiltration reduction. Finally, underfloor heating was investigated, resulting in enhanced comfort levels both with current and updated insulations levels. In all cases, a renovation has a positive effect on comfort levels and reduces heat transfers.

Table of Content

1. Introduction

The Netherlands is one of the most densely populated areas in Western Europe with a large social and middle-income housing shortage (Boelhouwer, 2020). During the second half of the 20th century, a steep increase in the total population could be seen. A consequence of this population increase was the need for more housing. Between 1945 and 1995 this resulted in the construction of a large amount of dwellings, many of which are still standing today (CBS, 2020).

These residences were built to live up to the standards for insulation values, energy consumption and comfort levels that were governing at that time, if any. Over recent years however, these standards have been adjusted in order to be compliant with EU objectives to cut down energy and material consumption by 2050 (Brilhante & Skinner, 2014). An example of a changing standard is presented in Table 1.1, which shows how the minimum thermal resistance (Rc) values have changed since 1965 up to the current laws stated in the ‘ Bouwbesluit’ (Dutch Building Decree).

Table 1.1: Minimum Rc values in the Netherlands since 1965 (Vakblad Warmtepompen, 2019)

Year	*Rc Roof (m2K/W)*	*Rc Façade (m2K/W)*	*Rc Floor (m2K/W)*
Current Standards	6	4,5	3,5
2012	3,5	3,5	3,5
1992	2,5	2,5	2,5
1985	1,3	1,3	1,3
1975	1,03	0,69	0,26
1965	0,86	0,43	1,17

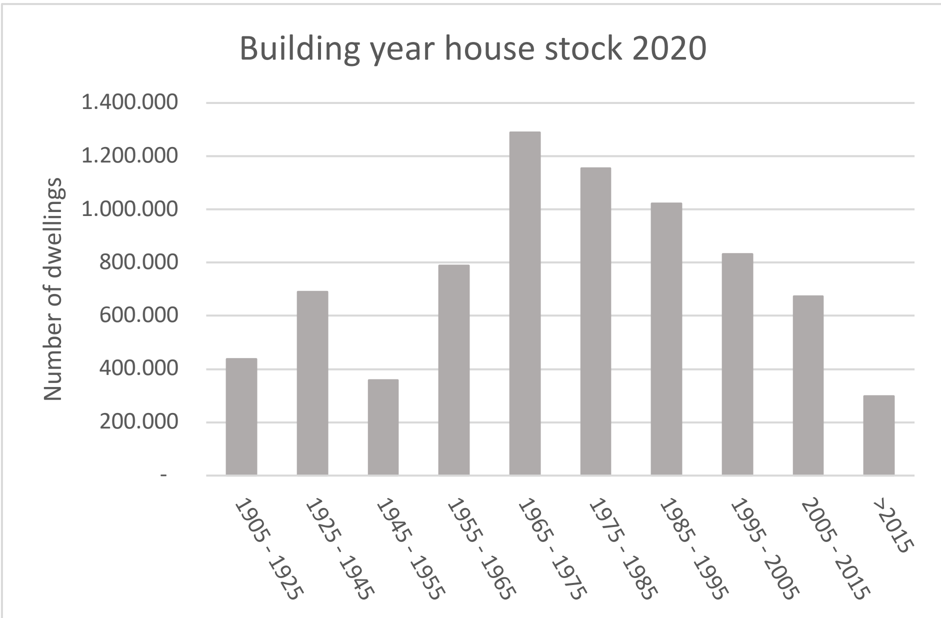


Figure 1.1: Housing Stock in The Netherlands (CBS, 2020)

Figure 1.1 shows that a majority of the current housing stock was built between 1965 and 1995. The corresponding Rc standards for houses in these years were significantly lower than the current regulations, as can be seen in table 1.1. These poor thermal properties are (at least partially) the reason for the high non-renewable energy use of buildings. In 2021, around 75% of the buildings in the European Union are considered to be energy inefficient, whilst nearly all of these buildings are predicted to still be standing in 2050 (European Commission , 2021). The energy use of buildings was around 40% of the total energy use in 2016 (Rousselot, 2016).

The need for energy demand reduction is further substantiated by the generally poor energy labels of the building stock in The Netherlands. Figure 1.2 shows that in 2012, most buildings constructed before 1980 have an energy label D or worse. Older residences perform even worse with energy labels of mostly E, F or G. In figure 1.3 it can be seen that in 2019, 60% of all houses had a label C or worse. These energy labels give an indication of the energy consumption of a dwelling with label G performing worst and A++ performing best. The label provides information on the insulation levels of the roof, façade and floor, the energy consumption of the dwelling and ways to reduce this energy consumption. Upgrading the thermal properties of these residences could significantly decrease their energy use.

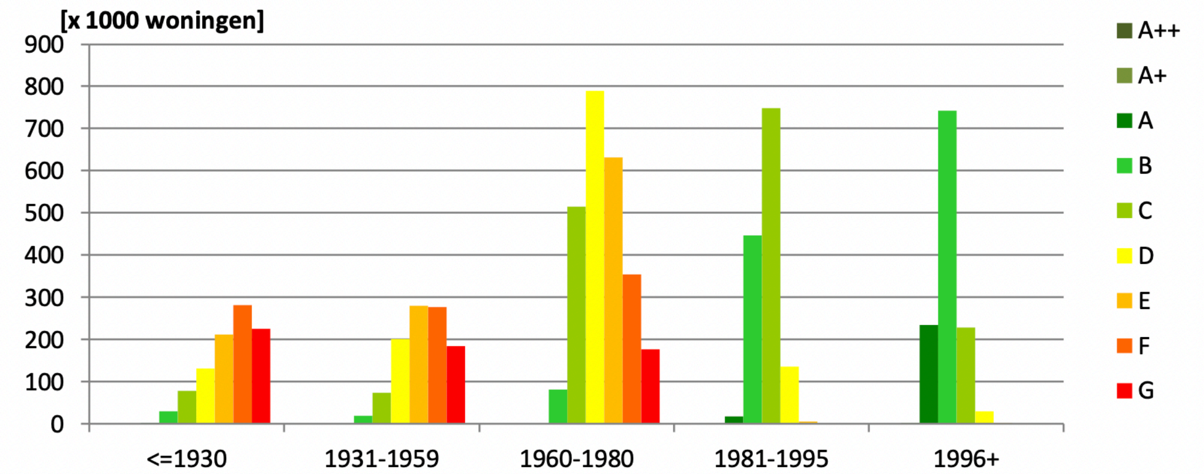


Figure 1.2: Energy labels per construction period (Tigchelaar & Leidelmeijer, 2013)

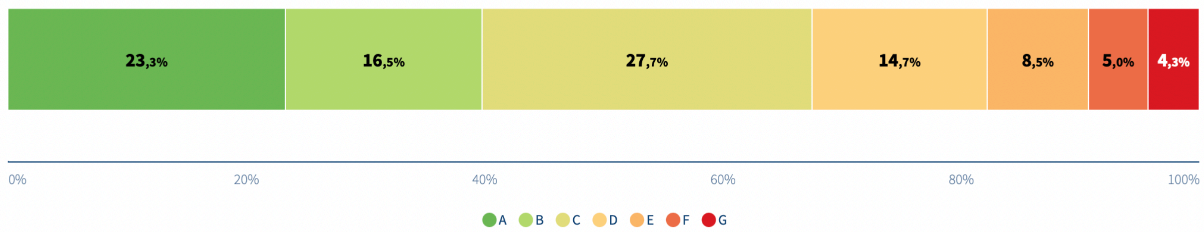


Figure 1.3: Percentage of energy labels (Rijksdienst voor Ondernemend Nederland, 2019)

In addition, one of the objectives for 2050 is for the entire Dutch economy, including the construction sector, to be completely circular (Ministerie van Infrastructuur en Waterstaat, 2019). For the old dwellings built in the 20th century to meet current standards in an energy and material efficient way, intensive upgrading is required. This upgrade can take place via a renovation or a demolish and rebuild principle. Which option is better, is highly dependent on the situation but compared to complete demolition and rebuild, renovation is generally less time consuming, less intrusive for current residents and more efficient when it comes to material use (Najah, 2012).

The most important challenge when upgrading existing buildings is, without a doubt, for them to become more energy efficient, fully circular and only use renewable energy in the near future. A potential way to improve the energy efficiency of buildings is the introduction of low temperature heating (LTH) systems. Improving the insulation levels of a dwelling will reduce the heat loss. This enables a lower maximum temperature of the heating delivery (e.g. radiators or underfloor heating). This will lead to more renewable energy alternatives for heat production (Lund, et al., 2014).

One of the risks of LTH systems is that surface areas of the heating delivery need to be exceedingly large or the peak capacity of the heating system is lowered. These diminished heating capacities may adversely affect the indoor thermal comfort when minimum desired temperatures cannot be achieved. So when renovating older buildings to LTH, it is imperative to also consider the indoor climate comfort for occupants in the process. By optimizing the façades, floors and roofs of the renovated houses, total heat demand and the required peak capacity of a heating system can be reduced and indoor thermal comfort can be substantially improved. Not only the indoor temperature comfort can be enhanced, but also aspects like sound hinderance and natural lighting conditions could be affected positively. This thesis will however focus on the thermal aspects of a façade and indoor climate comfort. Figure 1.4 shows a summary of the reason of this thesis.

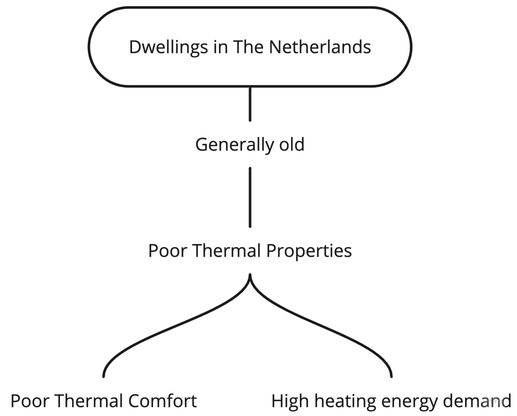


Figure 1.4: The state of the current Dutch building stock

Updating the building stock is an essential element in the energy transition needed to mitigate climate change and stop finite resource depletion (European Commission, 2020). This involves many detailed studies, which together should form the required integral design for a renovation meeting the objectives regarding sustainability. This research will focus on optimizing the façade for low temperature heating and the link to the indoor temperature comfort levels. This has been formulated in one main research question:

When changing to low temperature heating in renovation projects, what changes need to be taken to the façade, in order to realize a good thermal comfort?

In essence this comes down to a Min-Max-Min goal: Minimize grey energy demand, Maximize thermal comfort, with Minimum resources. The main goal of this research is to link several renovation options of an LTH system and the façade to the thermal comfort increase/decrease this brings. This will be done by means of a case study of an existing dwelling.

In order to answer the main research question, a set of sub-questions has been derived to divide the main topics involved. This list is presented below:

- How does low temperature heating impact thermal comfort?
- What is the influence of the façade on thermal comfort in current standards?
- What types of low temperature heating delivery are most efficient? And how does this impact thermal comfort?
- What are challenges/opportunities of façade design in renovation projects?

Before it is possible to start this research, it is important to set a scope boundary. In terms of location, this boundary is set at The Netherlands. The main reason for this choice is the desire to use measured data (this will be further substantiated in a later chapter) and the available timeframe. In The Netherlands, datasets are available regarding energy demand and surface temperatures. If required, these existing datasets can be further expanded with own measurements if time allows it. Also, in the Netherlands a large amount of natural gas is still used for space heating (Rijksdienst voor Ondernemend Nederland, 2018). There is the desire to significantly reduce if not completely eliminate this excessive gas consumption in the near future and switch to renewable alternatives.

The next step is to specify a certain building type. The first distinction that needs to be made, is the function type. This study focusses on residential buildings. This is a relevant focus-group because of the large number of relatively poor energy labels for residences compared to utility buildings. In addition, residences are still responsible for a large portion of the total used energy (Rijksdienst voor Ondernemend Nederland, 2019).

Residences can be subdivided by a large number of building characteristics. One of the most clear ones is the residence building type. The 'Centraal Bureau voor de Statistiek' (Central Bureau of Statistics in The Netherlands) divides housing types in four categories: detached, semi-detached and terraced houses and appartements. Figure 1.5 shows that terraced houses form the largest portion of the total residential building stock at 42.5% in 2015. This research will be about this building type, also because most measured data originates here. The assessed house in the case study also qualifies as a typical Dutch terraced house.

Dwelling types of homeowners in 2015

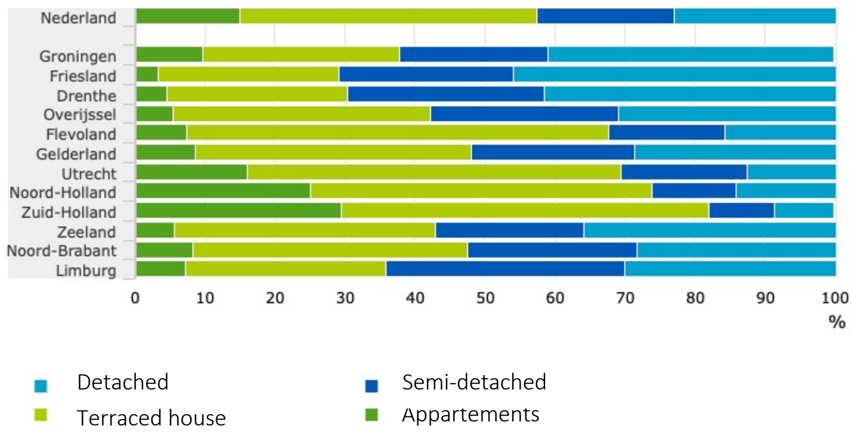


Figure 1.5: Residence building types in The Netherlands (CBS, 2016)

The new energy source is considered to be outside the scope of this research. The focus lies on the interaction of the heating delivery system with the individual residence. This means that it will not be investigated if the heat comes from for example a heat pump or a co-generation/waste heat source. In some cases it might be required to estimate the total required capacity however. In this case a heat pump will be assumed since this is a common LT heat source and can be installed on an individual dwelling basis. The heat transfer of the assessed systems is briefly touched upon. Other factors like life-span extensions, life cycle analyses and CO_2 emission calculations are considered outside the scope of this thesis however. Also other energy demanding aspects like hot tap water are not part of this assessment. The main focus is space heating and thermal comfort.

In the next chapter the methodology of the research will be elaborated. After that, a literature review on the main topics of this thesis will be conducted. Then a model resembling a real-life dwelling will be created and calibrated. This is done by comparing measurements from this dwelling and the model outcomes. This will be followed by the simulation of a set of renovation interventions, which will be further explored. This will lead to a set of conclusions and lastly recommendations on implementation of the outcomes.

2. Methodology

Combining multiple types of methodology goes by a number of different names. For this thesis, mixed method research will be conducted. With a mixed methods approach it is possible to combine both qualitative and quantitative data whereas for example a multi-method procedure focuses on solely qualitative or solely quantitative data (Schoonenboom & Johnson, 2012). The main reason for using a mixed-method approach in this thesis is to verify the validity of the findings and conclusions from individual steps in the research process. These individual steps are, in this case, a literature review, simulations via computer models and a data analysis.

A literature review forms the basis of most academic researches. It can act as justification of the research question and is vital for exploring existing knowledge of the studied subject (Snyder, 2019) (Verschuren & Doorewaard, 2010). When a scientific piece of work includes a good literature review, the authors familiarity with the topic will not only be strengthened but also demonstrated to readers (Randolph, 2009).

So also for this thesis, a literature review will be conducted. It is aimed at exploring and elaborating five main themes. These themes are: Energy, Facades, Low Temperature Heating, Indoor Thermal Comfort and Renovation implications. Literature should point out what is deemed 'state-of-the-art' or already is 'common practice' in current construction projects for each of these themes. Some of the themes are still broader than is desired and will need further specification. Exploring and specifying these specifications will take place in this part of the research. Also worth mentioning are the expected links between the main themes. There will be certain overlaps, which should also be explored and elaborated.

Computer simulations are a quick and useful tool for analyzing a design in relatively limited time with limited resources. Designers should however be cautious when using these computer models and ensure they have an understanding of what is happening in the model, its limitations and expected outcomes.

The verification of modelled results is increasingly important with growing complexity of computer models. This poses the threat of models becoming 'black-boxes'. Furthermore, even if the models have not yet become 'black-boxes', the calculated and actual energy consumptions still show large discrepancies. It is shown that old houses usually perform better than expected, whereas new houses perform poorer (Majcen, Itard, & Visscher, 2016). This leads to lower energy savings than predicted. Comparing measured and modelled outcomes should enhance the credibility of expected outcomes presented in this research.

For this research the energy simulations will be executed in TRNSYS (TRaNSient SYStem). This software uses visual programming to set up complex models by linking components, called Types. In TRNSYS, Types from different libraries can be placed and linked. Types are open source so their functioning can be explored or adjusted. Added versatility comes through the possibility to integrate MATLAB/Simulink models as components in TRNSYS and vice versa. A 3D visualization can be made with a SketchUp 2014 integration tool (Duffy, Hiller, Bradley, Keilholz, & Thornton, 2009).

The measured data will mainly be retrieved from the LT-Ready project (LT-Ready, 2020). The aim of this project is to find viable renovation solutions, which enable the use of low temperature heating by upgrading the thermal properties. 'Viable' in this context means that interventions are limited in terms of budget and time to implement. The main goal is to increase the sustainability of residences. The project aims to create buildings with low heating energy demands and increase or at least maintain comfort levels. Several pilot houses with the proposed interventions and a design web-tool will be the end result. The measured data will not only consist of energy demands for different houses with different façade types, but also air and surface temperatures which will be of great importance to the comfort levels indoors. This data can help with verifying the results of modelled outcomes and form the baseline of the achieved comfort levels.

3. Literature Review

In this section, the results of the literature review will be presented. As mentioned, the main research question has been divided into five main themes: thermal comfort, energy, facades, renovations and low temperature heating. For the literature review, these 5 topics are also used as points of reference. The main aim of carrying out a literature review is to obtain a better understanding of the main themes and to assess the current 'common practice' and 'state-of-the-art' in renovation projects.

3.1 Thermal Comfort

Thermal comfort is defined as *"the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation"* (ASHREA, 2017). Thermal comfort standards are currently formulated in NEN-EN ISO 7730, EN 15251 and their American counterpart ANSI/ASHREA. A large part of the underlying theory of all standards is based on Fanger's theory (Hoof, Mezej, & Hensen, 2010). This theory claims that a person's thermal sensation is based on an energy balance in a stationary situation (NEN-EN-ISO 7730, 2005). The energy fluxes are displayed in figure 3.1 and the simplified balance can be written as:

$$M = P_c + P_{zv} + P_g + P_{ma} + P_d + P_s + P_{av} + P_{al}$$

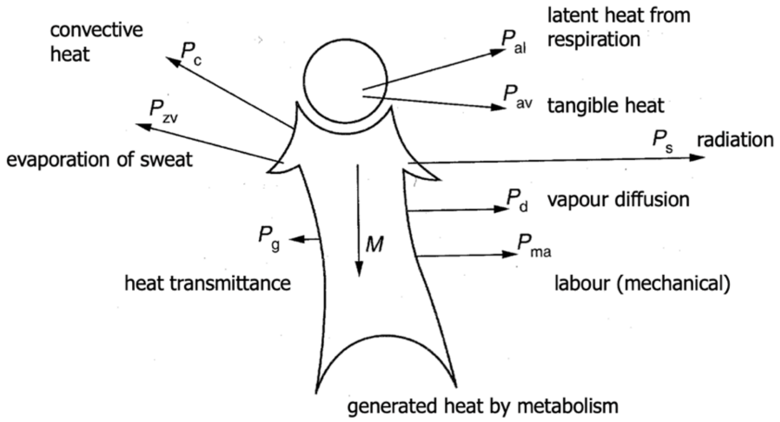


Figure 3.1: Energy fluxes in Fanger model (van der Linden, Kuijpers-Van Gaalen, & Zeegers, 2018)

The body can adjust factors like sweating or shivering or a person can change clothes or the activity they are partaking in to adjust the energy balance. All the corresponding factors for Metabolism and Clothing rates can be found in the ISO 7730 standard or databases like the 'engineering toolbox'. A sensation of thermal comfort is achieved when incoming and outgoing energy is equal. From this energy balance, the Predicted Mean Vote (PMV) can be calculated with the equations shown in annex B: Calculation of the PMV. The PMV is a point scale giving a numeric value usually between -3 and +3 to the thermal comfort of a large group of people (NEN-EN-ISO 7730, 2005). The PMV scale with values and descriptions is displayed in figure 3.2, zero being the neutral point.

The PMV is the predicted comfort level for a large group. However, no matter how closely the indoor temperature can be controlled, there will always be occupants who experience the thermal conditions as uncomfortable (Luo, Wang, Brager, Cao, & Zhu, 2018). One of the ways this is quantified is in the Predicted Percentage of Dissatisfied (PPD). This PPD is directly linked to the PMV via the equation in annex C: PMV to PPD. The graphical relation is shown in figure 3.3.

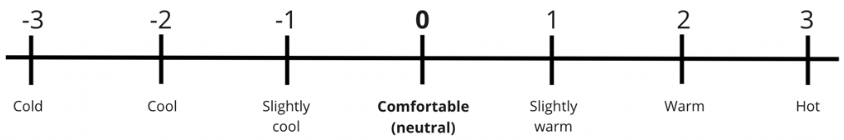


Figure 3.2: 7-point PMV scale (NEN-EN-ISO 7730, 2005)

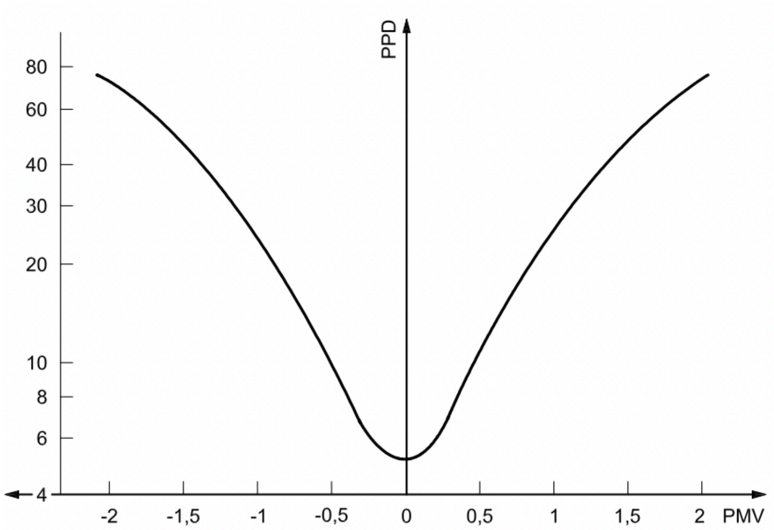


Figure 3.3: PPD as a function of the PMV (NEN-EN-ISO 7730, 2005)

From this figure 3.3 it can be seen that at even at a PMV of 0, still 5% of people are dissatisfied. At a PMV of ±0,5 roughly 10% of the people is dissatisfied and PMV levels of ±0,8 give a dissatisfied percentage of 20%. To accommodate for fluctuations, a PMV outside the ±0.5 range is allowed no more than 10% of the annual dwell time (van der Linden, Kuijpers-Van Gaalen, & Zeegers, 2018). A PPD of 15% is the standard set in ISO 7730.

Thermal comfort is influenced by several aspects of a building. The four main factors that influence the energy balance are air temperature, relative humidity, air velocity and the mean radiant temperature (MRT). This MRT is a parameter based on the surface temperatures and the orientation of the comfort sensor (or person) compared to these surfaces. Exact formulas for the MRT calculation are presented in chapter 4 of this thesis. Important aspects are the dimensions, surface temperatures and placement of radiators/heating elements. ASHREA has several graphs showing the relation between the individual comfort factors. Figure 3.4 shows such graphs plotting the comfortable zone at different air temperatures and air velocity, relative humidity and average wall temperature (note: this is not the same as the MRT).

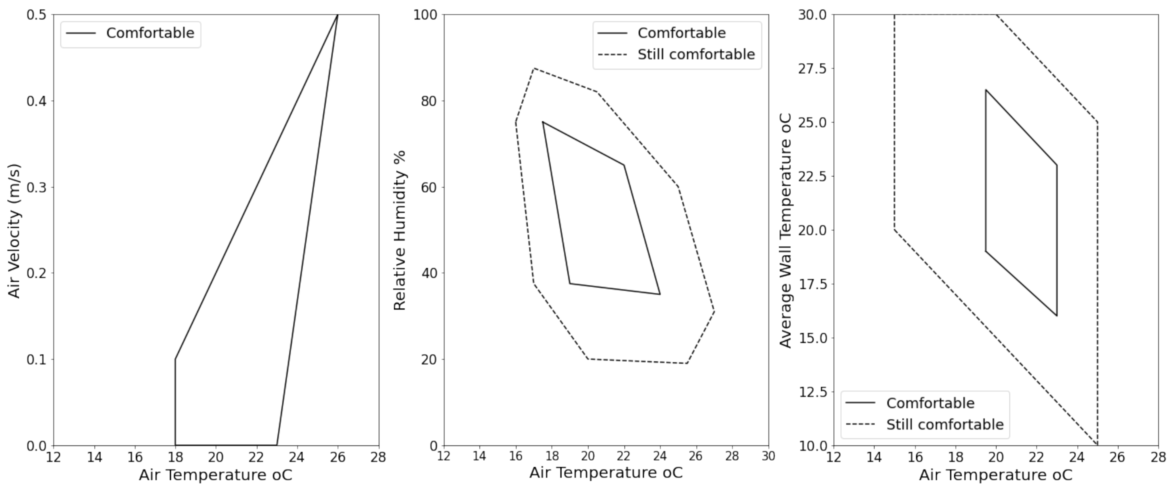


Figure 3.4: Air velocity, Relative humidity and MRT comfort levels

The predicted mean vote and percentage of people dissatisfied are based on the energy balance for the entire body. Yet it is also possible discomfort is caused by local phenomena (NEN-EN-ISO 7730, 2005). The main reasons for local discomforts are draughts, vertical air temperature differences between head and feet, floor temperature and radiant temperature asymmetry as shown in figure 3.5.

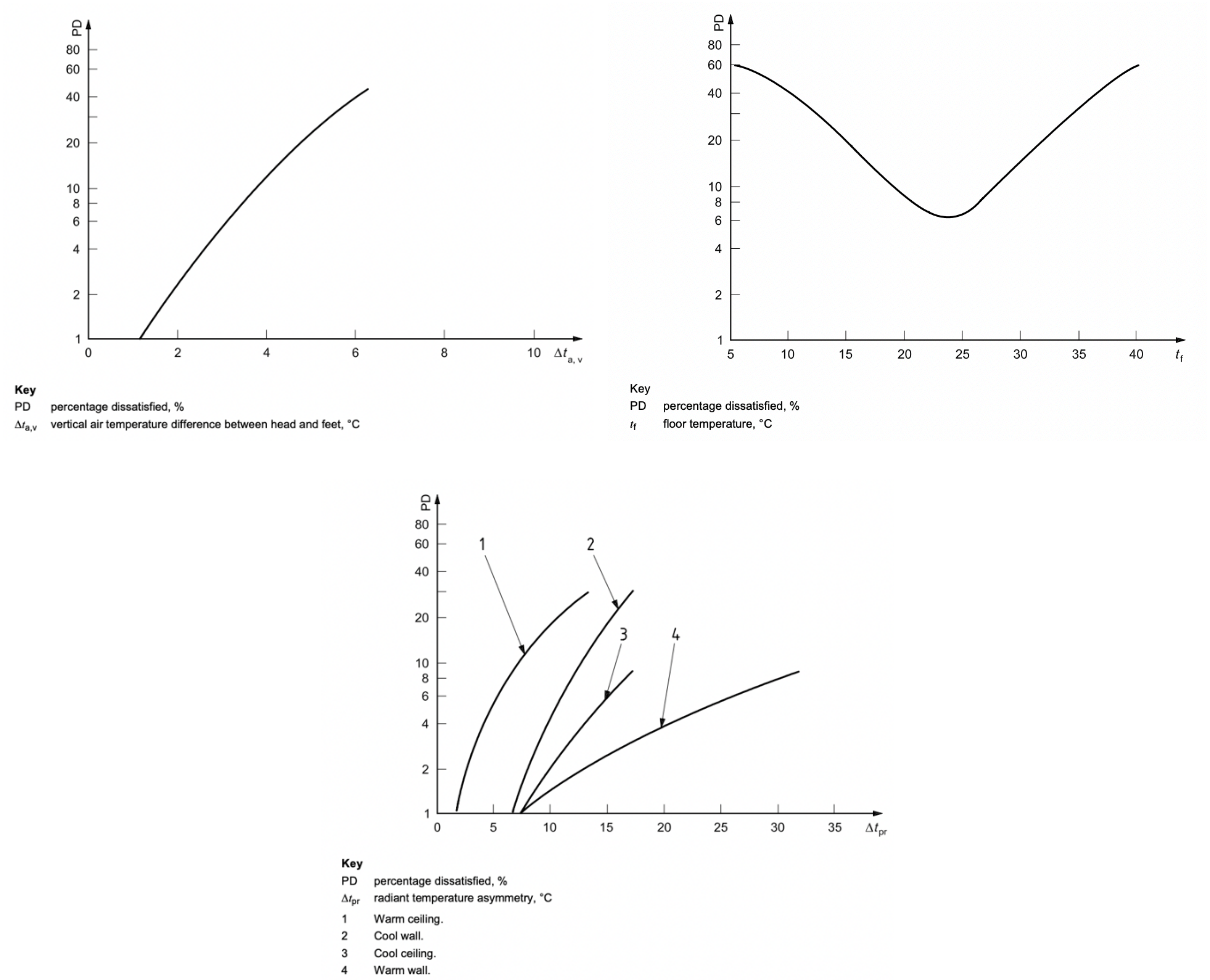


Figure 3.5: Local Discomfort Graphs (NEN-EN-ISO 7730, 2005)

Adaptive Thermal Comfort Model

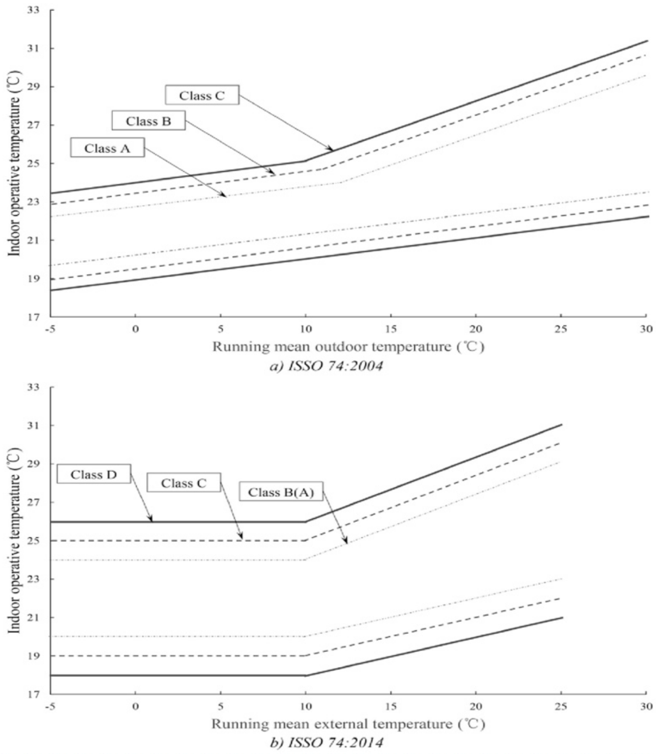
A second way of assessing thermal comfort in buildings is via the Adaptive Thermal Comfort Model. In this model people's tendency to adapt to changing environmental factors is the central point (Nicol & Humphreys, 2002). People have different options to interact with the naturally ventilated and free running building they are in. These interactions may range from for example opening a window to changing clothes. An important sidenote is that changing the thermostat is not included since this will create a non-free-running building (Hoof, Mezej, & Hensen, 2010).

Having people in charge of their comfort levels adds a layer of psychological reasoning to this model. People will feel more in control of their building. The more people are in control of their environment, the more 'forgiveness' there is for non-ideal conditions (Leaman & Bordass, 1997). This would suggest a higher level of control comes with a higher level of comfort. Because of this control, there is a larger variability of what is considered a comfortable temperature (Nicol & Humphreys, 2002).

This level of control leads to a second point: expectation. Several studies (Fountain, Brager, & de Dear, 1996) (Brager & de Dear, 1998) have tried to evaluate the relation between expectations and thermal comfort, but have not yet been able to provide strong evidence (Luo, Wang, Brager, Cao, & Zhu, 2018). It is important however that the control mechanisms are usable and effective in a timely manner, otherwise they will work counterproductive (Nicol & Humphreys, 2002).

Furthermore, outdoor climate does play a big role in how people perceive their indoor climate. In contradiction with the PMV theory, people in warmer climates will tolerate higher indoor temperatures (Hoof, Mezej, & Hensen, 2010). On the other hand, if these people are used to air-conditioned buildings, this effect is reversed and they will prefer cooler buildings. This effect becomes increasingly clear in studies which link migration to indoor climate comfort (Luo, Wang, Brager, Cao, & Zhu, 2018).

Also for the Adaptive model several graphs with comfort zones have been derived. Figure 3.6 shows the graphs provided in the ISSO 74 standard. In these figures, the indoor operative temperature is linked to the running outdoor mean temperature. This running mean outdoor temperature is a weighted mean and is used since a day to day fluctuation in temperature might occur but this does not affect 'climate'. The indoor operative temperature is derived from the air temperature, mean radiant temperature and the air velocity via the equations in appendix D: Operative Temperature. In the graphs, an upper and lower boundary for acceptance classes is provided. Buildings can then be ranked into their subsequent class. It can also be seen that the building class limits have changed in ISSO publication 74 2004 (figure 3.6a) and its successor in 2014 (figure 3.6b) and there is a more accurate link to the PMV and PPD in the newest version.



Document version	Class	Description	PPD	PMV	Acceptance
2004	Class A	Extra high-quality buildings. This class is appropriate for buildings with relatively sensitive users or building with high requirements as to comfort.	–	–	Min 90%
	Class B	Standard buildings. This class represents a neutral situation for standard offices.	–	–	Min 80%
	Class C	Buildings with an acceptable indoor climate. This class is appropriate for existing buildings or for temporary buildings.	–	–	Min 65%
2014	Class A	"High level of expectation. Select this category as a reference when designing spaces for people with limited load capacity (for instance, sensitive people or persons who are diseased) or when there is a higher demand for comfort".	Max 5%	–	–
	Class B	"Normal level of expectation. Select this category as a reference when designing or measuring new buildings or in the case of substantial renovations".	Max 10%	−0.5 to +0.5	–
	Class C	"Moderate level of expectation. Select this category as a reference in the case of limited renovations or when measuring older existing buildings".	Max 15%	−0.7 to +0.7	–
	Class D	"Limited level of expectation. Select this category as a reference in the case of temporary buildings or limited use (for instance, one to two hours of occupation per day)".	Max 25%	−1.0 to +1.0	–

Figure 3.6: ISO 7730 Adaptive comfort Graphs (Carlucci, Bai, de Dear, & Yang, 2018)

Comparison: PMV or Adaptive

The PMV model is a strictly numeric method and was originally designed for airconditioned offices. In naturally ventilated buildings, overestimations of 2.1K and underestimations of as much as 3.4K compared to the calculated comfortable temperature have been found (Brager & de Dear, 1998). This led to extensions of the PMV model in order to make it appropriate for naturally ventilated buildings too (Fanger & Toftum, 2002). This is only one of the extensions made over the years developing the

PMV model into a strong and up-to-date model, which is still widely used and prescribed by many standards for whole body comfort assessment (Hoof, Mezej, & Hensen, 2010).

Unlike ISO 7730, ASHREA does include an optional section based on the adaptive model. In this section, mean outdoor temperatures can be used to estimate the desired indoor temperature (Hoof, Mezej, & Hensen, 2010). The PMV-model is still a widely accepted tool for estimating thermal comfort levels inside buildings. With the new extensions added over time, this model is up-to-date and capable of incorporating people's control and expectations also in non-air-conditioned buildings.

Fanger's PMV-model is based on a full-body energy balance theory through the air temperature. The energy losses/gains are calculated based on the comfort factors which impact them. All these energy losses/gains are added in the energy balance leading to a PMV.

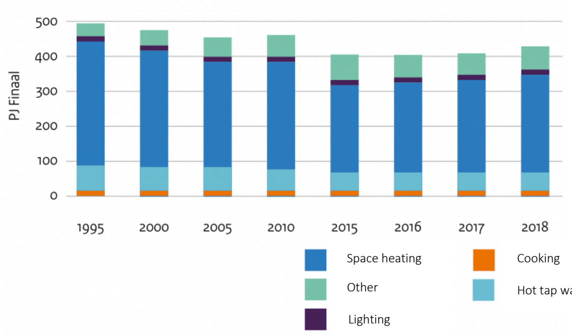
In the Adaptive model, the discomfort causes are combined in the operative temperature, which is plotted against the running mean outdoor temperature. This gives bandwidths between an upper and lower operative temperature in which a building should operate to be considered comfortable by a certain percentage of people.

In both models, local discomforts should be assessed via separate graphs which show a comfortable and uncomfortable combination of factors or. These local discomforts are a result of temperature differences between areas or surfaces. Local discomforts can also be calculated through numerically.

3.2 Energy

People use energy in buildings for several different purposes. A common energy use classification system is a division by function. The main functions are space heating/cooling, lighting, hot tap water, cooking and 'others'. Figure 3.7 (left) shows the distribution of energy used by these functions for several years. This research will focus on the energy used for space heating.

As mentioned in the introduction, buildings take up 40% of all consumed energy (Rousselot, 2016). In The Netherlands, residences were responsible for 22% of all energy consumed by buildings in 2017 (Rijksdienst voor Ondernemend Nederland, 2018). In figure 3.7 (right) it can be seen that the vast majority of this energy is still produced with natural gas. The Netherlands and the UK were the worst performing countries in the EU when it came to natural gas consumption in 2013 (European Commission, 2013).



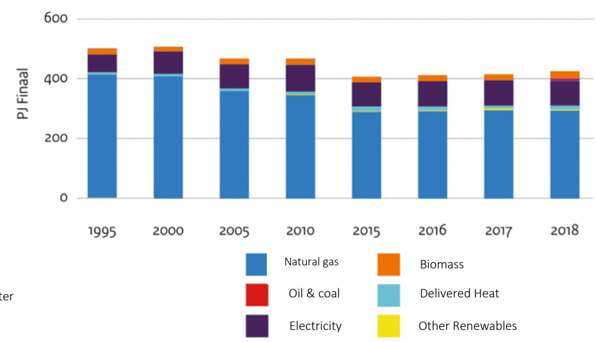


Figure 3.7: Different energy uses (left) and sources for dwellings in the Netherlands (Rijksdienst voor Ondernemend Nederland, 2018)

From figure 3.7 left and right, it can be derived that significant amounts of energy are still being consumed by household heating and that this is produced in a none sustainable way. In the period 2015-2018 both energy demand and gas consumption have actually increased after a long period of decrease.

Three ways to significantly reduce the energy use for heating in dwelling are (among others): Improve the insulative properties of the envelope; reduce heat losses in distribution systems; and improve the heating system (Chwieduk, 2003). The improvement of facades will be further explored in the section facades and renovation and the improvement of heating systems and reduction of heating losses will be elaborated in the section low temperature heating. The energy reducing factors mentioned, mainly focus on the building and its systems. Yet energy demand of residences also depends on occupant behavior (van den Brom, Meijer, & Visscher, 2018).

Energy transfer

Heating energy can flow via three ways: Conduction, convection or radiation. This is important because each flow will need to be managed carefully when trying to reduce the total heating energy demand of buildings. For all three flows a temperature difference must occur for flow to be possible. Other than that, they are very different.

Conduction is a property of a material and is usually denoted by the heat conduction coefficient lambda (W/(m*K)). This shows the heat flow through a material, at a temperature difference of 1K, with a surface of $1m^2$ and a thickness of 1m (van der Linden, Kuijpers-Van Gaalen, & Zeegers, 2018). The energy transfer takes place via the kinetic energy of molecules. Higher temperature molecules with higher kinetic energy 'collide' with low temperature low kinetic energy molecules. This causes the latter to gain some kinetic energy too continuing the process of 'collisions' until a uniform temperature and thus energy is achieved in a material (Williams, 2014). The energy transfer from conduction plays a big part in facades. An example of a material with high conductivity is a metal, whereas air has a low conductivity.

Convection on the other hand is when the medium these kinetically charged molecules are in acts as a driving force. Examples are air movement or water flow. Due to density differences or pressure differences at different temperatures, these fluids start to flow (van der Linden, Kuijpers-Van Gaalen, & Zeegers, 2018). This flow is determined by the convective heat coefficient ($W/(m^2*K)$) and the temperature difference. Important is the flow speed of the medium for determining this coefficient.

Radiation take place at the surface of a material. Due to the vibration of the molecules, infra-red light is transmitted, which is experienced as heat. The warmer the material is, the faster the molecules move, the more energy is given off. The amount of heat transferred via radiation is determined via the radiation coefficient (W/m^2) and the absolute temperature of a material (van der Linden, Kuijpers-Van Gaalen, & Zeegers, 2018). Figure 3.8 shows a summary of the three ways of heat transfer.

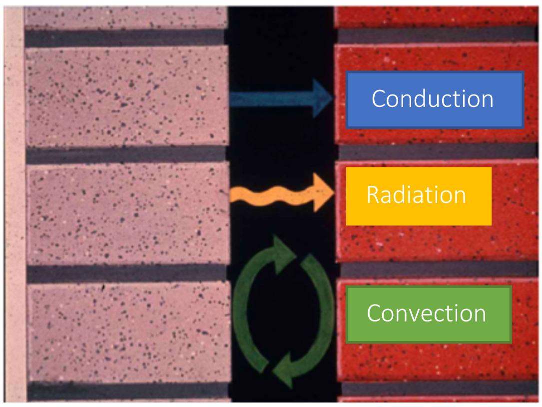


Figure 3.8: Energy flows through a cavity wall (van der Linden K. , 2017)

Heat Fluxes

Energy consumption of houses can be measured with increasing precision due to smart meters in homes. When designing a building (or a renovation) it is important to be able to quantify the expected energy demand in the new situation. This can be done via a thermal node network. In this network, like an electrical circuit, nodes are connected via resistors. The nodes represent parts of the building with equal temperatures and known thermal properties. The resistors represent the heat exchange via conduction, convection and radiation. Figure 3.9 shows what such a network for one room could look like.

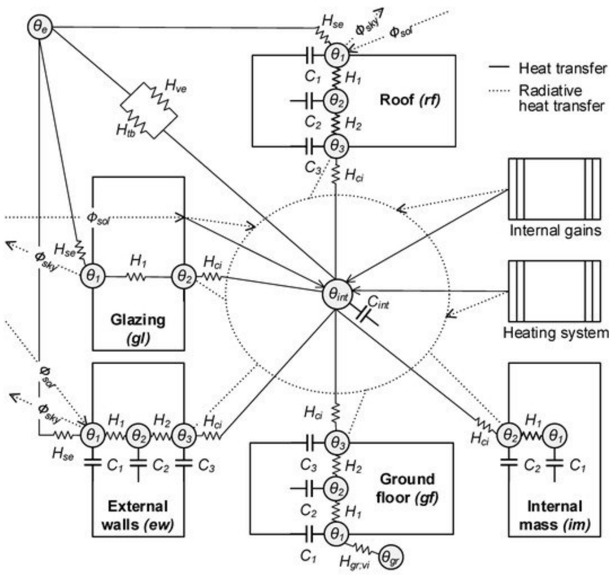


Figure 3.9: Example of a thermal network of a simplified room (Lundström, Akander, & Zambrano, 2019)

This network leads to a set of equations for each node with unknown temperature differences. Rewriting this in matrix form leads to (Itard & Rasooli, ME45110, 2020):

$$[M] * [T] = [B]$$

This equation can be solved via an inverse matrix calculation with for example MATLAB or Python. Note that the hourly data for outdoor temperatures is known via measured data. This solves the equation for the node temperatures. A condition is that the heating demand is known in that case. It can also be reversed, where the heating demand becomes unknown (and calculated) but the room temperature is known (or assumed).

A second important side note, is that this simplified model is only valid when no heat accumulation in nodes occurs (a steady state situation) and no heat sources are present in walls. When these phenomena do occur, an extension to the set of equations in required. A Fourier equation is added for a wall with only accumulation and a Poisson equation when only a heat source occurs (the steady state equations is called a Laplace equation).

When either accumulation or a heat source occurs (usually in a wall), the set of equations can be solved via either a finite difference method or a response factor theory. The finite difference method subdivides the wall in question in another set of nodes and resistors. The resistors represent the conduction in the wall. A strong point of this method is that it tells what is happening inside the wall. Solving it can be doing via Forward, Backward or Central Euler integration each with their own advantages but also disadvantages. An important factor when choosing a solver is the stability and computing time.

The response factor theory does not explain what is happening inside a wall, only what happens to the heat flux on either end of it. Often the assumption is made that the wall is homogenous and only 1 directional heat transfer occurs. By relating the heat flux and the surface temperature on each side of the wall to each other, it becomes possible to solve the equations through time for either the thermal properties of this wall or one of the heat fluxes.

The described thermal node network method is a useful tool to calculate annual energy demands for heating and cooling when the upper and lower boundary for the indoor temperature are set (e.g. by a thermostat). When models become more complex, the cannot be solved manually and computerized energy simulation software can be used. One example of such a software package is TRNSYS 17. This is a TRaNsient SYStem energy simulation package which can solve energy balances and is based on the response factor theory (Solar Energy Laboratory, 2009). The workings of TRNSYS 17 will be further explained in chapter 4 of this thesis.

3.3 Façades

A façade can be defined by the following characteristics (Boswell, 2013):

"It is the enclosing membrane in vertical, sloped, horizontal, or other geometric configurations separating exterior elements and forces from interior occupied areas. The exterior building enclosure begins either at grade or within the height of the building and terminates either on itself or at a roofing system."

Furthermore, Boswell (2013) defined some key functions every building enclosure has. More functions can be thought of, but they might differ per location. Examples are noise insulation, transparency for daylight or aesthetics. The four main functions will however be elaborated on here.

- Structural: withstand its own and applied loads

A façade can be part of the main load-bearing structure or not. In both cases however, it will have withstand certain loads. Firstly, as with any element of a construction, the façade will always have to be able to support its self-weight. Several other loads can however be thought of, even for non-loadbearing façade elements. Examples are wind loads and impact from collisions or explosions.

- Weathertightness: Separate outside weather from inside

One of the main characteristics of the building envelope is the separation between indoor and outdoor climates. This climate can include many factors. One of the main challenges in separating these climates is watertightness. A building envelope is usually formed by many individual elements. At the points where these elements meet, seams exist. Figure 3.10 shows six ways in which water can penetrate through these seams. Via primary and secondary layers of defense, these types of water infiltration can however be controlled.

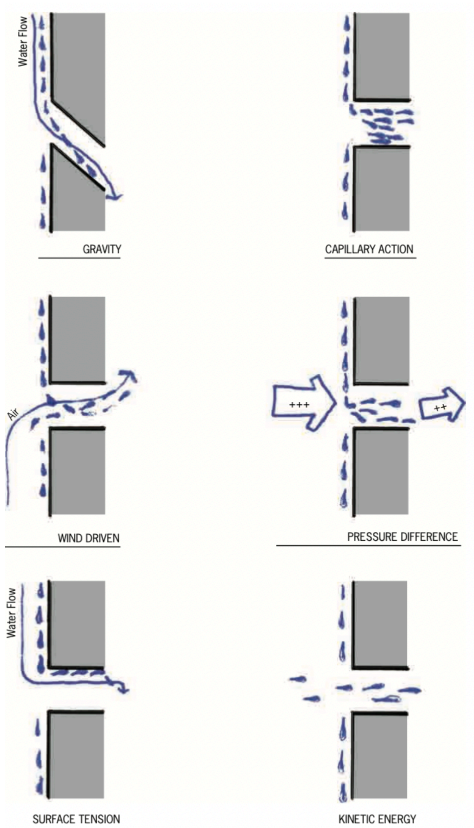


Figure 3.10: Different ways of water infiltration (Boswell, 2013)

Another key part of the separation of indoor and outdoor climates is the temperature difference. The thermal properties of a façade determine how well this membrane is capable of separating the temperatures by controlling energy flow through it. One of these thermal properties is the thermal resistance (Rc in m^2*K/W). This property is linked to the thickness of a material divided by its thermal conductivity. For multiple layers, the resistances of these layers can be simply added (van der Linden, Kuijpers-Van Gaalen, & Zeegers, 2018). For glass planes, the inverse of this Rc is usually used: the thermal transmission coefficient (U-Value in W/m^2K) (Boswell, 2013).

As mentioned, these thermal properties of a façade are key to reducing energy demand for space heating in buildings. By improving and managing the thermal properties of the facades, energy flow (and thus losses) can managed.

One of the façade properties worth mentioning separately is the Window-Wall ratio. This is the ratio of windows compared to the total façade surface. Although windows provide much needed transparency for daylight, they also tend to have poorer thermal insulative properties than opaque walls. The maximum allowed U-value of windows in the 'Bouwbesluit 2012' is 1.65 W/m^2K. With HR+++ glazing, 0.6 W/m^2K can be achieved. For an opaque façade the minimum thermal resistance is 4.7 m^2K/W for newly build dwellings (Bouwbesluit 2012, 2012). This corresponds to a U-value of 1/Rt = 0.22 W/m^2K. This means that windows cause greater energy losses than opaque sections. This is however also dependent on the orientation (since windows can also create solar gains) and use of the space (Yang, et al., 2014).

Additionally, a façade should not only be able to withstand the wind loads structurally, but also minimize the infiltration from it. People spend around 90% of the time inside a building (Mendes & Teixeira, 2014). Ventilation of these indoor environments is crucial for keeping these indoor climates free of pollutants. Uncontrolled ventilation however, also called infiltration, is a large contributor to energy losses (Liddament & Orme, 1998). The study by Liddament and Orme (1998) showed that up to 36% of energy losses in dwellings are due to poor ventilation or infiltration. In more recent years, this amount has been reduced by the increased airtightness of envelopes. Also the introduction of heat-recovery systems in Air Handling Units has contributed to energy savings, albeit economically costly (Dodoo, 2020).

- Energy efficiency: reduce energy demands (linked to weathertightness)

Energy efficiency is one of the main functions mentioned by Boswell (2013). It is however strongly linked to weathertightness. The importance of thermal insulation for energy demand reduction is elaborated in the previous section.

- Accommodate for movements: linked to the structural function

Due to variations in loads, buildings move. Although the absolute deflections might be small, they are always there. When designing a façade element, it is important to take these movements into consideration. A single piece of façade cladding, regardless the material, can be considered a more or less a ridged plate. Therefore, the deflections of members should be accounted for in the seams and connections. Two examples of how deflections and ridged plates interact is shown in figure 3.11.

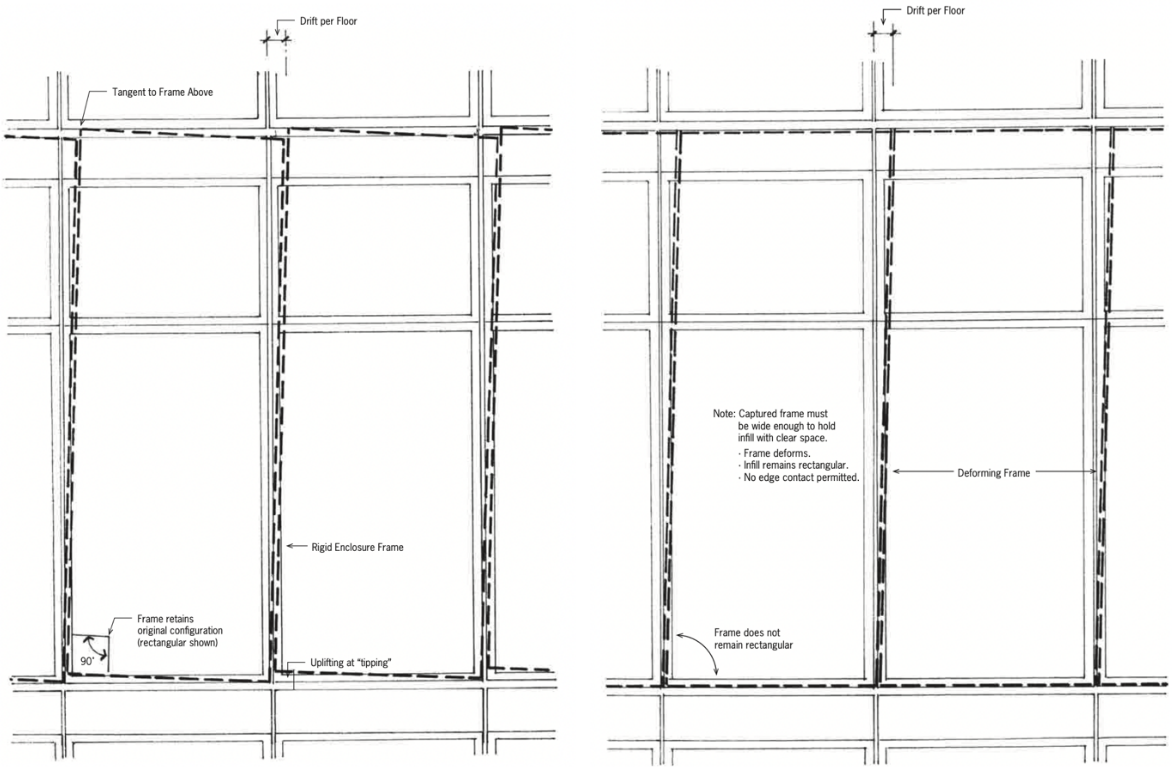


Figure 3.11: Deflections and ridged plates (Boswell, 2013)

Throughout history, different construction methods have been used for the building envelope with different insulation properties. An overview has been made by Konstantinou (2014). This overview of construction types in the 20th century can be found in Table 3.1. Important to note is that this overview is a generalization and exceptions might be found. Therefore, it is important to always investigate the dwellings in question. This overview can however help with estimating insulative properties for certain historic façade types.

Table 3.1: Construction types throughout the 20th century (Konstantinou, 2014)

	Construction type		Description	Structure	Windows	Roof	Period	Area	U-values (W/m²K)
Traditional	Timber-frame		Timber-frame structure with brick or wattle-and-daub filling	Loadbearing external walls	Single glazing Timber frames	Timber structure Clay roof tiles	<1920	North-west, centre-east, south Europe	2.0
	Masonry walls		Masonry of solid brick or stone, 250-400mm				<1950		2.0-1.8
	Cavity walls		Two leaves of masonry with intervening air cavity				1920-1950		1.5
Non-traditional			Two leaves with air cavity and/or insulation. Lightweight masonry units, concrete walls, lime stone. Insulation thickness varies from 30-50mm to today's standards	Load-bearing external walls or traverse walls	Double glazing timber or aluminium frames	Reinforced concrete or timber structure	1950-today	North-west, centre-east, Europe. Usually facing bricks	1.1- 0.5
				In-situ reinforced concrete frame		Reinforced concrete slab with insulation	1975-today	South Europe. Usually perforated bricks	0.6
	Lightweight concrete/ perforated bricks		Lightweight masonry units (concrete or hollow bricks), often cladded	Load-bearing traverse walls, in-situ or pre-fab	Single or double glazing timber or aluminium frames	Reinforced concrete or timber structure	1950-1975	North-west, centre-east, e.g. Germany, Denmark, France	1.4
			Single or double layer perforated brick masonry, plastered	In-situ reinforced concrete frame			1950-today	South Europe	1.0-0.8
	Panel building		Prefabricated concrete panels, sometimes with insulation 50mm	In-situ reinforced concrete frame or pre-fab load-bearing walls			1950-1975	North-west, centre-east Europe, e.g. Germany, Poland, Denmark	1.1-0.9
	Lightweight façade		Sandwich panels consisting of asbestos cardboard/ plasterboard and insulation (40-70mm). Different cladding materials possible	Load-bearing traverse walls, in-situ or pre-fab				North-west, Europe, e.g. the Netherlands, Denmark	0.8
	Timber-frame, brick cladding		Timber-frame with insulation infill, boxed in plasterboard, Brick veneer. Different cladding materials possible	Load-bearing timber frame wall		Timber structure, clay roof tiles	1950-today	North-west, centre-east Europe	0.8-0.5

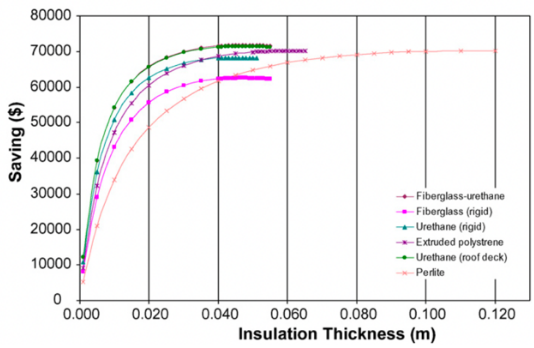
Facades and Energy

The thermal resistance of a façade can significantly reduce the energy consumption of the building it encloses. In the Dutch Building decree (Bouwbesluit), the minimum Rc value for facades is set at 4.7 m^2K/W. According to several developers, this value is however still too low. Experiments have been conducted with projects where the Rc of the façade has been increased to 6, 8 or even 10 m^2K/W (passive house standards). In these projects the aim was to create Zero-On-The-Meter (Nul op de Meter, NoM) buildings, which produce just as much energy from renewables on site as they use for domestic purposes, heating, hot water and cooling (Duurzaam Bouwloket, 2021). Also recently published 'Target

Values' ('Streefwaarden') suggest that an Rc of 6 m^2K/W is a better target value when designing façade insulation (Cornelisse, Kruithof, Valk, & Hartlief, 2021).

Projects proved that there is a tipping point after which the heating energy demand does not reduce as much anymore. Studies found that this point is reached at an Rc between 5 and 6 m^2K/W, which can be realized with 16cm glass fiber in the cavity wall giving the studied façade a total width of 40 cm (Roskam, 2015). This is also the conclusion of a study by Mahlia et al. (2007), which looked at the energy savings of 6 insulating materials at different thicknesses. In figure 3.12 left it can be seen that the savings stabilize at a certain thickness for all 6 materials. From this, an optimal thickness was derived and plotted for their thermal conductivity, which can be seen in figure 3.12 right.

An important sidenote is that glazing still is the weakest link in the thermal barrier of a house. Triple glazing systems have been introduced with U-Values as low as 0.6 W/m^2K. This requires specialized window frames but can significantly reduce energy losses through transparent parts (Roskam, 2015).



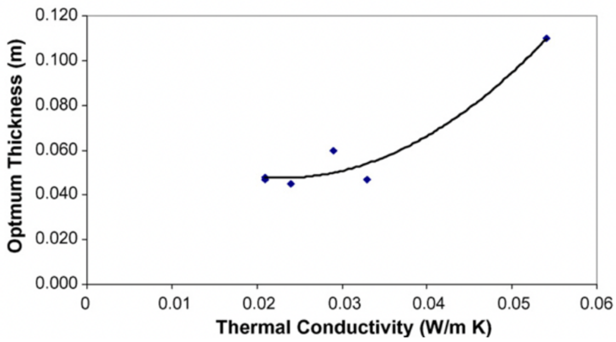


Figure 3.12:Relation between insulation thickness and savings (left) and thermal conductivity and optimum (Mahlia, Taufiq, Ismail, & Masjuki, 2007)

3.4 Low Temperature Heating

Buildings account for a large share of the total energy consumption. Especially in countries with colder climates like The Netherlands, space heating is a large contributor to energy use. Creating an envelope with a higher thermal resistance and better ventilation and infiltration management, can strongly reduce the energy required for space heating.

This energy, in the form of heat, is commonly supplied by warmwater. The energy this water releases to the radiator can be calculated with the following equation (Engineering Toolbox, 2021):

$$Q = \dot{m} * C_p * (T_h - T_c)$$

Where:

Q = Capacity (W)

$\dot{m}$ = Mass flow rate (kg/s)

C_p = Specific heat capacity of Water (J/kg °C)

T_h = inlet water (°C)

T_c = outlet water (°C)

From this equation it becomes clear the actual provided inlet temperature itself in the system is not governing for the capacity a radiator can provide but it is actually the difference between inlet and outlet and the mass flow rate. This means that LTH can provide the same capacity as HTH at the same temperature difference and mass flow rate. The capacity of the heat transfer from the radiator to the room happens through convection (to the air) and radiation (to other surfaces). This can be expressed via the following equations (Itard & Rasooli, ME45110, 2020):

$$Q_{conv} = h * A * (T_{rad} - T_{air})$$

Where:
Q_{Conv} = Capacity of the convective part (W)
h = convective heat coefficient (W/m^2 °C)
A = Surface area of the radiator (m^2)
T_{rad} = Surface temperature of the radiator (°C)
T_{Air} = Air temperature (°C)

$$Q_{rad} = \varepsilon * \sigma * A * T^4$$

Where:
Q_{rad} = Total radiation of radiator (W)
ε = Emissivity (-)
σ = Stefan Boltzmann constant ($5.67*10^{-8}$ W/m^2 °C)
A = Surface area of the radiator (m^2)
T = Surface temperature of the radiator (°C)

Here it can be seen that the heat transfer of the radiator to the room does in fact depend on the radiator temperature and area. Since this temperature will be lowered with LTH, the surface area will need to be increased in order to achieve a similar capacity to HTH. In order to enable LTH without radiator surfaces becoming exceedingly large, the total heat demand of a building should be reduced. As mentioned, this can be done by increasing the insulation and managing infiltration and ventilation.

