LT-READY

Affordable renovation concepts that enable low-temperature heating and provide thermal comfort

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Abstract

The Dutch building stock has to switch to alternative energy-efficient heat sources, such as district heating or heat pumps, which will provide a lower supply temperature for the heating system in dwellings. Yet, the consensus is that dwellings need to be intensively renovated, to provide thermal comfort with low-temperature heating. However, it can be argued that a more affordable renovation with less renovation measures can also provide the same level of thermal comfort as the original situation. To this day, it is unknown what the minimal combination of renovation measures could be. Thus, this research aimed to design combinations of renovation measures, which are both affordable, and are able to provide thermal comfort in Dutch terraced houses. These renovation concepts are referred to as *LT-Ready concepts*. Hence, the main research question answered in this thesis is: *"What combination of renovation measures for residential buildings is affordable and provides thermal comfort when using a lower supply temperature for heating?"*

First, a literature study is conducted. It investigated the available renovation budget of house owners, as well as thermal comfort, including current guidelines and local comfort aspects. Also, possible renovation measures to enable low-temperature heating were researched.

Second, to select the most cost-effective renovation measures, a cost analysis was performed. Using this, renovation concepts were developed and tested with dynamic simulation software. Here, the thermal and energy performance was simulated with an adaption of the ATG-method for dwellings. The renovation concepts included the placement of a ventilation system and additional renovation measures.

Results provided a variety of renovation concepts that were LT-Ready within a budget of €10,000. Different scenarios were developed with building or budget limitations, after which the best LT-Ready option was selected. In general, it was concluded that demand-driven exhaust ventilation (C2) or balanced ventilation with heat recovery (D1) is preferable. Wall insulation and replacing windows also showed a large effect on improving thermal comfort and reducing the heating demand. Add-on ventilators can boost thermal comfort, while having only a minimal effect on energy performance. In case no insulation can be applied, LT-radiators are an option to provide thermal comfort. This is however not preferred, because it increases the heating demand.

Additionally, local comfort was investigated for different measures on the room. It was shown that small interventions such as add-on fans and furniture placement could substantially influence the air currents and temperature distribution within the living room.

Also a tool which compares the heating demand of a dwelling with the available heating capacity at a lower supply temperature to determine whether a dwelling is LT-Ready, or what combination of measures is needed to make it LT-Ready. The tool is based on *ISSO-51* and has a general approach which can be used for every terraced dwelling.

Overall, it can be concluded that there is a variety of possible LT-Ready renovations that provides thermal comfort and is affordable, depending on the specific scenario. It is proven that *deep renovations* are not essential to provide thermal comfort with low-temperature heating.

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After 8 months of intensive work on the graduation project, the master thesis '*LT-Ready: Affordable renovation concepts that provide thermal comfort with low-temperature heating'*, is finalized. This finishes my master *Architecture, Urbanism and Building Sciences* with the master track *Building Technology* at the Delft University of Technology.

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Variables

Thermal comfort

T_{air}	[ºC]	Air temperature
T_{MRT}	[ºC]	Mean radiant temperature
T_{sx}	[ºC]	Surface temperature
φ_x	[-]	View factor
T_{op}	[ºC]	Operative temperature
$T_{comfort}$	[ºC]	Comfort temperature according to *ASHRAE 55* or *EN15251*
T_{limit}	[ºC]	Indicates upper or lower temperature limit for *ASHRAE 55*
T_{RMOT}	[ºC]	Weighted running mean of the outdoor temperature
T_{ed-x}	[ºC]	Average outdoor temperature [x] days before yesterday
T_n	[ºC]	Neutral temperature according to *Peeters et al., 2009*
T_{upper}	[ºC]	Upper limit range according to *Peeters et al., 2009*
T_{lower}	[ºC]	Lower limit range according to *Peeters et al., 2009*
w	[ºC]	Temperature limit according to *Peeters et al., 2009*
a	[-]	Limit according to *Peeters et al., 2009*

Local discomfort

DR	[%]	Draft rating, i.e., the percentage of people dissatisfied due to draft
v	[m/s]	Local mean air velocity
Tu	[%]	Local turbulence intensity

Stationary heat balance

Q_{demand}	[W]	Heating or cooling demand
Q_{trans}	[W]	Transmission losses
Q_{vent}	[W]	Ventilation losses
Q_{inf}	[W]	Infiltration losses
T_e	[ºC]	Outdoor temperature
T_i	[ºC]	Indoor temperature
U	[W/m^2.K]	Heat transfer coefficient
A	[m^2]	Area
ρ_{lucht}	[kg/m^3]	Density of air
c	[J/kg.K]	Specific heat capacity air
nV	[m^3]	Flow rate ventilation air
$Q_{heat\ emitter}$	[W]	Heating capacity heating system
k	[W/m^2.K]	Heat transfer coefficient
$\Delta\theta$	[ºC]	Logarithmic mean difference between supply and return temperature
α	[m^2/s]	Thermal diffusivity
δ	[m]	Thickness
λ	[W/m.K]	Conductivity
T_{supply}	[ºC]	Supply temperature
T_{return}	[ºC]	Return temperature
n	[-]	Radiator exponent
φ_0	[W]	Heating capacity at the original design temperatures

Cost analysis

R_c	[m^2.K/W]	Heat resistance
R_{si}	[m^2.K/W]	R surface interior
R_{se}	[m^2.K/W]	R surface exterior
ΔT_{avg}	[ºC]	Average outdoor temperature heating season = 13 ºC
$t_{heating\ season}$	[s]	Time heating season = 7 months = 210 days = 210 · 24 · 3600 = 18.1 Ms
$CV_{natural\ gas}$	[J/kg]	Caloric value natural gas
T_c	[ºC]	Contact temperature
b	[-]	Contact coefficient

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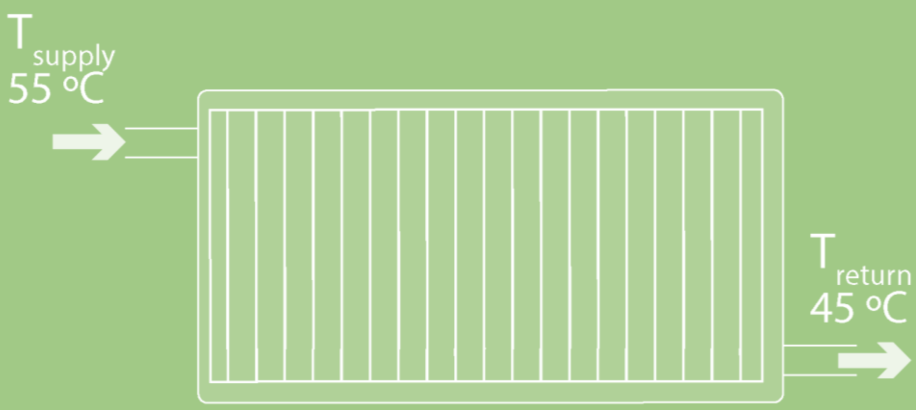
Introduction



1 Research framework

1.1 Background

Reducing the energy demand to limit the usage of fossil fuels is required to limit global warming. To achieve this, different countries, among the Netherlands, signed the Paris Agreement and committed themselves to limit global warming to below 2°C (European Commission, 2019). The Dutch government developed the *Climate Agreement*, which states that the Dutch residential building stock must be energy neutral in 2050 and stop using natural gas as a fuel source (Rijskoverheid, n.d.). With a total residential building stock of 6.800.000 dwellings, 50.000 dwellings per year should be disconnected from natural gas supply from 2021, and before 2030, this number should rise to 200.000 per year (Ministerie van Economische Zaken en Klimaat, 2019).

This results in a switch to alternative energy-efficient sources, such as low-temperature district heating or heat pumps. These heating sources usually have a lower supply temperature compared to current heating systems which use a supply temperature between 70 and 90°C (Hesaraki et al., 2015). A lower supply temperature leads however to a lower heating capacity of the current heating system, which is in Dutch dwellings mainly heating with radiators. The shift to an alternative heating system has therefore consequences that should be dealt with.

Because of the lower heating capacity with low-temperature heating, additional renovation measures are required to lower the heating demand and provide thermal comfort (Hesaraki et al., 2015). Upon investigating the solution to this problem, literature suggests that low-temperature heating requires high insulated dwellings with a balanced ventilation system with heat recovery (Milieucentraal, n.d.; Schoenmaker et al., 2021; Wang et al., 2015). This would result in a deep renovation for the existing building stock, which can be expensive and is showing a gap with the limited investment budget of house owners (Bos et al., 2020; Ipsos, 2019; Tertium, 2015). However, it can be argued that a more affordable renovation can also provide the same level of thermal comfort as in the original situation. Thus, I believe affordable renovations should be researched which still provide a comfortable indoor temperature with low-temperature heating.

Besides the indoor temperature, local comfort aspects are also relevant in the perception of thermal comfort. Low-temperature heating can increase the chances of local discomfort because of the lower supply temperature of the radiators. This can create difficulties in counteracting cold drafts caused by windows or ventilation grills, and thermal stratification (Myhren & Holmberg, 2008). A renovation that enables low-temperature heating should also consider these aspects.

Henceforth, an acceptable LT-Ready renovation inherits renovation measures that are affordable for house owners and guarantee thermal comfort, by providing a comfortable indoor temperature and minimizing the chances of local discomfort.

1.2 Problem statement

The main problem that will be tackled in this graduation thesis is two-fold:

Firstly, it is unclear what combination of renovation measures is needed to provide thermal comfort with low-temperature heating and is affordable.

Renovation measures can be divided in different scales:

- The building envelope scale
- The building installations scale
- The room scale

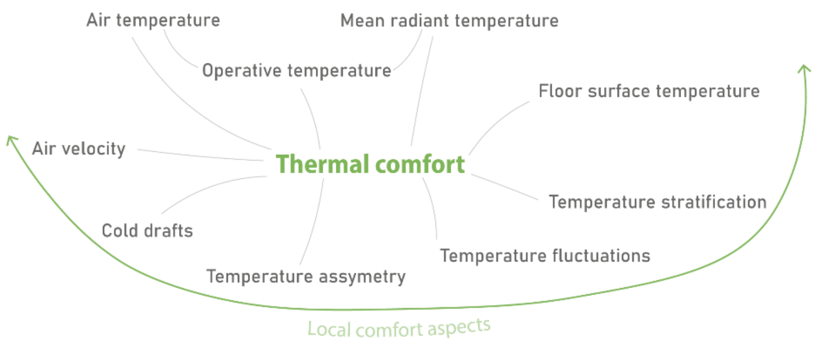
It is unknown what combination of measures on these three scales yields the optimal balance between costs and providing thermal comfort. For example, a large intervention on the building envelope scale is most effective but would also be the biggest investment (Wang et al., 2015). Alternatively, only insulating the cavity wall and replacing windows can also have a positive effect. Conversely, a moderate renovation and replacing the original radiators with low-temperature radiators can also be effective (Brand & Svendsen, 2013).

Secondly, the current research on low temperature heating excludes important factors which influence local thermal comfort. Most performed research focussed only on the air temperature or operative temperature to determine thermal comfort (Brand & Svendsen, 2013; Hesaraki et al., 2015; Østergaard, 2018; Vliet et al., 2016). However, to ensure thermal comfort, other factors must be taken into account as well (Eijdems et al., 1999; Myhren & Holmberg, 2008), such as:

- Cold drafts
- Thermal stratification
- Wall and floor surface temperatures

Hence, there is a gap in the current body of knowledge for thermal comfort with low temperature heating.

Figure 1.1: Thermal comfort aspects



1.3 Objectives

1.3.1 Objectives and research phases

The main goal of this research is:

To find out what combination of renovations measures is affordable and required to provide thermal comfort with low-temperature heating in residential buildings.

To achieve the main objective from the graduation project, the following steps will be taken:

Phase 1 - Exploration

Different topics have been explored in the first phase. An overview of renovation measures on the three scales, the building envelope scale, the building installations scale, and the room-scale, was provided. Also, thermal comfort was investigated regarding current thermal comfort guidelines and local thermal comfort aspects. The investment budget of house owners was also determined. Various databases were used to find relevant literature, including the Delft University of Technology Library, Google Scholar, and ResearchGate. The found literature included books, scientific articles, reports, and PhD-theses.

Phase 2 - Determine renovation concepts

To determine renovation concepts, first the cost-effectiveness of the renovation measures was determined with a cost analysis based on websites about renovation costs, a provided cost analysis by Arcadis and bills from the LT-Ready project by the TU Delft. Based on this analysis, most cost-effective renovation measures were selected to set up the renovation concepts. The renovation concepts were set up by placing a ventilation system and additional renovation measures, keeping the investment budget of house owners in mind.

Phase 3 - Test renovation concepts

The renovation concepts were applied to a case study building, which was currently used as test dwelling in the LT-Ready project. The concepts were applied using dynamic simulation software, in which a multi-zone model of the dwelling was made. This model was calibrated with measurements for both the air temperature in the living room and the gas usage of the entire dwelling. Simulations were performed with dynamic simulation software to examine the effect of the renovation measures on thermal comfort and energy performance. Thermal comfort was evaluated with an adaption of the ATG-method by determining the hours too cold.

Phase 4 – LT-Ready recommendations
Based on the simulation results, LT-Ready recommendations were given for the case study dwelling. A complete overview of all simulation results is presented in Appendix F. Recommendations were given per renovation measure about their effect based on the outcome of the simulations. Also, recommendations were given on the minimal required renovation measures per ventilation type. Different scenarios with limiting factors (e.g budget or building limitations) were developed to show which renovation concept performs best per scenario.

Phase 5 - Additional local comfort analysis
An additional local comfort analysis was performed to see the effect of different measures on the room scale. This was performed with CFD analyses. The analysis provided additional options on room-scale which could prevent local discomfort and gave insight into the effects of certain renovation measures.

Phase 6 - LT-Ready tool
The gained knowledge in Phase 4 helped to understand requirements to provide thermal comfort with low-temperature heating. However, a more general approach was required to develop a tool in which house owners can determine if their dwelling is already LT-Ready or not. Thus, the tool was developed based on the ISSO-51 which is a conventional standard for installers.

1.3.2 Final products
The final products are:

Phase 1	·	A descriptive analysis of renovation measures on the three scales
Phase 2	·	Cost analysis
Phase 4	·	Recommendations for LT-Ready renovations for case study
Phase 5	·	Recommendations to prevent local discomfort
Phase 6	·	LT-Ready tool for house owners

1.3.3 Boundary conditions
The scope of the research project was narrowed by the following boundary conditions:

1. The supply temperature used in this research was 55-45°C, based on the supply temperature for low-temperature heating from TKI Urban Energy (2020). TKI Urban Energy is an organization that stimulates the development of innovations for sustainable and affordable energy systems in the built environment and is financed by the Dutch government. Background information about supply temperatures for low-temperature heating can be found in Appendix A. The used return temperature was assumed to be similar to the return temperature used in the LT-Ready project by TU Delft.
2. The research was focused on residential buildings in the Netherlands, more specified terraced housing built in the period between 1920 and 1975. The decision for this building type and period is explained in Appendix B. Main reasons are the large number of dwellings built in this period and their current low energy level.
3. The research is limited to the thermal comfort aspects of low-temperature heated buildings. Other comfort aspects are disregarded.
4. Researched renovation measures are only limited to the dwelling. Other measures, such as the connection to the district heating system, are not taken into account.
5. This research aims to find out which minimum renovation measures are needed to provide thermal comfort in the dwelling. The reduced energy demand is beneficial but secondary, because we can assume that low-temperature heating can be generated with sustainable energy-efficient heating source (e.g., heat pumps or district heating).

1.4 Research questions

1.4.1 Main research question

According to the problem statement and objective, the main research question in this thesis that will be answered is:

"What combination of renovation measures for residential buildings is affordable and provides thermal comfort, when using a lower supply temperature for heating?"

1.4.2 Sub questions

To answer the main research question, different sub questions were set up.

Investment costs

1. What is the available investment budget of house owners for renovations?

Thermal comfort

2. Which thermal comfort criteria can be defined for low-temperature heated dwellings based on current thermal comfort regulations?
3. Which local comfort aspects needs to be researched to create comfortable low-temperature heated dwelling?

Measures

4. Which renovation measures are available for renovations to enable low-temperature heating?
5. Which measures are cost effective?
6. What combination of measures provides thermal comfort with low-temperature heating?

1.5 Relevance

1.5.1 Societal relevance

Dutch municipalities have a key role in renovating the building stock because they are responsible to develop a strategy for the energy transition strategy of their city. This strategy also includes the renovation of their building stock, the switch from high- to low-temperature heating, and disconnection of natural gas as the main heating source. This a large task for municipalities, and also leads to different challenges concerning the acceptance of residents and costs. Figure 1.2 shows headlines of different newspaper articles as precedents of these challenges.

Figure 1.2: Headlines renovation task municipalities (Corporatiewoning, w.d.)

Most renovation concepts merely focus on reducing the energy usage. However, having a thermally comfortable dwelling can be more valuable for residents than their energy usage. Thus, the focus could be on the minimal renovation measures that provide thermal comfort when a lower supply temperature for heating is used. With this focus less renovation measures are required than for an energy renovation, which makes it more affordable for the investors, which can be house owners, housing corporations or the municipality. Also, residents can be more acceptance towards these renovations because a comfortable dwelling is assured.

On the other hand, the focus of these renovations would not be on reducing the energy demand, because heat can be generated from sustainable sources such as district heating or heat pumps. Thus, by integrating thermal comfort into the renovation of dwellings, the number of renovation measures can be limited and become more affordable.

1.5.2 Scientific relevance

- *Building typology*
  Different researches have already been conducted on renovation measures on the building envelope and heating system to enable low-temperature heating (Brand & Svendsen, 2016; Østergaard, 2018; Wang et al., 2015). These researches had, however, the focus on the building stock of Sweden or Denmark and apartment flats heating (Brand & Svendsen, 2016; Wang et al., 2015) or detached housing (Østergaard, 2018). This shows a gap in the academic literature on renovation measures to enable low-temperature heating in terraced houses in the Netherlands.
- *Thermal comfort*
  Most research concentrate on the air or operative temperature to determine if a room, or building, can be heated with low-temperature heating (Brand & Svendsen, 2016; Østergaard, 2018). Other research, e.g. Wang et al. (2015), also include the PMV-scale and the floor surface temperature. Most research disregard the effect of local thermal comfort with low-temperature heating systems. Eijdems et al. (1999) provide an overview of possible advantages of local comfort. Myhren & Holmberg (2008) investigate these effects with CFD-models but only take the heating systems into account. This all shows a gap in the literature, especially on solutions that optimize the local comfort.
- *LT-Ready project*
  This graduation thesis is also related to the *LT-Ready project* of the *Delft University of Technology*, which investigates which measures are needed to heat dwellings with middle-temperatures.

Exploration

Phase 1

2 Investment budget of house owners

The investment budget can be a limiting factor for renovations. Therefore, an analysis is done to determine the investment budget of house owners. Section 2.1 discusses the available budget of house owners for renovations, where Section 2.2 provides options to lower the investment costs. An overview of used budget ranges within this thesis is given in Section 2.3.

2.1 Available budget for renovations

The available investment budget was determined by taking into account the budget house owners have, and the budget house owners are willing to pay for a renovation.

Figure 2.1 shows the available budget house owners have for investments (Bos et al., 2020). Half of the house owners have an available budget for renovations up to €10,000. The percentage of house owners with a certain available budget for investment decreases when the budget is increased. Another tendency is that house owners of a dwelling with a high energy label usually have a higher investment budget to renovate their dwelling compared to house owners of dwellings with a lower energy label. This is concerning because dwellings with a lower energy label have a higher priority for an energy renovation. Also, people with low incomes and thus less investment budget are less willing to invest in energy renovations for their dwelling.

Most people are willing to pay €5000 or less for energy-saving measures, see Table 2.1 and 2.2 (Tertium, 2015; Ipsos, 2019). According to Ipsos (2019), most people want to renovate their dwellings in the upcoming years but are uncertain about the needed budget for such renovations. Of those who did respond with a certain budget, the largest share was €5000. Tertium (2015) came to similar conclusions, half of the respondents to their questionnaire wanted to invest up to €5000 in an energy renovation.

Concluding, it seems logical to focus on cheaper renovations because of two reasons. Firstly, because more people can then actually afford the renovations, and secondly because it is within the budget range people are willing to invest in.

Figure 2.1: Available budget for investment (Bos et al., 2020)

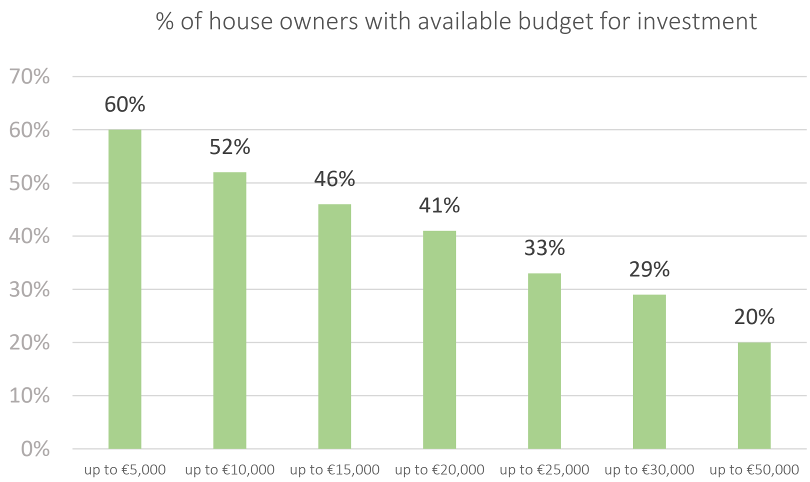


Table 2.1: Willing investment for energy renovations (Tertium, 2015)

I don't have the money	17.8%
< €500	13.9%
€500 - €1500	15.2%
€1500 - €5000	27.1%
€5000 - €25000	6.9%
> €25000	3.3%

Table 2.2: Willing investment for energy renovations (Ipsos, 2019)

No idea	71%
< €5.000	14%
€5000 - €10.000	7%
> € 10.000	8%

2.2 Options of reducing investment costs.

Because renovations can be quite expensive, there are options to reduce or finance the extra costs. Following options are available:

- Subsidies
  Different subsidies are available for renovation measures provided by the Dutch government or municipalities. An example is the *Sustainable energy subsidy,* which can be used to finance insulating measure to the building envelope, or measure that produce sustainable energy, such as heat pumps or

solar panels. The height of the subsidy compensation depends on which renovation measures are applied (Milieucentraal, n.d.).

- Loaning

  There are different options for a loaning provided by municipalities or banks to renovate a dwelling (Eigen Huis, n.d.). These loans have a special low-interest rate. Also, taking a higher mortgage is an option to enlarge the budget for renovations.

The focus within this graduation project is not on lowering the investment budget for renovations. This means that the total investment budget for renovation concepts mentioned in Chapter 13 is based on material and labour costs but without additional loans or subsidies.

2.3 Investment ranges

Different research shows that house owners have a limited investment budget for renovations. Slightly more than half of the house owners (52%) have an available investment budget of €10,000 (Bos et al., 2020). Also, most house owners are willing to pay up to €5,000 for a renovation (Ipsos, 2019; Tertium, 2015). Thus, to reach the largest group of house owners, it makes sense to focus on renovations within this budget by investigating the minimum required measures to enable low-temperature heating. The maximum investment budget for renovation measures is, therefore, €10,000. Besides the renovation measures, other additional costs can arise which are excluded from this research, such as the costs for a heat pump system.

3 Thermal Comfort

Thermal comfort can be defined as the *"condition of mind which expresses satisfaction with the thermal environment"* (ASHRAE, 2007). Because the satisfaction of the thermal environment is subjective, different standards have been developed to evaluate thermal comfort, which is discussed in Section 3.1. However, these standards are not entirely applicable to dwellings, because they are developed for offices. Section 3.2 elaborates on this and shows with which adaptions the methods can be suitable. Section 3.3 provides other methods to evaluate thermal comfort, and in Section 3.4 the decision to use the adapted ATG-method in this thesis is explained.

3.1 Conventional standards

Conventional comfort standards are based on *Fanger's model*, a mathematical model to predict the level of thermal comfort developed. Therefore, in Section 3.1.1, Fanger's model is explained including important aspects for low-temperature heating. This is followed by an overview of the conventional standards in Section 3.1.2.

Table 3.1: PMV value and thermal sensation

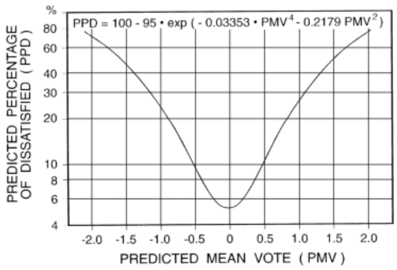
PMV value	Thermal sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

3.1.1 Fanger's model

Fanger's model is a mathematical model that estimates the predicted mean vote *PMV* for a theoretical group of persons, subjected to a set of environmental conditions (Nicol et al., 2012). The model is based on the stationary heat balance of the human body and includes different environmental variables, which are: the air temperature, mean radiant temperature, air velocity, relative humidity, metabolic rate, and clothing ensemble.

Based on Fanger's model a seven-point scale was developed by ASHRAE, shown in Table 3.1 (Peeters et al., 2009). This scale is used in different comfort standards. The percentage of people that are dissatisfied with the environment *PPD* can be derived from the PMV with Figure 3.1.

Figure 3.1: PPD based on PMV



Environmental variables that are most important to determine if low-temperature heating can provide a comfortable temperature within a room are the air temperature and radiant temperature.

- **Air temperature**
  The air temperature T_{air} is measured with a dry bulb thermometer, and is also called the dry-bulb temperature (Designing Buildings, n.d.). Several studies on low-temperature heating (Myhren & Holmberg, 2007; Østergaard, 2018; Wang et al., 2015) use the air temperature to determine thermal comfort.
- **Mean radiant temperature**
  The mean radiant temperature T_{MRT} is calculated with the 3D-dimensional view factor φ and the surface temperatures using Formula 3.1. From every point within a room, all view factors of the surrounding surfaces are 1. The view factor can be calculated with the online calculation tool *Thermal Radiation* (n.d.). The mean radiant temperature is used in several studies on low-temperature heating and thermal comfort by using the operative temperature (Brand & Svendsen, 2013; Østergaard & Svendsen, 2017; Wang et al., 2015).

$$T_{MRT} \approx \varphi_1 \cdot T_{S1} + \varphi_2 \cdot T_{S2} + \varphi_3 \cdot T_{S3} + \cdots \quad (3.1)$$

φ_x	View factor of surface	[-]
T_{Sx}	Surface temperature	[°C]

- **Operative temperature**
  The operative temperature is the average between the air temperature and the mean radiant temperature (Designing Buildings, n.d.). It is also referred to as the comfort temperature. Several studies on low-temperature heating (Brand & Svendsen, 2013; Østergaard & Svendsen, 2017; Wang et al., 2015)

use the operative temperature to determine thermal comfort in dwellings. In some researches (Brand & Svendsen, 2013; Østergaard & Svendsen, 2017) an operative temperature with a setpoint of 1 or 2 °C higher than the usual setpoint of 20 °C was used, because it corresponded better than with the behaviour of occupants.

3.1.2 Current comfort standards

This section provides an overview of four comfort standards which are commonly used in practice.

ISO Standard 7730

The ISO Standard 7730 is a standard used by their member states, including the Netherlands. It divides different categories shown in Table 3.2, and uses the PMV and PPD, as well as local comfort criteria (Nicol & Humphreys, 2012).

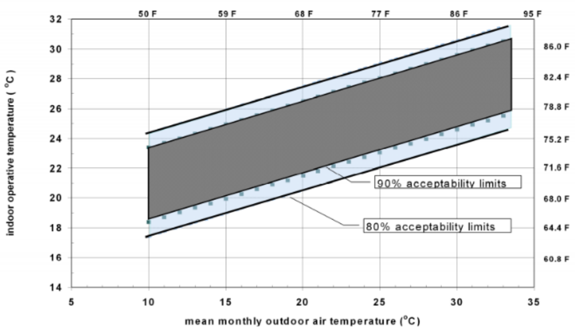
Table 3.2: Categories according to ISO 7730

Category	*PPD Predicted percentage discomfort*	*DR Draft rating*	*Local discomfort*	*PMV Predicted mean vote*
A	< 6%	< 10%	< 3-10%	-0.2 < PMV < +0.2
B	< 10%	< 20%	< 5-10%	-0.5 < PMV < +0.5
C	< 15%	< 30%	< 10-15%	-0.7 < PMV < +0.7

ASHRAE 55

The ASHRAE 55 standard is developed by the American Society of Heating Refrigeration and Air Conditioning Engineers and is mostly used in the US air conditioning industry. Since the United States are dominant within this field, the ASHRAE 55 is used as international standard that reflects the interests of the HVAC industry.

Figure 3.2: ASHRAE 55 temperature range



The ASHRAE 55 standard uses the monthly mean average outdoor temperature to determine the comfort temperature and includes an adaptive component by implying acceptable temperature ranges. The comfort temperature is calculated with Formula 3.2, which results in the graphs presented in Figure 3.2. A disadvantage of this standard is that sudden temperature differences within a month are disregarded.

$$T_{comfort} = 0.31 \times T_{monthly\ outdoor} + 17.8 \pm T_{limit} \quad (3.2)$$

$T_{limit}(80\%)$ 3.5 °C

$T_{limit}(90\%)$ 2.5 °C

European Standard EN 15251

The European Standard EN 15251 is developed by the Comité Européen de Normalisation for thermal comfort, but also includes other comfort aspects such as indoor air quality, lighting, and acoustics (Nicol et al., 2011). The standard has different classes which are shown in Table 3.3 and uses the comfort temperature to determine a temperature range. Formula 3.3 shows how the comfort temperature is calculated according to EN15251. A difference with ASHRAE 55 is that the comfort temperature is calculated with the weighted running mean of the outdoor temperature for 7 days with Formula 3.4.

Table 3.3: Classes according to EN15251

Class	*Description*	*PMV*	*K*
I	High level of expectation Recommended for spaces occupied by very sensitive and fragile persons with special requirements, such as handicapped, sick, very young children and elderly persons	± 0.2	± 2
II	Normal level of expectation Should be used for new buildings and renovations	± 0.5	± 3
III	Moderate level of expectation, can be used for existing buildings	± 0.7	± 4

$$T_{comfort} = 0.33 \times T_{rm} + 18.8 \qquad (3.3)$$

$$T_{RMOT} = 0.253 \times (T_{ed-1} + 0.8 \cdot T_{ed-2} + (0.8)^2 \cdot T_{ed-3} + (0.8)^3 \cdot T_{ed-4} + (0.8)^4 \cdot T_{ed-5} + (0.8)^5 \cdot T_{ed-6} + (0.8)^6 \cdot T_{ed-7} \quad \text{in [°C]} \qquad (3.4)$$

with:

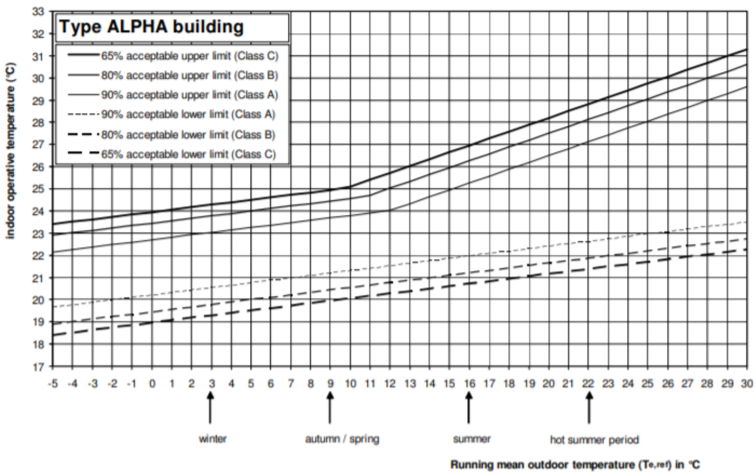
$T_{ed-1} = average\ outdoor\ temperature\ yesterday$ in [°C]
$T_{ed-2} = average\ outdoor\ temperature\ day\ before\ yesterday$ in [°C]
$T_{ed-3} = average\ outdoor\ temperature\ day\ before\ day\ before\ yesterday$ in [°C]

Adaptive Thermal Comfort Guidelines (ATG)

The adaptive thermal comfort limit (in Dutch: *Adaptieve Temperatuur Grenswaarde*) provides a temperature range with acceptable limits for indoor temperatures. The standard is based on the EN 15251, ISO 7730 regulations, and research on the indoor climate in offices. Buildings are categorized in classes A, B, and C. The ATG-method makes a difference between *alpha* and *beta* building types. *Alpha* building types are buildings with options for adaption, such as operable windows and the possibility to change clothing, where in *beta* buildings no adaption is possible. This results in a wider comfort range for alpha buildings (Raue et al., 2006). Residential buildings are usually considered alpha buildings (Peeters et al., 2009).

The ATG method uses the running mean outdoor temperature T_{RMOT} to determine the comfort temperature. From Figure 3.3, which shows the comfort range in alpha buildings, the comfort range at a specific running mean outdoor temperature can be looked up.

Figure 3.3 Temperature range in Alpha buildings



3.2 Why conventional methods are not suited for dwellings

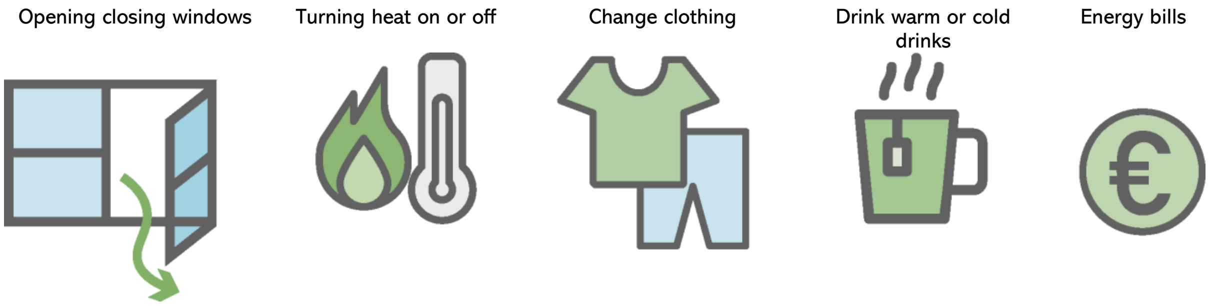
The former models were mainly designed for offices. This lead to a general critique on them because the models neglect the possibilities of adaptivity which are available in residential buildings. This can result in different requirements for thermal comfort in dwellings.

Adaption can occur in different forms (Peeters et al., 2009):

- Psychological adaption is the adaption based on experiences of the indoor environment, and habits of the occupants.
- Physiological adaption includes:
  - *general adaption,* which takes into account the effect of the timescales of multiple generations
  - *acclimatization*, which takes the adaption of a shorter time span, like a period of a few days or weeks
- Behavioural thermoregulation are all adaptions that a person can take, consciously or unconsciously.

Behavioural thermoregulation is the form of adaption that occurs the most in dwellings. People respond to discomfort in their environment in two ways: making adjustments to their environment or adjusting their requirements (Nicol &Humphreys, 2009; Peeters et al., 2009). Adjustment to the environment can be opening or closing windows or switching on the heating system. Adjustments to their requirements can be made by changing clothing, posture, or activity, and drinking cold or warm drinks. This all can create more comfort within a room. These options for adaptivity imply that a wider temperature range is possible inside a dwelling. Another reason to assume inhabitants are more willing to accept a wider temperature range is the reason that people must pay for their energy bills and are therefore more open to accepting lower temperatures.

Figure 3.4: Reasons for a wider temperature setpoint in dwellings



For these reasons, a temperature range for residential buildings per room with a wider comfort range was developed, based on current theories, available literature, and measurements by Peeters et al. (2009). A distinction was made between the bathroom, bedroom, and other rooms.

The range in the bathroom has a higher neutral temperature because the human body should feel comfortable both in wet and dry conditions. The bedroom is slightly colder because temperatures should not be too high to fall asleep. Other rooms, such as the kitchen and the living room, are categorized in the same category because they can have a comparable activity level. It must be considered that a bedroom can also have another function than only a bedroom, for example as a home office. In this case, the category other is better suitable.

The temperature range was developed by first calculating the neutral temperature per room with Formulas 3.9-16. and then applying the temperature ranges. The range is calculated for the upper and lower temperatures with Formula 3.5-8. It uses additional parameters *w* and α, which can be found in Table 3.3. This results in the following temperature curves for an acceptable temperature range for the bathroom (Figure 3.4), bedroom (Figure 3.5) and other rooms (Figure 3.6).

Bedroom

$$T_{upper} = \min\,(26℃, T_n + w \cdot \alpha) \quad (3.5)$$

$$T_{lower} = \min\,(16℃, T_n + (1 - w) \cdot \alpha) \quad (3.6)$$

Bathroom and other rooms

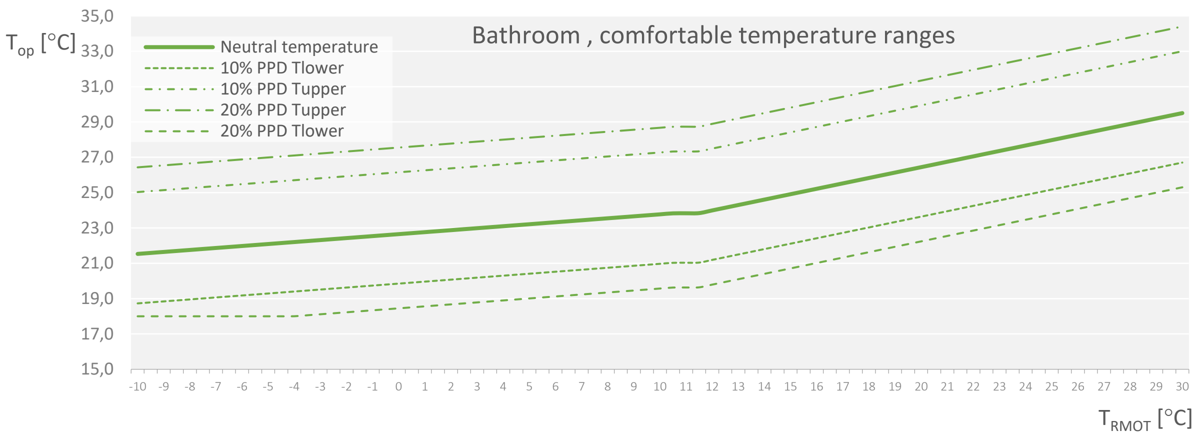
$$T_{upper} = T_n + w \cdot \alpha \quad (3.7)$$

$$T_{lower} = \min\,(18℃, T_n + (1 - w) \cdot \alpha) \quad (3.8)$$

Table 3.3: Values for w and α

10% PPD	20% PPD
w = 5 °C	*w* = 7 °C
α = 0.7	α = 0.7

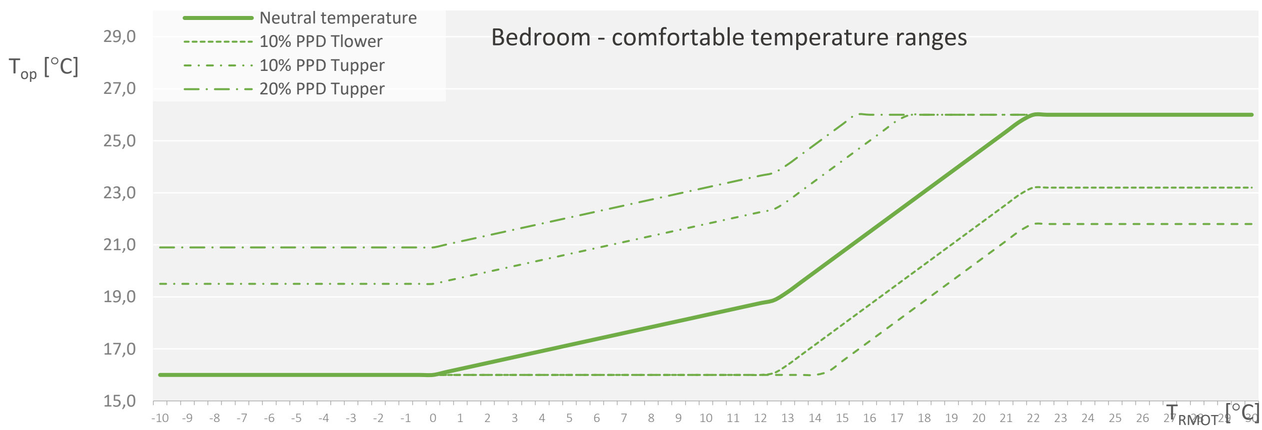
Figure 3.5: Comfortable temperature ranges in the bathroom



$$T_n = 0.112 \times T_{RMOT} + 22.65\ °C \quad \text{for} \quad T_{RMOT} < 11°C \quad \text{in [°C]} \quad (3.9)$$

$$T_n = 0.306 \times T_{RMOT} + 20.32\ °C \quad \text{for} \quad T_{RMOT} \geq 11°C \quad \text{in [°C]} \quad (3.10)$$

Figure 3.6 Comfortable temperature ranges in the bedroom



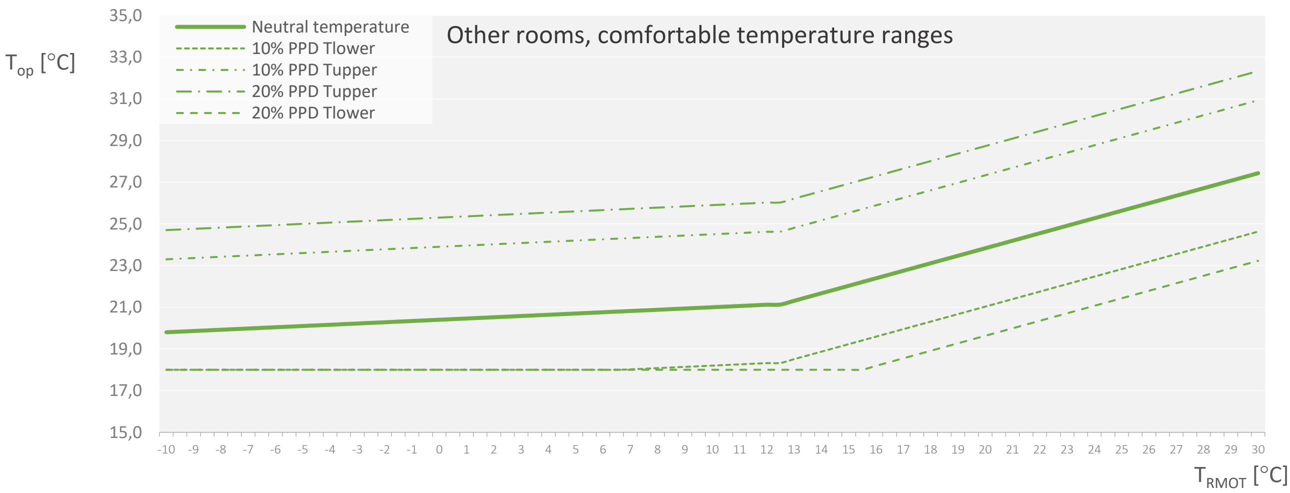
$$T_n = 16\ °C \quad \text{for} \quad T_{RMOT} < 0\ °C \quad \text{in [°C]} \quad (3.11)$$

$$T_n = 0.23 \times T_{RMOT} + 16\ °C \quad \text{for} \quad 0\ °C \leq T_{RMOT} < 12.6°C \quad \text{in [°C]} \quad (3.12)$$

$$T_n = 0.77 \times T_{RMOT} + 9.18\ °C \quad \text{for} \quad 12.6\ °C \leq T_{RMOT} < 21.8\ °C \quad \text{in [°C]} \quad (3.13)$$

$$T_n = 26\ °C \quad \text{for} \quad T_{RMOT} \geq 21.8°C \quad \text{for} \quad T_{RMOT} \geq 21.8°C \quad \text{in [°C]} \quad (3.14)$$

Figure 3.7: Comfortable temperature ranges in other rooms



$$T_n = 0.06 \times T_{RMOT} + 20.4\ °C \quad \text{for} \quad T_{RMOT} < 12.5\ °C \quad \text{in [°C]} \quad (3.15)$$

$$T_n = 0.36 \times T_{RMOT} + 16.63\ °C \quad \text{for} \quad T_{RMOT} \geq 12.5\ °C \quad \text{in [°C]} \quad (3.16)$$

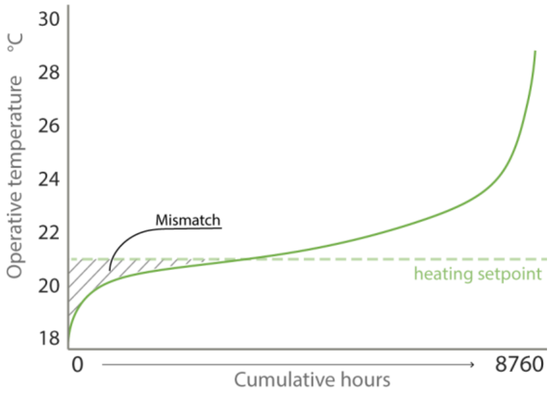
3.3 Other methods to determine thermal comfort

Other methods which are not based on comfort standards to check if thermal comfort is achieved, are also possible.