So an important aspect to keep in consideration is the required peak-capacity of the system. The system should be capable of delivering this maximum value. An improved insulation of the envelope will ensure the buffer capacity of the building increases, which in turn leads to a lower peak in the energy demand (van Vliet, et al., 2016). When changing to low temperature heating, the capacity of a conventional radiator can drop by as much as 80%, which can never be fully compensated by the improved façade insulation (Dictus, Kruithof, & Cornelisse, 2018). Even insulation values currently used for newly build homes, will not suffice. This means the heat delivery will have to be adjusted. LTH can also affect the diameter of pipes and tubes in the system. A different water temperature requires different flowrates or transfer surface areas which will result in different optimum pipe diameters in the system (Olsen, Christiansen, Hofmeister, Svendsen, & Thorsen, 2014).

Lund et al. (2014) provided an overview of four generations (eras) of district heating production systems through time. This overview can be found in figure 3.13. In the same figure, they also presented the global line of the efficiency and required temperatures. For every new generation, it can be seen that the energy efficiency increases as the maximum needed temperature decreases. A second observation is the increase in possibilities for more sustainable energy production systems as the water temperature decreases. One of the advantages of the newly available heat sources, is that they can be produced both on and off the building site.

Where first and second generation energy production was mainly based on the burning of fossil fuels, third and fourth generation production has increasing possibilities for renewable energy production and use of industry waste streams. The source of the energy for the low temperature heating is not necessarily the essence of this thesis. The delivery of heat in buildings however, hits the very core of the main research question since this will affect both energy demand and thermal comfort.

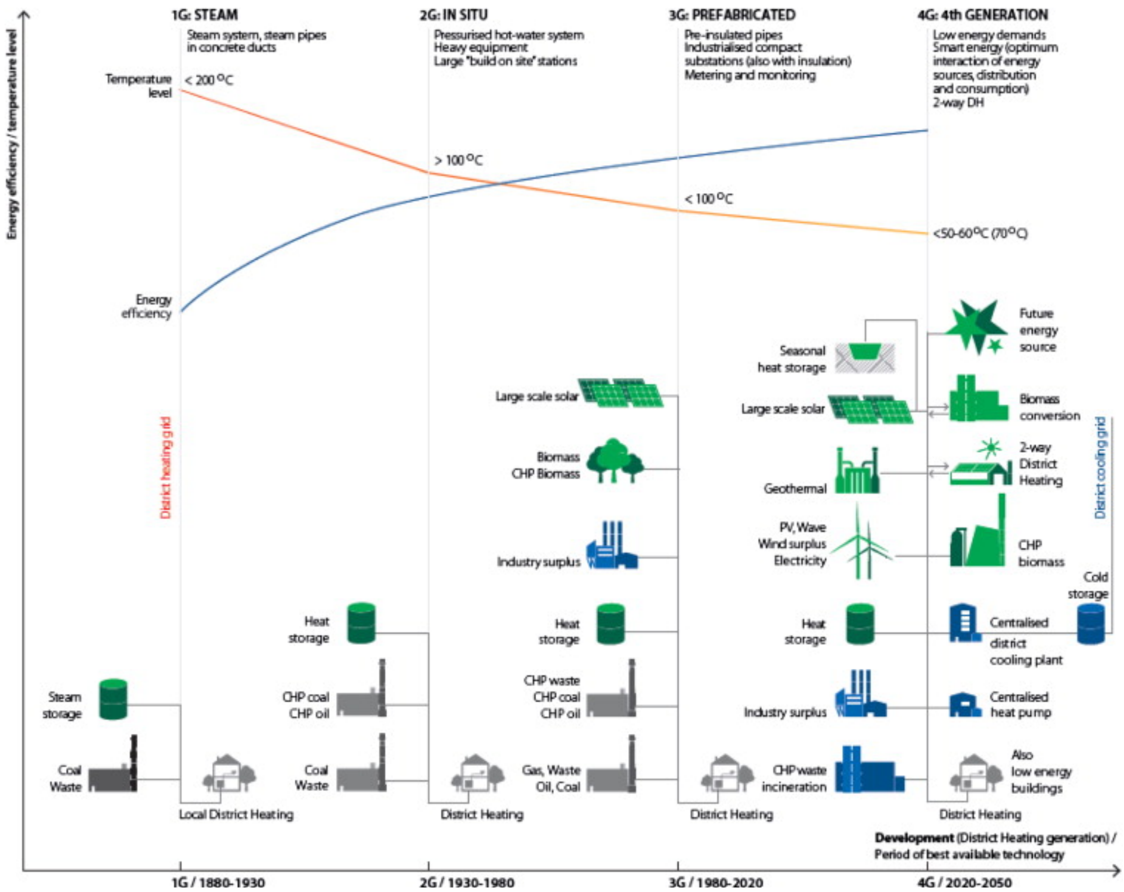


Figure 3.13: 4 generations of heating systems through time (Lund, et al., 2014)

When changing to LTH, a review of the capacity of the heating distribution and delivery system is required. This is important for both the energy demands and the indoor thermal comfort. In order to properly design the updated heat net and delivery systems, it is important to properly estimate current and future demand. Overdesigning the distribution system will create unnecessary losses, whereas underdesigning creates a system with insufficient capacity (van Vliet, et al., 2016).

Both van Vliet et al. (2016) and Dictus, Kruithof & Cornelisse (2018) provide a similar set of interventions. The first and most simple intervention is the addition of fans to current radiators adding an extra convective forcing to the heat exchange with the room. This only has a limited improvement on the capacity of the radiators. A second more invasive measure is to replace radiators by special low temperature radiators. These require more space and new distribution piping to meet the new capacity demands. The third and most complicated measure, is the replacement of radiators by underfloor heating. This requires completely new flooring and in some cases new underflooring. This does however have the biggest increase in capacity out of the three measures. A combination of radiators and underfloor heating is also possible, but was not assessed.

The report by Dictus, Kruithof & Cornelisse (2018) also provides suggestions for placement of heating elements when changing to 'average' or 'new building' insulation values in terraced houses. The layouts for the new heating delivery systems have been presented in Appendix E: LTH Delivery. In the appendix, the capacities of the systems are also mentioned and compared to the required heating capacity. From this case-study it becomes clear that underfloor heating provides a larger capacity than only LT-radiators. The study showed that the capacity of a standard radiator decreases by up to 73% when changing from high temperature heating to middle-low temperature heating (Dictus, Kruithof, & Cornelisse, 2018).

A report by energy engineering firms Ecofys and Greenvis (2016) includes a similar set of interventions that can be taken when changing to low temperature heating. This overview includes both measures for the heat distribution and the insulative properties. For the heat distribution, additional ventilators to the radiators, LT-radiators and floor heating were assessed. For the insulation values, the energy labels were taken as indication. The renovation proposals have been assessed for Costs in the CAPEX, the intrusiveness for the environment, the impact on the heating energy demand, the peak energy demand and the suitability for temperatures as low as 40 °C.

Table 3.2: Possible interventions and their ranking (van Vliet, et al., 2016)

Space heating		CAPEX	Impact environment	Total demand heat net	Peak Demand	Suitable for 40 oC
Delivery system	Radiator ventilators	+	+	n.a.	-	+/-
	LT-Radiators	+	+/-	n.a.	-	+
	Underfloor heating	+/-	-	n.a.	+	+
Insulation	Low; Label E	+	+	+/-	+	n.a.
	Middle; Label B	+/-	+/-	+/-	+	n.a.
	High; Label A+	-	+	+/-	+	n.a.

A study in Sweden, which included simulations and questionnaires, concluded that ventilated radiators provide a higher thermal comfort than under-floor heating systems (Hesaraki & Holmberg, 2013). This study's predicted and measured energy demands were in the range of 15% derivation with some over and underestimations.

However, from an energy perspective, under-floor heating systems might prove more beneficial than radiators. Especially in extremely low outdoor temperatures, under-floor heating delivery enables an even lower supply temperature than a mixed-system distribution (Hasan, Kurnitski, & Jakiranta, 2009). Figure 3.14 shows the required supply temperature for radiators, combined systems and all floor heating.

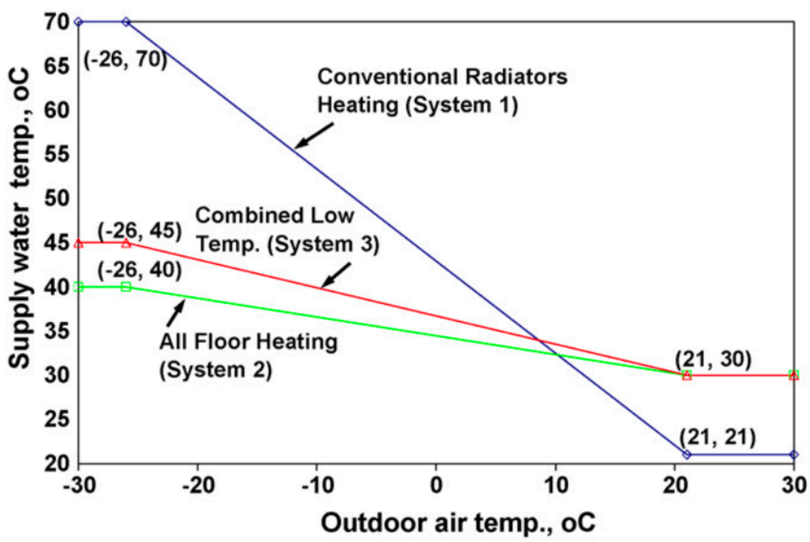


Figure 3.14: Supply temperatures for different systems (Hasan, Kurnitski, & Jakiranta, 2009)

3.5 Renovation

So far, it has become clear that the current building stock needs to be improved in terms of energy use in a circular way. One intervention meeting this need, is upgrading existing residential facades. There are many different words that can be used for the improvement or renewal of building-elements. These words all mean something slightly different yet no true consensus on the exact meaning of any of them was found. Figure 3.15 shows one example of how these different words can be ranked from a small to a large intervention. On this scale, the proposed intervention of façade upgrading would be qualified a 'refurbishment'.

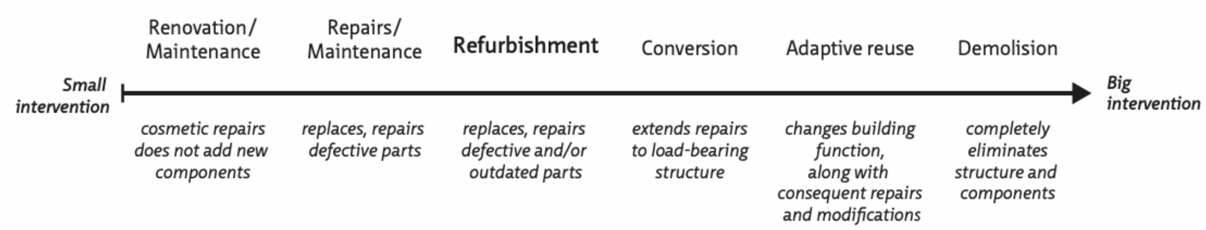


Figure 3.15: Different interventions of buildings (Giebeler, Krause, Fisch, Musso, & Lenz, 2009) (Konstantinou, 2014)

In contradiction to this scale proposed by Giebeler (2009) and adopted by Konstantinou (2014), the Cambridge English Dictionary provides the following definition for a renovation:

"the process of repairing and improving a building so that it is in good condition again, or the improvements that are carried out"

For refurbishment the Cambridge English Dictionary provides the following definition (Cambridge University Press, 2021):

"work such as painting, repairing, and cleaning that is done to make a building look new again"

These Cambridge Dictionary definitions would suggest a renovation is a heavier intervention than a refurbishment. This discussion could be considered a case of trivial semantics. However, it was deemed important to show the existence of different words for similar actions. In this thesis, the Cambridge English Dictionary definition is followed, meaning the proposed interventions will be called renovations.

Renovate or Rebuild

The largest share of the residential building stock in The Netherlands is a terraced house. In general, Dutch citizens are relatively satisfied with their housing situations (Beuningen, 2018). Especially important factors that determine the satisfaction levels of residents are social cohesion and a sufficient amount of rooms (Beuningen, 2018) (Ruimte voor Wonen, 2018). The neighborhoods and houses people live in, provide a large part of this social cohesion. Total demolish and replacement might reduce this cohesion followed by a reduction of the resident's satisfaction (Konstantinou, 2014). This finding would advocate for a renovation rather than demolish and replacement.

Also from an environmental perspective, a renovation would be preferred over demolish and rebuild. Studies of the Life-Cycle-Assessment (LCA) of a transformation (renovation) prove this is a far more environmentally friendly solution than a complete replacement (Itard & Klunder, Comparing environmental impacts of renovated housing stock with new construction, 2007). Furthermore, in terms of time, cost and intrusiveness for occupants renovation usually is the most sensible option (Power, 2008).

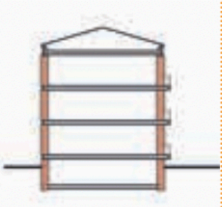
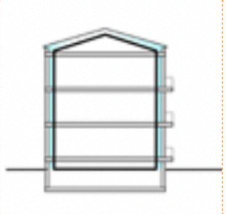
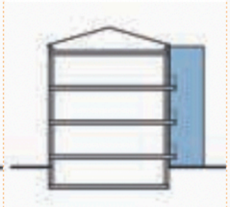
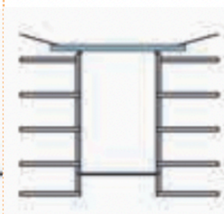
One important parameter that is often used when deciding how to move forward with a building is the expected life extension. This parameter is important for life cycle analyses and cost-benefit analyses.

Renovation principles

Konstantinou (2014) provided an overview of five different renovation strategies. This overview is presented in table 3.3. It shows different ways in which a building envelope can be improved. Within these strategies, sub-choices can be made. A first sub-choice is the component that will be renewed. Examples of components of the envelope are the roof, walls, windows or balconies.

A second sub-choice is the material used for the intervention. This is closely linked with the function of the element that will be changed. The material choice will highly impact the insulative properties of the new façade. It will also be of large influence of the outcome of the LCA of the proposed renovation. An ever increasing amount of natural materials is available with similar properties to their synthetic counterparts while emitting far less carbon and some actually store it (Arrigoni, et al., 2017).

Table 3.3: Different renovation strategies (Konstantinou, 2014)

	Replace	Add-in	Wrap-it	Add-on	Cover-it
					
Description	Old façade elements removed and replaced with new ones	Upgrade from the inside	'Wrapping' the building in a second layer	New structure is "added on" to the existing building	Cover parts or entire internal and external courtyards and atria
Intervention-variation	Replace the entire façade Replace parts	Internal insulation Cavity insulation Box window	External insulation, Cladding of the balconies Second skin façade	Small intervention, such as adding new balconies New building as an extension Additional floor	Cover parts or entire Heated or unheated space
Benefits	New components with better performance Eliminate the physical problems	Adequate for monu-mental status Increase the thermal resistance	Solve thermal bridges Increase the thermal resistance Different cladding possibilities Little disturbance	Out-dated façade no longer exterior New façade with performance Increase space Functional benefits	Create thermal buffer Enhance natural ventilation with stack effect Out-dated façade no longer exterior Additional space
Limitations	Great impact on users Higher costs	Critical connection thermal bridging need attention Big disturbance for users	Not applicable to mo-numental buildings Possible space limi-tation	Needs to be com-bined with other strategies for facades non-adjacent to new structure Structural limitation	Not applicable to all cases Depending on layout and function of the building Overheating risk

Renovation Regulations

Minimum values of several aspects of buildings are regulated by law. Regulations regarding the minimum values of insulative properties are stated in the 'Bouwbesluit' Article 5.6. The minimum required insulative values have recently been upgraded for both existing and new-build dwellings (Bouwbesluit 2012, 2012) to match the NTA 8800 BENG standard (NTA 8800+A1, 2020). The new minimum values required when renovating existing buildings built from 1965 onwards can be seen in figure 3.16. Especially for renovation projects, this is a significant raise in minimum insulative properties. This is important since a vast majority of existing dwellings in the EU are expected still be standing in 2050 (European Commission , 2021). By then they should all have gone through the energy transition in the same way as newly build dwellings.

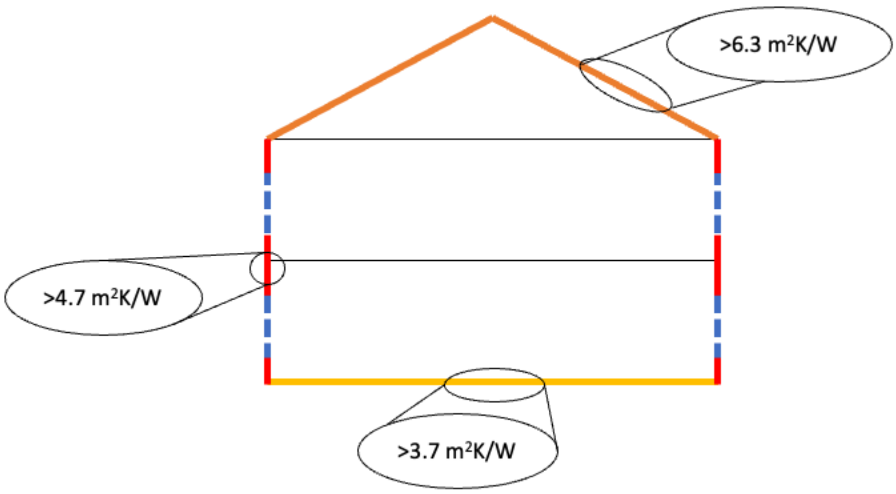


Figure 3.16: Insulative values of different building components according to Bouwbesluit regulations

When using values from regulations and standards, it should always be assessed what the purpose of the norm is. One example is the value of the minimum achievable temperatures for 'living spaces' state in ISSO edition 51. This publication states design temperatures for heating in a 'living space' such as living rooms at 22 °C in residences at an ambient temperature of -10 °C (Kennisinstituut voor de Installatiesector, 2018). This value is used to calculate the heat losses of a dwelling through transmission, ventilation and infiltration and occupational additions. The sum of the losses is used to design the minimum required heating capacities in each room. The sum of all losses to zones outside of the dwelling should result in the total heat capacity of the heat generator. In the NTA 8800, indoor temperature 'setpoints' are determined at 20 °C which can even be reduced for 10 hours a day to 16 °C (NTA 8800+A1, 2020). The aim of this norm is to determine the energy performance of a building. Then there are also the newly published 'Target Values'. These target values are not regulation but provide a target when designing energy efficient buildings. For comfort assessment, no standard temperature settings were found.

Renovation examples

A façade can be upgraded in many different ways. All interventions come with different results and implications. The intrusiveness for residents and required resources vary widely. Ranked from lowest impact to highest impact, a list of possible interventions is presented below.

1. Improving windows + frames

Allowing daylight to enter buildings is essential for the occupants' wellbeing. In order to realize daylight entrance, transparent sections need to be added to the envelope. In the heating season, windows are however a major contributor to energy losses through the façade. Over 40% of heat loss in buildings is caused by windows (Grynning, Gustavsen, Jelle, & Jelle, 2013).

On the other hand, windows can actually be a heating energy producer through solar gains. It is important to study this phenomenon well, since solar gains can also cause overheating in summer. When designing a façade renovation, most cases will require updated windows. Even if a building already has double glazing, it can still be beneficial to consider upgrading to triple glazing. Reducing the U-value of the windows from 1,2 to 0,8 W/m^2K can cause a heating and cooling energy demand reduction of 5-10%, also depending on the solar gains coefficient (Grynning, Gustavsen, Jelle, & Jelle, 2013). Figure 3.17 shows the ways energy transfer through windows occur.

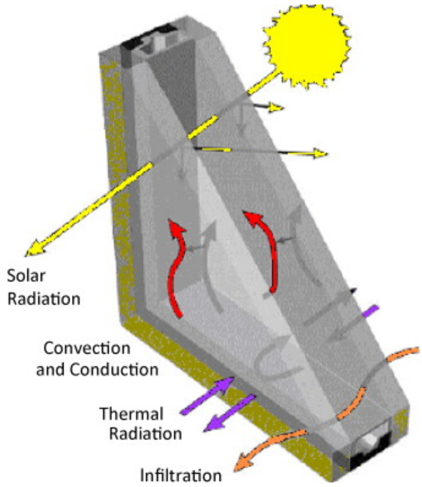


Figure 3.17: Heat transfer ways through glazing (Hassouneh, Alshboul, & Al-Salaymeh, 2012)

In figure 3.17 it can be seen that energy transfer not only takes place through the glass planes itself, but also via the window frame. One especially important source of heat loss is infiltration. Infiltration is the uncontrolled inlet/outlet of air through gaps in the façade. Infiltration can increase heating and cooling energy costs by as much as 30% (Hassouneh, Alshboul, & Al-Salaymeh, 2012). Changing the window frames might be a necessity for accommodating for the thicker high insulation windows. It should also be considered when trying to reduce the infiltration rates. For safety reasons, it is however important to create sufficient ventilation means at all times.

A second benefit of upgrading the windows and/or window frames is that thermal comfort will most likely improve. Not only will the ambient air temperature be able to be controlled more steadily, also the surface temperature of the windows will be improved resulting in less (local) discomfort. Also the air velocity will be able to be controlled more accurately, again creating greater comfort levels.

2. Insulating cavity wall

One of the ways a façade can be insulated is by filling an existing air-cavity with insulation material. This way of improving insulative values of a façade is relatively easy and cheap. Small holes are drilled in the outer leaf of the façade. Through these holes, a foam is injected into the existing cavity. Afterwards, the holes are filled again. This means no changes are made to the appearance, structure or inside finish of the façade. Figure 3.18 shows an illustration of this cavity insulation process.

There are however certain limitations. A first condition for cavity insulation to be feasible is the current state of the cavity. The cavity has to be clean and free of sharp edges. Secondly, there cannot already be forms of insulative material present. Especially in buildings after 1975 this usually already is the case. Additionally, the crawlspace under older buildings usually ventilates into the wall cavity. By filling this cavity with insulative material, another way of ventilation of the crawlspace has to be established (Milieu Centraal, 2021).


Figure 3.18: Illustration of cavity insulation being added (Ritsema, sd)

The most limiting factor of cavity insulation however is its width. A minimum of 4 cm is required and often not more than 6 cm is present. This limits the possible amount of insulative material that can be added. So with a cavity of 6cm, a realistic new Rc value of the façade is limited to 1.7 m^2K/W (Milieu Centraal, 2021) (Vereniging Eigen Huis, 2021). Compared to a non-insulated cavity façade, with a typical Rc of 0.4 m^2K/W, this is an improvement but whether it is enough to switch to low temperature heating should be investigated.

3. Add in (interior)

Another possibility is to place extra insulation on the interior side of the façade. This form of renovation comes with a set of advantages, but also with some risks. One of the advantages is that by placing the added layers on the inside, the external façade remains untouched. This is important if the façade is deemed to be of 'Architectural Value' (for example in the form of 'Beschermd Stadsgezicht') by a municipality. In case a building is classified to be 'Beschermd Stadsgezicht', it is not allowed to change the characteristics and appearance of this building (Gemeente Rotterdam, sd). This makes a wrap-it renovation procedure all the more complicated when it comes to permits and execution. A second advantage of an Add-in principle occurs when space around the building is limited. An example of how an extra insulation can be added on the inside is presented in figure 3.20. The added insulative value is in theory only limited by the available inside space.

Adding insulation on the inside of a dwelling also comes with risks. The main risk is the buildup of moisture creating mold and rot in the building. Moisture can form from condensation of warm, humid air from inside, creating condensation on the cold outer leaf. This principle is displayed in figure 3.20 right and middle. In figure 3.19 middle and 3.20 right, this is solved by installing a water retardant layer on the most inside surface (green). Another section where condensation might occur is on the cold bridges, which can be formed by the existing structural parts (the floor and the beams). These parts cross the thermal barrier and will remain cold, possibly causing condensation. Careful analysis of these thermal bridges should be carried out and where necessary, extra insulation around the floor needs to be added (as can be seen in figure 3.20 right).

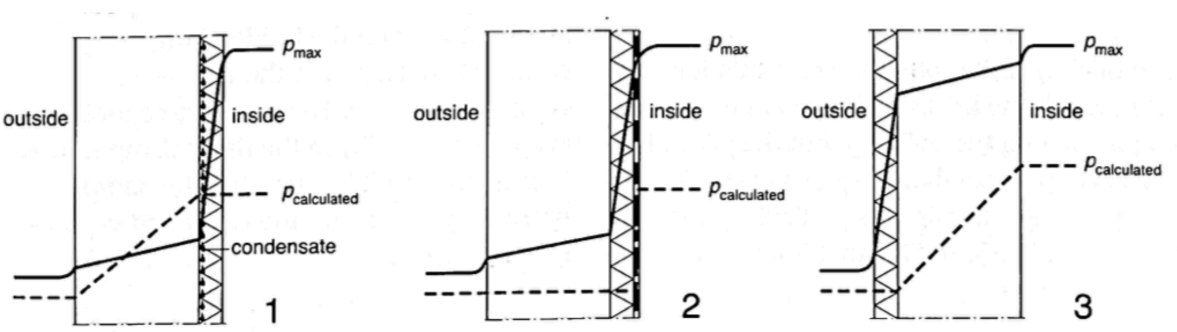


Figure 3.19: Moisture buildup when insulating inside vs. outside (van der Linden, Kuijpers-Van Gaalen, & Zeegers, 2018)

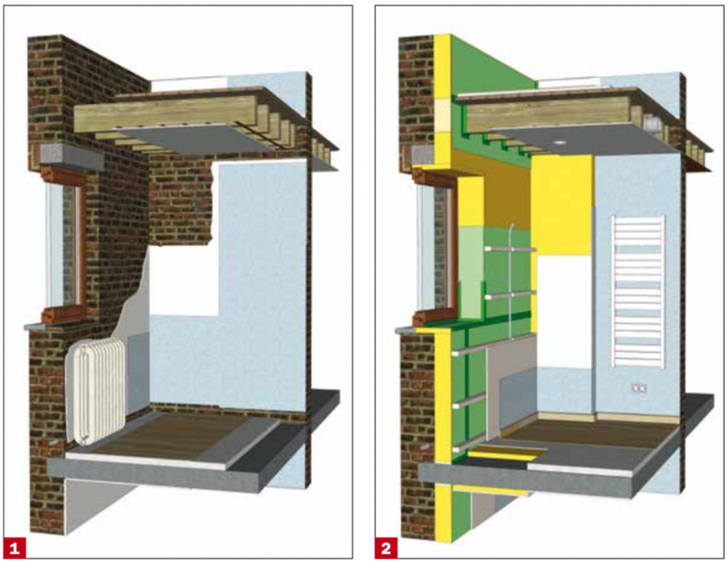


Figure 3.20: Existing dwelling section (left) and added insulation (right) (Dobbels, 2017)

An example of added layers on the inside of terraced residences is in Philipsdorp, Eindhoven. The characteristic appearance of the 711 dwellings, built in 1910 and now owned by housing association Woonbedrijf, was saved from being demolished. The renovation proposal was put together by residents. By adding layers inside their homes, the livable surface area became smaller, but they got to keep their houses. Renovations took around 8 weeks per dwelling and residents had to be moved to temporary houses in shifts. All this work resulted in energy labels being increased from D, E or even F to A or B (Ton, 2018).

4. Wrap it (exterior)

Creating a completely new thermal barrier around the existing building is one of the most thorough interventions in this list. It has many advantages among which are the ability to completely eliminate all existing thermal bridges, increase insulative values in the new situation and less intrusion for residents compared to a complete replacement of the façade (Milieu Centraal, 2021) (Konstantinou, 2014).

Covering the façade is not always possible however. In some situations there simply is no space around the building to add extra layers or restrictions could come from the previously mentioned 'Architectural Value' of the current façade. Figure 3.21 a before and after situation where the façade has been wrapped in a new layer and how this can change the appearance.

Figure 3.21: Added façade layers to improve the insulation (Milieu Centraal, 2021)

The three main renovation principles assumed suitable for this study are displayed schematically in figure 3.22. A combination of any of the interventions is also possible.

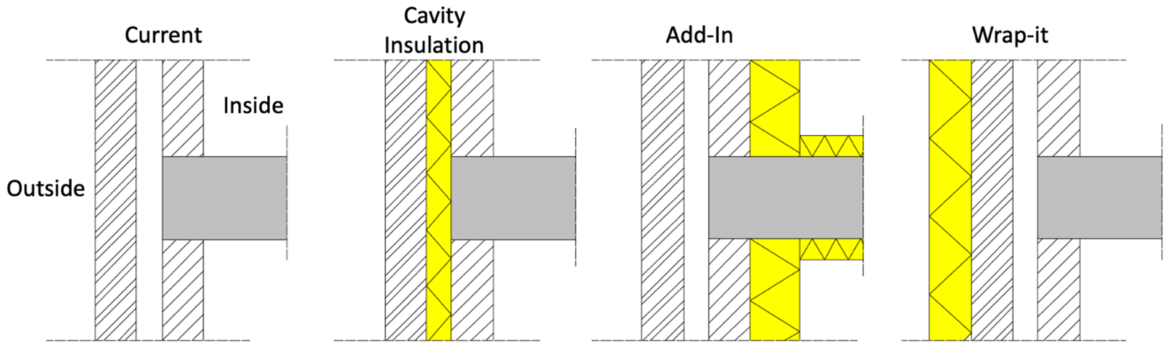


Figure 3.22: three main renovation principles

4. TRNSYS Model Verification

In this chapter the model used for the assessment of renovation interventions will be set up, tested and applied. After setting up the model, it is vital to verify its functioning. This verification is done through a comparison of measured data taken from the residence which the model should resemble, and the model outputs. After the model has proven to function sufficiently accurately, the renovation interventions can be applied and assessed.

The modelling will be done in TRNSYS (TRaNsient SYStem simulation tool) (Solar Energy Laboratory, 2009). This is a visual programming tool based on components, which are called Types. The in- and outputs of these pre-defined Types can be linked to each other creating a network resembling an actual system. The simulation is then run for a user defined period of time with adjustable intervals. The program was originally designed for solar network simulations but is now expanded to execute a much wider variety of simulations.

One of the most important Types in this thesis will be the Type56 Multi-Zone building component. This component can be used to create a thermal network of a house consisting of multiple thermal zones. For this multi-zone building, a large variety of outputs can be generated such as room and surface temperatures, energy demands or comfort levels.

Since the model will replicate an existing dwelling, it is important to start by making an inventory of the building's properties at the time of measurement. Unknown parameters will be estimated based on norms or common practice standards. When all parameters are in the inventory, the modelling can start. This will follow a predetermined set of steps.

Firstly, the geometry of the building is entered into the TRNSYS3D plugin for SketchUp 2014. This geometry is divided into zones (Thermal Zones of the model, usually rooms). Each surface of a zone is coupled to either the outdoors, the ground or another zone. These geometries and links are then transferred into TRNBuild. This program allows the assignment of building properties to the geometrical planes from TRNSYS3D. These building properties include the materials and thicknesses of different walls, floors and roof. Other characteristics for the building that can be inputted are the heating/cooling regimes, ventilation and infiltration and internal gains.

TRNBuild is directly linked to the TRNSYS Simulation Studio. This program runs the simulation over the set period of time with set intervals. It also reads weather data files which outputs parameters that can be inputted to the building (e.g. ambient air temperature, relative humidity and radiation exposure). The outputs of the building can then be plotted or read in a .OUT file. The data for each time-step in this output file can be read and assessed by for example Python or MATLAB. Figure 4.1 shows the steps followed for the modelling. It is an iterative process where the modeled outcome is compared to the measured data. If difference are too big, adjustments need to be taken in the model to mitigate this.

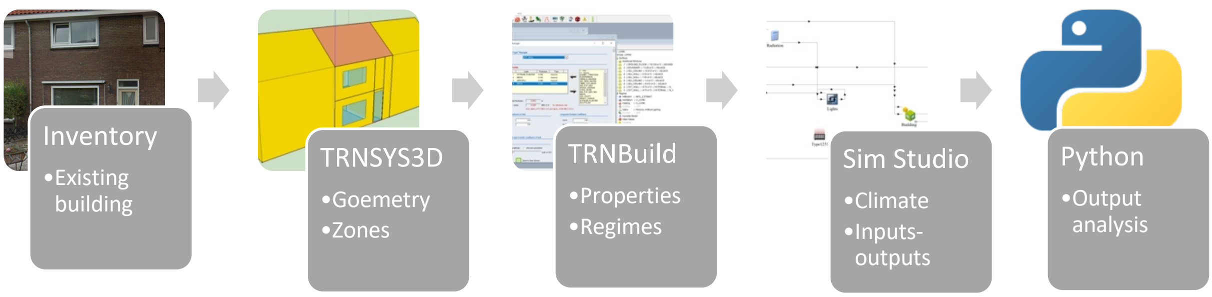


Figure 4.1: Steps to create a TRNSYS model

The first model is based on an existing residence located in a central town in the Netherlands. It is a typical Dutch terraced house as described in the introduction. Over several weeks in November and December, measurements regarding indoor air temperature, surface temperatures and energy consumption have been taken. Firstly, the steps to set up the model will be followed starting by making an inventory of the building.

4.1 Inventory

The assessed building is a typical terraced dwelling for this area. It was built in 1938 and its floor area is around 88 m^2. The dwelling has undergone several improvements. At the moment of writing it has a cavity insulation provided by Airofill, double glazing, improved window frames, ground floor insulation, roof insulation and a heat recovering ventilation system. Despite all this, the energy label is estimated at F (Huispedia, 2021), but this was not verified.

Figure 4.2: Aerial view of the residence (Google Earth, 2021) and its floorplan

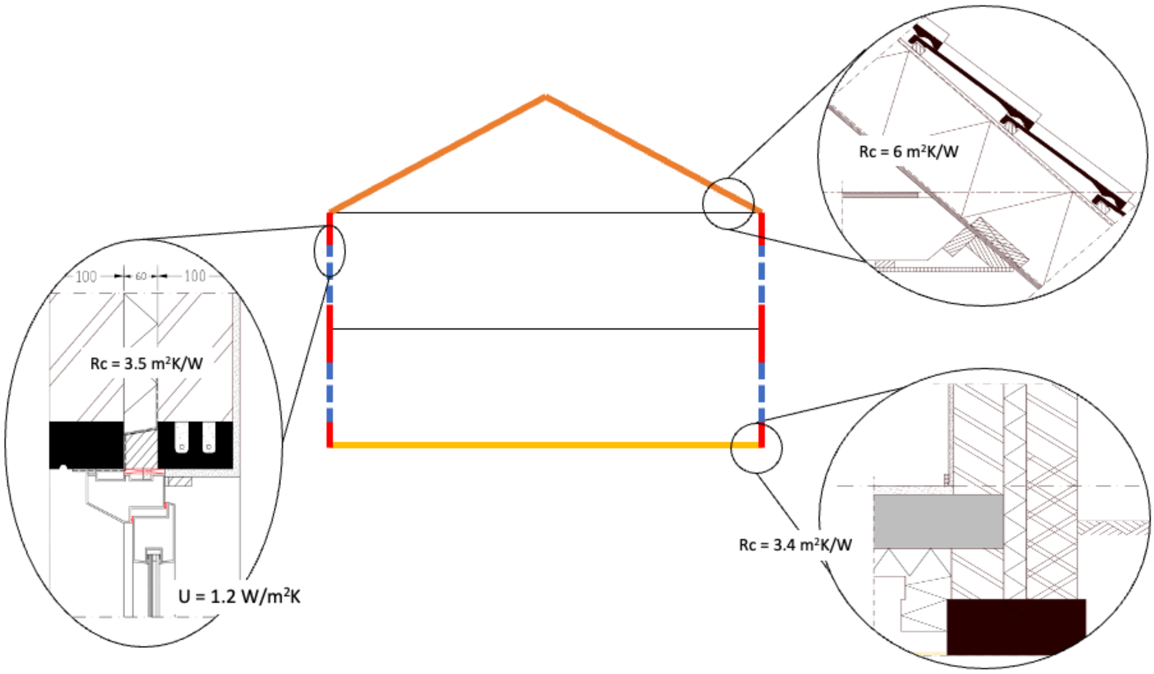


Figure 4.3: Properties of the dwelling

Figure 4.2 (top) shows an aerial view of the dwelling. Here it can be seen that the orientation is roughly North (back) South (front). The street name and house numbers have been removed for privacy reasons. The appearance of the dwelling is similar to the typical Dutch terraced house described in the introduction. Figure 4.2 (bottom) shows the floorplan of the dwelling with the radiator placement, their dimensions and types. The green dots represent the placement of the air temperature measurement sensors. The red dots represent the place of surface temperature measurements.

Figure 4.3 shows the properties of each wall type in the dwelling. The Rc values for the roof and ground floor are known. The Rc of the exterior walls has been estimated based on a 6mm cavity insulation (Haren, sd). Internal walls have however been estimated based on what can be expected from common practice. TRNBuild works with U-Values instead of Rc-Values. Therefore they have been converted. A more detailed table with all wall properties entered into TRNSYS can be found in Appendix F.

The house is occupied by three people. They state to have their thermostat set to 18 °C at all times except for mornings between 7:00 and 12:00 when they increase it to 20 °C. In the measured values, a deviation from this statement can be seen. This will be further elaborated in the results section. In the evenings they cook dinner in the kitchen resulting in an additional internal heat gain.

4.2 TRNSYS3D

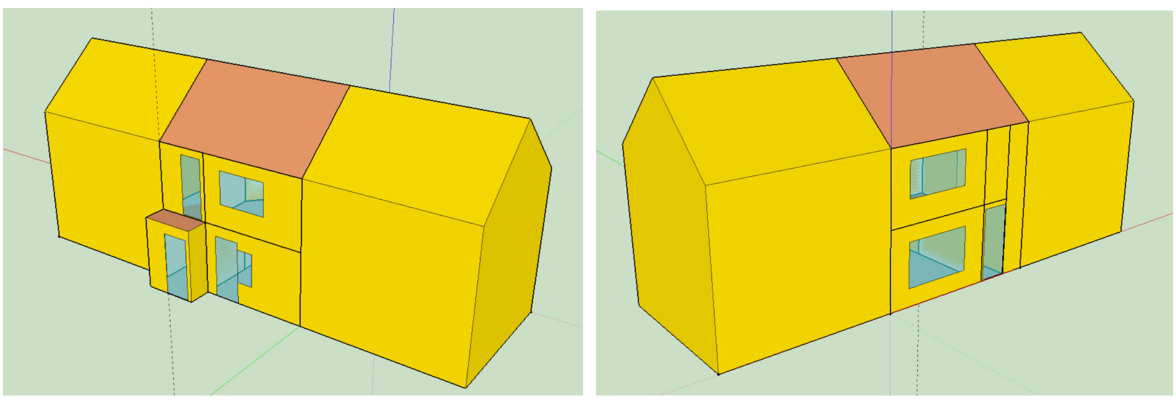


Figure 4.4: Geometry of the residence in TRNSYS3D

In figure 4.4, the dwelling is translated to geometry in TRNSYS3D. The neighboring dwellings on both sides are modelled as single volumes where the temperature is kept at a temperature of 18 ^{o}C. From 16:00 – 22:00 hours this is raised to 20 ^{o}C. The residence itself consists of 11 zones: the living room, kitchen, hallway, toilet, staircase, landing, bedroom 1 2 and 3, a bathroom and a loft.

4.3 TRNBuild

The wall properties are assigned to their matching geometries in TRNBuild. Other inputs are the heating and ventilation regimes. The heating capacity of the existing radiators have been estimated based on their size and types (Radson, 2020). An important note is that this capacity is only at High Temperature water inlets. The radiators itself, the heater and the pump are simulated in the Simulation Studio. These radiators have been added in their corresponding locations as gain in a 'Geolocation' in TRNBuild, more on this later. Heat gains from people are calculated in TRNBuild for the specified occupation rate and activity 'sitting, typing'. For the kitchen, once a day between 18:00 and 19:00 a heat gain from cooking has been specified based on a 0.7m^2 gas stove producing 1450 W/m^2 of heat (HVACMan, sd).

Ventilation takes place through an air handling unit, which preheats fresh incoming air through the outflowing air. The efficiency of this unit is not exactly known but is estimated at a value of 0.7. The unit for ventilation is air changes per hour (ACH) of a room. This is different for every room type and size. The amounts have been estimated based on the norm of 0.7 dm^3/s/m^2 floor area (Bouwbesluit 2012, 2012), the room type and use. For kitchens, Bouwbesluit 2012 states a minimum of 21 dm^3/s, for bathrooms 14 dm^3/s and 7 dm^3/s for toilets. This has been converted to Air Changes per Hour (ACH) per room. For infiltration, the values are based on NEN 2687. Table 4.1 shows an overview of $q_{v,10}$ values that can be assumed for different housing types. The current situation is estimated as Class 2 so $q_{v,10}$ = 0,6 dm^3/(s*m^2) for a building with a total volume smaller than 250 m^3. The table for ventilation calculations can be found in Appendix G: Model 1 Ventilation and Infiltration.

Table 4.1: infiltration rates for different types of houses (Kuindersma, 2013)

Class	Residence Volume (m^3)		Maximum $q_{v,10}$ (dm^3/s)	$q_{v,10}$ (dm^3/s*m^2)
	Larger than	Up until		
1. Basic	-	250	100	1
	250	500	150	1
	500	-	200	1
2. Good	-	250	50	0.6
	250	-	80	0.4
3. Excellent	-	250	15	0.15
	250	-	30	0.15

Table 4.2: Heating sources

Room	*Radiators*	*Capacity W*	*Capacity kJ/h*	*Gains*
Living	Type 21 190x400 Type 10 50x90	1892 411	6811 1480	People
Kitchen	Type 21 60x90	1214	4370.4	18:00-19:00 4566.24 kJ/h
Bathroom	Type 10 60x90	526	1893.6	-
Bedroom1	Type 11 190x50	1620	5832	22:00-07:00 People
Bedroom2	Type 11 190x40	1341	4822	22:00-07:00 People
Bedroom3	Type 10 60x90	493	1774.8	22:00-07:00 People

Table 4.3: Ventilation and Infiltration

Room	Scheme	ACH (1/h)	Heat Exchanger Efficiency	Infiltration (1/H)
Living	Continuous	0.97	0.7	0.83
Kitchen	0:00 – 18:00 1 18:00 – 19:00 5.5 19:00 – 24:00 1	5.1	0.7	0.83
Hall	Continuous	0.97	Inside air	0.83
Landing/ staircase	Continuous	0.9	Inside Air	-
Toilet	Continuous	22.11	Inside Air	-
Bathroom	Continuous	6	Inside Air	0.9
Bedrooms	Continuous	1.05	0.7	0.9
Loft	Continuous	1.87	Inside Air	1.61

Comfort Calculations

According to the Type56 manual, the PMV and PPD calculations in TRNSYS are based on NEN-EN ISO 7730. The formulas used in these calculations are displayed in appendix A. This calculation is mainly based on air temperature and mean radiant surface temperatures as room parameters. For the other inputs, a clothing factor of 1 clo and a metabolic rate of 1.2 met have been assumed. A full overview of the comfort settings in TRNBuild can be seen in figure 4.5.

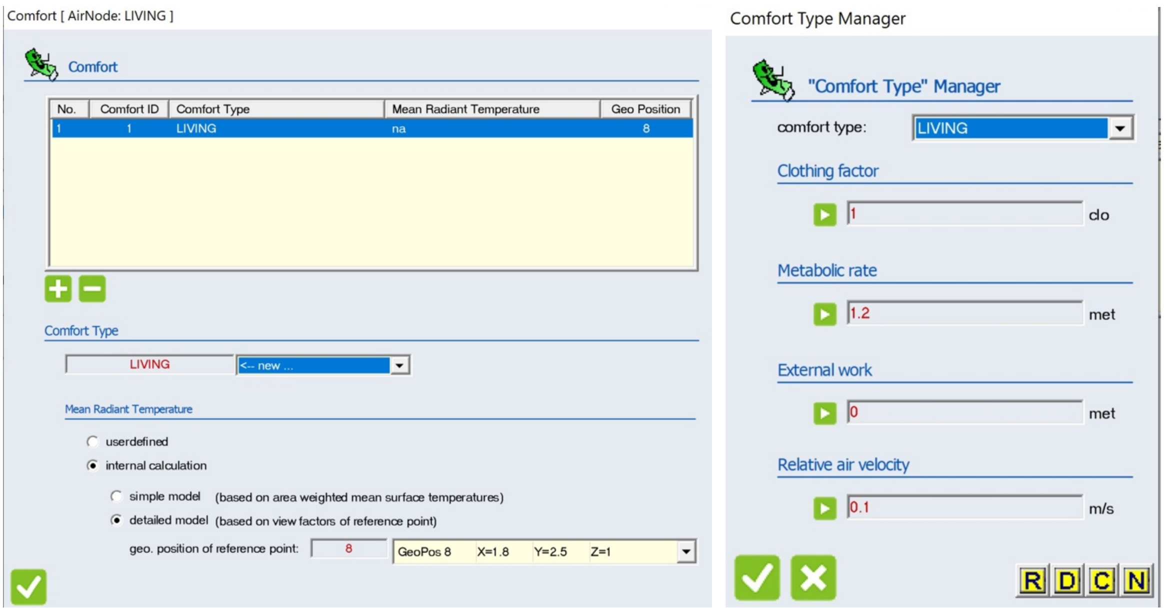


Figure 4.5: Comfort Settings

The comfort location is simulated as a spherical comfort sensor and is placed in the middle of the living room. The radiant wall temperatures are based on the Gebhardt view factors to and from this sphere, which is simulated as a bulb thermometer. Gebhardt factors are based on view factors but also include the emissivity of surfaces. This will be further explained in the next section. A sphere is sufficiently detailed to simulate a human in a seated position (Hiller, Aschaber, & Dillig, 2010). For a walking person, different geometries are to be taken into account. A seated person represented by a sphere is visualized in figure 4.6.

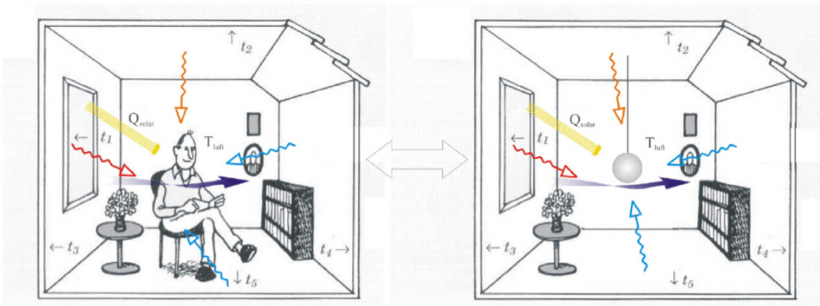


Figure 4.6: A bulb to simulate a seated person (Frenzel, Gröger, Hiller, Kessling, & Müllner, 2011)

4.4 Simulation Studio

In this stage the actual simulations will be executed. Weather data retrieved from the KNMI for the year 2020 is inputted to the Type56 Multi-Zone Building component. Some examples of weather data are the ambient air temperature, absolute humidity, relative humidity ratio and solar azimuth angles. A separate component, Type77, is added to estimate the ground temperature for the analyzed year. The heat recovering ventilation system is modelled by means of a Type667b 'air to air heat recovery device' component.

The central heating is modelled with a set of components. The principle of a central heating system can be seen in figure 4.7. The water heater is modelled as a Type60 'Detailed Fluid Storage Tank'. The water heater has an assumed capacity of 28 kW, which is typical for a terraced house (Feenstra, 2021). A splitter of Type647 connects the warm water heater to the individual radiators, which are modelled as Type1231. These radiators all receive a ratio of the total water flow based on the square meter area ratio they need to heat up. This results in heating capacities of the radiators closely matched to their design capacity. The Heat Transfer Rates (capacities in kJ/hr) of these radiator outputs are inputted into heat point sources in TRNBuild. This will be further elaborated in the verification step.

The loop is completed by a Type649 pipe merge connected to the water pump. The pump of Type654 with constant flowrate is the driving force of the water circulation. The controller behind the model is a Type1502 'Simple Thermostat' measuring the indoor air temperature in the living room. It compares the results to a daily preset temperature preference in a Type517 component. This results in a 1/0 signal switching a heating element in the tank on or off.

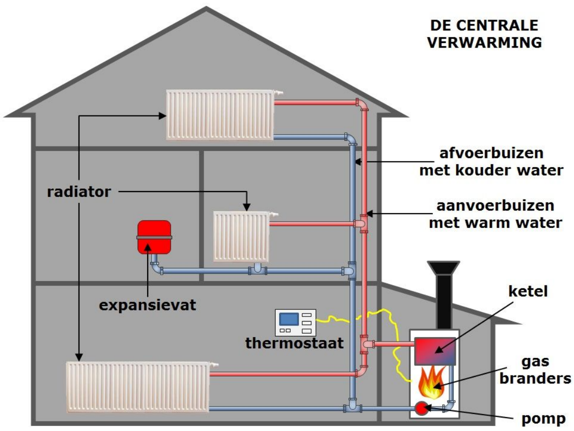


Figure 4.7: Central heating system (4NiX, 2021)

The simulation is run from 0 to 8760 hours resembling one year. The time steps are set at 0.01 hour (so 36 seconds). This level of detail was determined iteratively. Larger time steps result in long periods between 'decision making' of the model. This gives an unrealistic temperature pattern jumping between extreme values. For further computational analyses it is convenient to keep timesteps in multiples of 10. The total model on the Simulation Studio canvas can be seen in figure 4.8.

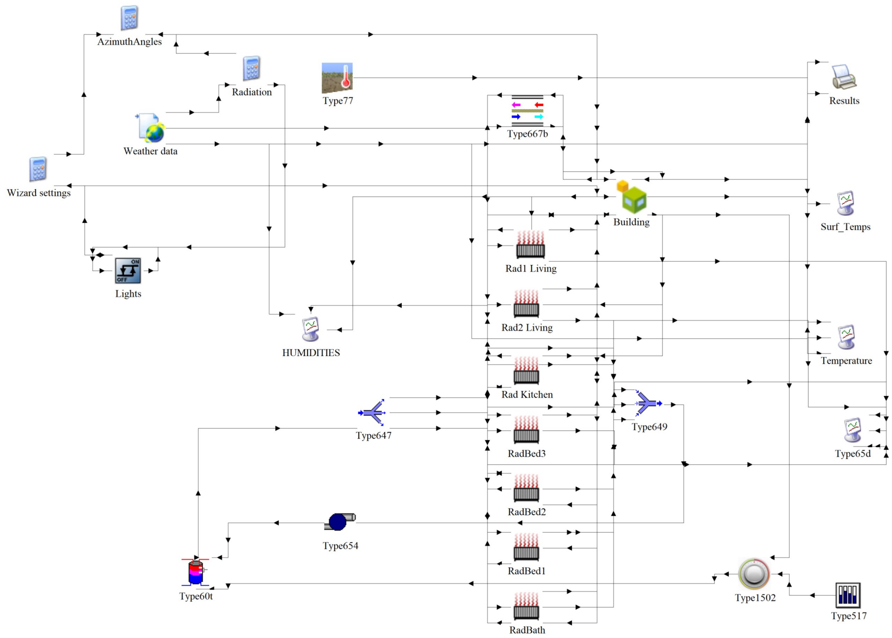


Figure 4.8: Simulation Studio model

4.5 MRT & PMV Verification

Now the TRNSYS simulation process is set up, an important step is to verify the modelled outcomes. Since the focus of this study is indoor thermal comfort, main parameters that need verifying are the factors used to calculate the PMV and the Operative Temperature such as surface and air temperatures outputted by TRNSYS. The information on the workings of the comfort models in TRNSYS is derived from the TRNSYS17 manual Volume 5: Multizone Building modeling with Type56 and TRNBuild (Solar Energy Laboratory, 2012). The main focus of the comfort study lies on the living room. This is a room where occupants spend a lot of their time. Also for computational reasons having only one zone as a detailed study is more suitable. The computation time increases 2-3 times when changing zones to a detailed study.

PMV TRNSYS vs ISO7730

Firstly, it was assessed how the PMV outcomes of TRNSYS compare to the NEN-EN ISO 7730 standard. This was done by comparing the PMV calculated by 4 different tools, including a self-made version, for the same main comfort parameters. The other calculation tools included the calcPMVPPD function in the comf R-package (Schweiker, Mueller, & Sarwar, 2021), an MS Excel tool developed by the Faculty of Mechanical Engineering at the University of Coimbra (Gameiro da Silva), an Online comfort tool developed by the Centre for the Built Environment at the University of Berkeley (Tartarini, Schiavon, Cheung, & Hoyt, 2020) and a Python function developed by the author of this thesis based on ISO7730.

The main environmental parameters impacting the PMV are Air Temperature, Mean Radiant Temperature, Relative Humidity and Air Velocity. For several PMV values calculated by TRNSYS, the corresponding parameters were found. These parameters were then used to calculated the PMV with the other 4 tools. The PMV results produced by the different tools are presented in Appendix H: PMV's by different calculators. From the charts in Appendix H it can be seen that with the exact same input parameters, the PMV calculated by TRNSYS is around 0.02 higher than the other four calculators. This difference is small but should not be there at all.

If all PMV points calculated by TRNSYS throughout 2020 are compared to what it should be according to the ISO7730 norm, the graph in figure 4.9 can be made. Here it can be seen that over the whole year, the PMV calculated by TRNSYS is higher than if it is calculated by the other tools. The differences vary between 0.036 and 0.026 overestimation of the PMV by TRNSYS with a mean difference of 0.028.

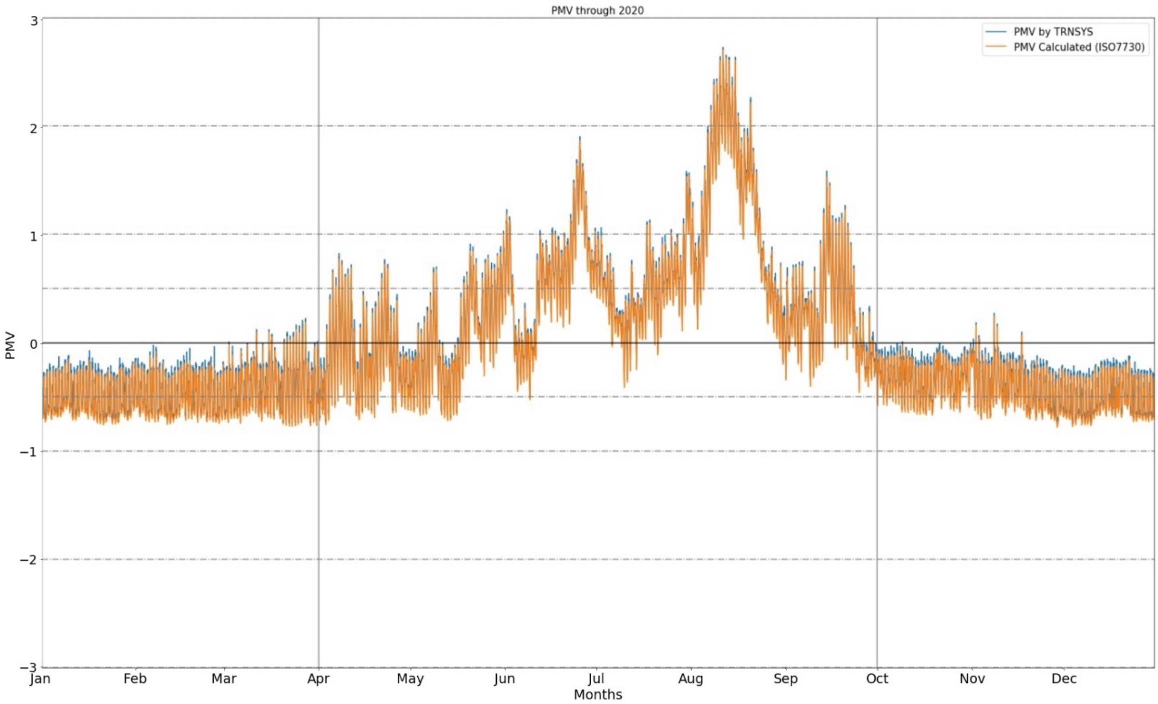


Figure 4.9: PMV calculated by TRNSYS and according to ISO7730

The reason for the PMV difference was investigated but not discovered. Factors like rounding-errors, unit conversion differences and the MRT measuring methods were examined but did not create a closer match between TRNSYS and the other calculation tools. Also, a difference due to solar radiation on the measurement sphere does not play a role since this is not taken into account in TRNSYS or other calculators. In view of time, the investigation had to the terminated. The self-made calculator presents a close match to the other calculation tools and will be used for further assessments of the PMV.

MRT Calculation in TRNSYS

A second point of concern was how TRNSYS deals with the Mean Radiant Temperature. When assessing thermal comfort, both via Fanger's PMV-model or the adaptive model, air temperature and (radiant) surface temperatures are important parameters.

In TRNBuild, several options for the Mean Radiant Temperature calculations are possible. It can either be user defined, calculated internally based on surface areas and temperatures in a simple model or calculated internally via view factors in a detailed model. For this thesis, the detailed model was deemed more suitable, especially for assessing the longwave radiation exchange within a zone. Combined with the settings for Comfort Levels, this should provide the most accurate results for comfort in a specific location. The basis of the detailed model is a bulb thermometer simulation. A grey bulb with a 0.07m diameter is placed at a Geolocation. The Type56: Multizone Building manual claims this bulb calculation is in accordance with ISO 7726 (Aschaber, Hiller, & Weber, 2009), but this norm states a normal bulb diameter of 0.15m with an emissivity of 0.95 instead of a diameter of 0.07m and emissivity of 0.82 as used by TRNSYS. This can be accounted for in the calculations of the convective coefficient.

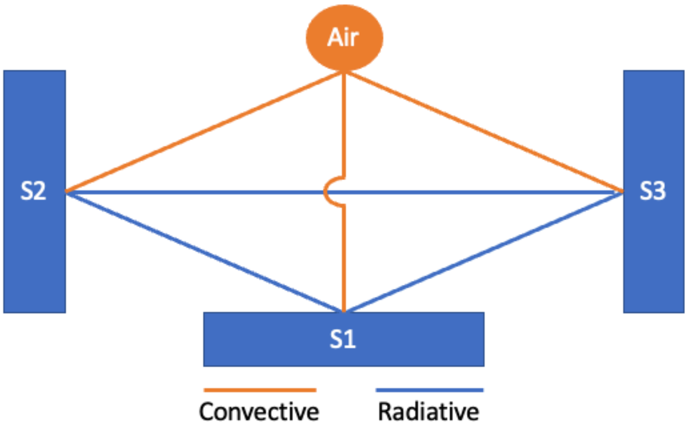


Figure 4.10: Energy fluxes in TRNSYS with detailed radiative settings

The heat fluxes between 3 surfaces and the air in a thermal zone in a detailed TRNSYS model can be seen in figure 4.10. In contrast to the standard model, radiation and convection are separated. This is important for a detailed assessment of radiation exchange within a room. The detailed model in TRNBuild is based on a set of 5 assumptions:

1. Net emission is a positive heat flux
2. Surfaces are assumed to be isothermal
3. Surfaces are non-transparent for longwave radiation (heat)
4. Emissivity and absorptivity do not depend on wavelength or direction (grey surfaces)
5. ρ is the hemispherical longwave reflectivity

In NEN-EN ISO 7726, one of the ways to determine the Mean Radiant temperature is via view factors (NEN-EN-ISO 7726, 2001). These view factors are used to assess the individual contribution of the planes to the MRT based on their orientation relative to a sphere. The view factors are collected in a matrix F from the person/sphere to surface *i*. The MRT calculation can be made with the following formula:

$$T_{MR} = (\sum_{i=0}^{n} T_i^4 * F_{p \rightarrow i})^{\frac{1}{4}}$$

The detailed radiation model in TRNBuild is however executed with Gebhardt factors. These factors are based on view factors and take all longwave radiation exchange between all surfaces into account via all paths. The advantage of Gebhardt factors over normal view factors, is the fact that Gebhardt factors also take emissivity into account. The Mean Radiant Temperature in the detailed model of TRNBuild is based on the following formula:

$$T_{MR} = (\sum_{i=0}^{n} T_i^4 * G_{s,i}^{LW})^{\frac{1}{4}}$$

Where:

T_i Temperature of surface i

$G_{S,I}$ The Gebhardt factor

The Gebhardt matrix can be formed using:

$$G_{ir} = (I - F\rho_{ir})^{-1} F \varepsilon_{ir}$$

Where:

G_{Ir} The Gebhardt factor matrix

I Identity matrix

F View Factor matrix

ρ_{ir} Hemispherical Longwave reflectivity

ε emissivity matrix

As a side note it should be mentioned that as standard the emissivity of all planes are assumed at 0.9 in TRNSYS. The hemispherical longwave reflectivity was not found in TRNSYS but is assumed to be 1- ε.

The matrix can be rewritten to calculate the heat flux vector as follows:

$$\dot{Q_{\imath r}} = G_{ir}^{*} T^{4}$$

With:

$$G_{ir}^{*} = \left(I - G_{ir}^{T}\right) A \varepsilon \sigma$$

Where:

G^T transposed matrix of G_{ir}

A the area matrix

σ Stefan-Boltzman constant

This matrix calculation of radiation exchange in an enclosed space with Gebhart factors is similar to other methods like the one developed by Hottel and Sarofin (Clark, Korybalski, & Arbor, 1974). The study by Clark et al (1974) also provides a more detailed explanation about the calculation of the Gebhardt factors.

For each thermal zone, TRNSYS builds a thermal network based on nodes. Most nodes are placed automatically in key positions, based on the pre-defined geometry in TRNSYS3D and the properties in TRNBuild. These nodes are linked by their energy transfers via either conduction, convection or radiation. This results in a thermal node network as described in section 3.2 of this Thesis. Some key nodes are however not placed automatically. One prime example being the internal heat sources. In the standard TRNBuild heating type, the locations of these radiators are neglected completely and the radiative part is distributed area-weighted over the opaque surfaces. However, in order to accurately model thermal comfort, the location of radiators should be taken into account

One way TRNSYS can deal with this placement of heat sources is to make points in the center of the radiator in the form of a Geolocation in TRNBuild. The radiators have a 20% radiative and 80% convective capacity, which is a common distribution for ordinary radiators (Feenstra, 2020). These points are defined as gains, with the radiator outputs from the Simulation Studio as input capacities. In the calculations of the Gebhardt factors, heat point sources and local comforts are taken into account in the form of a vertex (Aschaber, Hiller, & Weber, 2009). A representation of this can be seen in figure 4.11.

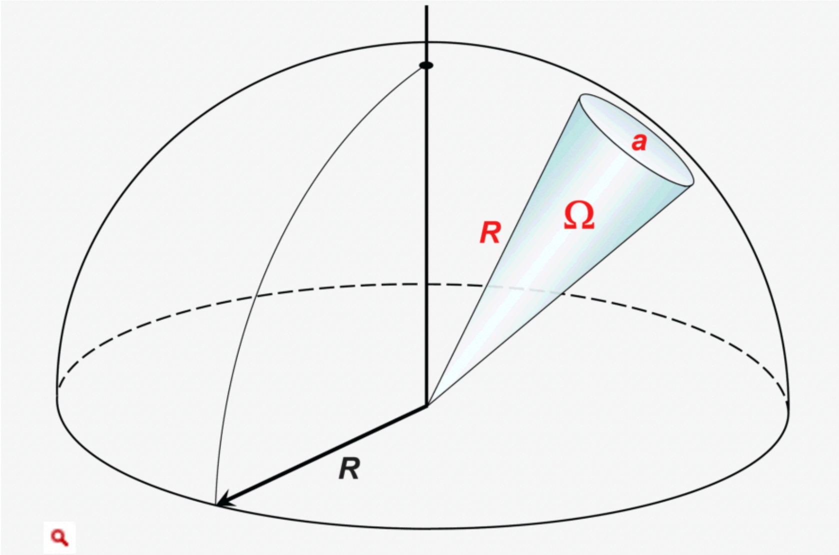


Figure 4.11: Solid Angle Omega from a point to polygon (SEOS, sd)

In this model, all previously mentioned equations and 5 assumptions still hold. One extra assumption is added (Solar Energy Laboratory, 2012):

6. A radiative source is a point source. They have an infinitesimal area and do not absorb radiation

A point source view factor matrix F^o is created and used for the following Gebhardt point source (ps) matrix:

$$G_{ps}^{*} = -\left(G_{ir}^{T} A \rho_{ir} + A \varepsilon_{ir}\right) * (F^{o} A^{-1})^{T}$$

The heat flux from this point source can then be calculated with:

$$\dot{Q}_{ps} = G_{ps}^{*} * \dot{Q}^{o}$$

Where:
$\dot{Q}^{o}$ = The heat point source capacity matrix

MRT ISO7730/ISO7726
The mean radiant temperature is one of the key parameters for determining indoor thermal comfort in both the adaptive and PMV-model. This is also taken into account in the comfort norm NEN-EN-ISO 7730 and NEN-EN-ISO 7726. Both these norms do not mention the use of Gebhardt factors for MRT calculations as used by TRNSYS however. Furthermore, TRNSYS uses a different globe than mentioned in NEN-EN-ISO 7726. The norm does mention the use of view-factors from a standard globe (person) to all individual surfaces to determine the MRT. These view factors are however to planes, and not to points as is the case in TRNSYS.

So it has become clear that the PMV output by TRNSYS with the same comfort parameters does not match the PMV levels as calculated by other tools based on ISO 7730, TNRSYS uses Gebhardt factors which are not prescribed by ISO 7726 and uses a different comfort sphere than this norm. In a detailed TRNSYS model, radiators are assumed points instead of planes, which could affect the MRT and thus PMV outcomes.

For these reasons, a more transparent and detailed way of simulating and calculating the MRT and PMV was deemed necessary for this study. One workaround is to subdivide walls and include a section where an active layer is added at the place of the radiators. Since the radiator should only exchange heat with the room, the outside insulative value would have to be increased drastically. This workaround was also suggested by the Technical Support Team of TRNSYS but was not deemed appropriate for this study for two reasons. Firstly, this way of modelling would decrease the façade area of the dwelling where the actual insulative properties are present. A second downside of modelling this way is the lack of convective heat transfer. For a normal radiator, around 80% of the heat is delivered via convection, which cannot be simulated with a heated wall.

The plan to work around the issue of not having radiators modelled as planes used for this study is elaborate but deemed the most accurate way possible in TRNSYS 17 and to get more in line with NEN-EN-ISO 7730 and NEN-EN-ISO 7726. An overview of the steps can be seen in figure 4.12. Each step will be further elaborated below.

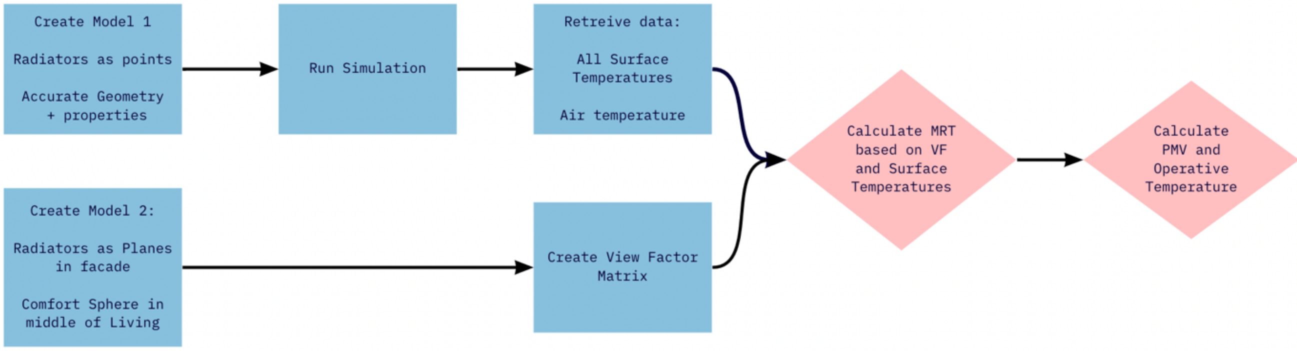


Figure 4.12: Step by Step radiator workaround

Step 1 is to run the simulation with the geometry as explained in the previous section. Radiators are simulated as points here. A major benefit of this model is that the façade and separation walls are not split (to accommodate active layers as radiators) and represent reality accurately.

Step 2 is to run this simulation for the full year of 2020. Then in *step 3* all relevant data for the MRT and PMV is retrieved.

Parallel to step 1 – 3, a second TRNSYS3D model is created based on the original model. In this geometry the radiators are added in the wall in their original locations. The blue numbers in figure 4.13 are the opaque planes, grey numbers are windows and doors and red numbers represent the radiators. The sphere S in the middle of the room represents a seated person. Now view factors can be created from the sphere to the individual planes. This last step can be done via TRNSYS3D and TRNBuild or another view factor calculation software package such as View3D.

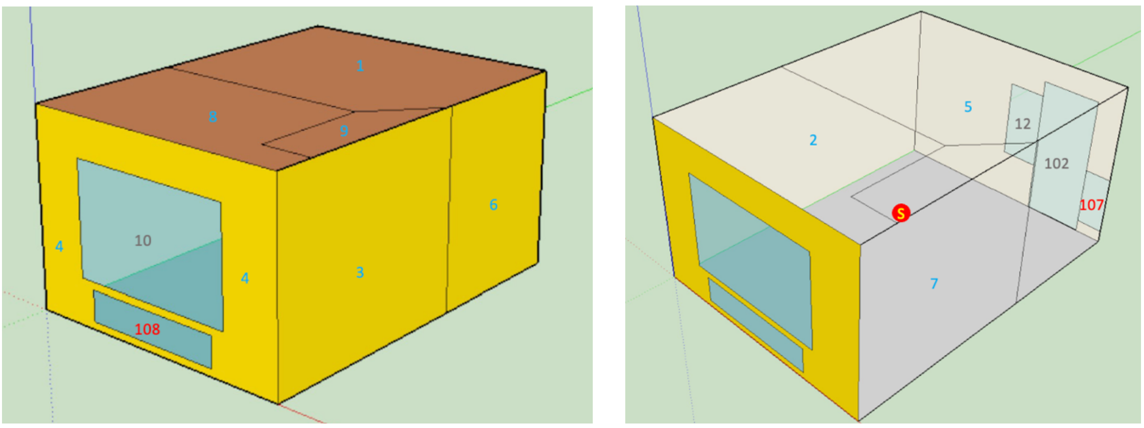


Figure 4.13: Living Room planes

Now all surface temperatures and view factors are known, the Mean Radiant Temperature can be calculated via:

$$T_{MR} = (\sum_{i=0}^{n} T_i^4 * F_{s \to i})^{\frac{1}{4}}$$

Where $F_{s->i}$ represents the view factor from the sphere to surface i and T_i the temperature of surface i. This calculation is done for each time step.

MRT and PMV via TRNSYS vs NEN-EN-ISO7726

The outcomes of these calculations as well as the TRNSYS MRT outputs are presented in figure 4.14. It can be seen that in the heating season, the MRT is underestimated by TRNSYS but in cooling season overestimated. The focus of this study lies on the heating season so this will be further examined. Differences in this heating season vary between -0.15 °C and 0.26 °C with an average difference of 0.07 °C and the Mean Square Error is 0.0084.

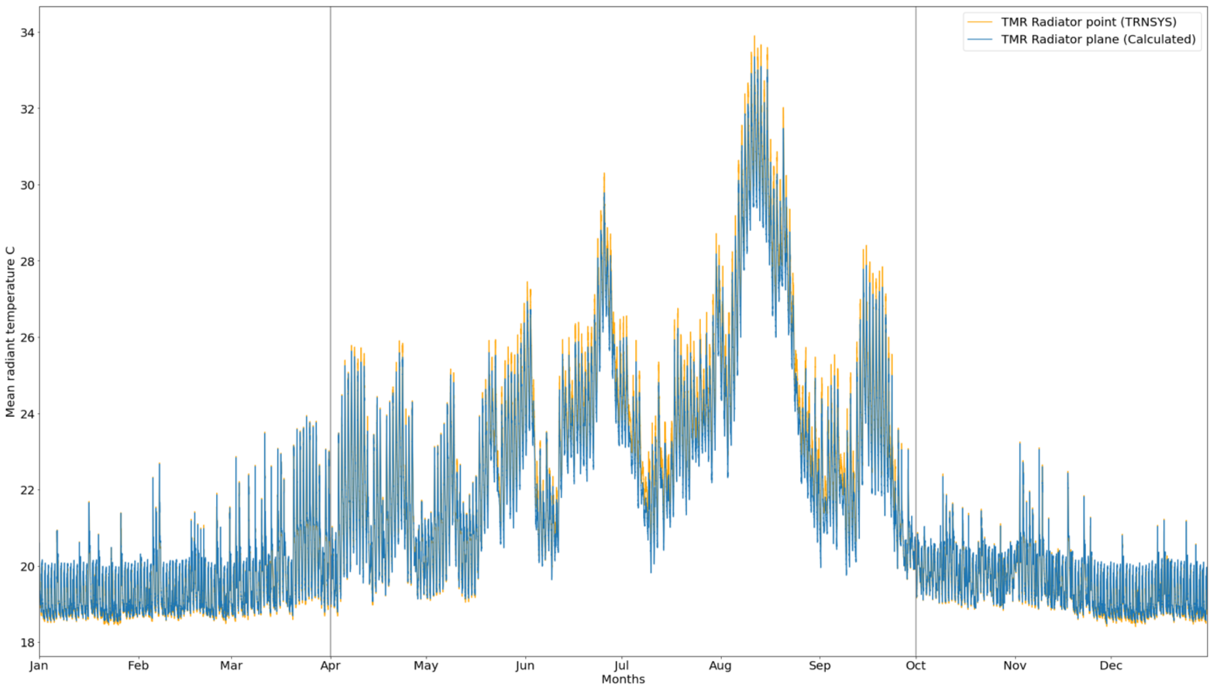


Figure 4.14: Mean Radiant temperature calculated by TRNSYS and via the workaround

Figure 4.15 shows the PMV throughout 2020 as simulated by TRNSYS and as calculated with the self-made tool with the calculated MRT. Again for the heating season, the difference in PMV lies between -0.0024 and -0.042 with a mean of -0.02 and a Mean Square Error of 0.000449.

The difference in MRT between TRNSYS and the View Factor method is deemed substantial enough to choose to continue with the View Factor method. The View Factor method is more in line with the NEN-EN-ISO 7726 standard whereas the way TRNSYS simulates radiators as points is not. As seen in the previous section is the PMV calculated by TRNSYS already shows discrepancies, even when inputted with the same parameters. Although the differences are small, it cannot be explained what their cause is. In order to keep calculation methods transparent and in line with standards, also the PMV will be calculated with the self-made tool.

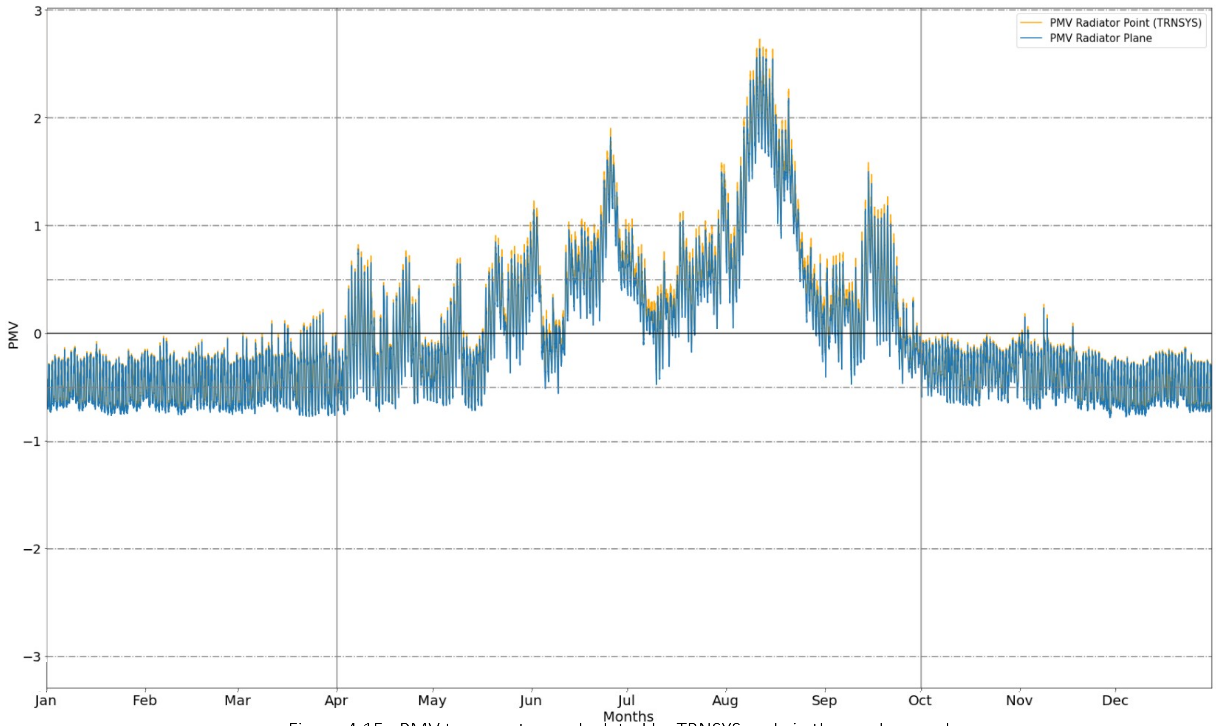


Figure 4.15: PMV temperature calculated by TRNSYS and via the workaround

The workaround presented does still contain some flaws. A first flaw is that the first model, used to simulate the air and surface temperatures, still includes radiators as points. The view factors from these points to the surrounding surfaces are not the same as when the radiators would be planes. This could impose a deviation in surface temperatures. The expected deviations are small however. View factors from a source radiating as sphere will be larger since their orientation is more aligned compared to a surface radiating in a certain plane. Distances from points to other surfaces might be larger however decreasing the view factors. These impacts combined are expected to result in a relatively small effect.

A second flaw in the workaround is that the comfort sphere used still deviates from the standard comfort sphere in NEN-EN ISO 7726. The emissivity of 0.82 as used in TRNSYS is however the emissivity of a standard human according to the TRNSYS 17 Volume 5: Multi-Zone building manual. This emissivity, as well as a different sphere diameter, can be accounted for in the comfort calculations. It should be kept in mind that the view-factors from a sphere with a different diameter are different however. The flaws in the workaround are acknowledged but overall, the proposed MRT and PMV calculation method is deemed more in line with the regulations than the regular way used in TRNSYS 17.

4.6 Calibration and Results

The outcomes of the simulation are presented in a set of graphs. Firstly, an overall outcome of the Simulation Studio results is given. Then the air and surface temperatures from the model are compared to the measurements. This comparison is made to make sure the parameters described in tables 4.3 and 4.5 match the real properties. At last, an analysis of the indoor thermal comfort is presented, based on the outcomes of the model.

Simulation Studio

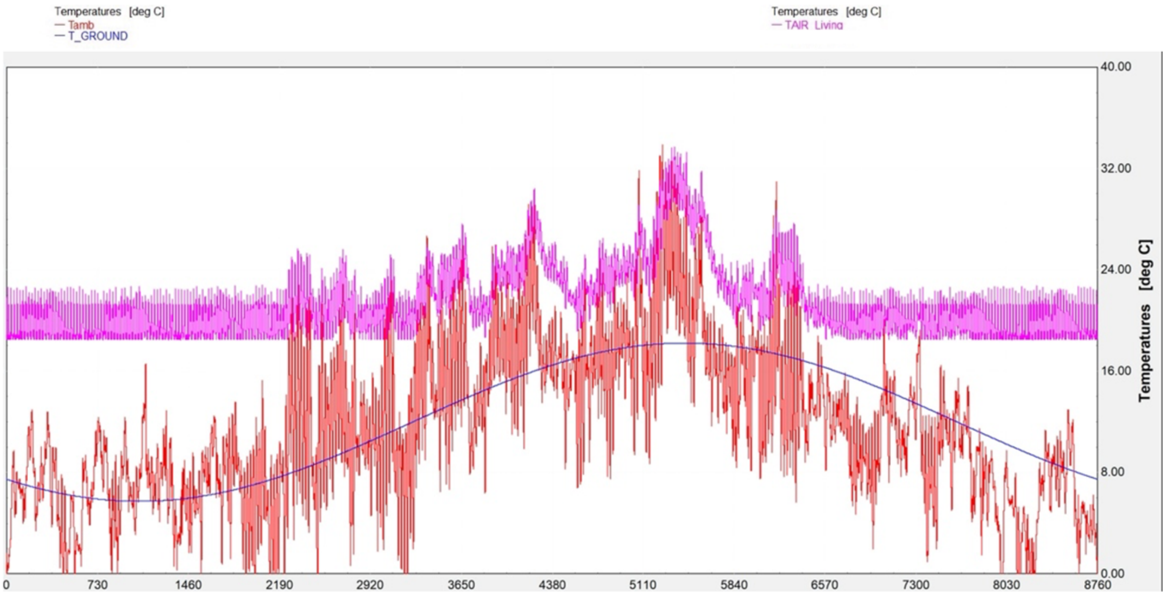


Figure 4.16: Simulation Studio model Ground temperature (blue), Ambient temperature (red) and Living room air temperature (pink)

Figure 4.16 shows the simulation output of TRNSYS. This graph shows the Ambient air temperature, ground temperature and the resulting indoor air temperature in the living room. The simulation starts at 01-01-2020 at 00:00 and ends at 31-12-2020. A clear pattern of winter – summer – winter can be distinguished in all three temperature developments.

Air Temperatures

Figures 4.17, 4.18 and 4.19 show the air temperatures of the living room, kitchen and bedrooms. The measured periods can be seen in table 4.4. The outcomes of the model should match the measured results as closely as possible.

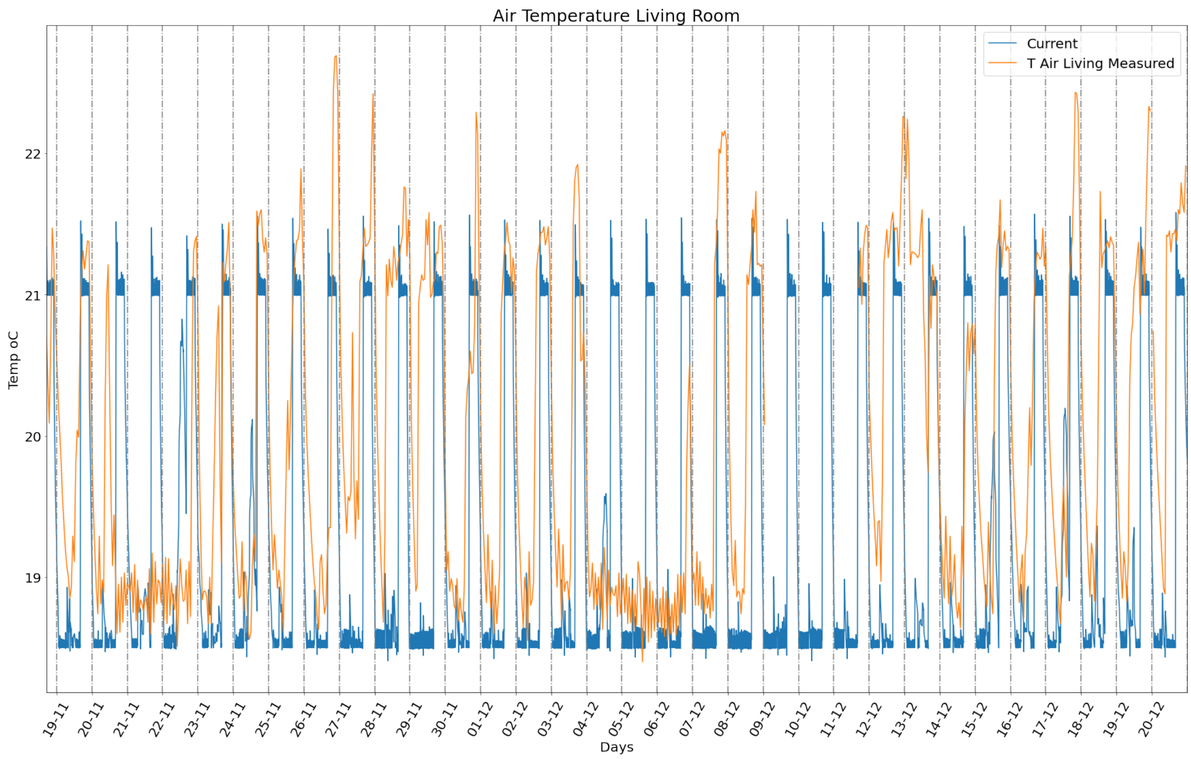


Figure 4.17: Air temperature in the living room Measured (Orange) and modelled with TRNSYS (Blue)

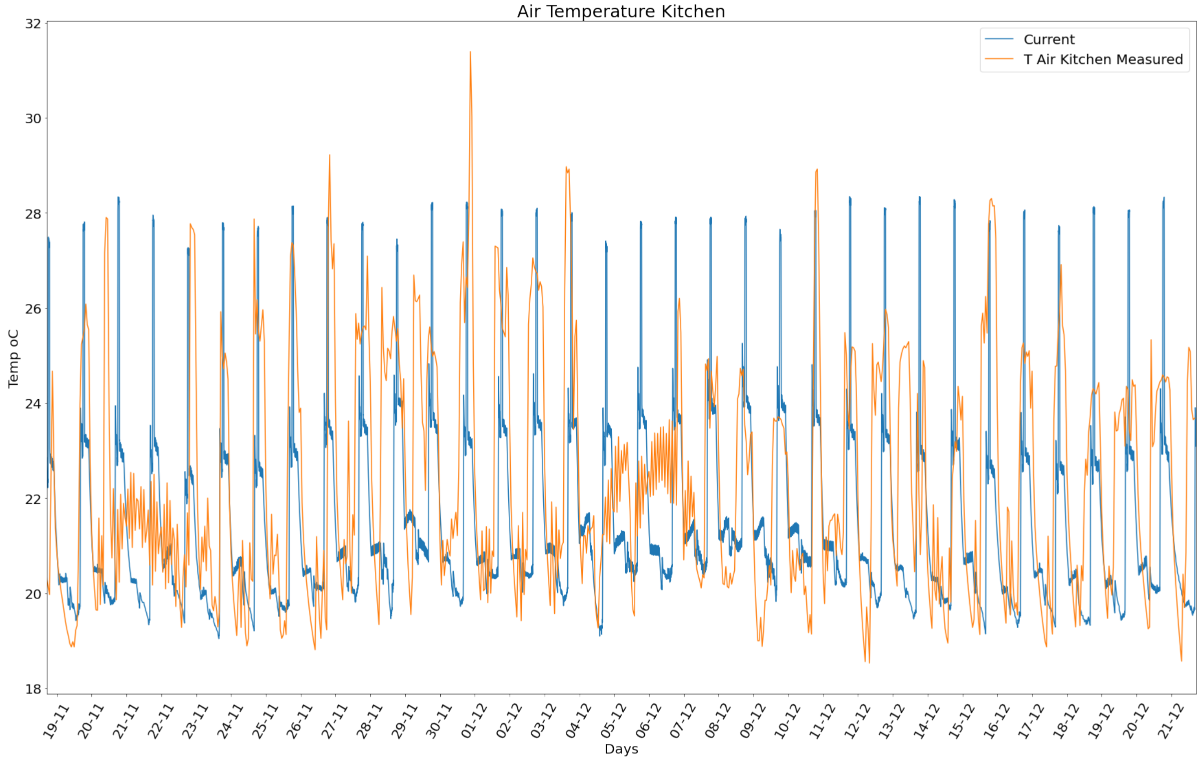


Figure 4.18: Air temperature Kitchen Measured (Orange) and modelled with TRNSYS (Blue)

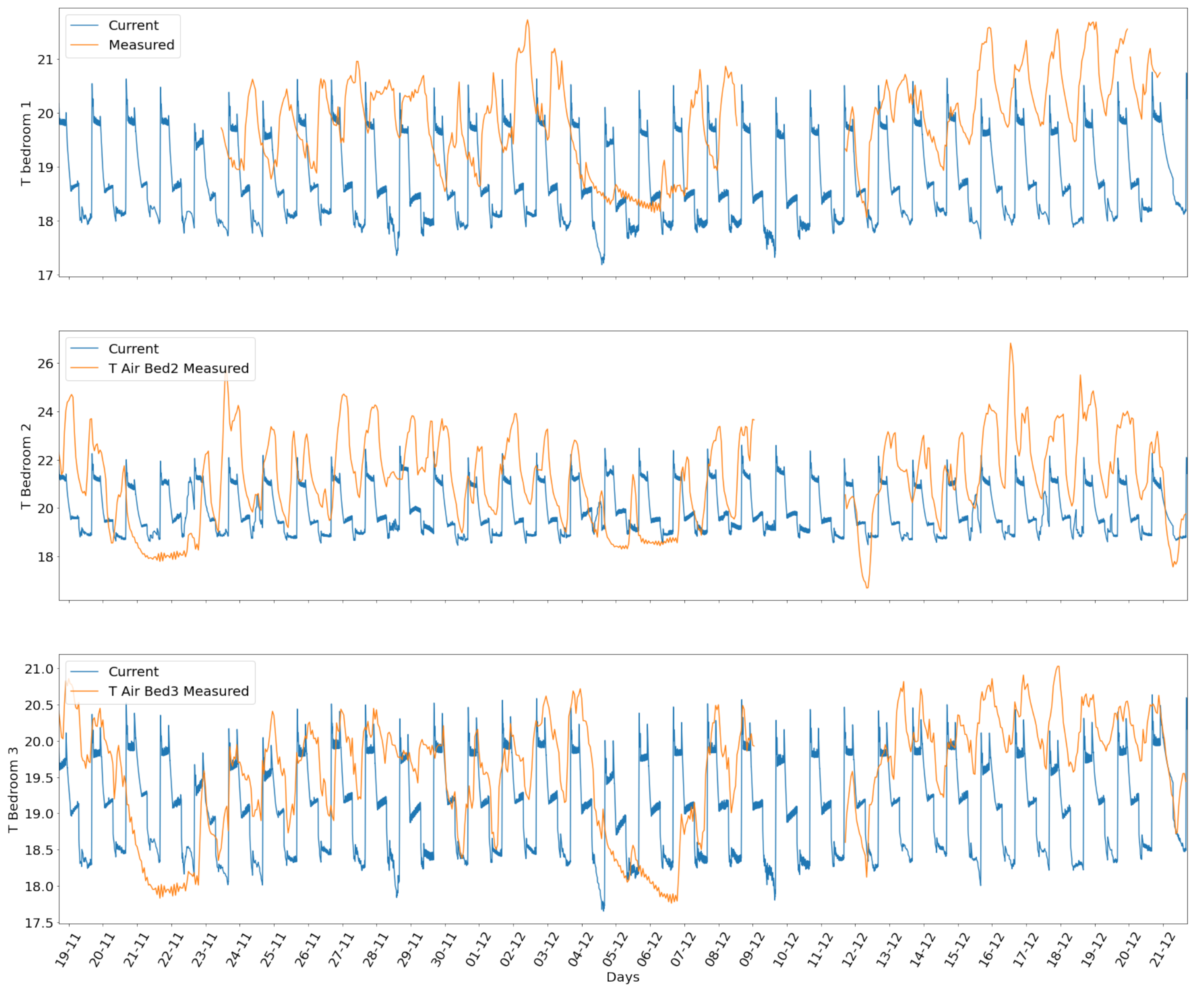


Figure 4.19: Air temperature Bedrooms Measured (Orange) and modelled with TRNSYS (Blue)

Table 4.4: Measured data periods

	FROM	TO
AIR TEMPERATURE LIVING ROOM	18-11-2020 17:00	20-12-2020 23:00
AIR TEMPERATURE KITCHEN	18-11-2020 17:00	21-12-2020 16:00
AIR TEMPERATURE BED 1	23-11-2020 11:00	21-12-2020 16:00
AIR TEMPERATURE BED 2 & 3	18-11-2020 17:00	21-12-2020 16:00
SURFACE TEMPERATURES	13-11-2020 12:00	23-11-2020 13:00

In the graph of the living room temperatures, dashed lines have been set at 00:00 hours, every 24 hours. It can now be seen that the measured pattern deviates from the stated temperature settings by the residents. The temperature ranges between 18.5 °C and 21 °C, instead of 18 °C and 20 °C which was mentioned by the residents. Furthermore, the peaks of 21 °C occur at the end of 24 hour period (so in the evening) instead of the morning. The model has been adjusted to fit this trend. So the thermostat is set to 18.5 °C and raised to 21 °C between 16:00 and 22:00. Although this temperature range is not an exact match with temperature setpoints in standards, it is considered to be an interesting range. By heating from 18.5 °C, which is relatively low, to 21 °C, which is relatively high, the warm-up time of the LTH can also be assessed. The deviations from stated temperatures is one example of human interactions with a building which differ per household, but can also deviate from results from surveys.

An example of what is considered to be a good match between reality and model is the spike in air temperature in the kitchen at times of cooking. Differences can again be explained by the occupant behavior. When the spikes start earlier or last longer, the residents might for example be baking and have the oven on for a prolonged period of time. The general pattern is however closely matched to the evening meals the residents have.

The bedrooms are considered to be a less close match. These display a less clear pattern over the measured period. This could have to do with occupant behavior again. Along the process it became clear the door to bedroom 3 was removed, making it practically the same thermal zone as the landing. The model has not been adapted for this, since it is not considered standard behavior for a residence of this style. The bandwidth of the measured and modelled temperatures are however in the same order of magnitude. For this reason, also for these rooms the model is considered sufficiently accurate.

Surface Temperatures

Figure 4.20 shows the measured and modelled surface temperatures of three walls. The measurements of the surface temperatures have been taken between 13-11-2020 12:00 and 23-11-2020 13:00. It can be seen that around November 21, all three walls are kept at a constant cooler temperature. This matches with the periods in the air temperatures where no rise in temperature in the evenings is seen. The occupants are known to be away for a weekend once a month which could explain this pattern.

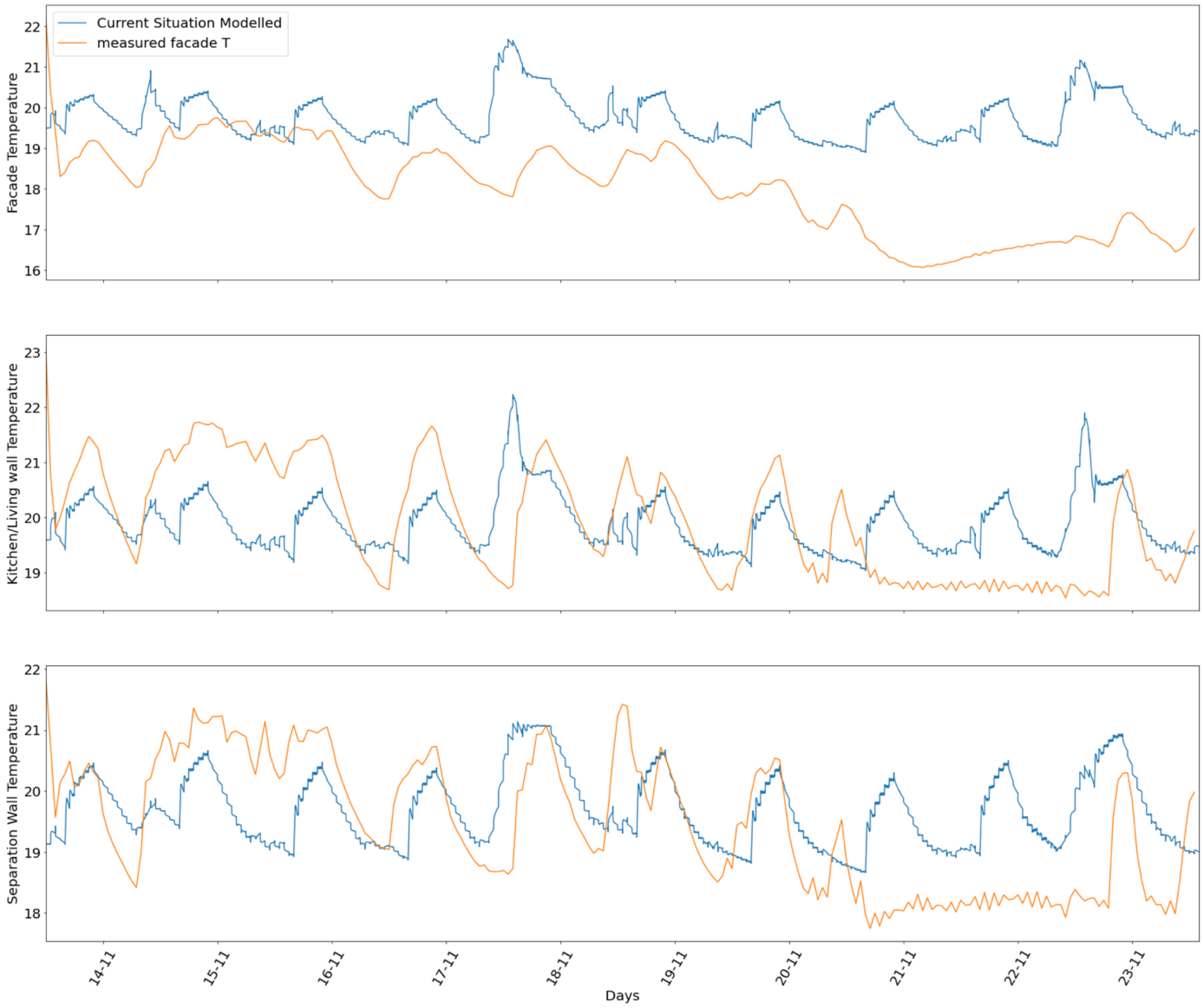


Figure 4.20: Surface temperatures of the three measured points (Orange) and the modelled outcomes (Blue)

Another observation is the higher modelled temperature for the façade than measured. For the measured temperature a sensor is placed halfway up the wall next to the window as can been seen in figure 4.2. TRNSYS measures with average wall temperatures which will be slightly higher due to the placement of the radiator in front of this wall. This could be a partial explanation of the difference. Another possible cause for this difference could be the way the cavity insulation performs in reality versus the claimed performance by the manufacturer. A typical cavity is around 5-6 cm which is also the required thickness for an effective cavity insulation according to the manufacturer. This thickness has also been assumed in the model, but in reality it might be smaller. It could also be that the faces are too rough creating a non-uniform distribution of the insulative material.

Another claim of the manufacturer is that their product achieves a *"…lambda waarde van 0.020…"* (Haren, sd) (translated: lambda value of 0.020). On the manufacturer website it is not specified what lambda is and what the units are. In this context, lambda is a common symbol for thermal conductivity of a material usually expressed in W/mK. In comparison, typical mineral wool has a thermal conductivity of 0.04 W/mK. Still standing air reaches a thermal conductivity of 0.025 W/mK (van der Linden, Kuijpers-Van Gaalen, & Zeegers, 2018). These figures are presented to display that the claim of a thermal conductivity of 0.020 W/mK is ambitious.

This is also substantiated by a temperature profile through the façade. On the coldest day both the air temperature and the surface temperature of the façade were measured, the ambient air temperature was 1.8 °C. This occurred at 22-11-2020 at 08:00. The measured indoor air temperature at this time was 18.8 °C while the surface temperature was measured at 16.7 °C.

If a conduction coefficient of 0.02 W/mK is assumed for the cavity insulation, a total thermal resistance of 3.5 m^{2}K/W is achieved. This would give the temperature profile from figure 4.21 left. The expected surface temperature in this situation would be 18.1 °C. In reality, it was found that the surface temperature of the façade was significantly lower at 16.7 °C. To match this measured value, the façade actually reaches an Rt of 1.06 m^{2}K/W. This would mean the conductivity coefficient of the insulative material actually reaches a value of 0.085 W/mK, for which the temperature profile can be seen in figure 4.21 right. The tables with numeric values can be found in Appendix I: Temperature Profiles. This strongly suggests a lower Rc value of the façade, but it is not deemed proven yet. Therefore, the Rc claimed by the manufacturer will be used in further models.

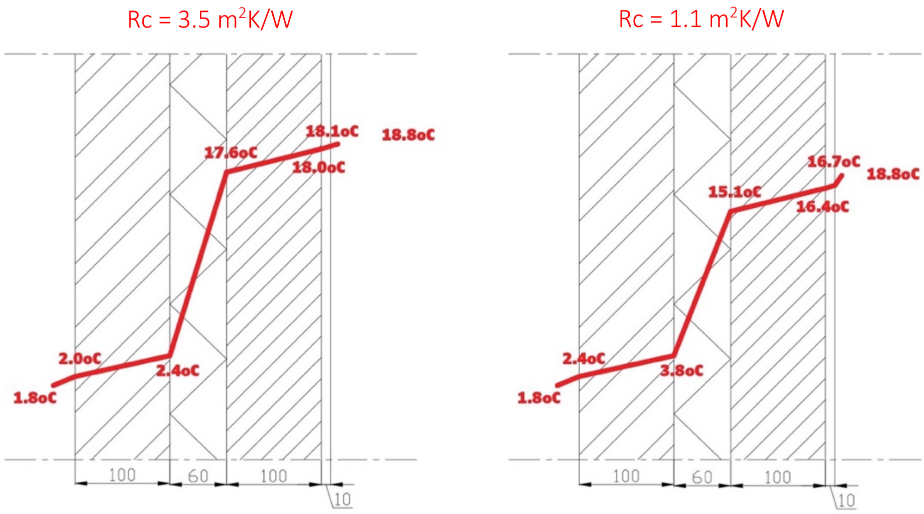


Figure 4.21: Temperature profiles of the façade at Rt = 3.4 m^{2}K/W and Rt = 1.06 m^{2}K/W

Comfort

For the assessment of the indoor thermal comfort, the living room has been taken as a governing zone. This is a zone where residents will spend a lot of their time and mostly in the same set of clothing. In bedrooms, thermal comfort might be more difficult to assess since people sleep here, for which the temperature, attire and duvet selection are more subject to personal preference.

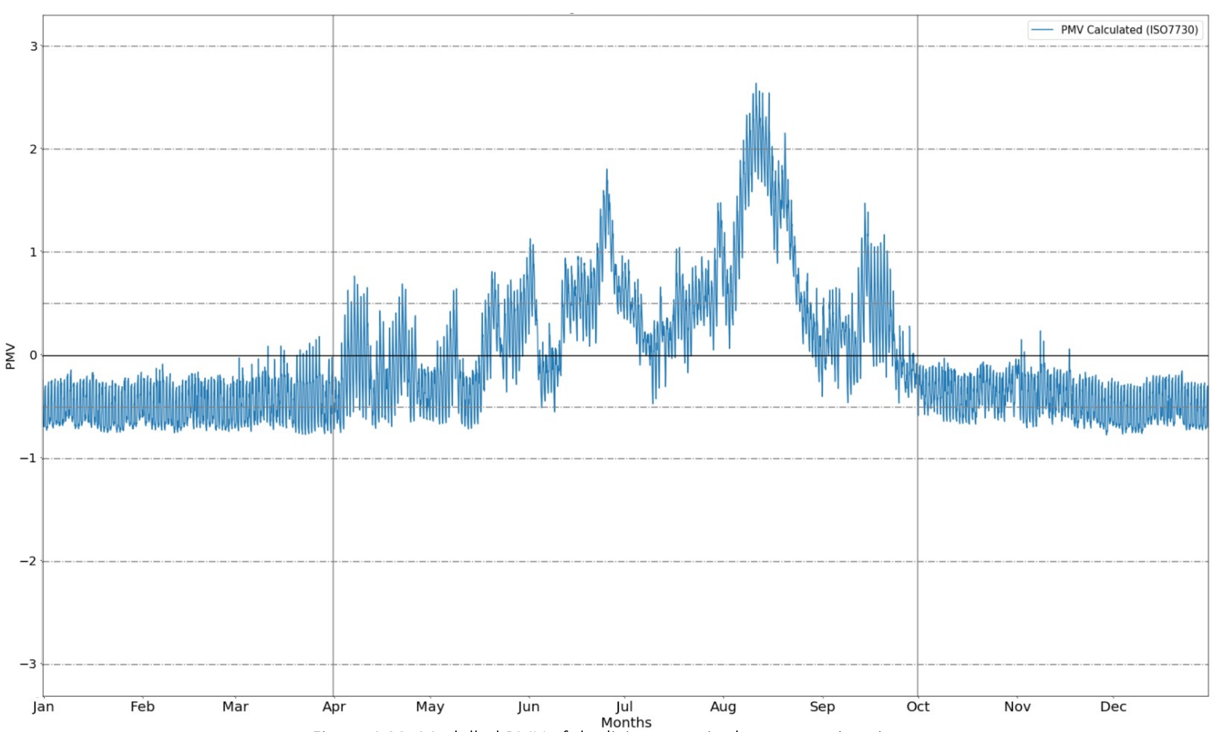


Figure 4.22: Modelled PMV of the living room in the current situation

Figure 4.22 shows the Predicted Mean Votes throughout the year 2020. A clear difference can be seen between the heating season (1st of October until the 1st of April) and cooling season. The separation dates are displayed by the vertical lines in figure 4.22. The heating season will be the main focus for the thermal comfort assessment in this study. It is however still interesting to see what happens in different scenarios during spring/summer months. A separate study could indicate the risk of overheating with too great insulative values. As mentioned, the clothing factor is 1 clo and the metabolic rate is estimated at 1.2 Met. Especially the clothing factor would be lower in summer, giving a different result.

In the current situation the Predicted Mean Vote in the heating season varies between just above 0 and -0.78. The average PMV for the heating season is -0.45, which lies just within the advised regions of -0.5 and +0.5. The PMV reaches a value below -0.5 at 47.23% of the time however, which is significantly more than the suggested 10% in the norms. The worst PMV reached is -0.78. This matches the Percentage Dissatisfied between 5 and 20%. The average PPD during the heating season is 10.07%. The highest PPD in the same time period is 17.77%.

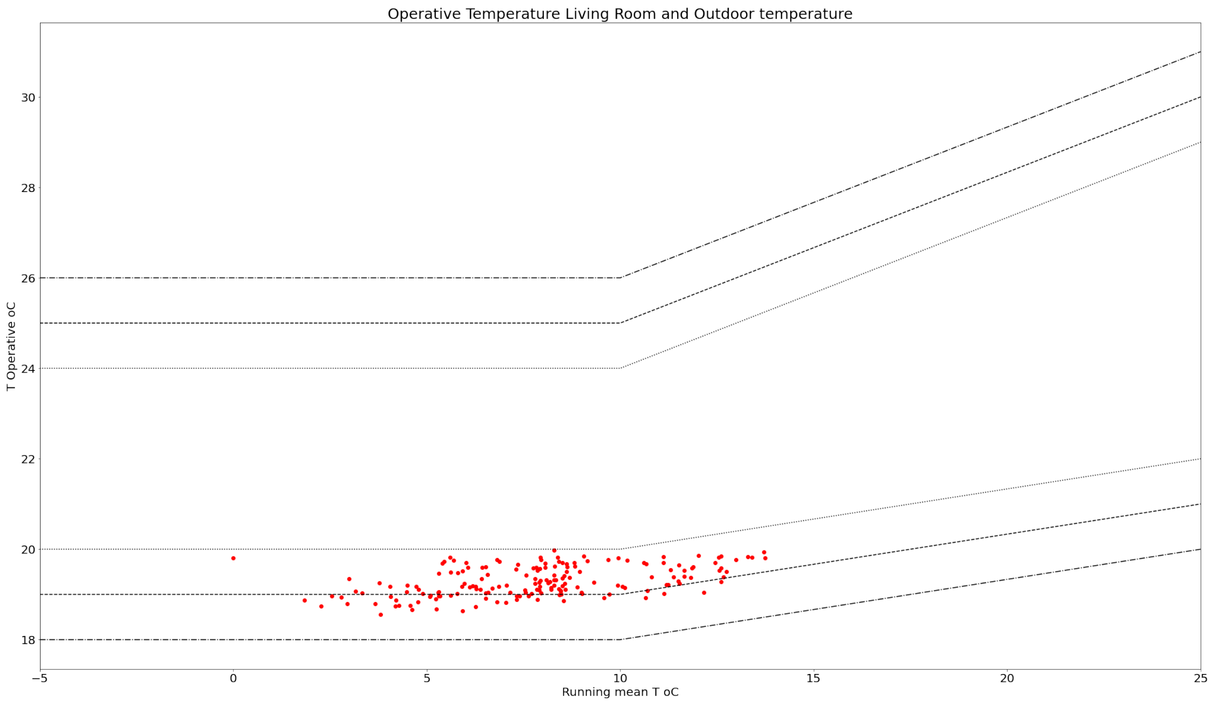


Figure 4.23: Adaptive comfort model in the current situation

Figure 4.23 shows the comfort levels when it is assessed according to the adaptive thermal comfort model. The operative temperature is calculated using the self-calculated MRT and Air temperature outputted by TNRSYS. The operative temperature is created based on the ambient air temperature and is taken over the previous 7 days. The red dots indicate the daily outcomes for the heating season. It can be seen that the dwelling lies on the edge of the Class B boundary, dropping just below it. This is in accordance with the PMV creating at least an 80% acceptance (van der Linden, Kuijpers-Van Gaalen, & Zeegers, 2018). It should be noted that this outcome is largely depended on the thermostat settings. The radiators have sufficient capacity to heat the living room to at least 19 °C, making it a Class B building.

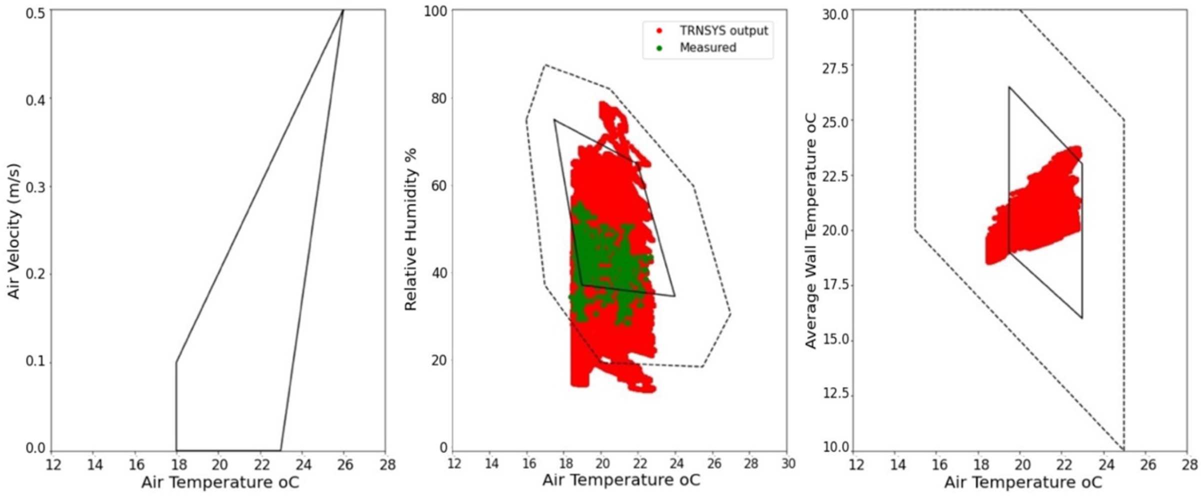


Figure 4.24: Individual comfort aspects for Air velocity (right) Relative Humidity (middle) and Average Wall temperature (right)

The comfort levels are dependent on three individual factors. Air velocity cannot be assessed in TRNSYS since this is not part of a thermal node network's set of equations. The relative humidity and average wall temperature can be assessed. In figure 4.24 middle, the relative humidity is plotted against the air temperature. An important Type in TRNSYS influencing the relative humidity is the Type667b air to air heat recovery. Here two flows run past each other interchanging energy and possible moisture. The settings have been calibrated to match a standard heat recovering ventilation unit and to match measured data. Important is that the old stale air and fresh air never mix but only exchange energy.

The red dots represent the modelled data from the heating season. The green dots are from measured data. The measured data was taken between 18-11-2020 17:00 and 20-12-2020 23:00. It can be seen that the modelled outcomes have a relatively larger spread for the relative humidity. A possible explanation for this could be the longer period over which this is assessed. Both the measured and the modelled assessment show that the building qualifies as 'still comfortable' most of the time.

Figure 4.24 right shows the modelled average wall temperature plotted against the air temperatures in the heating season. In this assessment, it becomes clear that the current building performs well in terms of its average wall temperature with most point lying within the comfortable zone. It is classified as 'still comfortable' when the air temperatures drop below 18.5 ^{o}C. An important note here however, is that the façade temperature is too high in the model. The actual thermal comfort caused by the average wall temperature might in reality be slightly poorer. Since not all wall temperatures were measured, an average of all walls cannot be made from the measurements for comparison.

The modelled minimum reached air temperature in the living room is 18.29 ^{o}C occurring in the night of the 5th of April. This would suggest the heating distribution system has sufficient capacity to maintain the pre-set temperature of 18.5 ^{o}C. The modelled minimum average wall temperature is 18.5 ^{o}C also substantiating the sufficient capacity of the heating system. The thermal storage of especially the stone/brick walls is used keeping them at a similar temperature as the air temperature.

Comfort Close to façade

For the calculation of the MRT, the location of the comfort measurement plays an important role. Therefore it was also investigated what the comfort levels would be close to the south facing façade (on the street side of the dwelling). The locations of the comfort spheres can also be seen in Appendix H. An important note is that the MRT calculations have been carried out via the workaround presented in chapter 4 of this thesis. The view factors are calculated for both comfort spheres. This is the only difference between the two MRT calculations highlighting the importance of this aspect of comfort calculations.

In this case, the location does not have a large impact on the general comfort levels. Relatively stable surface temperatures create a more uniform comfort pattern throughout the room. The average

PMV close to the façade is -0.44 with dips down to -0.84. The higher average compared to the middle of the room can be explained by the higher MRT peaks closer to the façade. These peaks can be caused by an increased MRT during periods with high solar load and increased ambient air temperatures, especially around March. Another reason for the MRT peaks could be the large ambient temperature differences in this period. With relatively warm days but colder nights, the radiators need to switch from 0 to 100% to create the desired peak temperature. This could create overly warm surface temperatures of the radiators. Close by this will have a large impact on the MRT. The lower peak PMV can be explained by a lower MRT during periods of low ambient air temperatures, especially close by the large glass plane in the façade. The comparison over the whole year 2020 can be seen in figures 4.25 and 4.26.

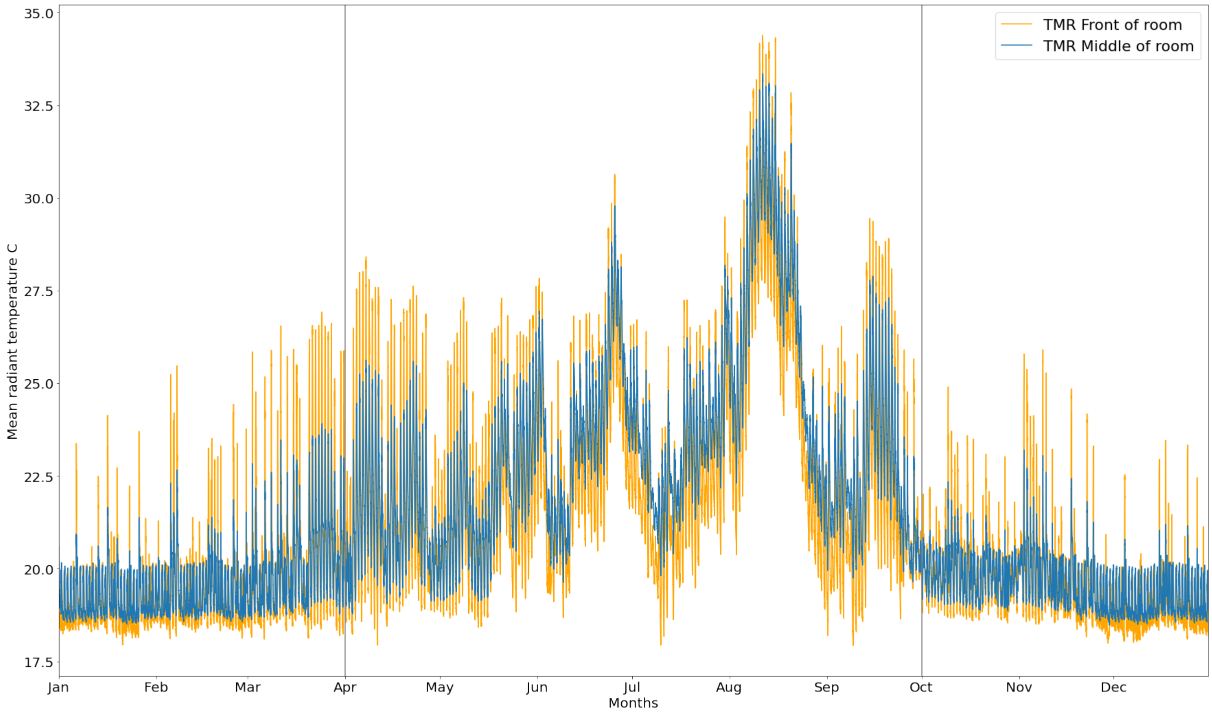


Figure 4.25: MRT in the middle and at the front of the room in the current situation

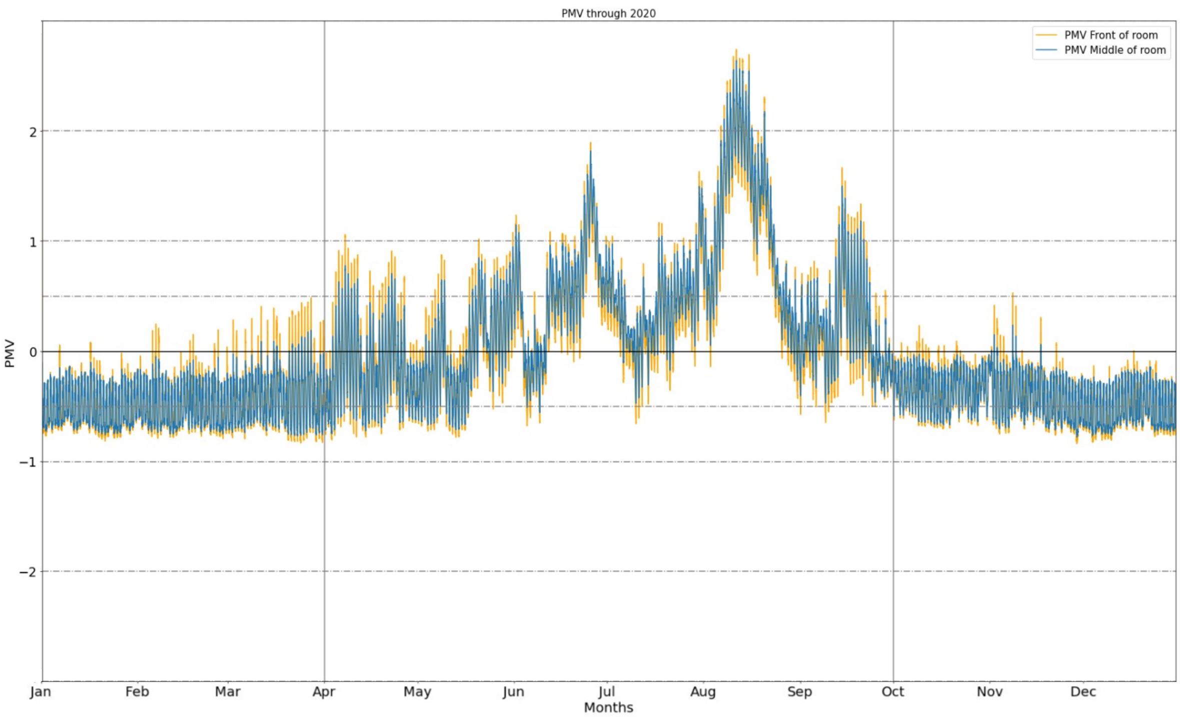


Figure 4.26: PMV in the middle and at the front of the room in the current situation

4.7 NTA 8800 setpoints

The thermostat temperature settings in the previous simulation were based on the pattern derived from the measured data. For energy simulations, NTA 8800 prescribes a different pattern. This norm states that the normal temperature in residential rooms is to be set to 20 °C and can be lowered to 16 °C for 10 hours per day. NTA 8800 does not prescribe which 10 hours of a day the temperature is to be lowered. One assumption is that this will be during the night time, when people are asleep. Figure 4.27 shows the thermostat settings as set by the residents and as stated in the NTA 8800.

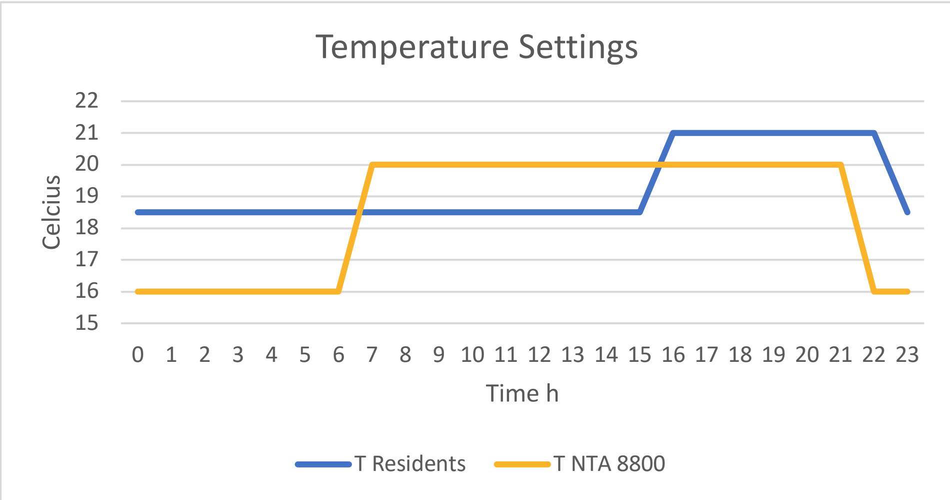


Figure 4.27: Temperature settings by residents and as prescribed in NTA 8800

The NTA 8800 is a regulation used to determine the energy consumption of a building. This is not necessarily the same as a comfort study. Both for energy and comfort studies, the desired temperature is an important factor. Therefore it was also assessed what comfort levels would be if the NTA 8800 is followed for the current situation of the dwelling.