Cumulative temperature duration curve

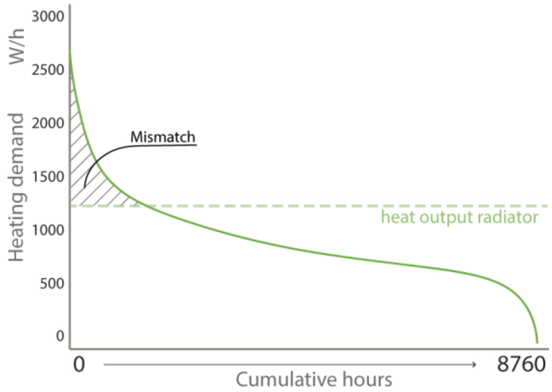
Wang et al. (2015) use a cumulative temperature duration curve for the operative temperature in their research, of which the principle is shown in Figure 3.7. The curve shows how many hours per year the operative or surface temperature falls within a temperature range. The duration curve can for example be compared with the heating setpoint. This method of plotting the temperature neglects options for adaption and outdoor temperature; when it is a few days cold outside, a lower indoor temperature can be accepted indoors.

Figure 3.7: cumulative temperature duration curve



Cumulative peak power duration curve

This method is similar to the cumulative temperature duration curve, but then for the required peak power (Figure 3.8). The peak power is provided should be equal to the heat output of the present heating system. The number of hours the required peak power exceeds the power provided by the heating system, the room is probably colder than the heating setpoint. To determine if a dwelling can be heated with lower supply temperatures, a percentage of required hours can be given for which the heating system should provide enough heat.



3.4 Preferred method for this research

Based on the overview of different methods to evaluate thermal comfort with the indoor temperature, the adapted ATG-method for different spaces in a dwelling developed by Peeters et al. (2009) was selected. Reasons to select this method were:

- It takes options for adaption into account, which are present in residential buildings
- It takes the outdoor weather of the past days into account, which influences the perception of the indoor temperature
- It provides comfort ranges for different spaces in the dwelling.

4 Local discomfort

Besides the temperature in the room, other comfort aspects can influence the thermal sensation within a space (Nicol et al., 2012). These aspects are usually referred to as *local discomfort*, which can cause thermal discomfort to occupants in a space. First, different forms of local discomfort aspects are explained in Section 5.1, followed by examples in Section 4.2. Section 4.3 provides an overview of most important local discomfort aspects and describes how local comfort is researched within this thesis.

4.1 Forms of local discomfort

In this section the definition is given for different forms of local discomfort, including current regulations and findings from literature. The following local discomfort aspects are explained:

- Thermal stratification
- Temperature asymmetry
- Floor surface temperature
- Heating up period
- Temperature fluctuations during the day
- Cold draft

Thermal stratification

Thermal stratification is an imbalance of temperatures between the floor and the ceiling. Warm air expands and is lighter, compared to colder and denser air. Thus warm air will rise, resulting in warmer air at the ceiling, and colder air on the ground (Figure 4.1). Table 4.1 shows the current ISO 7730 standards for thermal stratification.

The type of heating system influences thermal stratification within a room. Eijdems et al. (1999) mentioned that thermal stratification is lower with floor heating than with high-temperature radiators in well-insulated buildings. In contrast, Myhren & Holmberg (2008) experienced that a middle-temperature radiator provided a smaller temperature gradient than floor heating. This was possibly caused by the air inlet, in which the radiator directly reacts to the cold down-flow caused by the air-inlets.

Figure 4.1: Thermal stratification

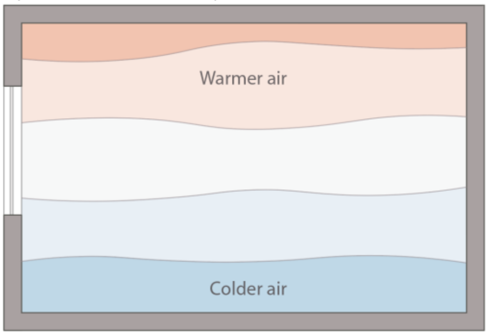


Table 4.1: Temperature differences between head and ankle

ISO 7730	
Class A	< 2 °C
Class B	< 3 °C
Class C	< 4 °C

Temperature asymmetry

Surfaces with lower surface temperatures than other surfaces of the room, such as windows, can cause cold radiance. When surfaces with higher surface temperatures, such as radiators, are presented in the room, temperature asymmetry can occur (Figure 4.2). This can cause discomfort to the occupants in the space.

Temperature asymmetry is mainly caused by the cold surface temperature of windows and is usually only an issue with single glazing, and not with double or triple glazing (Myhren & Holmberg, 2008). In almost all dwellings temperature assymetry is not a problem and meets the ISO 7730 regulations, which state a temperatire difference of 10 °C (DWA, 2016), In the past, the cold radiance from the windows was compensated by placing hot radiators below them (Eijdems et al., 1999).

Figure 4.2 Temperature asymmetry

Table 4.2: Temperature differences between head and ankle

ISO 7730	
Class A	< 10 °C

Floor surface temperature

When the floor has a cold surface temperature, people can feel cold in a space even when the temperatures have reached an acceptable level (Figure 4.3), because human beings are sensitive to cold feet and ankles. This is called the 'cold-feet effect' (Myhren & Stolmberg, 2008; Wang et al., 2015). Also, flooring material influences the experienced floor temperature. For this reason, ISO 7730 and Eijdems et al. (1999) provide recommendations for the floor temperature, presented in Table 4.3.

Wang et al. (2015) use the floor surface temperature with a temperature duration curve to show the influence of different refurbishment options on the floor surface temperature.

Figure 4.3: Cold floor surface temperature

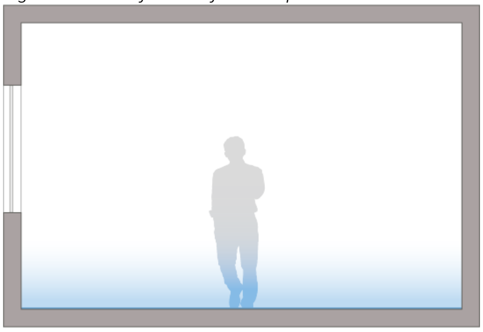


Table 4.2: Overview floor surfaces temperatures

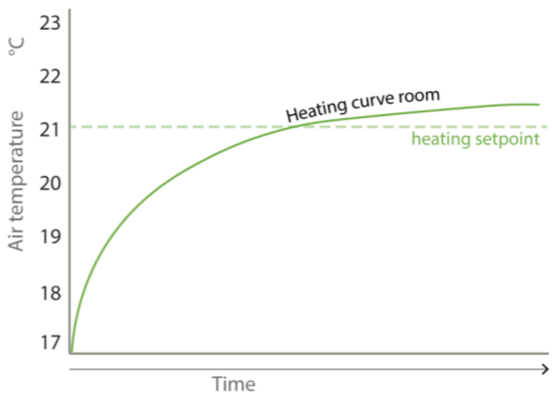
Eijdems et al. (2009)	
Shoes	20 - 28 °C
Bare feet	23 - 30 °C
ISO 7730	
Class A & B	19 - 29 °C
Class C	17 - 31 °C

Heating up period

Conventional high-temperature heating systems are designed to heat a space in a short time to the desired temperature, whereas low-temperature heating systems take up a longer period to reach this temperature. This is because of greater inertia. A small night setback is therefore recommended for low-temperature heating systems because this results in a lower temperature rise compared to conventional systems (Eijdems et al., 1999).

The heating up period is a potential local discomfort problem that easily can be solved. A simple, implementable solution is for example an automatic heating schedule, which already turns the before it is needed.

Figure 4.4: Heating up period

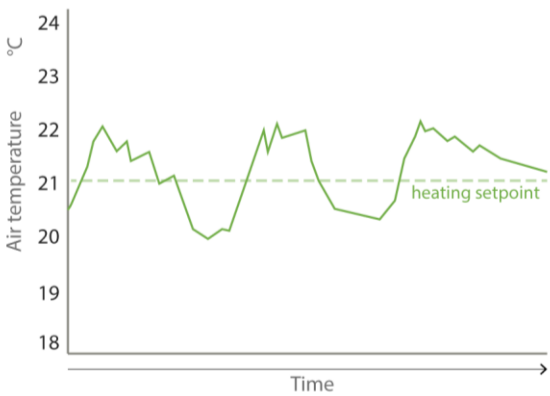


Temperature fluctuations during the day

Temperature fluctuations around a constant mean temperature can annoy people (Eijdems et al., 1999). Low-temperature heating systems have a slower reaction time because of the greater inertia, which causes fewer temperature fluctuations when a room is heated. This could, however, result in local discomfort when the heating is turned on and the sun starts shining through the windows and is heating the space as well. Due to the slower reaction time of the system, the heating system stops slowly.

Nicol & Humphreys (2009) gave recommendations for temperature fluctuations during the day, suggesting a constant temperature with fluctuations within ±2 °C and variations between occupied hours should not exceed ±1 °C. Wang et al. (2015) evaluate the thermal performance of a low-temperature heated dwelling by comparing temperature fluctuations before and after renovation. Results showed that after renovations temperature fluctuations were decreased.

Figure 4.5: Temperature fluctuations during the day



Cold draft and cold down-flow

Cold draft is the most common cause of local discomfort and is defined as *"an undesired local cooling of the human body due to air movement"* (ISO 7730). It is caused due to a pressure difference that starts air movement into the room, for example by cold window surfaces which cool the nearby air and causing a cold down-flow. Also, ventilation openings in the facades can cause cold drafts (Figure 4.6).

Cold draft can be prevented by installing radiators under the window zone to counteract the cold down-flow and mixing it with warm rising air from the radiators. When the air reaches the occupied zone, it already has a comfortable temperature. Other solutions are glazing with a low U-value and well-designed and ventilation grills (Eijdems et al., 1999; Myhren & Holmberg, 2008).

Figure 4.6 Cold drafts

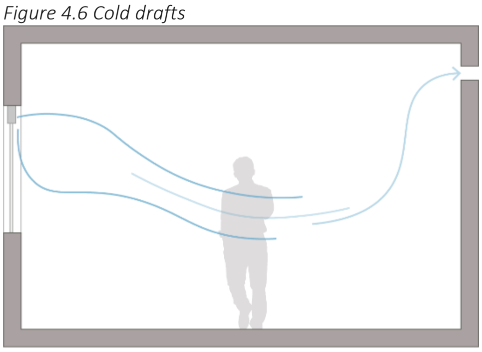


Table 4.3: Draft rates

ISO 7730	
Class A	< 15%
Class B	< 20%
Class C	< 25%

The type of heating system can prevent cold draft. Floor- and wall heating have difficulties with counteracting cold drafts, where radiators prevent cold drafts because of the warm rising air (Myhren & Holmberg, 2008). Obstacles in the room, such as furniture, can however block this effect. For example, when a table is placed under the window and above the radiator, it can form a barrier in counteracting the cold downflow.

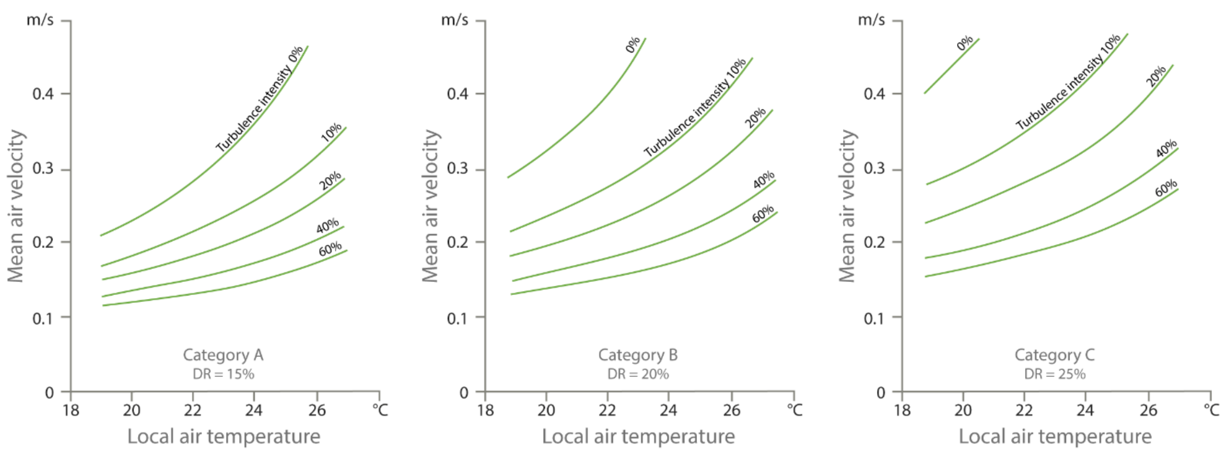
Cold draft can be evaluated with the draft rate, which is the percentage of people dissatisfied due to the draft. Recommendations provided by ISO 7730 are shown in Table 4.3. The cold draft rate can be calculated with Formula 4.1, (Fanger & Christensen, 1985).

$$DR = \left[(34 - T_{air}) \times (v - 0.05)^{0.62}\right] \times (0.37 \times v \times Tu + 3.14) \qquad (4.1)$$

with:

DR	Draft rating, i.e., the percentage of people dissatisfied due to draft	in [%]
T_{air}	Local air temperature	in [°C]
v	Local mean air velocity	in [m/s]
Tu	Local turbulence intensity, based on Figure 4.7	in [%]

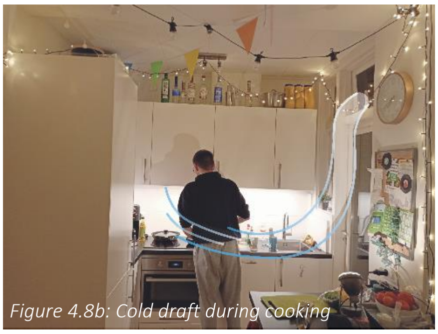
Figure 4.7: graphs for different categories to determine the local turbulence intensity



4.2 Local discomfort in the living room

Some precedents of local discomfort are shown in Table 4.4 with their causes.

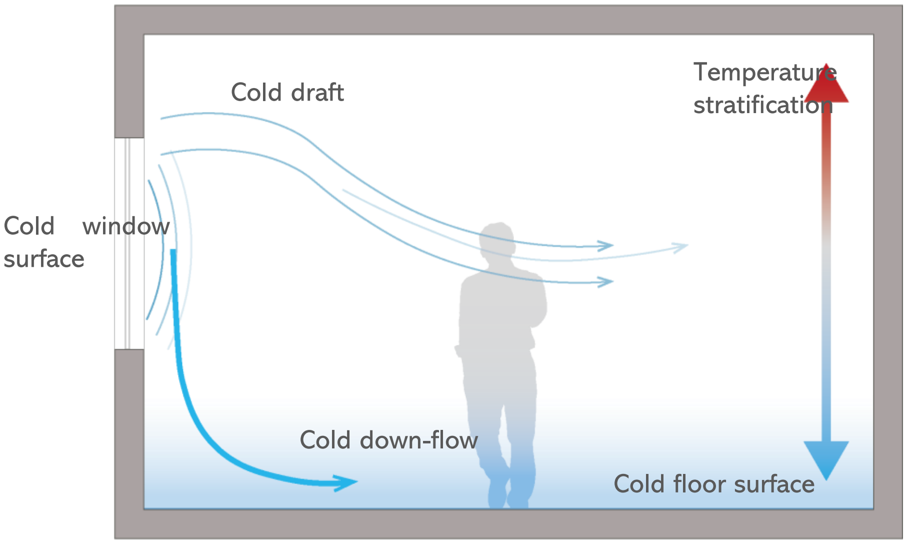
Table 4.4: Possible local discomfort issues in the living room

Comfort problem	Caused by
Cold radiation from the windows and cold down-flow  *Figure 4.8a: Cold radiation*	· Glazing with a high U-value has a colder window surfaces · Not closing the curtains at night · Cold down flow caused by cold window surface · Heating system cannot counteract the cold down-flow
Cold draft during cooking  *Figure 4.8b: Cold draft during cooking*	· The mechanical exhaust is turned on during cooking, which causes a pressure difference · Bad-designed ventilation grills. Ventilation grills that directly transfer cold, outside air to inside can cause cold drafts when they are opened.  *Figure 4.8c: Bad designed ventilation grill (Antares, 2020)*
Cold draft due to leakage of window frame  *Figure 4.8d: Leakage in window frame*	· Cracks and leaks from the window frame can cause cold drafts
Cold feet  *Figure 4.8e: Cold floor surface*	· Floor has a high U-value · Cold flooring material, such as tiles

4.3 Local comfort and low-temperature heating

Local comfort is as important as the temperature to determine the thermal sensation within a room. When the air or operative temperature is comfortable, but local discomfort issues occur, people can still feel thermally uncomfortable. Chances of local discomfort increase with low-temperature heating for both floor heating systems as radiators. Figure 4.9 shows the most common local discomfort issues that can occur in a room with low-temperature heating.

Figure 4.9: Overview of local discomfort aspects



The largest cause for local discomfort with low-temperature heating are cold drafts and cold down-flows in the room because the heating system has less capacity to counteract the cold air currents. This mostly happens when ventilation grills in the façade are placed.

The floor temperature is also important, because humans are sensitive to the cooling of their feet and ankles. The flooring material can influence the experienced temperature, which can be taken in mind when using low-temperature heating.

Cold radiation caused by windows is not a common cause of local discomfort within rooms, but it can influence the operative temperature. Thus, solutions as replacing windows with lower U-values or placing radiant screens can have the potential to research.

Another less important factor is temperature stratification because there is not much indication that problems will occur when using low-temperature heating. Temperature fluctuations during the day will occur less often with low-temperature heating, so this is not further researched. Also, the heating up period is disregarded because a solution to this can be to change the heating schedule.

Renovation measures that prevent local discomfort are researched on the room-scale. Also, an additional CFD-analysis is performed to determine the effect of several renovation measures.

5 Analytical overview of heat balance and heat output

An analytical overview of the heat balance of a dwelling and the heat output can provide insight into what is needed to provide thermal comfort with low-temperature heating. An overview of the stationary heat balance is given in Section 5.1 for a house or dwelling. Section 5.2 describes the method to calculate the heating capacity of a radiator or heating system. The stationary heat balance and calculated heat output are combined in Section 5.3, which also suggests different methods to provide a comfortable temperature with low-temperature heating.

5.1 Stationary heat balance

A stationary model can be used to calculate the heating demand of a dwelling or room with the energy flow as a result of the difference between the in- and outdoor temperature. It differs from dynamic simulations because the stationary heat balance does not take the heat into or out of surfaces surrounding indoor spaces into account as a result of dynamic behaviour, such as the heat storage in walls (Jansen, 2013).

The most important energy flows to determine the energy demand are the transmission, ventilation, and infiltration flow. Table 5.1 shows the definition of these energy flows. Internal and solar gains are not used to determine the energy demand in Formula 5.1 but do have an influence.

$$Q_{demand} = Q_{trans} + Q_{vent} + Q_{inf} \qquad (5.1)$$

Table 5.1: Energy balance of a building (adjusted from Jansen, 2013)

Flow	Description of the heat gain accompanying the flow of energy or matter	Abbreviation	Formula	
Transmission	Heat transfer from the building envelop into the conditioned indoor spaces	Q_{trans}	$\sum U_i A_i (T_i - T_e)$	(5.2)
Ventilation	Sensible heat gains from the supply and exhaust of controlled ventilation air	Q_{vent}	$\frac{\rho \times c \times nV \times (T_i - T_e)}{3600}$	(5.3)
Infiltration	Sensible heat gains from uncontrolled inlet and exhaust of air through cracks of the building	Q_{inf}	$\frac{\rho \times c \times nV \times (T_i - T_e)}{3600}$	(5.4)
Demand	The heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature	Q_{dem}	$Q_{trans} + Q_{vent} + Q_{inf}$	(5.1)

We can conclude from Formula 5.1 that when transmission, ventilation, and infiltration losses are reduced, the energy demand will consequently be lower. Options to reduce these losses are:

- Transmission losses can be lowered by improving the U-value of the building envelope.
- Ventilation losses can be limited by adding a heat recovery system to the ventilation system or apply demand-driven ventilation.
- Infiltration losses can be lowered by reducing cracks around, for example, windows and doors to reduce the air infiltration. This can be done by replacing window frames or air tighten the building.

5.2 Heating capacity radiator

The heating capacity determines how much heat can be supplied in a room and is important for achieving comfortable temperatures. The heating capacity of a radiator can be calculated with Formula 5.5 and is lower when lower supply temperatures are (Johansson, 2010; Hesaraki et al., 2015; Østergaard, 2018).

$$Q_{heat\ emitter} = k \times A \times \Delta\theta \qquad (5.5)$$

with:

k	heat transfer coefficient	[W/m²K]
A	surface area of the heating element	[m²]
Δθ	logarithmic mean difference temperature between the radiator and the surrounding air	[°C]

The heat transfer coefficient k describes the convection from water to the surrounding metal, the conduction through the metal, and convection from the outer surface of the radiator to the room (Formula 5.6). The outcome of the first two terms is very small, and can thus be neglected, which results into the rewritten Formula 5.7.

$$\frac{1}{k} = \frac{1}{\alpha_{water-metal}} + \frac{\delta_{metal}}{\lambda_{metal}} + \frac{1}{\alpha_{conv} + \alpha_{rad}} \quad (5.6)$$

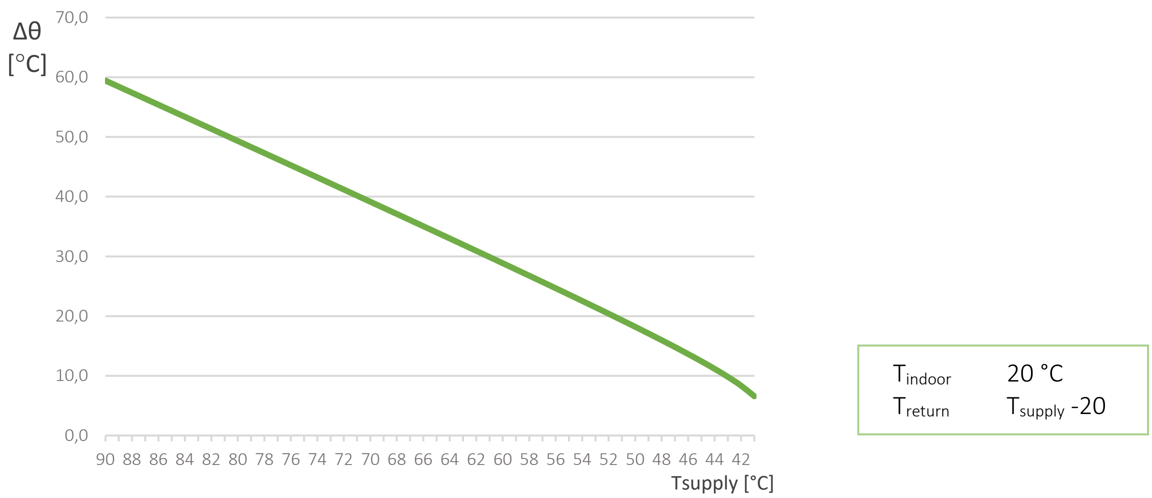
$$k = \alpha_{conv} + \alpha_{rad} \quad (5.7)$$

With low-temperature heating, a smaller difference can be expected between the supply and return temperature of the radiator system, and the surrounding air in the room (Østergaard, 2018). Formula 5.8 can be used to calculate this difference, which is the logarithmic mean difference $\Delta\theta$. When the supply temperature is lowered, while keeping the same indoor temperature and temperature difference ΔT between the supply and return temperature, the logarithmic mean difference will also be lower. This lower $\Delta\theta$ results into the lower heating capacity.

$$\Delta\theta = \frac{T_{supply} - T_{return}}{ln\frac{T_{supply} - T_{indoor}}{T_{return} - T_{indoor}}} \quad (5.8)$$

Figure 5.1 shows what happens with $\Delta\theta$ when the supply temperature is lowered, keeping a constant indoor temperature of 20 °C and a constant ΔT of 20 °C. It becomes visible that $\Delta\theta$ decreases rapidly when the supply temperature is lowered. For example, $\Delta\theta$ is halved at a supply temperature of 90.0 and 60.0 °C. A detailed overview is given in Appendix C.

Figure 5.1: Logarithmic mean difference for different supply temperatures



Formula 5.5 shows that both the logarithmic mean difference temperature $\Delta\theta$, the heat transfer coefficient k, and the area of the heat emitting surfaces A determine the heating capacity. The logarithmic mean difference temperature $\Delta\theta$ will be lower when a lower supply temperature is used. To provide the same heat output, or the area of the heat emitter must be enlarged, or the heat transfer coefficient must be optimized. Enlarging the area can be done with larger radiators or floor heating. Optimizing the heat transfer coefficient can be done with, for example, forced ventilation (Hesaraki et al., 2015).

Another method to calculate the heating capacity of a radiator, provided by Østergaard (2018), is shown in Formula 6.9. This method was used to calculate the heating capacity of radiators for the case study building in Chapter 9.

$$Q_{heat\ emitter} = \left(\frac{\Delta\theta\ lower\ supply}{\Delta\theta\ original\ supply}\right)^n \cdot \varphi_0 \quad [W] \quad (5.9)$$

$\Delta\theta$	logarithmic mean difference at the design temperatures, see Formula 5.8	[°C]
n	radiator exponent, = 1.3	[-]
φ_0	heating capacity at original temperature set	[W]

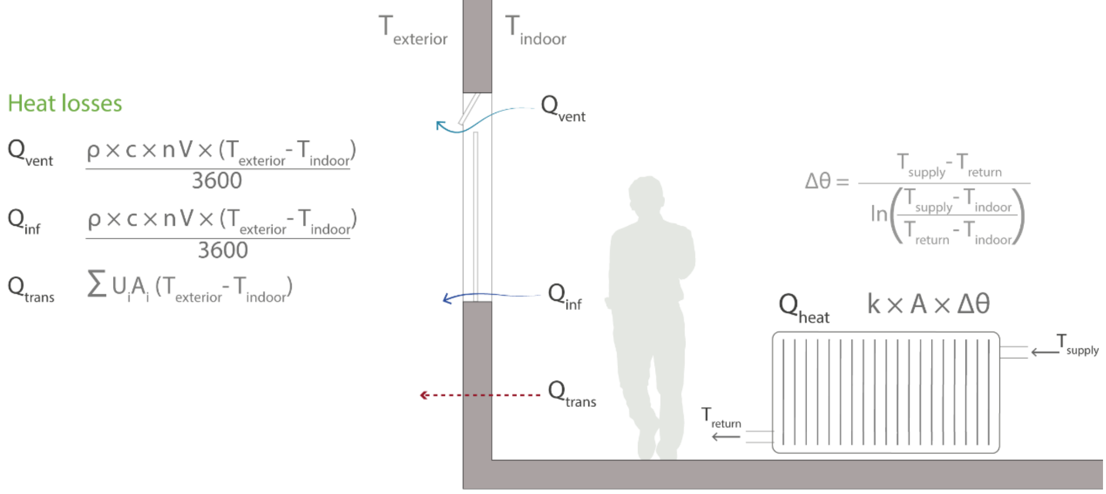
5.3 Combined

To provide comfortable temperatures inside a room or dwelling, the heating capacity of the heating system should be equal to the heating demand of the space (Formula 5.10-11). A graphical overview is provided in Figure 5.2.

$$Q_{heat\ emitter} = Q_{demand} \quad (5.10)$$

$$k \times A \times \Delta\theta = Q_{trans} + Q_{vent} + Q_{inf} \quad (5.11)$$

Figure 5.2: Overview of heat losses and gains



With low-temperature heating, the heating capacity of the heating system is reduced, due to the lower logarithmic mean difference temperature Δθ. Several options are possible to still provide thermal comfort within a room (Hesaraki et al., 2015):

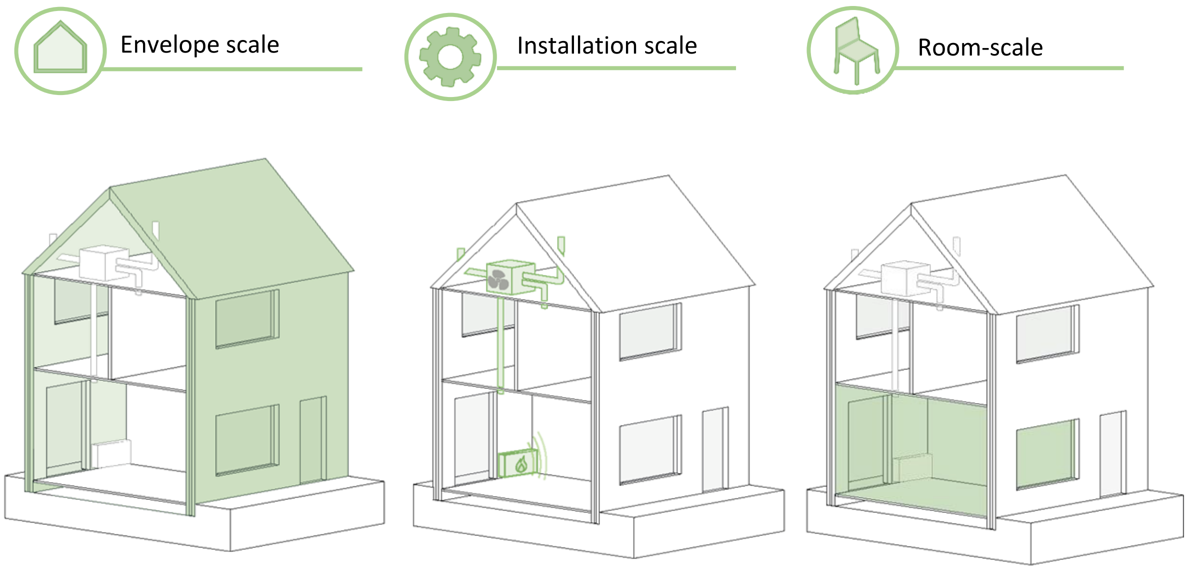
1. **Minimize the heating demand**
   If the heat output of the heating system does not match the heating demand, the building losses can be reduced. The U-value of the building can be increased by renovation measures to reduce the transmission losses. Ventilation losses can be minimized by adding heat recovery or demand-driven ventilation. Infiltration losses can be reduced by air tighten the building.
2. **Optimize the heat output**
   The heat output can be optimized by enlarging the surface of the heat emitter by placing larger (LT-)radiators or a floor heating system. Another option is to increase the heat emission coefficient, by placing special add-on fans to optimize that increase the convection.
3. **A combination between option 1 and 2**
   A combination of measures from options 1 and 2 can also provide enough comfort. Also, additional solutions on the room-scale can be applied.

6 Renovation measures for LT-Ready renovations

This chapter aims to provide an overview of renovation measures that can enable low-temperature heating and provide thermal comfort. Three different scales were devised to organize the found renovation measures (Figure 6.1), which are:

- The building envelope scale, including renovations to the walls, floor, windows, and roof; discussed in Section 6.1.
- The building installation scale, including the ventilation system and heating system; discussed in Section 6.2.
- The room-scale, including solutions to improve local comfort; discussed in Section 6.3.

Figure 6.1: Different scales for renovation measures



Some measures were difficult to categorize because they applied to multiple scales. An example is the ventilation system: the entire ventilation system applies to the installation scale, but ventilation grills also apply to the room scale. In this case, they are mentioned in both scales.

Finally, Section 6.4 discusses how measures on the different scales can be combined into a renovation concept and their expected effect based on literature.

6.1 Building envelope scale

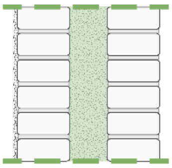
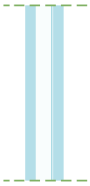
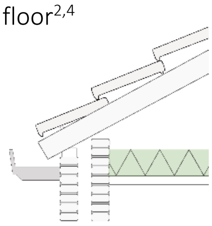
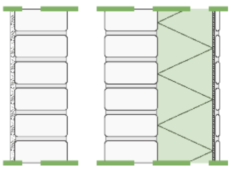
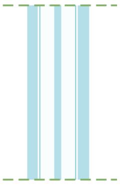
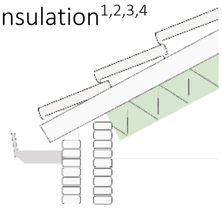
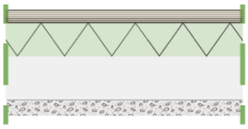
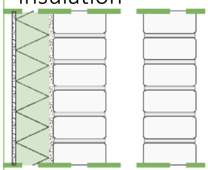
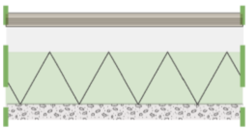
One method to provide thermal with low-temperature heating is to reduce the heating demand by reducing the transmission losses, which can be achieved by improving the building envelope (Hesaraki et al., 2015). Section 6.1.1 provides an overview of possible renovations to the building envelope, where Section 6.1.2 discusses the effect of renovation measures to the envelope and low-temperature heating based on found literature.

6.1.1 Building envelope measures

By insulating the building envelope, the U-value of the building can be improved which results in lower transmission losses. Also, the air tightness of the building can be improved to reduce infiltration losses.

The studies of Bone (2009), Konstantinou (2014) Milieu Centraal (n.d.) and Schoenmaker et al. (2021), are in accordance about possible measures for building envelope improvement. Based on these studies, an overview is provided in Table 6.1.

Table 6.1: Overview of possible measures on the building envelope scale, based on different studied literature

Measures on the building envelope scale				
Exterior wall	**Windows**	**Roof**	**Floor**	**Air tightness**
Cavity wall insulation[1, 2, 3] 	Window replacement with HR++ glazing[1,3,4] 	Insulation on top/attic floor[2,4] 	Insulation on top of floor slab[1,2,4] 	Low
Exterior wall insulation[1,2,3,4] 	Window replacement triple glazing[3,4] 	Pitched rocf insulation[1,2,3,4] 	Insulation under floor slab[1,2,4] 	Improved
Interior wall insulation[1,2,3,4] 		Flat roof insulation[1,2,3,4]	Insulation of crawl space[2] 	
			New floor with floor heating[1,4]	

Mentioned in literature:

1.	Schoenmaker, F., Ras, T., Schouten, F., & Heynen, R. (2021). Nationaal Warmtenet Rapport 2021. https://www.warmtenettrendrapport.nl/trendrapport/
2.	Bone, A. (2009). Basisboek Isoleren. ThiemeMeulenhoff bv.
3.	Milieu Centraal. (w.d.). Lage temperatuur verwarming (ltv). https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/lage-temperatuur-verwarming-ltv/#Is-jouw-isolatie-al-voldoende
4.	Konstantinou, T., & Knaack, U. (2013). An approach to integrate energy efficiency upgrade into refurbishment design process, applied in two case-study buildings in Northern European climate. Energy and Buildings, 59, 301–309. https://doi.org/10.1016/j.enbuild.2012.12.023

6.1.2 Effect of measures on the building envelope scale

Brand & Svendsen (2013), Østergaard & Svendsen (2016) and Wang et al., (2015), researched the effect of measures to the building envelope on the supply temperature, the energy demand, and thermal comfort when using a lower supply temperatures for heating. General conclusions were that after renovations to the building envelope, dwellings can be heated for a large part of the year with low-temperature heating.

Brand & Svendsen (2013) focussed on determining the required supply temperatures to heat dwellings in different stages of the building envelope: no renovation, a light renovation which included replacing windows, and an extensive renovation which included roof insulation, the replacement of windows with triple glazed low-energy windows, improved thermal bridges, and reduced infiltration. Without renovation, dwellings can already be heated with a supply temperature of 50 °C for 59.2% of the year. After replacing the windows, this increased to 83.5%, and with an extensive renovation, this number is increased to 96.6%.

Wang et al. (2015) focussed on achieving thermal comfort with low-temperature heating by determining the effect of renovation measures on the building envelope on the air and operative temperature, floor surface temperature, and energy demand. Conclusions were that all measures improved thermal comfort and reduced the energy demand of the building. Thermal comfort was improved by showing fewer temperature fluctuations, a higher floor surface temperature and a higher operative temperature. For energy savings, external wall insulation showed the largest effect followed by roof insulation. This is remarkable because it was expected that replacing windows had a higher effect than adding wall insulation.

Østergaard & Svendsen (2016) performed a study on different renovation scenarios for dwellings built in different periods in Denmark. Conclusions were that when the building envelope was upgraded, current radiator systems were over-dimensioned by 20 to 50% compared to their original state. This provides options for lowering the supply temperature.

Milieu Centraal (n.d.) recommended that dwellings should have a good or very good insulation level to provide thermal comfort with low-temperature heating. Their suggestions for insulation levels are shown in Table 6.2.

Table 6.2: Insulation levels, window types and thickness of insulation (Milieu Centraal, n.d.)

Thickness of insulation material for ground floor, walls, and roof	Windows	Insulation level
0 - 3 cm ($R_c < 1$)	Single glazing	Not / bad
5 - 7 cm ($1.0 < R_c < 1.7$)	Double glazing (no HR++)	Moderate
8 - 10 cm ($2.2 < R_c < 2.9$)	HR++ glazing	Good
13 cm or more ($R_c > 3.5$)	Triple glazing	Very good

6.2 Building installation scale

Measures to the building installation scale include the ventilation system and heating system. The different ventilation types are discussed in Section 6.2.1, and additional measures to the heating system in Section 6.2.2.

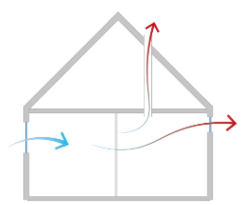
6.2.1 Ventilation system

When a dwelling is renovated, usually also a ventilation system is placed. Dwellings were in their original situation natural ventilated, but after renovation, the airtightness of the building is improved. This results in the demand for an additional ventilation system (Livius, 2019). Other reasons to replace the ventilation system were that it does not meet the current requirements, or that the dwelling can be more energy-efficient after replacing the ventilation system. Therefore, the four commonly used ventilation types (A, B, C, D) that are used in the Netherlands are summarized in this section(Linden et al., 2006).

Ventilation system A - Natural supply and exhaust

Ventilation system A is a form of natural ventilation (Figure 6.2). Ventilation air enters the dwelling via openings in the façade, such as open windows or ventilation grills, or unintendedly via cracks. Vertical ventilation channels are placed in the kitchen, toilet, and bathroom. Natural ventilation can occur with cross-ventilation, stack ventilation, or single-sided ventilation (Wood & Salib, 2013).

Figure 6.2: Ventilation type A

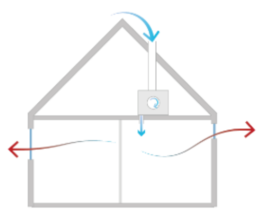


Ventilation system B - Mechanical supply and natural exhaust

With ventilation type B, ventilation air is mechanically supplied in all rooms. Vertical ventilation channels are placed in the kitchen, toilet, and bathrooms (Figure 6.3). The ventilation air is naturally exhausted by windows or ventilation grills.

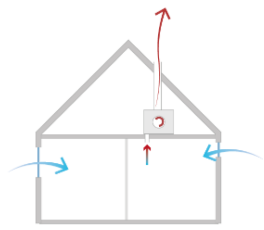
This ventilation system B is barely used in the Netherlands.