The results of the comfort analysis with the thermostat settings set to the NTA 8800 values are displayed in a set of graphs. In figure 4.28 the PMV calculation throughout 2020 can be seen. Figure 4.29 shows the comfort levels according to the adaptive model and figure 4.30 shows the individual comfort parameters.

From these graphs it becomes clear that the comfort levels of the dwelling drop significantly compared to thermostat settings by the residents. Especially the adaptive comfort levels are reduced at lower outdoor temperatures. This can be explained by the lower air temperatures but also by the lower surface temperatures from figure 4.30 right. These lower surface temperatures will create a lower MRT.

Since it is known that the comfort levels can be increased significantly with the thermostat settings matching the resident's preferences, the NTA 8800 temperature settings are not deemed representative to be used to compute the potential of the comfort levels of the dwelling. Therefore, the temperature settings of the residents will be used for further simulations. Another benefit of using these values in the model is that the outcomes can be compared to the measured data in a more accurate way.

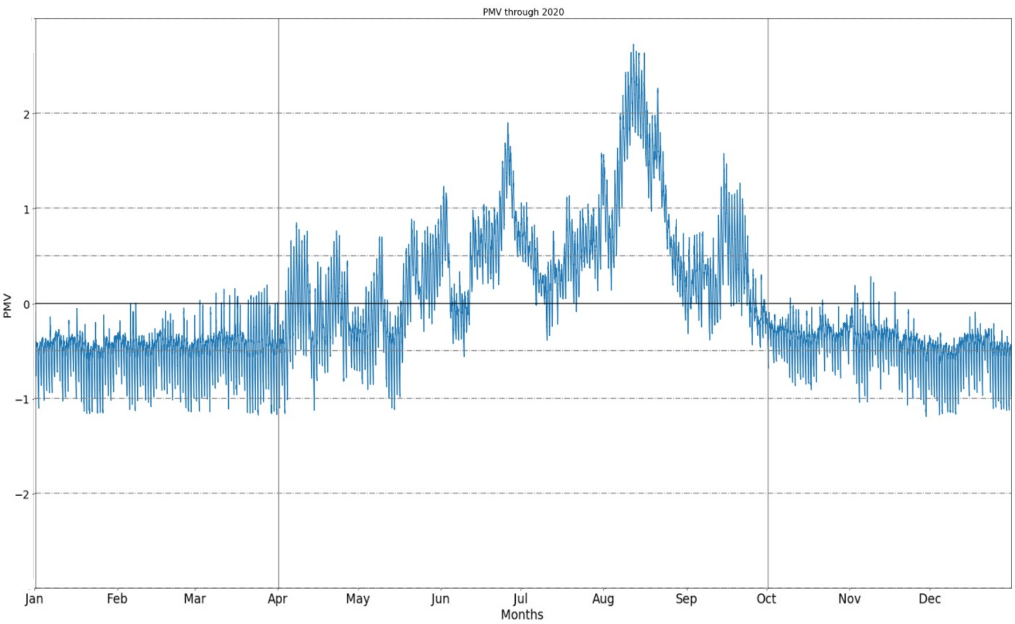


Figure 4.28: PMV in the living room throughout 2020 with NTA 8800 temperature settings

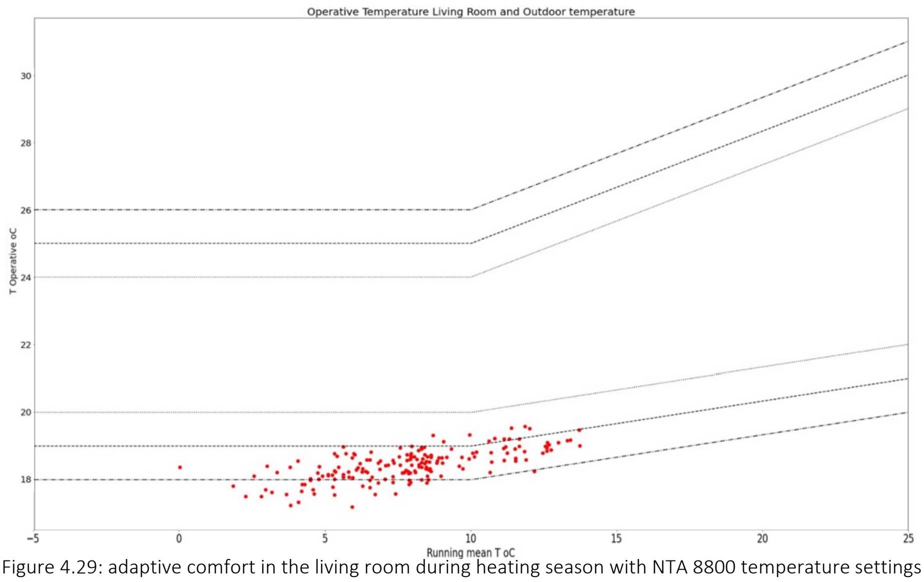


Figure 4.29: adaptive comfort in the living room during heating season with NTA 8800 temperature settings

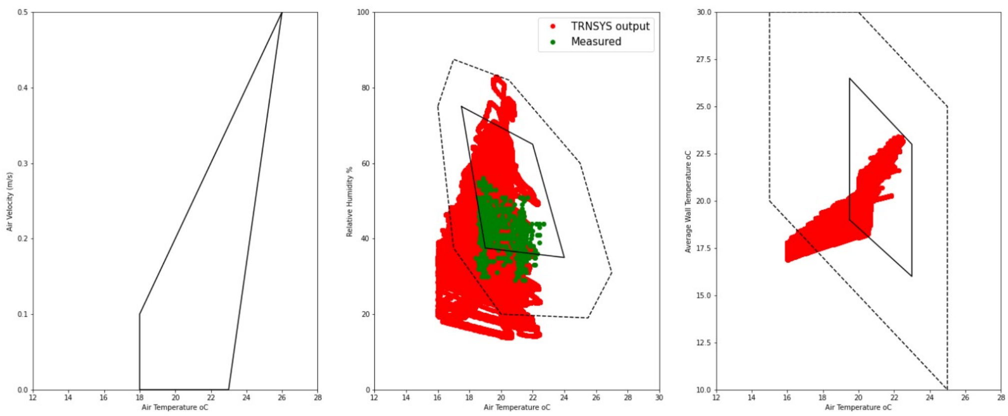


Figure 4.30: Individual comfort parameters in the living room during heating season with NTA 8800 temperature settings

5. Renovations

In this section the renovation proposals for the dwelling will be further elaborated and assessed. The order of doing this is similar for most renovation plans. Firstly a new heating system will be worked out. Then a simulation is made for the current façade situation and tested in terms of its thermal comfort. Based on these results the newly required thermal properties at which the thermal comfort is at least equally good as the current situation will be determined. This will lead to a required Rc value of the new façade. This will result in a set of suggestions for façade renovations with which this required Rc can be achieved.

5.1 Plan 1: Original state of the dwelling

The first renovation plan is different from the rest. This step aims to reverse the already implemented renovations of the dwelling. This will be done to investigate the impact of the already made interventions for high temperature heating systems.

The reversal of the renovation measures with the dwellings old properties can be seen in table 5.1. The renovations include installation of HR+ double glass, cavity insulation, roof insulation, ground floor insulation and a heat recovering ventilation system. These properties have been adjusted in the TRNBuild model. It should be mentioned that the values are extremes. For example, the dwelling might already have had an early form of double glazing from the start. Since this was not known, extremes were chosen.

In order to avoid confusion, the dwelling in its current state (as modelled in the previous chapter) will be named the current dwelling. This will be compared to the dwelling before the already carried out renovations, so with 'downgraded' properties compared to the current situation. How this fits in a timeline can be seen in Appendix J: Timeline.

Table 5.1: Renovation 1 updated properties over the current situation

ELEMENT	CURRENT	BEFORE
GLAZING	Double HR+ U = 1.1 W/m^{2}K	Single Glazing U = 5.7 W/m^{2}K
CAVITY	Airofill Cavity insulation	Air cavity
ROOF	Mineral wool Insulation U = 0.168 W/m^{2}K	No insulation U = 2.161 W/m^{2}K
GROUND FLOOR	Insulated U = 0.293 W/m^{2}K	No insulation U = 2.390 W/m^{2}K
INFILTRATION	Crack closure Inf = 0.6 dm^3/s/m^2	No Closure Inf = 1 dm^3/s/m^2
VENTILATION	Heat exchanger Efficiency of 0.8	No heat exchanger

Radiator Plan

In the next sections new heating systems will be further elaborated. In the comparison in this plan, the radiator placement has been left untouched. Maximum heating water temperatures are still set to 75 ^{o}C with the calculated radiator capacities explained in the previous chapter.

Results

In this section the results from TRNSYS will be presented and compared to the current dwelling's outcomes.

Air temperatures

Figure 5.1 shows the air temperature in the living room as modelled throughout 2020. It can be seen that the temperature pattern during heating season is relatively consistent, sometimes showing a drop below the preset 18,5 °C. These drops mainly happen when the ambient air temperature drops below 5 °C. Figure 5.2 shows the air temperature of the living room from the current situation and the modelled outcomes with the downgraded properties. The air temperature remains relatively similar compared to the original outcomes. Figure 5.3 shows the air temperatures in the kitchen. The biggest difference between the dwelling with downgraded properties and the dwelling in the current situation is the decreased spike temperature from cooking. The lower temperature boundaries are however similar to the current situation. The modelled air temperatures of the bedrooms are also similar to the modelled temperatures in the current situation as can be seen in figure 5.4. That the modelled air temperatures of the dwelling without renovations are similar to the current dwelling is in line with the expectations. The high temperature heating system was expected to have a surplus of capacity, as can be seen in the case study by Nieman presented in Appendix E. The energy demand will most likely be higher in the situation before the renovations however.

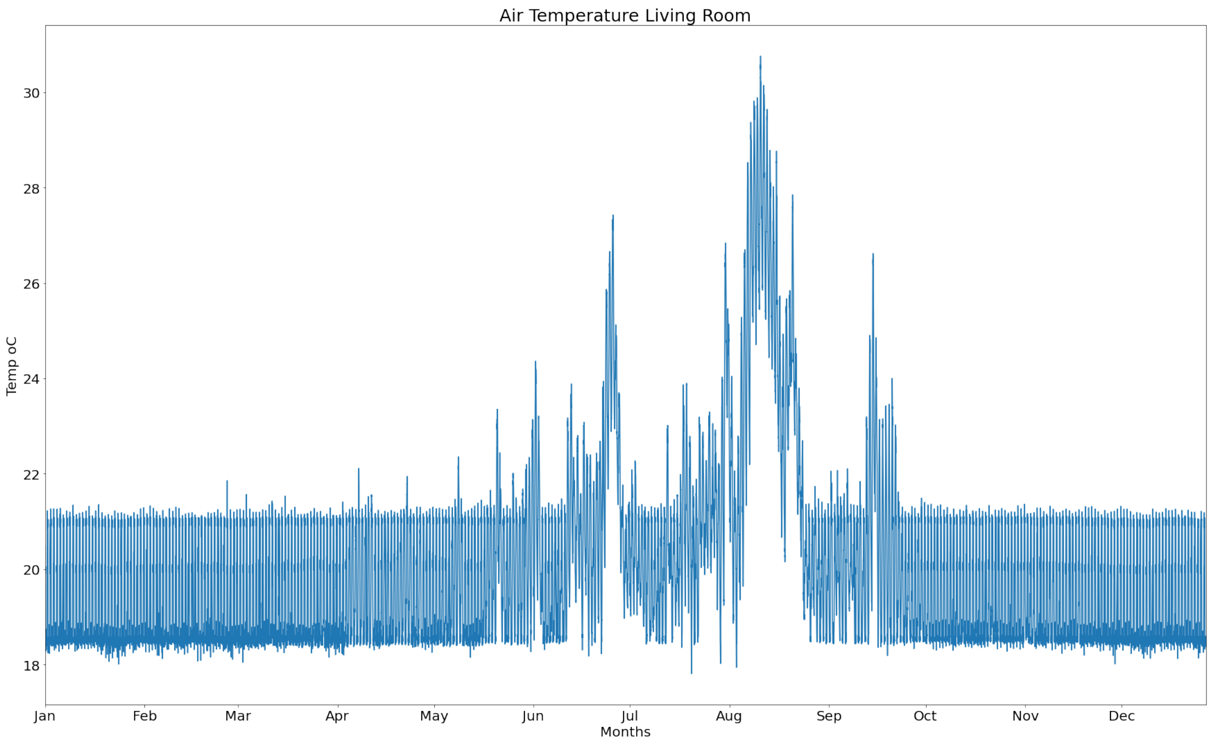


Figure 5.1: Air temperatures in the Living room throughout 2020 modelled without current renovations

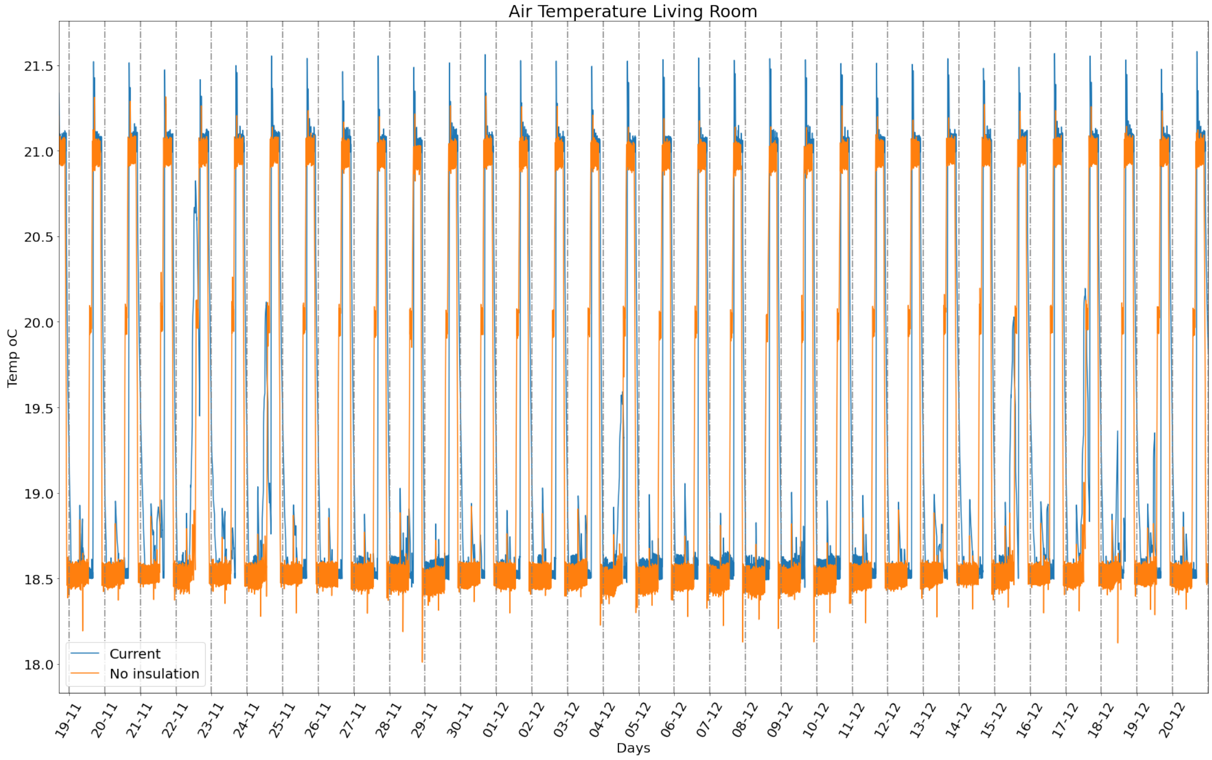


Figure 5.2: Air temperatures in the Living room as modelled in the current situation and modelled without current renovations

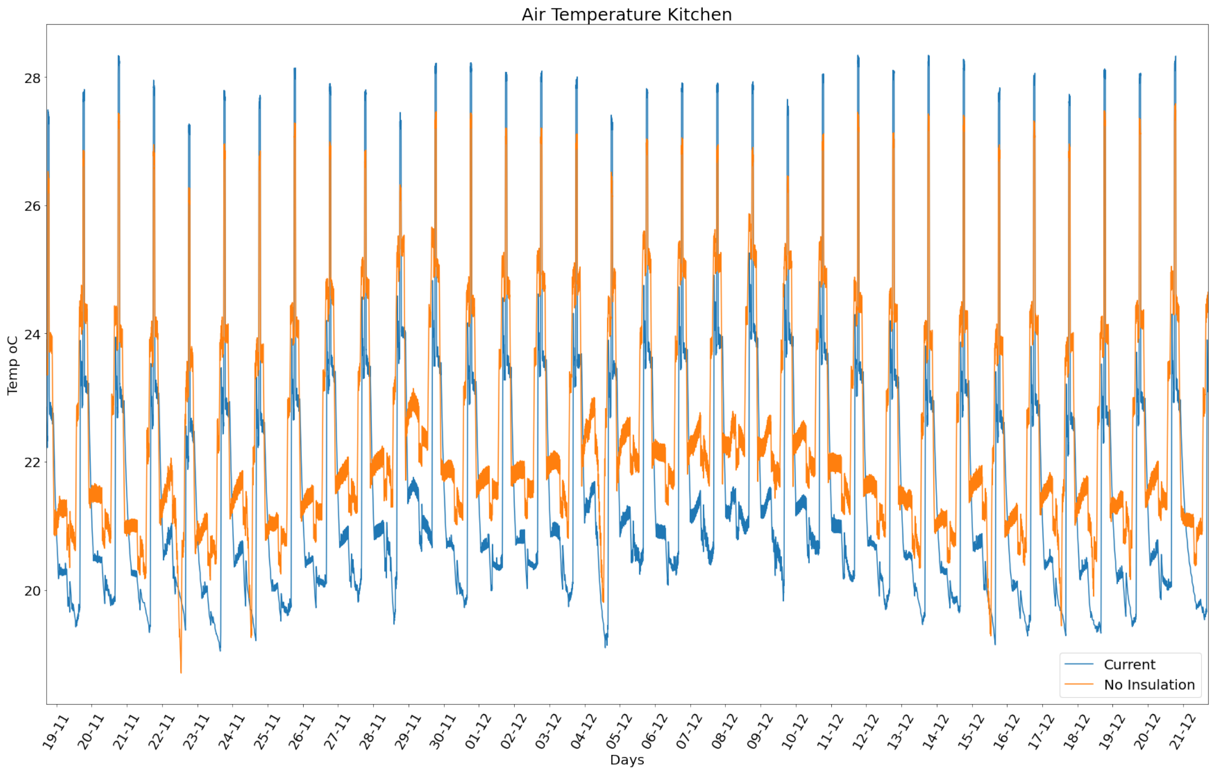


Figure 5.3: Air temperatures in the kitchen as modelled in the current situation and modelled without current renovations

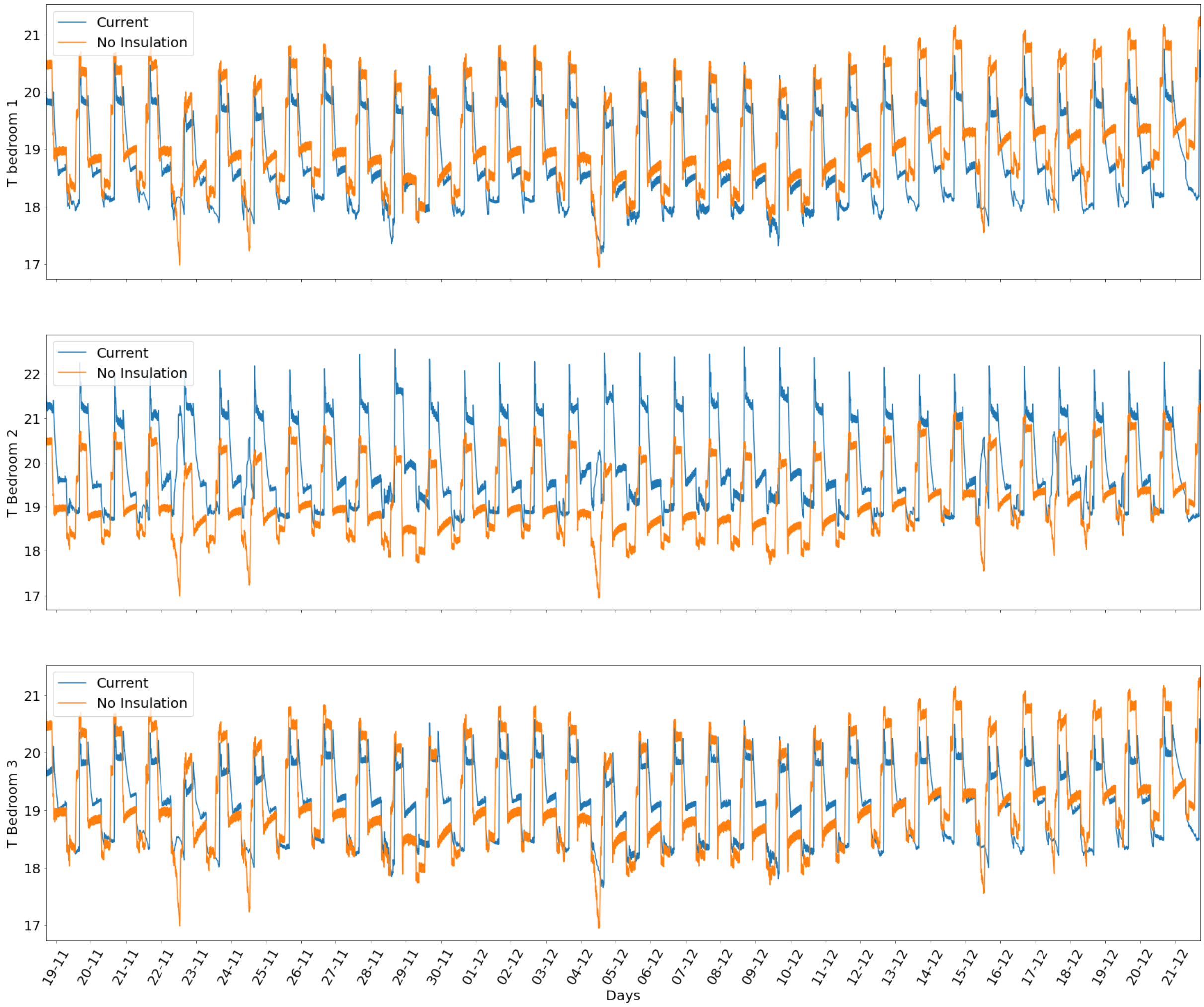


Figure 5.4: Air temperatures in the bedrooms as modelled in the current situation and modelled without current renovations

Surface temperatures

From figure 5.5 it becomes clear that all 3 surface temperatures are lower in the situation without the already carried out renovations. This trend is also in line with the expectations. Less thermal energy is stored in the brick and limestone, since more energy is required to heat the air. Especially the façade is cooler in the situation before renovations. The modelled temperature is significantly closer to the measured temperatures. This would suggest the cavity insulation performs closer to a still standing air cavity than an insulated area.

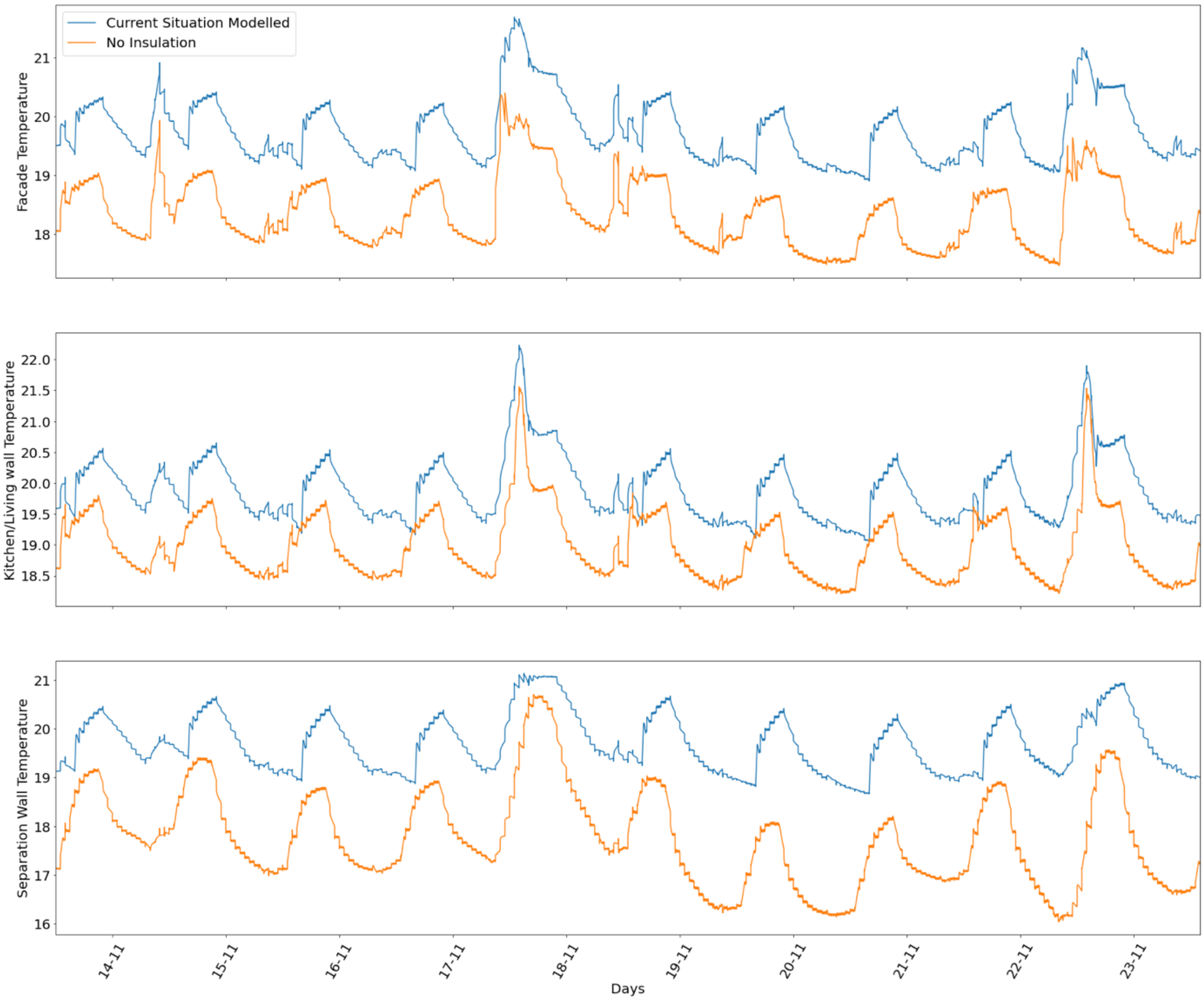


Figure 5.5: Surface temperatures in the Living room as modelled in the current situation and modelled without current renovations

Comfort

Figure 5.6 shows the Predicted Mean Vote of the dwelling before the current renovations. In the heating season, the PMV in the living room lies between -0.2 and -1.08 Compared to the outcomes of the current situation, which had a PMV between 0 and -0.77, this is a large decrease. The average PMV in the situation before renovations is -0.73, which is lower than the acceptable -0.5. For 83.89% of the time, the PMV lies below -0.5. The lowest PMV in the heating season gets down to -1.08. In the heating season, the percentage dissatisfied raises well over 20% for a considerable amount of time and reaches values as high as 29.60%. The average PPD is 16.99%. From these figures it can be concluded that this situation is uncomfortable for a majority of the time during heating season.

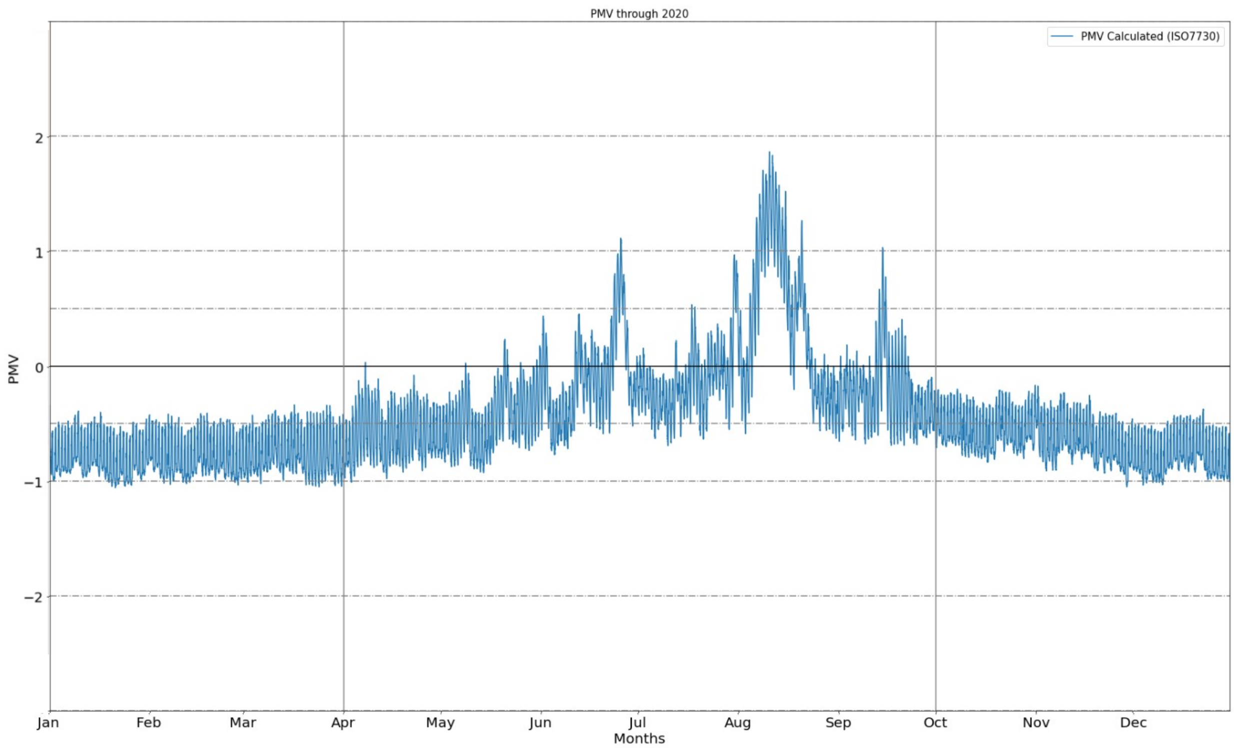


Figure 5.6: PMV in the Living room without renovations

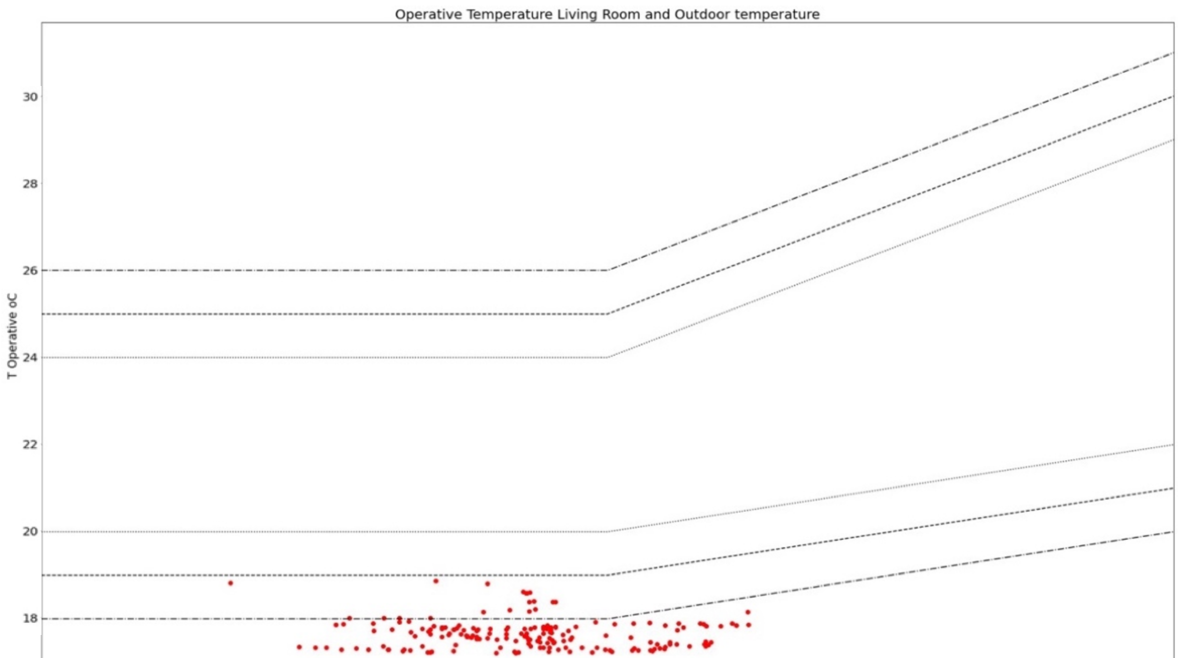


Figure 5.7: Adaptive comfort in the Living room without renovations

Figure 5.7 shows the comfort levels for the heating season in the situation before any renovations as would be determined with the adaptive model. The dwelling would now perform worse than a Class C building, which is not acceptable.

The low comfort levels in this situation can be considered unexpected. The capacities of the heating system should be calculated for this situation. Two reasons can be thought of for the low comfort levels. Firstly, the assumed values for insulation and infiltration are worse than they may actually have been. Especially the windows might have been more insulating than now assumed.

A second reason could be the lower surface temperatures. The calculations for heating systems depend on air temperatures, which are relatively well reached. Since the air temperatures are similar with or without any renovation interventions with the current radiators, the decrease in comfort levels is mainly due to worse performance in the mean radiant surface temperature. This is substantiated by the individual discomfort outcomes for average wall temperatures. Figure 5.8 right shows that the average wall temperature would indeed be lower in the situation before the renovations were executed. The minimum reached air temperature in the living room is 17.81 ^{o}C, which is slightly lower than in the current situation. The modelled minimum average wall temperature is however lower at 15.15 ^{o}C. The thermal capacity of especially the stone/brick walls is now not fully used.

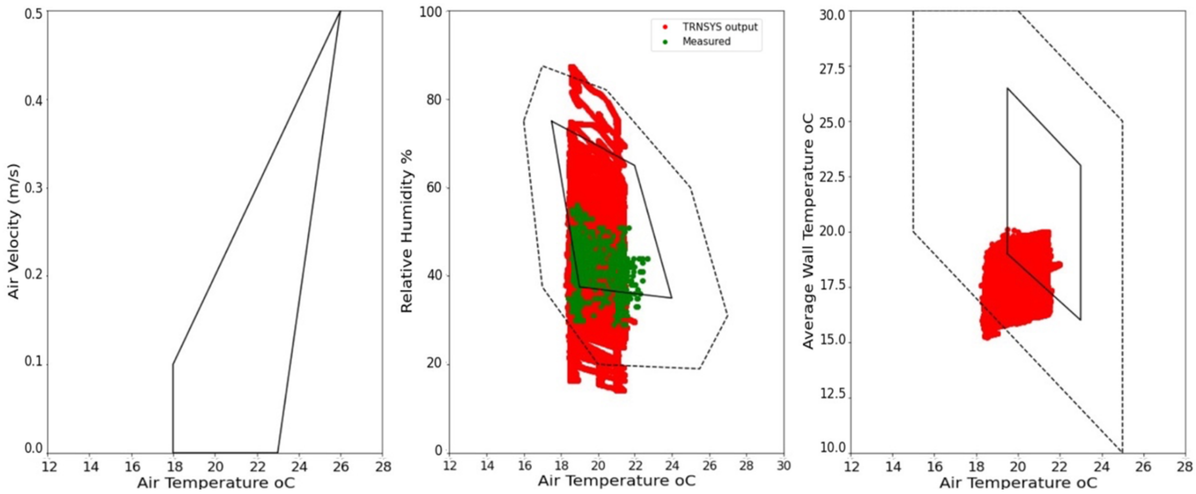


Figure 5.8: Individual comfort aspects for Air velocity (right) Relative Humidity (middle) and Average Wall temperature (right)

PMV Close to Façade

In this case the surface temperatures have a large impact on the comfort calculations. It was again investigated what the comfort levels would be close to the south facing façade (on the street side of the dwelling).

If the MRT calculated for the middle and front of the living room are plotted in the same graph, figure 5.9 can be derived. Both in heating and cooling season, a difference of as much as 2.81 ^{o}C in MRT can be seen. In figure 5.10, the PMV calculations for both locations are displayed again showing a difference. At the front of the living room, the average PMV is -0.804 and it reaches a minimum of -1.29. Compared to an average of -0.73 and a minimum -1.08 in the middle of the room, this is a big difference especially in a room that is relatively small.

This is an example of how the façade can play a large role in indoor thermal comfort. With identical heating systems, the current situation displays a much more uniform PMV throughout the room than the situation before renovations. Where the air temperature stays relatively stable in both cases, the surface temperatures do not. Especially the façade temperatures show a large drop at low ambient temperatures contribution to a lower thermal comfort closer to these walls. Also the poor thermal insulation of the glass planes are assumed to be a contributing factor to this lowered MRT.

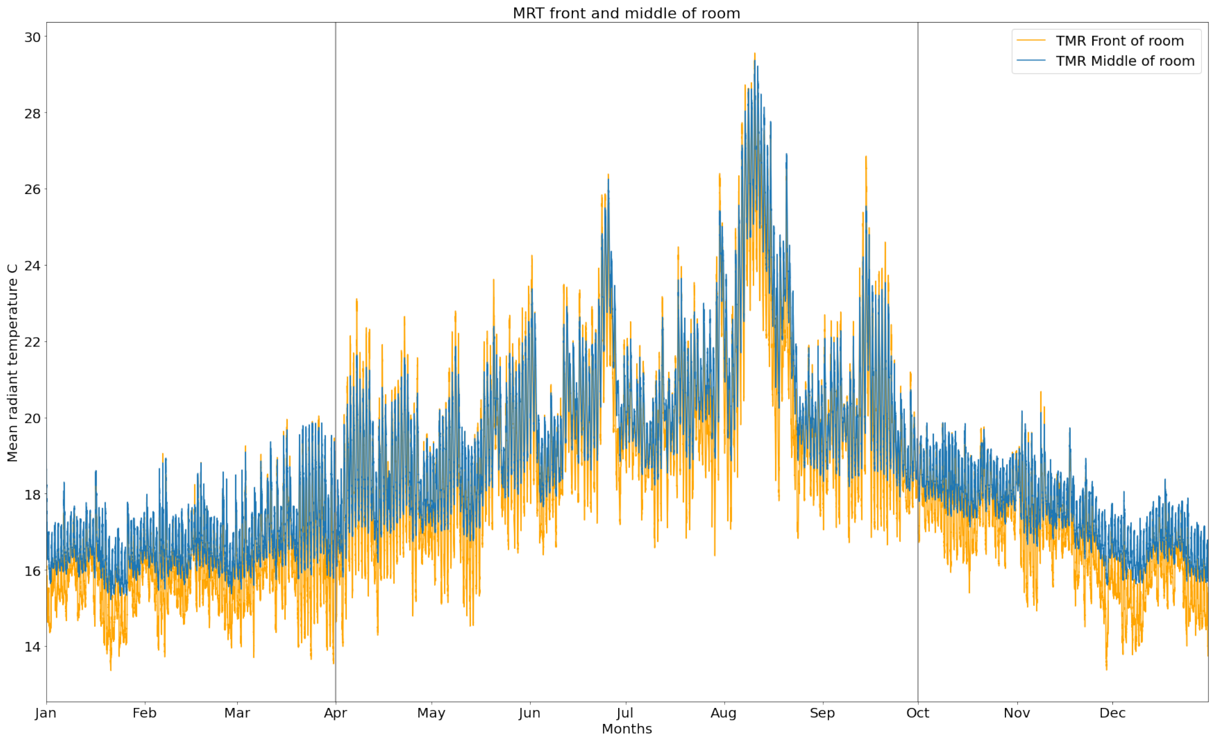


Figure 5.9: MRT in the middle and front of the living room throughout 2020 before current renovations

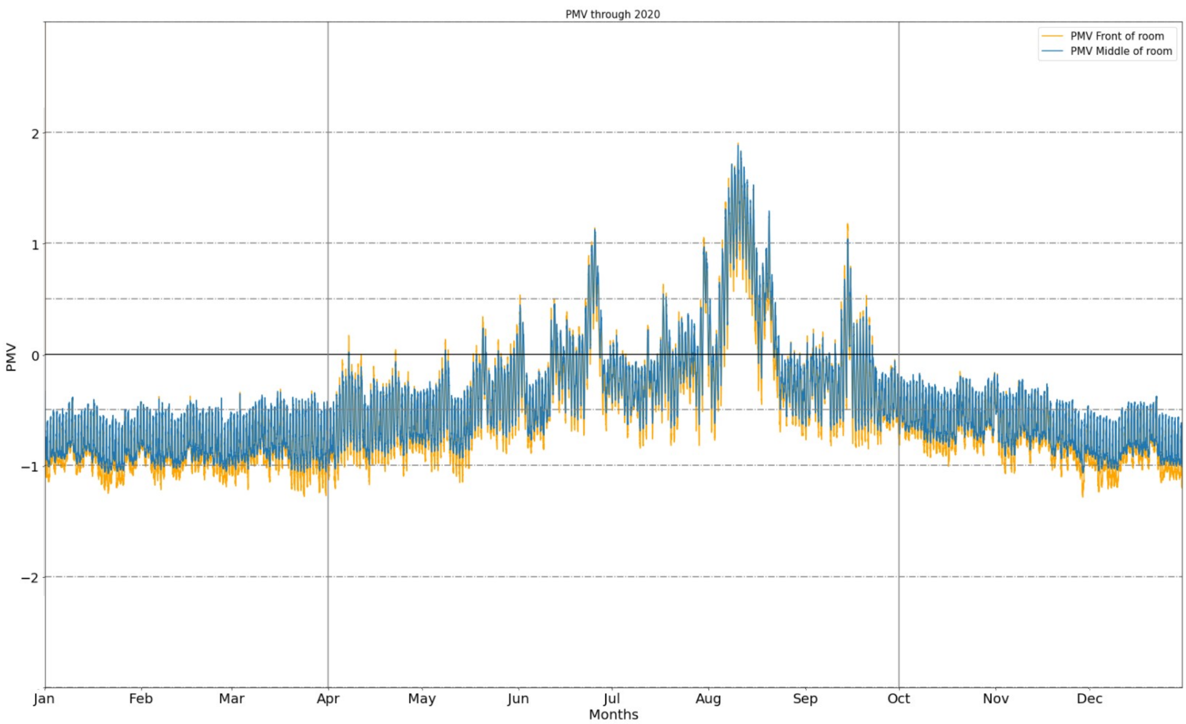


Figure 5.10: PMV in the middle and front of the living room throughout 2020 before current renovations

5.2 Plan 2: LTH with current radiators

The aim of this plan is to assess the performance of the current radiators when changing to low temperature heating. By keeping the same radiators and water distribution pipes, the renovation measures that need to be taken inside dwellings are minimized. The source for the heating energy (e.g. a heat pump or district heating) is placed outside the dwelling resulting in a minimized intrusion for residents and a minimum amount of resources required. Only the connection to the current system will have to be made.

Radiator plan

As seen in the literature review, the capacity of ordinary radiators, like the radiators in the dwelling in the case study, is reduced by up to 73% when changing to middle to low temperature heating (55-40 °C inlet water temperature). The heat production system will also change. The capacity of the central heating system was estimated at 28 kW, which provides a surplus of capacity. As an example of a LTH source a heat pump is chosen. This is a commonly used energy source for space heating and can be used on an individual dwelling basis. In order to estimate the required capacity of this single heat pump unit, the energy loss of a dwelling can be used. For this residence, the required capacity of the heat pump would be:

$$P_{required} * A * \beta * 3.6 = 101.6 \frac{W}{m^2} * 88\, m^2 * 1 = 8940.55\, W * 3.6 = 32186\, kJ/h$$

Where:

$P_{required}$ is the required heating demand (101.6 W/m^2 for an F label dwelling) (Warmtepomp Panel, sd)
A is the floor area
β is a reduction factor (1 for full-time electric LTH)

Table 5.2 shows the current and new low temperature heating capacities of the radiators when reduced by 73%. Figure 5.11 shows the placement of these radiators (which has not changed from the current situation). Internal heat gains, ventilation, infiltration and all geometric and thermal properties are equal to the current situation as described in chapter 4. The heating regime of the dwelling is also equal to the current situation, where the set temperature is 18.5 °C and 21 °C from 16:00 – 22:00. The place of the thermostat is again in the living room.

Table 5.2: Heating regime when changing to LTH

Room	*Radiators*	*Capacity Current HT W*	*Capacity Current LT W*
Living	Type 21 190x400	1891.9	510.8
	Type 10 50x90	411.1	153.7
Kitchen	Type 21 60x90	1186.2	327.8
Bathroom	Type 10 60x90	526	142
Bedroom1	Type 11 190x50	1620	437.4
Bedroom2	Type 11 190x40	1339.4	362.1
Bedroom3	Type 10 60x90	493	133.1

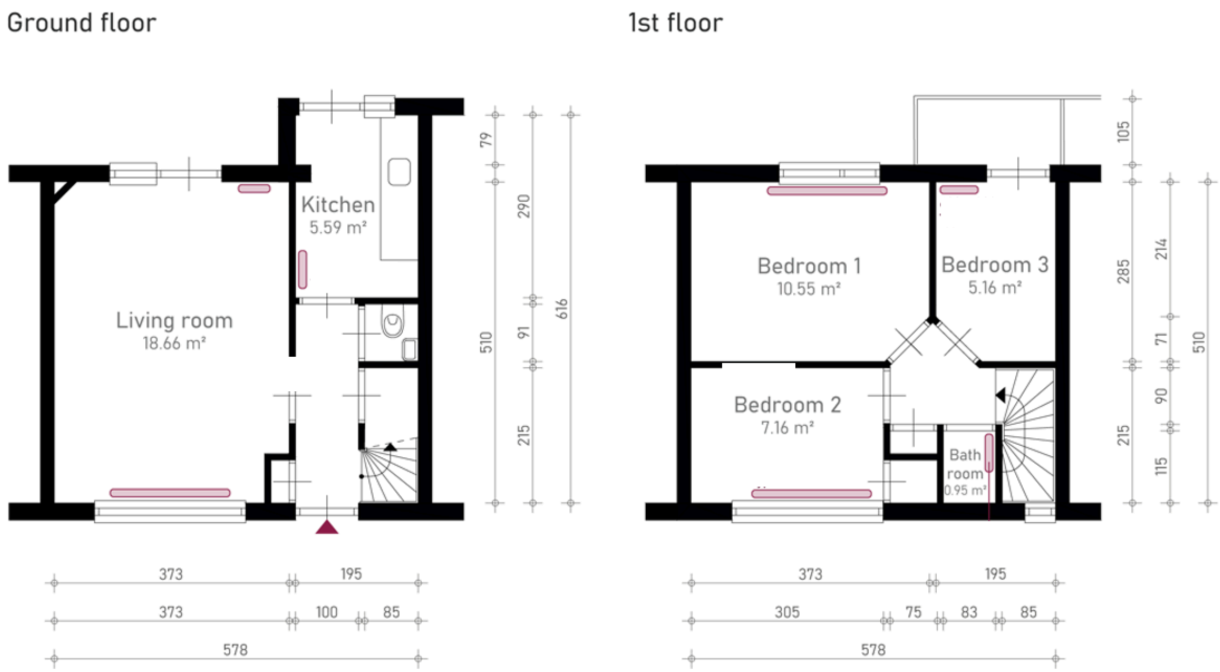


Figure 5.11: Radiator Placements

Results

The TRNSYS model is similar to the plan shown for the current situation. One deviation is the reduced radiator capacity as shown in table 5.2. The results from the model are again plotted in a set of graphs.

Air temperatures

Figure 5.12 shows the modelled air temperature in the living room throughout 2020. Large dips around January and December can be seen. Figure 5.13 shows the air temperatures in the living room calculated by the model in the current situation and with LT radiators. The modelled temperatures show a different pattern from the current situation. In most cases, the minimum set temperature of 18.5 ^{o}C can be maintained. At some points however, for example at the end of November, a drop can be seen to temperatures as low as 16.98 ^{o}C. These drops of indoor air temperature coincide with low outdoor temperatures. The pre-set peaks of 21 ^{o}C in the late afternoon/evening are not always achieved in the model.

Figure 5.14 shows the air temperatures in the kitchen. The modelled temperatures in this room show a more similar pattern to the current situation than in the living room. This could have to do with a lower façade surface area ratio in the kitchen than in the living room resulting in less heat loss to the outdoor. A second factor at play in the kitchen are the high internal heat gains from cooking every evening, boosting the temperature up significantly.

Figure 5.15 shows the temperatures modelled in the bedrooms. In all three bedrooms, the modelled temperatures lie significantly lower than in the current situation. Drops in the temperatures can again be seen around the same times as the drops in ambient air temperatures.

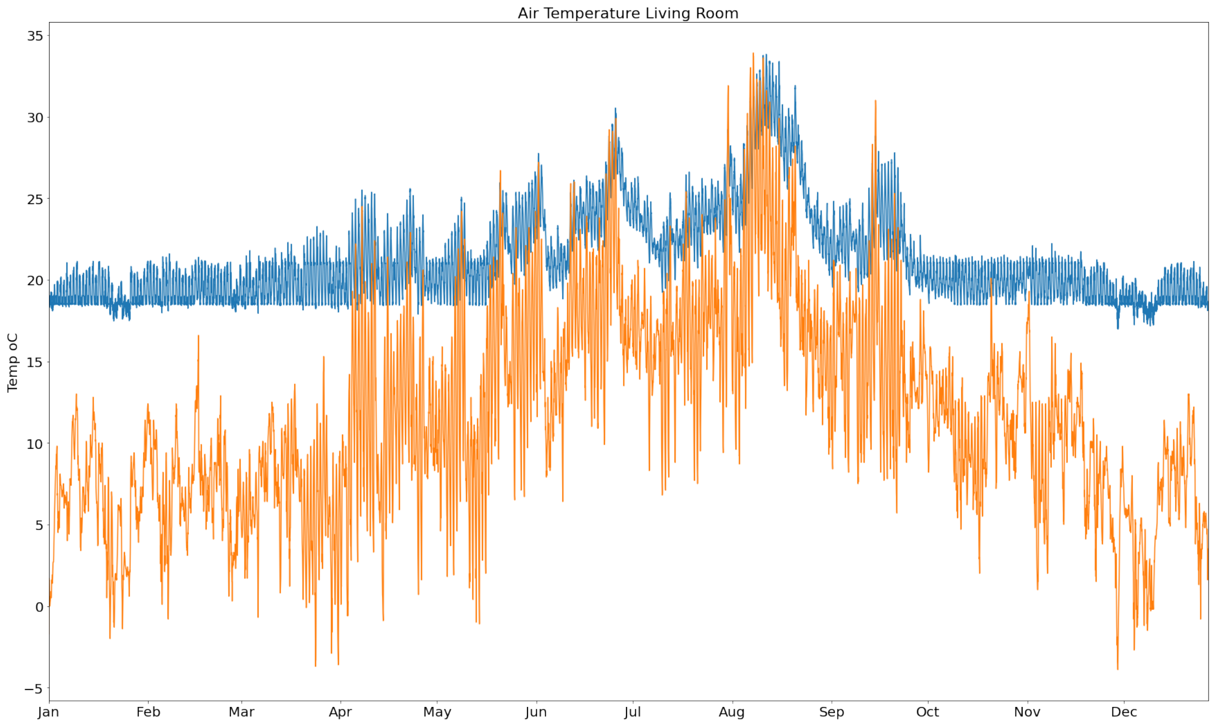


Figure 5.12: Air temperatures in the Living room when changing to Low Temperature (blue) and ambient air temperature (orange)

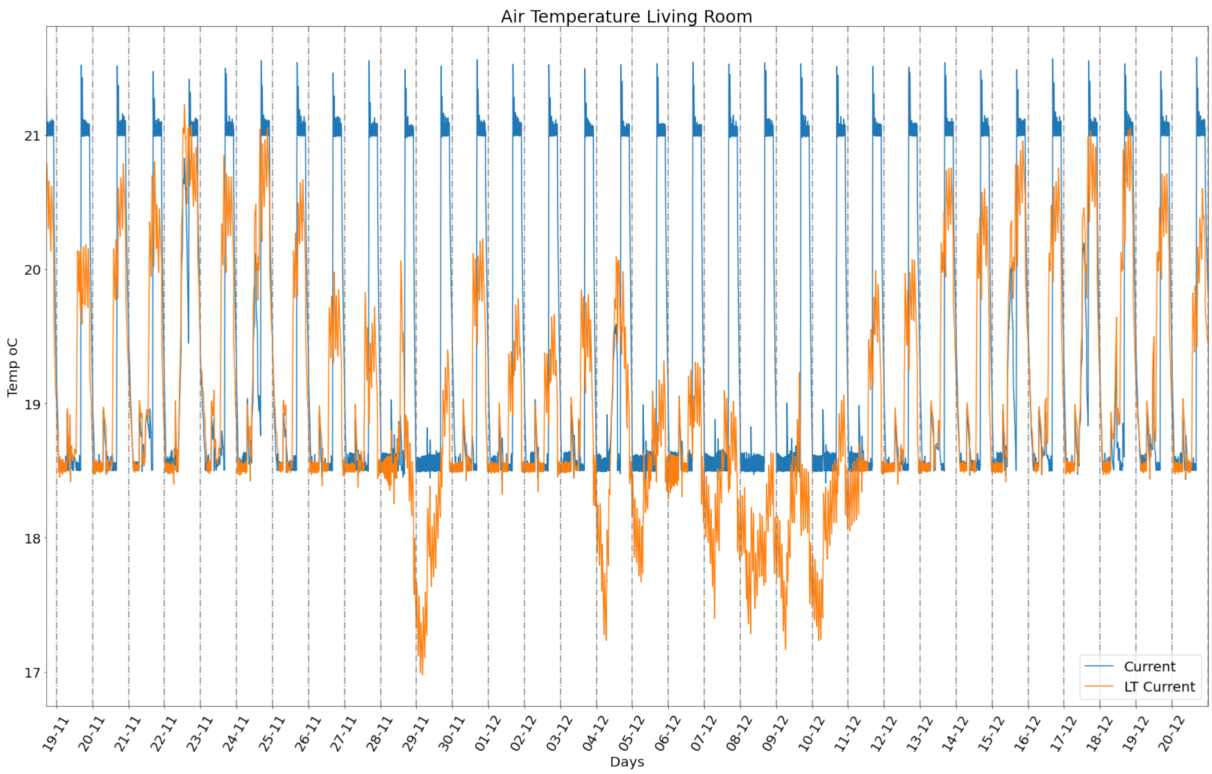


Figure 5.13: Air temperatures in the living room modelled with current HTH and modelled with LTH through the current radiators at current insulation levels

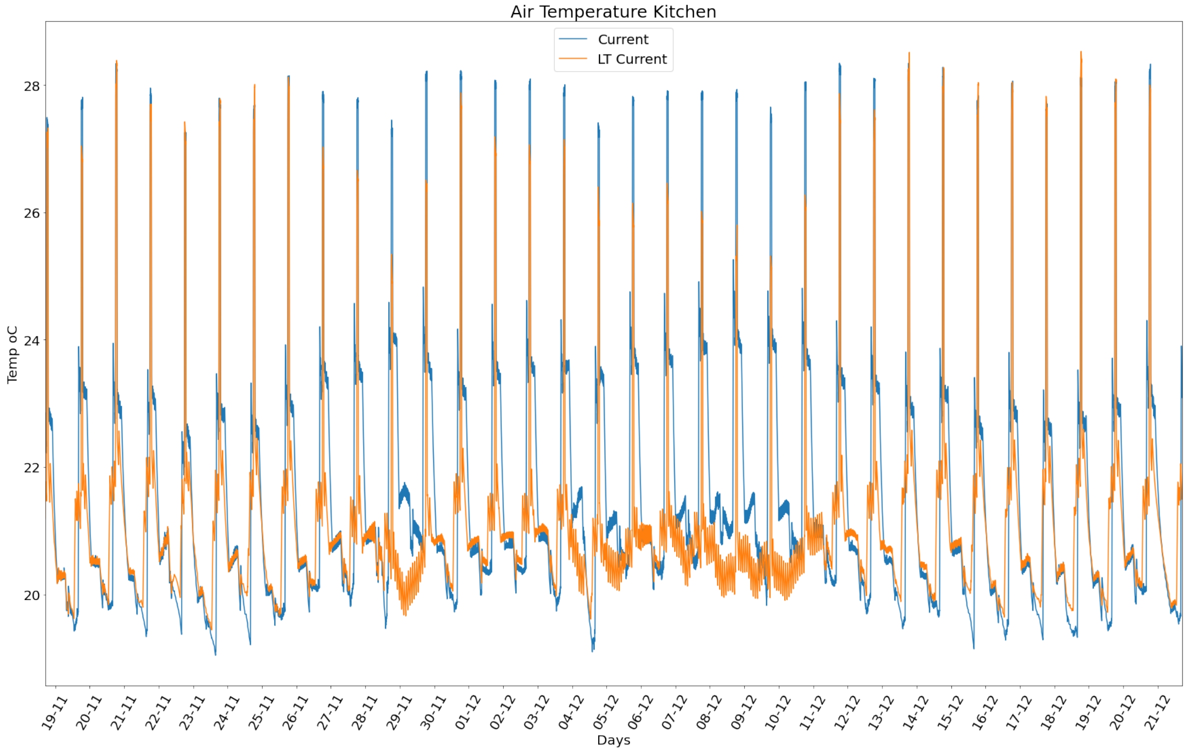


Figure 5.14: Air temperatures in the kitchen modelled with current HTH and modelled with LTH through the current radiators at current insulation levels

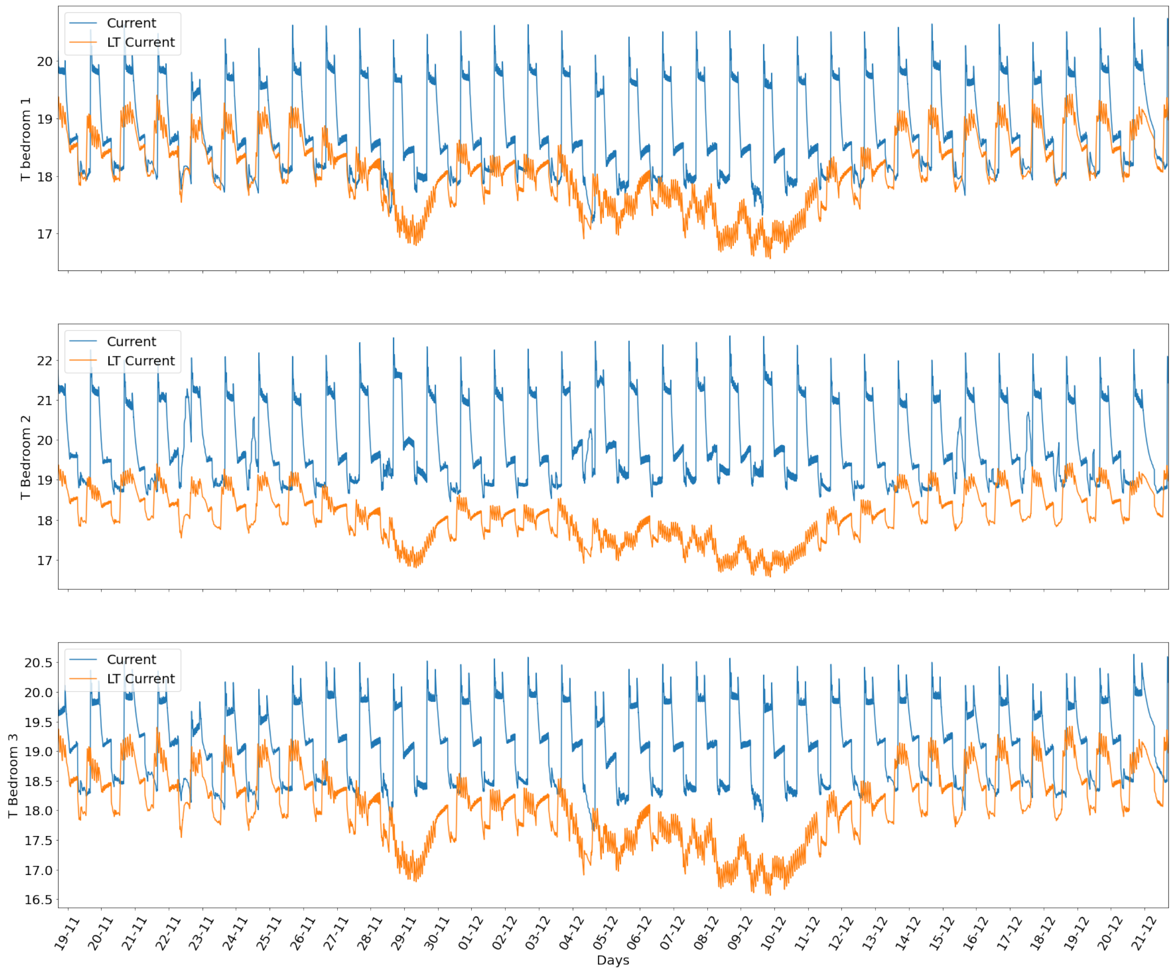


Figure 5.15: Air temperatures in the bedrooms modelled with current HTH and modelled with LTH through the current radiators at current insulation levels

Surface Temperatures

Figure 5.16 shows the surface temperatures at the measured locations. All three surface temperatures, show a similar pattern as the current situation albeit slightly cooler. The lowest façade temperature in this case reaches values as low as 17.75 °C in the entire heating season, which is only slightly lower than in the current situation.

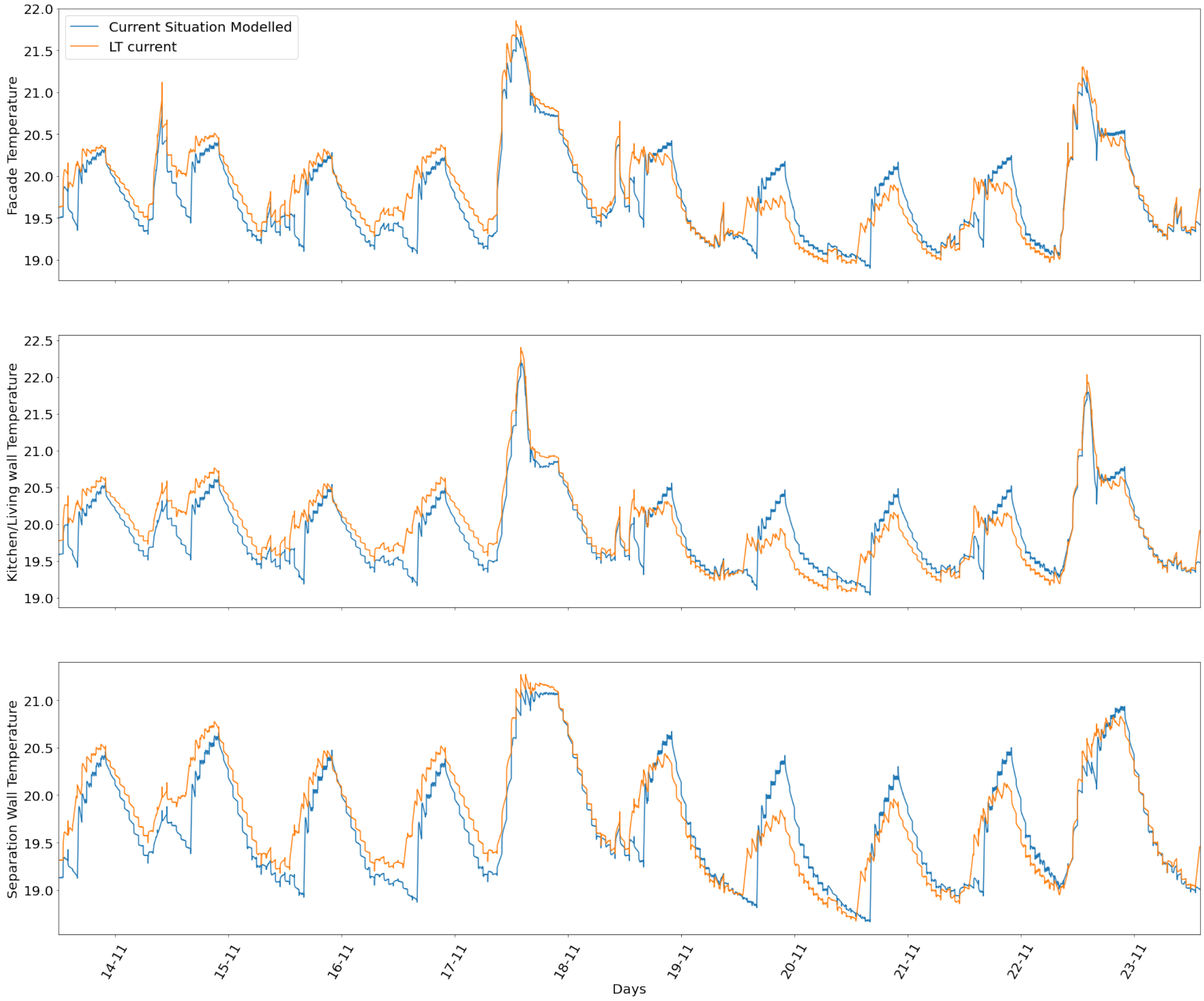


Figure 5.16: Surface temperatures in the living room modelled with current HTH and modelled with LTH through the current radiators at current insulation levels

Comfort

Figure 5.17 shows the modelled PMV for a whole year in case of low temperature heating through the current radiators and with current insulation levels. The average PMV for the heating season is -0.48, which still lies within the acceptable ±0.5 range. It reaches values below -0.5 for 51.96% of the time however, which exceeds the suggested 10%. The minimum PMV reached is -1.06. The average PPD for this situation is 13.70%. This is higher than the recommended 10% discomfort. The PPD reaches a maximum value of 27.64%.

Figure 5.18 shows the thermal comfort according to the adaptive model. This shows a wider scatter making the building class vary from B down to C. This fits in with the rest of the comfort results. Overall the performance is not declined by a significant amount. The capacity of the radiators is however not enough to cope with ambient temperatures dropping below around 5 °C. This causes large dips in the indoor air temperature to as low as 16.98 °C, which is well below the desired 18,5 °C. The peak capacity of the current radiators is not sufficient when changing to low temperature heating.

Figure 5.19 shows the individual comfort criteria. Especially for the average wall temperature, a much larger variety in outcomes can be seen compared to the current dwelling. The outcomes for low temperature heating range from too cold air and surface temperatures to those temperatures being too high. This further substantiates the assumption that there is a lack of peak heating capacity when changing to low temperature heating with the current radiators.

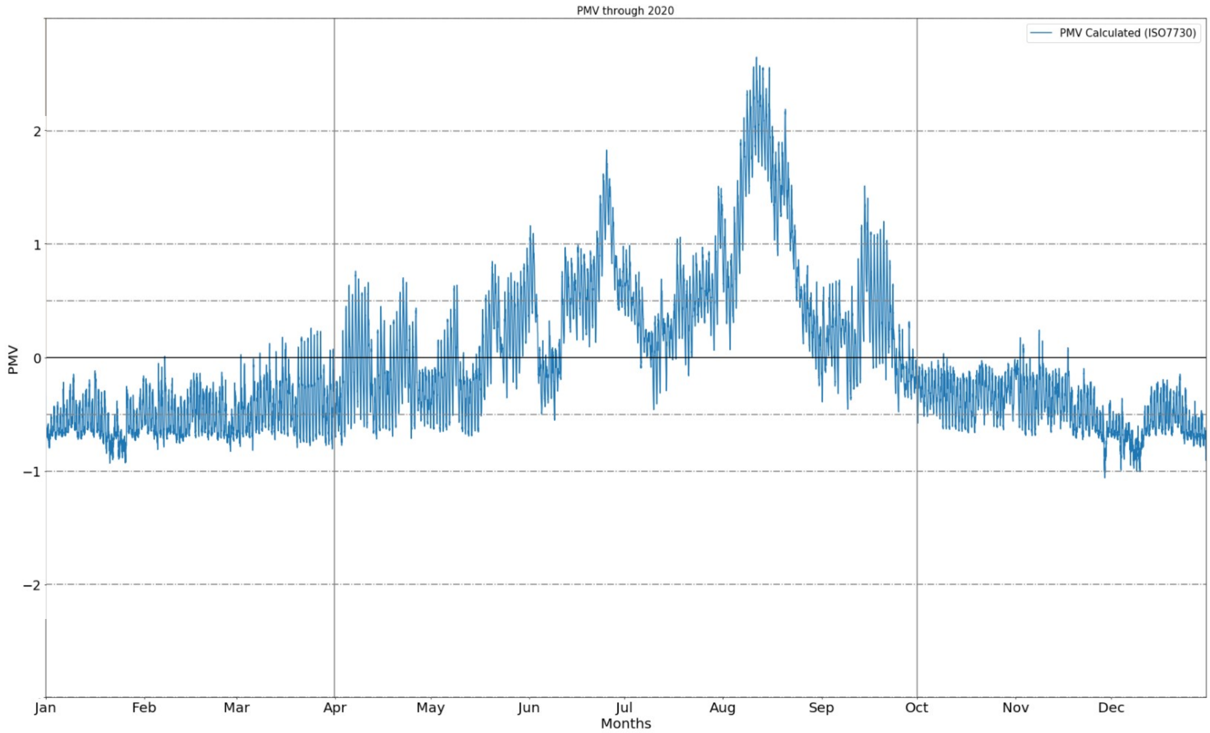


Figure 5.17: PMV in the living room when changing to low temperature heating through the current radiators

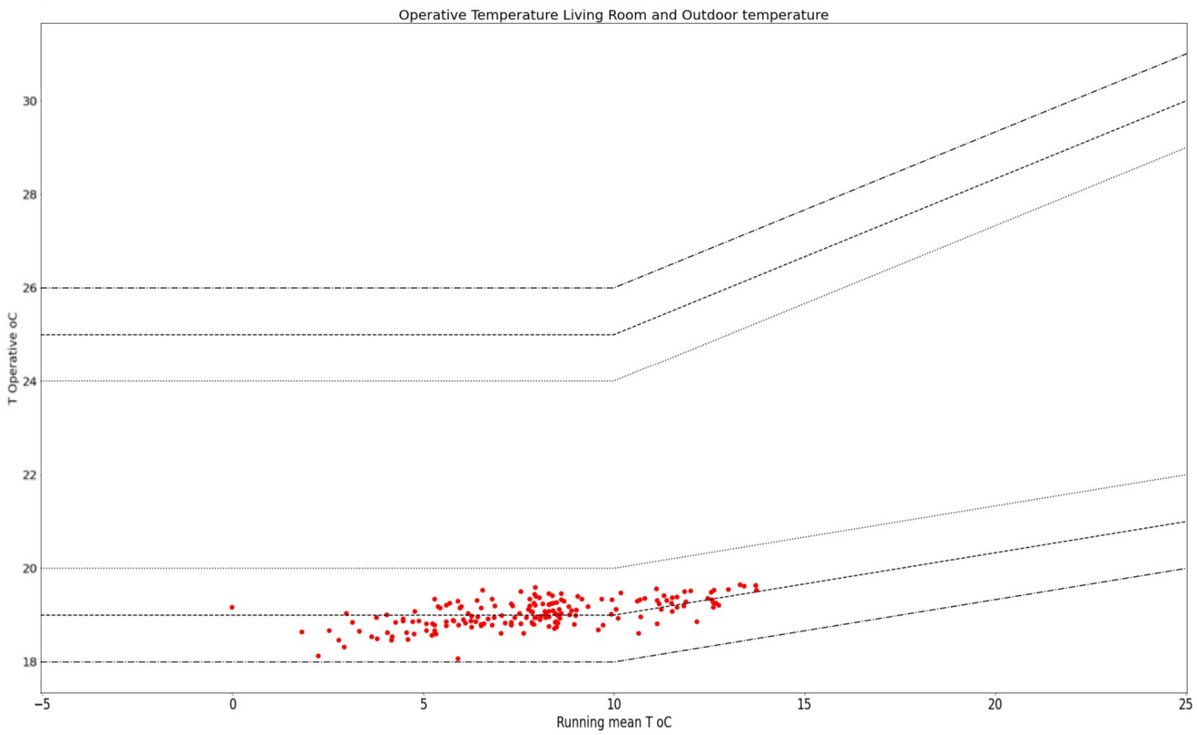


Figure 5.18: Adaptive comfort in the Living room when changing to Low Temperature heating through the current radiators

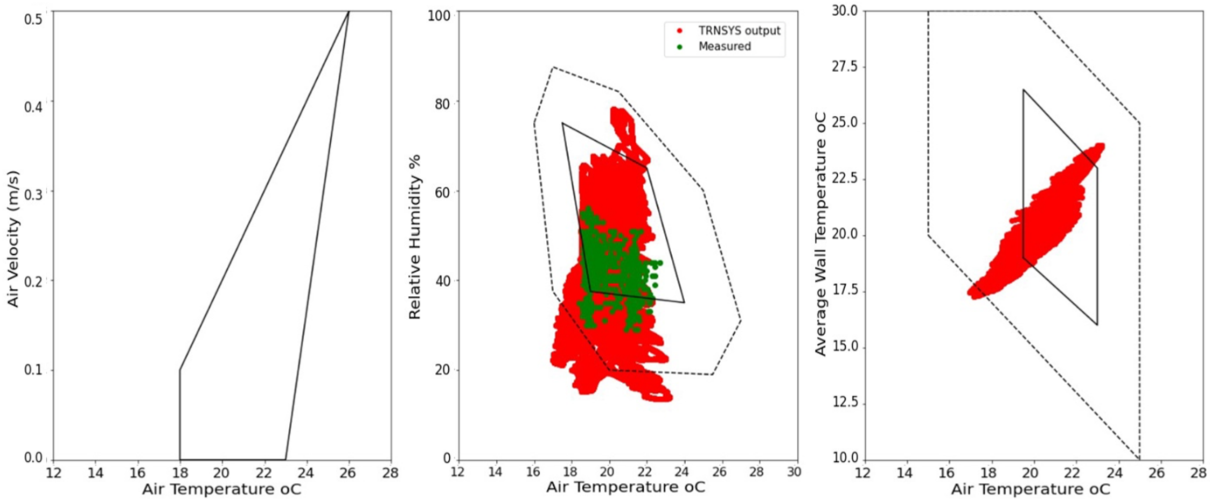


Figure 5.19: Individual comfort aspects when changing to low temperature heating through the current radiators

PMV Close to Façade

In this case the surface temperatures remain relatively stable, whereas the air temperature does not. During low ambient air temperatures below around 5 °C, the indoor air temperature drops as well. This creates discomfort from the air temperature being too low. The PMV close to the façade is, on average, however slightly better at -0.44 compared to the middle of the room at -0.48. This could be explained by the thermal energy stored in the opaque walls radiating, creating higher comfort levels close by. The lowest PMV is on the other hand slightly lower at -1.07 close to the façade. This could be explained by the cold window surface having a greater impact close to it during very cold days. Figure 5.20 shows the comparison in PMV for both locations throughout 2020.

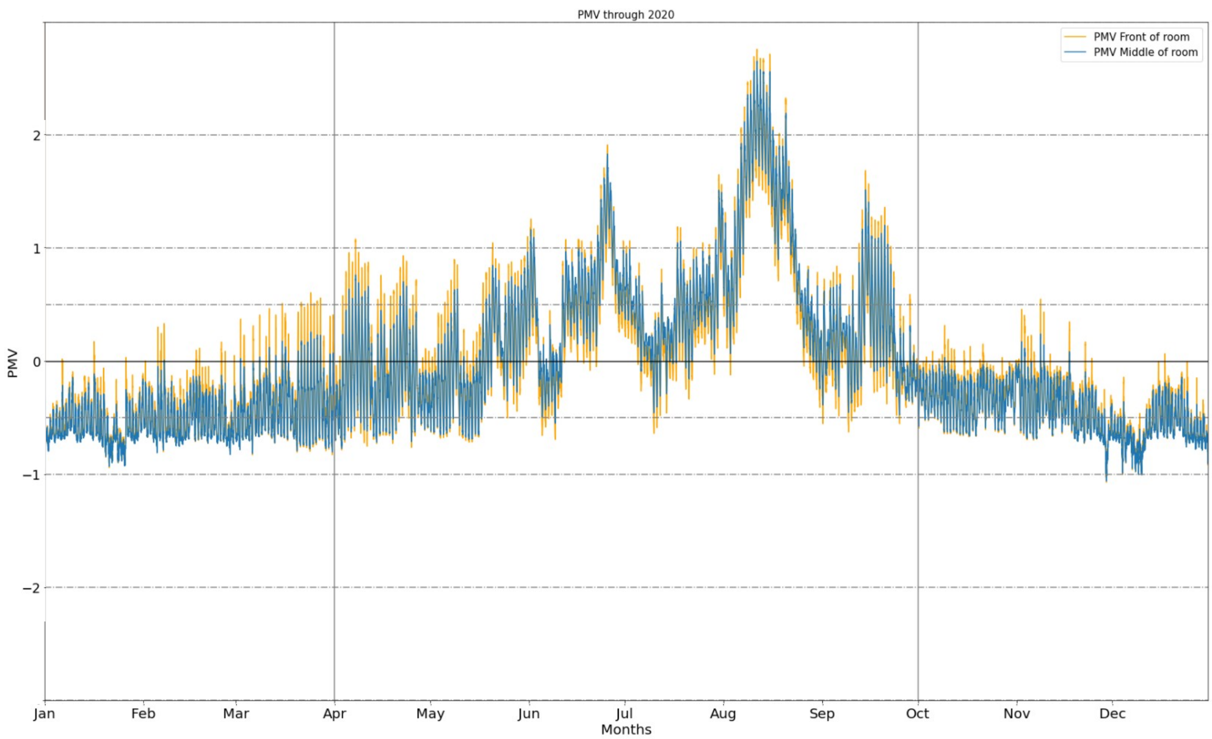


Figure 5.20: PMV throughout 2020 in the middle and front of the living room

Required Façade Update

The capacity of the radiators is not sufficient to heat the living room to the lowest desired temperature of 18.5 °C with Low Temperature water. This is shown by the adaptive model when the outdoor running mean temperature reaches below 5 °C, the operative temperature also drops. One of the ways to reduce the required peak-performance of the heating delivery system is to increase the façade insulation.

In this example, the windows have been updated to HR+++ with a U-value of 0.81 W/m^{2}K. With a U-Value of the façade of 0.056 W/m^{2}K (R_c = 17.85 m^{2}K/W), which is around 5 times higher than the current insulation level with a U-value of 0.288 W/m^{2}K and completely unrealistic, comfort levels are slightly enhanced. They do not reach current levels however. Table 5.3 shows the difference between the comfort parameters for the old and new façade in case of low temperature heating through the current radiators. Figure 5.21 shows the adaptive model. From this figure, it becomes clear that especially at lower running mean outdoor temperatures, the indoor operative temperature is still not sufficient. The lowest achieved comfort point is now closer to current heating and insulative properties.

Closer to the façade a similar pattern occurs. The average PMV is slightly better at -0.41 but the lowest value is slightly lower at -0.99 compared to the middle of the room. This can be explained by the same reasons as before a façade renovation.

Table 5.3: Façade and comfort parameters in case of LTH through the current radiators

	PLAN2: LTH ORIGINGAL FAÇADE MIDDLE	PLAN2: LTH NEW FAÇADE MIDDLE
U- VALUE FAÇADE	0.288	0.056
U-VALUE WINDOWS	1.2	0.81
MINIMUM AIR TEMPERATURE °C	16.98	17.31
AVERAGE PMV	-0.48	-0.44
MINIMUM PMV	-1.06	-0.97
% OUTSIDE ±0.5	51.96	49.33
AVERAGE PPD	13.7	9.8
MAXIMUM PPD	27.64	24.28
ADAPTIVE COMFORT CLASSIFICATION	B - C	B - C

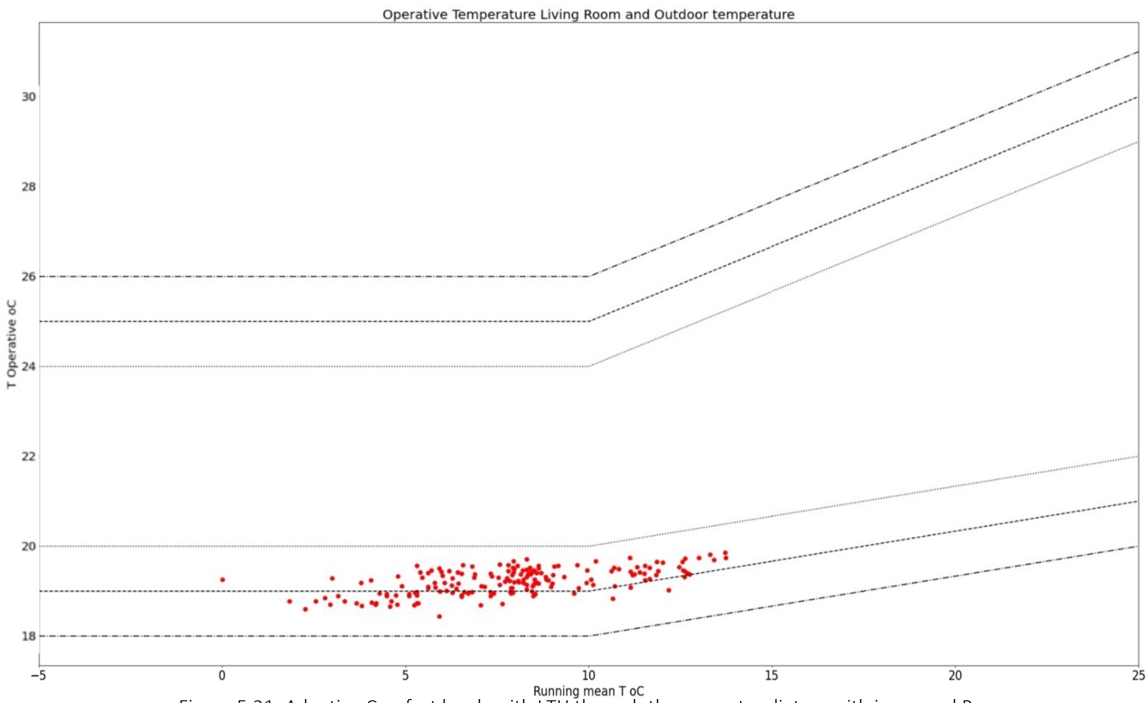


Figure 5.21: Adaptive Comfort levels with LTH through the current radiators with increased Rc

Renovation Plan

In order to realize a U-Value of 0.81 W/m^{2}K for the updated windows, triple glazing is required. This type of glass is widely available nowadays, but does not fit in all types of window frames due its larger thickness. It should be investigated if this triple glazing is possible in the current frames. If this is not the case, the frames will also need to be upgraded.

The main limitation in this plan is the required insulation of the façade. The proposed increased insulation value cannot realistically be achieved. The following section has only been included for illustrative purposes as to why this is not realistic.

In order to reach an Rc of 17.85 m^{2}K/W, which is not reasonable, the added layer needs to have a large thickness. This required thickness is dependent on the used insulation material. Most conventional insulation materials such as mineral or glass wool, but also most natural (bio-based) insulation materials such as hemp wool, have a thermal conductivity of around 0.04 W/mK. With these insulative material properties, the thickness of the added layer would have to be over 60 cm. This 60 cm is only insulative material, so excluding finishing or cover panels. The total thickness of the layer will be slightly higher. As can be seen in the literature review, the study by Mahlia et al. (2007) shows that for a thermal conductivity of 0.04 W/mK, a thickness of 0.06 m would be the optimum. With a thickness of 10 times this value and a still relatively poor thermal comfort performance compared to the current situation, it could be questioned whether this is an advisable renovation measure.

If this renovation were to be carried out however, the two options available are the add-in or wrap-it principles. The add-in principle would reduce the usable living surface area significantly. Therefore, the recommend principle would be to 'wrap-it'.

An alternative to the conventional insulation materials is to use a more innovative insulative material with a lower thermal conductivity. One example is silica aerogel, which can have a thermal conductivity of as low as 0.018 W/mK (Caps & Fricke, 2004). This would reduce the required thickness of the added layer down to 26 cm. The study by Mahlia et al. (2007) showed however that the optimum thickness for a material with a thermal capacity this low is around 0.05 m. It could again be questioned whether this option is advisable considering the achieved comfort levels.

Another option would be a Kingspan Vacuum panel. This has a Lamba value of 0.007 W/mK. The maximum thickness of these panels is 50 mm however, creating an Rc of 7.1 m^{2}K/W (Kingspan, 2021). This could be solved by adding multiple layers. But again, this is not deemed a feasible renovation plan. A second objective against this form of insulation is the price, which is not yet published openly by Kingspan. It could be assumed to be higher than more commonly used insulation materials.

5.3 Plan 3: LTH with LTH Radiators

This plan aims to assess the impact of low temperature heating through low temperature radiators. These radiators are adjusted to provide higher capacities than ordinary radiators when the water temperature is lowered. One of the ways this is achieved is with an increased convective part, for example by forced convection in the form of fans inside the radiators. These LTH radiators are usually larger and have more coils running through them. If space allows it, the LTH radiators can be installed at the location of the old radiators if this is desired. This would impose minimal renovation measures and intrusion for residents. It should be mentioned however that in most cases the distribution of the water from the heat generator (e.g. a heat pump) to the radiators needs to be adjusted too. This means the pipes inside a dwelling need to be updated resulting in an intense renovation. All other insulative values of the façade and windows and ventilation specifications are kept the same as the current situation in this simulation.

Radiator plan

In this plan, the locations of the radiators are assumed equal to the current situation. The capacity of the radiators is however increased. This increase can be up to 50% compared to the situation where LTH is ran through the current radiators. This provides the capacities displayed in table 5.4. This 50% increase can be achieved by placing convector fans in the current radiators (Milieu Centraal, 2021).

A more accurate way to determine the required heating capacity per room is by following the ISSO publication 51. In this document, a calculation method for the heat loss from transmission, infiltration and ventilation and from occupational requirements is presented. This heat loss is then governing for determining the required capacity of the heat delivery system per room. Also for the dwelling in this case study a calculation following the ISSO 51 was made. This results in the capacities presented in table 5.4. It can be seen that the required capacity according to ISSO 51 is more than the 50% increase from radiators fans. Therefore it is most likely necessary to update the LTH radiators entirely so the values based on ISSO 51 will be used in this simulation. A detailed overview of the ISSO 51 calculation can be seen in Appendix K: ISSO 51 Calculation. The new LTH radiators will possibly have to have a larger surface area than the current radiators. This can be achieved by installing several different radiators or using one large surface. Since this installation can have several different configurations, for now the view factors are based on the current radiator plan. The main capacity increase is then assumed to be from forced convection changing the convective coefficient of the energy delivery to the room.

Table 5.4: Heating Capacity of LTH Radiators

Room	*HT Capacity Current W*	*LT Capacity Current Radiators with fan W*	*Required capacity ISSO 51 W*
Living	2303	932.7	1304
Kitchen	1186.2	491.7	564.9
Bathroom	526	213	284.9
Bedroom1	1620	656.1	645.7
Bedroom2	1339.4	543.1	596.3
Bedroom3	493	199.7	441

Results

Air temperatures

The air temperatures outputted by TRNSYS with this radiator plan can be seen in figures 5.22 and 5.23. These graphs show that for during 2020, the required temperatures are met for the most part. But zoomed in on the measured time period in figure 5.23, it becomes clear this is not always the case. Especially the peaks to 21 °C are not always met. The minimum of 18.5 °C is maintained most of the time. The air temperature in 2020 in the living room got to as low as 17.29 °C. This can be seen in figure 5.23 in the night of November 29.

Figure 5.24 shows the air temperature in the kitchen. This shows a similar pattern to the current situation. Again this could be explained by the relatively small façade ratio in this room and the large internal gains each evening. Figure 5.25 shows the air temperatures in the bedrooms. These drop below the measured temperatures indicating a lack of capacity in these rooms.

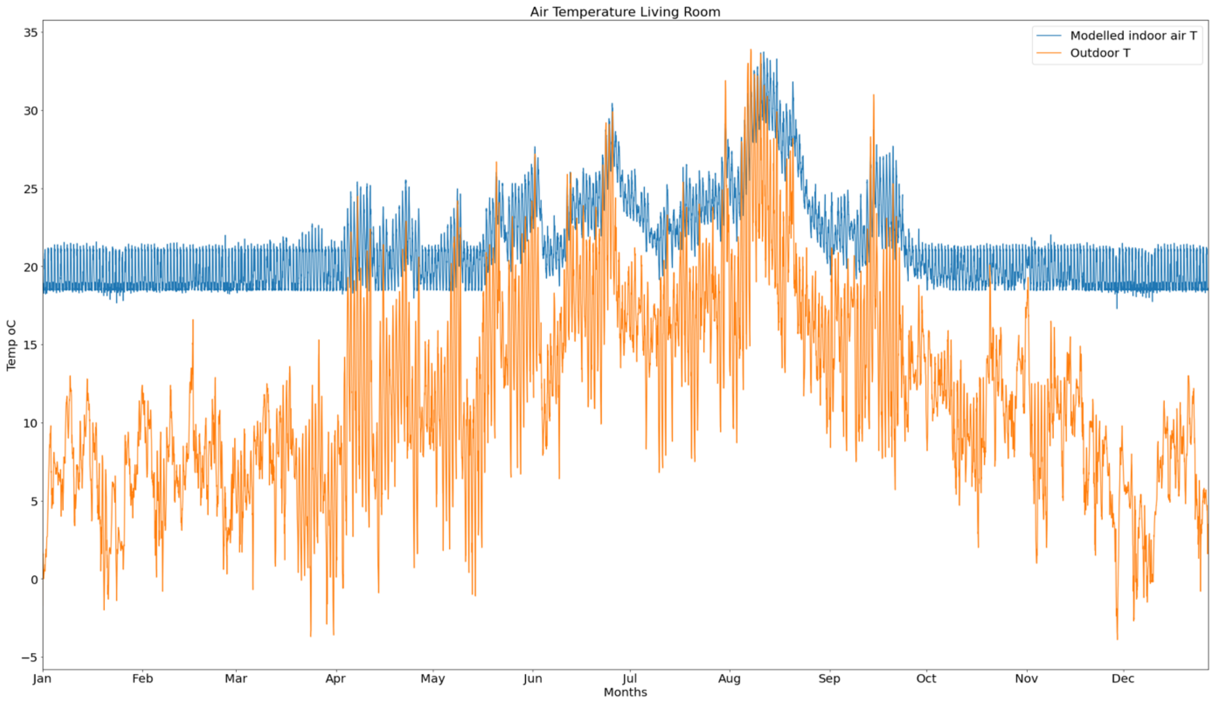


Figure 5.22: Air temperatures living room 2020 for LTH through LTH radiators

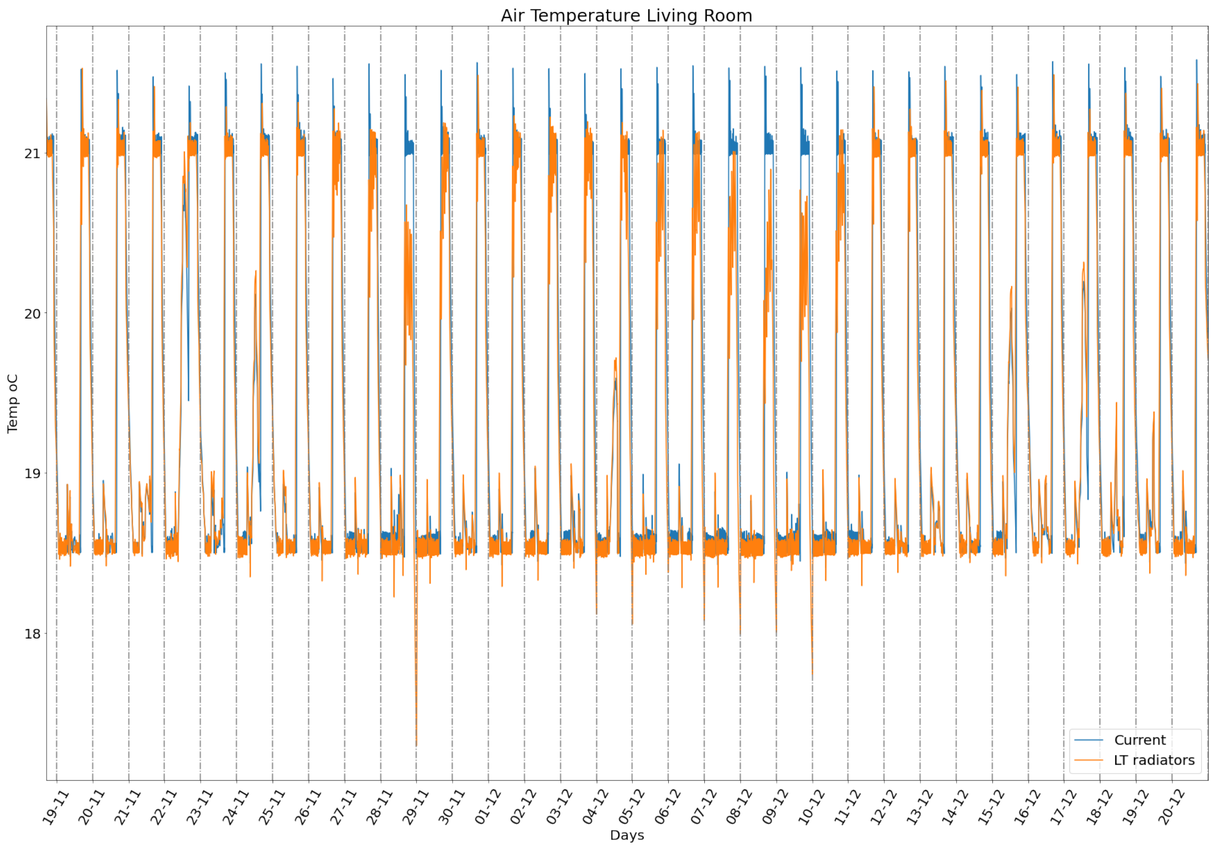


Figure 5.23: Air temperatures in the living room modelled with current HTH and modelled with LTH through LT radiators at current insulation levels

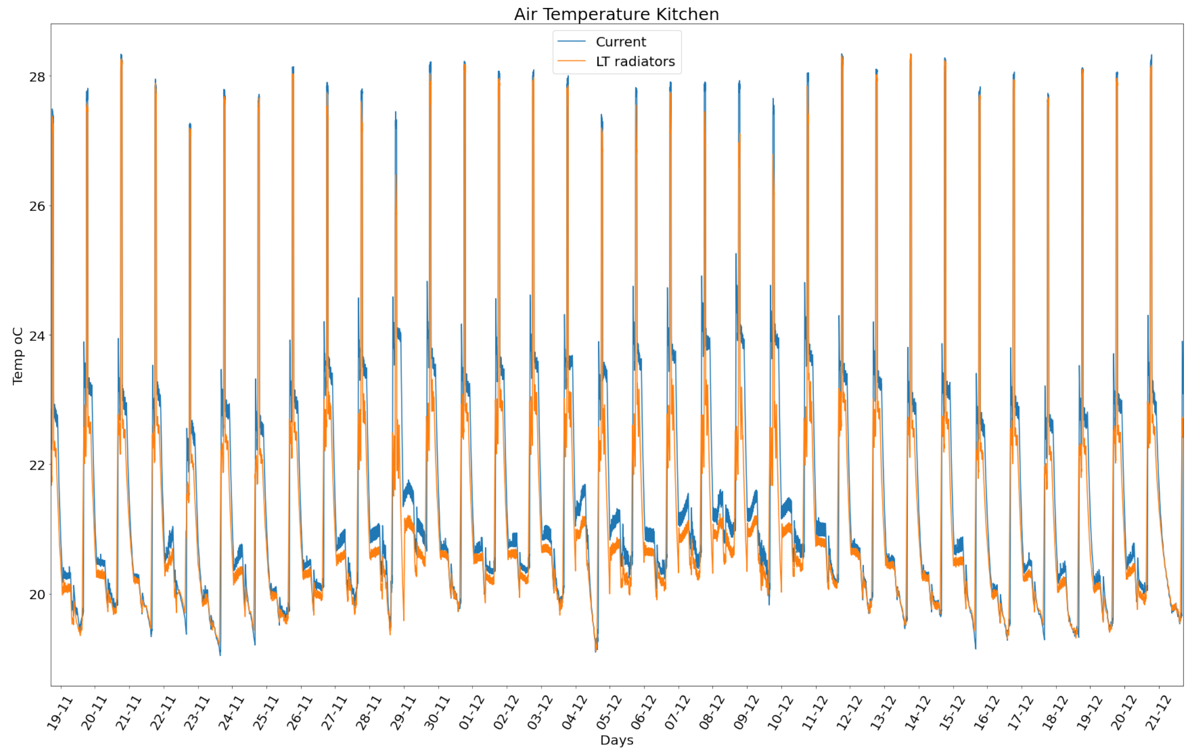


Figure 5.24: Air temperatures in the kitchen modelled with current HTH and modelled with LTH through LT radiators at current insulation levels

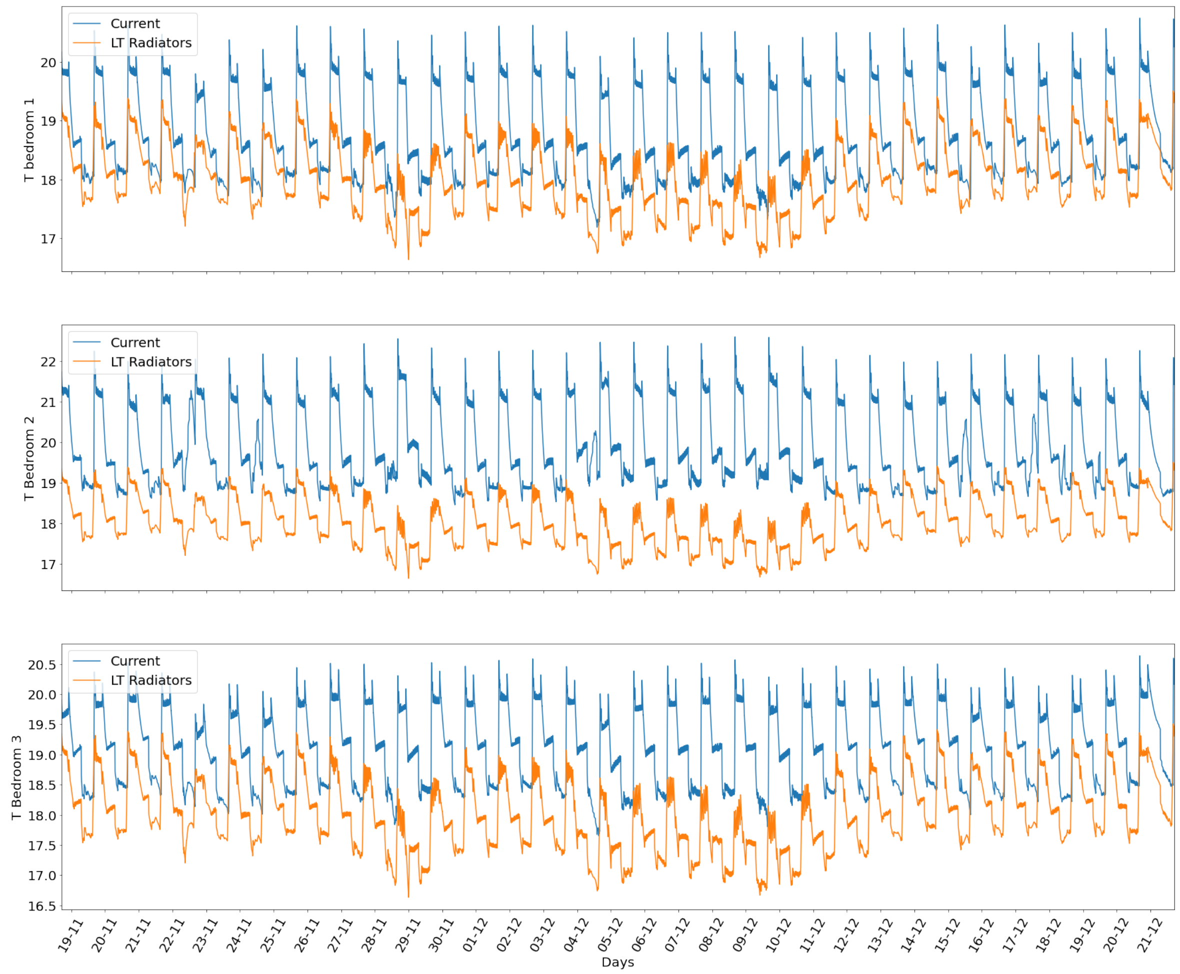


Figure 5.25: Air temperatures in the bedrooms modelled with current HTH and modelled with LTH through LT radiators at current insulation levels

Surface temperatures

Figure 5.26 shows the modelled surface temperatures of the planes for the current situation and with LT radiators. The separation wall between the kitchen and living room and the adjacent house show similar patterns to the current situation and the measured situation. The modelled temperatures of the façade are higher than the measured temperatures however. They do display a large resemblance to the modelled temperatures of the façade in the current situation.

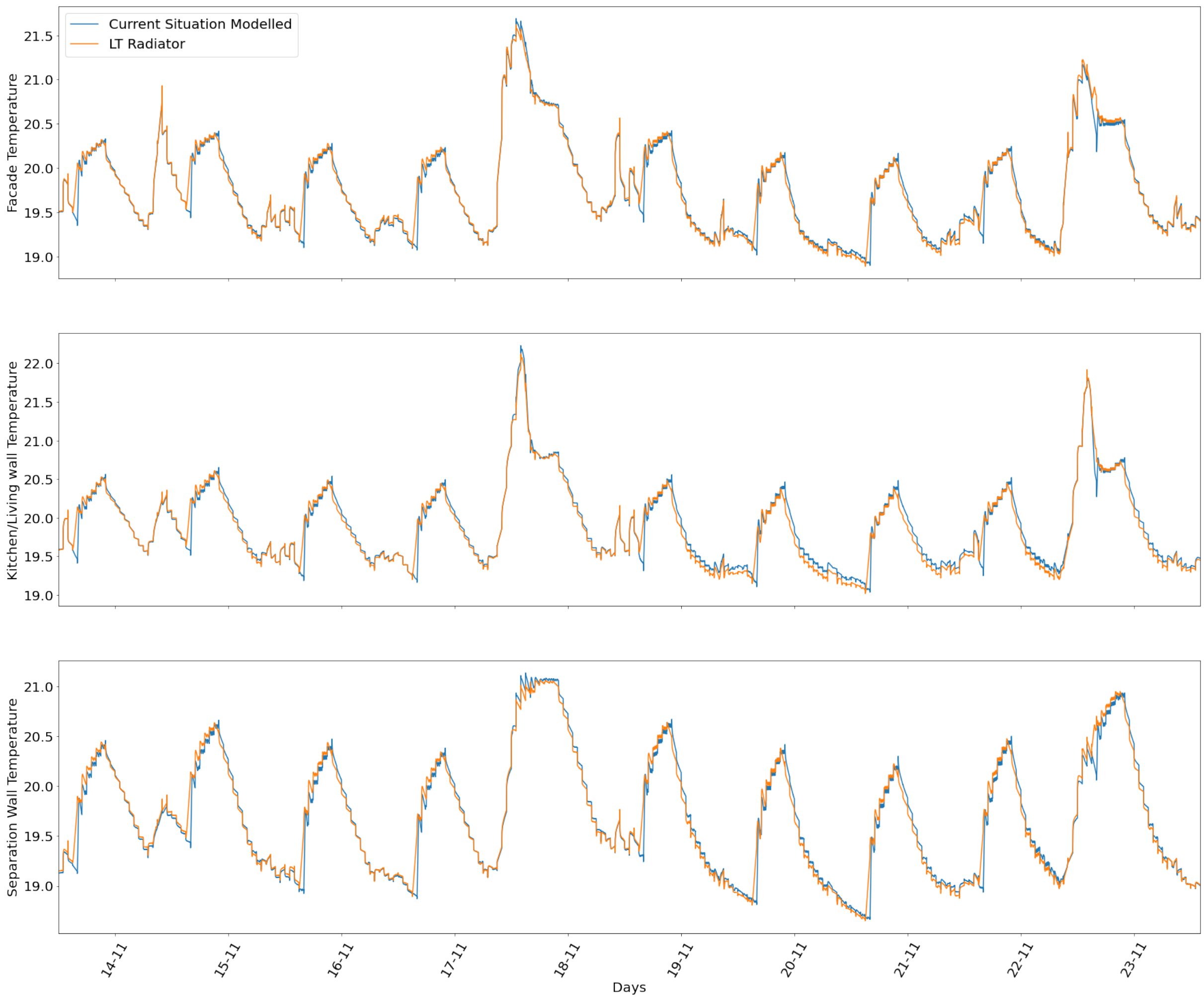


Figure 5.26: Surface temperatures in the living room modelled with current HTH and modelled with LTH through LT radiators at current insulation levels

Comfort

The comfort levels in the middle of the living room were again determined by the workaround presented in chapter 4 of this study. Figure 5.27 shows the resultant PMV throughout 2020. On average this PMV had a value of -0.47 and reached a minimum value of -0.94 during heating season. It reached values outside of ±0.5 for 52.32 % of the time. This matches an average PPD of 10.22 with a maximum of 22.79.

In figure 5.28 the comfort levels according to the adaptive model are displayed. The building reaches a class B and C. Similar to the situation with LTH through the current radiators, the comfort levels drop when the running mean outdoor temperatures drop as well. Below 8 °C the general comfort class of the building drops from mainly B to mainly C. This would indicate the heating system still lacks peak capacity when outdoor temperatures drop. The individual comfort parameters stay within the 'still comfortable' regions, as can be seen in figure 5.29. The average surface temperature does show a more diagonal pattern similar the situation of LTH through the current radiators.

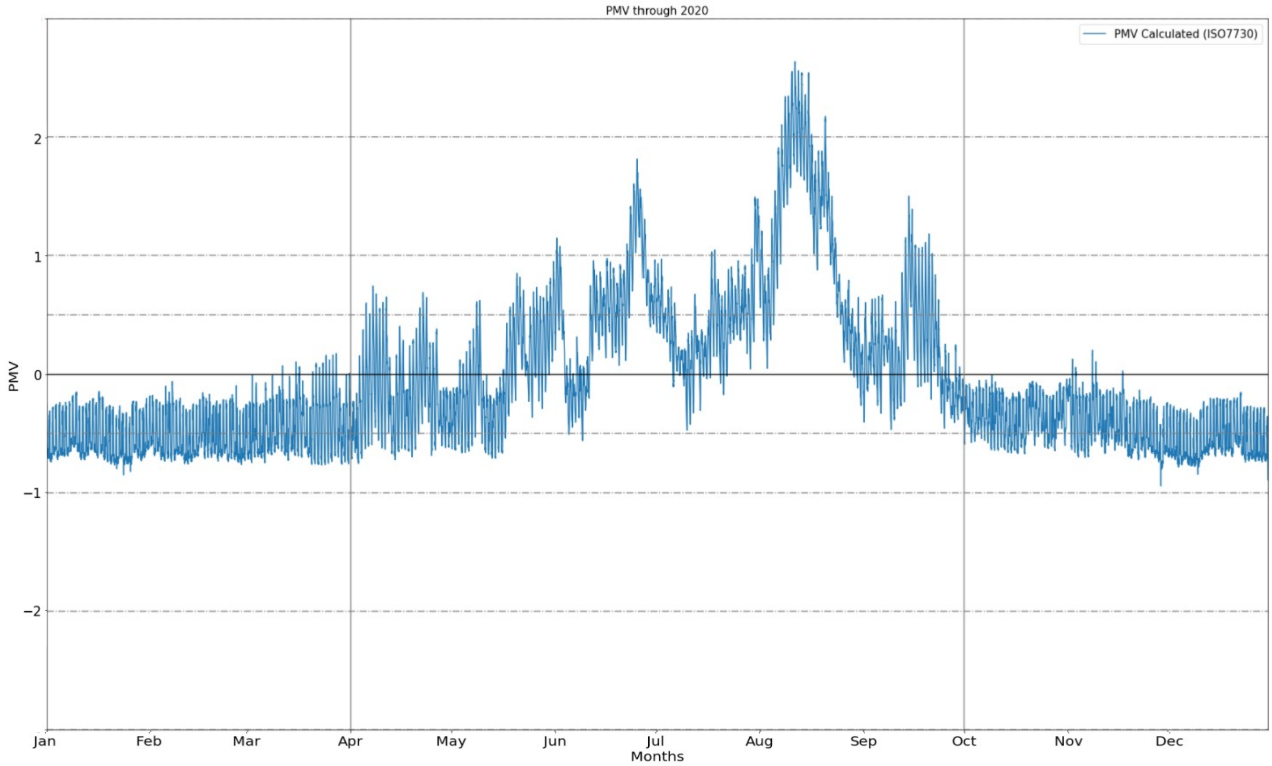


Figure 5.27: PMV for LTH through LTH radiators throughout 2020

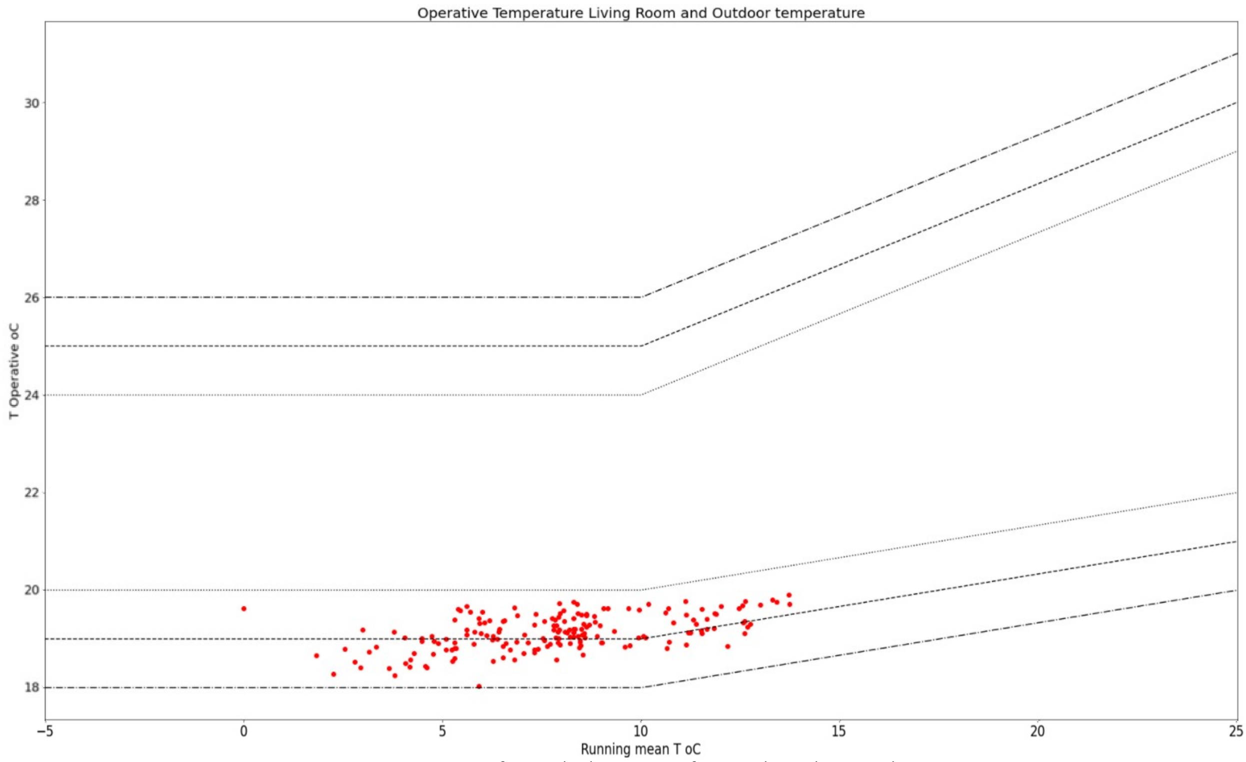


Figure 5.28: Operative comfort in the living room for LTH through LTH radiators

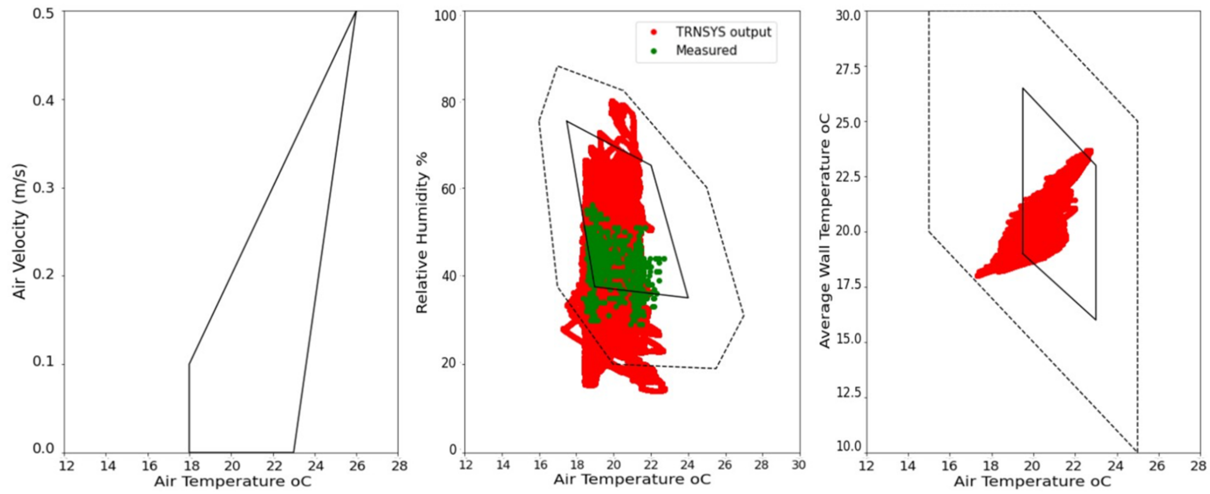


Figure 5.29: Individual Comfort parameters LTH through LTH radiators

Comfort close to façade

The comfort levels were also modelled close to the façade. Here an average value of -0.46 is reached with drops down to -1.0 during heating season. The higher average can be explained by the higher peaks in PMV close to the façade, for example in March. This can be explained by higher solar loads heating up the walls creating a greater MRT. That the lowest PMV in the heating season is lower here can again be explained by the large cold glass plane in this façade. The comparative graph for 2020 is displayed in figure 5.30.

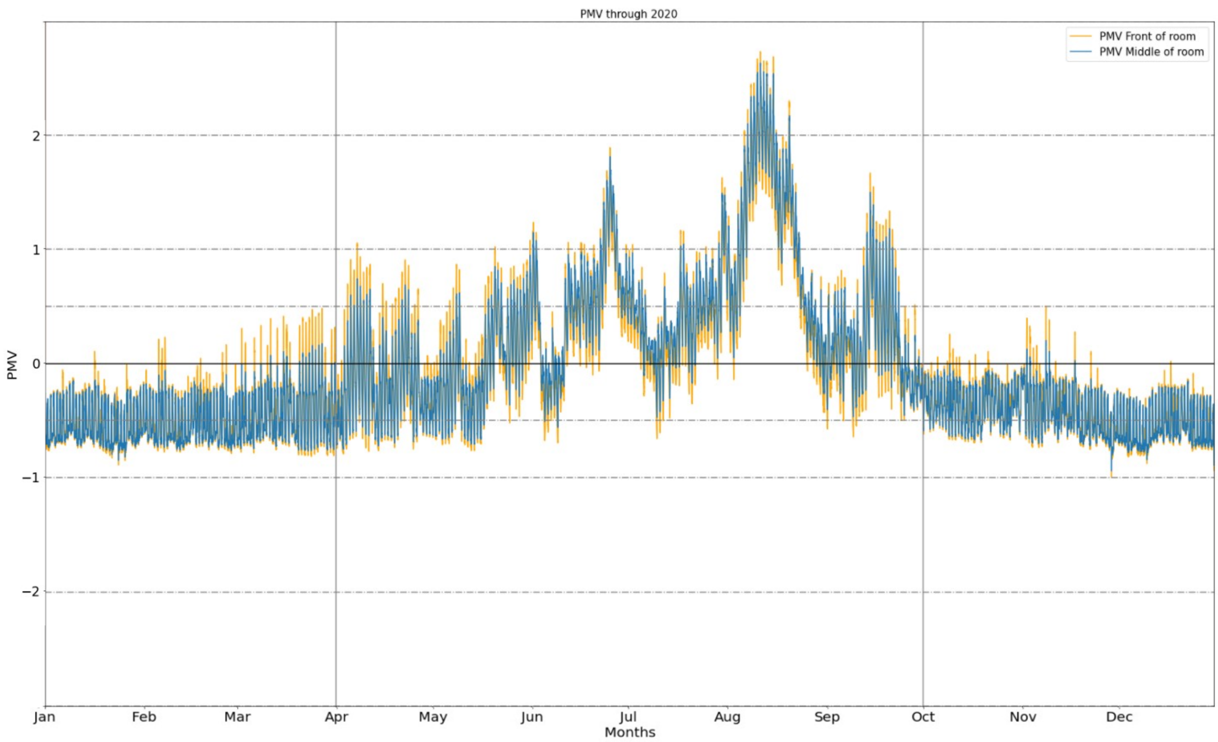


Figure 5.30: PMV throughout 2020 close to the façade and in the middle of the room for LTH through LTH radiators

Required Renovation

In order to create a comfort level that matches or exceeds the current situation, a renovation is required. The aim of this renovation is to limit the heat loss through the façade. This can again be done by updating the insulative properties of the façade. The minimum reached air temperature, with the current insulative properties, is 17.29 ^{o}C. Most of the time the modelled air temperature is not too far off the desired minimum temperature of 18,5 °C. From figures 5.22 and 5.23 it can be derived that the desired increase to 21 °C is not always achieved.

One commonly used standard for insulative values are Passive House Standards. This includes a façade insulation with an Rc of 6 m^2K/W. This insulative value for a façade coincides with the recently presented 'Target Values' (Cornelisse, Kruithof, Valk, & Hartlief, 2021). Compared to the current Rc of 3.47 m^2K/W, this is an achievable target to renovate to. Besides the increased façade insulation, triple glazing will be installed bringing the U-value down to 0.8 W/m^2K. These measures alone have a big impact. A simulation with these parameters created an average PMV of -0.44 dropping down to as low as -0.83 during heating season. The average PPD is now 8.66 dropping down to 18.88. The minimum reached air temperature was 17.73 °C. This is still not considered acceptable if the desired temperature is set to 18.5 °C. The operative comfort levels for the living room are shown in figure 5.31. The building still performs significantly worse than a class B building.

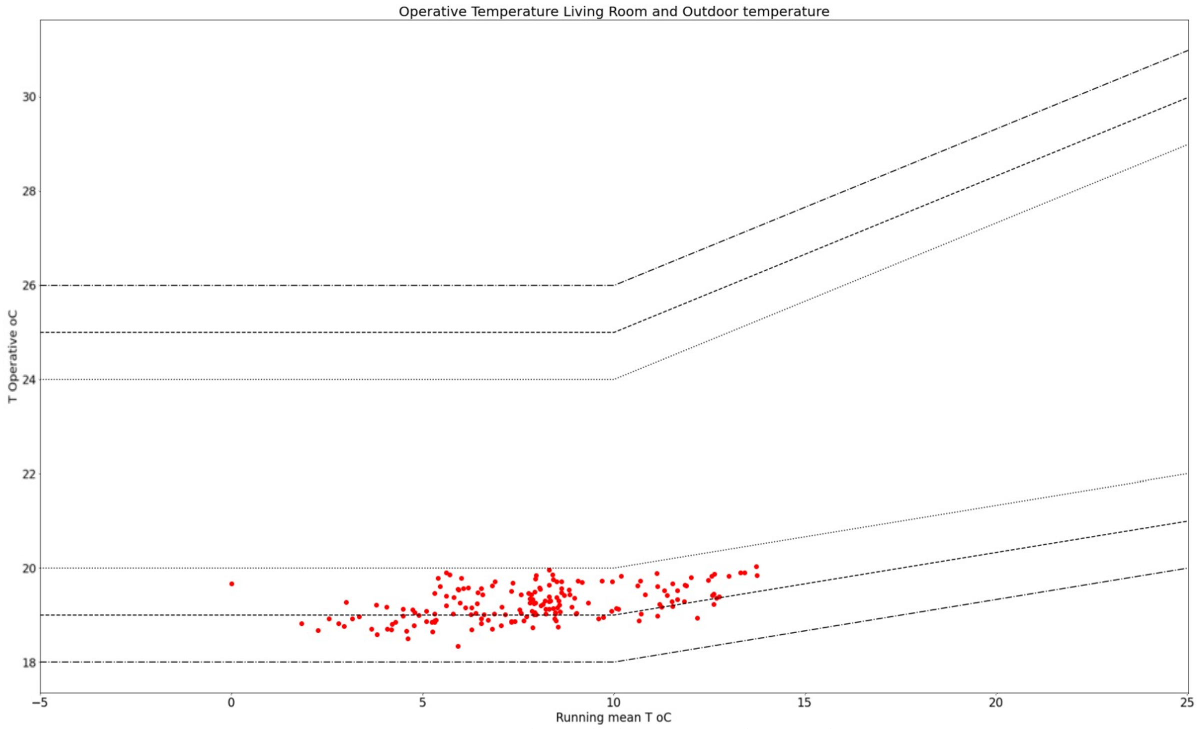


Figure 5.31: Operative comfort in the living room with Passive house Rc

One extra step that can be taken to improve the thermal comfort inside the building is the minimization of infiltration. Especially for renovations this is a challenging task. In table 4.1 it can be seen that a building qualifying as 'excellent' for airtightness has a $q_{v,10}$ value of 0.15 $dm^3/s\ m^2$. This has again been converted to air changes per hour. The results of this conversion can be seen in Appendix H. The results for this simulation are significantly closer to the initial runs for the current situation with HTH.