Figure 6.3: Ventilation type B



Ventilation system C - Natural supply and mechanical exhaust
Adjustable ventilation grills are placed in the façade for the air supply, and mechanical ventilation outlets are placed in the kitchen, toilets, and bathrooms (Figure 6.4). This system, also known as exhaust ventilation, is referred to as ventilation system C1. A disadvantage of this ventilation system is that cold drafts can occur through the ventilation grills.

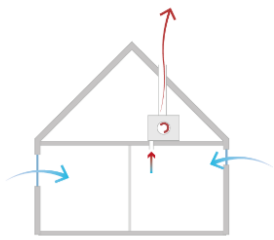
Figure 6.4: Ventilation type C



Exhaust ventilation can also be combined with CO_2 sensors to have demand-driven ventilation, also known as ventilation system C2. With these sensors, the ventilation system is only active with a certain amount of CO_2 in the air. This system has the advantage that ventilation only occurs when it is needed, which reduces ventilation losses.

Ventilation system D - mechanical supply and exhaust
Ventilation type D1 is a balanced ventilation system, controlling both the ventilation supply and exhaust. Fresh ventilation air is mechanically supplied in every room, except the bathroom, kitchen, and toilet in which a mechanical exhaust is placed (Figure 6.5). Balanced ventilation can be used in combination with heat recovery, which preheats the incoming ventilation air with the exhaust air. This can reduce the ventilation losses substantially (Hesaraki et al., 2015). Also decentral ventilation is an option (D2), which is a balanced ventilation system designed to ventilate one room. This can also be combined with heat recovery.

Figure 6.5: Ventilation type D



6.2.2 Heating system

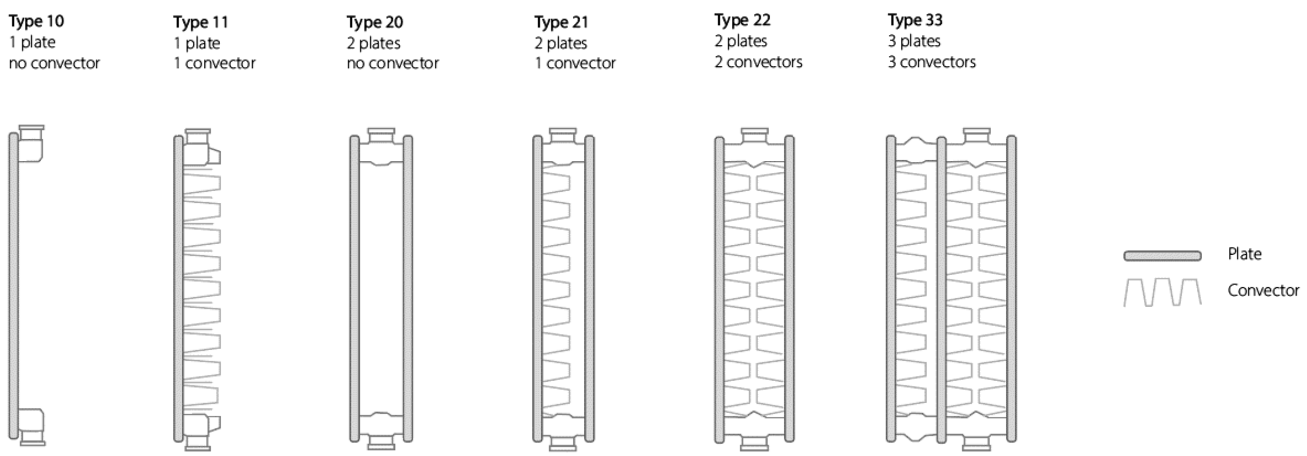
The heating capacity of a heating system is reduced when using a lower supply temperature. To keep the same heating capacity as before, the area of the heating system must be enlarged or the heat emission coefficient (Hesaraki et al., 2015). An overview of different types of heating systems is provided in this section.

1) Conventional hydraulic radiators

A hydraulic radiator heating system is the most common system in the Netherlands (Milieucentraal.nl, n.d.). A radiator has one or more plates through which hot water flows and can have additional convectors. Different types of radiators exist, visualized in Figure 6.6 from the top view (MulcoTherm, n.d.).

Radiator types are numbered with two numbers: the first number stands for the number of plates, and the second number for the number of convectors. Radiators with more plates and convectors a radiator have a higher heating capacity. Smaller rooms usually have radiator type 10 or 11, and larger rooms radiator type 21 or 22.

Figure 6.6: Different radiator types



Radiators already installed in a building can be used with a lower supply temperature (Brand & Svendsen, 2013; Hesaraki et al., 2015; Østergaard, 2018). Possible reasons for this are according to Østergaard (2018):

1. The reduced energy demands due to energy renovations
2. The increased internal gains due to equipment
3. Original dimensioning of radiators was based on design methods with extreme conditions
4. Over dimensioned radiators because of the limited choice of element sizes available at the time

An advantages of using the original radiators IS that not replacing them saves money and causes less disturbance for the residents. However, there is a higher risk for thermal stratification in the room than with a special LT-radiator (Hesaraki et al., 2015).

Radiators can still provide thermal comfort in a room with low-temperature heating. Østergaard & Svendsen (2017) showed that the supply temperature of hydraulic radiators could be lowered without compromising thermal comfort for four dwellings in Denmark. Also, Brand & Svendsen (2013) showed that dwellings can be heated for more than half of the year even without renovation, and even for larger periods after renovations.

Different additional measures can be taken to improve the heating capacity of radiators. Two examples are using heat reflective foil and an add-on fan to boost the radiator.

Heat reflective foil

Heat reflective foil is a foil that can be placed behind the radiators on the wall or on the radiator itself with magnets (Figure 6.7). By using this foil, the heat-transfer losses through the wall are reduced (Figure 6.8). It is thus an energy-saving measure (Vattenfall, n.d.). Figure 6.9 shows the heat losses of a radiator through an uninsulated wall without using radiator foil.

Placing heat-reflective foil behind radiators is a low-budget measure that pays back in less than one winter. It can save up to 10 m^3 gas per m^2 radiator foil (Milieucentraal.nl, n.d.).

Figure 6.7: Heat reflective foil (Amazon, n.d.)

Figure 6.8: Effect of heat reflective foil

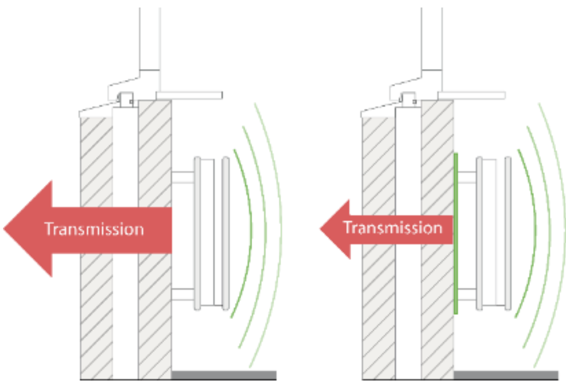
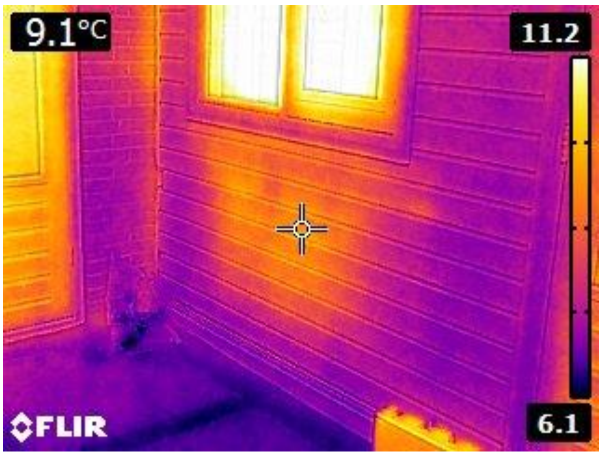


Figure 6.9: Transmission losses through the wall by a radiator (Duurzaam Bouwloket BV, n.d.)



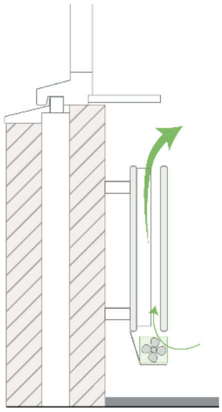
Add-on fan radiator

An add-on fan, or radiator booster, placed below a radiator can increase the heating capacity of the radiator due to the increased convection along the panel surfaces (Figure 6.10-11). This means that a lower supply temperature can be used without reducing the heat output. Advantages of add-on fans are that the current radiators can be used with an increased heat output, but the add-on fans do cause some noise and are thus not suitable for bedrooms (Hesaraki et al., 2015).

Estimations of the increased heat capacity when using add-on fans differ per research. Johannson (2010) showed with a numerical study that placing five fans below a radiator can double the heat output; Vliet et al. (2016) mentioned that add-on fans on existing radiators increase the heat output by 0.2 to 1.0 kW. In this thesis, increased heat output of 20% is used when placing add-on fans, which is based on information provided by manufacturers (Zelf energie besparen, 2021.).

Figure 6.10: Add-on fan (Wilms, 2021)

Figure 6.11: Effect of add-on fan



2) Low-temperature radiators

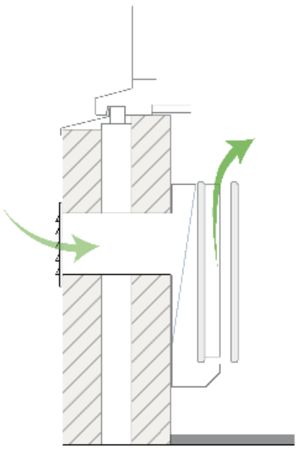
The current trend for low-temperature radiators is to increase the number of plates and convectors to improve the convection and make them possible to operate at lower temperatures while maintaining the same heat output (Filgueira Luaces, 2020). Another method is placing a case above the convector, so it starts acting like a chimney to increase the convection. An LT-radiator that uses this method is the Jaga Strada, shown in Figure 6.12. A combination of placing add-on fans and a case is also an option to force convection.

A special type of LT-radiator presented in the literature by Myhren & Holmberg (2009), Hesaraki et al. (2015), and Wang et al. (2015) is the ventilation radiator, which includes both ventilation and heating (Figure 6.13). By using this system an air supply inlet is placed behind the radiator in the wall. The heating capacity of the radiator is increased due to a forced convection by blowing cold ventilation air behind the radiator and a larger temperature difference between the ventilation air and the radiator surface.

The ventilation air is preheated by the radiator before it enters the room, which minimizes the chances of cold drafts and reduces thermal stratification (Myhren & Holmberg, 2009). The disadvantages of this system are that an opening in the external wall behind the radiator

Figure 6.12: Jaga Strada LT-radiator (Warmteservice, n.d)

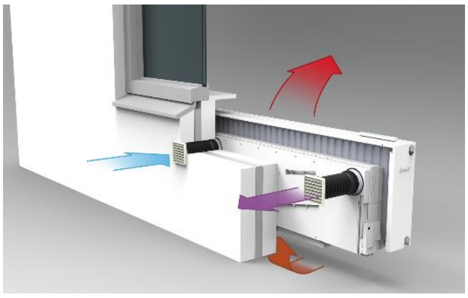
Figure 6.13: Ventilation radiator



must be made and that the air filter needs to be cleaned regularly.

A more commonly used type of ventilation radiator in the Netherlands is one with a decentralized ventilation system combined with heat recovery, such as the Climarad 2.0 radiator (Figure 6.14). It is demand-driven ventilation, combined with CO_2-sensors.

Figure 6.14: Climarad (Climarad BV, n.d.)



3) Large surface emitters

Large surface emitters are integrated heating systems in the floor, walls, or ceiling (Figure 6.15). They usually have a supply temperature of 35 °C and create a uniform indoor temperature. The heating system becomes invisible, which can aesthetically be appealing. Another advantage of floor heating is that by having warmer floor surfaces, people are more comfortable because the feet usually have a lower temperature than other parts of the body. However, maintenance can be difficult, and installing the floor or wall heating can be quite complex (Hesaraki et al., 2015).

Floor heating does however have difficulties in counteracting cold-down flow, caused by cold window surfaces or ventilation grills (Myhren & Stolmberg, 2007).

Figure 6.15: Floor heating (Watts, n.d.)

6.3 Room-scale

Also, additional measures on the room-scale are possible. To find innovative low-tech solutions of measures on the room-scale, we can divert to non-scientifically published solutions presented by regular websites and manufacturers. In future research, these measures can be tested scientifically on their effectiveness.

1) Heat reflectance

With heat reflectance radiant heat is reflected into the room. This results in a higher operative temperature and thus provides more thermal comfort. Two options for heat reflectance are heat reflective radiator foil discussed in Section 6.2, and heat reflective paint.

Heat reflective paint applied to the interior surfaces can reflect radiant heat, which can provide options to widen the heating setpoints. Heat reflective paint contains ceramic particles which reflect heat to all sides of the room (ClimateCoating, n.d.). The manufacturer claims that energy savings could lead up to 10% of the total heating demand, but this has not been proved. Other remarks are that inhabitants cannot repaint their wall after painting it with heat reflective paint, because the paint will lose its effectiveness. Also, no objects can be hanged on the wall because then the heat reflective effect of the paint is blocked.

Tests with heat reflective paint showed that surfaces with the paint had a lower surface temperature than other materials, but distribute heat more evenly (Wetering, 2017).

Figure 6.16: Heat reflective paint (ClimaCoating, 2020)

2) Radiant screen

Radiant screens can be used to block cold radiance caused by cold window surfaces. They prevent temperature asymmetry in a room and cold down-flows. Different options are available for radiant screens:

Curtains

Curtains are a simple method to reduce cold radiation from the windows at night (Figure 6.17). By closing curtains transmission losses are reduced and cold radiance can be blocked from the windows, which both reduce the heating demand. In summer, curtains can be closed during the day to minimize the incoming infrared solar radiation keeping the house cool.

Secondary double glazing

Secondary double glazing is a form of additional glazing on single- or double-glazed windows. This second glass sheet improves the U-value of the window, but also functions as a radiant screen (Figure 6.18).

Additional plexiglass panels

An additional plexiglass panel can also function as a radiant screen. Plexiglass can transmit visible light, while it reflects and blocks infrared radiation. By placing an additional plexiglass panel, the U-value of the window will be increased (Figure 6.18). It also forms a barrier from cold radiation from the windows. Plexiglass panels can be placed in the heating season to reduce transmission losses and block cold radiance from the windows. In summer, the plexiglass panels can be removed to minimize the chance of overheating (Build it Solar, 2009).

Figure 6.17: Curtains (own image)

Figure 6.18: Secondary glazing (CN Glass UK, n.d.)

Figure 6.19: Additional plexiglass panel (Build it Solar, 2009)

3) Ventilation grilles

Ventilation grills must be designed adequately to prevent cold down-flow, especially because low-temperature heating systems have difficulties in counteracting this (Myhren & Holmberg, 2007).

Ventilation grills designed for comfort

Ventilation grills designed for thermal comfort include wind-driven ventilation grills or ones that bend the airflow upwards to prevent cold drafts (Milieucentraal, n.d.). Figure 6.20 shows an example of a ventilation grill that bends the airflow upwards.

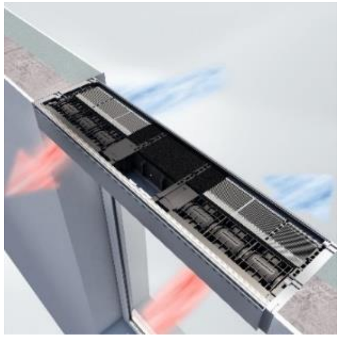
Figure 6.20: Ventilation gril that bends airflow upwards (Renson, n.d.)

Heat recovery ventilation grill

Using a heat recovery ventilation grill can be a solution for the living room to prevent cold drafts because the incoming air is preheated (Milieucentraal, n.d.). A disadvantage of heat recovery ventilation grills is that they are relatively expensive.

Figure 6.21 shows an example of a heat recovery ventilation grill developed by Schueco. This ventilation grill includes a demand-driven decentralized ventilation system with an inlet and outlet. In the ventilation grill, a heat recovery system is placed which preheats the incoming air with the outgoing air. The heat recovery can be up to 80%.

Figure 6.21: Heat recovery ventilation unit (Schueco, n.d.)



Ventilation radiator

Ventilation radiators can also prevent cold drafts, which is discussed in Section 6.2.

4) Reduce floor contact losses

As mentioned in Chapter 5, humans are sensitive to the cooling of their feet and ankles. Thus, it makes sense to provide a warm floor surface and minimize floor contact losses. This can be done with:

- providing a warmer floor surface with floor heating
- reducing floor contact losses by selecting a flooring material with a lower heat coefficient, such as carpet or wood instead of tiles

5) Interior design

The location of furniture in front or above radiators can minimize the heat transfer into the room (Myhren & Holmberg, 2008). This is only a problem with radiator heating and cannot be expected with floor heating. Problems can occur when:

- A table is placed in front or above the radiator. The heat output of the radiator is blocked in this way, which leads to a cold draft because cold air is not mixed with warm radiator air (Figure 6.22).
- A coach is placed in front of the radiator which blocks the radiant heat transfer into the room (Figure 6.23a)

These situations can lead to less radiant heat in the room and thus a lower operative temperature. A different placement of the furniture could be more optimal, such as:

- The placement of furniture 50 cm in front of radiators (Figure 6.23b)
- The placement of furniture next to the radiator (Figure 6.23c)

Figure 6.22: Table blocking radiator heat

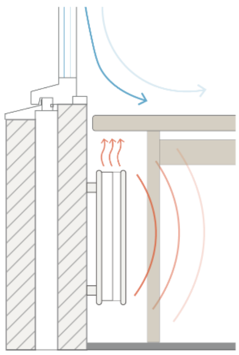
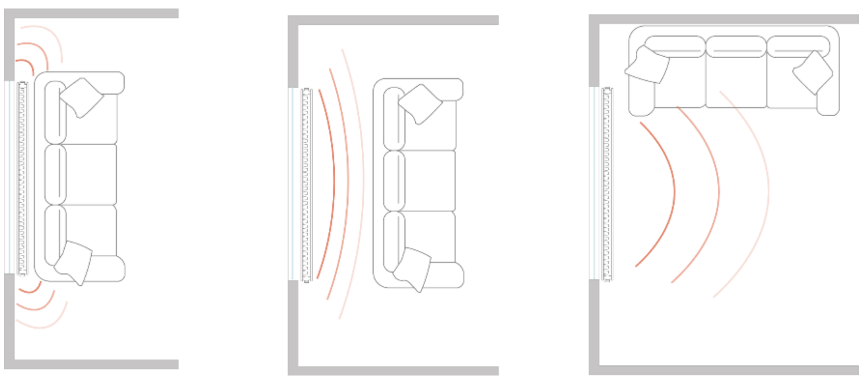


Figure 6.23: Placement of couch in room

a: blocking radiator *b: 50 cm in front of radiator* *c: next to radiator*



6) Infrared heating panel

An additional infrared heating panel can be a good solution when the heating capacity is occasionally not sufficient (Figure 6.24). The panel provides extra radiant heat into the room and functions as a local heating system which provides extra thermal comfort when needed.

Infrared heating consumes however a lot of energy, and when the heating panel is turned on more than necessary, the heating system works inefficiently. Important aspects to consider when placing an infrared heating panel are the location of the panel on the wall or ceiling and the size of the panel.

Figure 6.24: Infrared heating panel (Thackerey, 2015)

6.4 Combination between measures on the different scales

Different studies (Brand & Svendsen, 2013; Van Vliet et al., 2016; Wang et al., 2015) showed that a combination between measures on the building envelope and the installations showed good results regarding lowering the supply temperature, providing thermal comfort and costs. The influence of measures on the room scale has not been researched yet.

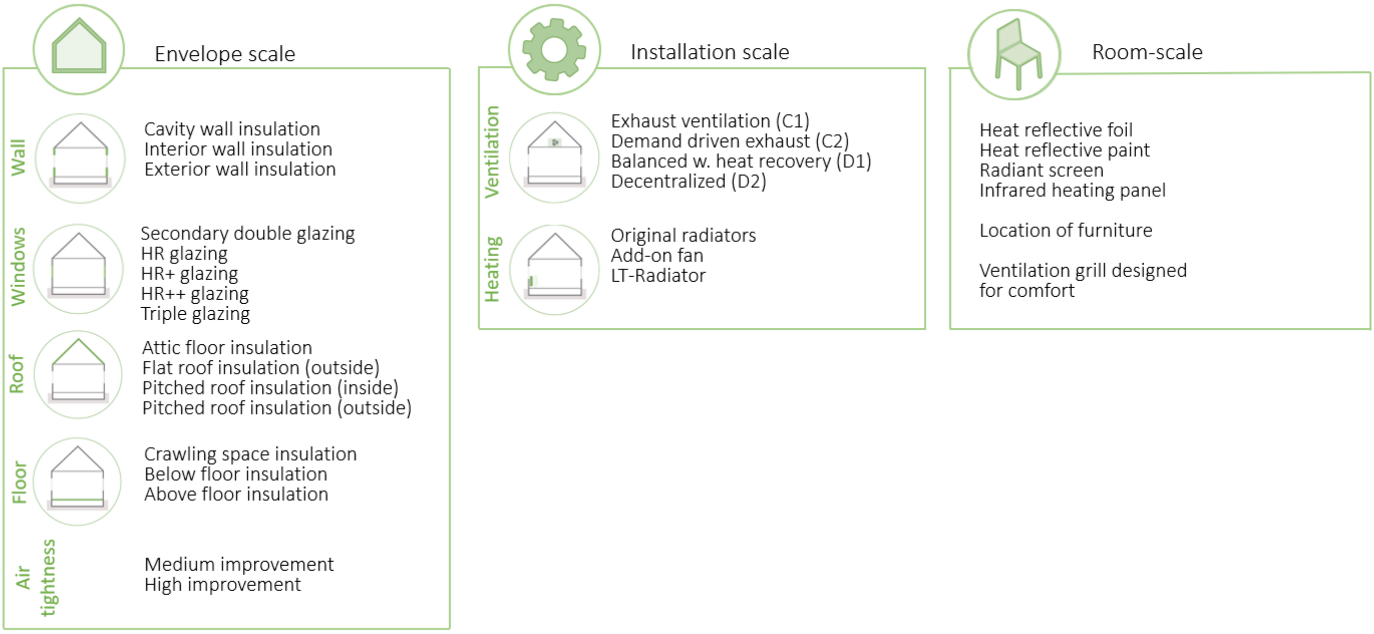
Brand & Svendsen (2013) concluded that both the effect of renovations and replacing radiators by LT-radiators was large on lowering the supply temperature for the heating system. Wang et al. (2015) suggested that a combination of measures to the building envelope (e.g., upgrading the facade, roof, and windows) and adding heat recovery to the current ventilation system led to a high reduction of the energy demand and improvement of thermal comfort.

Van Vliet et al. (2016) researched the effect of measures related to costs and comfort. Conclusions were that adding minimal insulation and replacing radiators with special LT-radiators was the most cost-effective method to provide thermal comfort with low-temperature heating. Thermal comfort can also be provided by applying different insulation measures and keeping the existing hydraulic radiator system, but this option would be more expensive.

6.5 Overview of available measures

Figure 6.25 provides an overview of available measures found in the literature study. Extra details have been added to several measures (such as: *Pitched roof insulation inside*) as a starting point for the cost analysis. Also, secondary double glazing is placed in the Envelope-scale.

Figure 6.25: Overview of available measures



Determining renovation concepts

Phase 2

7 Cost analysis

Because costs are an important aspect in renovations, and the budget of house owners is limited, a cost analysis was developed for the renovation measures mentioned in Chapter 6. The cost analysis includes the estimated costs, expected and calculated effect, and the cost-effectivity per renovation measure. The estimated costs include the Dutch sales tax (BTW) and labour costs. A description of the cost analysis is given in Section 7.1. Section 7.2 explains how the cost analysis was composed, and in Section 7.3 the most cost-effective measures are selected based on the cost analysis.

7.1 Cost analysis

The final cost analysis is shown in Table 7.2. The cost analysis includes all measures on the three scales mentioned in Chapter 6. In the cost analysis, the measures are more specified for example with a certain thicknesses. For all measures an expected effect, calculated effect, costs, and cost-effectivity are given.

7.2 Method

The cost analysis was set up with a different method for every part. Section 7.2.1 describes how the average costs for every measure are defined. In 7.2.2, the method of determining the effect of the cost analysis will be explained, for both the expected and calculated effect. The method to determine the cost-effectivity is described in 7.2.3.

7.2.1 Costs

Costs for every renovation measure were, depending on the renovation measure, calculated per m^2 or per dwelling. The used sources to determine the costs per renovation measure can be found in the *Cost analysis Excel file*, in the tabs per category. Sources included websites, bills for renovations, and other cost analyses. Used websites involved websites that inform house owners about expected costs for renovation measures, and webs shops that sell building materials. Also, bills for already performed renovations were used provided by the LT-Ready project from the TU Delft (2021), as well as a cost analysis provided by Arcadis (2020).

An average between the different sources was taken to determine the expected costs per measure. For building envelope scale, this also included an average for different types of insulating materials and finishing layers, for the building envelope. Some sources did not specify R_c-values for building envelope measures. In this case, a *general average* between these types of sources was calculated. This general average was also used in calculations for renovation measures with a specific R_c-value.

Table 7.1 shows the cost calculation for a cavity wall as an example.

Table 7.1: Cost calculation for cavity wall

1.1.a	Cavity wall insulation						€ 26,49		per m^2
				[min]		[max]		[gem]	Source:
	Websites	Not specified	€	13,75	€	20,00	€	16,88	Spouwmuurisolatie kosten - Takkenkamp Isolatie (takkenkamp-isolatie.nl)
		Mineral wool	€	25,00	€	26,67	€	25,83	Spouwmuurisolatie kosten - Takkenkamp Isolatie (takkenkamp-isolatie.nl)
		EPS parels	€	27,50	€	32,50	€	30,00	Spouwmuurisolatie kosten - Takkenkamp Isolatie (takkenkamp-isolatie.nl)
		Insulation foam	€	28,33	€	28,33	€	28,33	Spouwmuurisolatie kosten - Takkenkamp Isolatie (takkenkamp-isolatie.nl)
		Not specified	€	15,00	€	30,00	€	22,50	Muurisolatie plaatsen: mogelijke methodes en kosten per m2 (isolatiewaarde.eu)
	Cost analysis	Mineral wool	€	23,93	€	26,12	€	25,03	Cost analysis Arcadis
		EPS parels	€	27,67	€	29,66	€	28,66	Cost analysis Arcadis
		PUR	€	33,44	€	35,44	€	34,44	Cost analysis Arcadis
	Case study projects			[total]		[m^2]		[costs/m^2]	
	Schiestraat 18	EPS parels	€	993,00		34,84	€	28,50	Case study dwelling LT-Ready project
	Seringstraat 67	EPS parels	€	1.498,73		60,72	€	24,68	Case study dwelling LT-Ready project
	Average						€ 26,49		

Table 7.2: Cost analysis renovation measures on the three scales

Renovation measure	Expected effect				Calculated effect					Cost and cost effectiveness				
Building envelope scale										*Cost effectiveness*				
Transparant parts of facade	Local discomfort	Effect on heating demand	Reduce demand	Increase heat output	Old U-value	New U-value	ΔU	Saved heating demand	Saved gas usage	Costs	U-value	Heating demand	Saved gas usage	Payback period
					[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]	[W/m^2]	[m^3/m^2]	[€/m^2]	[ΔU/€]	[(W)/€]	[m^3/€]	[yrs/m^2]
Windows														
Secondary double glazing, *U = 1.3*	●○○	●○○	●○○	○○○	2,70	2,70	0,00	0,0	0,0	173	-	0,00	0,00	0
Double glazing, *U = 2.7*	●○○	●○○	●○○	○○○	2,70	2,70	0,00	0,0	0,0	115	-	0,00	0,00	0
HR glazing, *U = 1.9*	●○○	●●○	●○○	○○○	2,70	1,85	0,85	25,5	6,8	120	0,01	212,5	0,06	21,68
HR+ glazing, *U = 1.5*	●●○	●●○	●●○	○○○	2,70	1,45	1,25	37,5	10,0	137	0,01	274,22	0,07	16,80
HR++ glazing, *U = 1.1*	●●○	●●●	●●○	○○○	2,70	1,10	1,60	48,0	12,8	137	0,01	350,36	0,09	13,15
Triple glazing, *U = 0.7*	●●○	●●●	●●●	○○○	2,70	0,70	2,00	60,0	16,0	182	0,01	329,22	0,09	13,99
Window frame														
Plastic	●●●	○○○	○○○	○○○	The window frame needs to be replaced when the frame cannot support other glazing types.					566				
Wood	●●●	○○○	○○○	○○○						760				
Aluminium	●●●	○○○	○○○	○○○						833				
Closed parts of facade	Local comfort	Effect on heating demand	Reduce demand	Increase heat output	Old R-value	New R-value	ΔU	Saved heating demand	Saved gas usage	Costs	U-value	Heating demand	Gas usage	Payback period
					[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]	[W/m^2]	[m^3/m^2]	[€/m^2]	[ΔU/€]	[(W)/€]	[m^3/€]	[yrs/m^2]
Wall														
Cavity wall insulation, *extra Rd = 1.0*	●○○	●○○	●○○	○○○	0,41	1,41	1,10	33,1	8,8	27,55	0,04	1,20	0,32	2,54
Exterior wall insulation														
10 cm, extra Rd = 2.8	●●○	●●○	●●○	○○○	0,41	3,21	1,44	43,3	11,5	117,02	0,01	0,37	0,10	8,26
15 cm, extra Rd = 4.5	●●○	●●●	●●●	○○○	0,41	3,91	1,49	44,8	11,9	134,31	0,01	0,33	0,09	9,15
Interior wall insulation														
5 cm, extra Rd = 1.4	●○○	●○○	●○○	○○○	0,41	1,81	1,23	37,0	9,9	39,38	0,03	0,94	0,25	3,25
10 cm, extra Rd = 2.8	●○○	●●○	●●○	○○○	0,41	3,21	1,44	43,3	11,5	53,63	0,03	0,81	0,22	3,78
Roof														
Attic floor														
15 cm, extra Rd = 4.0	○○○	●●●	●●●	○○○	0,39	4,39	1,67	50,1	13,4	22	0,08	2,31	0,62	1,32
20 cm, extra Rd = 5.0	○○○	●●●	●●●	○○○	0,39	5,39	1,71	51,3	13,7	25	0,07	2,02	0,54	1,51
Flat roof, outside														
10 cm, extra Rd = 2.8	○○○				0,46	3,11	1,37	41,1	11,0	52	0,03	0,79	0,21	3,88
15 cm, extra Rd = 4.5	○○○	●●●	●●●	○○○	0,46	4,81	1,48	44,3	11,8	63	0,02	0,70	0,19	4,37
Pitched roof, inside														
10 cm, extra Rd = 2.8	○○○	●●○	●●○	○○○	0,51	3,16	1,23	36,9	9,8	63	0,02	0,59	0,16	5,20
15 cm, extra Rd = 4.5	○○○	●●●	●●●	○○○	0,51	4,86	1,33	40,0	10,7	89	0,01	0,45	0,12	6,80
Pitched roof, outside														
15 cm, extra Rd = 4.5	○○○	●●●	●●●	○○○	0,51	5,01	1,34	40,2	10,7	89	0,02	0,45	0,12	6,77
15 cm, extra Rd = 5.5	○○○	●●●	●●●	○○○	0,51	6,01	1,37	41,1	11,0	100	0,01	0,41	0,11	7,44
Floor insulation														
Crawling space	○○○	●●○	●●○	○○○	0,01	4,00	0,25	7,5	2,0	34	0,01	0,22	0,06	13,87
Top of ground floor														
4 cm, extra Rd = 1.8	●●○	●●○	●●○	○○○	0,50	2,30	0,81	24,3	6,5	74	0,01	0,33	0,09	9,37
8 cm, extra Rd = 3.5	●●○	●●○	●●○	○○○	0,50	4,00	0,96	28,7	7,7	77	0,01	0,38	0,10	8,14
Under ground floor														
10 cm, extra Rd = 3.5	●○○	●●○	●●○	○○○	0,50	4,00	0,96	28,7	7,7	40	0,02	0,72	0,19	4,21
10 cm, extra Rd = 4.5	●○○	●●●	●●●	○○○	0,50	5,00	1,00	30,0	8,0	41	0,02	0,73	0,19	4,19
Air tightness	Local comfort	Effect on heating demand	Reduce demand	Increase heat output	Old level	New level		Saved heating demand	Saved gas usage	Costs		Heating demand	Gas usage	Payback period
								[W/m^2]	[m^3/m^2]	[€ / dwelling]		[(W/m^2)/€]	[m^3/€]	[yrs/m^2]
Medium upgrade	●●○	●●○	●●○	○○○	603,40	301,7		301,70	80,45	447		0,674	0,180	4,53
Complete upgrade	●●●	●●●	●●●	○○○	603,40	150,85		452,55	120,68	1560		0,290	0,077	10,52
Building installation scale										*Cost effectiveness*				
Ventilation system	Local comfort	Effect on heating demand	Reduce demand	Increase heat output				Saved heating demand	Saved gas usage	Costs		Heating demand	Gas usage	Payback period
								[W]	[m^3]	[€]		[W/1k€]	[m^3/1k€]	[yrs/m^2]
					origineel	0,75 x bb		1833						
C.1: Mechanical exhaust	●○○	○○○	○○○	○○○	0,9 l / m2	70 m2		1100	293	2515		437,31	116,615	6,98
C.2: Mechanical exhaust, demand driven	●●○	●●○	●○○	○○○	aanname c1 is basis, c2, d e bgeven besparing			1466	391	4304		340,72	90,859	
														8,96
D: Balanced ventilation with heat recovery	●●●	●●●	●●●	○○○				1650	440	6123		269,43	71,849	11,33
E: Decentralized ventilation system with heat recovery	●●●	●●○	●●○	○○○	aanname: ventilatie is 0,75 x bouwbesluit			110	29	4835		22,75	6,066	134,20
Heating system	Local comfort	Effect on heating demand	Reduce demand	Increase heat output	Heat output	Increased output				Costs		Heat output		
					[W]	[W]				[€]		[extra W/€]		
Radiator heating														
Small radiator														
Original, e.g. small (0.4 m^2), type 33	○○○	○○○	○○○	○○○	731					0				
With add-on fan, increases heat output with 20%	●○○	●○○	○○○	●○○	877	146				66		2,23		
LT-Radiators		●●●	○○○	●●●	1300	569				528		1,08		
Large radiator														
Original radiator (0.85 m^2), type 33		○○○	○○○	●●○	1462					0				
With add-on fan, increases heat output with 20%	●●○	●○○	○○○	●○○	1754	292				197		1,49		
LT-Radiators	●●○	●●●	○○○	●●●	3405	1943				905		2,15		
Ventilation radiator														
Ventilation channel behind original radiator	●●●													
Floor heating					[W/m2]	[W]								
Small living room, 20 m^2	●○○	●●●	○○○	●●●	50	1000				897		0,00		
										Cost effectiveness				
Heat reflectance	Local comfort	Effect on heating demand	Reduce demand	Increase heat output			ΔU	Saved heating demand	Saved gas usage	Costs	U-value	Heating demand	Gas usage	
							[W/m^{2}K]	[W/m^2]	[m^3/m^2]	[€/m^2]	[ΔU/€]	[(W/m^2)/€]	[m^3/m^2/€]	
Heat reflective foil (behind radiators)	○○○	●○○	●○○	○○○			0,80	23,9	6,36	6	0,14	4,29	1,14	
Heat reflective paint	○○○	●○○	●○○	○○○			0,12	3,7	0,99	13	0,01	0,29	0,08	
Radiant screen	Local comfort	Effect on heating demand	Reduce demand	Increase heat output	Δ T_{RMT}	Δ Tair		Saved heating demand	Saved gas usage	Costs		Heating demand	Gas usage	
					[°C]	[°C]		[W]	[m^3]	[€/m^2]		[(W/m^2)/€]	[m^3/m^2/€]	
Curtains	●●○	●○○	●○○	○○○	0,83	-0,83		2,3	0,6	0		0	0	
Additional plexiglass panel	●●○	●●○	●●○	○○○	0,83	-0,83		2,3	0,6	62		0,037	0,010	
Window temperature from 10 to 15 °C, other surface temperatures 18 °C, T_{op} 20 °C														
Ventilation grills	Local comfort	Effect on heating demand	Reduce demand	Increase heat output						Costs				
										[€/m^2]				
Ventilation grill designed for comfort	●●●	○○○	○○○	○○○	Ventilation grills desigined for comfort can reduce cold drafts in a room, which reduces the chance for local discomfort. Ventilation grills are also included in					56				
Minimize floor contact losses	Local comfort	Effect on heating demand	Reduce demand	Increase heat output				Contact coefficient	Floor contact temperature	Costs				
								[Jm^{-2}K^{-1}s$^{-½}$]	[°C]	[€/m^2]				
Tiles, flagstones	○○○	○○○	○○○	○○○				1420	26,6	97				
Parquet flooring	●○○	○○○	○○○	○○○				520	30,2	88				
Laminate flooring	●○○	○○○	○○○	○○○	Different floor material can feel warmer o			475	30,5	33				
Carpet	●●○	○○○	○○○	○○○				123	33,5	48				
Carpet with carpet underlay	●●●	○○○	○○○	○○○				93	33,8	57				
Interior design	Local comfort	Effect on heating demand	Reduce demand	Increase heat output	Δ T_{RMT}	Δ Tair		Saved heating demand	Saved gas usage	Costs		Heating demand	Gas usage	
					[°C]	[°C]		[W]	[m^3]	[€/m^2]		[(W/m^2)/€]	[m^3/m^2/€]	
Furniture in front or above radiator					0,00	0,00		0,0	0,0	0		0	0	
Furniture placed at 50 cm of radiator					1,11	1,11		3,1	0,8	0		0	0	
Furniture next to radiator					2,22	2,22		6,2	1,6	0		0	0	
Radiator temperature 50 °C, window temperature from 10 °C, other surface temperatures 18 °C, T_{op} 20 °C														
Additional heating element	Local comfort	Effect on heating demand	Reduce demand	Increase heat output				Extra heating demand		Costs				
								[W]		[€/m^2]				
Infrared heating panel	●●●	○○○	○○○	○○○	1,50	1,50		167,6		168		1,00		

7.2.2 Expected and calculated effect

For every measure, an indication of the expected effect was given based on several discussions and conclusions from the literature study. The effect was also calculated for the improved U-value, saved heating demand, and gas usage to add more certainty.

Building envelope

The calculated effect for the building envelope was based on the improvement (ΔU-value) compared to the original situation. Formula 7.1 calculates the ΔU-value for windows and Formula 7.2. calculates the ΔU-value for closed parts of the building envelope. Ventilation system A is a form of natural ventilation.

$$\Delta U_{window} = U_{old} - U_{new} \qquad [W/m^2K] \qquad (7.1)$$

U_{old}	U-value original window	$[W/m^2K]$
U_{new}	U-value new window	$[W/m^2K]$

$$\Delta U_{envelope} = \frac{1}{R_{c,old}+R_{si}+R_{se}} - \frac{1}{R_{c,new}+R_{si}+R_{se}} \qquad [W/m^2K] \qquad (7.2)$$

$R_{c,old}$	Calculated R_c-value old situation	$[m^2K/W]$
$R_{c,new}$	Calculated R_c-value new situation	$[m^2K/W]$
R_{si}	Depends on building envelope part, see appendix D	$[m^2K/W]$
R_{se}	Depends on building envelope	$[m^2K/W]$

Based on the ΔU-value, the reduced heating demand and the annual gas savings per m^2 were calculated. Formula 7.3 calculates the reduced heating demand per m^2 for a stationary heat balance. The difference between the outdoor and indoor temperature is based on a very cold winter day with an indoor temperature of 19 °C and an outdoor temperature of -11°C.

$$\Delta Q_{trans} = \Delta U \cdot A \cdot (T_e - T_i) \qquad [W/m^2] \qquad (7.3)$$

A	1	$[m^2]$
$T_e - T_i$	30 °C (extreme winter condition)	[°C]

The saved gas usage per year was calculated with Formulas 7.4 and 7.5. Formula 7.4 calculates the reduced heat losses through transmission for a year in MJ per m^2. The average temperature difference (ΔT_{avg}) is based on the average indoor and outdoor temperature between October and April, respectively 19 and 6 °C. By dividing the heat losses through transmission with the caloric value of natural gas the saved gas usage can be calculated with Formula 7.5.

$$\Delta Q"_{trans} = \Delta U \cdot \Delta T_{avg} \cdot t_{heating\ season} \qquad [MJ/m^2] \qquad (7.4)$$

ΔT_{avg}	13 °C	[°C]
$t_{heating\ season}$	7 months = 210 days	
	$210 \cdot 24 \cdot 3600 = 18.1$ Ms	

$$Saved\ gas\ usage = \Delta Q"_{trans} \,/\, CV_{natural\ gas} \qquad [m^3/m^2] \qquad (7.5)$$

$CV_{natural\ gas}$	30.0	$[MJ/m^3]$

Ventilation and airtightness

The effect of replacing the ventilation system and improving the airtightness of the building is calculated with Formula 7.6. Results are compared to the ventilation or infiltration losses of the original situation. The renovation measures, like placing a ventilation system or improving the airtightness, determine the air change rate (nV). Chosen air change rates are shown in Table 7.3, of which the ventilation setpoints were based on Bouwbesluit regulations.

$$Q_{vent,inf} = \frac{\rho \times c \times nV \times (T_e - T_i)}{3600} \cdot A \qquad [W] \qquad (7.6)$$

ρ	1.200	[kg/m³]
c	1000	[J/kg.K]
nV	See Table 7.3	[m³/h/m²]
$T_e - T_i$	30 °C (extreme winter condition)	[°C]
A	Area of dwelling	[m²]

Table 7.3: Ventilation and infiltration setpoints

Ventilation			Infiltration	
	x Bouwbesluit (0.9 l/s/m²)	nV (m³/h/m²)		ACR/h
Original situation	0.75	2.43	Original situation	0.4
C1	1.00	3.24	Improved	0.2
C2	0.50	1.62	Highly improved	0.1
D1	0.30	0.97		

The saved gas usage per year was calculated with Formulas 7.7 and 7.8, which are rewritten formulas for ventilation and infiltration based on Formula 7.4 and 7.5.

$$Q"_{vent,inf} = \frac{\rho \times c \times nV \times \Delta T_{avg}}{3600} \cdot t \cdot A \qquad [W] \qquad (7.7)$$

ρ	1.200	[kg/m³]
c	1000	[J/kg.K]
nV	See Table 7.2	[m³/h/m²]
ΔT_{avg}	13 °C	[°C]
$t_{heating\ season}$	7 months = 210 days 210 · 24 · 3600 = 18.1 Ms	
A	Area of dwelling	[m²]

$$Saved\ gas\ usage = Q"_{vent,inf} / CV_{natural\ gas} \qquad [W] \qquad (7.8)$$

$CV_{natural\ gas}$	30.0	[MJ/m³]

Room scale

Various measures on the room-scale were determined of which the expected results are calculated with different methods. An overview of used methods per measure is given in Table 7.4.