Air temperatures

With the updated Rc and infiltration values described, the simulation in TRNSYS provides the following graphs for the air temperatures. Figure 5.32 shows the air temperature in the living room for the year 2020 with low temperature water running through the updated radiators with a renovated façade. It can be seen that during heating season the minimum desired temperature of 18.5 °C is maintained throughout. Zoomed in on the measured time period, displayed in figure 5.33, it can be seen that also the desired peaks of 21 °C in the evening is achieved steadily. Figure 5.34 shows the coldest night at 29-11. Here it can be seen that the updated façade helps mitigate the drop during the night. Lastly, from figures 5.35 and 5.36 it becomes clear that the air temperatures in the kitchen and bedrooms are now also maintained similarly to the original situation.

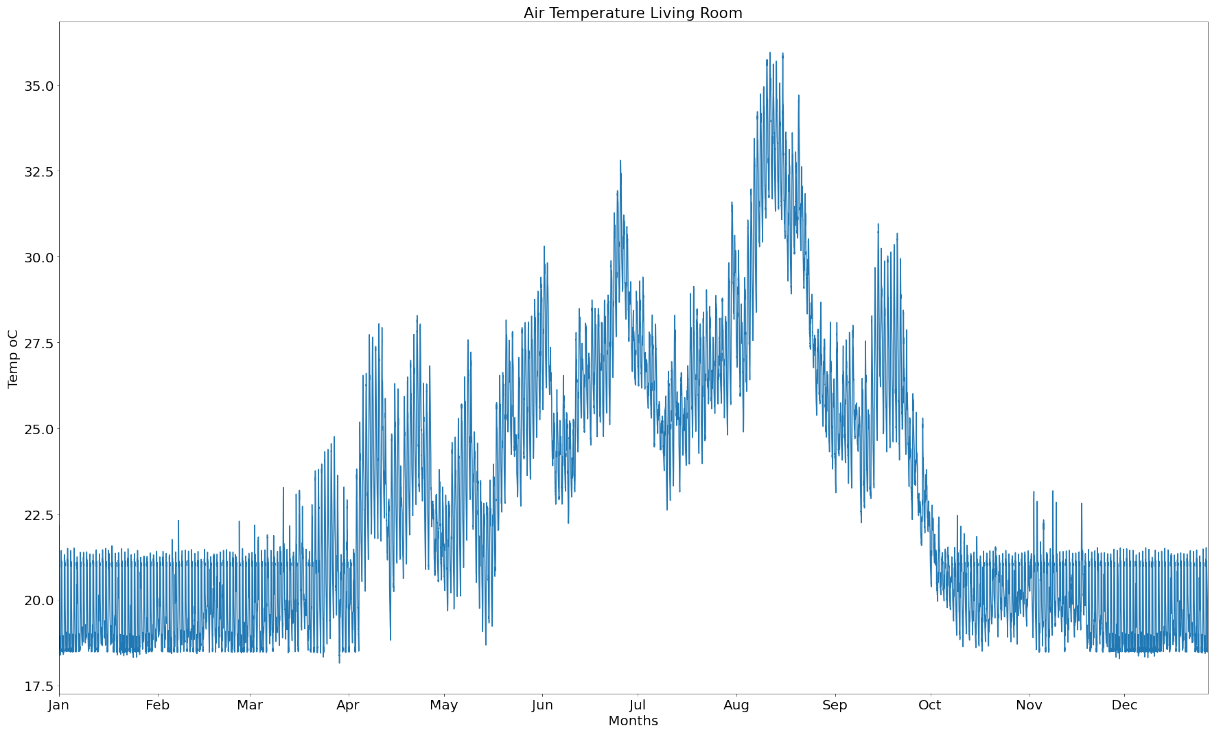


Figure 5.32: Air temperature in the living room throughout 2020 modelled for LTH through LTH radiators with updated facade

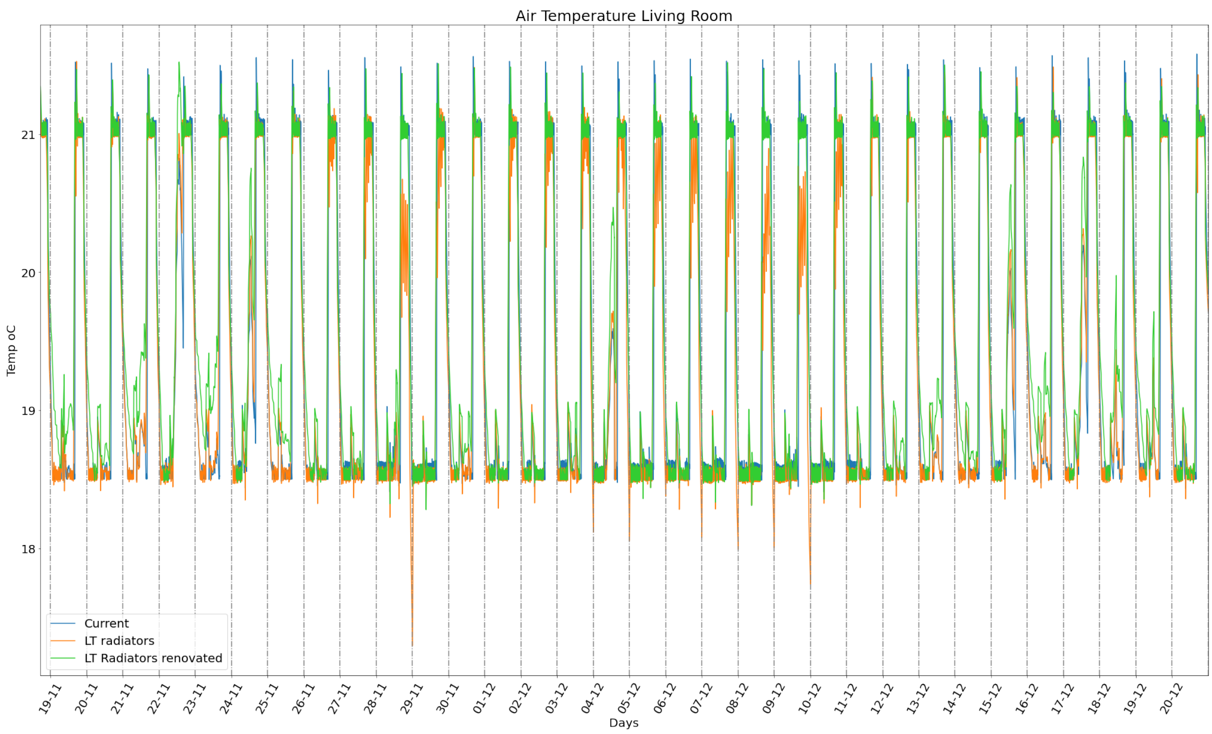


Figure 5.33: Air temperatures in the living room modelled with current HTH and modelled with LTH through LT radiators at current insulation levels and modelled with LT radiators with renovated facade

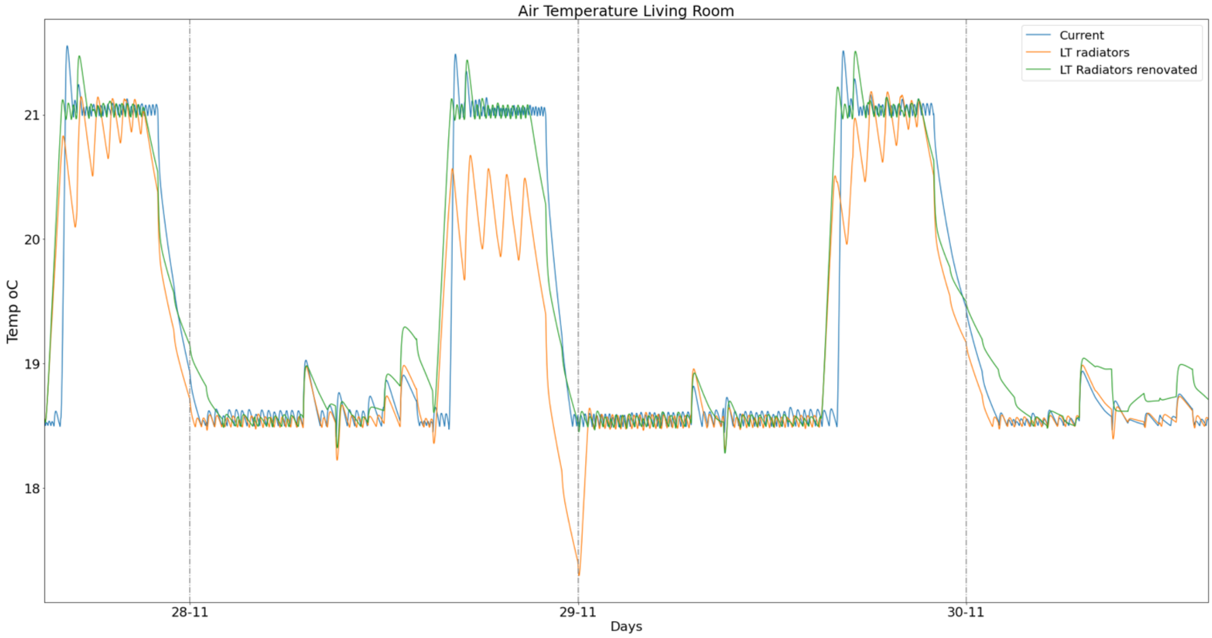


Figure 5.34: Air temperatures in the living room modelled with current HTH and modelled with LTH through LT radiators at current insulation levels and LT radiators with renovated façade at the coldest night (29-11 to 30-11)

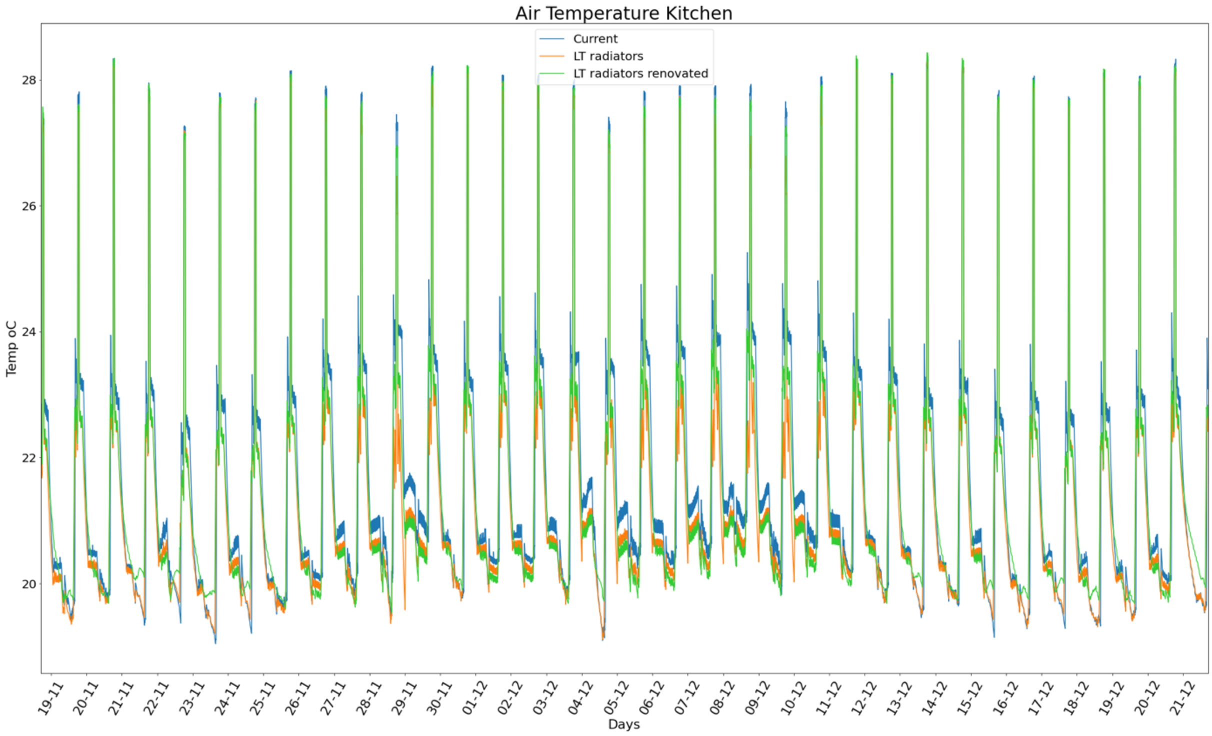


Figure 5.35: Air temperatures in the Kitchen modelled with current HTH and modelled with LTH through LT radiators at current insulation levels and modelled with LT radiators with renovated facade

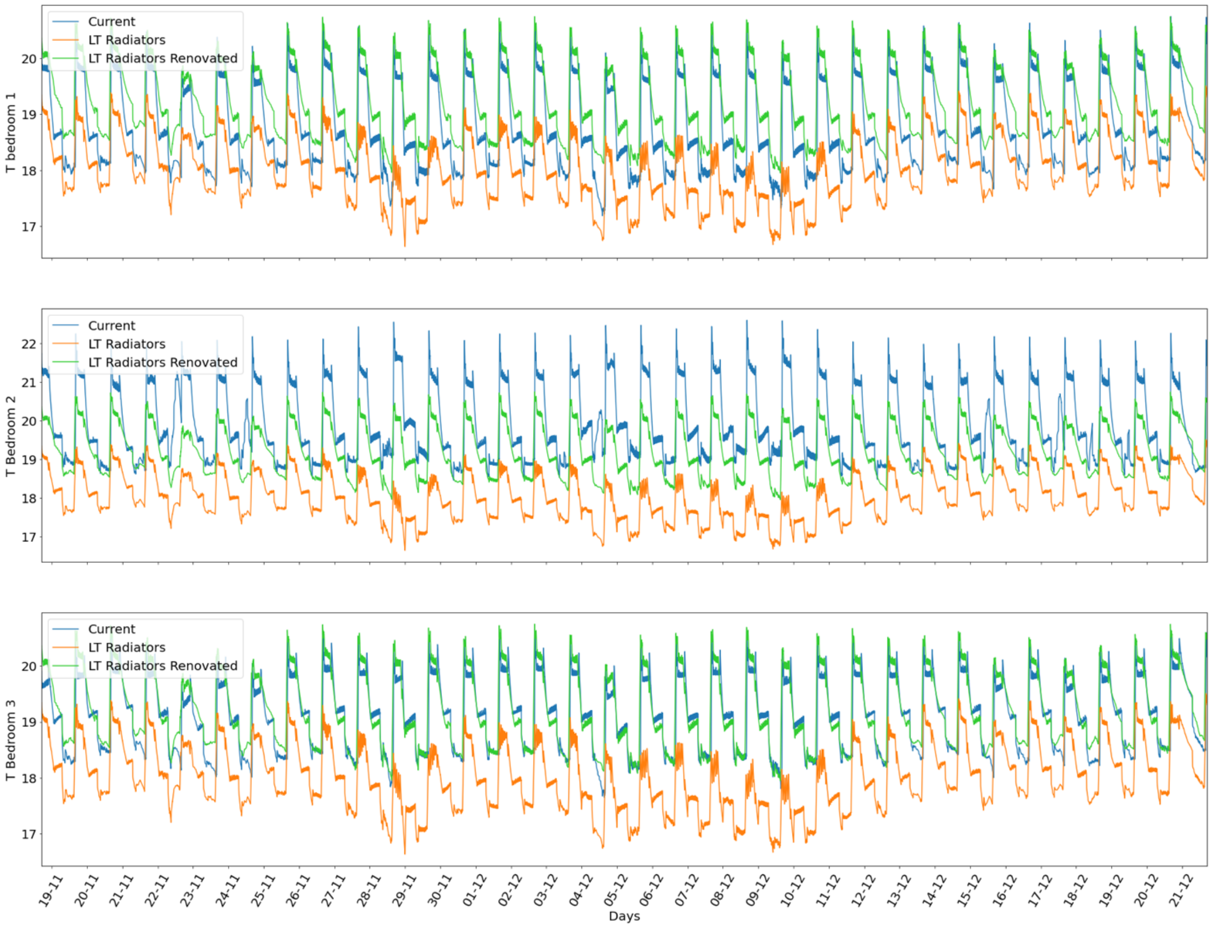


Figure 5.36: Air temperatures in the bedrooms modelled with current HTH and modelled with LTH through LT radiators at current insulation levels and modelled with LT radiators with renovated facade

Surface Temperatures

Figure 5.37 shows the modelled surface temperatures at the three measured points. These surface temperatures show a large resemblance to the surface temperatures in the current situation. The amplitude of the difference between peak and lows appears to be smaller however indicating a decreased release of thermal energy from the stone walls to the air compared to the current situation.

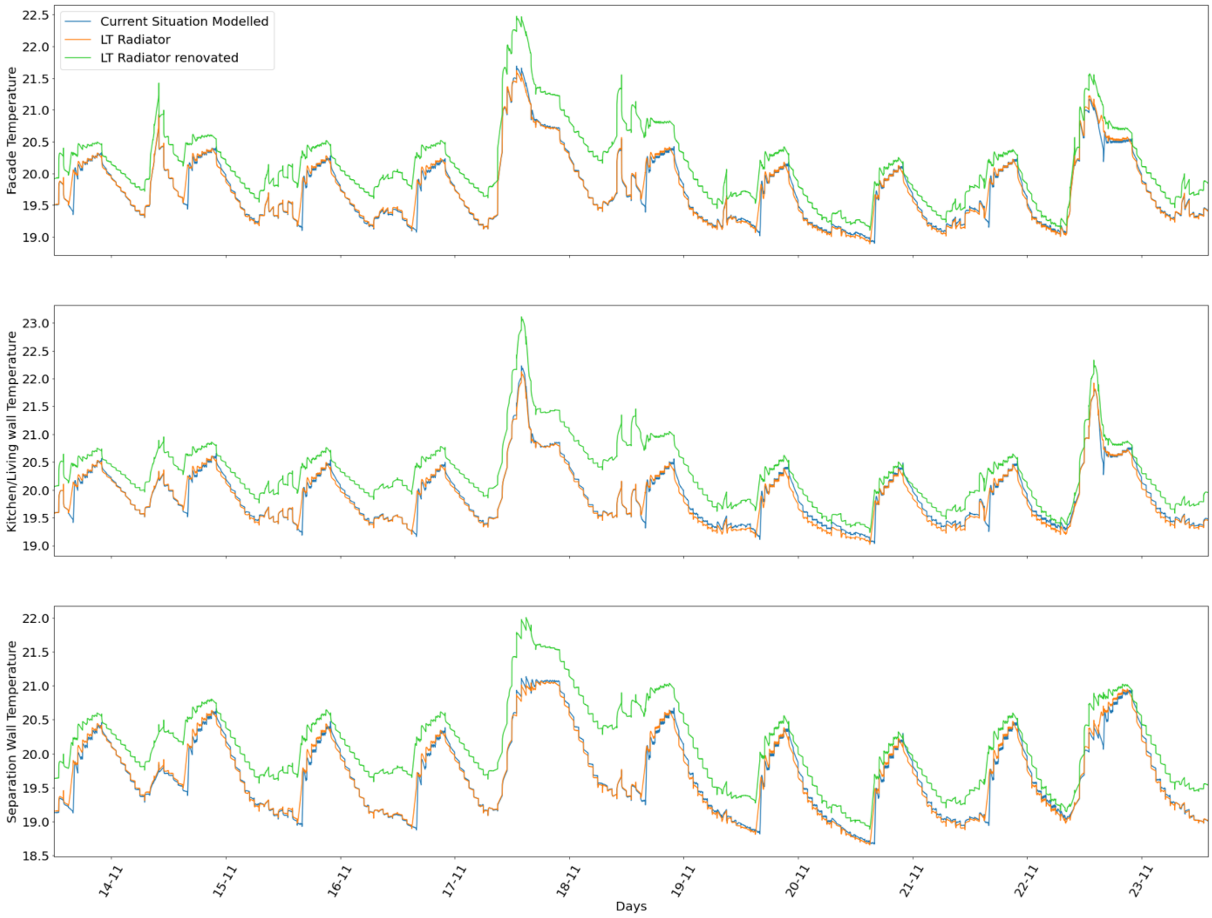


Figure 5.37: Surface temperatures in the living room modelled with current HTH and modelled with LTH through LT radiators at current insulation levels and modelled with LT radiators with renovated facade

Comfort

The comfort levels in the living room have again been assessed with the proposed workaround from chapter 4. The results are presented in the following set of graphs. Figure 5.38 shows the PMV as calculated for each timestep in 2020. The average PMV during heating season in this case is -0.39, which is an improvement compared to the average PMV of -0.45 in the current situation. The lowest PMV reached was -0.77 which is similar to the extreme of -0.78 in the current situation. The PMV reaches a value outside of ±0.5 for 38.0% of the time during heating season. These numbers coincide with an average PPD of 8.86 and an extreme of 17.05. Figure 5.39 shows the comfort classification by the adaptive model. Here it can be seen that the building now performs as a class B building for a large majority of the time. Also the individual comfort aspects show in figure 5.40 show that this intervention would create a relatively comfortable building.

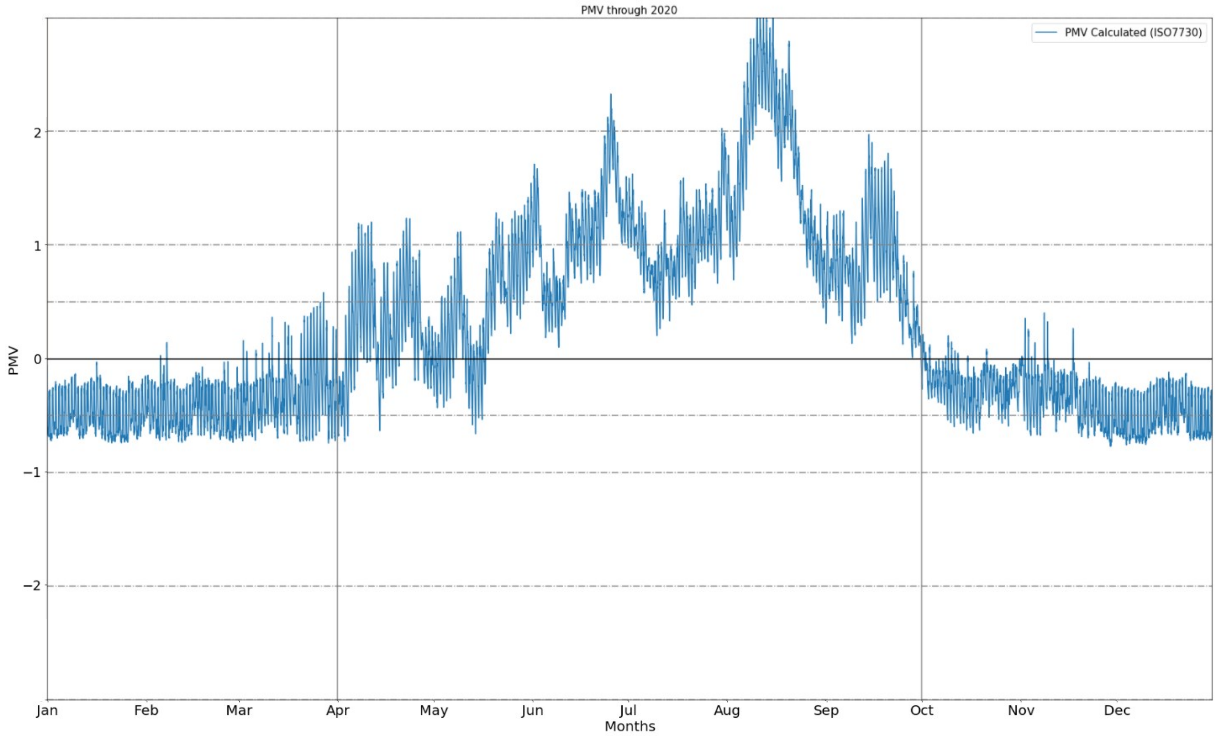


Figure 5.38: PMV throughout 2020 for LTH through LTH radiators with updated facade

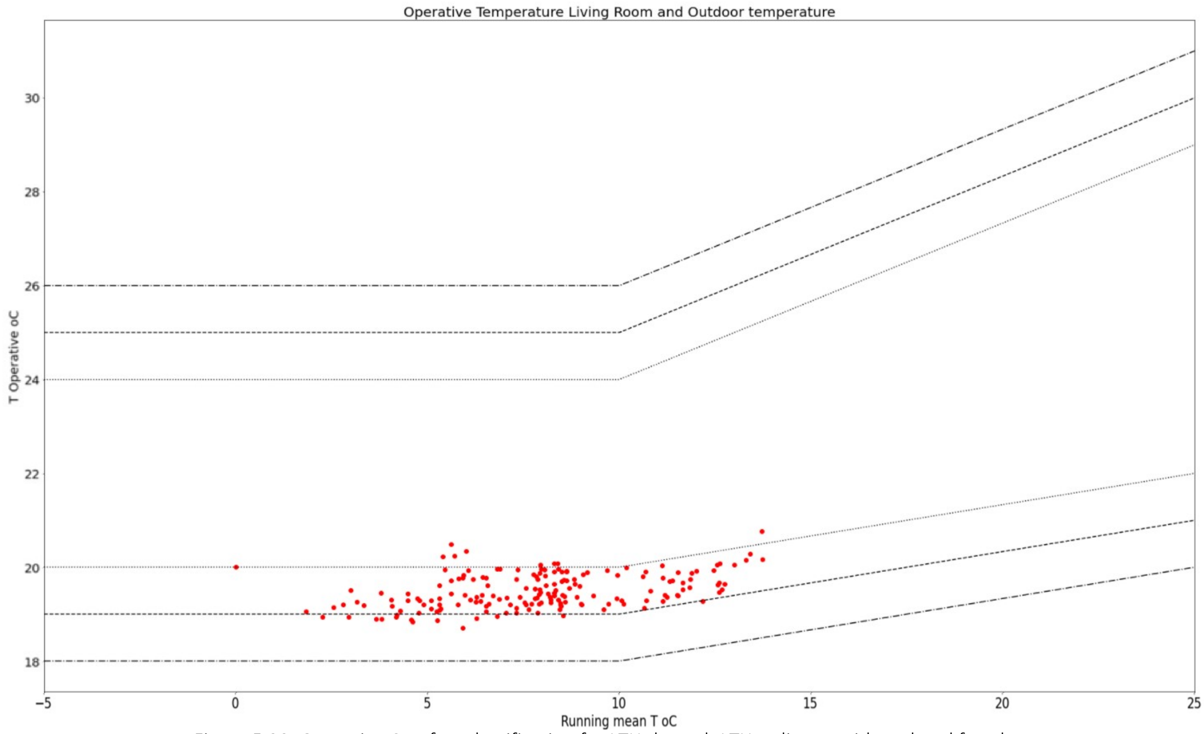


Figure 5.39: Operative Comfort classification for LTH through LTH radiators with updated facade

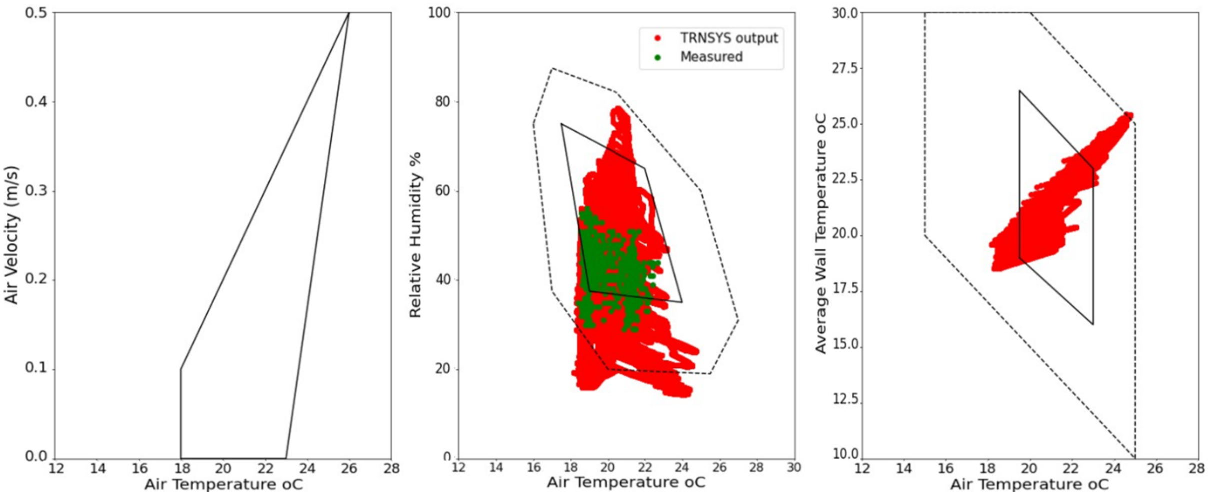


Figure 5.40: Individual comfort aspects for LTH through LTH radiators with updated facade

Comfort close to façade

A comparison of the comfort levels in the front and middle of the living room has also been carried out for the proposed renovation. This can be seen in figure 5.41. The average PMV in the front of the living room is -0.40, which is similar to the average in the middle of this room. The lowest reached PMV is -0.84, which is slightly lower than the lowest point in the middle of -0.76. Although it has increased insulative properties, this lower PMV drop can still be explained by the presence of a large window in this area.

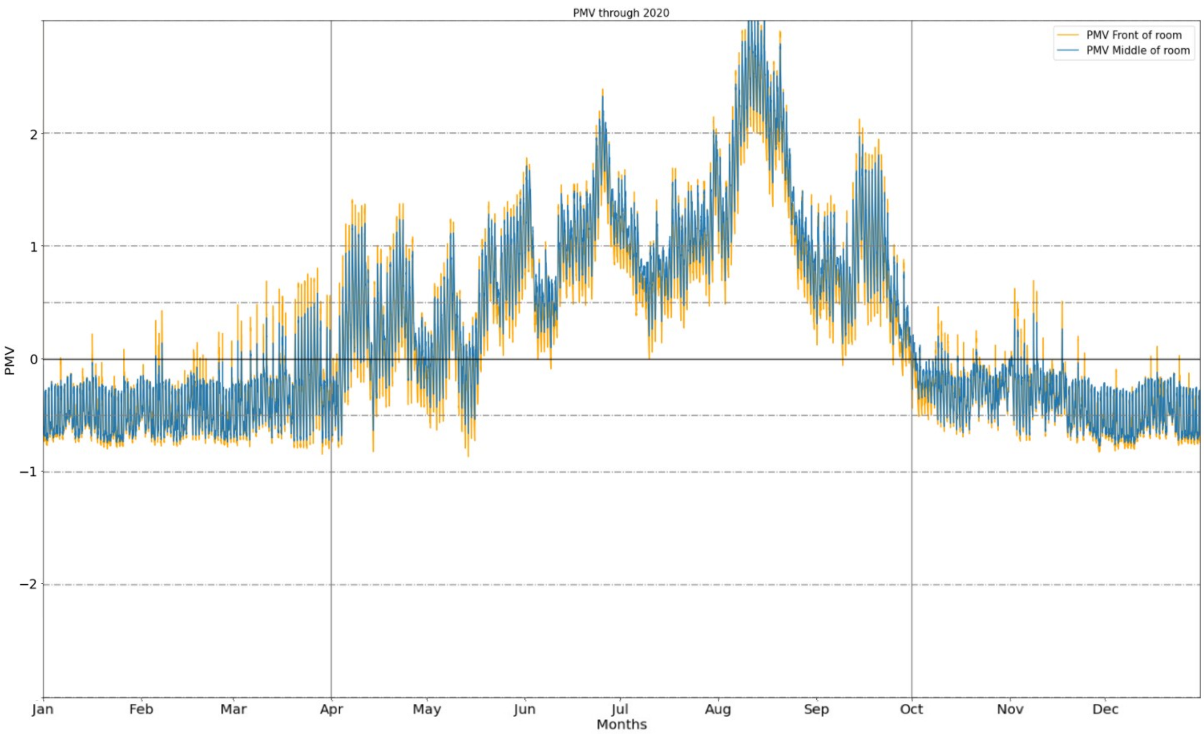


Figure 5.41: PMV comparison front and middle of the living room

Renovation Plan

This proposed renovation is based on two principles. Firstly, it is key to increase the overall insulative properties of the façade. This ensures the surface temperatures stay within comfortable regions and the minimum desired temperature of 18.5 °C can be maintained throughout the year. In order to ensure sufficient capacity to reach the desired peaks of 21 °C, it is important to also improve the airtightness of the building.

A first objective of the renovation is to improve the insulative value of the façade and to install triple glazing. This will bring the U-Value of the transparent parts down from 1.2 to 0.8 W/m^{2}K. This will possibly require the upgrading of the window frames too to accommodate the larger glass thickness. It is advisable to update the window frames anyway in order to ensure they are fitted in the most airtight manner possible.

The opaque parts will need further insulation measures too. Their current Rc of 3.5 m^{2}K/W does not suffice the required 6 m^{2}K/W. The new updated Rc value can be achieved by adding an insulative material with a conduction coefficient of 0.04 W/mK (like mineral or rock wool) with a thickness of 0.11 m. This can be achieved by either using a wrap-it or add-in principle explained in figure 3.3. It should be noted that these values are only valid if the claimed Rc value of the cavity insulation is actually achieved. From some of the earlier façade temperature results it could be concluded that this is not always the case. Furthermore, this cavity insulation may not have been carried out in other dwellings. The desired Rc of 6 m^{2}K/W can then still be achieved by placing an insulative material with a conductive coefficient of 0.04 W/mK with a thickness of 0.23 m. In this case a definite preference would go to a wrap-it principle. An add-in would reduce the floor area of the living room alone from 19 m^2 to 17 m^2 which is not desirable.

The second objective of this renovation proposal is to increase the airtightness of the façade. Some upgrades of the airtightness had already been carried out in the current situation, which caused an estimated improvement of the $q_{v,10}$ value from 1 to 0.6 dm^3/s m^2. This will need to be decreased even further however. To qualify as ‘excellent’ in airtightness, a value of 0.15 dm^3/s m^2 will need to be achieved. This value is ambitious, especially for renovation projects. It is key to create a continuous air seal around the building. Especially seams and connections between sections will require special attention during the design. An important focus point when creating an airtight building, is to ensure sufficient active ventilation to keep the building and its occupants healthy.

In order to create the continuous air seal, eliminate thermal bridges efficiently and manage moisture buildup, a wrap-it principle is considered most beneficial. Figure 5.42 left shows the airflow through the façade in its current state (with triple glazing). Especially the orange infiltration lines play a big role. This path of infiltration follows from (poor) connections between the window frame and the opening in the opaque sections. Adding a curtain wall style wraparound outside the existing façade can eliminate this form of infiltration. The blue lines represent infiltration going around the seams between the frame and the windows/panels. This type of infiltration will remain in the updated situation too.

The outside panel shown in figure 5.42 right is purely for demonstrative purposes. This outer most layer can take many different forms including a prefab brickwork or lookalike if the current aesthetics should be maintained. Figure 3.20 showed that outside insulation should not create condensation on the outer cold leaf. This should still be closely examined in this situation. If the outside layer creates a vapor seal, this cold surface will still create condensation and thus moisture problems. One option that could mitigate this is making sure the most outer layer has a low vapor diffusion resistance making it vapor open but water sealed. Alternatively, a vapor retardant layer should be added on the most inside section of the wall.

In the left detail, the window can open, causing the green infiltration line. Opening windows always cause more infiltration, regardless of the upgrade. It is important to ensure sufficient ventilation can still take place and preferably be adjustable, especially when installing more fixed windows.

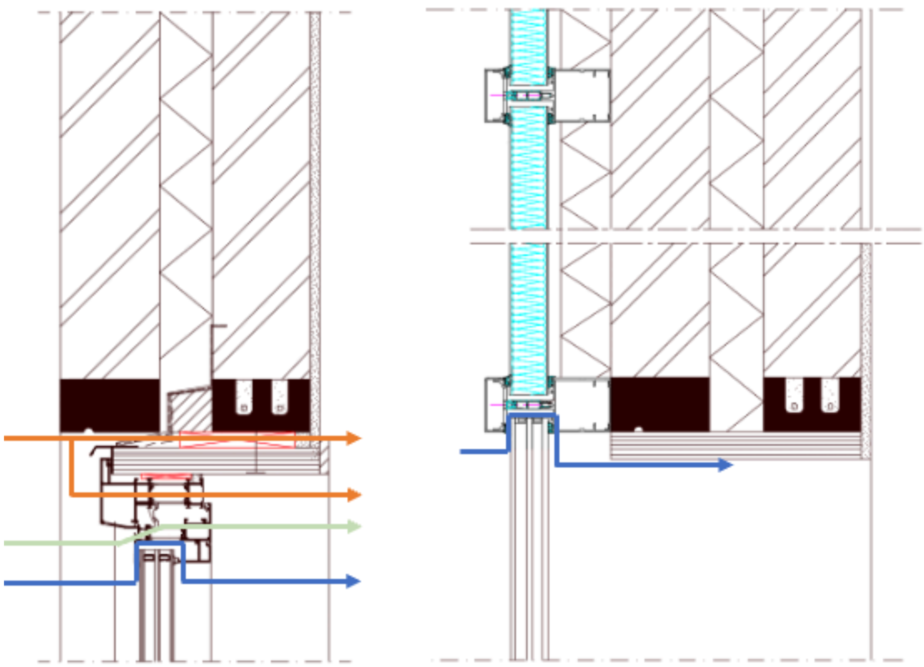


Figure 5.42: Airflow through current connections (left) and air flow through renovated façade (right)

5.4 Plan 4: LTH with Underfloor heating and Radiators

In this renovation plan, the comfort levels achieved by underfloor heating with LTH will be assessed. Underfloor heating has the advantage of using the large surface area of the floor. Common risks of underfloor heating are slow heating times and large temperature differences between the bottom and top of a room however.

Radiator plan

In TRNSYS, underfloor heating can be simulated in TRNBuild by implementing an Active Layer. In this Active Layer a number of parameters can be specified. These parameters are outside tube diameter, tube wall thickness and center to center pipe spacing. Common numbers for these parameters are 2 mm wall thickness, 16 mm outside diameter and 150 mm pipe spacing.

The following step is to implement the active layer into a 'Wall' (in this case situated as a floor). This can be done in the Wall Type Manager in TRNBuild by adding the active layer to an existing wall specification. Important is to make sure the existing layer on top of the active layer is at least 0.3 * pipe spacing thick. After adding the Active Layer, TRNBuild automatically duplicates the top layer below the Active Layer. Then an insulative layer with a thermal resistance larger than 0.825 m^2W/K can be added. After this, the thickness of the layer below the Active Layer can be reduced to be at least the outside pipe radius. Furthermore, it is important to set the convective heat transfer coefficient to 'internal calculation' so it will be dependent on the surface temperature. The resulting cross-section of the underfloor heating set-up as modelled in TRNSYS can be seen in figure 5.43. The top layer is a stony material as finish.

Besides the Active Layer, similar parameters to the previous setups had to be defined. The capacity of the heat source, for example a heat pump, has been calculated in the same manner as in section 5.2 of this thesis. For financial reasons, underfloor heating is usually only implemented on ground floors. Also in this model that is assumed to be the case. The bedrooms and bathroom are not assessed in detail but are assumed to have the LTH radiators specified in section 5.3 of this thesis.

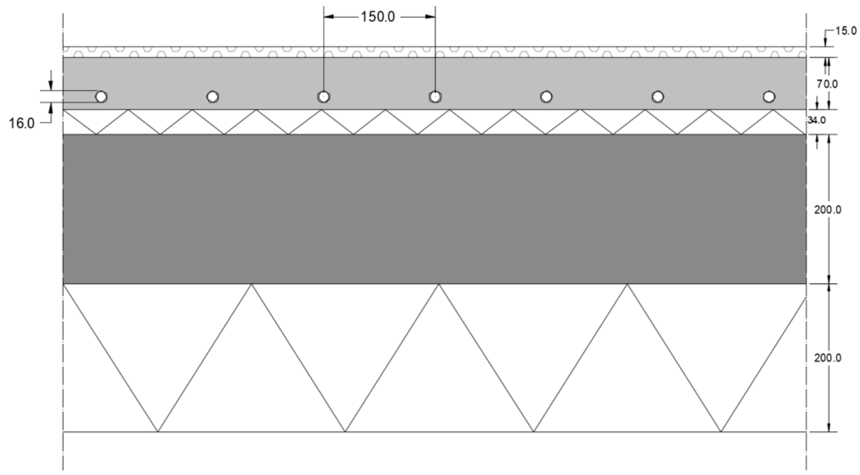


Figure 5.43: Cross section of the ground floor with underfloor heating

TRNSYS results

In this section the outputted results by TRNSYS and the derived comfort analysis will be elaborated.

Air temperatures

The modelled air temperatures of different rooms at current insulation levels have again be plotted in a set of graphs. Figure 5.44 shows the modelled air temperature in the living room and the ambient air temperature throughout 2020. From this graph, it becomes clear that the minimum desired temperature of 18.5 °C is relatively well maintained. The desired peaks of 21 °C are not always reached however. In figure 5.44 it can be seen that during the measured period of time, the peaks are below 21 °C for a substantial amount of days. Here it becomes clear that even the minimum temperature of 18.5 °C is also not always reached.

Figure 5.46 shows the modelled air temperatures in the kitchen. The modelled temperature in this room is also lower than in previous models. Figure 5.47 shows the modelled air temperatures of the bedrooms which show a similar pattern to other heating systems simulated in this thesis. This is in line with the expectations since their heating is still provided by radiators, albeit LTH alternatives.

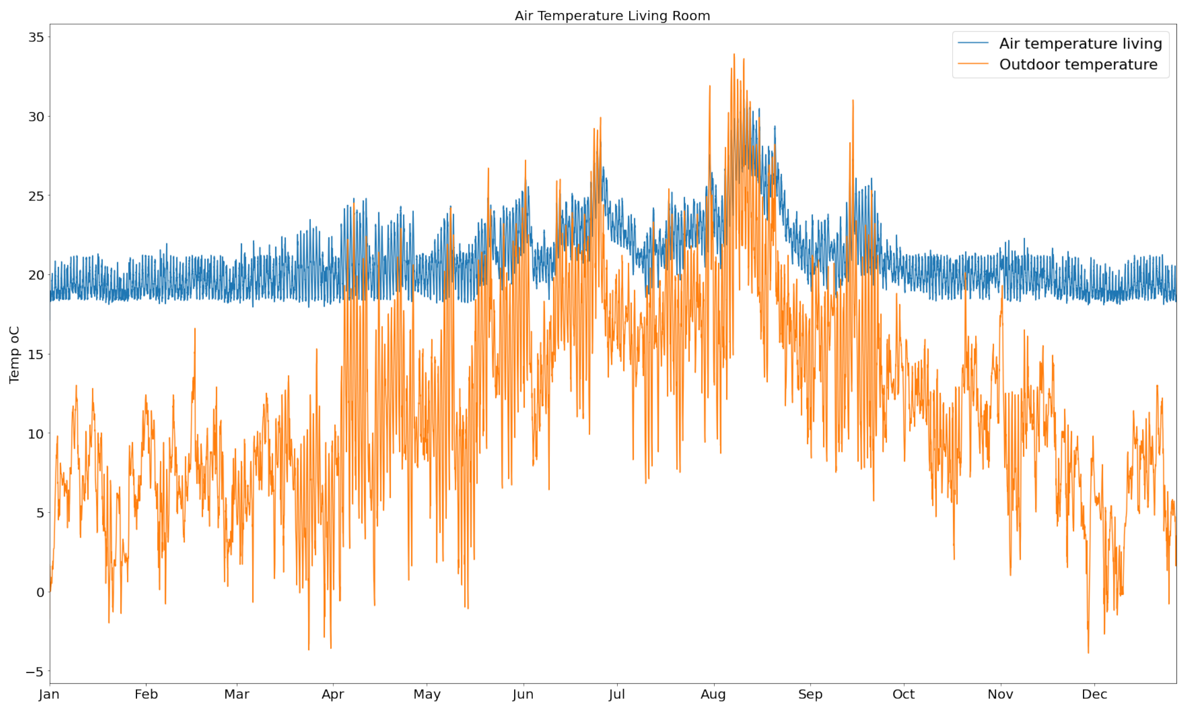


Figure 5.44: Air temperatures modelled in the living room with LTH underfloor heating throughout 2020 at current insulation levels

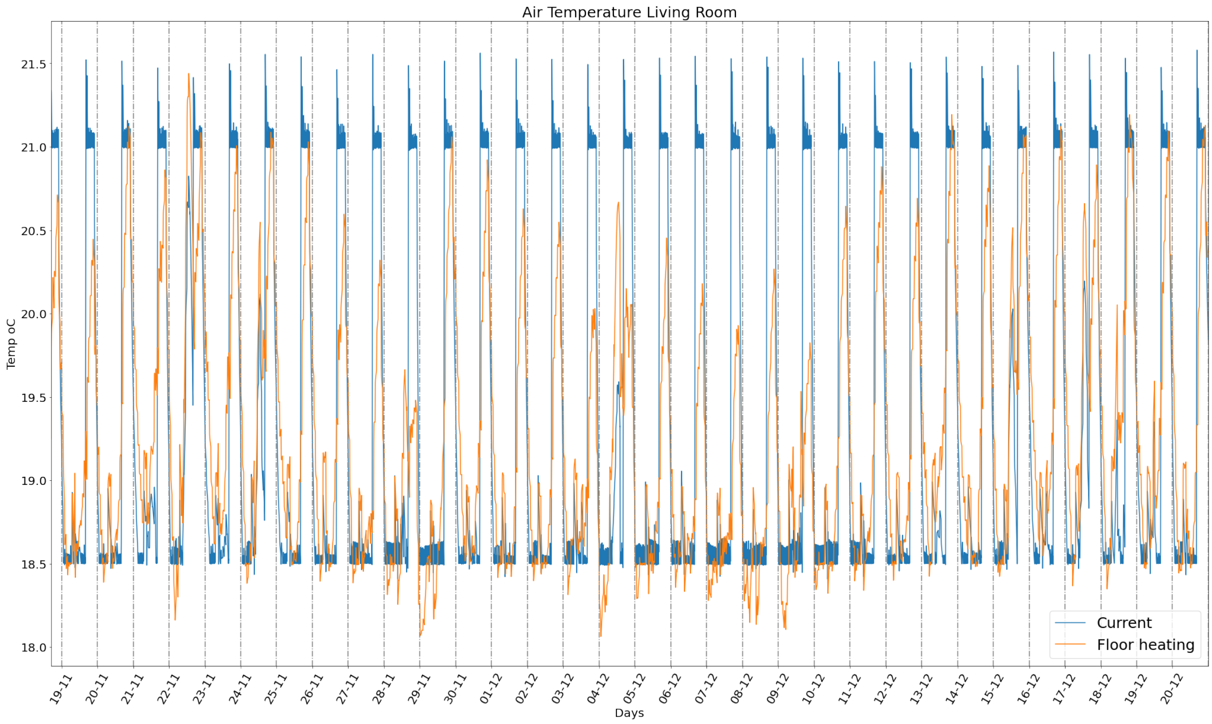


Figure 5.45: Air temperatures in the living room modelled with current HTH and modelled with LTH through underfloor heating at current insulation levels

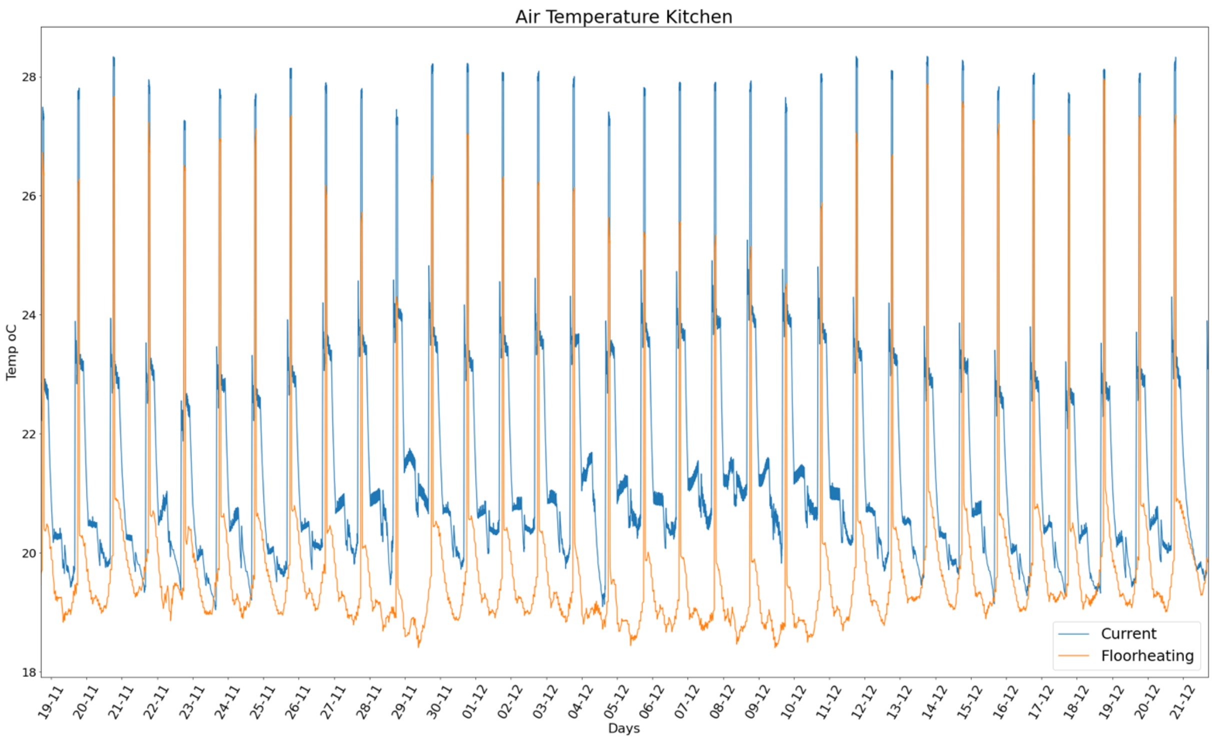


Figure 5.46: Air temperatures in the Kitchen modelled with current HTH and modelled with LTH through underfloor heating at current insulation levels

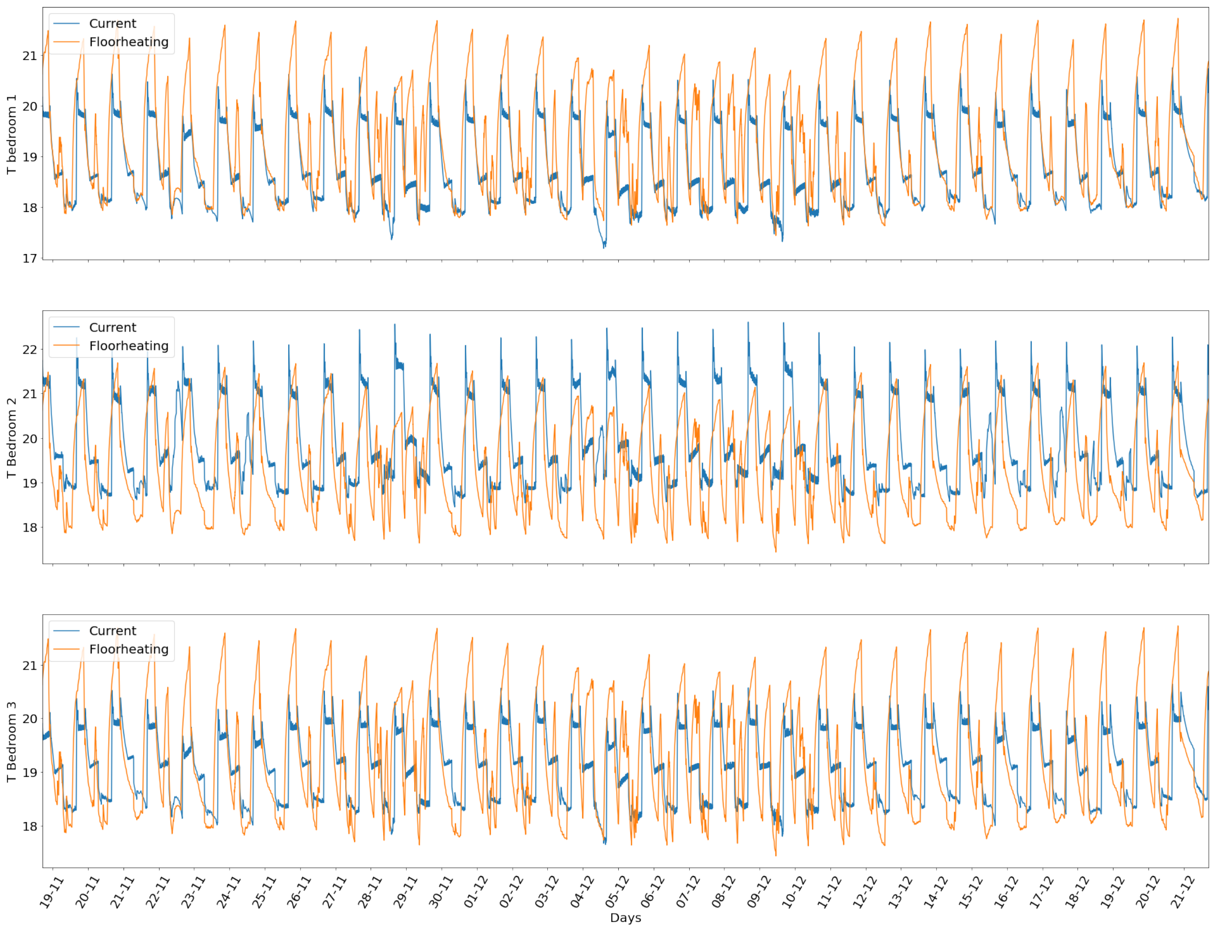


Figure 5.47: Air temperatures in the bedrooms modelled with current HTH and modelled with LTH through underfloor heating at current insulation levels

Surface temperatures

The surface temperatures have also been displayed in a graph similar to the previous sections. This can been in figure 5.48. All three surface temperatures show a similar pattern to the current situation. The façade is substantially warmer than measured again, whereas the modelled temperatures of the separation wall to the kitchen and the adjacent residence are similar to the modelled outcomes of the current situation.

With underfloor heating, another important parameter to keep in mind is the surface temperature of the floor itself. If the floor gets too warm, this can create discomfort from asymmetry and simply that people have too warm feet. In figure 5.49 the modelled surface temperature of the floor in the living room has been displayed. Here it can be seen that during heating season the maximum surface temperature is 27.13 °C. This lies well within the recommended maximum temperature of 29 °C for residential living rooms. The average surface temperature during heating season is 22.88 °C which also lies withing the recommended optimum for residential living rooms (Kennisinstituut voor Installatietechniek, 2013).

Figure 5.50 shows the surface temperature of the living room zoomed up over a 48 hour period. This figure shows that the period of the floor heating up from around 21 °C to 26 °C takes around 5 to 6 hours. It then does the cool down from 26 °C to 21 °C in around 10 to 12 hours. A common problem with underfloor heating is the warm up time. One degree Celsius raise per hour is not enough to heat the whole room from 18.5 °C to 21 °C as can be seen from the modelled air temperatures in figures 5.44 and 5.45. A solution to this problem could be to increase the desired temperature earlier in the day to provide sufficient time for the system to reach this. Another alternative is to place an additional radiator to speed up the process.

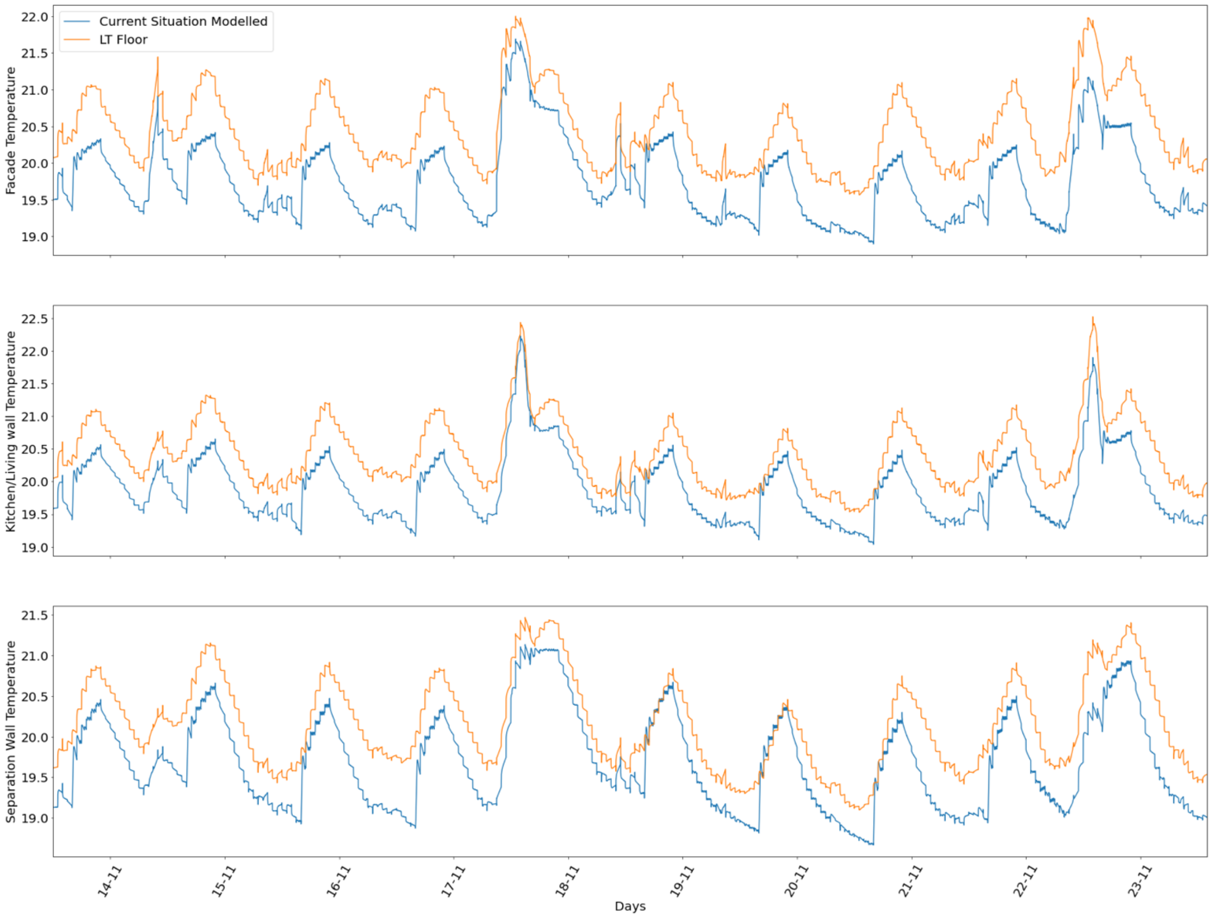


Figure 5.48: Surface temperatures in the living room modelled with current HTH and modelled with LTH through underfloor heating at current insulation levels

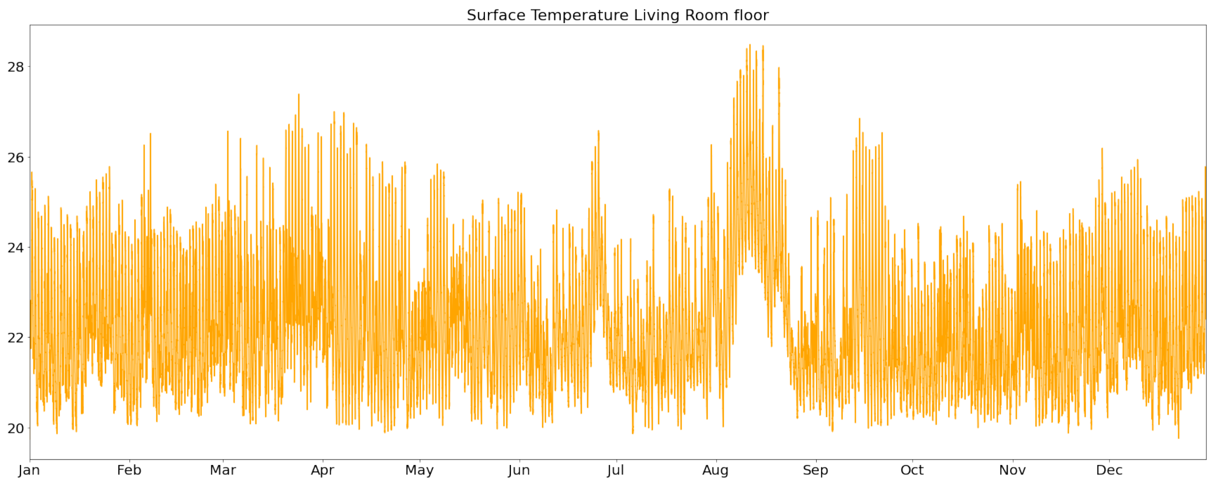


Figure 5.49: Modelled surface temperature of the floor with LTH with underfloor heating throughout 2020

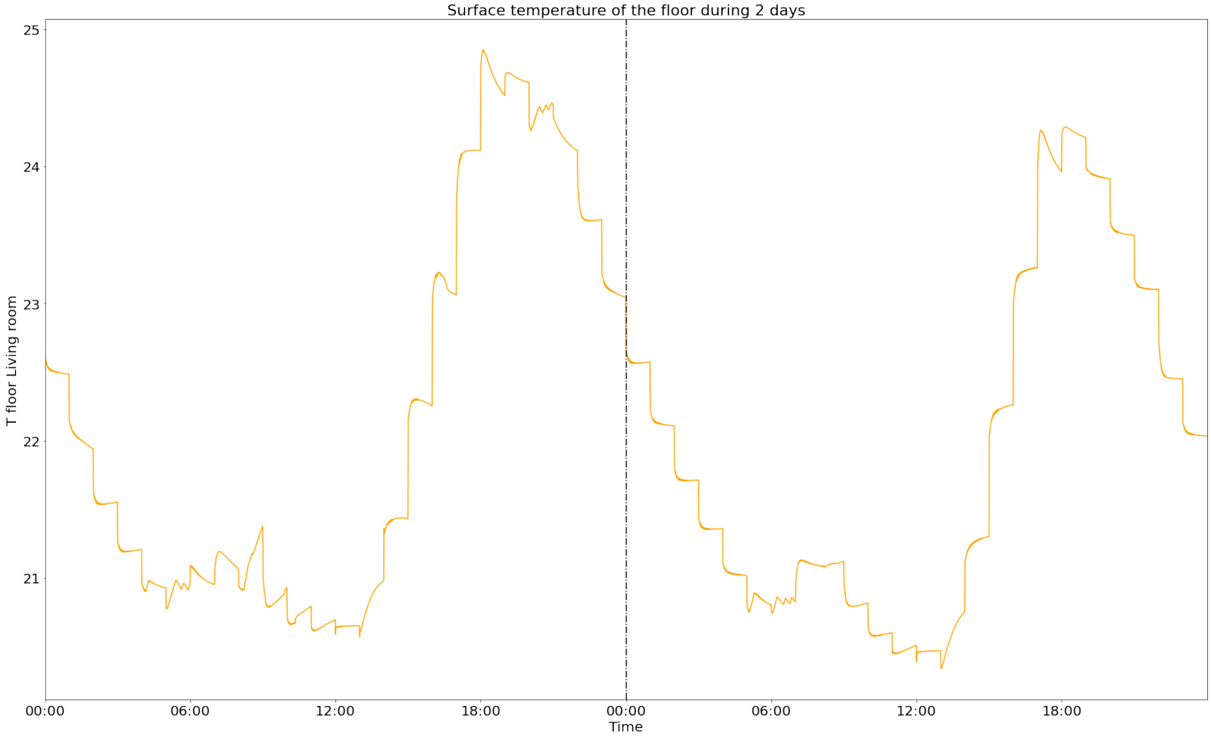


Figure 5.50: Modelled surface temperature of the floor with LTH with underfloor heating during 2 days in heating season

Comfort

Comfort levels have again been assessed via the workaround presented in chapter 4 of this thesis. In this case, the view factor calculation can be done in the same model as the simulations however since radiators are not part of this model in the living room. For continuity it is important to use the workaround and not the standard PMV and operative temperature outputs from TRNSYS for two reasons. Firstly, as can be seen in chapter 4, the PMV calculated by TRNSYS shows a small but inexplicable deviation from other calculation methods. Secondly, TRNSYS calculations will use Gebhardt factors for the MRT calculation, which is not in line with ISO 7726.

Figure 5.51 shows the calculated PMV in the living room throughout 2020. The mean PMV during heating season with LTH underfloor heating is -0.36 reaching a minimum of -0.81. It reaches a value below 0.5 for 32.04 % of the time. This results in an average PPD of 8.51 with a maximum of 18.69. Figure 5.52 shows the comfort levels if they are assessed via the adaptive model. This results in a Comfort Class A-B for the residence with this type of heating. Figure 5.53 shows the individual comfort parameters. Again the dwelling would score as comfortable for a large amount of points.

From all these outcomes it could be concluded that the dwelling would be relatively comfortable with underfloor heating at its current insulative values. However, the minimum air temperature reached in heating season is 17.9 °C, which well below the desired 18.5 °C. Also the desired peaks of 21 °C are often not met. The high calculated comfort levels, even at lower air temperatures, can be explained by the increased MRT from underfloor heating. This increase in MRT could impact the calculated comfort outcomes in such a way, they are not in line with real life experiences any more.

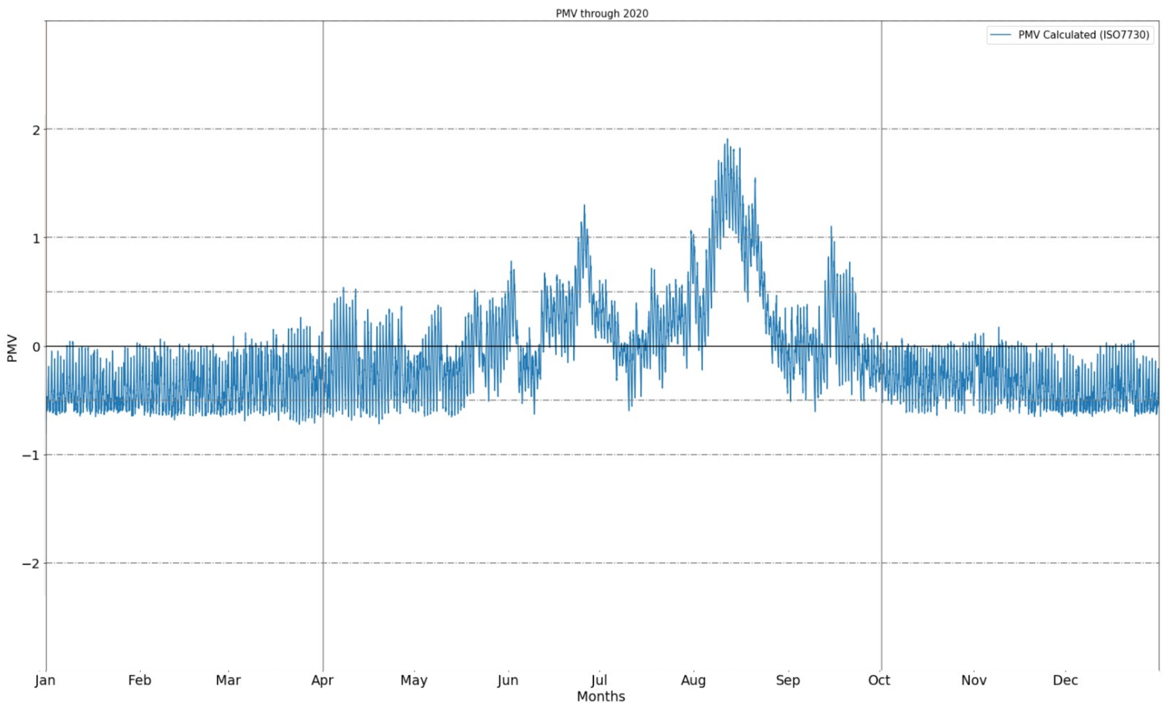


Figure 5.51: PMV with LTH with underfloor heating throughout 2020

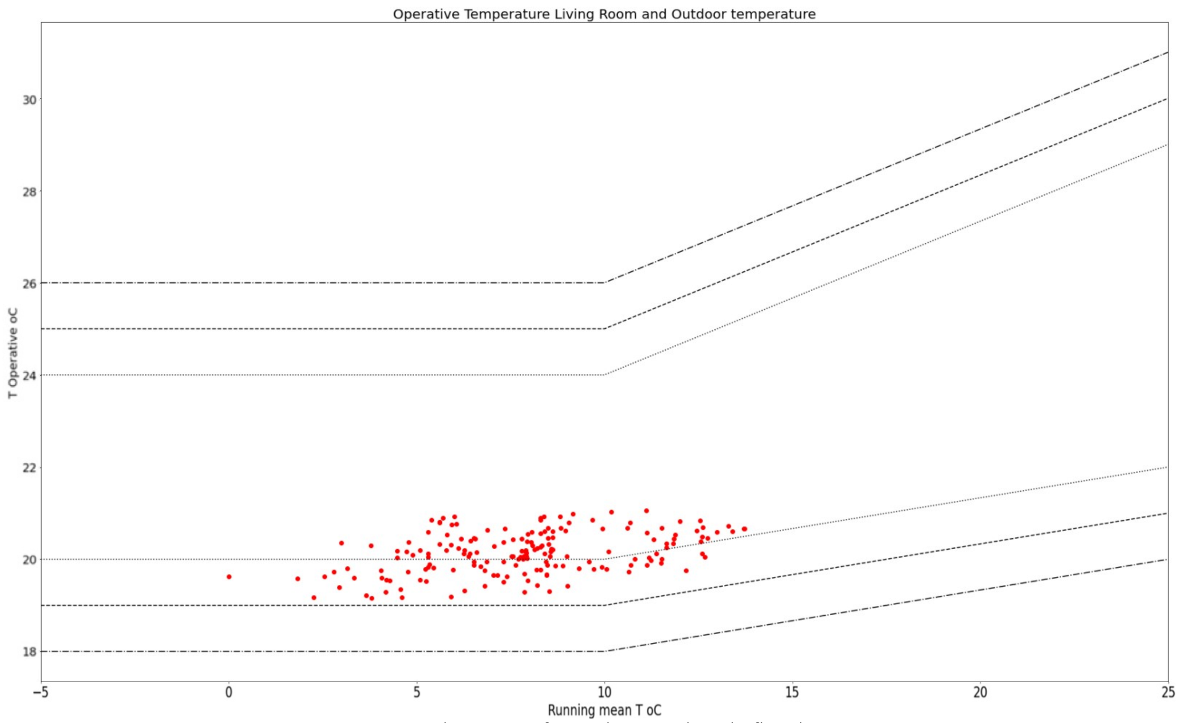


Figure 5.52: Adaptive comfort with LTH with underfloor heating

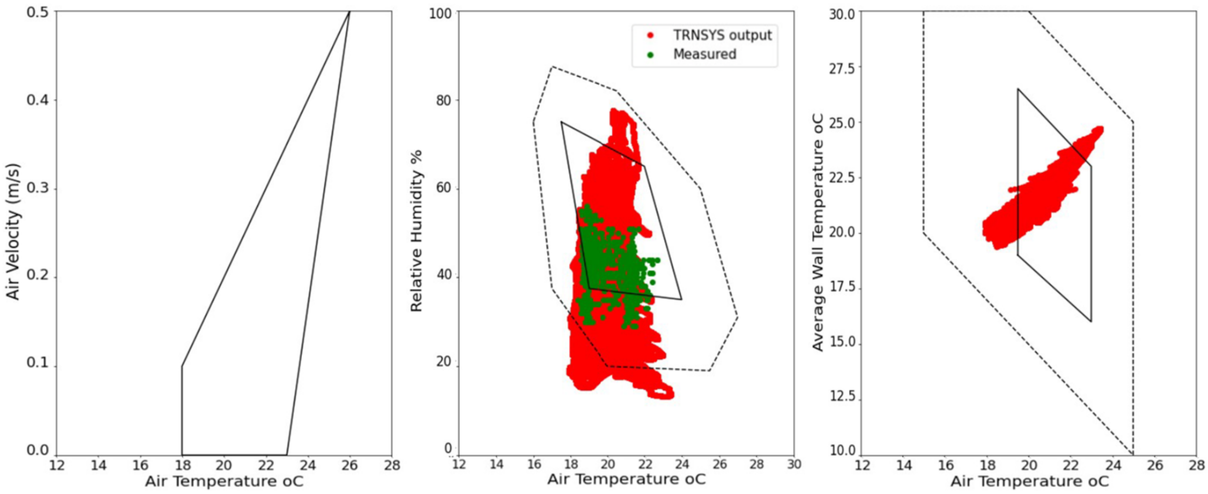


Figure 5.53: Individual Comfort parameters in the living room for LTH with underfloor heating

Comfort front of the room

In this case, the PMV in the front of the room is similar to that in the middle of the room. This can be seen in figure 5.54 where both lines are equal throughout nearly the entire year 2020. The average PMV during heating season at the front of the room is -0.33 with a minimum of -0.75 making it perform slightly worse than the middle of the room.

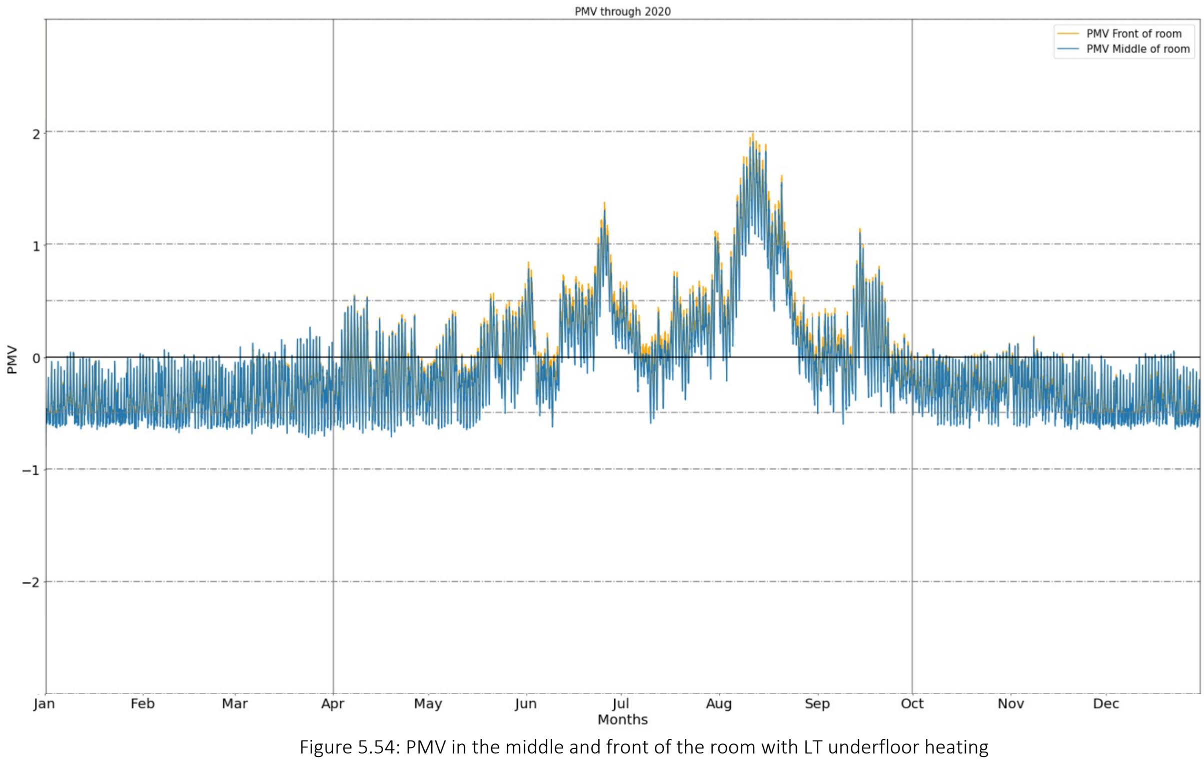


Figure 5.54: PMV in the middle and front of the room with LT underfloor heating

Required Renovation

The dwelling with LTH and underfloor heating performs relatively well according to the calculated comfort levels. The achieved air temperatures in the living room indicate a lack of capacity to reach the desired peak of 21.5 ^{o}C in sufficient time however. Therefore also for this heating plan a renovation proposal will be investigated.

The changed façade parameters in this renovation plan are equal to the ones in the previous section. The Rc of the façade will be increased to 6 m^2W/K, in accordance to the recently published

'Target Values'. Since the main problem is again the insufficient air temperature, also the airtightness of the building will be increased to match the 'Excellent' mark from table 4.3. This gives the results presented in the following graphs.

Air temperature

The air temperatures in the living room are shown in figures 5.55 and 5.56. Here it becomes clear that the upgraded façade has a positive effect on the achieved indoor air temperatures. The minimum reached air temperature is 18.24 °C which is better than the achieved 17.9 °C with the current façade properties. From figure 5.55 it becomes clear that the peaks of 21.5 °C are met more often than before, but still not in all cases. Figure 5.57 shows a closeup of the temperature pattern during the coldest night of the heating season. Here it can be seen that even after renovating, desired temperatures are still not always met. This could be due to long warmup times of the floor heating system. A temperature regime with less fluctuations might mitigate this lack of peak temperatures.

Figure 5.58 shows the air temperatures in the kitchen which show a similar pattern to the outcomes with the current façade properties. Figure 5.59 shows the air temperatures in the bedroom which are still within a decent range and in line with the measured data from the current situation.

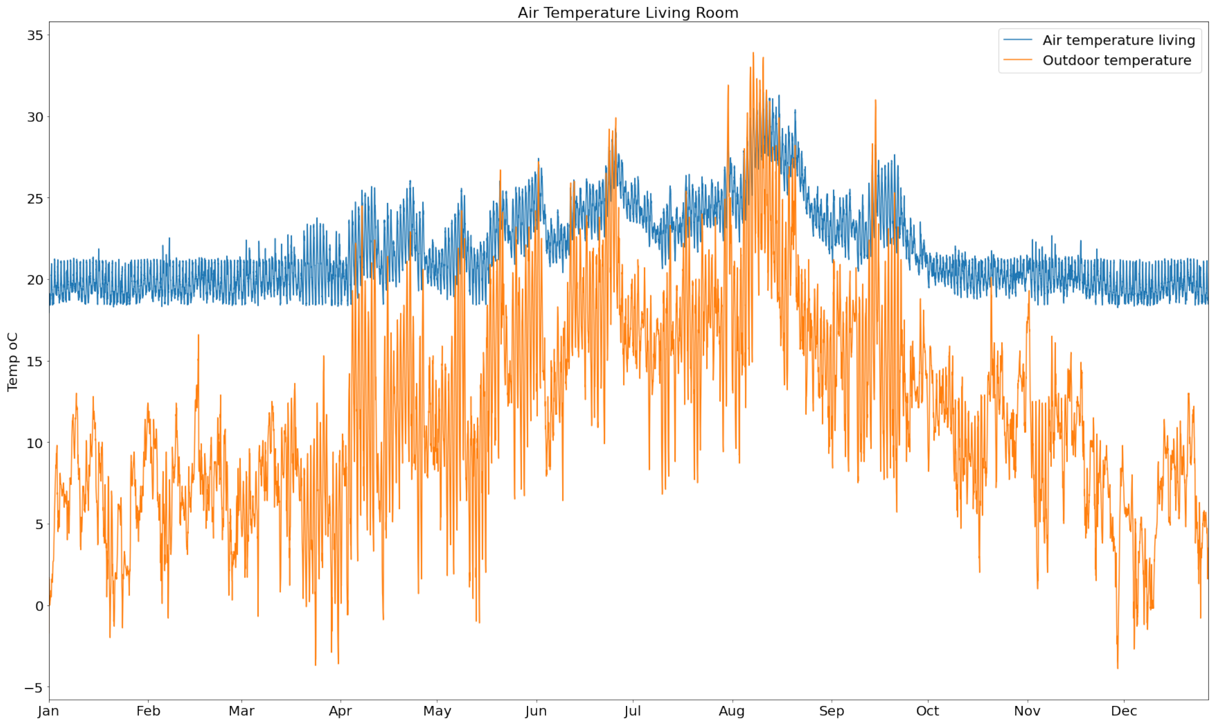


Figure 5.55: Modelled Air temperature in the living room throughout 2020 with LTH through underfloor heating with updated façade

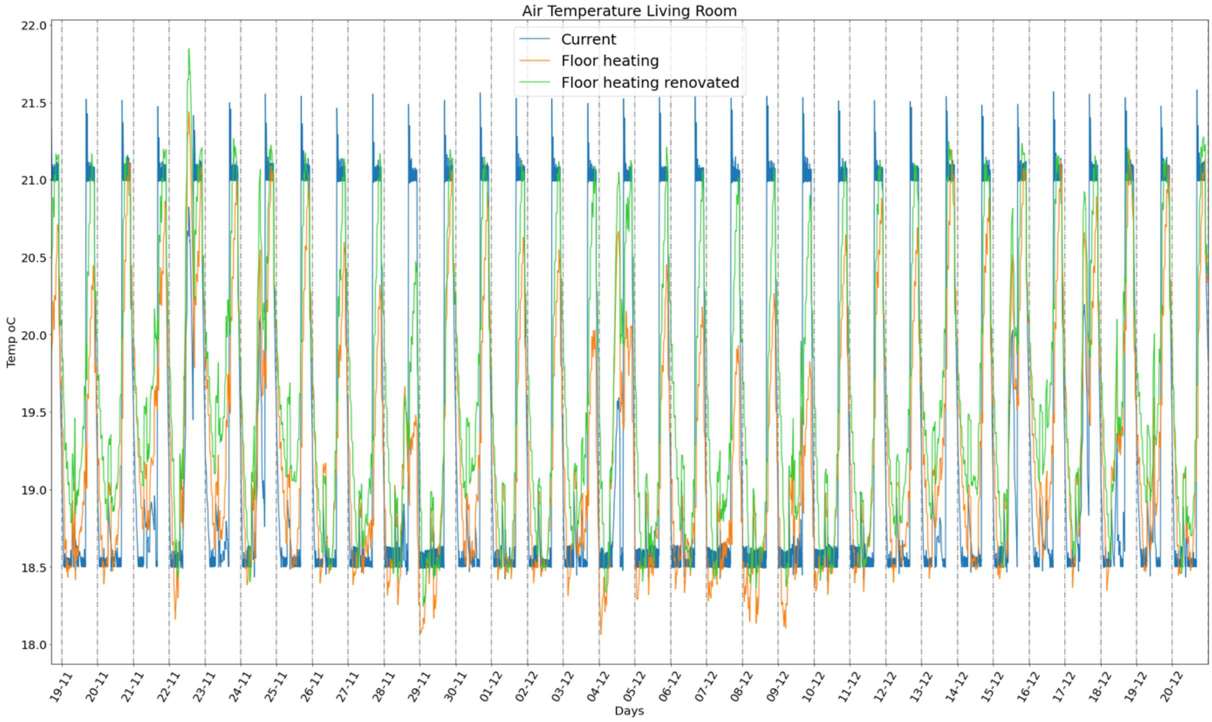


Figure 5.56: Air temperatures in the living room modelled with current HTH and modelled with LTH through underfloor heating at current insulation levels and modelled with LT underfloor heating with renovated facade

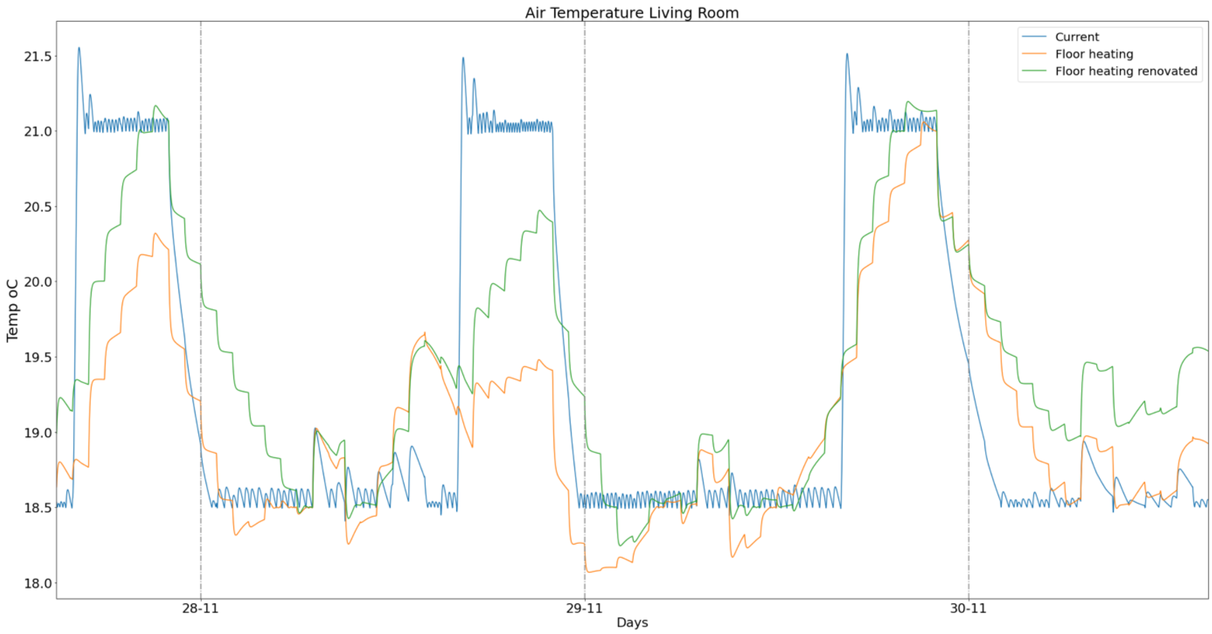


Figure 5.57: Air temperatures in the living room modelled with current HTH and modelled with LTH through underfloor heating at current insulation levels and modelled with LT underfloor heating with renovated façade on coldest day

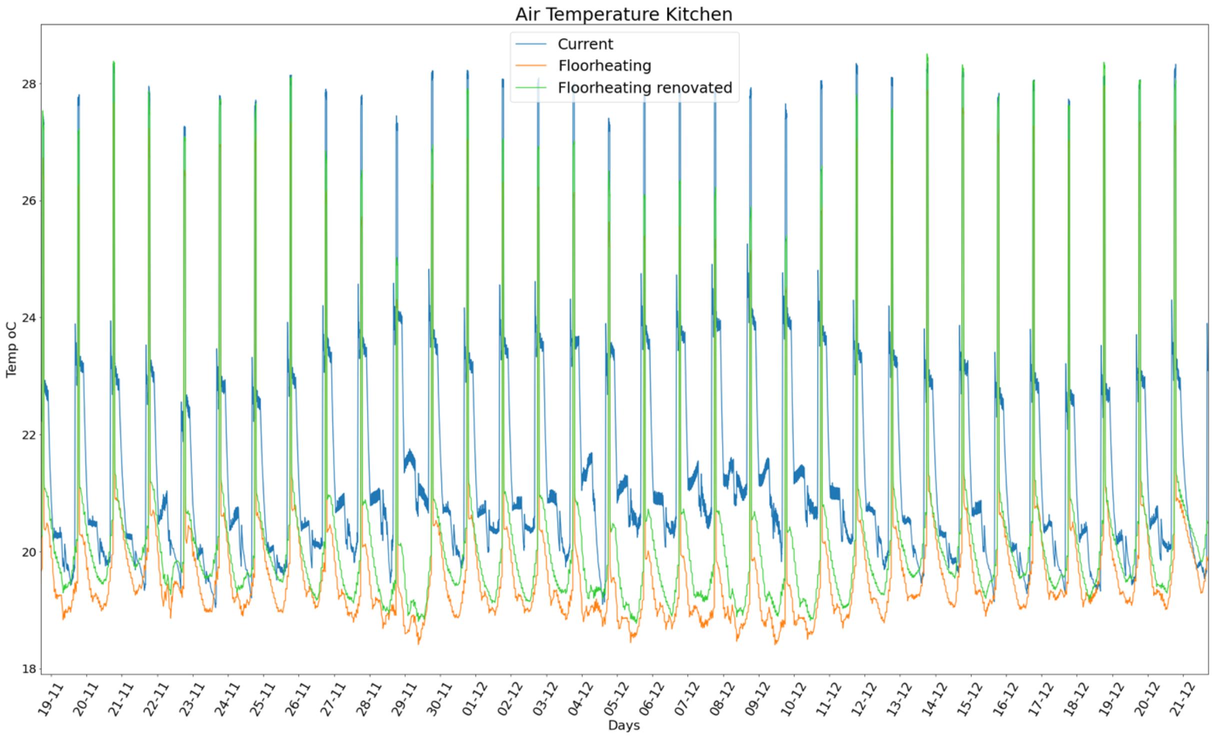


Figure 5.58: Air temperatures in the kitchen modelled with current HTH and modelled with LTH through underfloor heating at current insulation levels and modelled with LT underfloor heating with renovated facade

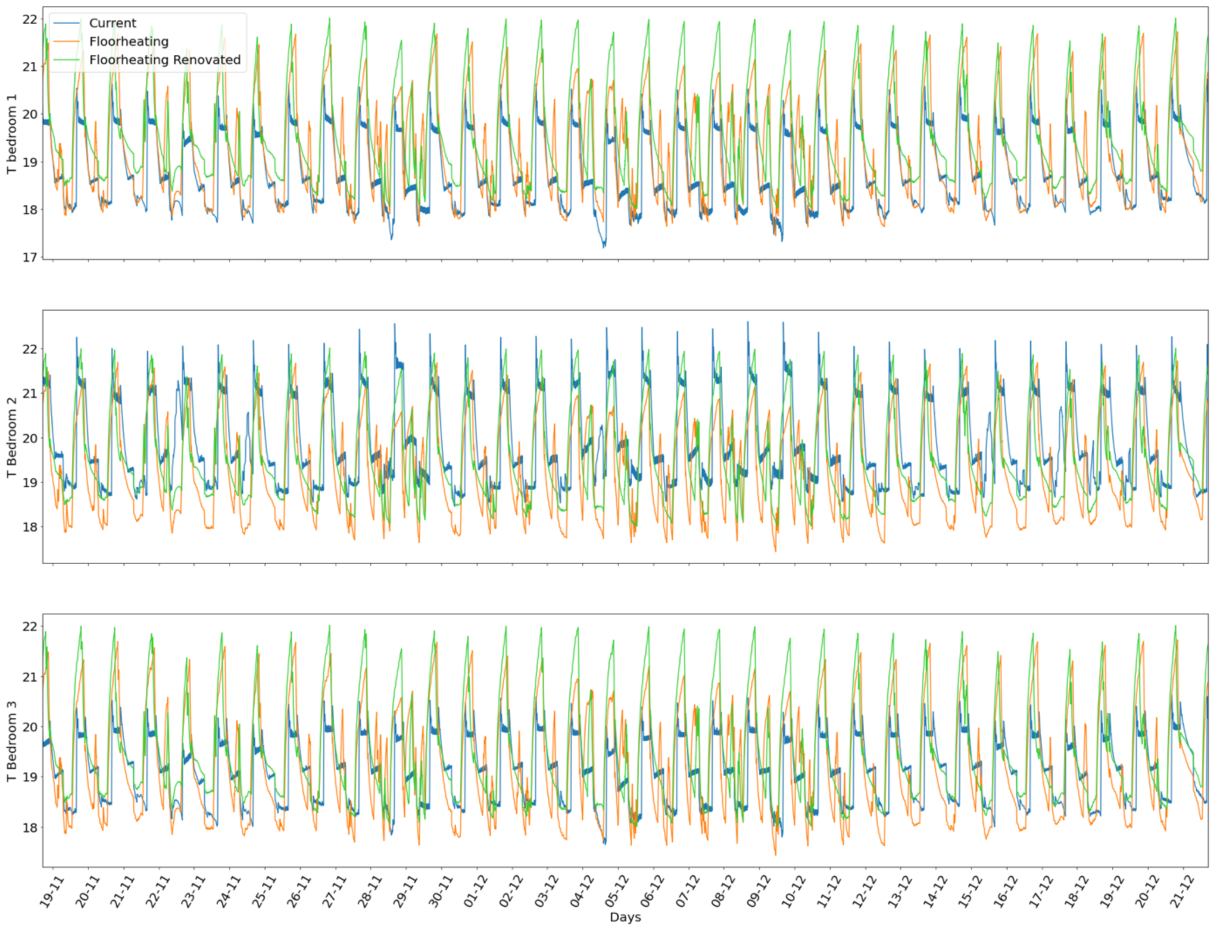


Figure 5.59: Air temperatures in the bedrooms modelled with current HTH and modelled with LTH through underfloor heating at current insulation levels and modelled with LT underfloor heating with renovated facade

Surface Temperature

The modelled surface temperatures have all three increased compared to the simulation with current insulative properties. Especially the façade temperature is now warmer at all points compared to the outcomes of the current situation. This can be seen in figure 5.60.

Figure 5.61 shows the surface temperature of the floor in the living room. This is again important to check for overheating which can cause discomfort. The maximum surface temperature of the floor during heating season is 26.45 °C which is lower than the situation with current façade properties, which reached 27.13 °C. Figure 5.61 shows the surface temperature of the floor in the living room for 48 hours at the start of the measured time period (mid-November). The warm-up for the heating system is still around 5 hours. Compared to the plot with the current façade properties (figure 5.49), the surface temperature in this model shows an more steady pattern for its cooldown period. Between 18:00 one day and 12:00 the next day, a steady decrease can be seen where the previous system required an extra 'boost' in heating around 06:00 the following day.

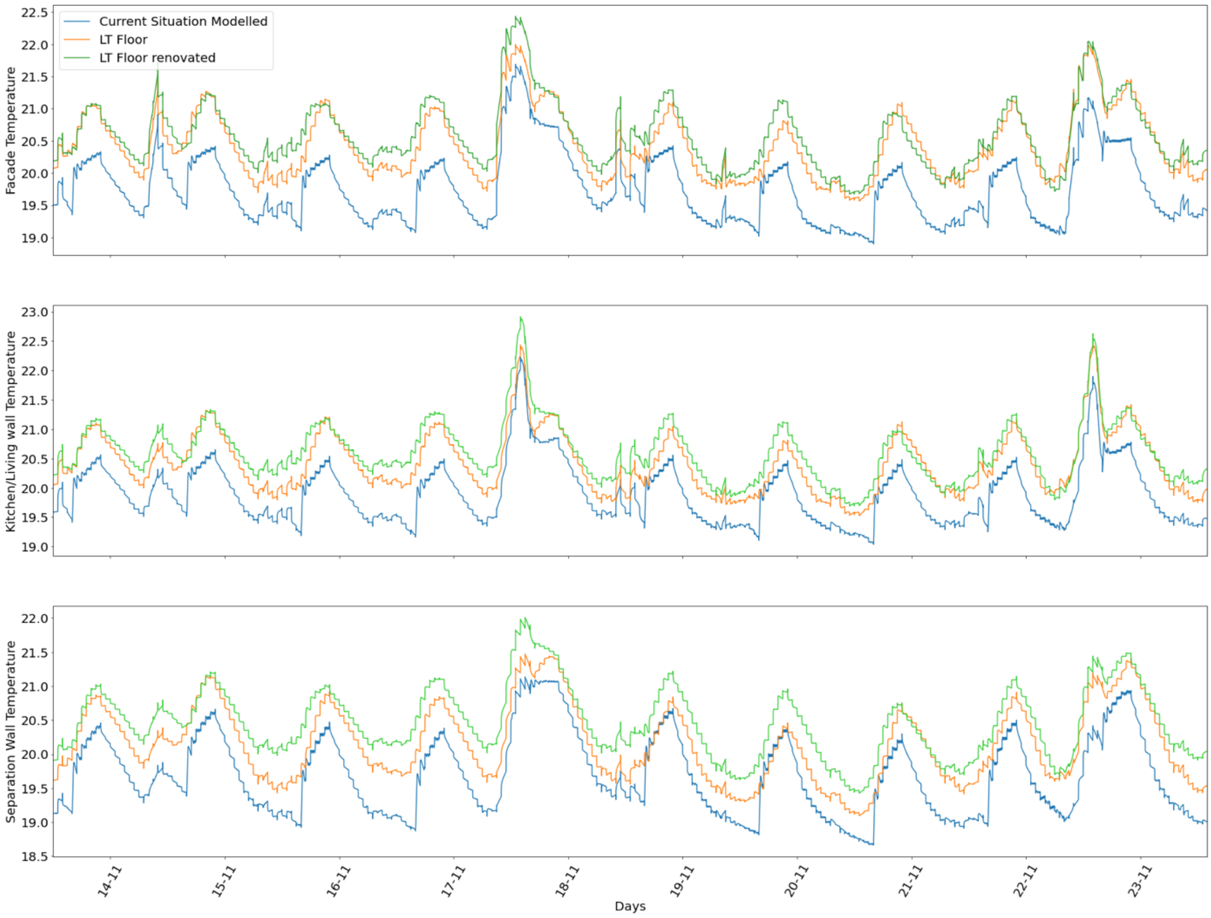


Figure 5.60: Surface temperatures in the living room modelled with current HTH and modelled with LTH through underfloor heating at current insulation levels and modelled with LT underfloor heating with renovated facade

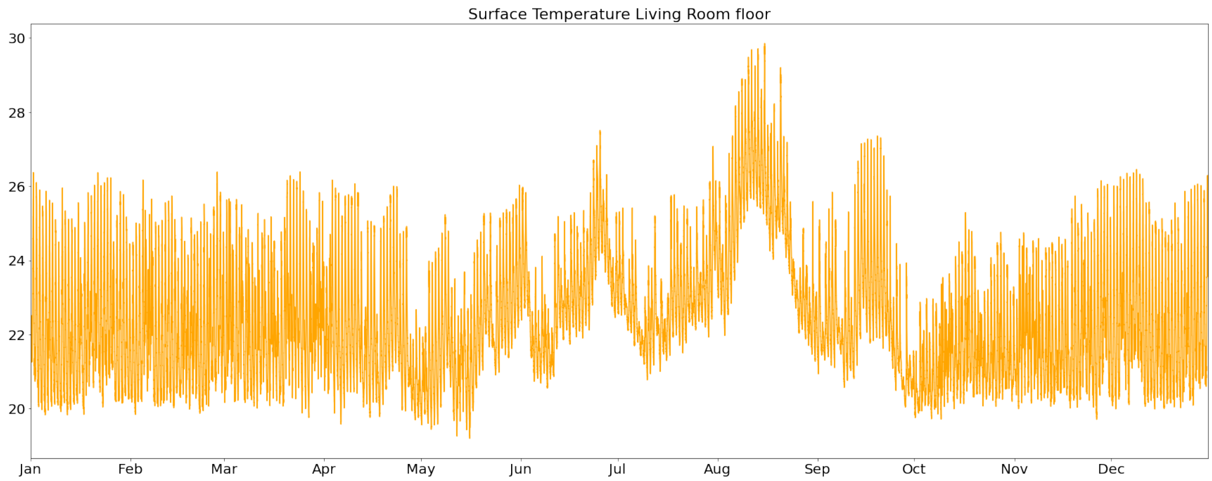


Figure 5.61: Modelled surface temperatures of the floor in the living room with LT underfloor heating with updated façade

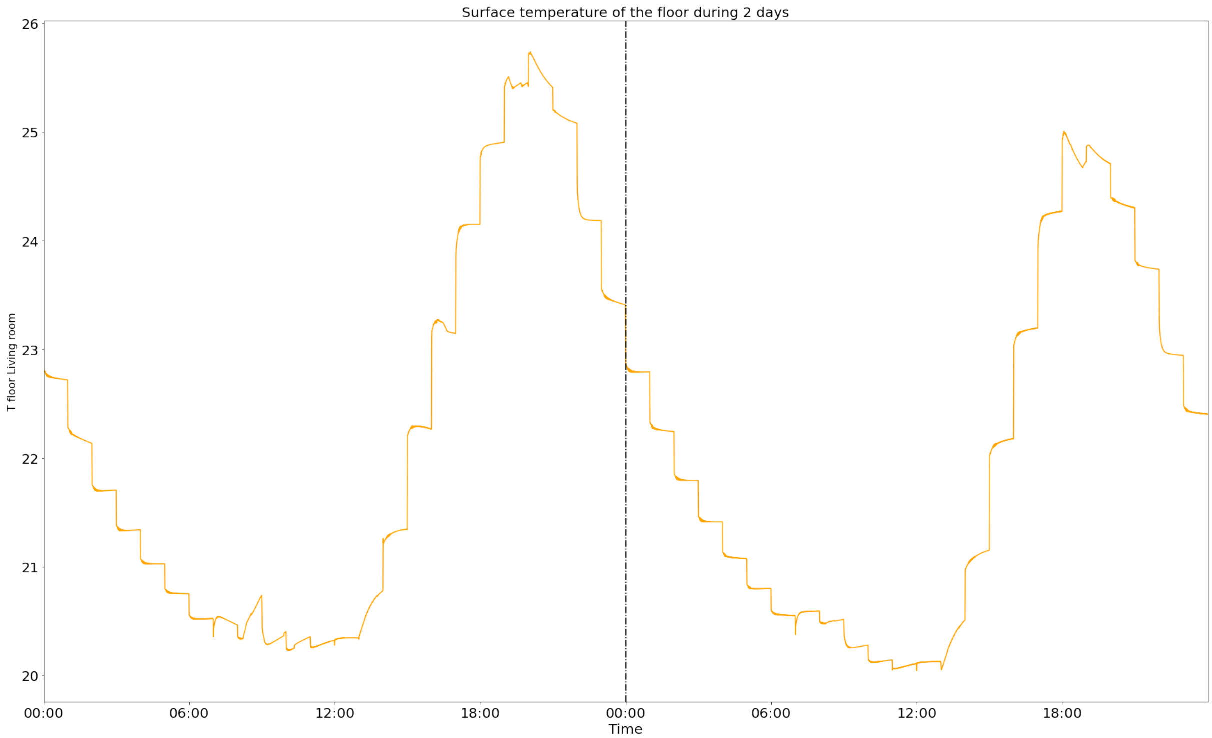


Figure 5.62: Modelled surface temperature of the floor in the living room with LTH through underfloor heating with updated façade during 48 hours

Comfort

The comfort levels have again been calculated using the workaround presented in chapter 4 of this thesis. The calculated PMV throughout 2020 can be seen in figure 5.63. The average PMV during heating season is -0.34 which is only marginally better than the average of -0.45 in the model with the current façade properties. The minimum reached PMV during heating season is -0.74. It reaches a value below -0.5 for 27.28 % of the time. This results in an average PPD of 8.31 with a maximum of 16.55.

Figure 5.64 shows the adaptive comfort classification for this model. It can be seen that this has increased slightly compared to the model with current façade properties. The dwelling still is a Class A-B building but does not come as close to a Class C. Figure 5.65 shows the individual comfort levels. These are, like the model with current façade properties, comfortable for a majority of the time.

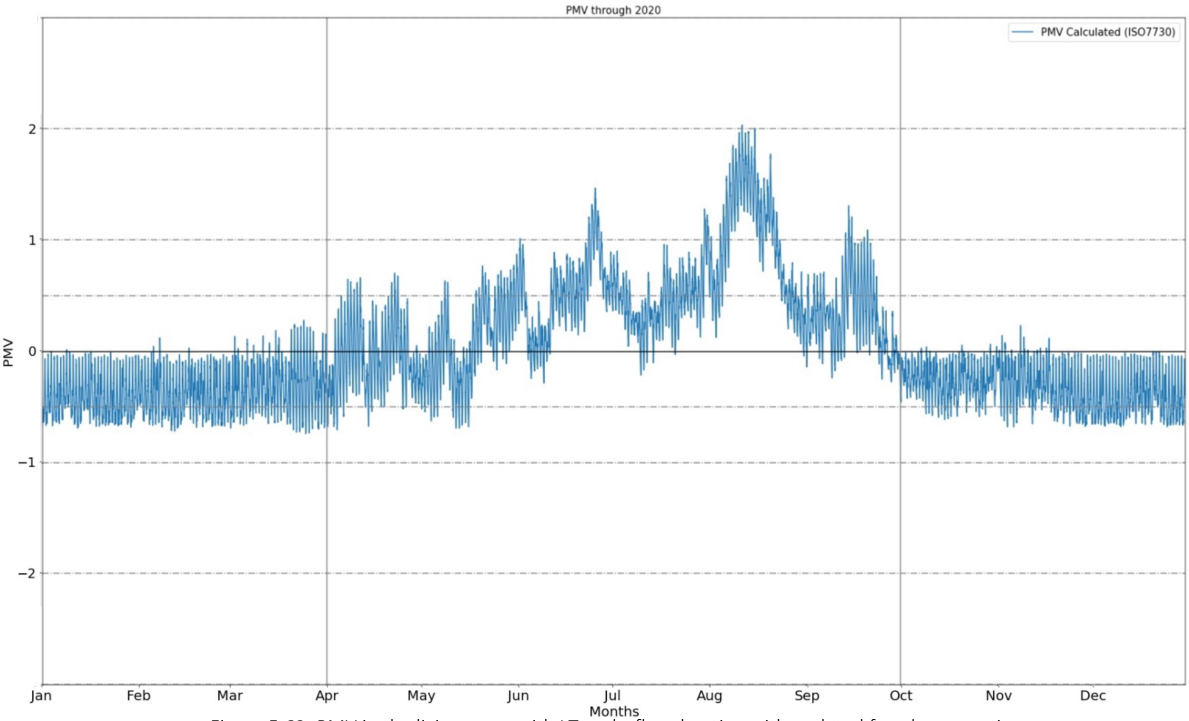


Figure 5.63: PMV in the living room with LT underfloor heating with updated façade properties

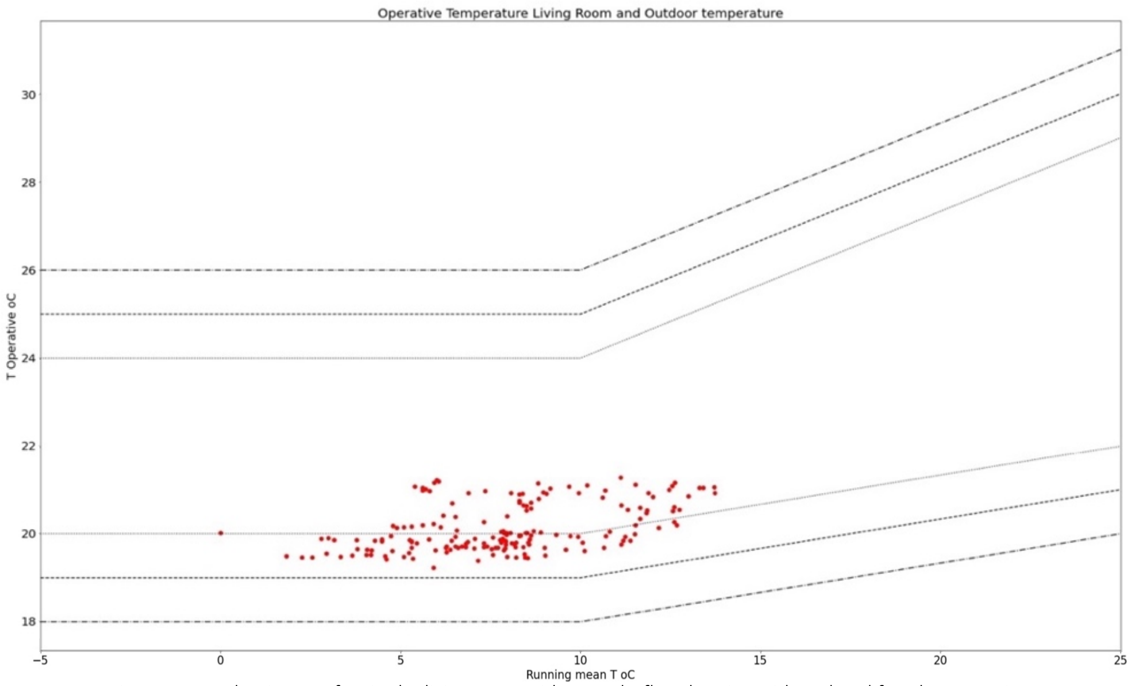


Figure 5.64: Adaptive comfort in the living room with LT underfloor heating with updated façade properties

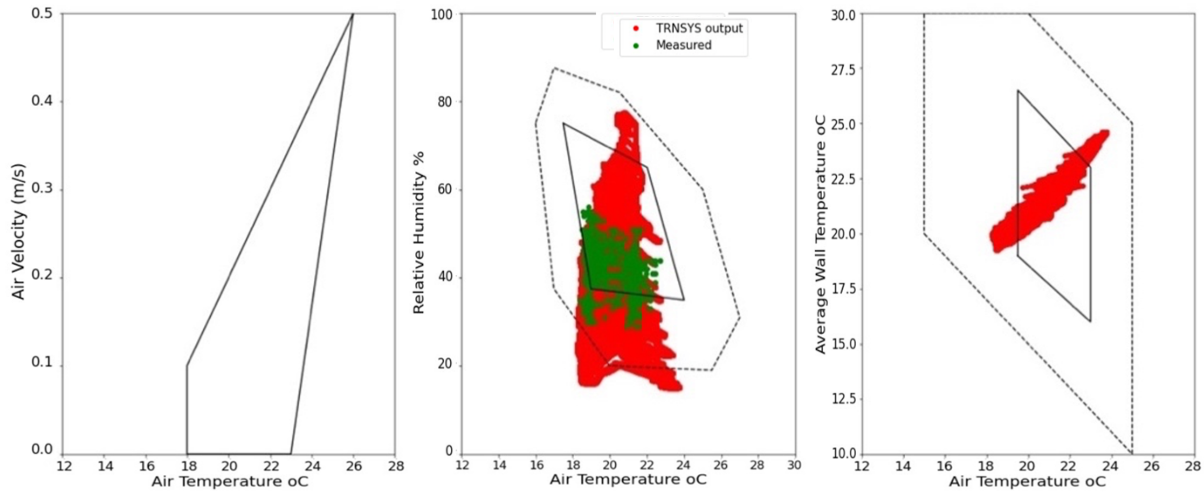


Figure 5.65: Individual comfort parameters in the living room with LT underfloor heating with updated façade properties

Comfort at the front of the room

The PMV at the front of the room has an average value of -0.30 during the heating season. It reaches a minimum of -0.66. The overview can be seen in figure 5.66.

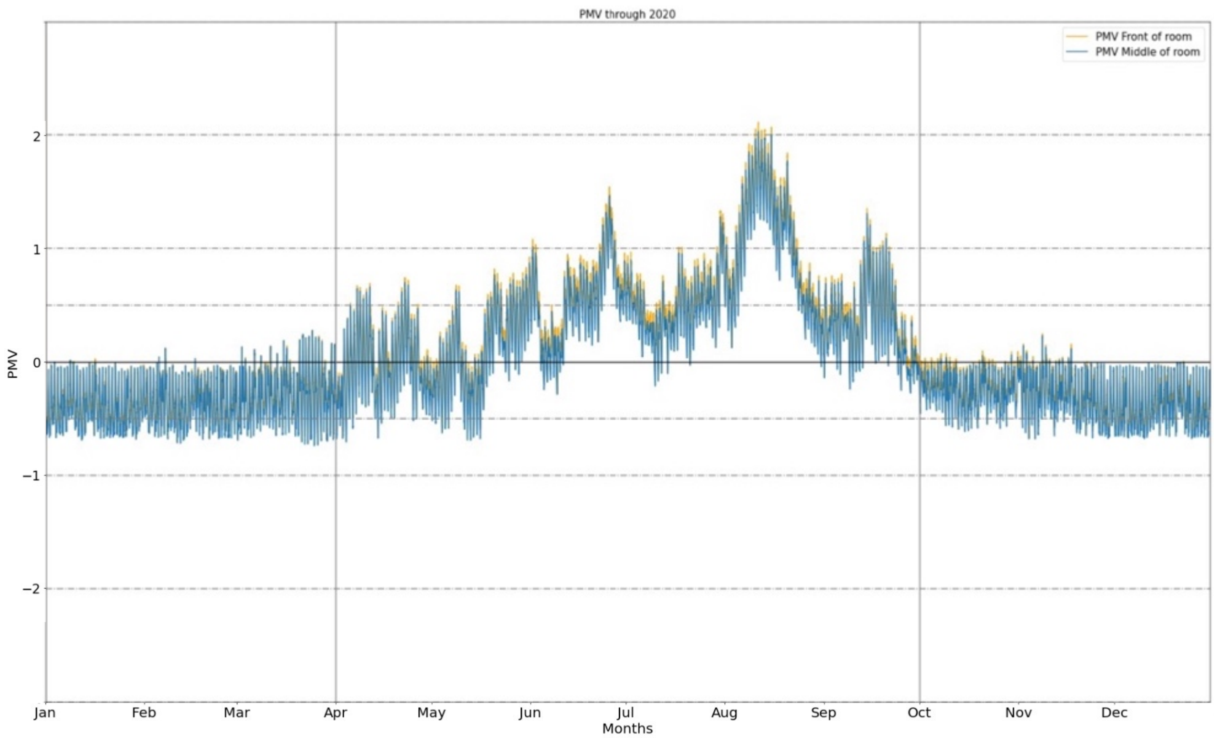


Figure 5.66:PMV at the front of the room with LT underfloor heating in the living room

Renovation Plan

Since the renovation measures are identical to the measuring from section 5.3 of this thesis, the way to achieve this is also equal. The comfort increase is so slim, that it could be argued that this renovation is not worthwhile.

5.5 Energy use

The main focus of this thesis is to assess the indoor climate comfort when changing to low temperature heating in dwellings. The reason for wanting to change to low temperature is however to increase renewable energy possibilities for space heating. In real-life renovation projects, the amount of energy saved or renewable energy increase is likely to be a deciding factor for a go-ahead vote. Therefore, an estimation of energy use will also be made in this thesis.

Although TRNSYS is a very suitable program for calculating energy demands or productions, the model set up for this thesis is not optimized for this purpose. The focus of the models described in this report are focused on comfort. The reason for not focusing on the energy use of the heating system is twofold. On the one hand, the production of heating energy can be carried out in several ways. These production methods all have their own efficiencies and distribution losses. For different types of residences and in different locations, different results may be found. On the other hand, available computing/modelling time is limited. By creating a hugely detailed model, which focusses on all aspects, simulation time is also greatly increased. One example of this is the detailed radiation model, which multiplies the simulation time by 2-3 times. This was deemed vital for a good comfort analysis however.

Nonetheless, it is possible to estimate and compare heat transfer rates. The model will determine how much energy is needed in order to achieve the desired room temperature and adjust the energy flow accordingly. In TRNSYS, this is outputted as the heat transfer rate of the radiators for each timestep and is expressed in kJ/hour. The heat transfer rate in kJ/hour can be converted to Watts by dividing by 3.6. Timesteps in the model are set at 0.01 hours so multiplying these Watts by 0.01 hour and adding all individual timesteps up gives the total Wh used for heating energy (which can in turn be expressed in the more frequently used kWh). This can then be converted to m^3 of gas. For natural gas in The Netherlands a conversion rate of 1 m^3 natural gas for 9.769 kWh can be used (De Energieconsultant, 2021).

In the dwelling in the case study, the actual gas use has been measured from 10-11-2020 00:00 until 31-12-2020 00:00. The total measured gas use for this period adds up to 188.96 m^3. The converted total gas use needed to heat the radiators in the model during this period is calculated at 174.73 m^3. The difference can be explained by the gas use for hot tap water in the measured data.

Figure 5.67 shows the total heat transfer during the heating season and how this is divided over the different radiators. The total gas use for the heating season adds up to 514 m^3. Compared to the average gas use for residential terraced houses of 970 m^3 in a full year (CBS, 2020) this is a lot lower. This can partially be explained by the heating being required also outside of the heating season. A second cause is the exclusion for hot tap water in the model. In case of a combined central heating/water heater, this will also add to the yearly gas consumption. A third reason can be the efficiency of the central heating system. If this is a slightly older system, the efficiency will be lower causing a higher gas consumption.

From figure 5.67 it can be seen that all façade updates decrease the required heat transfer from the radiators. The large peak in heat transfer for the situation with HTH and no insulation shows that HTH has an abundance of capacity. The most beneficial option from a heat transfer perspective is the use of low temperature radiators. These require the least amount of heat transferred to the living room, while still maintaining decent comfort levels, especially after the façade renovation proposal. The heat transfer from underfloor heating is relatively high. This could also be due to high heat transfer efficiencies.

It should be mentioned that these figures are heat transfer rates from the heat delivery elements. This does not take efficiencies of distribution and production of the heat into account. The coefficient of performance of low temperatures can be as high as 4-6 whereas the efficiency of a central heating system for HTH tops out at around 1. This means that the required primary energy use is much lower for LTH heating options. Since this COP depends largely on the way the heat is generated, this is not taken into account in this study. Another important factor for wanting to change to LTH, despite the small changes in energy transfer in the dwelling, is the option to generate this heat via renewable energy sources.

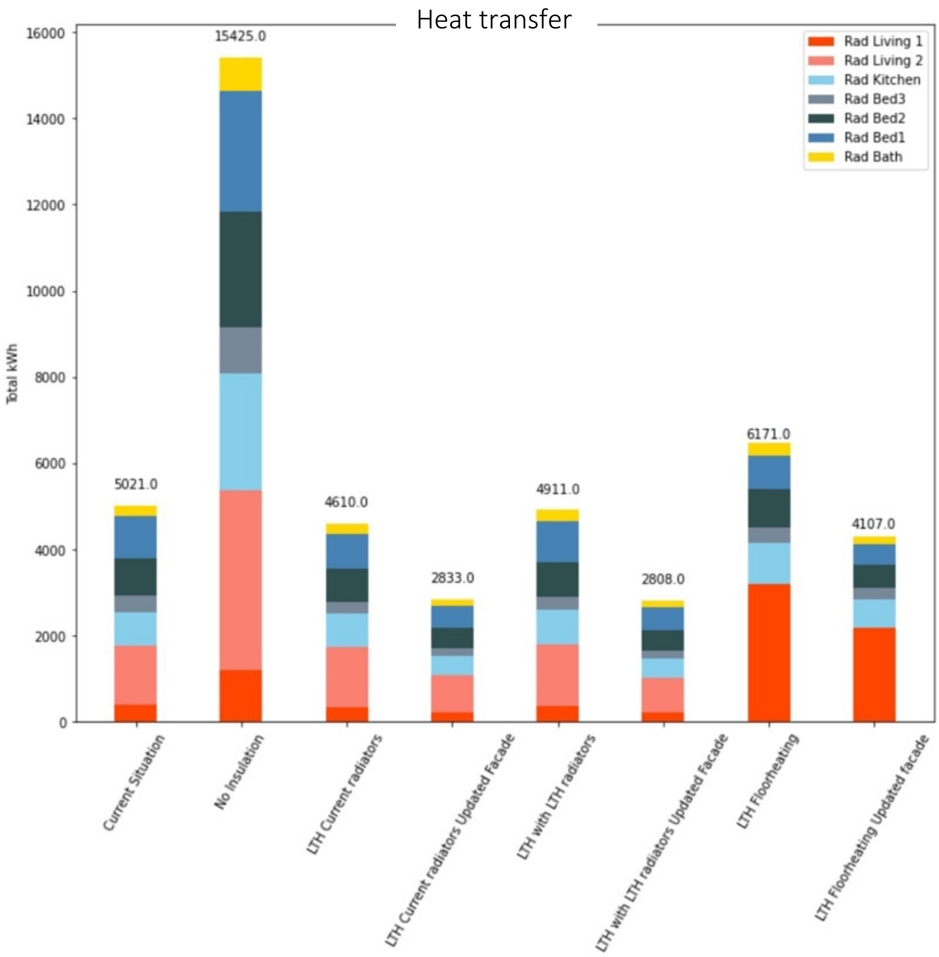


Figure 5.67: Total heat transfer during heating season per radiator per renovation proposal

5.6 Summary

The study consists of 4 heating systems, including 1 high temperature option and 3 low/mid temperature alternatives. For each heating system, two façade types were investigated. Firstly, the current façade properties were analyzed followed by a renovation proposal for the low/mid temperature options. For the high temperature heating system, it was investigated what the impact of the current renovations was by stripping the building of all insulative materials bringing it back to its original state.

The average PPD during heating season of 6 of the 8 simulations are very similar. The option with HTH with no insulation scores significantly worse. This option reached lower surface temperatures throughout the heating season compared to the other options while still achieving the desired air temperatures. This highlights the importance of surface and mean radiant temperatures when assessing indoor thermal comfort. It also means that increasing the desired temperature settings of the thermostat will most likely not fix the comfort levels since the air temperatures were relatively well achieved. One conclusion could be that for high temperature heating, the current renovations done to the dwelling are effective. It should be mentioned that the claims by the manufacturer exceed insulative values of cavity insulation by a factor two compared to what could be expected from studies. This could also explain why the façade, which matches the contractor's claims in the model, has a higher modelled temperature than what was measured for the same time period.

The LTH option through the current radiators also scores relatively poorly in terms of average and maximum PPD during heating season. In this case that is due to a large drop in air temperature. During periods of cold ambient air temperatures, the capacity of the radiators is not sufficient to heat the indoor air to the desired temperatures. This is also displayed well by the points in the adaptive model. At lower running mean outdoor air temperatures, the comfort classification also drops. It could also be seen that it is not feasible to increase the comfort levels to match or exceed current levels. The indoor air temperature still drops to as low as 17.31 ^{o}C, which is over 1 degree lower than desired, after renovation measures were implemented in the model. Therefore using the current radiators is not deemed a viable option when changing dwellings to low temperature heating.