Table 7.4: Methods to calculate effect for measures on room scale

Measure	Method
Heat reflectivity	Transmission calculations
Floor surface material	Contact temperature
Radiant screen Infrared heating panel Interior design	Calculated reduction of air temperature based on higher radiant temperature

Heat reflectivity

Literature provided the saved gas usage for heat reflectivity measures. Other effects were calculated using Formulas 7.3 and 7.4 based on the saved gas usage.

Floor surface material

Different floor surface materials can feel warmer or colder. The experienced temperature of the floor surface is the contact temperature *Tc*, which is calculated with Formula 7.9 (Klimapedia, 2013). To calculate the contact temperature, the contact coefficient of the finishing layer needs to be calculated with Formula 7.10.

$$T_C = \frac{b_{flooring\ material} T_{floor} + b_{skin} T_{skin}}{b_{flooring\ material} + b_{skin}} \quad [°C] \quad (7.9)$$

$b_{flooring\ material}$	Calculated with formula 7.10	
b_{skin}	1120	
T_{floor}	20	[°C]
T_{skin}	35	[°C]

$$b = \sqrt{\lambda \cdot \rho \cdot c} \quad (7.10)$$

λ	Heat conductivity of a material	[W/mK]
ρ	Densitiy of a material	[kg/m^3]
c	Specific heat of a material	[W/kgK]

The contact coefficient and contact temperature for different materials were calculated and are shown Table 7.5. Also the minimum floor temperature is provided for a comfortable floor surface. We can see that the contact temperature is higher for warm materials such as carpet, and lower for floor tiles.

Table 7.5: Contact temperature for different flooring materials

Flooring material	*Contact coefficient*	*Contact temperature [°C]*	*Minimum T_{floor} [1] [°C]*
Tiles, flagstones	1420	26.6	22.0
Parquet flooring	520	30.2	18.0
Laminate flooring	475	30.5	15.0
Carpet	123	33.5	-25.0
Carpet with carpet underlay	93	33.8	-25.0

1 Klimapedia. (2013). Tabellarium Warmte. Klimapedia.Nl.

Radiant screen, infrared heating panel and interior design

The effect of placing radiant screens, additional infrared heating panels, and changes to the interior design was calculated with the increased or reduced mean radiant temperature compared to the original situation. The effect of the mean radiant temperature on the operative temperature was determined, while keeping an indoor air temperature of 21 °C.

The mean radiant temperature T_{MRT} was calculated by using Formula 3.1 with the view factors φ and the surface temperatures. As an example, a room with the dimensions of 4 x 4 x 2 meters is used, with a window of 2 m^2 (Figure 7.1). The used surface temperatures are shown in Table 7.6. The view factor was calculated with the online calculation tools *C-157* and *C-159* provided by Thermalradiation.net (n.d.), which are the view factors for a seated person to horizontal and vertical surfaces. Results are shown in Table 7.7. We can see that adding a radiant screen and infrared heating panel increase the operative temperature, and the position of furniture also have an influence.

Figure 7.1: Room used for radiant temperature calculations

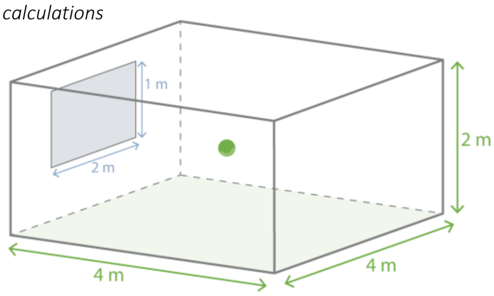


Table 7.6: Surface temperatures

Surface	Surface temperature [°C]
Wall (interior)	18
Wall (exterior)	16
Floor	18
Ceiling	18
Window	10
Radiator	50
Radiant screen	15
Infrared heating panel	90
Furniture	20

Table 7.7: Surface temperatures

	T_{MRT} [°C]	T_{air} [°C]	T_{op} [°C]
Original situation (without radiator)	17.27	21.00	18.9
Radiant screen for window	17.60	21.00	19.3
Additional infrared heating panel	18.77	21.00	19.9
Radiator on, not blocked	18.78	21.00	19.9
Furniture in front of radiator	17.67	21.00	19.3
Furniture in half front of radiator	16.56	21.00	18.8

7.2.3 Cost-effectivity

The cost-effectivity was calculated for measures on the building envelope and building installation scale by dividing the effect of the renovations measures with the costs (Formula 7.11). A higher number means a larger effect per euro. Calculating the cost-effectiveness of different renovation measure can form a base to select measures which have a large effect related to their required investment. The cost effectivity can be calculated for the ΔU, the reduced heating demand in W, and the saved gas usage. From these methods, using the reduced heating demand has the preference, because the effect of renovation measures over a year becomes visible. This can also be calculated with the saved gas usage, however, when using a lower supply temperature the switch can be made to altnerative, sustainable heating sources. Thus, calculating the cost-effectiveness with the saved gas usage seems less logical.

$$Cost\ effectivity_{trans,vent,inf} = \frac{\Delta U}{costs} = \frac{reduced\ heating\ demand}{costs} = \frac{saved\ gas\ usage}{costs} \qquad (7.11)$$

In: $[\Delta U/€]$ $\quad [(\frac{W}{m^2}.year\ )/€]$ $\quad [(m^3/m^2.year\ )/\ €]$

The payback period is another method to calculate cost effectiveness, and is inversely proportional with the cost effectiveness. It is calculated by comparing the saved gas usage with the gas price and total investment costs (Formula 7.12). The payback period can be used to determine the number of years in which the renovation measures pays itself back, and can be used as a selection criteria to select cost effective measures. Measures with short payback period are cost-effective.

$$Payback\ period = \frac{costs}{(Saved\ gas\ usage \times gas\ price)} \qquad [years] \qquad (7.12)$$

The cost effectivity of placing another heating system was calculated by comparing the extra heat output of this system with the heat output in the original situation (Formula 7.13). In this case, measures which have a high extra heat output compared to the investment costs are cost-effective.

$$Cost\ effectivity_{heating} = \frac{extra\ heat\ output}{costs} \qquad [W/€] \qquad (7.13)$$

7.3 Selected measures from cost analysis

A selection was made from the measures to set up different renovation concepts on their cost-effectivity. This because renovation concepts should not be too expensive keeping in mind the limited investment budget of house owners. Table 7.8 shows all measures with costs and payback period, including a motivation whether the measure was selected or not.

- Measures were mainly selected based on their cost-effectiveness by looking at the payback period. Measures with a relatively short payback period were then selected per category.

- It was assumed that window frames did not need to be replaced in case the window glazing was replaced because this is a very expensive measure.

- Measures such as exhaust ventilation (C1) and the current radiator system were selected because these are already present in most dwellings.

- Measures which have the potential to improve local comfort, such as an additional plexiglass panel, were selected to determine their effect on building or room-scale.
- Decentralized ventilation (D2) was not selected, because this system should be combined with another ventilation system. This would be too expensive for an affordable renovation. This system does however have high potential because not in every dwelling is space for a balanced ventilation system with heat recovery.

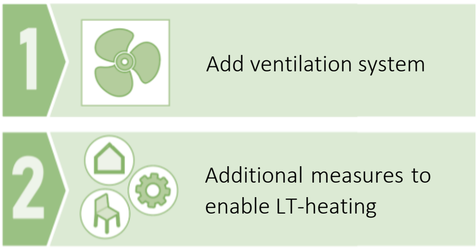
Table 7.8: Selected measures based on cost analysis

Measure	*Costs*	*Payback period*	*Selected*	*Motivation*
Building envelope-scale				
Window	[€/m²]			
Secondary double glazing, U = 1.3	€ 172,6	0,0	no	Less cost effective than other measures
Double glazing, U = 2.7	€ 115,0	0,0	no	Less cost effective than other measures
HR glazing, U = 1.9	€ 120,0	14,4	no	Less cost effective than other measures
HR+ glazing, U = 1.5	€ 136,8	11,1	no	Less cost effective than other measures
HR++ glazing, U = 1.1	€ 137,0	8,7	yes	Cost effective
Triple glazing, U = 0.7	€ 182,3	14,0	yes	Relative high insulation level
Window frame - plastic	€ 566,1	-	no	Does not need to be replaced
Window frame - wood	€ 759,7	-	no	Does not need to be replaced
Window frame - aluminium	€ 833,0	-	no	Does not need to be replaced
Wall	[€/m²]			
Cavity, extra Rd = 1.0	€ 27,6	2,4	yes	Cost effective
Exterior, 10 cm, extra Rd = 2.8	€ 117,0	8,3	yes	Cost effective
Exterior, 15 cm, extra Rd = 4.5	€ 134,3	9,2	no	Less cost effective than other measures
Interior, 5 cm, extra Rd = 1.4	€ 39,4	3,3	yes	Cost effective
Interior, 10 cm, extra Rd = 2.8	€ 53,6	3,8	yes	Cost effective
Roof	[€/m²]			
Attic, 15 cm, extra Rd = 4.0	€ 21,7	1,3	yes	Cost effective
Attic, 20 cm, extra Rd = 5.0	€ 25,4	1,5	no	Less cost effective than other measures
Flat roof, 10 cm, extra Rd = 2.8	€ 52,3	3,9	no	Not applicable for building type
Flat roof, 15 cm, extra Rd = 4.5	€ 63,4	4,4	no	Not applicable for building type
Pitched roof inside, 10 cm, extra Rd = 2.8	€ 62,8	5,2	yes	Cost effective
Pitched roof inside, 15 cm, extra Rd = 4.5	€ 89,0	6,8	no	Comparable with other measures, extensive measure
Pitched roof outside, 15 cm, extra Rd = 4.5	€ 89,0	6,8	no	Comparable with other measures, extensive measure
Pitched roof outside, 20 cm, extra Rd = 5.5	€ 100,3	7,4	no	Comparable with other measures, extensive measure
Ground floor	[€/m²]			
Crawling space, extra Rd = 4.0	€ 34,1	13,9	yes	Cost effective
Above ground floor, 4 cm, extra Rd = 1.8	€ 74,5	9,4	yes	Cost effective
Above ground floor, 8 cm, extra Rd = 3.5	€ 76,6	8,1	no	Comparable with other measures, thickness might cause problems
Below ground floor, 10 cm, extra Rd = 3.5	€ 39,6	4,2	yes	Cost effective

Below ground floor, 15 cm, extra Rd = 4.5	€ 41,2	4,2	yes	Cost effective
Air tightness	[€/dwelling]			
Medium upgrade	€447	9,2	yes	Cost effective
Complete upgrade	€1.560	16,1	no	Less cost effective than other measures
Building installation scale				
Ventilation	[€/dwelling]			
C.1: Mechanical exhaust	€ 2.515	-16,7	yes	Already present in many dwellings
C.2: Mechanical exhaust, demand driven	€ 4.304	28,5	yes	Cost effective
D.1: Balanced ventilation with heat recovery	€ 6.123	20,7	yes	Cost effective
D.2: Decentralized ventilation system with heat recovery	€ 4.835	16,0	no	Too expensive combined if also an additional ventilation system has to be placed
Heating	[€/unit]			
Original heating system	€ 0		yes	Already present in dwelling
Add-on fans (increase heating capacity with 20%)	€ 66		yes	Cost effective
LT-radiator (0.4 m2)	€ 528		yes	Cost effective
Room-scale				
Heat reflectivity	[€/m^2]			
Heat reflective foil (behind radiators)	€ 6	0,7	yes	Potential to improve local comfort
Heat reflective paint	€ 13	10,6	yes	Potential to improve local comfort
Radiant screen	[€/m^2]			
Curtains	€ 0		no	Already present in dwellings
Additional plexiglass panel	€ 62		yes	Potential to improve local comfort
Ventilation grill	[€/unit]			
Ventilation grill designed for comfort	€ 56		no	Not tested
Flooring material	[€/m^2]			
Tiles, flagstones	€ 97		no	Not tested
Parquet flooring	€ 88		no	Not tested
Laminate flooring	€ 33		no	Not tested
Carpet	€ 48		no	Not tested
Carpet with carpet underlay	€ 57		no	Not tested
Interior design				
Furniture in front or above radiator	€ 0		yes	Potential to improve local comfort
Furniture placed at 50 cm of radiator	€ 0		yes	Potential to improve local comfort
Furniture next to radiator	€ 0		yes	Potential to improve local comfort
Additional heating	[€/unit]			
Infrared heating panel	€ 168		no	Not tested

8 Renovation concepts

To find out to which extent renovations are needed, different renovation concepts were simulated to get an overview of the required renovation measures to provide thermal comfort with low-temperature heating. The renovation concepts were set up based on the following aspects:



1) Add ventilation system

The ventilation system is often replaced during a renovation because the current system does not meet the regulations for ventilation (Livios, 2019). Replacing the ventilation system can provide better indoor air quality, and, depending on the type, lead to a higher or lower energy demand. Mechanical exhaust ventilation C1 is the cheapest ventilation system but also has the highest ventilation losses. Demand-driven mechanical exhaust ventilation C2 and balanced ventilation with heat recovery D1 are more expensive but also reduce the ventilation losses.

2) Add additional renovation measures to enable low-temperature heating

Additional renovation measures are required to compensate for (additional) ventilation losses, as well as for the lower heating capacity of the radiators when using a lower supply temperature. The selected renovation measures should reduce the energy demand of the building, increase the heat output of the heating system, or both, to enable lower supply temperatures and providing thermal comfort (Brand & Svendsen, 2013; Hesaraki et al., 2015).

3) The investment budget

The majority of the house owners have an available budget for a renovation up to €5.000. A smaller share has a budget of up to €15.000 (Ipsos, 2019; Tertium, 2015). Thus, the selected measures for the renovation concepts should be within this budget.

Testing renovation concepts

Phase 3

9 Case study building

The renovation concepts were tested on a case study dwelling to determine their effect on thermal comfort with low-temperature heating. The selected case study dwelling is a terraced house that currently takes part in the LT-Ready research project by the TU Delft (2021). Motivations to select this dwelling were that the terraced housing type represents a large part of the Dutch Building stock, which is further discussed in Appendix A, and different data was already available from the research project. Section 9.1 describes the architectural layout of the case study dwelling, and Section 9.2 the current heating system of the dwelling.

9.1 Architectural layout

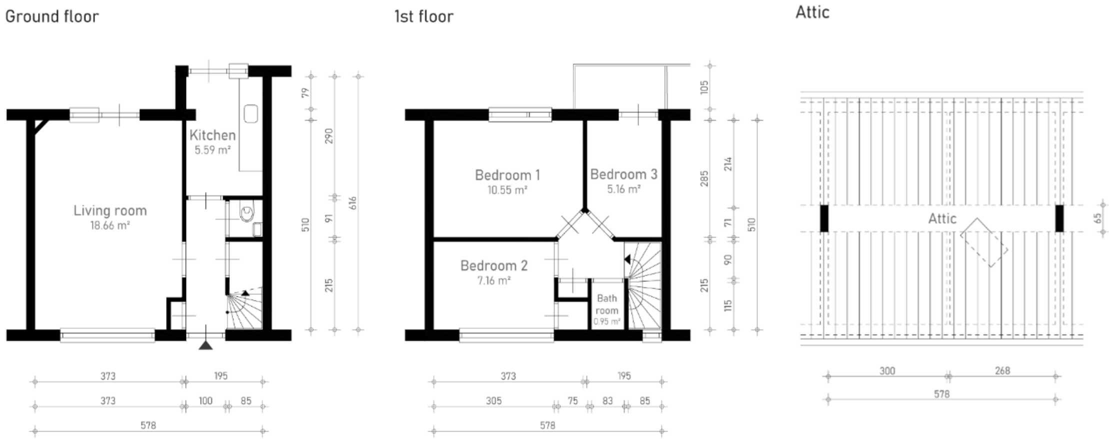
A general description of the case study dwelling is provided in Section 9.1.1. The original drawings of the dwelling are provided in Section 9.1.2, and Section 9.1.3 presents the performed renovation measures.

9.1.1 General description

The case study is terraced housing, shown in Figure 9.1. The dwelling is located in Amersfoort and was built in 1938 (Kadaster, n.d.). The dwelling has a north-south orientation with a shift of 13°. Figure 9.2 shows the floor plans of the building, which has 2 floors and an attic. The living room, kitchen, and toilet are located on the ground floor. The first floor contains three bedrooms and a bathroom, the attic on the second floor is used as storage. The dwelling has a total area of 60.9 m^2.

Figure 9.1: Case study dwelling

Figure 9.2: Floor plans



The dwelling has a window to wall ratio of 19.4%. The elevations are shown in Figure 9.3, on which the windows and doors are visible. The dimensions of the windows and doors are given in Table 9.1.

Figure 9.3: Elevations

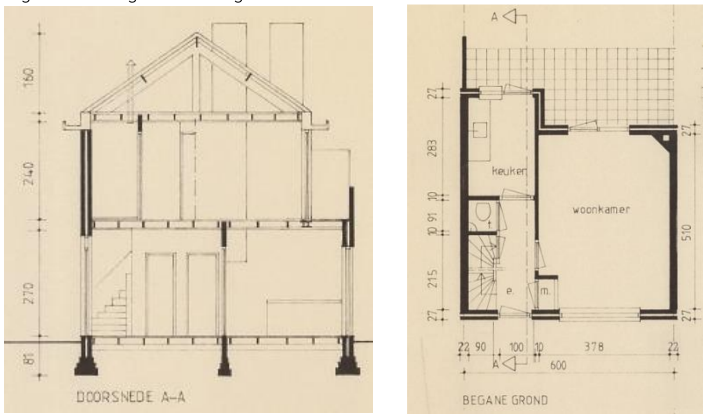
Table 9.1: Dimensions of windows and doors

Front façade		
Ground floor	2.27 x 1.48	3.36 m^2
1st floor	2.18 x 1.15	2.51 m^2
	0.50 x 1.15	0.58 m^2
Door	0.95 x 2.20	2.09 m^2
Rear façade		
Ground floor	0.63 x 1.52	0.96 m^2
1st floor	1.71 x 1.15	1.97 m^2
	0.50 x 0.62	0.31 m^2
Door kitchen	0.90 x 2.20	1.98 m^2
Door living	1.56 x 2.20	3.43 m^2
Door bedroom 3	0.83 x 2.20	1.74 m^2
Total window area		18.93 m^2
Exterior envelope area		97.37 m^2
Window to wall ratio		19.4%

9.1.2 Original situation

Typical drawings of the original situation of the dwelling are shown in Figure 9.4. The dwelling has cavity walls with a cavity of 7 centimetres. The separation walls between dwellings have a cavity of 2 centimetres. All floors and the roof originally had a wood-construction, and the dwelling had in its original state no additional insulation.

Figure 9.4: Original drawings



9.1.3 Renovated situation

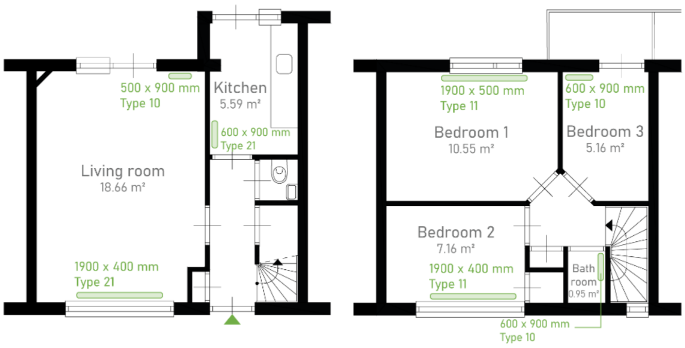
The original glazing and window frame have been replaced with new window frames with HR++ glazing. An additional renovation was performed in 2020. The following renovation measures have been caried out:

- Balanced ventilation with heat recovery
- Improved air tightness
- Cavity wall insulation with Airofill - The dwelling was a test location for a new type of insulation. The renovation process is shown in the following video: [Takkenkamp isolatie - YouTube]
- Roof insulation from inside
- Floor insulation with EPS pearls
- New front and back door

9.2 Heating system

The dwelling is currently heated with radiators placed in different rooms and a natural gas boiler placed in the attic. Figure 9.5 shows the locations of the radiators, including their dimensions and type. The heating capacity for different supply temperatures was calculated with Formula 5.9 per radiator, of which the results are Figure 9.6. As already mentioned in Chapter 5, lowering the supply temperature decreases the heating capacity of the radiator.

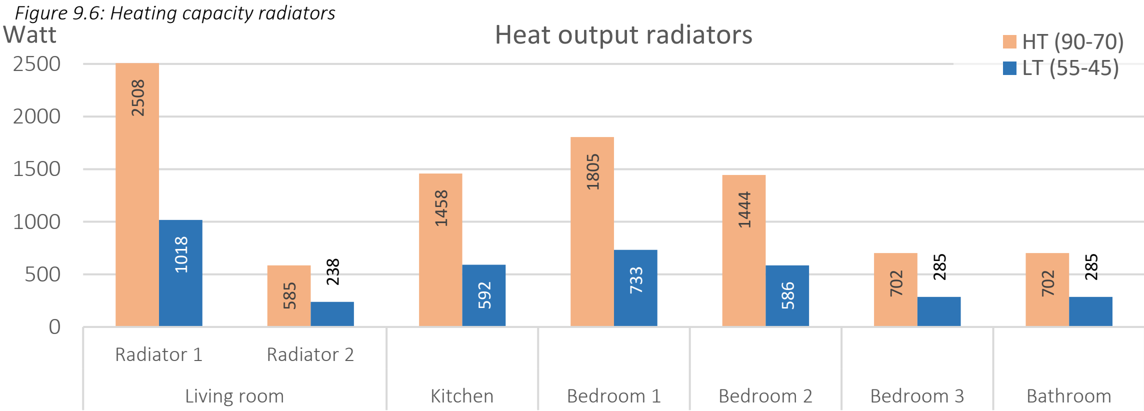
Figure 9.5: Radiators



Heating schedule

Occupants provided their heating schedule in conducted interviews for the LT-Ready project. The dwelling is usually heated between 9:00 and 13:00 at 20 °C, and then lowered to 18 °C. All rooms usually are heated except bedroom 3 which is usually not heated.

Figure 9.6: Heating capacity radiators



10 Testing method: dynamic simulation software

To determine the energy performance and thermal comfort of a building, dynamic simulation software is preferred over a steady state simulation. Reasons for this are that dynamic simulation takes the outdoor environment that varies over time into account, as well as the heat transfer from surfaces surrounding a zone, so heat transfer due to dynamic behaviour.

Section 10.1 discusses the advantages and disadvantages of dynamic simulation software, as well as the different types of software that can be used. Section 10.2 dives deeper into the used software: DesignBuilder. It provides general information about the software, the used workflow, and modelling low-temperature heating.

10.1 Dynamic simulation software

Using dynamic simulation software has advantages and disadvantages, which are discussed in section 10.1.1. An overview of different types of dynamic simulation software is given in 10.1.2.

10.1.1 Experienced advantages and disadvantages of dynamic simulation software

Dynamic simulation software has both advantages and disadvantages, which both have been experienced in the simulation process. In general, advantages of dynamic simulation software include:

- The effect of renovation measures can be studied without actually building it.
- Results can be more accurate compared to a stationary model.
- It takes the outdoor environment into account that varies over time because the software works with weather files per year. This gives possibilities to carry out detailed simulations for a longer period, e.g., an hourly simulation for a specific year.
- It takes the heating up period of a building into account.

Dynamic simulation software also has disadvantages, which should be kept in mind when interpreting the results of simulations as well as the final results. Some disadvantages are:

- It can be time-consuming to set up and calibrate the model.
- It can be difficult to understand the simulation results.
- A lot of input is required for a simulation model in the case of building energy and comfort performance, for example, the U-value of the surfaces but also the ventilation, infiltration, heating, and internal gains setpoints. This all is an interpretation by the person who set up the model and can thus have **a large influence on the result and cause discrepancies**.

10.1.2 Types of dynamic simulation software

Different types of dynamic simulation software are available for building energy and comfort simulation. Table 10.1 shows some examples of software, including authors that used this in their research. The DesignBuilder software was used for the dynamic simulations for this graduation project.

Table 10.1: Overview of dynamic simulation software used in literature

Dynamic simulation software	Used by:
TRNSYS	Jansen (2013) Filgueira Luaces (2020)
DesignBuilder	Konstantinou (2015)
IDA ICE	Wang et al., (2015) Østergaard (2018)

10.2 DesignBuilder

Section 10.2.1 provides general information about DesignBuilder. The used workflow for the simulations is described in Section 10.2.2, and the method to simulate low-temperature heating in Section 10.2.3.

10.2.1 General information

DesignBuilder is a graphical interface for the simulation engine EnergyPlus™ and is mainly used for energy, comfort, and daylight calculations. It also provides options for CFD modelling. The combination of these were the main reason to select this simulation software.

The simulation model is set up with 3D modelling for the entire building. The program includes a large database including materials, building envelope types, HVAC systems, and occupancy-related functions. The final DesignBuilder model is translated to a *.idf-file* for the EnergyPlusTM simulation, from which the output is load back into DesignBuilder and translated to graphs.

DesignBuilder makes use of a hierarchy of data transfer and uses different levels: Location, Building, Block, and Zone (Table 10.2). When change is made on a higher level, it applies to all sub-levels. Changes to the model made at the building level will directly apply to all zones and individual surfaces. An exception applies when specific changes were already made at zone or surface level; in this case, changes on a higher level will not apply.

Table 10.2: Hierarchy of data transfer

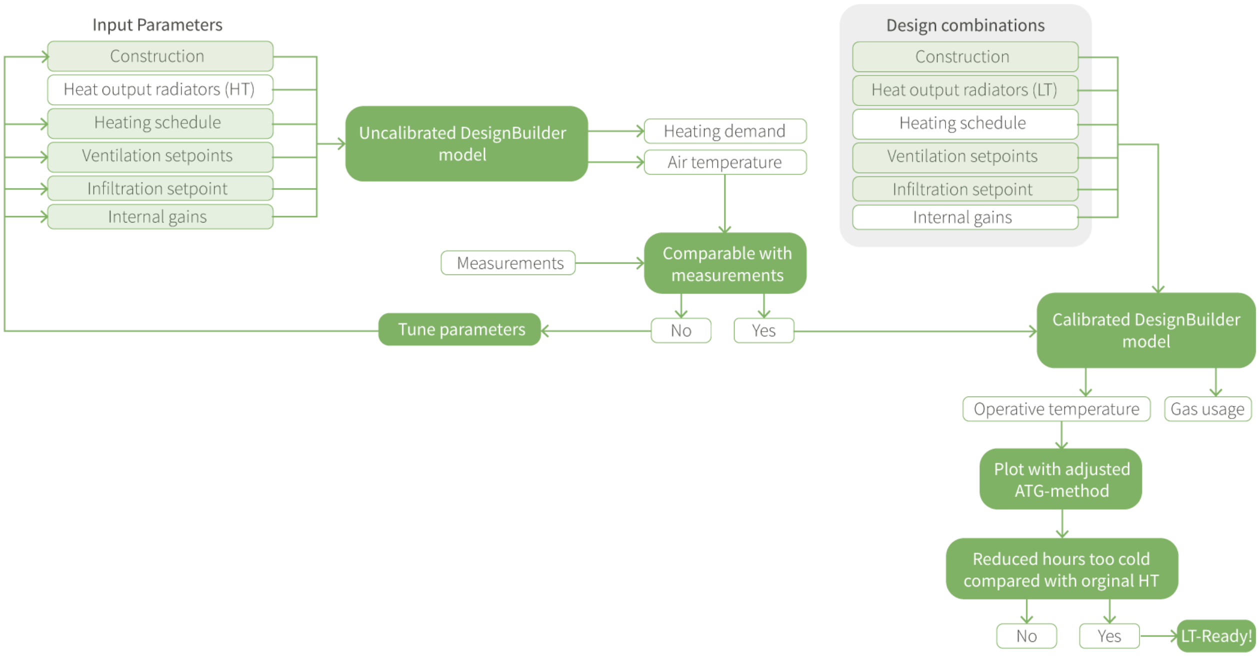
> Location	Location data, orientation, weather file
> Building	Geometry of building
> Block	Floor, form together the entire building
> Zone	Internal divisions to form spaces
> Surface	Individual surfaces that surround a zone

10.2.2 Workflow for DesignBuilder

The used workflow to set up the DesignBuilder model and perform simulations is shown in Figure 10.1. The workflow consisted of two different phases:

1) Setting up the base model
   In the first phase, the base model was set up on location data, geometry, construction data, and HVAC settings. The model is also calibrated with measurements of the gas usage and air temperature in the living room.
2) Testing phase for renovation combinations
   After calibrating the model, different renovation combinations were applied to the base model. The combinations were simulated by changing the construction data, heating capacity, ventilation rate, and infiltration rate. Results were tested with the ATG-method combined with specific setpoints for dwelling, as described in Chapter 3.

Figure 10.1: Workflow DesignBuilder model and simulations



Detailed HVAC

Detailed HVAC system models use different templates for heating, cooling, and ventilation and are connected with loops to specific groups or zones. One template is a radiator component, which requires input for the heating capacity and the water temperature. Figure 10.2 shows a loop used in the details HVAC mode including the radiator template. The detailed HVAC mode has more freedom compared to the simple HVAC mode. A more specific input can be given, such as the supply temperature of the heating system, which can help with comparing high- with low-temperature heating.

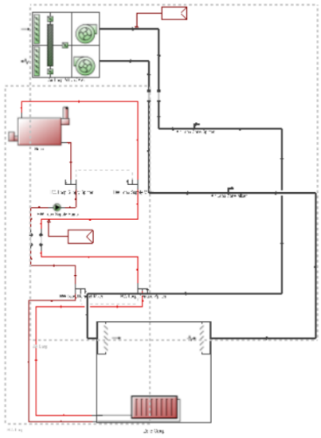


Figure 10.2: Detailed HVAC

The decision to not use detailed HVAC was made because of inaccuracies in the result that were difficult to explain. Also, combining different ventilation templates with radiator templates was also difficult.

Simple HVAC

With the Simple HVAC method also templates can be selected according to the heating and ventilation type. The template *“Radiator heating, HW boiler, Mechanical vent supply + extract”* was selected to simulate low-temperature heating with the current radiators. Different setpoints for this template are shown in Table 10.3.

Simulation in EnergyPlusTM is performed with ‘High Temp Radiant System’. This can however also be used for low-temperature heating since only the heat output of the heating system is lower.

Table 10.3: Setpoints template “Radiator heating, HW boiler, Mechanical vent supply + extract”

HVAC	Setpoints:
Mechanical ventilation	Air Change Rate outside air Ventilation schedule
Heating	COP Heating capacity Heating type including radiant fraction Heating schedule

11 Dynamic simulation of case study dwelling

Different inputs are required to determine the thermal performance of a building with simulation software, such as information about the location and climate, the size and geometry of the building, construction and HVAC data, and the function of the building. This chapter describes the input data of the simulation model and its output.

Section 11.1 provides information about the location data, where Section 11.2 explains the setup of the geometry and zones. Section 11.3 describes the model for the dwelling's renovated situation, the calibration of the model with measurements, and additional validation of the model. After calibration, the model input was changed to the original situation, which formed the base model for testing the different renovation concepts. This input is described in Section 11.4. Section 11.5 discusses the results on the energy demand for both high- and low-temperature heating in the original and renovated situation.

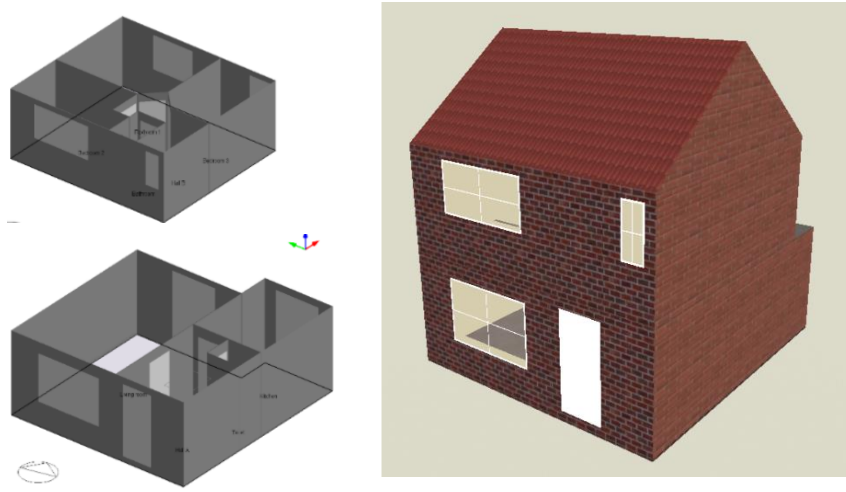
11.1 Location data

Every simulation uses the same location data. The dwelling is located in Amersfoort, Utrecht. The closest weather station is located at a distance of 16 kilometres, the KNMI weather station De Bilt- Utrecht (52,10°, 5,18°). The dwelling is measured for the period of 10 November to 31 December 2020 for the air temperature and gas usage. For these reasons, the weather data of De Bilt for the year 2020 was used. The dwelling has a site orientation of 283°.

11.2 Geometry and zones

Every simulation uses the same geometry and zone setup, which were modelled using the interface of DesignBuilder with every room as a separate zone (Figure 11.1). The decision to simulate a multi-zone dwelling was because every room has a different radiator and heating capacity. Doors and windows were modelled according to their sizes, as well as internal doors to simulate a realistic airflow between the zones. Also, a void at the location of the stairs was modelled between the ground and first floor.

Figure 11.1: Modelled geometry in DesignBuilder



11.3 Simulation model renovated situation

The input settings used for the renovated situation were different than for the inputs for the original situation. The current, renovated situation formed the base for the calibration. The input parameters were the construction data, heating and ventilation settings, infiltration rate, and internal gains, which are described in Section 11.3.1. An overview of the calibration is given in 11.3.2, and additional validations of the simulation model in 11.3.3.

11.3.1 Input parameters

This section provides an overview of the used input parameters to set up the model. An overview of all input parameters per zone is shown in Table 11.1., and is followed by a description of the different input parameters.

Table 11.1: Overview of input parameters per zone

		Living room	Kitchen	Toilet	Hall A	Bedroom 1	Bedroom 2	Bedroom 3	Bathroom	Hall B
Zone type		Standard, conditioned	Standard, conditioned	Standard, conditioned	Standard, conditioned	Standard, conditioned	Standard, conditioned	Standard, conditioned	Standard, conditioned	Standard, conditioned
Area	[m^2]	18.40	6.37	0.85	6.09	11.41	6.59	6.02	1.13	2.90
Height	[m]	2.45	2.45	2.45	2.45	2.25	2.25	2.25	2.25	2.25
Volume	[m^3]	44.84	15.52	2.06	14.85	25.54	14.76	13.48	2.54	8.48
Heating										
Heating on		yes	yes	no	no	yes	yes	no	yes	no
Heat output HT	[W]	3093	1458	-	-	1805	1444	702	702	-
Heating schedule	[h]	8-12	8-12	-	-	8-12	8-12	-	8-12	-
Heating setpoint	[°C]	20	20	-	-	20	20	-	20	-
Heating setback	[°C]	18	18	-	-	18	18	-	18	-
Ventilation										
Ventilation rate	[dm^3/s]	28.0				20.6				
Air change rate	[1/h]	0.385				0.361				
Air tightness										
Infiltration rate	[1/h]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Internal gains	[W/m^2]	4.90								
Schedule		7-22, 1 22-7, 0.5								

Construction data

The construction input is based on the performed renovation measures mentioned in Chapter 9. The data includes the build-up of the building surfaces, consisting of different layers, and results in a calculated R_c- and U-value (Table 11.2). A detailed overview of all layers can be found in Appendix E.

Table 11.2: Surface layers and properties

Renovated situation		R_c-value [m^{2}K/W]	U-value [W/m^{2}K]
Wall	Cavity wall with Airofill	2.16	0.46
	Interior wall	0.42	2.36
	Separation wall	0.71	1.40
Floor	Ground floor	3.63	0.28
	Separation floor	0.64	1.57
Roof	Insulated roof	4.50	0.22
Window	HR++ glazing	-	1.10

Ventilation setpoints

The used ventilation setpoints (Table 11.3) are based on the Bouwbesluit regulations, determining the total ventilation demand per floor and equally distribute the ventilation demand per m^2. This does not correspond with the actual situation, in which air can flow from one room to another room. The decision to calculate the ventilation demand per m^2 per floor, and not modelling the airflow with separate inlets and outlets, was made because it is difficult to model this airflow and is outside the scope of this research.

Table 11.3: Ventilation setpoints

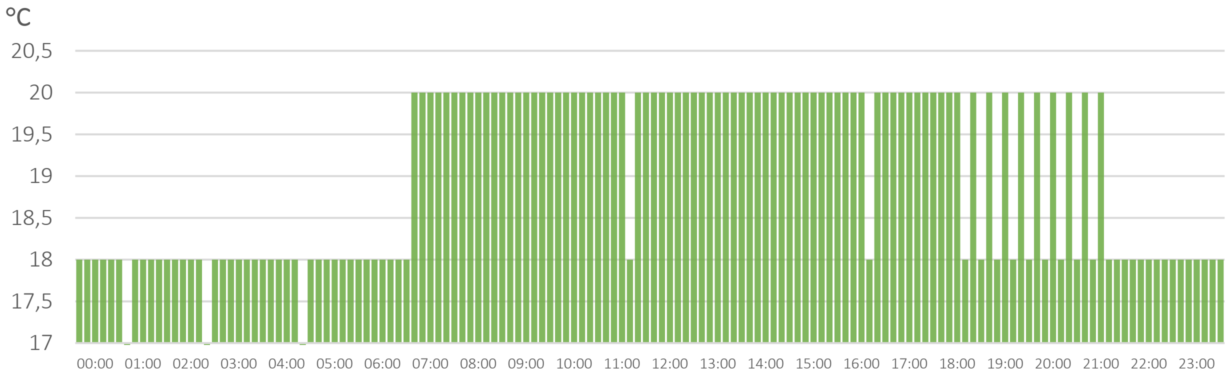
	Required ventilation demand	Total ventilation demand	Air Change Rate	Including heat recovery (x 0.30)
Ground floor				
Kitchen	21.0 dm^3/s	28.0 dm^3/s	1.28	0.385
Toilet	7.0 dm^3/s			
Living room	16.9 dm^3/s			
First floor				
Bedroom 1	9.5 dm^3/s	20.6 dm^3/s	1.21	0.361
Bedroom 2	6.4 dm^3/s			
Bedroom 3	4.6 dm^3/s			
Bathroom	14.0 dm^3/s			

The dwelling is naturally ventilated when the indoor air temperature reaches 21.5 °C by opening windows in the room. The crawl space is always ventilated with an air change rate of 0.5.

Heating

The heating is turned on or off per zone depending on the presence of a radiator in the room. The heating in bedroom 3 is turned off for the calibration of the model with the gas usage. Other inputs were the heating capacity, radiant fraction, and distribution. The radiant fraction of the heating is set at 0.4, and the radiant distribution at equal. The heating schedule was developed based on information provided by the occupants and was adjusted during the calibration of the model with the air temperature. This resulted in the final heating schedule shown in Figure 11.2.

Figure 11.2: Heating schedule



Infiltration setpoint

The air tightness of the building was improved during the renovation, and thus an Air Change Rate of 0.2 was chosen as infiltration setpoint.

Internal gains

Internal gains are based on the occupancy of the dwelling and are different for every zone. However, to minimize the chance of a wrong assumption and an inaccuracy of the model, a simple occupancy schedule was developed based on the NTA 8800 calculation for internal gains. This resulted in 4.63 W/m^2, which was changed to 4.50 W/m^2 after calibration of the simulation model. A schedule was used for the difference during the day and night, using 100% of the setpoint between 07:00 and 22:00, and using 50% of the setpoint between 22:00 and 07:00.

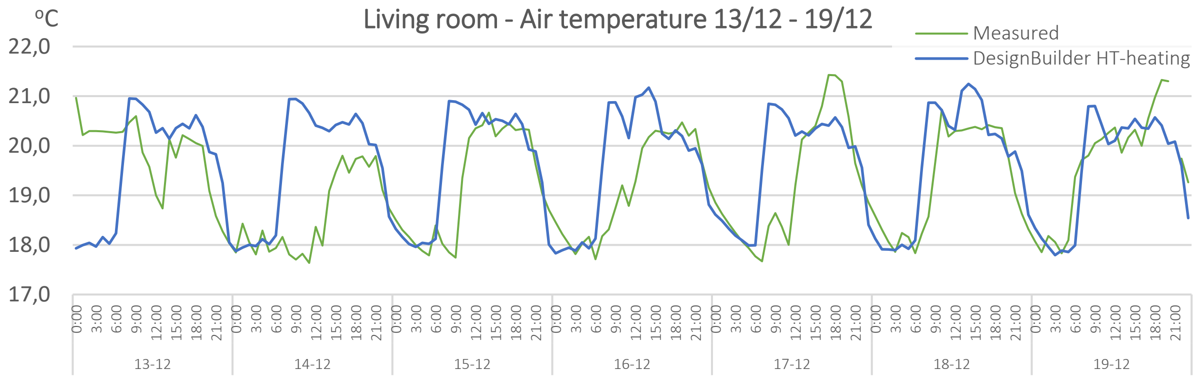
11.3.2 Calibration of the simulation model

The simulation model was calibrated with measurements of the gas usage of the dwelling, and air temperature inside the living room. The air temperature was measured in the period between 18 November and 20 December; the gas usage in the period from 10 November to 31 December.

Calibration of the air temperature in the living room

The living room was calibrated with the measured air temperature. A week with a similar temperature progression for multiple days was selected as a reference, which was the week from Monday 13 December to Sunday 19 December. Results for measurements and calibration are presented in Figure 11.3.

Figure 11.3: Calibration air temperature



Calibration of the gas usage for the entire dwelling

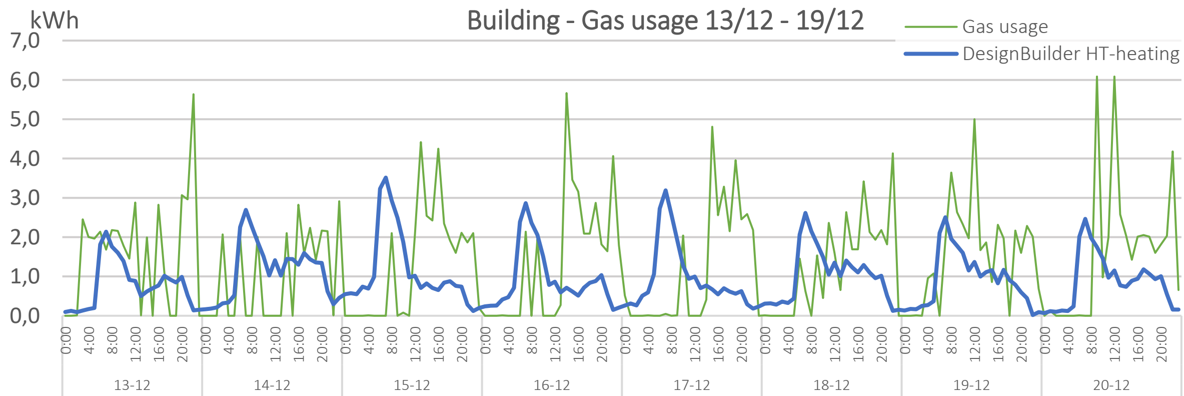
The gas usage of the dwelling was calibrated with measurements of the gas usage. These measurements included both the gas usage for heating as domestic hot water. Therefore, the total number was multiplied by the share that is used for heating, i.e., 72.7% of the total overall energy usage (Majcen, 2015). This number was compared with the heating demand derived from DesignBuilder in Table 11.3. After calibration, the DesignBuilder model is slightly higher than the measurements.

An additional comparison was made for the same week selected for air temperature calibration (Figure 11.4). We can see that the peak power in gas usages is smaller in DesignBuilder. An explanation for this can be that domestic hot water usage, such as showering, is not taken into account in these comparisons.

Table 11.3: Calibration gas usage

Measured				DesignBuilder		
Total	1846.0	kWh				
Heating	1342.0	kWh	x 72.7%, based on Majcen (2015)	Heating	1382.5	kWh
	22.0	kWh/m²			22.7	kWh/m²

Figure 11.4: Calibration gas usage



11.4 Additional validation of model

Besides the calibration, the model was additionally validated with different simulations to check the behaviour of building simulation software. The effect of different simulations was compared with the week of 1 to 7 December.

Figure 11.5 shows the results of a simulation that was carried out to determine the effect of the ventilation-, infiltration-, heating- and internal gains-setpoints to see if their performance behaved normally. First, a situation with all setpoints turned off was simulated as a baseline. Then the situation without windows was simulated, which shows the expected result of a more evenly distributed temperature during the week. Turning the infiltration- and ventilation setpoints on gives a slightly lower air temperature compared to the original situation, where the internal gains provide a slightly higher indoor temperature.

The results behave as expected. When only the heating is turned on, the heating schedule becomes visible in the temperature. Having all setpoints on gives a temperature which is slightly lower than when only the heating is turned on. This can be explained with the ventilation- and infiltration losses, and internal gains.

Figure 11.5: Effect of different setpoints

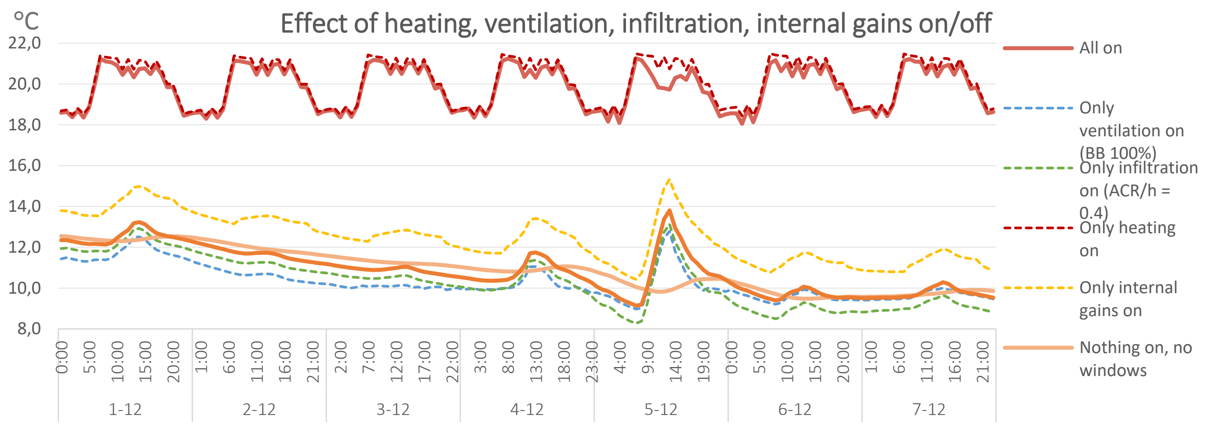
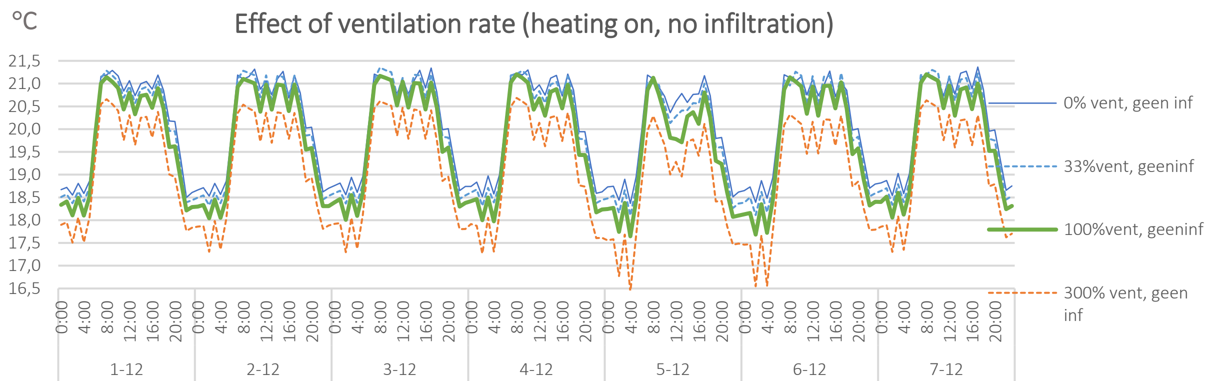


Figure 11.6 shows the effect of the ventilation rate on the air temperature when the heating is switched on. 100% ventilation is based on the ventilation demand provided by the Bouwbesluit. Results show that increasing the ventilation rate leads to a lower indoor temperature.

Figure 11.6: Simulations with different ventilation rates



11.5 DesignBuilder model original situation

After calibrating and validating the simulation model for the renovated situation, construction-, ventilation-, and infiltration-setpoints were changed to simulate the original dwelling. The construction data was changed to the original situation based on the original drawings presented in Section 9.1.2. Also, the assumption was made that the current ventilation demand did not meet the Bouwbesluit requirements. Thus, the chosen ventilation setpoints were calculated by multiplying the ventilation demand from the Bouwbesluit with 0.75. The heating and internal gains setpoints were not changed. An overview of all setpoints for the original situation is shown in Table 11.4. All setpoints for the original situation are shown in Table 11.4, with changes highlighted in green.

Table 11.4: Changed setpoints for original situation

Construction			
Green = changed construction		R_c-value	U-value
Wall	Cavity wall (7 cm)	0.70	1.44
	Interior wall	0.42	2.36
	Separation wall	0.71	1.40
Floor	Ground floor without insulation	0.64	1.57
	Separation floor	0.64	1.57
Roof	Roof (outdated insulation)	1.74	0.58
Window	Double glazing		2.40

Ventilation		
Original situation = 0.75 x Bouwbesluit		
Ground floor		
Air change rate	[1/h]	0.962
First floor		
Air change rate	[1/h]	0.903
Infiltration		
Air change rate	[1/h]	0.4

11.6 Results for high- and low-temperature heating, current and original situation

The renovated and original situation of the dwelling were simulated for both high- and low-temperature heating, of which the results are presented in Table 11.5. The renovated situation has a higher comfort level and a lower energy demand than the original situation for both high- and low-temperature heating. The difference in thermal comfort and energy performance is small for the renovated situation.

The original situation has a large difference in thermal comfort and energy performance when using a lower supply temperature. Also, the energy performance is significantly higher compared to the renovated situation. The hours too cold in the original situation with high-temperature heating is used a base line to determine thermal comfort.

Table 11.5: Results renovated situation and original situation for 2020

	Heat output	Hours too cold	Energy demand	
	[W]	7:00 – 23:00, 20% PPD	Total kWh	kWh/m^2
Renovated situation				
HT (90-70 °C)	9204	0	3523	57.8
LT (55-45 °C)	3737	10	3353	55.1
Original situation				
HT (90-70 °C)	9204	144	8978	147.4
LT (55-45 °C)	3737	554	8349	137.1

LT-READY recommendations

Phase 4

12 Results

Different simulations have been performed on the case study dwelling to investigate which renovation concepts are LT-Ready. The focus of LT-Ready is on maintaining thermal comfort, which was analysed only for the living room because people spent most of their time in the living room. However, when thermal comfort is provided in the living room, other spaces still be thermally uncomfortable, which should be kept in mind. The energy performance was determined with a simulation for the entire. The used method is further explained in Section 12.1.

This resulted in a variety of results which can be found in Appendix F, of which a lot of them are suitable for low-temperature heating. However, to select well-performing renovation concepts different scenarios were devised depending on the context. These are explained in Section 12.2. The minimum renovation measures per ventilation type are provided in Section 12.3, and recommendations per individual renovation measures in 12.4.

12.1 Used method

LT-Readiness focuses on maintaining thermal comfort. Thus, to determine whether renovations concepts are LT-Ready, the hours too cold in the living room are compared with the original situation including high-temperature heating. An overview of this method is presented in Figure 12.1.

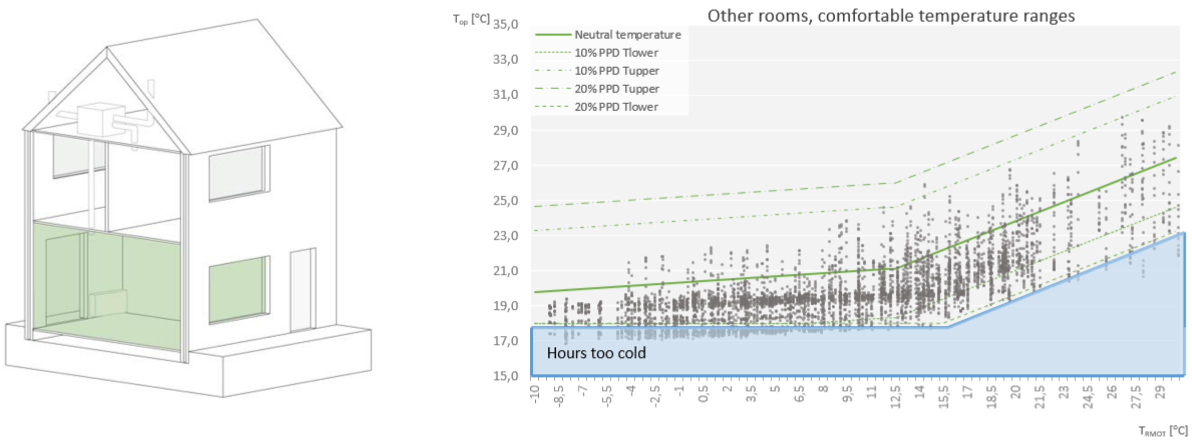
The hours too cold is determined with an adaption of the ATG-method (Dutch: *Adaptieve Temperatuur Grenswaarde*), combined with heating setpoints developed for dwellings by Peeters et al. (2009). The number of hours below the 20% PPD limit is calculated; first for the original situation, then for the renovation concepts, and are compared with each other. A dwelling is:

- LT-Ready, when: the number of hours too cold for the renovation concept with LT-heating **is equal to** *or* **lower than** the number of hours too cold for the original situation with HT-heating
- Not LT-Ready, when: the number of hours too cold for the renovation concept with LT-heating **is higher than** the number of hours too cold for the original situation with HT-heating

It must be mentioned that the LT-Readiness is determined for the living room, and no other rooms. This means these rooms can still be uncomfortable with LT-heating. However, people spent most of their time in the living room and can accept lower temperatures in other rooms. Thus, it is most important the living room is LT-Ready.

Because inaccuracies with dynamic simulations can occur, results must thoughtfully be interpreted. A range of ± 10 hours too cold or warm can be held as a guideline. The energy performance was determined for the entire dwelling.

Figure 12.1: Overview of used method



Original situation

144 hours too cold in living room
147.2 kWh/m² for dwelling

12.2 Recommendation for different scenarios

To provide suitable renovation concepts for different scenarios were devised to select well-performing renovation concepts. A scenario is a fictive composition that represents the most common building situations before a renovation, based on limitations provided by the context. Two contextual limitations have been devised:

- Limitations of the building
- Limitations of the investment costs

Within these limitations different scenarios have been developed. Also the best performing renovation concepts are two of the scenarios. An overview of the selected scenarios and their motivation is presented in Table 12.1.

Table 12.1: Scenarios and motivations

Scenario		Motivation
Building limitations		
1	C1 already installed	A large share of Dutch dwellings has already exhaust ventilation. In this case, it makes more sense to see which additional measures are required to provide comfort with low-temperature heating.
2	No space for D1	Balanced ventilation with heat recovery has a large heat recovery unit. Not all dwellings have space for this unit.
3	Wall insulation not possible	Sometimes wall insulation is not possible because the cavity is too small and house owners think interior or exterior insulation is too radical.
4	Cavity wall insulation not possible	In some cases, the cavity is too small to add cavity wall insulation.
Investment costs		
5	< €5000	The best solution for different investment costs is investigated because house owners have a limited budget available for renovation. From chapter 2 was concluded that most house owners have an available budget up to €10,000. Thus, different budget ranges below €10,000 were defined to provide insight which renovation concept performs best per budget.
6	€5000 - €7500	
7	> €7500	
Best performing solution		
8	Thermal comfort	The overall best performing solutions
9	Energy performance	

For every scenario, an overview is provided of the best performing renovation concepts on thermal comfort and energy performance within the given limitations. From this options, 1 or 2 options are selected as *best performing* renovation concepts. The gained knowledge for every scenario is also noted, as well as a visible overview of the impact of the best performing renovation concepts.

12.2.1 Best performing renovation concepts for building limitations

Scenario 1: Already ventilation type C1

Figure 12.2 shows possible renovation concepts when ventilation type C1 is already installed in a dwelling with the estimated investment costs. These costs are without the costs for ventilation type C1 because it is already installed in the building. Table 12.2 provides a detailed overview of renovation measures per selected concept.

Figure 12.2: Selected renovation concepts for scenario 1

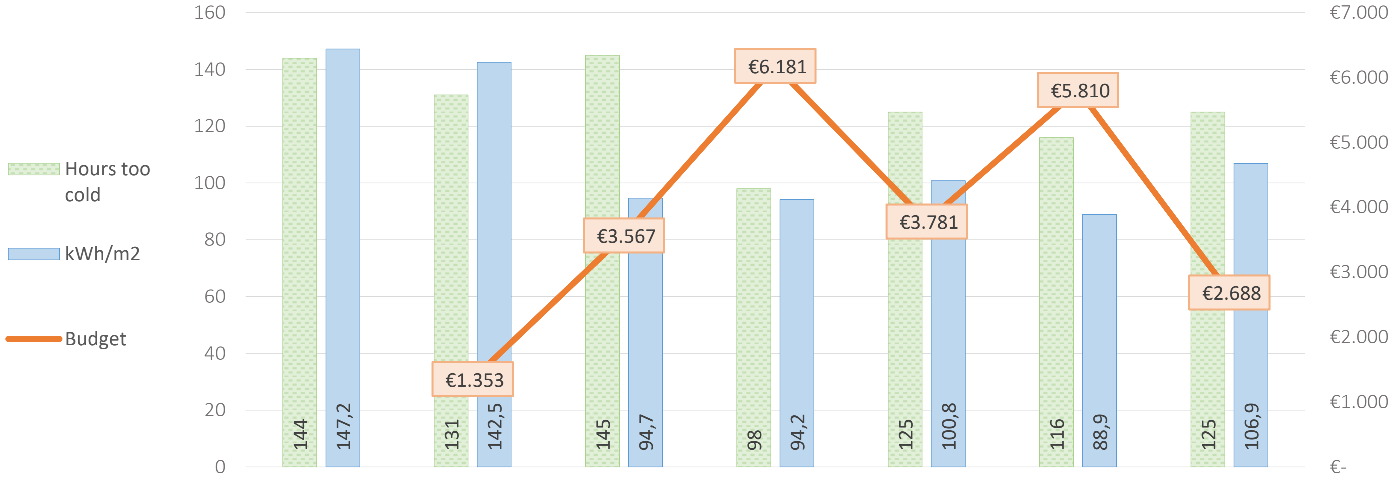
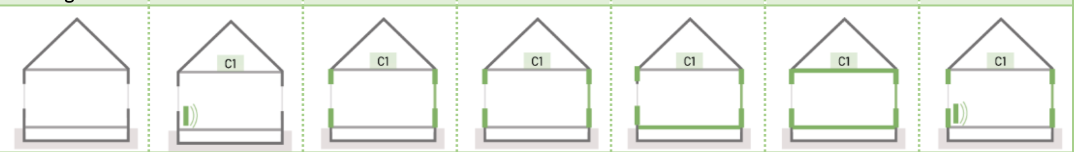
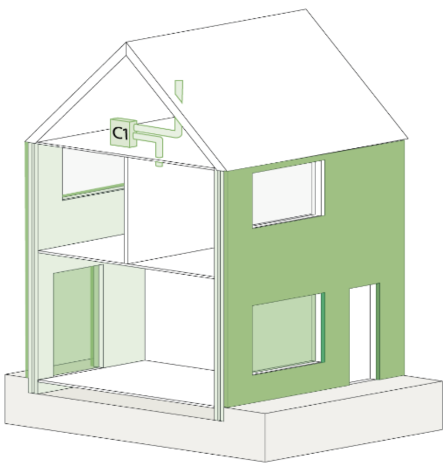


Table 12.2: Overview of selected renovation concepts for scenario 1

Option	Original	C1.5	C1.6a	C1.6b	C1.6c	C1.6d	C1.6e
							
Ventilation system	C1	C1	C1	C1	C1	C1	C1
Windows	Double gl.	Double gl.	HR++ (living)	HR++ (living)	HR++ (living)	HR++ (living)	HR++ (living)
Wall	Original	Original	Interior (R_c=2.8)	Exterior	Cavity	Cavity	Cavity
Roof	Original	Original	Original	Original	Original	Attic	Original
Floor	Original	Original	Original	Original	Below floor	Below floor	Original
Heating system	Original	LT-radiator	Original	Original	Original	Original	Add-on fan
Heating capacity	9204 W	6119 W	3737 W	3737 W	3737 W	3737 W	3988 W
Additional measures	-	-	-	-	-	-	-

Renovation concepts with the best balance between reduced hours too cold, reduced energy demand and the investment budget are option C1.6b and C1.6e. It can be concluded from the renovation concepts that with exhaust ventilation *C1* replacing windows and adding wall insulation with a high insulation level is necessary to provide comfort with low-temperature heating. When wall insulation with a lower insulation level is used, additional measures must be taken such as insulation measures or measures that increase the heat output of the heating system. The impact of renovation concept C1.6b is shown in Figure 12.3.

Figure 12.3: Impact of renovation concepts C1.6b for scenario 1



<u>Renovation concept C1.6b</u>

Budget: €6,181
Exhaust ventilation (C1)
Exterior wall insulation
HR++ (living room)

98 hours too cold
94.2 kWh/m^2

Scenario 2: no space for ventilation type D1

Figure 12.4 shows possible renovation concepts when there is no space available for ventilation type D1, for example, in case the attic is too small. The possible renovation concepts shown are thus the best performing renovation concepts for ventilation type C1 and C2. Table 12.3 provides a detailed overview of these renovation measures.

Figure 12.4: Selected renovation concepts for scenario 2

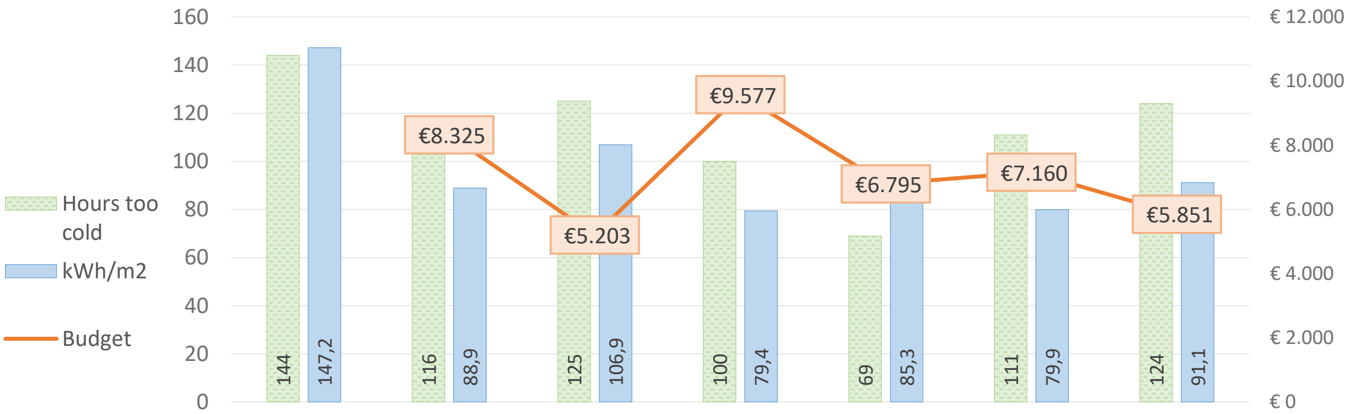
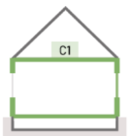
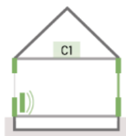
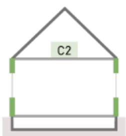
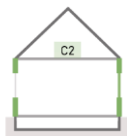
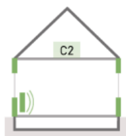
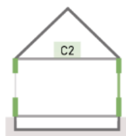
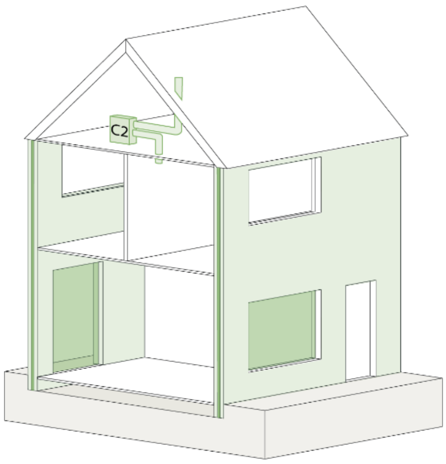


Table 12.3: Overview of selected renovation concepts for scenario 2

Option	Original	C1.6d	C1.6e	C2.2d	C2.6a	C2.6g	C2.6h
							
Ventilation system	-	C1	C1	C2	C2	C2	C2
Windows	Double gl.	HR++	HR++	Double gl.	HR++ (living)	Double gl.	Double gl.
Wall	Original	Cavity	Cavity	Exterior	Cavity	Interior (R_c=1.4)	Interior (R_c=1.4)
Roof	Original	Attic	Original	Original	Original	Original	Original
Floor	Original	Below floor	Original	Original	Original	Original	Original
Heating system	Original	Original	Add-on fan	Original	Original	Add-on fan	Original
Heating capacity	9204 W	3737 W	3988 W	3737 W	3737 W	3988 W	3737 W
Additional measures	-	-	-	-	-	-	Radiant screen

Renovation concepts with the best balance between reduced hours too cold, reduced energy demand and the investment budget are option C2.6a and C2.6g. It can be concluded that demand-driven exhaust ventilation *C2* is a better option than placing only exhaust ventilation *C1*, because less renovation measures are required to provide thermal comfort and leads to a bigger reduction of the energy demand. Adding wall insulation is mandatory for all renovation concepts, however, options where wall insulation is not added can be found under scenario 3 and 4. The impact of renovation concept C2.6a on the building is shown in Figure 12.5.

Figure 12.5: Impact of renovation concepts C2.6a for scenario 2



<u>Renovation concept C2.6a</u>

Budget: €6,795
Demand-driven ventilation (C2)
Exterior wall insulation
HR++ (living room)

69 hours too cold
85.3 kWh/m^2

Scenario 3 & 4: (Cavity) wall insulation not possible

Figure 12.6 shows possible renovation concepts when no (cavity) wall insulation is possible in a renovation. Placing LT-radiators is always an option to guarantee thermal comfort, but in this scenario, options are shown with mostly insulating measures. Table 12.4 provides a detailed overview of these renovation measures.

Figure 12.6: Selected renovation concepts for scenario 3 and 4

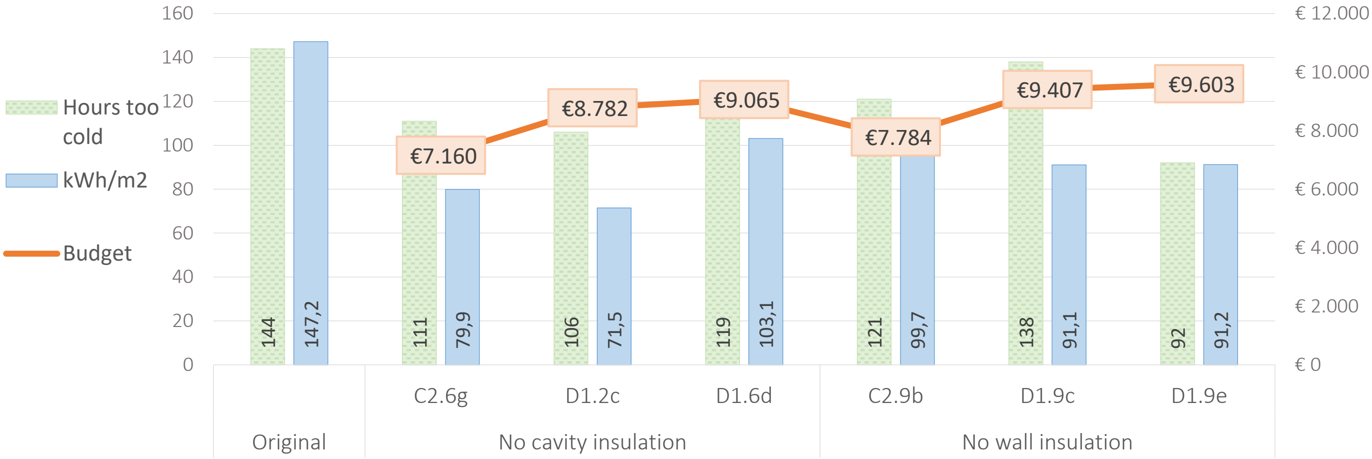
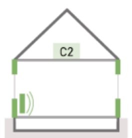
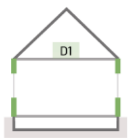
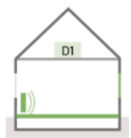
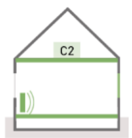
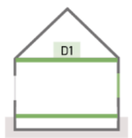
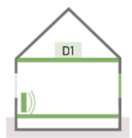
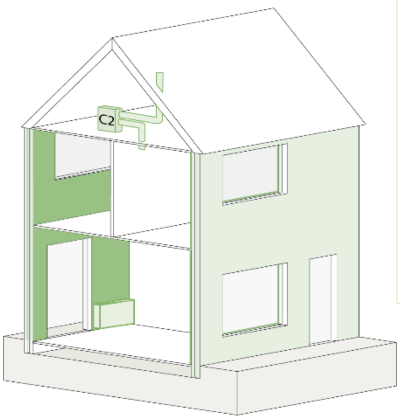


Table 12.4: Overview of selected renovation concepts for scenario 3 and 4

Option	Original	C2.6g	D1.2c	D1.6d	C2.9b	D1.9c	D1.9e
							
Ventilation system	-	C2	D1	D1	C2	D1	D1
Windows	Double gl.	Original	Original	HR++ (living)	HR++ (living)	HR++ (living)	HR++ (living)
Wall	Original	Interior (R_c=2.8)	Interior (R_c=2.8)	Original	Original	Original	Original
Roof	Original	Original	Original	Original	Attic	Attic	Attic
Floor	Original	Original	Original	Below floor	Below floor	Below floor	Below floor
Heating system	Original	Add-on fan	Original	Add-on fan	Add-on fan	Original	Add-on fan
Heating capacity	9204 W	3988 W	3737 W	3988 W	3988 W	3737 W	3988 W
Additional measures	-	-	-	-	-	-	-

Based on Figure 12.6 and Table 12.4, it can be concluded that ventilation losses must be reduced to provide thermal comfort, so demand-driven ventilation (C2) or balanced ventilation with heat recovery (D1). LT-radiators are required when exhaust ventilation (C1) is used. Thus, C2 or D1 are recommended. Insulating from the interior or exterior with a high insulation level provides options when no cavity wall insulation can be added, which shows a better effect than using a combination of other insulating measures. In case no type of wall insulation can be used, a combination must be made between all other insulating measures and add-on fans. Renovation concept C2.6g would be recommended if no cavity wall insulation can be placed, and D1.9e when no wall insulation at all can be used. Figure 12.7 shows the impact of the renovations on the building.

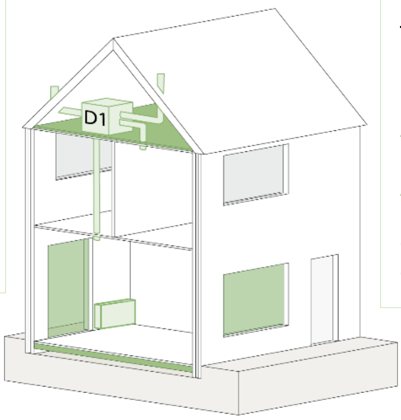
Figure 12.7: Impact of renovation concepts C2.6g and D1.9e for scenario 3 and 4



Renovation concept C2.6g

Budget: €7,160
Demand-driven ventilation (C2)
Interior insulation (R_d=2.8)

111 hours too cold
79.9 kWh/m^2



Renovation concept D1.9e

Budget: €9,603
Balanced ventilation (D1)
Attic insulation
Below floor insulation
Add-on fan

92 hours too cold
91.2 kWh/m^2

12.2.2 Scenario 5, 6 and 7: Best performing per budget

Figure 12.8 ranges all renovation concepts on investment budget to find out which renovation concepts have a good balance between thermal comfort and energy performance when compared with each other. This is done for three budget categories: below €5000, between €5000 and €7500 and above €7500. Table 12.5 shows the best performing renovation concepts per budget category and the required renovation measures.

Figure 12.8: Renovation concepts ranged on budget

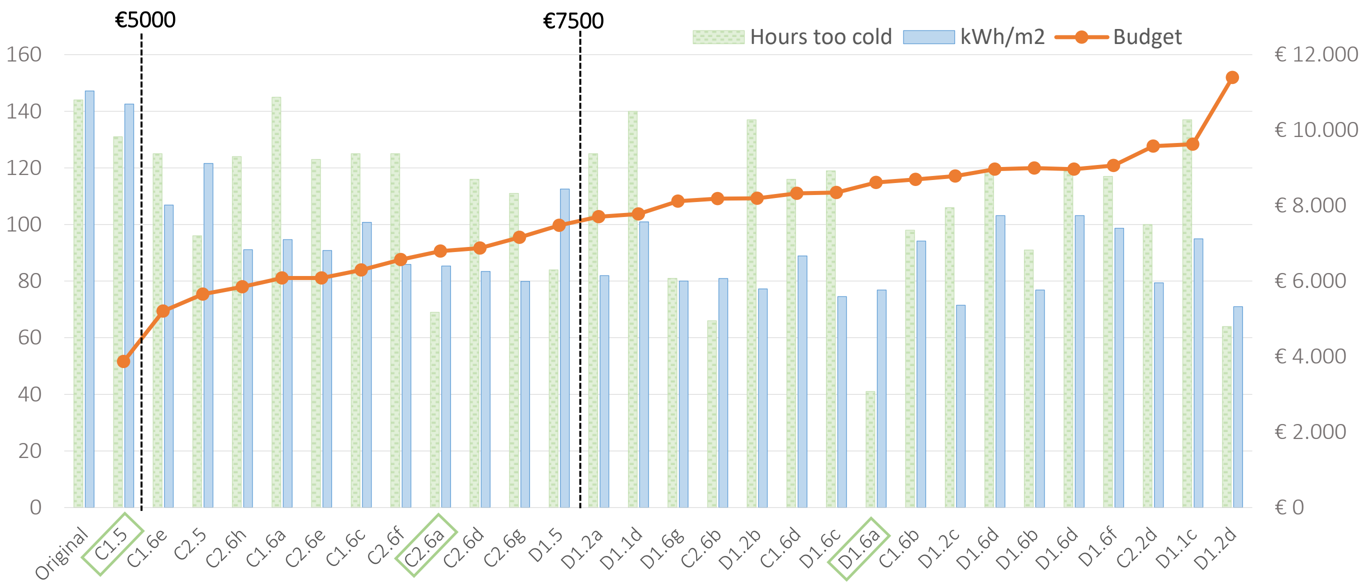
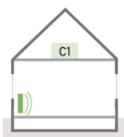
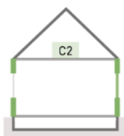
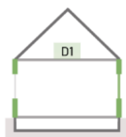


Table 12.5: Overview of best performing renovation concepts per budget

Option	Original	C1.5 < €5000	C2.6a €5000 - €7500	D1.6a > €7500
				
Budget		**€3868**	**€6795**	**€8641**
Hours too cold	144	**131**	**69**	**41**
Energy performance	147.2	**142.5**	**85.3**	**76.8**
Ventilation system	-	C1	C2	D1
Windows	Double gl.	Double gl.	HR++ (living)	HR++ (living)
Wall	Original	Original	Cavity	Cavity
Roof	Original	Original	Original	Original
Floor	Original	Original	Original	Original
Heating system	Original	LT-radiator	Original	Original
Heating capacity	9204 W	6119 W	3737 W	3737 W
Additional measures	-	-	-	-

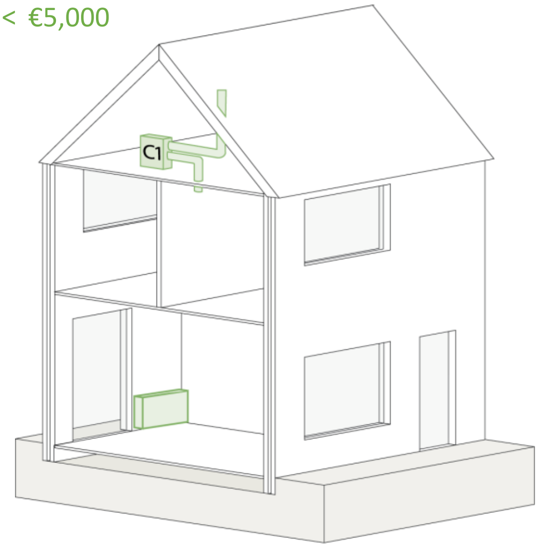
Best performing renovation concepts for the different budget ranges are C1.5 for below €5000, C2.6a for the budget range between €5000 - €7500, and D1.6a for a budget above €7500. From scenario 3, 4 and 5 can be concluded that dwellings for the lowest price must be renovated, placing LT-radiators is a good option. This has only a minimal effect on improving thermal comfort and reducing the energy demand, and thus it can be discussed if this is a good solution.

It might be better to spend a slightly larger budget on insulating renovations that try to reduce the energy demand. With a higher budget, the decision can be made for demand-driven exhaust ventilation or balanced ventilation with heat recovery, which reduces both the energy demand and the number of hours too cold. Also, another conclusion from renovation concepts is that replacing windows in the living room and adding cavity wall insulation gives the highest reduction of hours too cold and energy performance compared to investment budget.

Figure 12.9 shows the impact of the three renovations for scenario 5, 6 and 7.

Figure 12.9: Impact of renovation concepts C1.5, C2.6d and D1.6d for scenario 5, 6 and 7

< €5,000

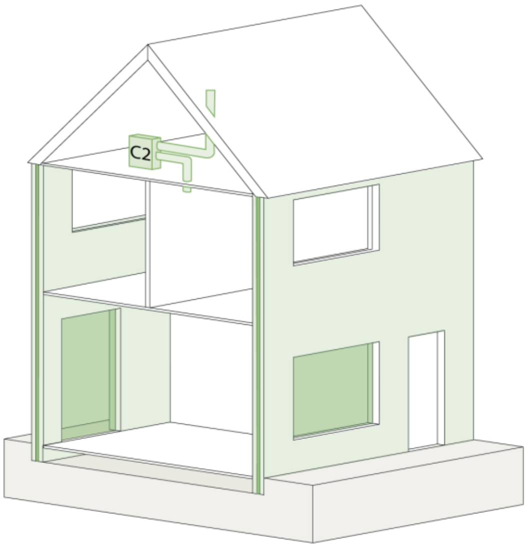


Renovation concept C1.5

Budget: €3,868
Exhaust ventilation (C1)
LT-radiator

131 hours too cold
142.5 kWh/m^2

€5,000 - €7,500

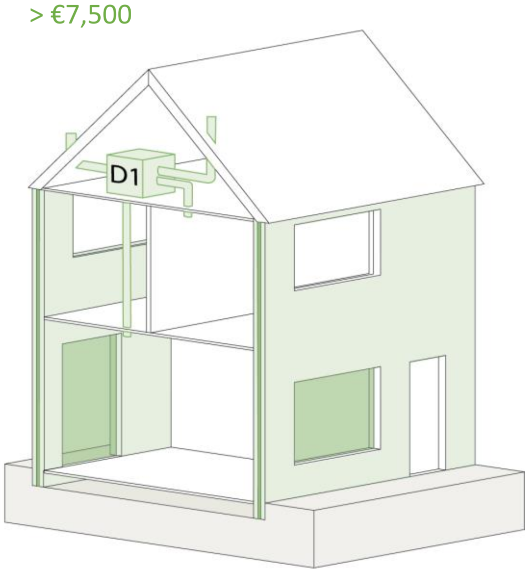


Renovation concept C2.6d

Budget: €6,795
Demand-driven (C2)
Cavity insulation
HR++ (living room)

69 hours too cold
85.3 kWh/m^2

> €7,500



Renovation concept D1.6a

Budget: €8,641
Balanced ventilation (D1)
Cavity insulation
HR++ (living room)

41 hours too cold
76.8 kWh/m^2

12.2.3 Scenario 8 & 9: Best performing renovation concepts

Based on Figure 12.8 which shows all renovation concepts ranged on budget, the overall best performing renovation concepts were selected. Best performing is defined as best performing on thermal comfort, which is the lowest number of hours too cold compared to the investment budget, and on energy performance, which is the lowest energy demand per investment budget. An overview of the selected renovation concepts is given in Table 12.6 and Figure 12.10. These show that the lowest number of hours too cold compared to the investment budget can be found in combination D1.6a, and the lowest energy demand per investment budget is found in combination D1.2c.

Based on this outcome, several conclusions can be made. First, balanced ventilation with heat recovery excels in providing thermal comfort and energy reduction compared to the investment budget. Also, replacing windows improves thermal comfort by significantly reducing the hours too cold compared to a situation where this has not been done. However, the budget difference between renovation concept D1.6a and D1.2c is rather small. This also counts for the energy demand per square meter per year, which is only 5 kWh. Therefore, a renovation with concept D1.6a, where thermal comfort is largely improved, seems more logical.

Table 12.6: Overview of selected renovation concepts for scenario 8 & 9

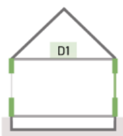
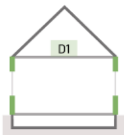
Option	Original	D1.6a on thermal comfort	D1.2c on energy performance
			
Ventilation system	-	D1	D1
Windows	Double gl.	HR++ (living)	Double gl.
Wall	Original	Cavity	Interior (Rc=2.8)
Roof	Original	Original	Original
Floor	Original	Original	Original
Heating system	Original	Original	Original
Heating capacity	9204 W	3737 W	3737 W
Additional measures	-	-	-

Figure 12.10: Selected renovation concepts for scenario 8 & 9

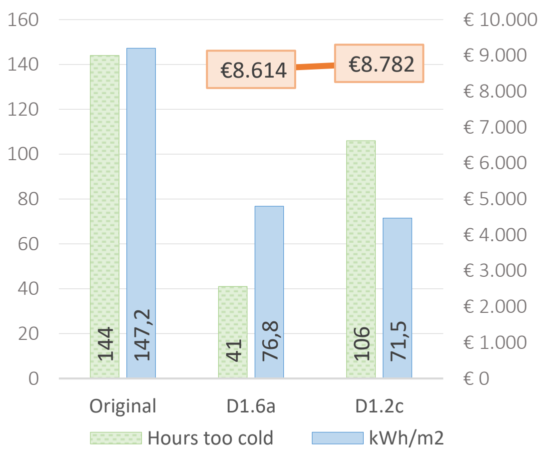
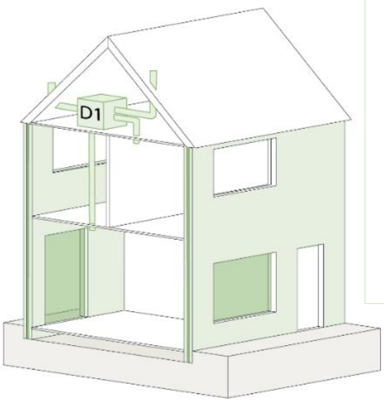


Figure 12.11 shows the impact of the best performing scenarios on the building itself.