Low temperature heating through radiators specifically designed for LTH creates capacities of the heating delivery elements to match the levels determined through ISSO publication 51. At the current insulation levels, this causes an average PPD and adaptive comfort classification close to the current HTH system. The minimum reached PMV and PPD are on the other hand slightly poorer. This can be explained by a lower air temperature than desired. After renovating to the 'Target Values', the air temperatures, surface temperatures and comfort levels are similar or better than the current situation making this a viable option for a renovation proposal. Especially the increased airtightness is a contributing factor to the increased air temperature whereas the updated insulative values mainly increase the surface temperatures.

The last evaluated option is underfloor heating on the ground floor living room and kitchen. Although this requires intensive renovation measures inside the dwelling, it does provide the best comfort levels in this study. Even at current insulation levels, underfloor heating exceeds current comfort levels in both comfort theories. The air temperature itself lacks behind however. At current insulative levels, both the lowest desired air temperature and the desired increased peaks in the evenings are not met. Therefore a renovation of the façade is still deemed necessary. Again a combination of increased insulative properties and increased airtightness was opted. This increases comfort levels only marginally, but the indoor air temperatures are now a lot closer to the desired levels. It should be mentioned that the peak temperatures in evenings are still not always met. This could be explained by the time it takes for underfloor heating to heat up. This is a lengthy procedure that cannot heat up the entire room in a sufficiently short time period. An option could be to introduce a small radiator to help reduce the warm up period of the air temperature or to start warming up the floor earlier in the day. What option is most effective should be investigated in future studies.

The total heat transfer from LTH radiators is the lowest, while still maintaining decent comfort levels. All renovation proposals result in a lower total heat transfer during the heating season indicating that façade renovations are in fact beneficial for both increasing comfort while decreasing energy use.

For all options, it was also assessed what the influence of the location had on the comfort levels. The main place was assumed to be in the middle of the room, but a second comfort sphere was placed close to the front façade near the large window. The results show that in all options, except for the situation without any insulation, the location close to the façade can actually perform better on average but worse at the lowest point. In the situation without insulation, it was the air temperature that dropped significantly and not the surface temperatures. The surface temperatures will actually increase the thermal comfort in this case.

That extremes are lower close to the façade can be explained by the large window, creating a cool surface resulting in discomfort. That the average is better can be due to solar irradiation on the floor and surface, heating them up creating a higher thermal comfort overall. Figure 5.68 shows the minimum temperature. Figure 5.69 shows the average and extreme PMV, the time the PMV is below -0.5 in heating season and the average and extreme PPD in the middle of the living room during heating season. A table with the numeric values can be found in Appendix L: Comfort summary.

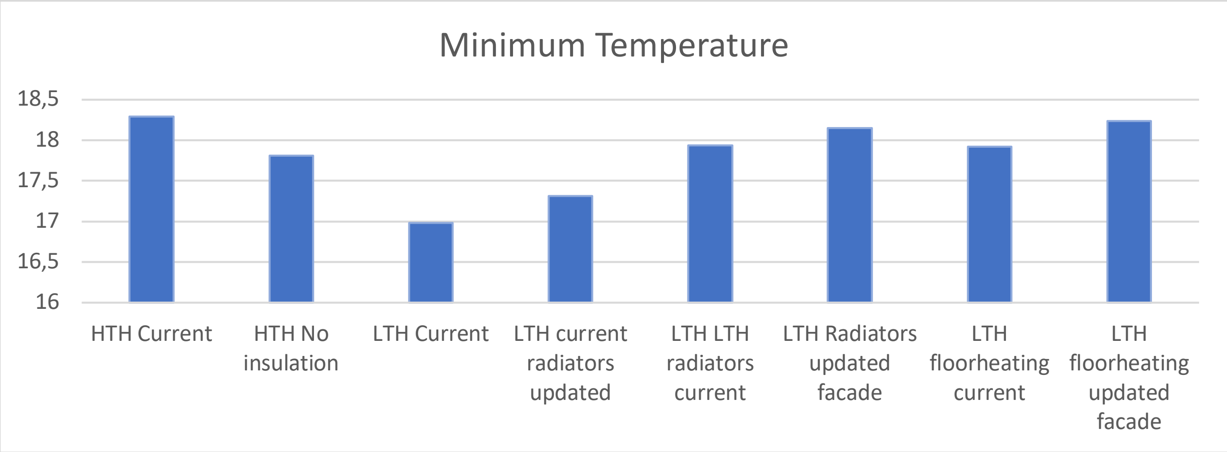


Figure 5.68: Minimum temperatures in living room during heating season

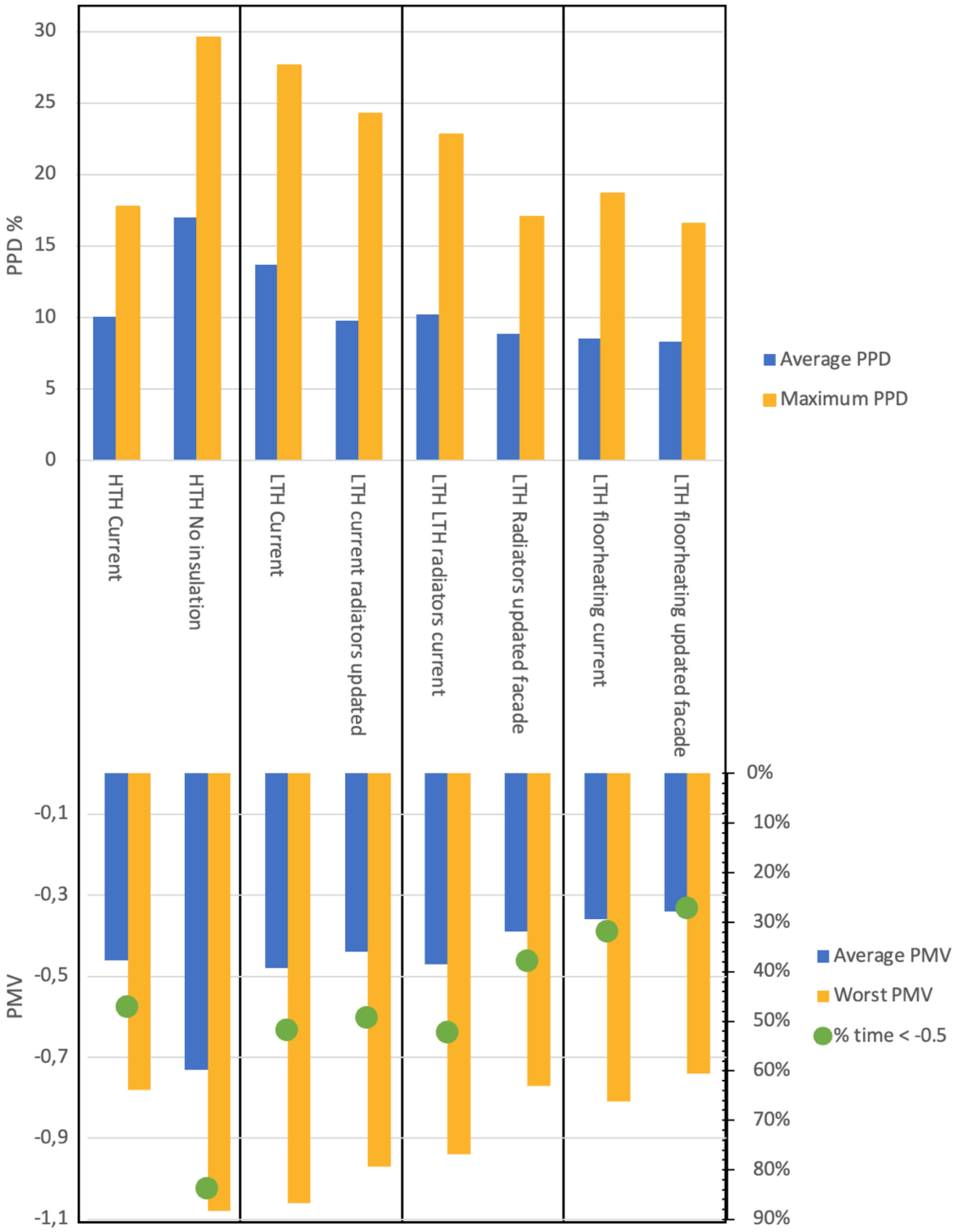


Figure 5.69: Average and extreme PPD and PMV during heating season in middle of the Living room

6. Discussion

In this section the results of the study will be further elaborated. General findings on indoor thermal comfort as a building parameter and the assessment thereof will be discussed. Also the results of the different heating systems and insulation levels will be elaborated. In addition, limitations of this study, and thermal comfort analyses in general, will be discussed.

Comfort at Low Temperature Heating

When conducting a detailed thermal comfort study, it is important to distinguish the different comfort theories and parameters. As for the theories, thermal comfort can either be assessed by means of Fanger's Predicted Mean Vote or by building Comfort Classes in the adaptive model. Where the PMV was initially created for airconditioned office spaces, the adaptive model primarily focused on free running buildings. Both have been adapted over the years and additions were made so both models are now suitable for a large variety of buildings.

Key parameters that determine thermal comfort are air temperatures, the mean radiant temperature, relative humidity, airspeed, the clothing factor of the garments worn by the occupants, the metabolic rate caused by activity and the external work. Some of these parameters, such as relative humidity and airspeed are key examples of outputs of an HVAC study. The focus of this study lies on façade design, which mainly impacts the air temperature and the MRT. Both in the PMV and adaptive model, the MRT has a large impact on comfort levels. The MRT is largely dependent on surface temperatures and areas and the orientation of the comfort sensor relative to those surfaces. The heating delivery elements (such as radiators or floor heating) play a large part in the MRT since they will reach relatively high temperatures. Again, it should be stressed that all comfort parameters are linked and cannot be used separately to evaluate comfort. In simpler comfort studies, simpler assumptions of some parameters might be sufficient. The more detailed a study becomes, the more detailed the reasoning behind parameters should become.

How these individual comfort parameters can be determined and used in (comfort) calculations is described in regulations and standards. The main European standards are NEN-EN ISO 7726 and NEN-EN ISO 7730. Focusing on the European norms, NEN-EN ISO 7730 gives a detailed description of the PMV calculation and how the individual parameters can be determined or calculated. The MRT measurement and calculation is further elaborated in NEN-EN ISO 7726. For the insulative values of dwellings, 'Target Values' were introduced. These values are not mandatory to implement but go beyond regulations and are deemed necessary for buildings to get energy efficient and comfortable. These 'Target Values' were also assessed in this research and proved to be a good target for the insulative properties. The required heating capacities per zone can be calculated with ISSO publication 51.

So thermal comfort is the resultant of a large variety of individual elements of a building. In order to accurately set up a model with the purpose of conducting a comfort assessment, not only the building geometry is important but also all window and wall properties, the complete HVAC system and occupant behavior are key parameters. This requires knowledge of many different areas of expertise such as façade engineering, HVAC design and occupancy behavior studies. It is recognized that on an individual dwelling basis, it is not always possible to conduct a detailed comfort study like this research simply due to lack of time or resources. On a building block or neighborhood level, with many similar units, a detailed comfort study can, and should, be conducted however, especially when changing to low temperature heating systems. It was demonstrated that the LT radiators, for which the capacities were based on the ISSO 51 publication, did not always create sufficient capacity to achieve the desired minimum temperatures. Since they are designed to have sufficient capacity to heat rooms to 22 ^oC at ambient temperatures of -10 ^oC this is unexpected. A factor that could influence these results is the temperature decrease and increase on a daily basis. A more consistent temperature profile might increase the achieved indoor air temperature in heating season and thus thermal comfort.

Changing to low temperature heating systems is undeniably important for buildings to get through the energy transition. It is not realistic to create sufficient renewable energy for all buildings to be heated with high temperature heating systems at current insulation levels. Increasing insulation and decreasing infiltration levels, and thus lowering the total energy loss and demand, enables lower temperatures for space heating which in turn opens up more renewable alternatives for heat generation like low temperature geothermy, solar heat or heat pumps. Besides all the benefits of low temperature heating there are, of course, also risks. One of the main risks is that diminished heating capacities may adversely affect the indoor thermal comfort of buildings. This became especially clear in the situation where LTH was implemented with the current HT radiators. The capacities dropped, resulting in lower surface temperatures and lower comfort levels. In order to mitigate the impact of decreased capacities, radiators need to become exceedingly large or renovations can be carried out to increase thermal insulation values of the ground floor, façade and roof and reduce infiltration rates. This decreases heat losses and thus the required capacity. There is however a limit to this mitigating potential of renovations. In the case study it became clear that LTH through HT radiators reduces capacities so much, that no realistic insulation levels will mitigate this sufficiently and thermal comfort cannot be improved to acceptable levels.

Comfort Simulation Software

The large variety of the parameters that influence indoor thermal comfort also adds to the complexity of computer models used to conduct a detailed thermal comfort study. Simulation software can be a powerful tool to assist with complex issues. With increased complexity, increased caution should be taken however. When using computer models for a design, it is imperative the user not only understands the physical phenomena of the problem at hand but also how the computer model deals with this. Without this understanding, the computer models are in danger of turning into black boxes and results cannot be verified. This verification is a vital step when working with complex software simulations. Also in this study, a verification and validation was carried out resulting in the use of a workaround to enhance transparency of used calculation methods.

The simulation software used in this thesis is TRNSYS 17. It is a powerful software package widely used and validated to simulate energy flows in transient systems. In earlier versions it focused mainly on solar power production. Over the years, additions were made, enabling a larger variety of simulation types including energy consumption of buildings. Via an array of plug-ins, the buildings geometry and properties can be specified. One of the added functions in TRNBuild is the possibility to directly output the PMV and operative temperature. The PMV is claimed to be calculated via the NEN-EN ISO 7730 standard. At the start of this thesis this was believed to make TRNSYS 17 a highly suitable software package for the detailed comfort study this research set out to be.

During the verification of the model and the PMV calculations some anomalies were found however. It could not be verified how TRNSYS actually calculates the PMV. With the same comfort parameters, TRNSYS showed an overestimation of the PMV of 0.02 compared to three other PMV calculators based on NEN-EN ISO 7730. Several attempts were made to uncover what this difference is caused by but the reason was not found. On the PMV scale of ±3 with a comfortable region of ±0.5 the difference of 0.02 could be considered sufficiently small to not have a significant impact on the comfort classification of the dwelling under investigation. Nevertheless, because the reasons for the deviations could not be discovered, the PMV calculations by TRNSYS 17 were considered too unreliable to be used.

Furthermore, the way TRNSYS takes space heating into account, either with standard or detailed settings, were deemed insufficiently realistic for an accurate MRT calculation. The workaround presented in chapter 4 should increase the accuracy and bring the calculation method more in line with the procedure described in NEN-EN ISO 7726. This is done by using ordinary view factors instead of Gebhardt factors. The drawbacks of the presented workaround are that the model used for the simulation still uses point sources as radiators and the deviating comfort sphere from standards. The MRT calculated by TRNSYS and the workaround show a maximum difference of 0.26 ^{o}C. This difference is relatively small, especially considering temperature sensor sensitivities are of the same order magnitude. It also could be argued that this difference does not greatly impact the comfort outcomes. The fact that the TRNSYS calculation does not follow ISO standards was still considered a valid reason to use the workaround presented for the MRT calculations.

Developing and verifying the new MRT and PMV calculation procedures was time consuming but is considered to have increased the transparency of the calculations behind the results and thus the reliability of the outcomes.

Results

The results of the study are summarized in table 6.1. The 3 tested LTH systems are ranked on a 5 point scale including --, -, O, + and ++. The first assessment criterium is the intrusiveness of the renovation of the heating system. ++ means little to no intrusion whereas -- means a very intrusive renovation where residents will most likely need to be temporarily relocated. The following criterium is the capacity of the heating system. Here -- means a large capacity deficit. ++ in this category would mean 'more than sufficient' capacity. Then the impact of the façade renovation is ranked from -- where a façade renovation is not feasible to create sufficient comfort and ++ means a highly efficient façade renovation is possible. A last index is the effect of the heating system and the façade on the comfort levels. -- means the comfort levels are strongly negatively affected and a ++ means a strong improvement. All these criteria together form a verdict saying whether or not an option is considered viable when renovating to low temperature heating.

Table 6.1: Overview of outcomes

	Plan2: LTH current radiators	Plan 2: LTH façade update	Plan3: LTH with LTH Radiators	Plan 3: LTH radiators façade update	Plan4: Underfloor heating and radiators	Plan4: Underfloor heating Updated Façade
Intrusiveness of heating renovation	++	++	-	-	--	--
Capacity of heating system	--	-	-	+	O	+
Impact façade renovation		O		+		+
Comfort affect	--	--	-	+	+	++
Comfort levels LT-Ready?	--	-	O	+	+	++

General remarks and possible improvements

On first glance, some of the calculated comfort levels might seem to match current levels. But at closer inspection, it was found that the desired minimum air temperatures in the living room are not actually always met. The mean radiant temperature of the walls has such a large effect on the comfort levels, that the air temperature is sometimes not factored in as much as it maybe should be. This could have to do with the relatively low assumed airspeed. This impacts the convective coefficient in turn increasing the relative influence of the radiative part. An HVAC expert could be consulted or measurements could be taken to estimate the airspeeds in the living room caused by the ventilation system. During this study, the details of this ventilation system were not fully known, only that it was a heat recovering unit. The modelled properties are based on common practice values.

It should also be noted that, especially for the average values, the calculated PMV and PPD levels are very close together. It could be argued that differences are so small, they can be neglected. Together with the adaptive model, the air and mean radiant temperatures and percentages of time of comfort levels outside a boundary a comprehensive overview of all comfort parameters can be given. When taking all these factors into account, a complete picture of the comfort levels can be created and in this thesis differences were deemed more significant. This is especially applicable to the option for LTH through LT radiators. Here the average PPD is similar for the current insulative values or with the insulation set to 'Target Values'. The peak PPD, drop in minimum air temperature and percentage of PMV below -0.5 show an improvement that is believed to be significant. LTH through underfloor heating shows a higher similarity for comfort between the current insulative values and 'Target Values' however. Here it could be argued that a facade renovation does not significantly improve the comfort levels and could be debated if a renovation is required or an extra radiator can increase comfort. A full Life Cycle Analysis could point out if the energy savings during the life time extension after renovation is weighs up against the required renovation material. This LCA should take all environmental impact categories, such as greenhouse gas emissions, acidification or ozone layer depletion into account. This could also include health benefits for occupants. Several different energy production methods and insulation materials could be examined and compared over the full life time of the renovation proposal.

It is expected that a more stable thermostat regime will already increase the minimum air temperature in the living room since the system does need to heat up as often which can be time consuming. Then if temperatures occasionally drop below the setpoint during nighttime, this could be considered acceptable for a living room. If this is not acceptable, then a booster heater (e.g. in the form of a small radiator) could be installed to mitigate this. More formal studies should be conducted to assess the impact of these thermostat settings and at what point a booster is required.

The outcomes of this thesis are based on the inspected residence and assumed temperature settings. Although the dwelling shows a large resemblance to a large portion of the housing stock in The Netherlands, it should be investigated to what extend results apply to (terraced) dwellings in general. Layouts of terraced dwellings might differ in such a way, the thermal zone plan assumed for this thesis does not apply anymore. An example could be the opening of the kitchen to be a part of the living room. This would significantly change internal heat gains in the living room when cooking. Also the weather input might affect the outcomes. A Typical Mean Year weather file could also be investigated.

Another point of attention is how TRNSYS 17 simulates a building. A thermal node network is a powerful model to calculate heat energy flows through thermal zones. Calculations with detailed timesteps can be made relatively quickly and accurately. A calibration was carried out to have the model resemble measured data as best as possible. Extending the measured datasets could highly increase the reliability of this calibration step. An example of what could help is the measurement of all surface temperatures in a zone for a full year. Modelling in a thermal node network in TRNSYS 17 also comes with limitations. For example airspeed is not a parameter taken into account in an ordinary thermal node network. In this case it assumed to be uniform throughout the zone for the comfort calculations. A way to take variable airspeed into account is by using a Finite Element Method software package or a Computational Fluid Dynamics tool. With a FEM model, the room can be split up in a mesh, creating a grid where parameters can be inputted for each node. This way, the differences throughout a room can be calculated and visualized. This could increase the level of detail of the comfort study even further than this research. It should be noted however that these types of simulations are time and resource intensive. Therefore it is not always recommended to run simulations of this type for longer assessed time periods. It also does not necessarily contribute to a general comfort study of a dwelling but it does show how comfort levels may vary within a zone. In this thesis variation was assessed by implementing two comfort spheres in key locations. This amount of comfort spheres can be extended but this will increase complexity significantly.

Only one renovation proposal was designed more in detail. There are more possible interventions that could be explored and tested against a set of pre-determined parameters such as construction time, circularity, costs and intrusiveness. The proposed renovation does take the recently published 'Target Values' into account and it can be seen that these values do have a positive impact on required heat transfer rates and comfort levels. Another option that could be included in the heating systems in a future detailed comfort analysis is the use of wall heating.

A recommendation for future research would be to conduct a formal sensitivity analysis of the different comfort parameters. This way a more well founded estimation of the level of accuracy of a simplification in a model can be made. This could for example explain what the exact implications of an area-weighted radiation distribution is compared to radiative point or plane sources. This could also contribute to the explanation as to why TRNSYS calculates the PMV slightly different from other tools. A sensitivity analysis could also contribute to more insight in the required level of accuracy of parameters. This could help when choosing temperature sensors and their parameters in terms of accuracy and reliability.

TRNSYS was the main software tool used during the process of this research. The outcomes were assessed in Python however. This is one example of how linking software packages and utilizing each individual package's strengths can enhance and accelerate the workflow. During this research it became clear that TRNSYS does include an integrated PMV calculator but the accuracy of this calculator should be further investigated. It could also be argued that the primary function of TRNSYS is not to conduct a detailed comfort study but to simulate energy flows. When a transient energy study for a dwelling is carried out with TRNSYS, a large portion of the individual comfort parameters are also determined. Examples of these comfort parameters used in energy simulations are air and surface temperatures. By exporting these comfort parameters and linking them to other software packages, which are specialized in comfort studies, a stronger assessment of all areas of expertise can be made. This way, also accurate estimations of for example the air velocities at different points in a thermal zone can be outputted by a detailed mechanical HVAC model and used in the detailed comfort study.

During this thesis it was seen that the outputted datasets by TRNSYS got relatively large. With timesteps set to 0.01 hours, and running for 8670 hours, the list lengths reached 867000 values. For the assessment of the comfort levels in just the living room, 14 surfaces temperatures had to be assessed. On top of that air temperatures, heat transfer rates of all radiators and comfort outcomes calculated by TRNSYS were also stored. This means that for each model around 30 million data values were constructed. Powerful tools to work with relatively large datasets are scientific programming tools such as Python or MATLAB. These tools can be used simply for visualization of data in the forms of graphs and diagrams, but also provide great computational power for data analyses. A further advantage is a large variety of readily available libraries with numerous predefined functions.

For the workaround presented in chapter 4 of this thesis, an MRT and PMV calculator were developed. These functions were later converted to a MATLAB script. This was done because TRNSYS allows a direct MATLAB plug-in via Type155. This way, the outputs of TRNSYS can be linked directly in the Simulation Studio to MATLAB inputs. Further advantages are that MATLAB computations can be done in real-time or after a TRNSYS run is complete. The written MRT and PMV calculators in Python and MATLAB can be a quick, transparent and accurate method for computing the values in line with NEN-EN ISO 7726 and 7730.

Another powerful tool with gaining popularity is parametric designing through Rhinoceros and Grasshopper. By having the ability to change a large variety of parameters and instantly receiving computational results as well as a Rhino visualization, a large amount of design options can be assessed relatively quickly. What makes this especially powerful is the increasing amount of plug-ins and their variety. Examples are Karamba3D for structural analyses and Heteroptera for animations and mathematics.

In case of indoor thermal comfort, a possible Grasshopper plug-in would be Ladybug. This package provides several components regarding PMV calculations, adaptive comfort calculations and local comfort parameters. Outputs for the surface and air temperatures computed by TRNSYS can be used as inputs for these components. Combined with outputs of a possible HVAC study such as airspeeds and extra Ladybug options such as the 'Outdoor Solar Temperature Adjustor', this can create a powerful workflow to asses designs for several areas of expertise. This package could have been a viable alternative for the comfort analysis conducted in this thesis.

7. Conclusion

The main research question of this thesis is:

When changing to low temperature heating in renovation projects, what changes need to be taken to the façade, in order to realize a good thermal comfort?

In order to answer the research question, a typical terraced dwelling in the Netherland was analyzed. One HTH and three LTH systems were evaluated in terms of their comfort levels and the required heat transfer with 2 different façade alternatives.

The influence of the façade on thermal comfort is twofold. By improving the insulative values of the façade, the mean radiant temperature was affected positively which increases the sense of comfort. Secondly, a façade renovation can increase the airtightness of a building. In this study, this primarily affected the possibility to reach desired air temperatures. With HTH a main issue was a deficit of surface temperatures at insufficient insulation values, whereas air temperatures were maintained relatively well. When changing to LTH, the problem shifted to insufficient air temperatures. This was the case for the dwelling in the case study, but will likely also be a trend in general. Therefore, increasing air tightness of the façade will become more important when changing to LTH.

From the case study it became clear that changing to LTH is not feasible with current ordinary radiators. Not only for the dwelling in this case study but also in general it is likely that capacities will diminish with such substantial amounts that comfort cannot be achieved. The lack of capacity is so large that it cannot realistically be compensated by insulating the façade.

In terms of comfort, the most beneficial heating system with LTH in the studied dwelling is underfloor heating. Whether this is true for all (terraced) dwellings should be investigated but in general underfloor heating maximizes capacity by using the large surface area of the floor. In the case study another viable option was to use LTH radiators. Although the LTH radiator capacities were calculated with ISSO 51 at current insulation values, the façade still required renovating to achieve good thermal comfort. What the impact of LTH is for ISSO 51 calculations in renovation projects in general should be further investigated. A more stable temperature regime might affect thermal comfort positively.

For the dwelling presented in this case study, an Rc value of 6 m^2K/W in combination with an infiltration rate of 0.15 $dm^3/(s*m^2)$ was found to be sufficient to create a good indoor thermal comfort level in combination with both LT radiators and underfloor heating. This insulation value matches the target set in the ‘Target Values’ indicating that this is a good aim when renovating or constructing new-builds. Peak temperatures are not always achieved however, which is possibly due to long warmup times. Reducing temperature fluctuation of a thermostat regime will likely enhance the capability of LTH systems to reach the desired peak temperature.

In general, low temperature heating can play a large role in getting buildings through the energy transition. However, it is imperative that, in conjunction with LTH, insulation levels are adequate, infiltration is limited and ventilation is controlled. With this combination of factors, heat losses are reduced. Only then a switch to renewable energy can be achieved whilst still maintaining highly comfortable living situations. The tool presented in this thesis was used to show some examples of how LTH and façade design go hand in hand when renovating a dwelling in a comfortable way. Whether it is through the tool presented in this thesis or another, it is going to be increasingly important to keep comfort in mind when designing facades, roofs and floors of buildings with LTH systems. If this is done properly however, energy for space heating can be renewable whilst homes are as comfortable as ever.

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Appendix A: Building Stock table

Regio's	Perioden	Beginstand woningvoorraad										
		Totaal										
		Totaal	1905 tot 1925	1925 tot 1945	1945 tot 1955	1955 tot 1965	1965 tot 1975	1975 tot 1985	1985 tot 1995	1995 tot 2005	2005 tot 2015	vanaf 2015
		aantal										
Nederland	2012	7 386 743	430 460	684 082	372 297	808 113	1 303 642	1 136 173	1 004 001	826 390	489 660	
	2013	7 449 298	431 533	685 452	370 738	803 242	1 301 003	1 136 481	1 003 671	826 600	556 368	
	2014	7 535 316	432 787	686 649	369 091	804 501	1 304 839	1 143 619	1 010 317	829 376	617 127	
	2015	7 587 964	438 271	686 671	367 606	803 093	1 305 457	1 145 955	1 013 086	830 779	663 605	
	2016	7 641 323	435 361	686 848	365 436	800 526	1 304 810	1 148 355	1 016 491	831 875	673 016	40 823
	2017	7 686 178	435 563	687 514	363 860	797 473	1 295 746	1 148 252	1 018 131	832 463	673 373	96 180
	2018	7 740 984	435 618	688 250	361 997	793 190	1 289 812	1 149 569	1 019 713	831 209	673 921	158 921
	2019	7 814 912	437 350	689 714	360 175	791 265	1 289 632	1 152 323	1 020 370	832 269	674 141	225 941
	2020	7 891 786	438 324	690 311	358 620	789 428	1 289 790	1 153 387	1 022 792	833 130	673 220	298 675

Appendix B: Calculation of the PMV

Calculate the PMV using Equations (1) to (4):

$$PMV = \left[0{,}303 \cdot \exp(-0{,}036 \cdot M) + 0{,}028\right] \cdot \left\{ \begin{aligned} &(M-W) - 3{,}05 \cdot 10^{-3} \cdot \left[5\,733 - 6{,}99 \cdot (M-W) - p_a\right] - 0{,}42 \cdot \left[(M-W) - 58{,}15\right] \\ &-1{,}7 \cdot 10^{-5} \cdot M \cdot (5\,867 - p_a) - 0{,}001\,4 \cdot M \cdot (34 - t_a) \\ &-3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{aligned} \right\} \quad (1)$$

$$t_{cl} = 35{,}7 - 0{,}028 \cdot (M-W) - I_{cl} \cdot \left\{3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\} \quad (2)$$

$$h_c = \begin{cases} 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} > 12{,}1 \cdot \sqrt{v_{ar}} \\ 12{,}1 \cdot \sqrt{v_{ar}} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} < 12{,}1 \cdot \sqrt{v_{ar}} \end{cases} \quad (3)$$

$$f_{cl} = \begin{cases} 1{,}00 + 1{,}290\, l_{cl} & \text{for } l_{cl} \leqslant 0{,}078 \text{ m}^2 \cdot \text{K/W} \\ 1{,}05 + 0{,}645\, l_{cl} & \text{for } l_{cl} > 0{,}078 \text{ m}^2 \cdot \text{K/W} \end{cases} \quad (4)$$

where

M is the metabolic rate, in watts per square metre (W/m^2);

W is the effective mechanical power, in watts per square metre (W/m^2);

I_{cl} is the clothing insulation, in square metres kelvin per watt ($m^2 \cdot K/W$);

f_{cl} is the clothing surface area factor;

t_a is the air temperature, in degrees Celsius (°C);

$\bar{t}_r$ is the mean radiant temperature, in degrees Celsius (°C);

v_{ar} is the relative air velocity, in metres per second (m/s);

p_a is the water vapour partial pressure, in pascals (Pa);

h_c is the convective heat transfer coefficient, in watts per square metre kelvin [$W/(m^2 \cdot K)$];

t_{cl} is the clothing surface temperature, in degrees Celsius (°C).

NOTE 1 metabolic unit = 1 met = 58,2 W/m^2; 1 clothing unit = 1 clo = 0,155 $m^2 \cdot °C/W$.

(NEN-EN-ISO 7730, 2005)

Appendix C: PMV to PPD

$$PPD = 100 - 95 \cdot \exp(-0{,}033\,53 \cdot PMV^4 - 0{,}217\,9 \cdot PMV^2)$$

(NEN-EN-ISO 7730, 2005)

Appendix D: Operative Temperature

$$T_{operative} = \frac{T_{mean\,radiant} + T_{air} * \sqrt{10 * v_{air}}}{1 + \sqrt{10 * v_{air}}}$$

Or

$$T_{operative} = \frac{a_{radiant} * T_{mean\,radiant} + a_{convective} * T_{air}}{a_{radiant} + a_{convective}}$$

Or

$v_{air} < 0{,}1\,m/s$:

$$T_{operative} = \frac{T_{mean\,radiant} + T_{air}}{2}$$

$$a_{radiant} = Radiative\ transfer\ coefficient$$
$$a_{convective} = Convective\ transfer\ coefficient$$

(NEN-EN-ISO 7726, 2001)

Appendix E: LTH Placement

(Dictus, Kruithof, & Cornelisse, 2018)

Appendix F: Build-up of different house elements

Layer	*Build-up*	*Thickness*	*U-Value*
External wall	Brick Airofill Brick 2 Plaster	0.15 0.06 0.1 0.02	0.288
Internal wall	Plaster Limestone Plaster	0.012 0.1 0.012	2.238
Adjacent Wall	Plaster Brick Cavity Brick Plaster	0.012 0.15 - 0.15 0.012	1.116
Ground Floor	Wood Insulation Concrete	0.01 0.12 0.2	0.293
Floor	Finish Concrete	0.02 0.2	2.978
Roof	Roof tiles Wood Cavity Insulation Plaster	0.015 0.02 - 0.2 0.002	0.168
Windows	Glass Cavity Glass	-	1.2
Doors	Wood	-	1.2

Appendix G: Model 1 ventilation and infiltration

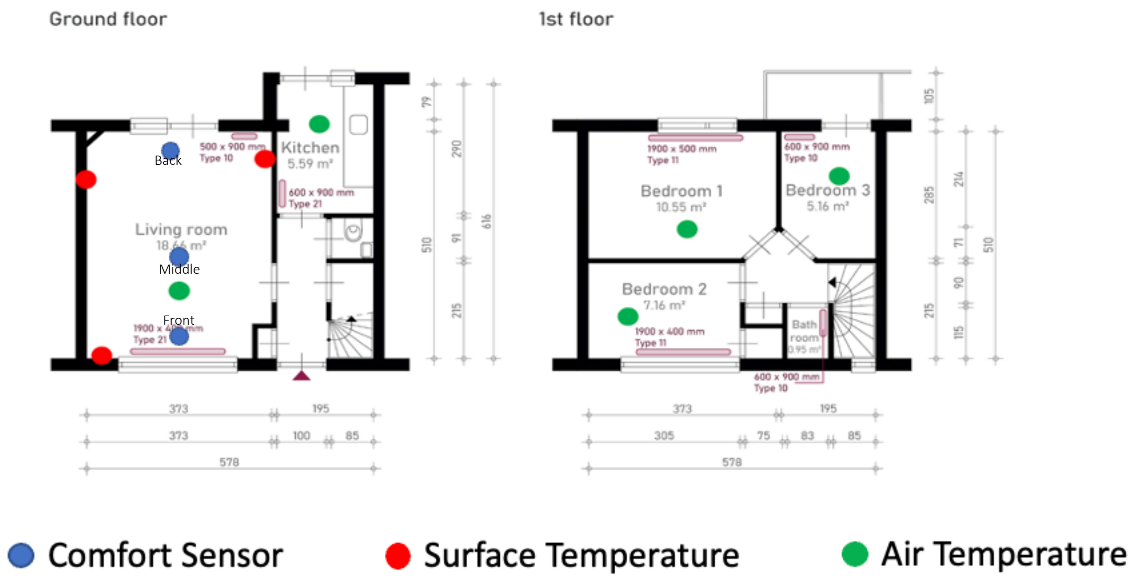
	Ventilation Norm		*Floor Surf*	*Height*	*Volume*		*Total Vent*	*Air change rate*
			m2	m	m3	dm3/s	m3/h	1/h
Living	0,7	$dm^3/s/m^2$	19,00	2,60	49,4	13,3	47,88	0,97
Kitchen	21	dm^3/s	5,70	2,60	14,82	21	75,6	5,10
Toilet	7	dm^3/s	1,20	2,60	3,12	7	25,2	8,08
Hall	0,7	$dm^3/s/m^2$	3,00	2,60	7,8	2,1	7,56	0,97
Staircase								
Bathroom	14	dm^3/s	0,95	2,40	2,28	14	50,4	22,11
Landing	0,9	$dm^3/s/m^2$	1,50	2,40	3,6	1,35	4,86	1,35
Bed 2	0,7	$dm^3/s/m^2$	10,68	2,40	25,632	7,476	26,913	1,05
Bed 3	0,7	$dm^3/s/m^2$	5,55	2,40	13,32	3,885	13,986	1,05
Bed 1	0,7	$dm^3/s/m^2$	6,55	2,40	15,72	4,585	16,506	1,05
Loft	0,7	$dm^3/s/m^2$	29,00		39	20,3	73,08	1,87

	Infiltration Norm		*Floor Surf*	*Height*	*Volume*	*Total Vent*		*Air change rate*
			m2	m	m3	dm3/s	m3/h	1/h
Living	0,6	$dm^3/s/m^2$	19,00	2,60	49,4	11,4	41,04	0,83
Kitchen	0,6	dm^3/s	5,70	2,60	14,82	3,42	12,312	0,83
Toilet	0	dm^3/s	1,20	2,60	3,12	0	0	0,00
Hall	0,6	$dm^3/s/m^2$	3,00	2,60	7,8	1,8	6,48	0,83
Staircase								
Bathroom	0,6	dm^3/s	0,95	2,40	2,28	0,57	2,052	0,90
Landing	0	$dm^3/s/m^2$	1,50	2,40	3,6	0	0	0,00
Bed 2	0,6	$dm^3/s/m^2$	10,68	2,40	25,632	6,408	23,0688	0,90
Bed 3	0,6	$dm^3/s/m^2$	5,55	2,40	13,32	3,33	11,988	0,90
Bed 1	0,6	$dm^3/s/m^2$	6,55	2,40	15,72	3,93	14,148	0,90
Loft	0,6	$dm^3/s/m^2$	29,00		39	17,4	62,64	1,61

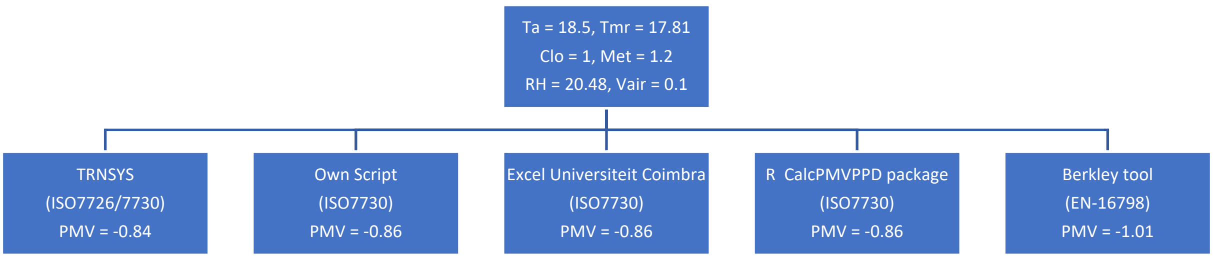
Improved values:

	Ventilatie eis		Oppervlakte	Hoogte	Volume	Totale ventilatie		Air change rate
			m2	m	m3	dm3/s	m3/h	1/h
Woonkamer	0,15	dm³/s/m²	19,00	2,60	49,4	2,85	10,26	0,21
Keuken	0,15	dm³/s	5,70	2,60	14,82	0,855	3,078	0,21
Toilet	0	dm³/s	1,20	2,60	3,12	0	0	0,00
Hal	0,15	dm³/s/m²	3,00	2,60	7,8	0,45	1,62	0,21
Badkamer	0,15	dm³/s	0,95	2,40	2,28	0,1425	0,513	0,23
HalB	0,15	dm³/s/m²	1,50	2,40	3,6	0,225	0,81	0,23
Slaapkamer 2	0,15	dm³/s/m²	10,68	2,40	25,632	1,602	5,7672	0,23
Slaapkamer 3	0,15	dm³/s/m²	5,55	2,40	13,32	0,8325	2,997	0,23
Slaapkamer 1	0,15	dm³/s/m²	6,55	2,40	15,72	0,9825	3,537	0,23
Bergzolder	0,15	dm³/s/m²	29,00		39	4,35	15,66	0,40

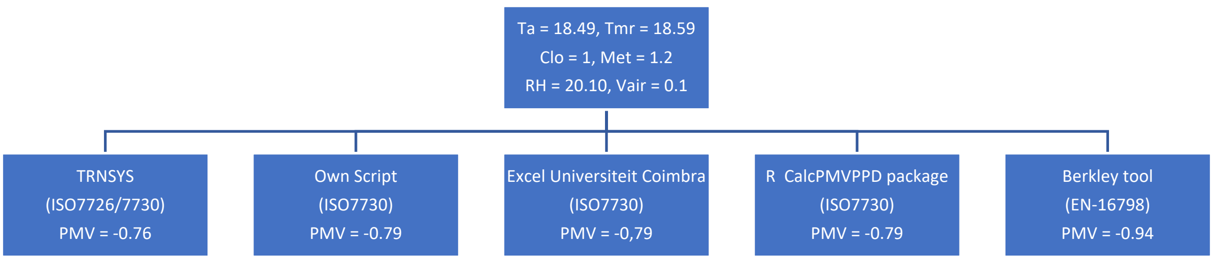
Appendix H: PMV's by different calculators



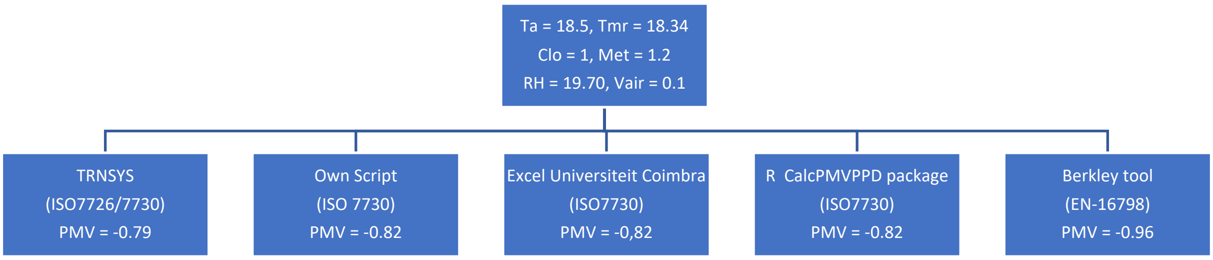
Extreme value front of room



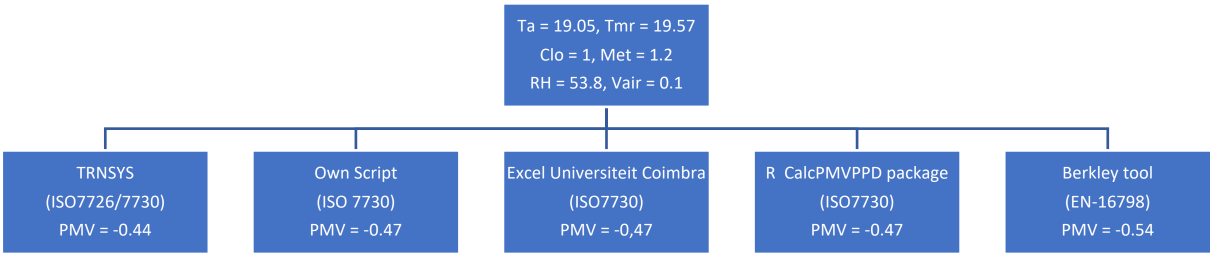
Extreme value middle of the room



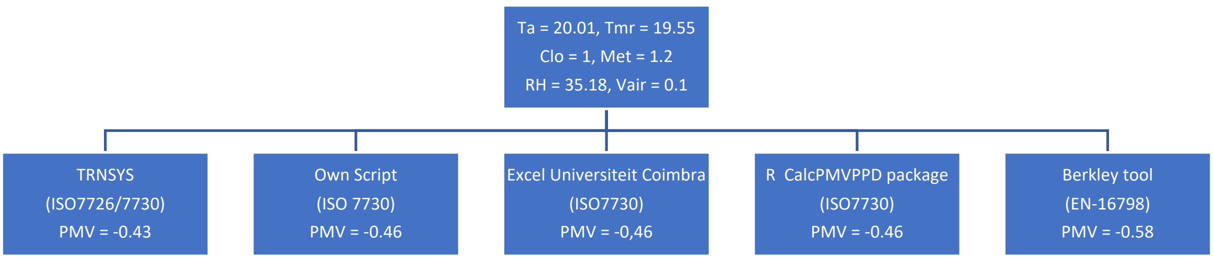
Extreme value back of the room



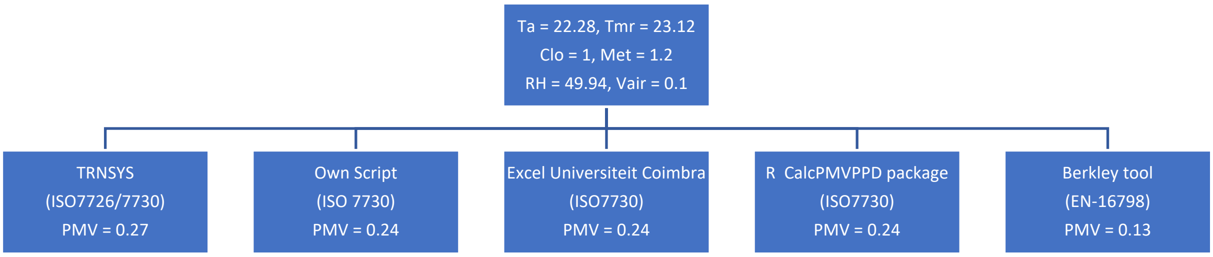
Mean value front of the room



Mean value middle of the room



Mean value Middle of the room (cooling season)


Ta = 22.28, Tmr = 23.12
Clo = 1, Met = 1.2
RH = 49.94, Vair = 0.1
TRNSYS
(ISO7726/7730)
PMV = 0.27
Own Script
(ISO 7730)
PMV = 0.24
Excel Universiteit Coimbra
(ISO7730)
PMV = 0.24
R CalcPMVPPD package
(ISO7730)
PMV = 0.24
Berkley tool
(EN-16798)
PMV = 0.13

Appendix I: Temperature Profiles

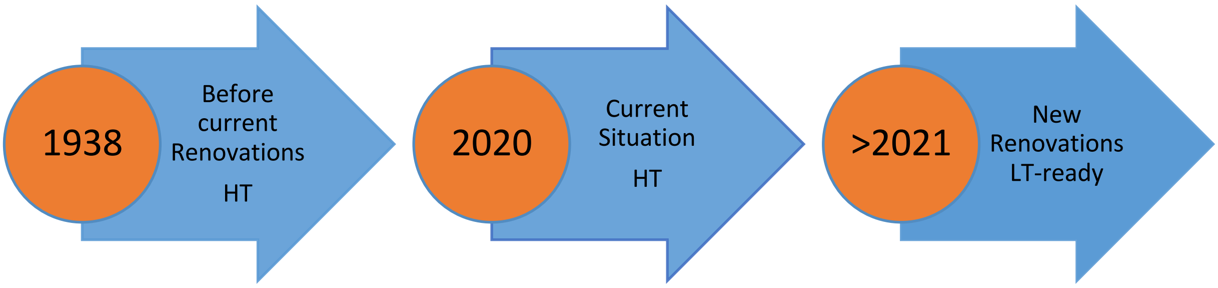
Temperature Profile Airofill conduction coefficient 0.02 W/mK

construction layer		d	λ	R	ΔT	T
	units	m	W/(m.K)	(m2.K)/W	°C	°C
outside air						1,8
	transfer resistance r_e			0,04	0,2	
						2,0
1	Masonry	0,1	1,2	0,08	0,4	
						2,4
2	Cavity	0,06	0,02	3,00	15,2	
						17,6
3	Masonry	0,1	1,2	0,08	0,4	
						18,0
4	Gypsum Board	0,01	0,5	0,02	0,1	
						18,1
5				0,00	0,0	
						18,1
6				0,00	0,0	
						18,1
7				0,00	0,0	
						18,1
	transfer resistance r_i			0,13	0,7	
inside air						18,8
	Total			3,36	17,0	

Temperature Profile Airofill conduction coefficient 0.085 W/mK

construction layer		d	λ	R	ΔT	T
	units	m	W/(m.K)	(m2.K)/W	°C	°C
outside air						1,8
	transfer resistance r_e			0,04	0,6	
						2,4
1	Masonry	0,1	1,2	0,08	1,3	
						3,8
2	Cavity	0,06	0,085	0,71	11,3	
						15,1
3	Masonry	0,1	1,2	0,08	1,3	
						16,4
4	Gypsum Board	0,01	0,5	0,02	0,3	
						16,7
5				0,00	0,0	
						16,7
6				0,00	0,0	
						16,7
7				0,00	0,0	
						16,7
	transfer resistance r_i			0,13	2,1	
inside air						18,8
	Total			1,06	17,0	

Appendix J: Timeline



Appendix K: ISSO 51 Calculation

Transmissie verliezen

Te =	-10	Ti =	22	Tb =	##	Ti gang	18

Woonkamer				
To Outside	A	U	fk	Ak*fk*(Uk+0.1)
Buitenwand	6,39	0,288	1	2,47932
Raam	3,36	1,2	1	4,368
Buitenwand	7,08	0,288	1	2,74704
Raam	1,99	1,2	1	2,587
Deur	0,68	1,2	1	0,884
	19,5			
	13,47	6,03		13,06536
				418,09152
To Other Rooms	A	U	Fiak	Ak*Uk*Fiak
Bedroom 1	10,81	2,979	0,09375	3,019030313
Bedroom 2	6,91	2,979	0,09375	1,929833438
Overloop	1,4	2,979	0,21875	0,91231875
Keuken	5,33	1,96	0	0
Gang	7,93	1,96	0,125	1,94285
				7,8040325
				93,64839
Naar buren	A	U	Fb	A*U*Fb
Muur	13,26	1,116	0,375	5,54931
				5,54931
				66,59172
Naar Grond	A	U	Fg	1,45*1,15*AUF
BG	19,13	0,293	0,375	3,021493828
				3,021493828
Total Tansmissie:				**942,0862825**

Keuken				
To Outside	A	U	fk	Ak*fk*(Uk+0.1)
Buitenwand	2,21	0,288	1	0,85748
Buitenwand	2,21	0,288	1	0,85748
Buitenwand	2,82	0,288	1	1,09416
Dak	1,57	0,168	1	0,42076
Deur	1,99	1,1	1	2,388
	10,8			
	5,03	5,77		5,61788
				67,41456
To Other Rooms	A	U	Fiak	Ak*Uk*Fiak
Toilet	2,21	1,96	0,125	0,54145
Bedroom 3	3,79	2,96	0,09375	1,051725
Living	5,33	1,96	0	0
Gang	2,6	1,96	0,125	0,637
				2,230175
				26,7621
Naar buren	A	U	Fb	A*U*Fb
Muur	5,33	1,116	0,375	2,230605
				2,230605
				26,76726
Naar Grond	A	U	Fg	1,45*1,15*AUF
BG	19,13	0,293	0,375	3,021493828
				3,021493828
				419,2049225

Toilet				
To Outside	A	U	fk	Ak*fk*(Uk+0.1)
				0
To Other Rooms	A	U	Fiak	Ak*Uk*Fiak
Hallway	4,58	1,96	0	0
Bedroom 3	0,77	2,96	-0,03125	-0,071225
Kitchen	2,21	1,96	-0,125	-0,54145
				-0,612675
Naar buren	A	U	Fb	A*U*Fb
Muur	2,37	1,116	0,25	0,66123
				0,66123
Naar Grond	A	U	Fg	1,45*1,15*AUF
BG	0,77	0,293	0,25	0,081078594
				0,081078594
				4,148275

Gang				
To Outside	A	U	fk	Ak*fk*(Uk+0.1)
Buitenmuur	4,69	0,288	1	1,35072
Deur	2,16	1,2	1	2,592
				3,94272
To Other Rooms	A	U	Fiak	Ak*Uk*Fiak
Kitchen	2,6	1,96	0	0
Toilet	4,58	1,96	0	0
Livingroom	7,93	1,96	-0,125	-1,94285
Landing	1,15	2,96	0	
				-1,94285
Naar buren	A	U	Fb	A*U*Fb
Muur	10,7	1,116	0,25	2,9853
				2,9853
Naar Grond	A	U	Fg	1,45*1,15*AUF
BG	0,77	0,293	0,25	0,081078594
				0,081078594
				162,119955

Bedroom 1				
To Outside	A	U	fk	Ak*fk*(Uk+0.1)
Buitenwand	7,03	0,288	1	2,72764
Raam	1,97	1,2	1	2,561
				5,28864
				63,46368
To Other Rooms	A	U	Fiak	Ak*Uk*Fiak
Loft	10,81	2,979	0,21875	7,044404063
Bedroom 2	7,32	1,96	0	0
Bedroom 3	5,14	1,96	0	0
landing	2,59	1,96	0,125	0,63455
Living	10,81	2,96	-0,09375	-2,999775
				4,679179063
				56,15014875
Naar buren	A	U	Fb	A*U*Fb
Muur	7,1	1	0,375	2,97135
				2,97135
				35,6562
Naar Grond	A	U	Fg	1,45*1,15*AUF
BG				0
				0
Total Tansmissie:				**414,05341**

Bedroom 2				
To Outside	A	U	fk	Ak*fk*(Uk+0.1)
Buitenwand	6,49	0,288	1	2,51812
Raam	2,51	1,2	1	3,263
				5,78112
				69,37344
To Other Rooms	A	U	Fiak	Ak*Uk*Fiak
Loft	6,91	2,979	0,21875	4,502944688
Bedroom 1	7,32	1,96	0	0
Bath	1,32	1,96	0	0
landing	3,82	1,96	0,125	0,9359
Living	6,91	2,96	-0,09375	-1,917525
				3,521319688
				42,25583625
Naar buren	A	U	Fb	A*U*Fb
Muur	5,14	1	0,375	2,15109
				2,15109
				25,81308
Naar Grond	A	U	Fg	1,45*1,15*AUF
BG				0
				0
Total Tansmissie:				**366,51295**

Bedroom 3				
To Outside	A	U	fk	Ak*fk*(Uk+0.1)
Buitenwand	2,78	0,288	1	1,07864
Raam	1,66	1,2	1	2,158
				3,23664
				38,83968
To Other Rooms	A	U	Fiak	Ak*Uk*Fiak
Loft	5,07	2,979	0,21875	3,303897188
Bedroom 1	5,14	1,96	0	0
Staircase	2,04	1,96	0	0
landing	3,1	1,96	0,125	0,7595
Toilet/hallway	1,2	2,96	0,03125	0,111
				4,174397188
				50,09276625
Naar buren	A	U	Fb	A*U*Fb
Muur	7,1	1	0,375	2,97135
				2,97135
				35,6562
Naar Grond	A	U	Fg	1,45*1,15*AUF
BG				0
				0
Total Tansmissie:				**332,23639**

Bathroom				
To Outside	A	U	fk	Ak*fk*(Uk+0.1)
Buitenwand	2,4	0,288	1	0,9312
Raam	0	0	0	0
				0,9312
				29,7984
To Other Rooms	A	U	Fiak	Ak*Uk*Fiak
Loft	1,15	2,979	0,21875	0,749404688
Bedroom 1	1,32	1,96	0	0
Staircase	2,76	1,96	0,125	0,6762
landing	1,44	1,96	0,125	0,3528
Hallway	1,15	2,979	0,03125	0,107057813
				1,8854625
				60,3348
Naar buren	A	U	Fb	A*U*Fb
Muur	0	0	0	0
				0
				0
Naar Grond	A	U	Fg	1,45*1,15*AUF
BG				0
				0
Total Tansmissie:				**90,1332**

Loft				
To Outside	A	U	fk	
Roof	37,72	0,168	1	6,33696
				6,33696
				202,78272
To other rooms	A	U	fk	
Bedroom 1	10,81	2,979	-0,21875	-7,044404063
Bedroom 2	6,91	2,979	-0,21875	-4,502944688
Bedroom 3	5,07	2,979	-0,21875	-3,303897188
Bathroom	1,15	2,979	-0,21875	-0,749404688
Landing	0			
				-15,60065063
				-499,22082
Naar buren	A	U	fk	
Right	12,24	1,116	0,09375	1,28061
Left	12,24	1,116	0,09375	1,28061
				2,56122
				81,95904
Total Transmissie				**-214,47906**

Woonkamer			
Infiltratie			
Qi	Au	Fv	1200*Qi*Au*fv
1,20E-04	13,47	1	1,94
Ventilatie			
Qv	A	Fv	
9,00E-04	19,023	0,3	6,163452
			259,300224

Keuken			
Infiltratie			
Qi	Au	Fv	1200*Qi*Au*fv
1,20E-04	9,23	1	1,33
Ventilatie			
Qv	A	Fv	
9,00E-04	5,655	0,3	1,83222
			101,16288

Hallway			
Infiltratie			
Qi	Au	Fv	1200*Qi*Au*fv
1,20E-04	6,85	1	9,86E-01
Ventilatie			
0	0	0	0
			31,5648

Toilet			
Infiltratie			
Qi	A	Fv	
0	0	0	0
Ventilatie			
Qv	A	Fv	
0,007		0,175	1,47
			47,04

Bedroom 1			
Infiltratie			
Qi	Au	Fv	1200*Qi*Au*fv
1,20E-04	9	1	1,30
Ventilatie			
Qv	A	Fv	
9,00E-04	10,81	0,3	3,50244
			153,55008

Bedroom 2			
Infiltratie			
Qi	Au	Fv	1200*Qi*Au*fv
1,20E-04	9	1	1,30
Ventilatie			
Qv	A	Fv	
9,00E-04	7,16	0,3	2,31984
			115,70688

Bedroom 3			
Infiltratie			
Qi	Au	Fv	1200*Qi*Au*fv
1,20E-04	4,44	1	0,64
Ventilatie			
Qv	A	Fv	
9,00E-04	5,16	0,3	1,67184
			73,9584

Bathroom			
Infiltratie			
Qi	Au	Fv	1200*Qi*Au*fv
1,20E-04	2,4	1	0,35
Ventilatie			
Qv	A	Fv	
1,40E-03		0,3	5,04
			172,3392

Loft			
Infiltratie			
Qi	Au	Fv	1200*Qi*Au*fv
1,20E-04	37,72	1	5,43168
Ventilatie			
Qv	Aui	Fv	
9,00E-04	37,72	0,3	0,0101844
			174,1396608

Woonkamer	Bedrijfsbeperking	P	3,7	
	fa	Ak	P	fa*Ak*P
Steenisolatie	0,7	39,7	3,7	102,823
Steen				
Overig	1	6,03	0	0
y	8,56%			**102,823**

Kitchen				
	fa	Ak	P	fa*Ak*P
Steenisolatie	0,7	33,27	3,7	86,1693
Steen				0
Overig	1	32,38	2,5	80,95
				167,1193
				44,5366901

Bed 1				
	fa	Ak	P	fa*Ak*P
Steenisolatie	0,7	1,404	3,7	3,63636
Steen	1	36,67	3,7	135,679
				139,31536
				48,5794483

Bed 2				
	fa	Ak	P	
Steenisolatie	0,7	6,49	3,7	16,8091
Steen	1	26,28	3,7	97,236
				114,0451
				78,1196125

Bed 3				
	fa	Ak	P	
Steenisolatie	0,7	2,78	3,7	7,2002
Steen	1	16,55	3,7	61,235
				68,4352
				34,7649709

Bath				
	fa	AK	P	
Steenisolatie	0,7	2,4	3,7	6,216
Steen	1	7,82	3,7	28,934
				35,15
				22,4642107

TOTAL W			
Woonkamer **1304,209507**	Kitchen **564,9044926**		
Bedroom 1 **645,7231025**	Bedroom 2 **596,26493**	Bedroom 3 **440,959761**	Bathroom **284,9366107**

HP Capacity	
Transmission	2416,28
Luchttoetreding	1128,76
Bedrijfsbeperking	331,29
Total W:	**3876,33**

Appendix L: Comfort Summary

Middle	Current situation	Plan1: Back to basics	Plan2: LTH current radiators	Plan 2: LTH façade update	Plan3: LTH with LTH Radiators	Plan 3: LTH radiators façade update	Plan4: Underfloor heating and radiators	Plan4: Underfloor heating Updated façade
minimum air temperature °C	18.29	17.81	16.98	17.31	17.29	18.15	17.92	18.24
Average PMV	-0.45	-0.73	-0.48	-0.44	-0.47	-0.39	-0.36	-0.34
Minimum PMV	-0.78	-1.08	-1.06	-0.97	-0.94	-0.77	-0.81	-0.74
% outside ±0.5	47.23	83.89	51.96	49.33	52.32	38.0	32.04	27.28
Average PPD	10.07	16.99	13.7	9.8	10.22	8.86	8.51	8.31
Maximum PPD	17.77	29.60	27.64	24.28	22.79	17.05	18.69	16.55
Adaptive Comfort Classification	B – C	<C	B - C	B – C	B – C	B	A – B	A – B

Front	Current situation	Plan1: Back to basics	Plan2: LTH current radiators	Plan 2: LTH façade update	Plan3: LTH with LTH Radiators	Plan 3: LTH radiators façade update	Plan4: Underfloor heating and radiators	Plan4: Underfloor heating Updated Façade
Average PMV	-0.44	-0.80	-0.44	-0.41	-0.46	-0.40	-0.34	-0.30
Minimum PMV	-0.84	-1.29	-1.07	-0.99	-1	-0.84	-0.75	-0.66