Figure 12.11: Impact of renovation concepts D1.6a and D1.2c for scenario 8 and 9

Thermal comfort & investment budget

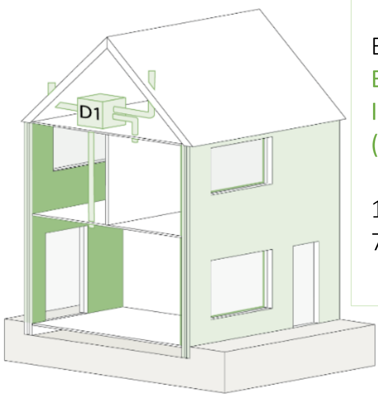


<u>Renovation concept D1.6a</u>

Budget: €8,641
Balanced ventilation (D1)
Cavity insulation
HR++ (living room)

41 hours too cold
76.8 kWh/m^2

Energy performance & investment budget



<u>Renovation concept D1.2c</u>

Budget: €8,782
Balanced ventilation (D1)
Interior insulation
(Rd=2.8)

106 hours too cold
71.5 kWh/m^2

12.2.4 Overview of best renovation concepts for scenarios

An overview of all best performing renovation concepts for the different scenarios is provided in Figure 12.12.

Figure 12.12: Scenarios and best performing solution

Original situation		
High supply temperature 90 °C	Hours too cold	144 hours
	Energy demand	147.2 kWh/m²

	Scenarios	Best performing solution	Performance
Building limitations	**C1 already installed** Low-budget	HR++ (living room) Cavity insulation Add-on fans More options	Hours too cold: 125 hours Energy demand: 106.9 kWh/m² Budget: €2688
Building limitations	**C1 already installed** Medium-budget	HR++ (living room) Exterior wall insulation More options	Hours too cold: 98 hours Energy demand: 94.2 kWh/m² Budget: €6181
Building limitations	**No space for D1**	Ventilation type C2 Interior insulation Add-on fans More options	Hours too cold: 111 hours Energy demand: 79.9 kWh/m² Budget: €7160
Building limitations	**Wall insulation not possible**	Ventilation type C2 HR++ (living room) Attic floor Below ground floor Add-on fans More options	Hours too cold: 92 hours Energy demand: 91.2 kWh/m² Budget: €9603
Building limitations	**Cavity insulation not possible**	Ventilation type C2 Interior insulation Add-on fans More options	Hours too cold: 111 hours Energy demand: 79.9 kWh/m² Budget: €7160
Budget	**Low-budget renovation** < €5000	Ventilation type C1 LT-radiator Only option	Hours too cold: 131 hours Energy demand: 142.5 kWh/m² Budget: €3868
Budget	**Medium-budget renovation** €5000 - €7500	Ventilation type C2 HR++ (living room) Cavity insulation More options	Hours too cold: 69 hours Energy demand: 85.3 kWh/m² Budget: €6795
Budget	**High-budget renovation** > €7500	Ventilation type D1 HR++ (living room) Cavity insulation More options	Hours too cold: 41 hours Energy demand: 76.8 kWh/m² Budget: €8641
Best performing on...	**Thermal comfort & investment budget**	Ventilation type D1 HR++ (living room) Cavity insulation More options	Hours too cold: 41 hours Energy demand: 76.8 kWh/m² Budget: €8641
Best performing on...	**Energy performance & investment budget**	Ventilation type D1 Interior insulation More options	Hours too cold: 106 hours Energy demand: 71.5 kWh/m² Budget: €8782

12.3 Recommendations for renovation measure per ventilation system

The results are calculated for the case study dwelling, but can possibly apply also to other dwellings. The minimum required renovation measures are different for every ventilation system, because of the different ventilation losses per system. For this reason, simulations have been performed to determine which renovation measures are needed per ventilation system to ensure thermal comfort. The results are shown in Table 12.7.

Table 12.7: Minimum renovation measures per ventilation system

Variants	Exhaust ventilation (C1) +	Demand-driven exhaust ventilation (C2) +	Balanced ventilation with heat recovery (D1) +
1	LT-Radiator	LT-Radiator	LT-Radiator
2	Wall insulation (extra Rc=2.4) **and** HR++ glazing	Exterior wall insulation	Triple glazing
3	Cavity wall insulation **and** HR++ glazing **and** floor *or* roof insulation	Wall insulation **and** HR++ glazing *or* radiant screen *or* add-on fans	Wall insulation
4	Cavity wall insulation **and** HR++ glazing **and** add-on fan	HR++ glazing **and** floor insulation **and** attic insulation **and** add-on fans	HR++ glazing **and** floor insulation **and** roof insulation

In general, with higher ventilation losses more additional renovation measures are needed to provide the same level of thermal comfort. This means that balanced ventilation with heat recovery D1 needs fewer additional renovation measures than demand-driven ventilation C2. Exhaust ventilation C1 has the highest ventilation losses and thus needs the most additional renovation measures. However, all dwellings can be heated with lower temperatures when LT-radiators are placed by enlarging the heat capacity of the heating system.

It can also be concluded that for exhaust ventilation C1 more additional measures are mandatory to maintain thermal comfort, with at least one measure as wall insulation. Demand-driven exhaust ventilation C2 can already be heated with lower temperatures if the wall is insulated from the exterior. Another type of wall insulation can also provide thermal comfort when combined with other measures. It is also possible to provide thermal comfort without wall insulation by taking different measures. Balanced ventilation with heat recovery D1 can provide thermal comfort with any type of wall insulation, triple glazing, or different combined measures.

If one has the option to choose between different ventilation systems, system C2 or D1 is preferred because of the lower ventilation losses. This provides more opportunities to reduce the energy demand of the dwelling and make it comfortable with low-temperature heating.

12.4 Recommendations per renovation measure

The results are calculated for the case study dwelling, but can possibly apply also to other dwellings. All renovation measure were individually simulated per ventilation system and compared with the original situation to determine the effect on thermal comfort and energy performance. Based on the output recommendations can be given for every measure. Figure 12.13 shows the effect on the hours too cold per renovation measure combined with different ventilation systems, Figure 12.14 the energy performance per renovation measure.

Figure 12.13: Hours too cold per renovation measure

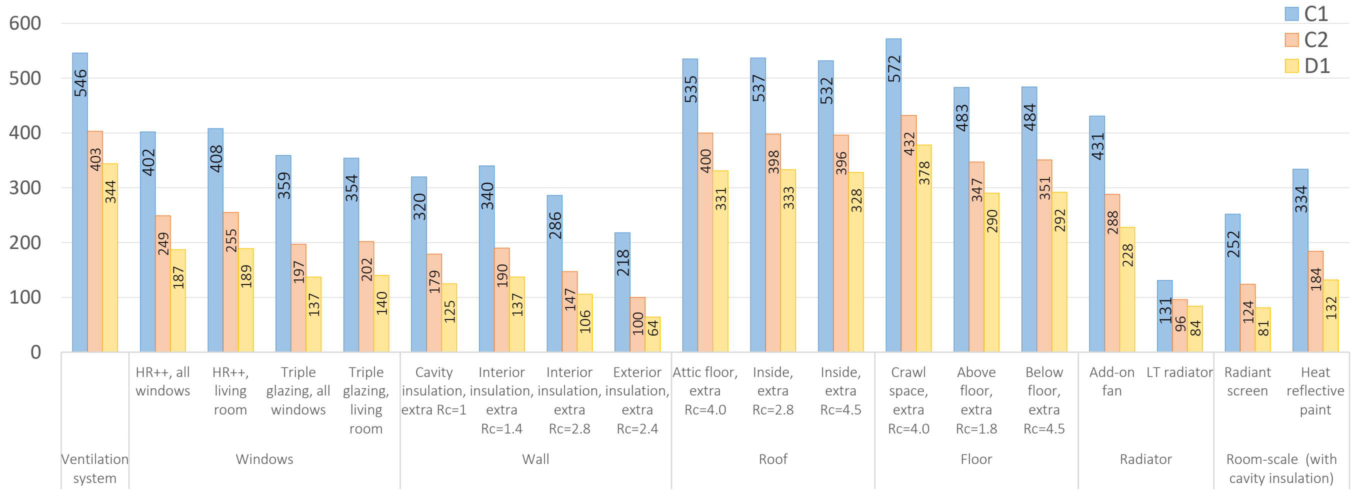
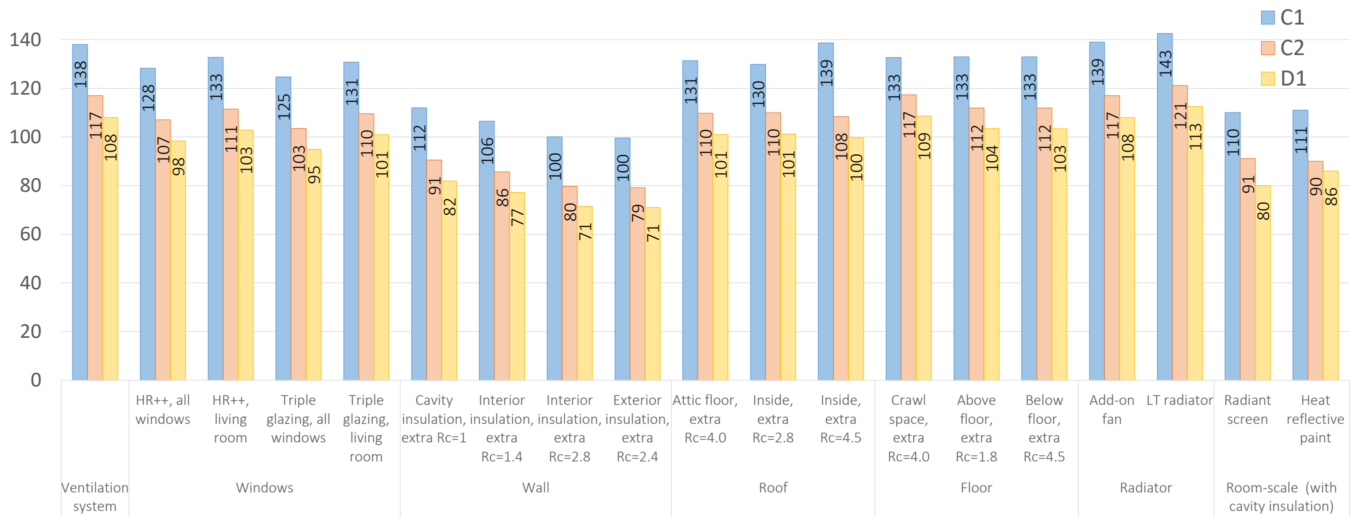


Figure 12.14: Energy performance per renovation measure



Figures 12.13 and 12.14 show which measures are effective on thermal comfort and energy performance, and which not. Thus, Table 12.8 provides different recommendations per renovation measure on their effectiveness. The measures are sorted in the three different scales and arranged on their effectivity starting with the most effective measures. Overall, can be concluded that the ventilation system is a very important factor if a dwelling is LT-Ready or not, because of the ventilation losses. Also, wall insulation and windows are the most important renovation measures to provide comfort and reduce the energy demand.

Table 12.8: Recommendation per measure

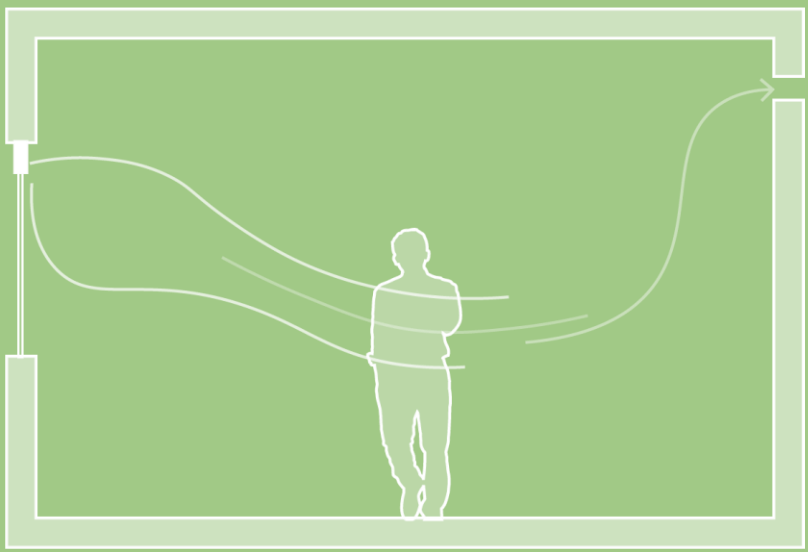
Building envelope	Wall insulation 	· <u>Most effective measure for thermal comfort and energy demand</u> · Differences per type of wall insulation: – Interior of exterior insulation with a higher insulation -value (extra Rc=2.4) gives the largest effect, but is also relatively expensive – Cavity wall insulation (extra Rc=1.0) has a positive effect, but smaller than high insulation grade. It is also relatively cheap – Interior insulation lower with a lower insulation value (extra Rc=1.4) reduces the heating demand, but the effect on thermal comfort is smaller than with cavity wall insulation. An explanation for this can be that the interior wall insulation results in a lower mean radiant temperature, and thus a lower operative temperature.
	Windows 	· <u>Improves thermal comfort and reduces energy demand</u> · Effect is smaller than adding wall insulation. This also depends on the window percentage of the façade. · Triple glazing (U=0.7) is more effective than HR++ glazing (U=1.1), but is also more expensive · Replacing windows in the living room, instead of entire building: – Results in 2-6 extra hours too cold in the living room – Large difference in costs – If this is the only measure, other spaces in the dwelling are probably uncomfortable with low-temperature heating
	Floor insulation  	· Effect is comparable to roof insulation, but: – Larger effect on thermal comfort in living room – Smaller effect on heating demand · Differences per type of floor insulation: – Insulation placed on the crawl space floor (Rc= 4.0) does not improve thermal comfort, but reduces the heating demand – Above (Rc= 1.8) or below (Rc= 4.5) floor insulation has a comparable effect, but below floor insulation is cheaper
	Roof insulation  	· Has limited effect on thermal comfort in living room · Differences per type of roof insulation: – Attic insulation (Rc= 4.0) and adding a thin layer insulation from inside (Rc= 2.8)have a similar effect on thermal comfort and heating demand – Insulating from inside with a higher insulation level (Rc= 4.5) has a larger effect, also more expensive. The costs outweigh these advantages.

Building installations	Ventilation system 	· Important factor for determining to what extend the building can be made LT-Ready · Mechanical exhaust ventilation (C1) has high ventilation losses, which result in more renovation measures · Demand-driven ventilation (C2) and balanced ventilation (D1) have lower ventilation losses, so fewer renovation measures are needed to provide thermal comfort
	LT-radiator 	· Provides thermal comfort for all ventilation systems because of the higher heating capacity · Increases the heating demand because of the higher heating capacity, and thus uses more energy
	Add-on fan 	· Boost the heat output of radiators · Can be used when a room is slightly uncomfortable after renovation, instead of an additional measure · Reduces uncomfortable hours so improves thermal comfort · Minimum impact on energy demand of the dwelling

Room scale	Heat reflective paint	· Has a negative effect on thermal comfort and energy demand · Provides a lower surface temperature of the walls, and thus a lower operative temperature
	Radiant screen	· Has a positive effect on thermal comfort and the heating demand · Can be used instead of replacing windows as a cheaper measure

Local comfort analysis

Phase 5



13 Local comfort results

Additional analyses on local comfort were performed to give insight in the effect of renovation measures on room scale. The effect was determined with additional CFD analyses and dynamic simulations performed in DesignBuilder. The setup of the CFD-model is explained in Section 13.1. The separate effects on local comfort that are evaluated are:

- The ventilation system in Section 13.2
- Placing add-on fans below radiators in Section 13.3
- The location of furniture in a room in Section 13.4
- The effect of a radiant screen in Section 13.5

The findings presented in Section 13.2-13.5 might be limited because of the limitations on CFD-calculations within the DesignBuilder software. The CFD calculations are rather simple, but can still show the expected effect. Other CFD calculation software might be more accurate regarding temperatures and air velocities. Therefore, only an interpretation of the results is given.

13.1 Set up of CFD model

The CFD model of the living room of the case study dwelling was set up using the DesignBuilder software, shown in Figure 13.1. The coloured boundaries represent different building parts. *Y*ellow boundaries represent window surfaces, the blue boundary represents the door, grey boundaries represent ventilation supplies or exhausts. The grey blocks represent components, which can have a temperature, a heat flux, or a neutral thermal boundary. Also, the surface temperature of the walls, windows, and floor must be specified of which the calculated temperatures are shown in Table 13.1. The radiators were modelled with the *component blocks* with assigned *heat flux*. This heat flux is the convective fraction of the heating capacity and was calculated according to Table 13.2.

Figure 13.1: CFD-model

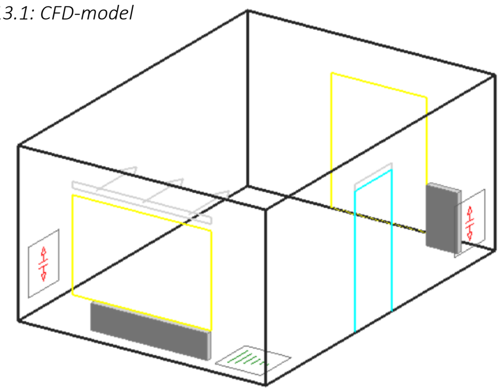


Table 13.1: Surface temperatures

Surface	Calculated surface temperature
Wall	
Insulated cavity wall	18.08 °C
Interior wall	20.00 °C
Floor	
Insulated wooden floor	21.90 °C
Windows	
HR++ glazing (U=1.1)	16.95 °C

Table 13.2: Heat flux of radiators

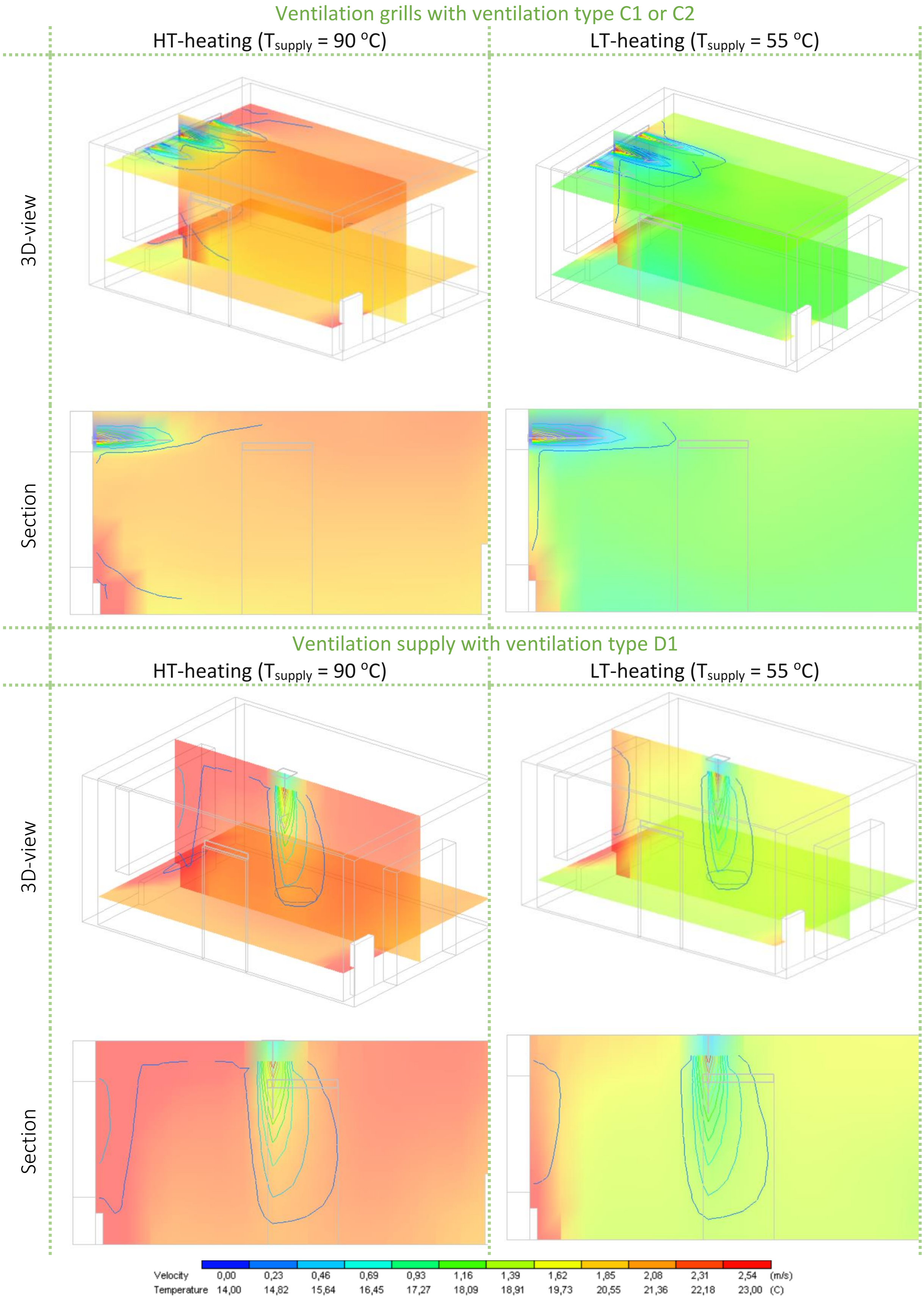
Radiator		Heating capacity [W]	Convective fraction [Heating capacity x 0.6]
1	HT (T_{supply} = 90 °C)	2508	1504
	LT (T_{supply} = 55 °C)	1018	610
2	HT (T_{supply} = 90 °C)	585	351
	LT (T_{supply} = 55 °C)	238	142

13.2 Effect of ventilation system

The decision for a certain type of ventilation system can influence the level of local comfort within a room. The difference is generally caused by the decision for ventilation grills combined with (demand-driven) exhaust ventilation, which can be the cause for cold drafts, or the decision for a balanced ventilation system with supplied ventilation in the living room.

The effect on local comfort for both ventilation systems becomes visible in Figure 13.2.Comparing the two ventilation systems with each other, the presence of air velocities with colder temperatures caused by the ventilation grills is visible. With low-temperature heating, the cold drafts are slightly larger than with high-temperature heating. When a ventilation supply is used, still high air velocities can be present in the room. The temperature of them is however higher. An overall higher temperature is achieved with balanced ventilation than with ventilation grills because the air is already preheated.

Figure 13.2: Expected effect of different ventilation systems on room-scale

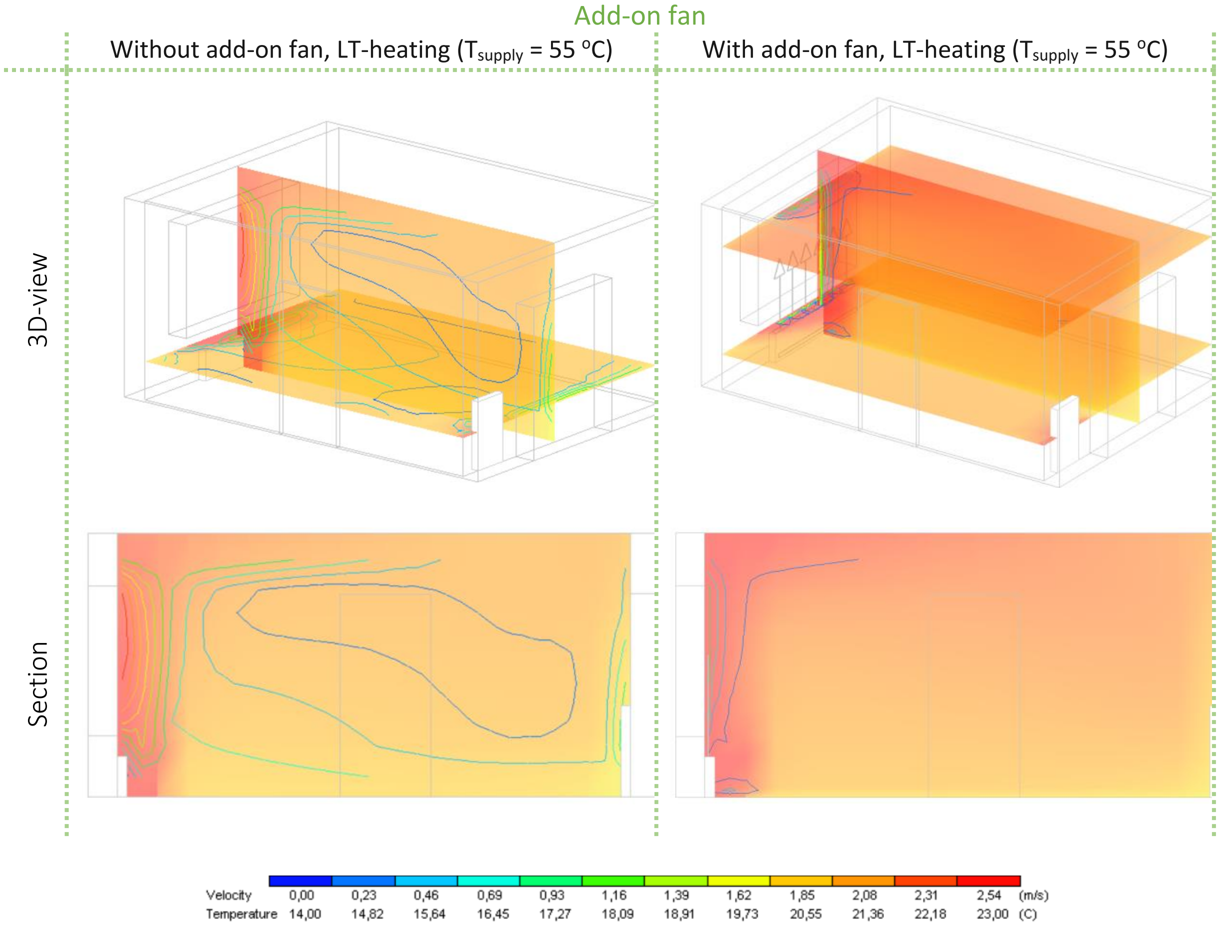


13.3 Effect of add-on fans

Figure 13.3 shows the effect of using add-on fans on the room-scale. Add-on fans were simulated by adding extra ventilation supplies on the radiator with an extra heat flux, and an exhaust underneath the radiator. In a situation without add-on fans, higher air currents are present in the room and the overall air temperature is lower. When add-on fans are placed below the radiators, the present air currents seem to be smaller compared to the original situation. Also, the overall air temperature is higher.

In the original scenario, the cold window surfaces caused cold downflows, which in turn cause high air currents. However, by placing add-on fans below the radiator, this cold down-flow is immediately counteracted by the extra air circulation and the slightly increased heating capacity. The usage of add-on fans would thus be recommended to counteract cold down-flows.

Figure 13.3: Effect of using add-on fans on room-scale



13.4 Effect of location of furniture

The position of furniture can affect the heat distribution within a room. For this reason, different locations of the couch in the living room have been analysed by placing the couch directly in front of the radiator, 50 centimetres in front of the radiator, and next to the radiator (Figure 13.4). The couch was modelled by placing a component block without a thermal boundary.

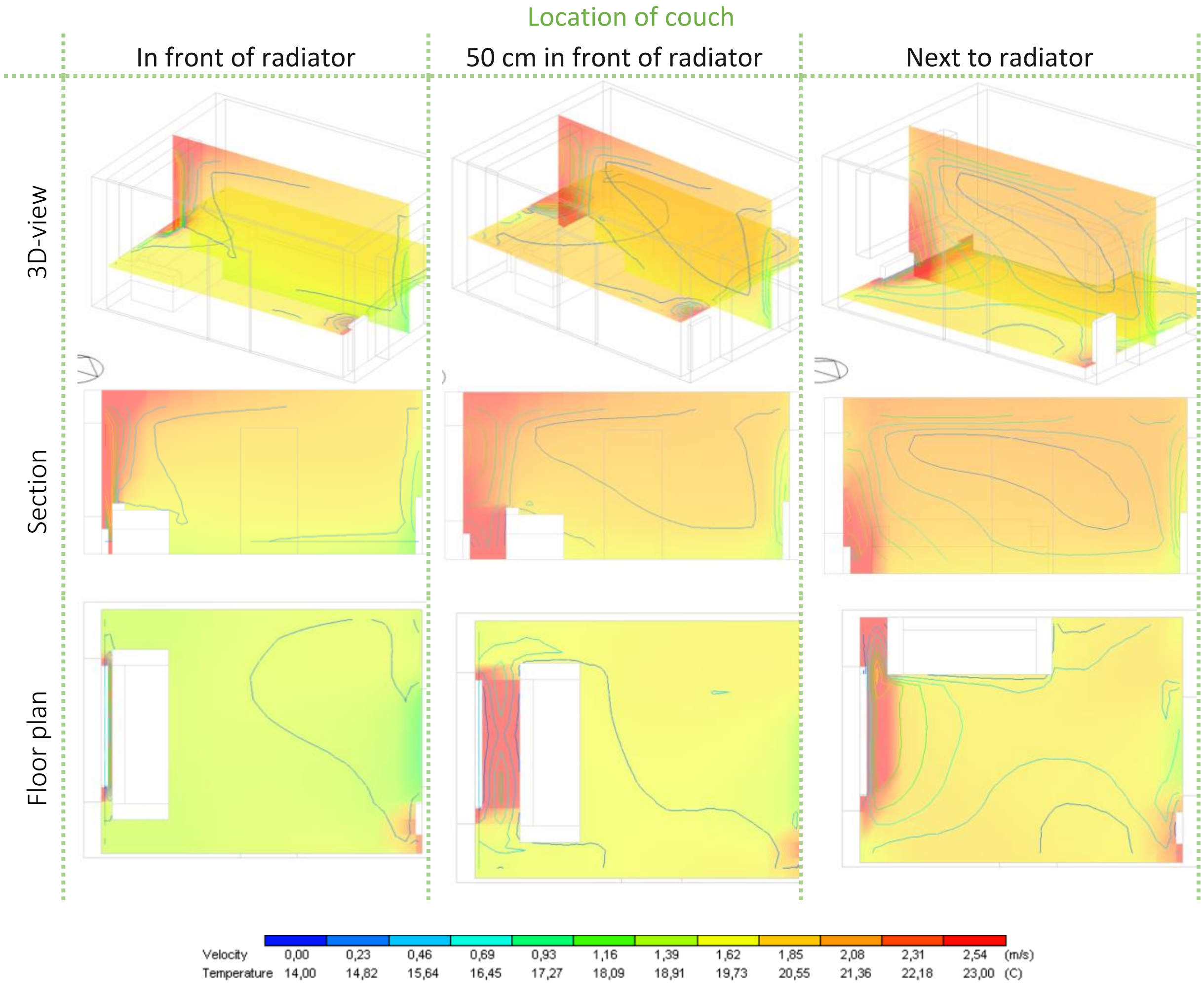
Based on Figure 13.4, it can be concluded that if the coach is directly placed in front of the radiator the air currents in the room are lower because the warm air of the radiator can only rise upwards. This directly counteracts cold down-flow. However, by blocking the radiator, the overall air temperature is lower.

In a situation where the couch is 50 centimetres in front of the radiator, the heat is unevenly distributed towards the window. The overall air temperature becomes higher, but the air currents also increase slightly compared to the situation when the radiator is directly placed in front of the radiator.

When the couch is placed next to the radiator, the overall air temperature is the highest compared to the other situations because heat can be distributed within the room. The air currents do however also increase due to less directly counteracting of the cold down-flows.

Overall, placing the couch next to the radiator would be recommended to provide the highest indoor temperatures but placing the couch in front of the radiator would be recommended to prevent air currents within the room.

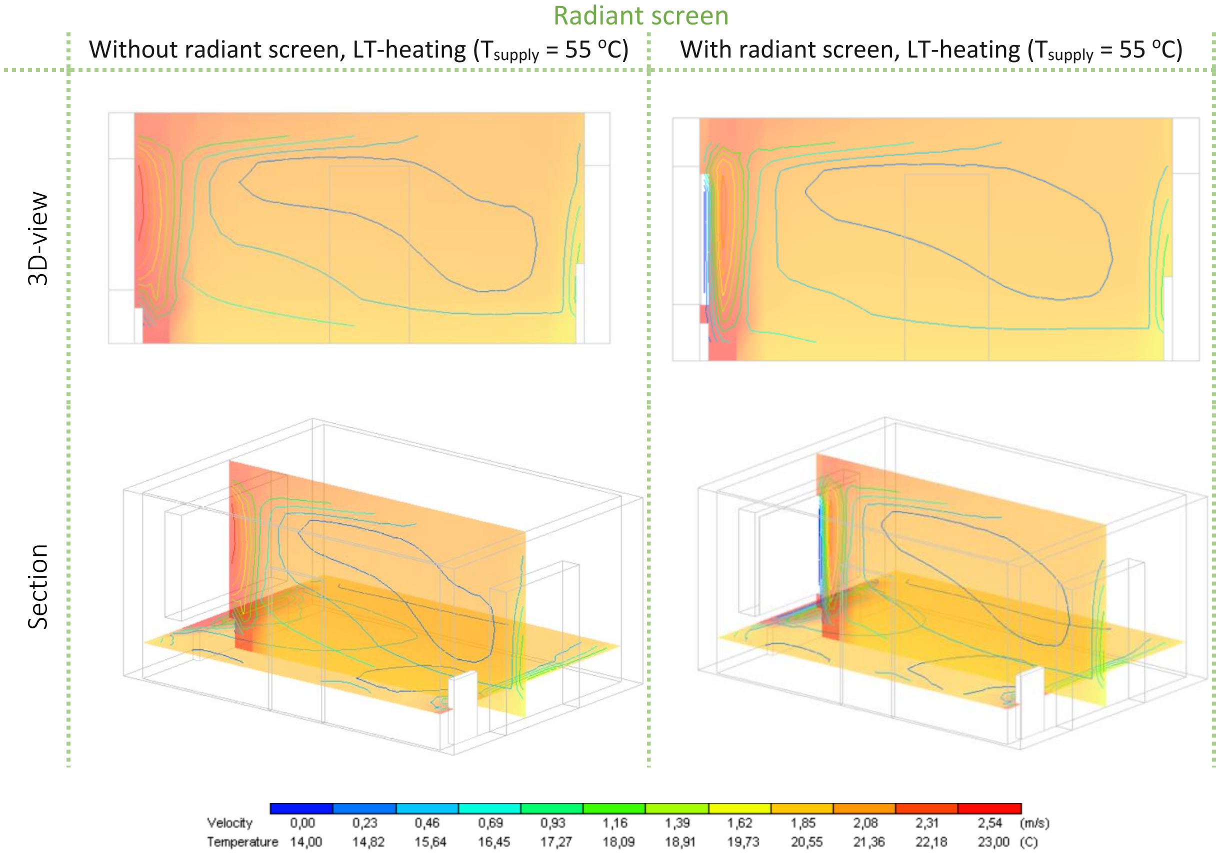
Figure 13.4: Effect of furniture on heat distribution in living room



13.5 Effect of radiant screen

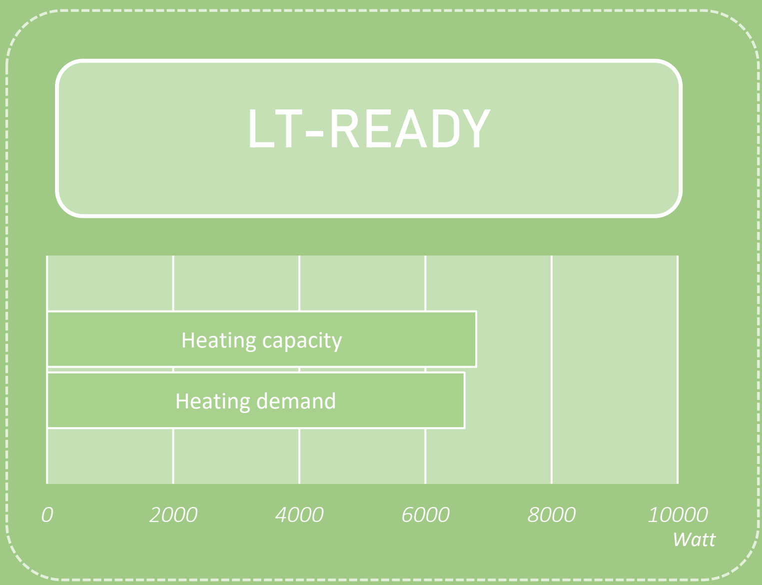
Lastly, the effect of placing a radiant screen was simulated (Figure 13.5). The radiant screen was modelled as thin *component block* without thermal boundaries and placed in front of the window. The simulation results show an air circulation in front of the radiant screen, which is probably caused by the reflectance of warm uprising air from the radiator. However, the overall air currents in the room are comparable for the situation with and without radiant screen. Ultimately, the effect of placing the is marginal for air temperature. However, the radiant screen can have an effect on the radiant temperature by having a higher surface temperature than the window. This can increase the operative temperature, and therefor thermal comfort.

Figure 13.5: Effect of radiant screen



LT-READY tool

Phase 6



14 Tool

The required renovation measures to maintain thermal comfort with low-temperature heating were researched in Chapter 12 and 13 for one case study dwelling by using dynamic simulation software. A more general approach is however needed to determine the required renovation measures for other dwellings. One method for this is comparing the available heating capacity at lower supply temperatures with the heating demand calculated with *ISSO-51*, a calculation method for installers to determine the required capacity per room or dwelling. This approach was developed into a tool in which house owners can enter their dwelling and determine the LT-Readiness, and which renovation measures are needed to make it LT-Ready.

The concept of this tool is described in Section 14.1, and the graphical interface and how the tool should be used in Section 14.2. Section 14.3 compares the tool's results for the case study building with the results from DesignBuilder, and Section 14.4 describes how the tool could be further developed.

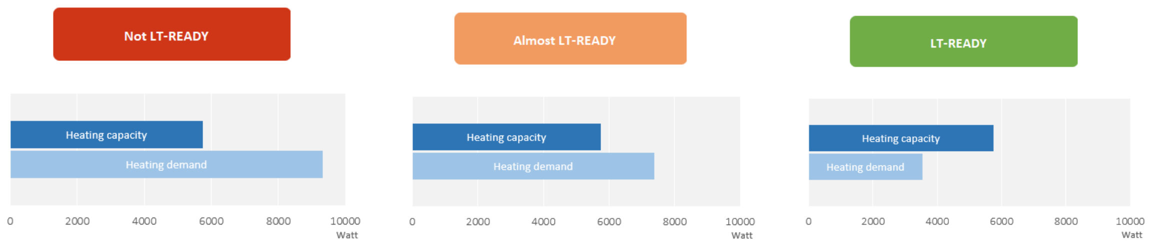
14.1 Concept

The main goal of the tool is to inform house owners if their dwelling is LT-Ready, and if not, which combination of measures is required to achieve this. These combination of measures, also referred to as *renovation concepts*, should be compared with each other on their performance as well as for their estimated investment.

The tool compares the required heating demand for both the entire dwelling and the living room with the available heating capacity. The required heating demand is calculated according to ISSO-51. The available heating capacity is calculated with Formula 5.9. Figure 14.1 shows the 3 types of results derived from the tool:

- Not LT-READY, when the heating demand is higher than 1.5x the available heating capacity. This means that additional measures need to be taken to guarantee thermal comfort for most of the year.
- Almost LT-READY, when the heating demand is between 1.5x the available heating capacity and the available heating capacity. This means that most of the time the dwelling is LT-READY, but to provide thermal comfort on the coldest days some additional measures need to be taken.
- LT-READY, when the heating demand is lower than the heating capacity. Thermal comfort is guaranteed through the entire year.

Figure 14.1: Results tool



Limitations

The tool has several limitations, which must be taken in mind before using the tool. The limitations are:

- The tool is developed only for terraced housing.
- The tool is validated with DesignBuilder results for the case study dwelling. Additional validation with other dwellings can improve the accuracy of the tool.
- The tool uses ISSO-51 to determine the required heating demand. This does however include different safety factors to minimize the hours of discomfort. However, maintaining the same level of thermal comfort is difficult to calculate. For example, the required heating capacity for the case study dwelling according to ISSO-51 is 5600 W, while only 3500 W is available. However, with 3500 W the same level of thermal comfort is achieved as in the original situation. Thus, it can be assumed that ISSO-51 is slightly over dimensioned. Based on the case study results, a factor of 1.5 is used to determine the category *Almost LT-READY.*

14.2 GUI (Graphical User Interface)

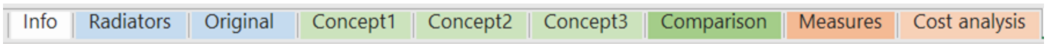
The tool is developed in Excel. Section 14.2.1 provides an overview of the available tabs of the tool, and Section 14.2.2-14.2.6 provides information about the different tabs.

14.2.1 Tabs

The tool consists of different tabs which are shown in Figure 15.2. The tabs are divided into 5 categories, which are:

White	This tab provides information on how to use the tool.
Light blue	In these tabs information about the current dwelling must be entered for the building envelope (surface areas and insulation levels) and the radiators.
Light green	In these tabs different renovation concepts can be entered.
Green	In this tab the different renovation concepts are compared to the original situation.
Orange	In this tab an overview of used measures is given, including possibilities to change the values.
Light orange	In this tab an overview of the cost analysis is given, mentioned in Chapter 7.

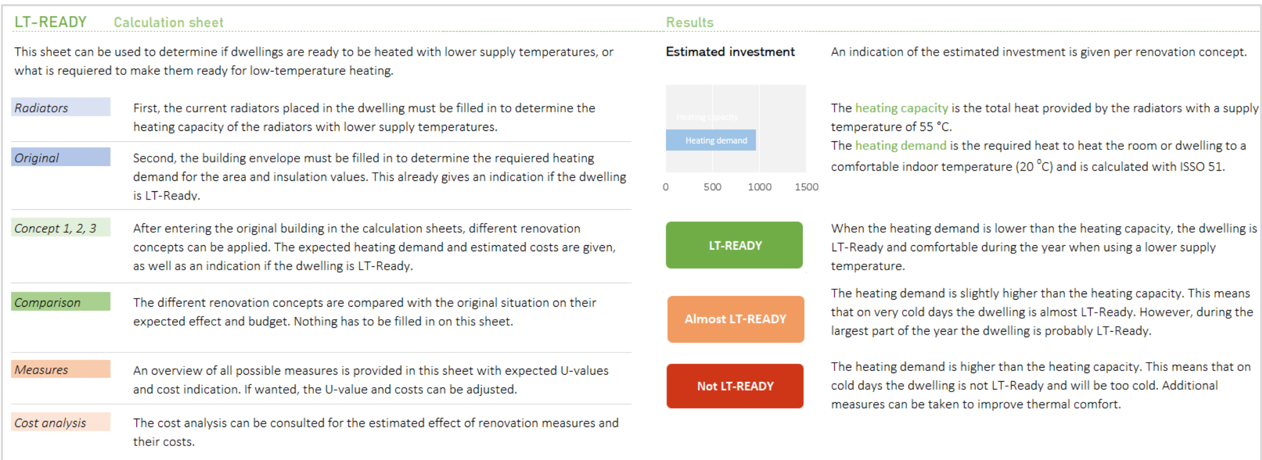
Figure 14.2: Excel tabs



14.2.2 Info

The first tab of the LT-Ready tool is shown in Figure 14.3. It provides information for the users of the tool how to use the tool and interpret the results.

Figure 14.3: Info tab



14.2.3 Current situation

The light blue tabs correspond to the current situation, for which information about the radiators and building envelope should be provided by the users of the tool.

Radiators

In the second tab, information about the radiators must be entered to calculate the available heating capacity for high- and low-temperature heating (Figure 14.4). The radiator type and its dimensions must be provided to determine the heating capacity per radiator. The accompanying image provides an overview of common radiator types. Also, the room has to be entered to determine the heating capacity of the living room. The heating capacity for high-temperature (90-70 °C) and low-temperature (55-45 °C) heating is calculated by using Formula 5.9

provided by Østergaard (2016). The used heating setpoint and lower supply and return temperature must also be entered.

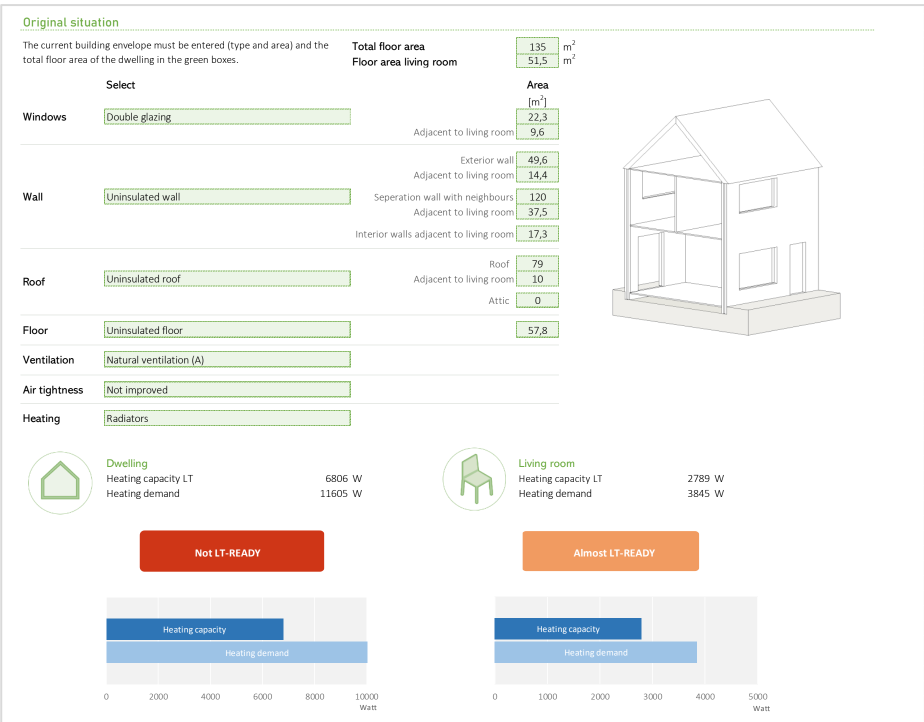
Figure 14.4: Radiator tab

Original

In the third tab information about the original building envelope must be provided to determine the required heating demand. In the accompanying image an overview of the insulated building parts are shown. Parameters that must be entered in the green boxes are:

- Total floor area of the dwelling in m^2
- Floor area of the living room in m^2
- Surface areas of the windows, walls, ground floor and roof in m^2
- Surface areas adjacent to living room of the windows, walls, ground floor and roof in m^2
- Surface properties (e.g., HR++ glazing for windows)
- Ventilation system
- Level of air tightness
- Heating system

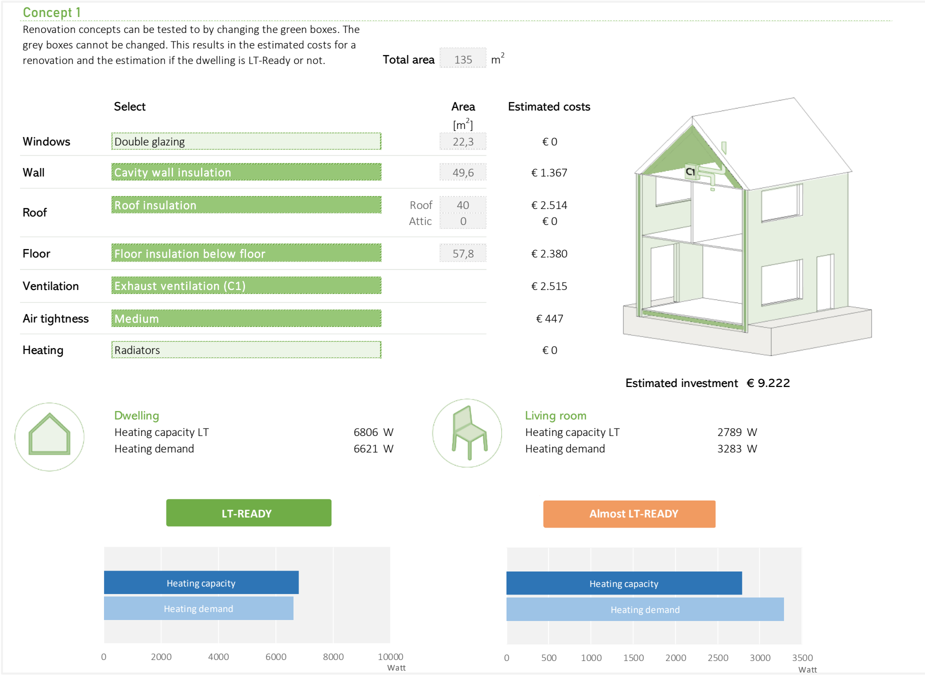
Figure 14.5: Original Tab



14.2.4 Concepts

After entering the original situation, 3 different renovation concepts can be added to the tool (Figure 14.6). The green boxes can be adjusted for the window, wall, roof, and floor properties, the ventilation system, level of airtightness, and the heating system. The colour of the box changes to dark green if an adjustment has been made compared to the original situation. Simultaneously, the estimated investment is calculated for the renovation concepts as well as the LT-Readiness for both the living room and the dwelling.

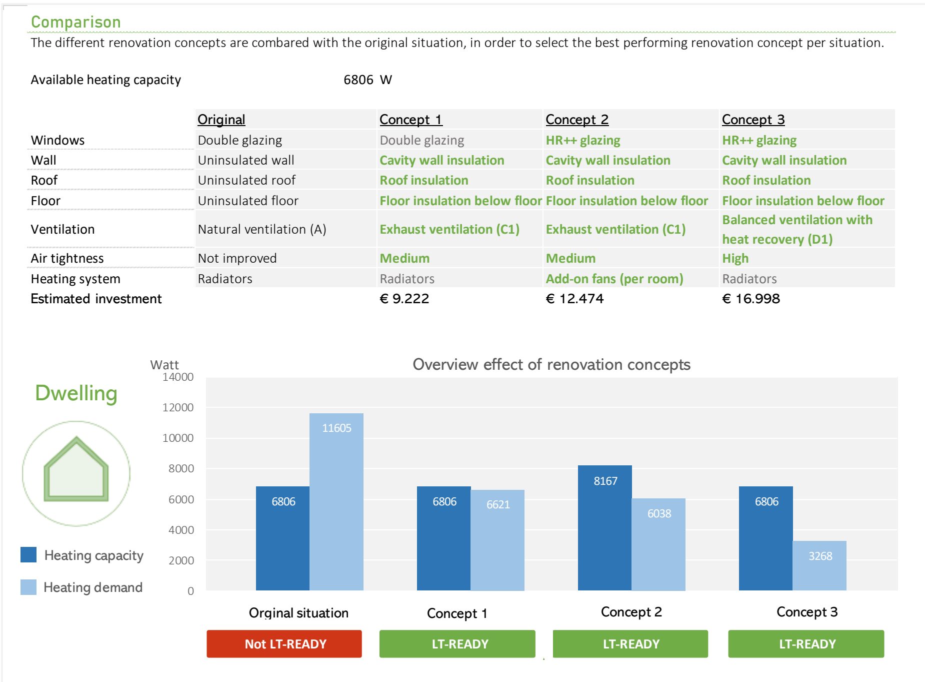
Figure 14.6: Renovation concept tabs



14.2.5 Comparison

After adding the 3 different renovation concepts, all options can be compared to the original situation in the comparison tab (Figure 14.7). An overview of all measures is provided with changes in green, as well as the estimated investment per renovation concept and the LT-Readiness. A comparison between the available heating capacity and heating demand is given per concept. This is done for both the living room as the entire dwelling.

Figure 14.7: Comparison tab


Comparison

The different renovation concepts are combared with the original situation, in order to select the best performing renovation concept per situation.

Available heating capacity 6806 W

	Original	Concept 1	Concept 2	Concept 3
Windows	Double glazing	Double glazing	HR++ glazing	HR++ glazing
Wall	Uninsulated wall	Cavity wall insulation	Cavity wall insulation	Cavity wall insulation
Roof	Uninsulated roof	Roof insulation	Roof insulation	Roof insulation
Floor	Uninsulated floor	Floor insulation below floor	Floor insulation below floor	Floor insulation below floor
Ventilation	Natural ventilation (A)	Exhaust ventilation (C1)	Exhaust ventilation (C1)	Balanced ventilation with heat recovery (D1)
Air tightness	Not improved	Medium	Medium	High
Heating system	Radiators	Radiators	Add-on fans (per room)	Radiators
Estimated investment		€ 9.222	€ 12.474	€ 16.998

14.2.6 Measures

In the last tabs an overview of the used renovation measures is provided (Figure 14.7) and the performed cost analysis. The green boxes, which provide an indication of the U-value, heating capacity of the LT-radiator and costs, can be adjusted to ones wishes. The cost analysis can be used as guideline for the U-values and estimated costs.

Figure 14.7: Measures tab

Measures

Overview of available renovation measures. The value of the green boxes can be changed to match the current situation.

		U-value	Costs	
Windows	Double glazing	2,2	€ 0	per m²
	HR++ glazing	1,1	€ 137	per m²
	Triple glazing	0,8	€ 182	per m²
Wall	Uninsulated wall	2,56	€ 0	per m²
	Cavity wall insulation	0,56	€ 28	per m²
	Interior wall insulation	0,65	€ 54	per m²
	Exterior wall insulation	0,41	€ 117	per m²
Roof	Uninsulated roof	2,05	€ 0	per m²
	Insulated attic	0,42	€ 22	per m²
	Roof insulation	0,42	€ 63	per m²
Floor	Uninsulated floor	2,09	€ 0	per m²
	Floor insulation below floor	0,3	€ 41	per m²
	Floor insulation above floor	0,53	€ 74	per m²
Ventilation	Natural ventilation (A)	0,75	€ 0	per dwelling
	Exhaust ventilation (C1)	1	€ 2.515	per dwelling
	Demand-driven exhaust ventilation (C2)	0,5	€ 4.304	per dwelling
	Balanced ventilation with heat recovery (D1)	0,2	€ 6.123	per dwelling
Heating	Radiators	'Radiator'-sheet	€ 0	per unit
	Add-on fans (per room)	extra 20%	€ 197	per unit
	LT-radiators (per room)	2500	€ 528	per unit
Airtightness	Not improved	0,00019	€ 0	per dwelling
	Medium	0,00010	€ 447	per dwelling
	High	0,00005	€ 1.560	per dwelling

14.3 Compared to case study results

Section 12.3 mentioned the minimum required renovation measures per ventilation type to maintain thermal comfort with low-temperature heating for the case study building. These variants have all been entered into the tool, of which the output was compared to the DesignBuilder results in Table 14.1. The results from DesignBuilder were all LT-Ready, where the results for the tool were never LT-Ready. An explanation for this can be that the ISSO-51 calculates the required capacity for the coldest day of the year, where the DesignBuilder simulations compare the hours too cold before and after renovation. The hours too cold are the moments when the capacity does not meet the heating demand so it accepts a limit when the heating demand exceeds the heating capacity. This illustrates the difference in method between the ISSO-51 and comparing hours too cold with dynamic simulations because the second one accepts that the heating system does not always meet the demand. ISSO-51 is thus over-dimensioned.

Table 14.1: Tool results compared with DesignBuilder results

Ventilation system	Variant	Minimum renovation measures to provide thermal comfort	Entire dwelling	Living room
Exhaust ventilation – C1	1	LT-radiator	Almost LT-READY	LT-READY
	2	Wall insulation (extra Rc=2.4) **and** HR++ glazing	Not LT-READY	Almost LT-READY
	3	Cavity wall insulation **and** HR++ glazing **and** add-on fan	Almost LT-READY	Almost LT-READY

	4	Cavity wall insulation **and** HR++ glazing **and** floor *or* roof insulation	Almost LT-READY	Almost LT-READY
Exhaust ventilation – demand driven – C2	1	LT-radiator	Almost LT-READY	LT-READY
	2	Exterior insulation	Almost LT-READY	Almost LT-READY
	3	Wall insulation **and** HR++ glazing *or* radiant screen *or* add-on fans	Almost LT-READY	Almost LT-READY
	4	HR++ glazing **and** floor insulation **and** attic insulation **and** add-on fans	Almost LT-READY	Almost LT-READY
Balanced ventilation with heat recovery – D1	1	LT-radiator	Almost LT-READY	LT-READY
	2	Triple glazing	Not LT-READY	Not LT-READY
	3	Wall insulation	Almost LT-READY	Almost LT-READY
	4	HR++ glazing **and** floor insulation **and** roof insulation	Almost LT-READY	Almost LT-READY

14.4 Further development

The tool provides different options for house owners to determine the LT-Readiness of their dwelling, but it could be developed further in several ways.

First of all, the tool was developed after performing the dynamic simulations for the case study building, but these were not performed while having the tool in mind. The tool is stationary and does not include a dynamic component, which performs well enough but should be validated with dynamic simulation software. Thus, additional dynamic simulations can be performed to check if the tool is behaving correctly. Also, dynamic simulations with other case study buildings can benefit the validation.

Secondly, the tool can be further developed by extending the tool with other building types, such as corner houses, apartments, and (semi-)detached dwellings to make it applicable to more buildings.

Another component that could be added is checking for which outdoor temperature the renovation concepts would be LT-Ready. For example, a renovation cannot be LT-Ready with an outdoor temperature of -10 °C but could be when it is 5 degrees outside. This means that when it has a colder outdoor temperature, the indoor temperature would be lower because the heating demand is higher than the capacity, but in this case, lower indoor temperatures can be acceptable.

15 Tool used on 1st case study

Chapter 12 provided several recommendations for LT-Ready concepts based on a variety of results derived from dynamic simulations. However, to select suitable LT-Ready concepts, a context was required with limiting factors such as building limitations or limitations to the budget. It was concluded that for a different context, a different LT-Ready concept would work best.

This chapter elaborates on this fact and shows how the tool can be used to derive renovation concepts for different contexts. When a different context is used as the original situation, the result would be different LT-Ready concepts than for example with another context. Two scenarios have been applied to the tool as context: in Section 15.1 when already exhaust ventilation (C1) is used, and Section 15.2 when no wall insulation can be applied to the dwelling.

15.1 Scenario 1: Already exhaust ventilation (C1) installed

In scenario 1, the dwelling already has exhaust ventilation (C1) and HR++ glazing. Figure 15.1 shows three possible renovation concepts with their effect on the LT-Readiness of the entire dwelling and living room and budget. All concepts are LT-Ready for the living room, and concept 3 also for the entire dwelling.

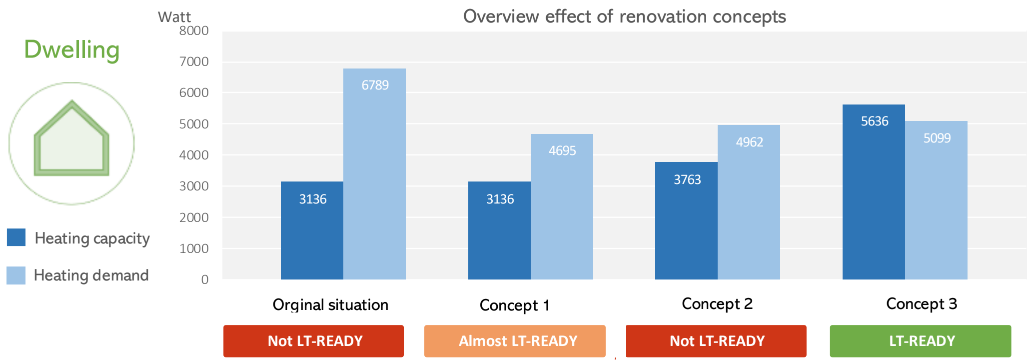
Figure 15.1: Results for scenario 1

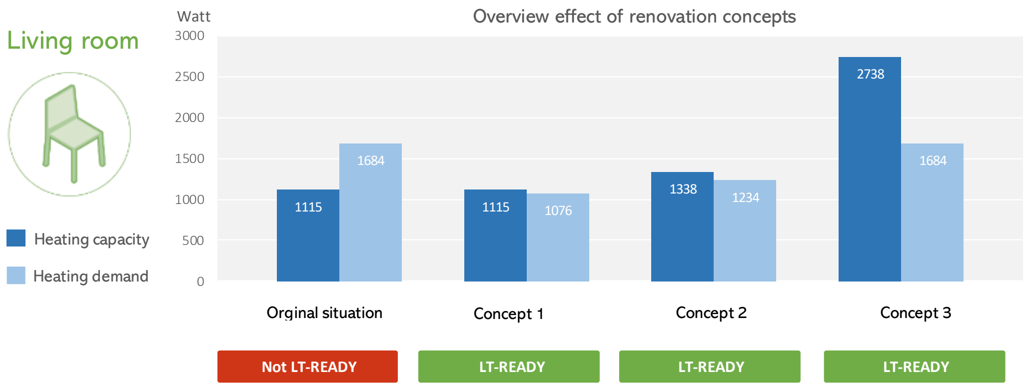
Comparison

The different renovation concepts are combared with the original situation, in order to select the best performing renovation concept per situation.

Available heating capacity 3136 W

	Original	Concept 1	Concept 2	Concept 3
Windows	HR++ glazing	HR++ glazing	HR++ glazing	HR++ glazing
Wall	Uninsulated wall	**Exterior wall insulation**	**Cavity wall insulation**	Uninsulated wall
Roof	Uninsulated roof	Uninsulated roof	Uninsulated roof	**Roof insulation**
Floor	Uninsulated floor	**Floor insulation below floor**	Uninsulated floor	**Floor insulation below floor**
Ventilation	Exhaust ventilation (C1)	Exhaust ventilation (C1)	Exhaust ventilation (C1)	Exhaust ventilation (C1)
Air tightness	Medium	Medium	Medium	Medium
Heating system	Radiators	Radiators	**Add-on fans (per room)**	**LT-radiators (per room)**
Estimated investment		€ 6.438	€ 1.354	€ 4.565





15.2 Scenario 2: No wall insulation possible

In scenario 2, the dwelling is not insulated and does not have a ventilation system. Also, no wall insulation is possible. Figure 15.2 shows three possible renovation concepts with their effect on the LT-Readiness of the entire dwelling and living room and budget. Only concept 3 is LT-Ready for the living room, the other concepts are almost LT-Ready. For the entire dwelling, all concepts are Almost LT-Ready. It can be concluded that reaching an LT-Ready dwelling is more difficult when no wall insulation can be applied. This scenario led to different results than scenario 1 due to the limitations of the dwelling.

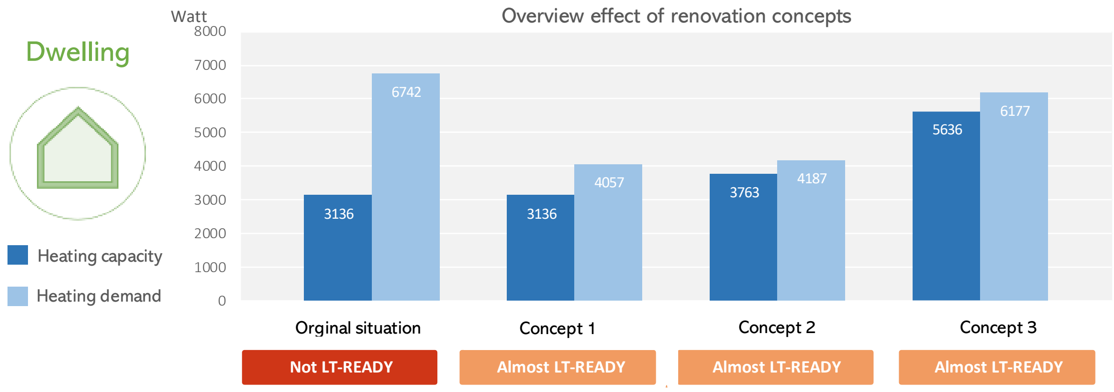
Figure 15.2: Results for scenario 2

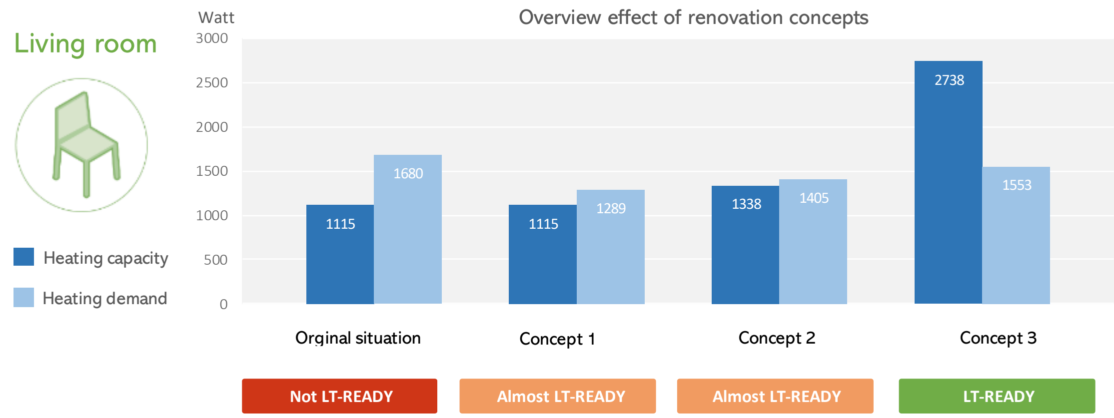
Comparison

The different renovation concepts are combared with the original situation, in order to select the best performing renovation concept per situation.

Available heating capacity 3136 W

	Original	Concept 1	Concept 2	Concept 3
Windows	Double glazing	**HR++ glazing**	**HR++ glazing**	**HR++ glazing**
Wall	Uninsulated wall	Uninsulated wall	Uninsulated wall	Uninsulated wall
Roof	Uninsulated roof	**Insulated attic**	**Insulated attic**	Uninsulated roof
Floor	Uninsulated floor	**Floor insulation below floor**	Uninsulated floor	Uninsulated floor
Ventilation	Natural ventilation (A)	**Balanced ventilation with heat recovery (D1)**	**Balanced ventilation with heat recovery (D1)**	**Demand-driven exhaust ventilation (C2)**
Air tightness	Medium	Medium	Medium	Medium
Heating system	Radiators	Radiators	**Add-on fans (per room)**	**LT-radiators (per room)**
Estimated investment		€ 10.186	€ 8.859	€ 6.612





16 Tool used 2nd case study

In this chapter, the tool is demonstrated on a second case study dwelling. The tool has a simpler approach to determine if a dwelling is LT-Ready than the dynamic simulations because it is designed for house owners. Thus, a short description of the case study dwelling is provided in Section 16.1 which was used as information for the tool. Section 16.2 presents the results based on the tool to determine if the dwelling is LT-Ready.

16.1 Description of dwelling

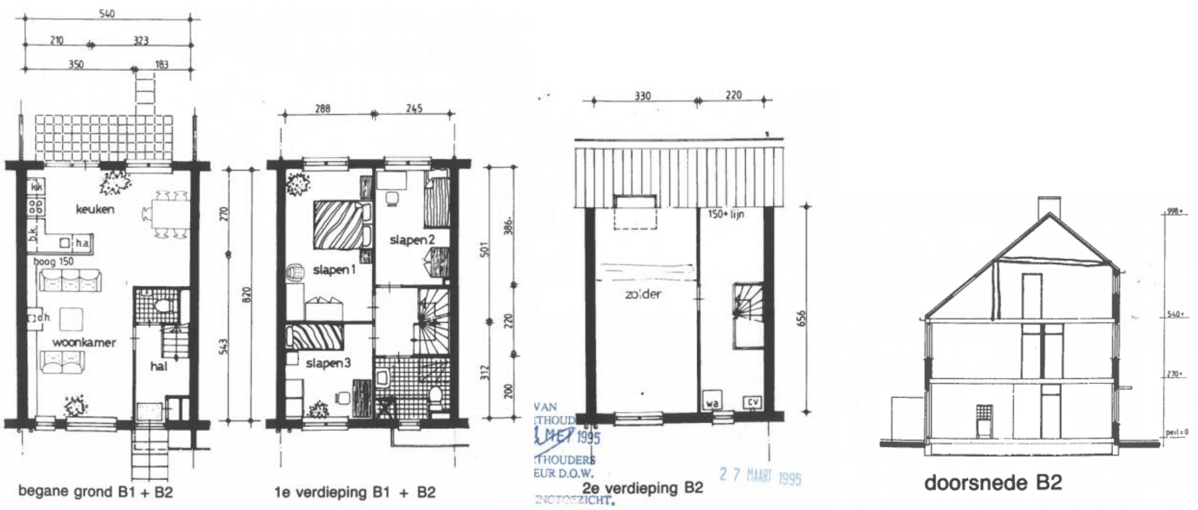
Figure 16.1 shows the second case study dwelling, which is also a type of terraced housing and located in Rijswijk (Zuid-Holland). The dwelling was built in 1989. This section provides an overview of available drawings, radiators and the insulation level of the dwelling.

Figure 16.1: Case study building

Drawings

Figure 16.2 shows the original drawings of the case study building of the floor plans and sections. One change has been made to the floor plans, which is an extension of the living room and the wall between the kitchen and living room was demolished. Also a dormer has been added to the dwelling.

Figure 16.2: Drawings of case study building



Radiators

The dwelling is heated with radiators placed in different rooms. An overview of the radiators is provided in Figure 16.3. Table 16.1 shows the radiator type and its dimensions.

Table 16.1: Overview of radiators

Radiator	Type [-]	Height [cm]	Width [cm]
Living room - 1	33	225	45
Living room - 2	22	140	50
Hall	22	100	50
Bedroom 1 - 1	11	120	50
Bedroom 1 – 2	11	120	50
Bedroom 2	10	140	50
Bathroom		900 W	
Bedroom 3	22	160	40
Bedroom 4	21	140	50

Figure 16.3: Overview of radiators

Ventilation system

The dwelling has exhaust ventilation.

Insulation level

The insulation level of the dwelling are derived from the documentation of the dwelling provided by the constructors. An overview is provided in Table 16.2

Table 16.2: Building parts and properties

Building part	Properties
Windows	Double glazing
Ground floor	Combination floor (Dutch: *Combinatie/Broodjesvloer*) R_c = min. 2.2 m^2K/W
Exterior wall	Brick 100 mm Cavity insulation (λ=0.033 W/mK) 70 mm Sand-lime brick 100 mm Calculated R_c = min. 3.0 m^2K/W
Roof	P.P.V.-sheet R_c derived from Appendix = 2.5 m^2K/W

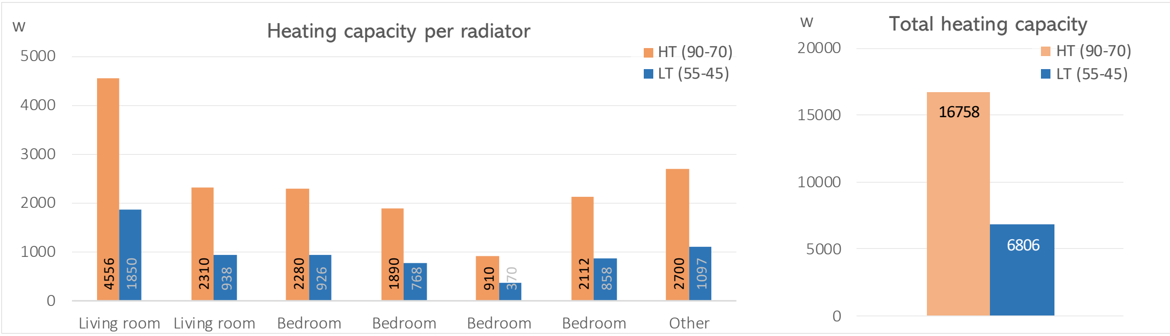
16.2 Results tool

The description of the dwelling was used to for the LT-Ready tool. The results per tab are provided.

Heating capacity

The available heating capacity in the dwelling is shown in Figure 16.4 per radiator and for the entire dwelling, for high-temperature (supply = 90°C, return = 70°C) and low-temperature (supply = 55°C, return = 45°C) heating.

Figure 16.4: Available heating capacity of the radiators



Original situation

The required information for the tool was provided based on the description of the dwelling to calculate the heating demand. Results are provided in Figure 16.5. The case study dwelling originally was already a bit insulated and has a large heating capacity, which implies enough to be LT-Ready. The living room is almost LT-Ready.

Figure 16.5: Original situation

Comparison

Since the dwelling is already insulated and LT-Ready, not many additional renovation measures are required. Still, 3 different renovation concepts were developed to determine suitable renovation concepts to make the living room LT-Ready and compared with the estimated costs (Figure 16.6). The first concept includes adding HR++ glazing to the dwelling, which reduces the heating demand but not that much to make the dwelling entirely LT-Ready. Adding add-on fans combined with HR++ glazing makes the dwelling LT-Ready, as well as replacing the exhaust ventilation with a ventilation system with heat recovery. There is however a large difference in estimated investment. Ventilation with heat-recovery reduces the heating demand but is more expensive, where add-on fans are relatively cheap and increase the heating capacity but not reduce the heating demand.

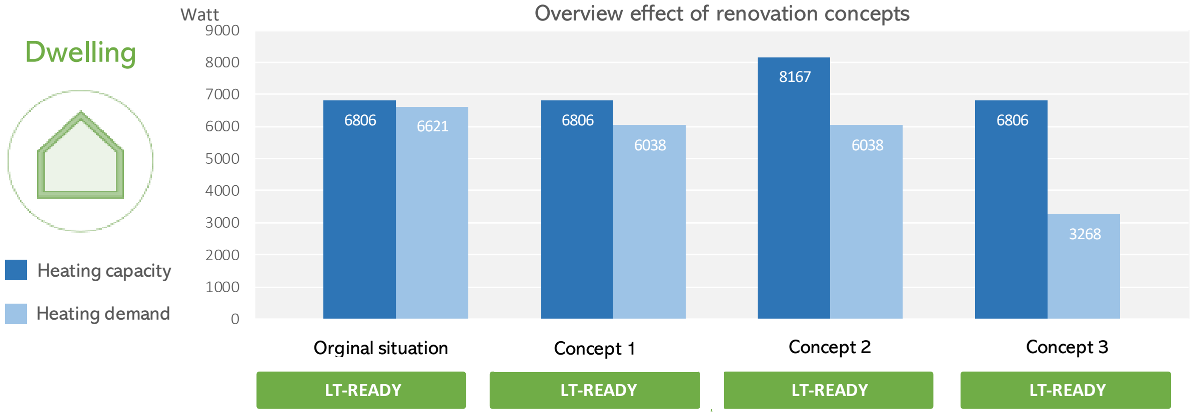
Figure 16.6: Comparison of different renovation concepts

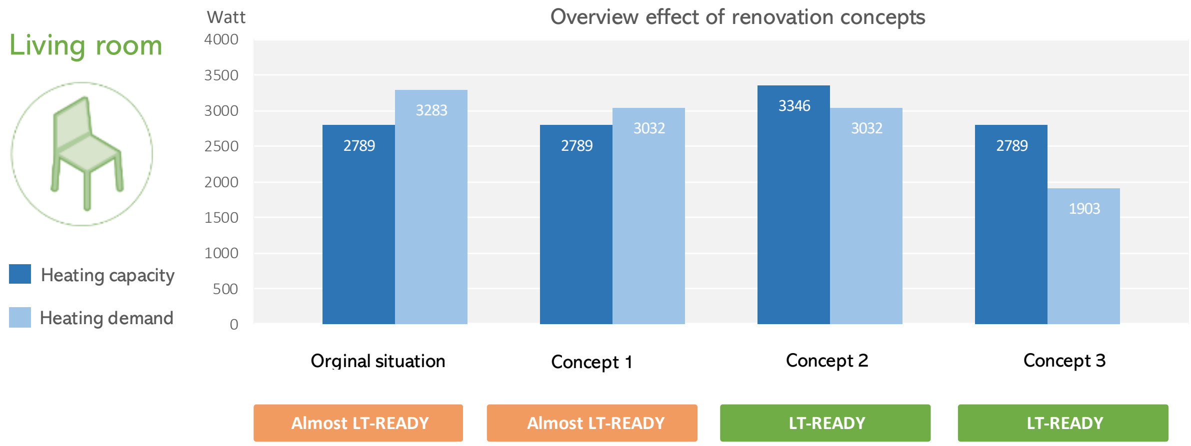
Comparison

The different renovation concepts are combared with the original situation, in order to select the best performing renovation concept per situation.

Available heating capacity 6806 W

	Original	Concept 1	Concept 2	Concept 3
Windows	Double glazing	**HR++ glazing**	**HR++ glazing**	**HR++ glazing**
Wall	Cavity wall insulation	Cavity wall insulation	Cavity wall insulation	Cavity wall insulation
Roof	Roof insulation	Roof insulation	Roof insulation	Roof insulation
Floor	Floor insulation below floor	Floor insulation below floor	Floor insulation below floor	Floor insulation below floor
Ventilation	Exhaust ventilation (C1)	Exhaust ventilation (C1)	Exhaust ventilation (C1)	**Balanced ventilation with heat recovery (D1)**
Air tightness	Medium	Medium	Medium	**High**
Heating system	Radiators	Radiators	**Add-on fans (per room)**	Radiators
Estimated investment		€ 3.055	€ 3.252	€ 10.738





Conclusion and discussion

17 Conclusion

The main goal of this research was to investigate what minimal renovation measures are required to provide comfort with low-temperature heating for terraced housing in the Netherlands. This chapter answers the main research question and discusses results and conclusions. First, the sub-questions are answered, followed by answering the main research question and providing options for further research.

The main research question within this graduation project was:

> *"What combination of renovation measures for residential buildings is affordable and provides thermal comfort, when using a lower supply temperature for heating?"*

Before answering the main research question, the different sub questions are answered.

1. What is the available investment budget of house owners for renovations?
Only half of the house owners have an available investment budget of €10,000. Also, the majority of house owners have no idea how much they want to spend on a renovation for their dwelling. Researched budget ranges that people were willing to pay were mostly below €5000.

Another finding was that house owners with a dwelling with a low energy label usually have a lower investment budget available for a renovation than house owners with a high energy label. This is problematic because dwellings with a lower energy label require a renovation to provide the same level of thermal comfort when they are heated with lower supply temperatures. The investment budget for renovation can however be reduced by subsidies or loans.

Thus, the used budget ranges within this research project focus on the lower side and the minimum renovation measures needed. The used budget ranges were below €5000, between €5000 and €7500, and above €7500. By focussing on less expensive renovation, the step for renovation becomes more accessible for a large group of house owners with a minimal investment budget.

2. Which thermal comfort criteria can be defined for low-temperature heated dwellings based on current thermal comfort regulations?
Thermal comfort is subjective but can be determined by using different (international) standards. A standard that is widely used in the Netherlands is the ATG-method (*Adaptieve Temperatuur Grenswaarde*), which makes a distinction between buildings with and without options for adaptability. It can be used to calculate the hours too cold or too warm for a dwelling.

A disadvantage of current thermal comfort standards is that they are usually developed for offices, and not for dwellings. Dwellings have more options for adaptability, such as opening windows, turning the heat on or off, but also drinking hot drinks, grabbing blankets, or changing clothes. Also, house owners are responsible for paying their energy bills. This all implies that a wider setpoint is possible for dwellings than current thermal comfort standards suggest.

Therefore, an adapted version of the ATG-method is used specially developed for different rooms in dwellings by Peeters et al. (2009). The hours too cold after renovation with low-temperature heating is compared to hours too cold of the original, not renovated situation with high-temperature heating. If this number of hours too cold is reduced, the renovation concept improves thermal comfort with low-temperature heating and can thus be considered as LT-Ready.

3. Which local comfort aspects needs to be researched to create comfortable low-temperature heated dwellings?
Besides the temperature, local discomfort is also an important factor in evaluating thermal comfort. When low-temperature heating is used, the chances of local discomfort are increased. Local comfort aspects that were further analysed included thermal stratification, the floor surface temperature, and cold drafts within the room.

4. Which renovation measures are available for renovations to enable low-temperature heating?
Using a lower supply temperature for heating reduces the heating capacity of the heating system. This results in less provided heat, and therefore lower indoor temperatures. To maintain the same level of thermal comfort or the heating capacity of the system has to be enlarged, or the losses of the building have to be reduced, or a combination of both. The heating capacity of the heating system can be enlarged by increasing the area or the heat transfer coefficient. Building losses

can be reduced by reducing transmission, ventilation- and infiltration losses. This results in an overview of measures on three scales: the building envelope-, installations-, and room-scale. A complete overview of renovation measures is shown in Figure 6.25.

Measures to the building envelope include insulating the wall, roof, and ground floor and replacing windows. These measures reduce the transmission losses of the building. Also improving the airtightness of the building can be done to the building envelope, which reduces the infiltration losses.

Replacing the ventilation and heating system belong to measures to the building installation scale. Usually, when a dwelling is renovated, a ventilation system is also placed. This can increase or reduce the ventilation losses depending on the ventilation type; exhaust ventilation (C1) will increase the ventilation losses, where demand-driven exhaust ventilation (C2) or balanced ventilation with heat recovery (D1) will reduce the ventilation losses. Replacing original radiators with LT-radiators or placing add-on fans increases the heat capacity of the heating system.

Renovation measures to the room scale are mostly related to preventing local discomfort issues, such as ventilation grills that prevent cold drafts or placing furniture in a way it does not block the heat out of the radiator.

5. Which measures are cost effective?

Only cost-effective renovation measures were selected to match the budget ranges answered in sub-question 1. To determine the costs and cost-effectiveness of renovation measures, a cost analysis was developed which can be found in Table 7.1. The cost-effectiveness was determined by calculating the effect of renovation measures. Based on the cost analysis, the most cost-effective measures were selected to set up renovation concepts. These can be found in Table 7.7.

6. What combination of measures provides thermal comfort with low-temperature heating?

With low-temperature heating, the heating capacity of the radiators is reduced which can reduce thermal comfort. This can be prevented by reducing the heating demand of the building, by replacing the ventilation system for demand-driven ventilation (C2) or balanced ventilation with heat recovery (D1), improving the airtightness, or insulating the building envelope. Another option is to increase the heating capacity of the heating system by placing add-on fans below the original radiators or replacing them with LT-radiators. Based on this approach, different renovation concepts were set up and tested with dynamic simulation software for a case study dwelling.

For this case study dwelling, the simulated renovation concepts lead to a large variety of options that provide thermal comfort. However, to select renovation concepts from this variety, different scenarios were set up based on limitations provided by the context. For example, the best option for thermal performance without building limitations would be adding balanced ventilation with heat recovery (D1), combined with cavity wall insulation, and replacing the windows in the living room with HR++ glazing. However, in a situation without space for the heat recovery unit, demand-driven exhaust ventilation would work best. And when it is not possible to add wall insulation to the building, demand-driven exhaust ventilation can be combined with attic and floor insulation, replacing windows in the living room with HR++ glazing and placing add-on fans. Thus, different renovation concepts can provide thermal comfort with low-temperature heating for the case study. However, which renovation concept works best depends on the context, e.g., the building limitations and the budget.

The case study represents a common scenario in the Dutch building stock. Thus, general conclusions on the effectiveness of measures can apply to other dwellings as well. In general, replacing the ventilation system with demand-driven or balanced ventilation showed the largest effect, as well as insulating the walls and replacing windows. This all leads to the largest reduction of ventilation- and transmission losses. Also, add-on fans have the potential to boost thermal comfort, since they are relatively cheap, have a large effect on thermal comfort but only a small effect on energy performance. In case no insulation can be applied, LT-radiators can be placed because of the increased heating capacity.

The decision for certain renovation measures does influence local comfort, and it is good to inform house owners of these consequences. Results for local comfort are also applicable to other dwellings. A ventilation system with ventilation grilles can cause cold drafts within a room, but balanced ventilation can also cause high air currents. The overall air temperature would be higher choosing for balanced ventilation with heat recovery. The location of the coach influences the heat distribution within the room and using add-on fans can prevent cold down-flow.

To determine which combination of measures provides thermal comfort with low-temperature heating with a more generic approach, the LT-Ready tool can be used which is based on *ISSO-51*. It compares the available heating capacity with the available heating demand for any terraced dwelling, so it applies also to other dwellings. It enables the user to identify which renovation measures their dwelling needs to make it LT-Ready. The tool is based on ISSO-51, which indicates the required heating demand on the coldest days, where the dynamic simulations accept that sometimes the available heating capacity does not meet the demand (i.e., hours too cold). This leads to an underprediction to LT-Readiness of a dwelling within the tool.

After answering the sub-questions, the main research question can be answered:

> *"What combination of renovation measures for residential buildings is affordable and provides thermal comfort, when using a lower supply temperature for heating?"*

Different combinations of renovation measures are possible within the investment budget of house owners to provide thermal comfort with low-temperature heating. A combination of renovation measures, also referred to as a renovation concept, is required because the thermal performance of dwellings must be upgraded for most dwellings to provide thermal comfort with low-temperature heating. Which combination of measures is required per dwelling depends on the dwelling's scenario, which includes limiting factors such as building or budget-related limitations.

Overall, important aspects to make a dwelling LT-Ready includes reducing the losses by upgrading the ventilation system to demand-driven exhaust ventilation or balanced ventilation with heat-recovery and insulating the building envelope with a focus on the windows and walls. Another option is to increase the heating capacity by using add-on fans. When insulating the dwelling is not possible, an LT-radiator can provide thermal comfort in every situation.

To determine which renovation measures are required to provide thermal comfort with low-temperature heating dynamic simulation software can be used for the case study building. This led to several options that were LT-Ready. Also, the developed tool can be used to determine LT-Ready concepts, which is based on ISSO-51.

An LT-Ready renovation is affordable and provides thermal comfort when lower supply temperatures are used, and in this thesis, multiple renovation concepts are presented which are LT-Ready. The challenge now lies in implementing the results in the renovation process and taking the first steps to an energy-neutral building stock: the LT-Ready renovation!

18 Discussion

18.1 Limitations of research

This research has several limitations, of which a few are described below:

- Dynamic simulation software
  Using dynamic simulation software provides a lot of options, but also has limitations. A general limitation of this type of software is a large amount of required data as input, especially in the used simulation software *DesignBuilder*. This large amount of data needed can lead to inaccuracies, which can lead to too positive or negative results. For example, data for the internal gains can be quite specific, with an assigned schedule per room which can lead to too detailed results. Therefore, for the internal gains, a standard value was used for the entire dwelling. This can however also result in a non-realistic simulation. It is thus difficult to find the level of required detail to perform an accurate dynamic simulation, which should be kept in mind interpreting the results.
- CFD-analysis
  The local discomfort analysis was performed with the CFD function of DesignBuilder. This function is however quite limited, experienced by teachers on this faculty. Therefore, the results are only interpreted for their fluid behaviours, but not for specific temperatures or airspeeds.
- Only 1 building type
  This study focussed on finding suitable LT-Ready renovations for the terraced housing building type. However, only one dwelling was researched in this project which can lead to too general conclusions based on too few case studies projects. Results should be checked with other dwellings before they are broadly applied.
- Focus on traditional renovation measures
  The focus within this project was mostly on traditional and affordable renovation measures. By focussing on this instead of innovative measures, e.g., PCM or high insulating materials, these measures could be overlooked while having a larger effect.
- Low-temperature heating and heating schedule
  Another limitation of the research was not changing the heating schedule. Because of the greater inertia of low-temperature heating systems, the system reacts slowly to changes. Thus, a constant temperature without night setback could have a large influence on improving thermal comfort and would not increase the energy demand that much.

18.2 Recommendations for further research

Based on the experiences within this graduation project, but also as research assistant for the LT-Ready project by TU Delft, different recommendations can be made for further research. Some recommendations are described below:

- Upscaling: research other building types and the effect on neighbourhood or city scale
  In this study, the required renovation measures to provide thermal comfort were only investigated for a terraced dwelling. Further research could focus on investigating the requirements for other types of dwellings, such as corner houses, (semi-)detached housing, or portiek flats.
- Implementing costs for sustainable heating sources
  The performed cost analysis included costs for renovation measures such as insulating the building envelope, adding a ventilation system, and changes to the heating system. However, costs related to sustainable heat production (e.g., heat pump system [possibly combined with PVT-panels], a connection to district heating network, additional boiler for domestic hot water) are not taken into account. To give a complete overview of the total required investment budget, these costs should also be taken into account.
- Domestic hot water
  With the transition to low-temperature heating is made, additional measures are required in dwellings to provide domestic hot water. This is to prevent diseases like legionella but also required to reach certain temperatures for hot water. This project can be extended by researching how to integrate the domestic hot water supply cost-effectively.

- Experimental testing with already renovated dwellings

  The findings of this study were mainly based on the outcome of dynamic simulation software. To evaluate these outcomes, additional research can be performed on already renovated dwellings by lowering the supply temperature. Thermal comfort can be evaluated with, for example, questionnaires for the situation with high-temperature and the situation with low-temperature heating.
- Additional research to local discomfort

  Additional research on low-temperature heating and local comfort can be done. Some ideas for future research are the position of the radiator in a room, the effect of floor heating and local comfort, the position of additional infrared heating panels and ventilation grills. The effect of local discomfort on the general conception of thermal comfort could also be researched, as well as which aspects are causing the most discomfort.

References

19 References

19.1 Literature

Agentschap NL. (2011). *Voorbeeldwoningen 2011 - Bestaande bouw*. https://www.rvo.nl/sites/default/files/bijlagen/4.%20Brochure%20Voorbeeldwoningen%202011%20bestaande%20bouw.pdf

Bone, A. (2009). *Basisboek Isoleren*. ThiemeMeulenhoff bv.

Bos, J., Verberk, M., & Warnaar, M. (2020, September 10). *Kunnen woningeigenaren energie-investeringen betalen?* Https://Www.Eigenhuis.Nl/Docs/Default-Source/Downloads/Actueel/Kunnen-Woningeigenaren-Energie-Investeringen-Betalen-Rapport.Pdf?Sfvrsn=1939b696_2

Brand, M., & Svendsen, S. (2013). Renewable-based low-temperature district heating for existing buildings in various stages of refurbishment. *Energy*, *62*, 311–319. https://doi.org/10.1016/j.energy.2013.09.027

Build It Solar. (2009). *Acrylic Storm Window*. https://www.builditsolar.com/Projects/Conservation/acrylicstormwindow.htm

CBS StatLine. (2012). *Energieverbruik particuliere woningen; woningtype, wijken en buurten, 2012* [Dataset]. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83023NED/table?ts=1609749320825

ClimaRad BV. (n.d.). *ClimaRad 2.0*. https://www.climarad.nl/producten/actueel/climarad-2.0/

Designing Buildings. (n.d.). Designing Buildings Wiki. https://www.designingbuildings.co.uk/wiki/Home

Duurzaam Bouwloket BV. (n.d.). *Radiatorfolie | Duurzaam Bouwloket*. https://www.duurzaambouwloket.nl/maatregel/radiatorfolie

DWA. (2016). *Comfortbeleving in goed geïsoleerde woningen met ventilatiesysteem C en lage temperatuurverwarming*. https://docplayer.nl/111187420-Comfortbeleving-in-goed-geisoleerde-woningen-met-ventilatiesysteem-c-en-lage-temperatuurverwarming.html

Eigen Huis. (n.d.). *Geld lenen voor energiebesparing*. Eigenhuis.nl. https://www.eigenhuis.nl/energie/financieel/geld-lenen-voor-energiebesparing#/energiebespaarlening

Eijdems, H. H. E. W., Boerstra, A. C., & Op 't Veld, P. J. M. (1999). *Low Temperature Heating System: Impact on IAQ, Thermal Comfort and Energy Consumption*. https://www.aivc.org/sites/default/files/members_area/medias/pdf/Conf/1999/paper002.pdf

European Commission. (2019, November 15). *Paris Agreement*. Climate Action - European Commission. https://ec.europa.eu/clima/policies/international/negotiations/paris_en

Fanger, P. O., & Christensen, N. K. (1986). Perception of draught in ventilated spaces. *Ergonomics*, *29*(2), 215–235. https://doi.org/10.1080/00140138608968261

Filgueira Luaces, S. (2020). *From gas to geothermal energy - Master thesis*. https://repository.tudelft.nl/islandora/object/uuid%3A32dcb3ab-d29e-45dd-8fcf-fc4a793aae7b

Hesaraki, A., Ploskic, A., & Holmberg, S. (2015). Integrating Low-temperature Heating Systems into Energy Efficient Buildings. *Energy Procedia*, *78*, 3043–3048. https://doi.org/10.1016/j.egypro.2015.11.720

Holmberg, S., Myhren, J. A., & Ploskic, A. (2010). *Low-temperature heat emission with integrated ventilation air supply*. 10th Reva World Congress on Sustainable Energy Use in Buildings, Clima 2010, Antalya, Turkey.

Ipsos. (2019, March 22). *Nederlander staat open voor verduurzaming van woning*. Ipsos. https://www.ipsos.com/nl-nl/nederlander-staat-open-voor-verduurzaming-van-woning

Jansen, S. C. (2013). *Exergy in the built environment. The added value of exergy in the assessment and development of energy systems for the built environment.* http://dx.doi.org/10.4233/uuid:04ce62bc-a5df-4706-a380-b2f5b156a3c2

Jansen, S., Mohammadi, S., & Bokel, R. (2021). Developing a locally balanced energy system for an existing neighbourhood, using the 'Smart Urban Isle' approach. *Sustainable Cities and Society*, *64*, 102496. https://doi.org/10.1016/j.scs.2020.102496

Klimapedia. (2013). *Tabellarium Warmte*. Klimapedia.Nl. https://klimapedia.nl/wp-content/uploads/2013/10/W-tabellarium.pdf

Konstantinou, T. (2014). *Facade Refurbishment Toolbox*. Van Haren Publishing.

Konstantinou, T., & Knaack, U. (2013). An approach to integrate energy efficiency upgrade into refurbishment design process, applied in two case-study buildings in Northern European climate. *Energy and Buildings*, *59*, 301–309. https://doi.org/10.1016/j.enbuild.2012.12.023

Linden, van der, A. C., Kuijpers-Van Gaalen, I. M., Zeegers, A., Erdtsieck, P., & Selten, T. A. J. (2006). *Bouwfysica* (6th ed.). ThiemeMeulenhoff.

Livios. (2019). *Ventilatie bij renovatie: hoe pak je het aan? - Ventilatie plaatsen en onderhouden - Livios*. Livios.be. https://www.livios.be/nl/bouwinformatie/technieken/ventilatie/ventilatie-plaatsen-en-onderhouden/ventilatie-bij-renovatie-hoe-pak-je-het-aan/

Milieu Centraal. (n.d.-a). *Lage temperatuur verwarming (ltv)*. https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/lage-temperatuur-verwarming-ltv/#Is-jouw-isolatie-al-voldoende

Milieu Centraal. (n.d.-b). *Subsidie voor isolatie*. https://www.milieucentraal.nl/energie-besparen/energiesubsidies-en-leningen/subsidie-voor-isolatie/

Ministerie van Economische Zaken en Klimaat. (2019, November 12). *Gebouwde omgeving*. Klimaatakkoord. https://www.klimaatakkoord.nl/gebouwde-omgeving

Myhren, J. A., & Holmberg, S. (2008). Flow patterns and thermal comfort in a room with panel, floor and wall heating. *Energy and Buildings*, *2008*(40), 524–536. https://doi.org/10.1016/j.enbuild.2007.04.011

Nicol, F., Humphreys, M., & Roaf, S. (2012). *Adaptive Thermal Comfort: Principles and Practice*. Amsterdam University Press.

Nicol, J. F., & Humphreys, M. A. (2009). New standards for comfort and energy use in buildings. *Building Research & Information*, *37*(1), 68–73. https://doi.org/10.1080/09613210802611041

Østergaard, D. (2018, November). *Heating of existing buildings by low-temperature district heating*. https://www.researchgate.net/publication/329308971_Heating_of_existing_buildings_by_low-temperature_district_heating

Østergaard, D. S., & Svendsen, S. (2016a). Theoretical overview of heating power and necessary heating supply temperatures in typical Danish single-family houses from the 1900s. *Energy and Buildings*, *126*, 375–383. https://doi.org/10.1016/j.enbuild.2016.05.034

Østergaard, D. S., & Svendsen, S. (2016b). Theoretical overview of heating power and necessary heating supply temperatures in typical Danish single-family houses from the 1900s. *Energy and Buildings*, *126*, 375–383. https://doi.org/10.1016/j.enbuild.2016.05.034

Peeters, L., Dear, R., Hensen, J., & D'haeseleer, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy*, *86*(5), 772–780. https://doi.org/10.1016/j.apenergy.2008.07.011

Ploskic, A. (2013). *Technical solutions for low-temperature heat emission in buildings*. Stockholm: PhD thesis in KTH. http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A660277&dswid=-2030

Raue, A. K., Kurvers, S. R., van der Linden, A. C., Boerstra, A. C., & Plokker, W. (2006). Dutch Thermal Comfort Guideliens: From weighted temperature exceeding hours towards adaptive thermal guidelines. -.

https://www.researchgate.net/publication/238693341_DUTCH_THERMAL_COMFORT_GUIDELINES_FROM_WEIGHTED_TEMPERATURE_EXCEEDING_HOURS_TOWARDS_ADAPTIVE_TEMPERATURE_LIMITS

Schoenmaker, F., Ras, T., Schouten, F., & Heynen, R. (2021). *Nationaal Warmtenet Rapport 2021*. https://www.warmtenettrendrapport.nl/trendrapport/

Tertium. (2015). *Apeldoornse Energie Agenda*. https://www.tertium.nl/wp-content/uploads/2015/11/Bijlage-A-Enquete-Apeldoorn-Energie-Neutraal.pdf

Thermo Shield. (n.d.). *Interieur*. https://www.thermoshield.nl/winkel/binnenwand-en-plafond/thermoshield-interieur/

TKI Urban Energy. (2020, May 14). *Warmtenetten*. www.topsectorenergie.nl. https://www.topsectorenergie.nl/tki-urban-energy/kennisdossiers/warmtenetten

TU Delft (2021). Information provided by *LT-Ready project.*

Vattenfall. (n.d.). *Radiatorfolie met magneettape | Vattenfall*. Vattenfall.nl. https://www.vattenfall.nl/kennis/radiatorfolie/

Vliet, van, E., Keijzer, de, J., Slingerland, E., Tilburg, van, J., Hofsteenge, W., & Haaksma, V. (2016). *Collectieve warmte naar lage temperatuur - Een verkenning van mogelijkheden en routes*. https://www.topsectorenergie.nl/sites/default/files/uploads/Urban%20energy/publicaties/Collectieve%20warmte%20naar%20lage%20temperatuur%20-%20definitief.pdf

Wang, Q., Ploskić, A., & Holmberg, S. (2015). Retrofitting with low-temperature heating to achieve energy-demand savings and thermal comfort. *Energy and Buildings*, *109*, 217–229. https://doi.org/10.1016/j.enbuild.2015.09.047

Wetering, van de, J. (2017). *Passive solutions for individual comfort systems*. https://repository.tudelft.nl/islandora/object/uuid%3A6563d7d2-74db-499a-9c6f-ed5f7bd26b37?collection=education

Wood, A., & Salib, R. (2013). *Guide to Natural Ventilation in High Rise Office Buildings*. Routledge.

Zelf energie besparen. (2021, March 25). *Radiator ventilator: gas besparen in een warmer huis!* https://www.zelfenergiebesparen.nl/gas-besparen/radiator-ventilator/

19.2 Figures

Figure 1.2	Corporatiewoning.com Newpapers: “Inwoners draaien op voor kosten om van het gas af te gaan” | Telstar Online - Actueel nieuws uit Pijnacker-Nootdorp (telstar-online.nl) 'Huizen aardgasvrij maken is complex en kost ook meer dan verwacht' | Nieuwsuur (nos.nl) Rotterdam: 3 miljard euro nodig voor duurzame woningen - Gemeente.nu Tilburg wil 900 woningen in West verduurzamen, vraagt 12 miljoen euro subsidie | Tilburg e.o. | bd.nl
Figure 2.1	Adapted from Bos, J., Verberk, M., & Warnaar, M. (2020, September 10). Kunnen woningeigenaren energie-investeringen betalen? From: https://www.eigenhuis.nl/docs/default-source/downloads/actueel/kunnen-woningeigenaren-energie-investeringen-betalen-rapport.pdf?sfvrsn=1939b696_2
Figure 3.1-2	Nicol, F., Humphreys, M., & Roaf, S. (2012). *Adaptive Thermal Comfort: Principles and Practice*. Amsterdam University Press.

Figure 3.3 Raue, A. K., Kurvers, S. R., van der Linden, A. C., Boerstra, A. C., & Plokker, W. (2006). Dutch Thermal Comfort Guideliens: From weighted temperature exceeding hours towards adaptive thermal guidelines.

Figure 3.5-3.7 Peeters, L., Dear, R., Hensen, J., & D'haeseleer, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy*, *86*(5), 772–780. https://doi.org/10.1016/j.apenergy.2008.07.011

Figure 4.7 Fanger, P. O., & Christensen, N. K. (1986). Perception of draught in ventilated spaces. *Ergonomics*, *29*(2), 215–235. https://doi.org/10.1080/00140138608968261

Figure 4.8c Antares. (2020, April 16). Ventilatieroosters: Gebruiksadvies. Retrieved from https://www.thuisbijantares.nl/handleidingen/ventilatieroosters-gebruiksadvies/

Figure 6.7 Amazon. (n.d.). RADIATOR COMMERCIAL GRADE REFLECTIVE FOIL HEAT REFLECTOR(16' X 2')-DOUBLE THICK 7.95mm CERTIFIED AND TESTED FOR CUSTOMER SAFETY. DOES NOT EMIT DANGEROUS TOXINS WHEN HEATED.SAVE ENERGY AND SAVE MONEY - - Amazon.com. Retrieved 13 May 2021, from https://www.amazon.com/COMMERCIAL-REFLECTIVE-FOIL-REFLECTOR-HEATED-SAVE/dp/B0851THWTL

Figure 6.9 Duurzaam Bouwloket BV. (n.d.). Radiatorfolie. Retrieved from https://www.duurzaambouwloket.nl/maatregel/radiatorfolie

Figure 6.10 Wilms, T. (2021, March 16). Minder gasverbruik door radiator-ventilator. Retrieved from https://www.gawalo.nl/klimaattechniek/nieuws/2019/09/minder-gasverbruik-door-radiator-ventilator-1017779

Figure 6.12 Warmteservice. (n.d.). Jaga Strada Hybrid convectorradiator DBH RAL9016 Verwarmen stand3 max. 1218 Watt(55/45/20) koelen stand3 max. 289 Watt(17/19/26) 50x80x11 batt STRW.05008011.133ACO. Retrieved from https://www.warmteservice.nl/Verwarming/Lage-temperatuur-verwarming/Lage-temperatuur-radiator/Jaga-Strada-Hybrid-convectorradiator-DBH-RAL9016/p/26356450

Figure 6.14 ClimaRad. (n.d.). ClimaRad 2.0. Retrieved from https://www.climarad.nl/producten/actueel/climarad-2.0/

Figure 6.15 Watts. (n.d.). Radiant Heating Systems. Retrieved from https://www.watts.com/solutions/systems/hydronic-heating-systems

Figure 6.16 ClimateCoating. (2020). ClimateCoating - Keramische filtertechnologie. Retrieved from https://climatecoating.nl/wp-content/uploads/2020/12/ClimateCoating_drieluik-map-1.pdf

Figure 6.18 CN Glass. (2019, December 2). Secondary Double Glazing. Retrieved from https://www.cnglass.co.uk/windows/secondary-double-glazing/

Figure 6.19 Build It Solar. (2009). Acrylic Storm Window. https://www.builditsolar.com/Projects/Conservation/acrylicstormwindow.htm

Figure 6.20 Renson. (n.d.). Invisivent COMFORT. Retrieved from https://www.renson.eu/nl-be/producten-zoeken/ventilatie/raamverluchtingen/roosters-op-het-raam/invisivent-comfort

Figure 6.21 Schueco. (n.d.). VentoTherm Twist. Retrieved from https://www.schueco.com/de-en/architects/products/ventilation-systems/ventilation/ventothermtwist

Figure 6.24 Thackeray, D. (2020, March 24). Infrared Heating: Frequently Asked Questions. Retrieved from https://www.infraredheatersdirect.co.uk/news/infrared-heating-faq/

Figure 9.1 Google maps

Figure 9.2-5 Adapted from LT-Ready project, TU Delft (2021)

Figure 15.2 Obtained from house owners

19.3 Tables

Table 2.1 Tertium. (2015). Apeldoornse Energie Agenda. https://www.tertium.nl/wp-content/uploads/2015/11/Bijlage-A-Enquete-Apeldoorn-Energie-Neutraal.pdf

Table 2.2 Ipsos. (2019, March 22). Nederlander staat open voor verduurzaming van woning. Ipsos. https://www.ipsos.com/nl-nl/nederlander-staat-open-voor-verduurzaming-van-woning

Table 3.1 Peeters, L., Dear, R., Hensen, J., & D'haeseleer, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy*, *86*(5), 772–780. https://doi.org/10.1016/j.apenergy.2008.07.011

Table 3.2-3.3 Nicol, F., Humphreys, M., & Roaf, S. (2012). *Adaptive Thermal Comfort: Principles and Practice*. Amsterdam University Press.

Table 3.3 Peeters, L., Dear, R., Hensen, J., & D'haeseleer, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy*, *86*(5), 772–780. https://doi.org/10.1016/j.apenergy.2008.07.011

Table 4.1-4.3 ISSO 7730

Table 4.2 Eijdems, H. H. E. W., Boerstra, A. C., & Op 't Veld, P. J. M. (1999). *Low Temperature Heating System: Impact on IAQ, Thermal Comfort and Energy Consumption*. https://www.aivc.org/sites/default/files/members_area/medias/pdf/Conf/1999/paper002.pdf

Table 5.1 Adjusted from Jansen, S. C. (2013). Exergy in the built environment. The added value of exergy in the assessment and development of energy systems for the built environment. http://dx.doi.org/10.4233/uuid:04ce62bc-a5df-4706-a380-b2f5b156a3c2

Table 6.2 Milieu Centraal. (n.d.). *Lage temperatuur verwarming (ltv)*. https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/lage-temperatuur-verwarming-ltv/#Is-jouw-isolatie-al-voldoende

Appendix

20 Appendix

A. Supply temperature for low temperature heating

Low-temperature heating can be supplied with different systems, e.g., district heating or an individual heat pump system. These are recognized as the most sustainable solutions and the most efficient heat production methods (Hesaraki et al., 2015). In this chapter, the supply temperatures for district heating and a heat pump system as a heat source will be given.

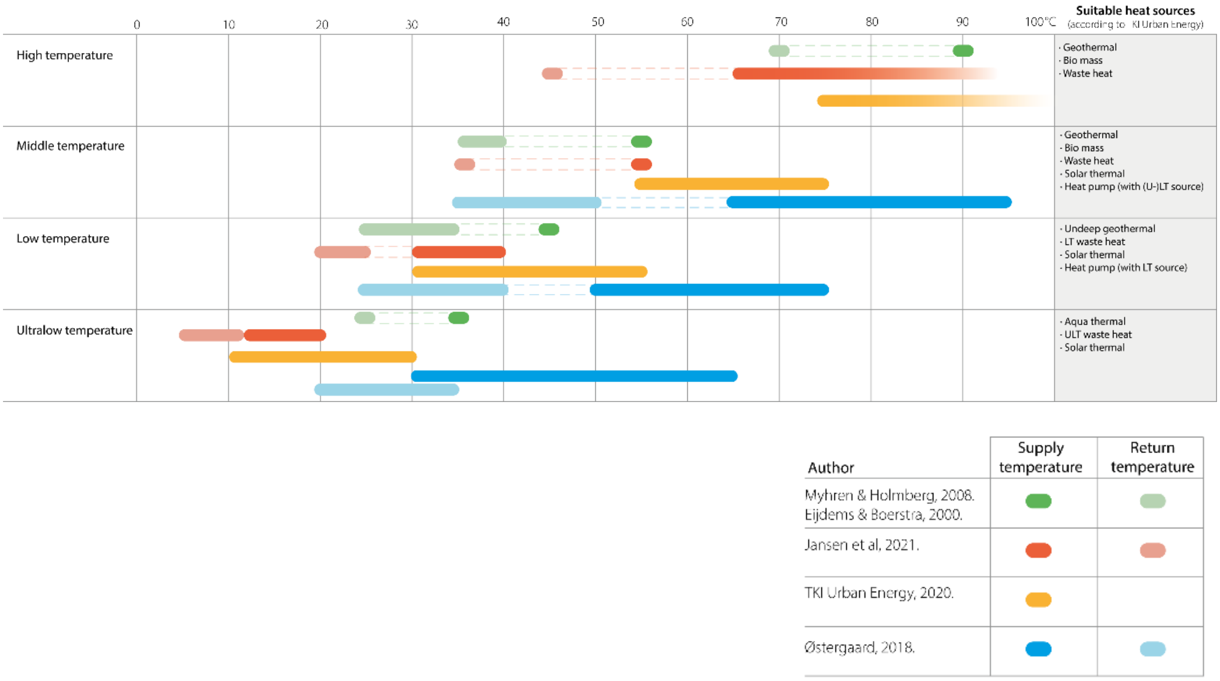
District heating

To achieve a comfortable indoor temperature of 20 °C, it is inefficient to use a conventional supply temperature of 90 °C. Also, sustainable heating sources mostly supply lower temperatures (TKI Urban Energy, 2020). Thus, the transition to low-temperature district heating as a heating source must be made. In general, four supply temperature ranges can be distinguished for district heating, which are:

- High-temperature
- Middle-temperature
- Low-temperature
- Ultra-low temperature

Myhren & Holmberg (2008), Eijdems et al. (1999), Østergaard (2018), TKI Urban Energy (2020), and Jansen et al. (2021), all use different temperature ranges within the mentioned categories. This makes the outcome of different research difficult to compare. It also creates confusion about the definitions for the temperature ranges. The temperature ranges provided by different authors are shown in figure 2.1. Confusion can occur when looking at Østergaard (2018) and TKI Urban Energy (2020); what Østergaard (2018) sees as a low-temperature, TKI Urban Energy (2020) recognize this temperature range as middle-temperature.

Figure A.1: Temperature ranges for different supply temperature levels (own work)



The definition of the different supply temperatures from TKI Urban Energy (2020) will be used in this graduation report because TKI Urban Energy is an organization that stimulates the development of innovations for sustainable and affordable energy systems in the built environment. This is financed by the Dutch government.

TKI Urban Energy also provides sustainable heating sources for the four categories. It does not give a return temperature. The return temperature will therefore be calculated with Formula A.1:

$$T_{return} = T_{supply} - 20°C \quad (A.1)$$

Heat pump

An alternative heat source for low-temperature heating is a heat pump. Heat pumps use renewable energy, stored in ambient air, in outgoing air from the building, in the ground, or groundwater, and increase their temperatures (Hesaraki et al., 2015). The efficiency of a heat pump is determined with the coefficient of performance (COP). If a COP is 4, the heat pump uses 1 kWh of electricity and 3 kWh of renewable energy, to deliver 4 kWh of heat. This is shown in Figure A.2. A higher COP is thus more efficient.

The COP is determined with the temperature difference between the temperature of the source and the desired temperature. If the temperature of the heating system is lower, the heat pump requires less effort. Thus, the system becomes more efficient (Hesaraki et al., 2015). An overview of the COP and the relation to the temperature difference between the desired temperature and the temperature of the source is shown in Figure A.3.

Figure A.2: Heat pump principle (own work)

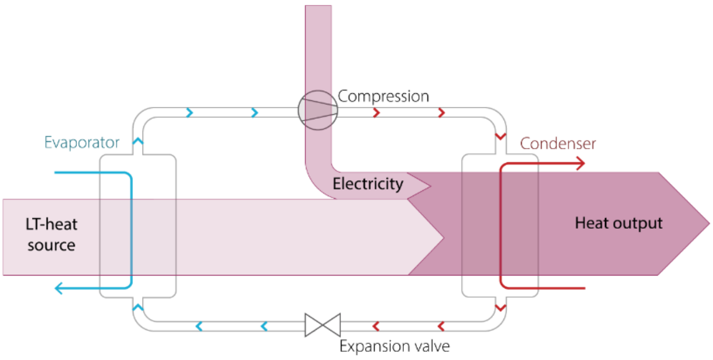
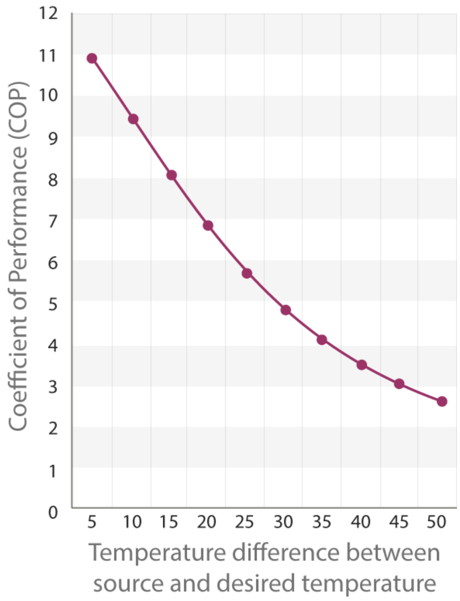


Figure A.3: COP of heat pumps (own work)



B. Dutch building stock

In this chapter, an overview of the residential building stock in the Netherlands is given. First, a timeline of the building regulations and most intensive building periods is given, followed by an overview of the status of the building stock. Based on this, the case study type building can be determined.

Timeline of building regulations and periods

An overview of the timeline of building regulations in the Netherlands is given in Figure B.1.

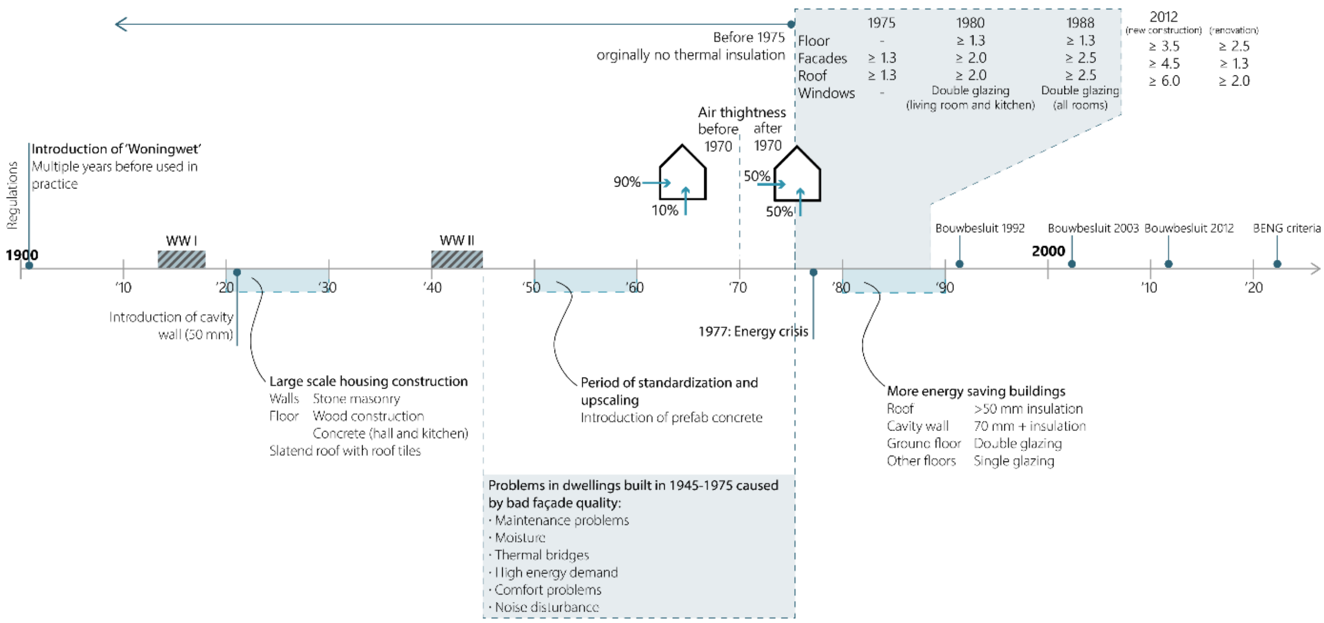
The Dutch building stock did not have any regulations until 1901, the year the 'Woningwet' was implemented (Bone, 2009). This law focussed mostly on creating healthy buildings since most buildings before 1900 were small and not healthy. It took multiple years before buildings were constructed according to the law.

In times of the first world war (1914-198), no houses were built because of the lack of building materials. After the war ended, construction slowly begun despite the lack of good materials. From 1920 to 1930 large-scale housing construction took place. The cavity wall was also introduced in this period, with an uninsulated cavity of 50 mm. The suite dwellings with terraced housing were very popular in this period, until the beginning of the second world war.

Again, during the second world war, no construction took place due to the lack of materials. After the war, another period with a lot of construction followed. Alternative building materials were used, like prefab concrete, to create an easy construction process with possibilities for standardization and upscaling. This resulted in buildings ranging from big apartment blocks to standardized terraced housing. The facades of the buildings constructed in this period mostly have bad quality and were originally not insulated. This can result in problems like maintenance problems, moisture, thermal bridges, high energy demand, thermal comfort problems, and acoustical problems.

In 1977 the oil crisis took place, which caused an awareness of energy as a product. This was translated into new building regulations. From 1975, regulations were made about thermal insulation, which increased multiple times in 15 years. In 1992 the first version of the Bouwbesluit was presented. The insulation levels indicated in the Bouwbesluit date from 2012. From January 2021, new BENG-regulations (nearly zero energy buildings) are made for new build dwellings.

Figure B.1: Timeline of building regulations and periods



Current state of the building stock

The total residential building stock in the Netherlands consists of 6.801.000 dwellings. Agentschap NL (2011) made an overview of the most common building types. These are:

- Terraced housing
- Detached houses
- Semi-detached houses
- Portiek houses
- Apartments
- Maisonette houses
- Other

Figure B.2: Building types and share of the building stock

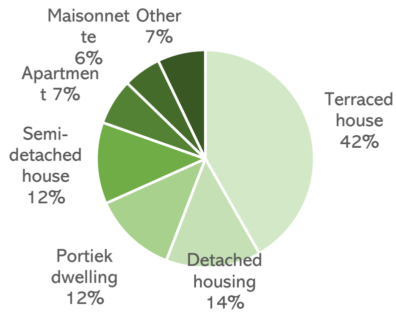


Table B.1: Terraced housing details

Building type[1]	Number[1]	Percentage of total building stock[1]	Average energy label[1]	Average demand for space heating[2]
Terraced house				
until 1945	523.000	7.7%	G (3,18)	116

1946 – 1964	478.000	7.0%	F (2,49)	101
1965 – 1974	606.000	9.0%	E (2,08)	97
1975 – 1991	879.000	12.9%	D (1,64)	88
1992 – 2005	353.000	5.2%	C (1,31)	75

1. Agentschap NL (2011)
2. CBS Statline (2012)

Building type[1]	Number[1]	Percentage of total building stock[1]	Average energy label[1]	Average demand for space heating[2]
Detached house				
until 1964	441.000	6,5%	G (2,96)	133
1965 – 1974	119.000	1,8%	F (2,42)	134
1975 – 1991	221.000	3,3%	D (1,63)	117
1992 – 2005	178.000	2,6%	B (1,22)	98
Semi-detached house				
until 1964	285.000	4,2%	F (2,79)	126
1965 – 1974	142.000	2,1%	E (2,38)	122
1975 – 1991	224.000	3,3%	C (1,56)	99
1992 – 2005	173.000	1,6%	B (1,29)	87
Terraced house				
until 1945	523.000	7,7%	G (3,18)	116
1946 – 1964	478.000	7,0%	F (2,49)	101
1965 – 1974	606.000	9,0%	E (2,08)	97
1975 – 1991	879.000	12,9%	D (1,64)	88
1992 – 2005	353.000	5,2%	C (1,31)	75
Maisonette dwelling				
until 1964	226.000	3,3%	G (3,02)	116
1965 – 1974	22.000	0,3%	D (1,82)	88
1975 – 1991	94.000	1,4%	C (1,45)	75
1992 – 2005	40.000	0,6%	B (1,17)	65
Apartment				
until 1964	69.000	1,0%	D (1,67)	88
1965 – 1974	174.000	2,6%	E (2,18)	95
1975 – 1991	109.000	1,6%	C (1,48)	74
1992 – 2005	113.000	1,7%	B (1,28)	62
Portiek housing				
until 1945	256.000	3,8%	F (2,90)	100
1946 – 1964	267.000	3,9%	E (2,06)	95
1965 – 1974	112.000	1,7%	D (1,72)	88
1975 – 1991	142.000	2,1%	C (1,31)	74
1992 – 2005	70.000	1,0%	B (1,14)	62
Apartment (other)				
until 1964	99.000	1,5%	E (2,03)	95
1965 – 1974	125.000	1,8%	E (2,20)	95
1975 – 1991	125.000	1,8%	C (1,49)	74
1992 – 2005	136.000	2,0%	B (1,22)	62

Derived from:

1. Agentschap NL. (2011). *Voorbeeldwoningen 2011 - Bestaande bouw*. https://www.rvo.nl/sites/default/files/bijlagen/4.%20Brochure%20Voorbeeldwoningen%202011%20bestaande%20bouw.pdf
2. CBS StatLine. (2012). Energieverbruik particuliere woningen; woningtype, wijken en buurten, 2012 [Dataset]. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83023NED/table?ts=16097493208
   Average space heating demand is based on average energy label

Terraced housing

Original energy level

First an overview of the original energy level of terraced housing for different building periods is provided in table 2, based on the *Voorbeeldwoningen* published by Agentschap NL (2011).

Table 2: Overview of original energy level in different building periods

	Building envelope	Windows	Installations
Until 1945 	Walls Before 1930: no cavity walls After 1930: cavity wall of 50 mm Floors Ground floor and other floors: Wood Hall and kitchen: concrete	Glazing Single glazing Window frame Steel or wood	Heating Local gas heating and electrical boilers Ventilation Natural ventilation
1946 – 1964 	Walls & floor Not insulated	Glazing Single glazing Window frame Steel	Heating Local gas heating and electrical boilers Ventilation Natural ventilation
1965 – 1974 	Walls & floor A bit insulated	Glazing First introduction of double glazing	Heating Local gas heater
1975 – 1991 	Walls, floor & roof 1975 – 1988: increased insulation level of different parts of the building envelope In general, buildings in the first part of this period are not good insulated.	Glazing Double glazing	Heating Central heating with HR-boiler
1992 – 2005 	Walls, floor & roof Better insulation, at least R_c = 2.5 Air tightness Improved air tightness	Glazing Double glazing or HR glazing	Heating Central heating with VR boiler Ventilation Mechanical ventilation (73%)

Current energy levels

During the lifespan of the building, different parts of the building can have undergone renovations or maintenance can be performed. For the building envelope, renovations can be performed to:

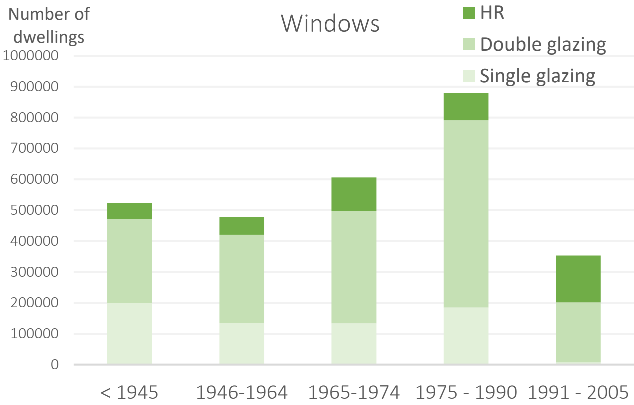
- Windows
- Walls
- Roof
- Floor

The maintenance performed to terraced housing for different building periods, based on research conducted by Agentschap NL (2011).

Windows

Replacement of the windows is common maintenance to a dwelling because the lifespan of a window is approximately 30 years (Brand & Svendsen, 2013). Figure B.3 shows the current window types for terraced houses built in different periods. Most single glazing is already replaced with double glazing and a smaller part with HR glazing. Dwellings built since 1991 do not have single glazing (Agentschap NL, 2011).

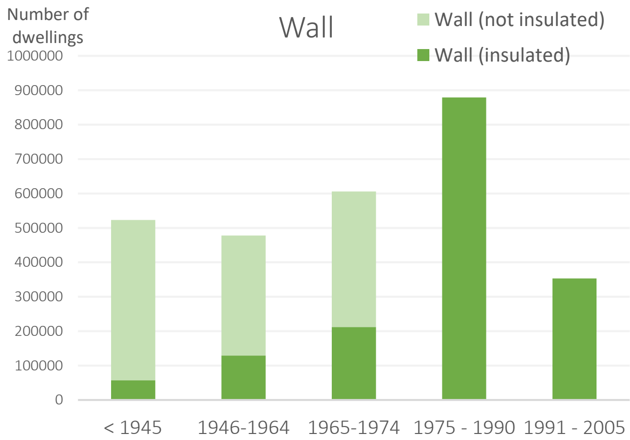
Figure B.3: Window types per building period



Walls

Figure B.4 shows that dwellings built after 1975 all have wall insulation (Agentschap NL, 2011). The insulation of dwellings built in the period between 1975 and 1990 might be outdated. Before 1975, dwellings originally had no insulation. This meant that the insulated share of these buildings is done through renovation. An increase in insulation percentages is seen per period for the buildings built before 1945, within 1946 to 1964, and from 1965 to 1974.

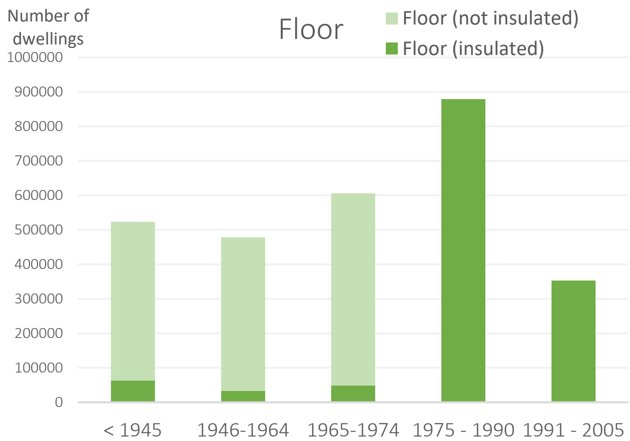
Figure B.4: Wall insulation per building period



Floor

Figure B.5 shows that dwellings built after 1975 all have floor insulation (Agentschap NL, 2011). The floorinsulation of dwellings built in the period between 1975 and 1990 might be outdated. Before 1975, dwellings originally had no insulation. The number of dwellings before 1975 with floor insulation is very low, even lower compared to the insulated walls. This ranges between 7 to 12% for the different building periods.

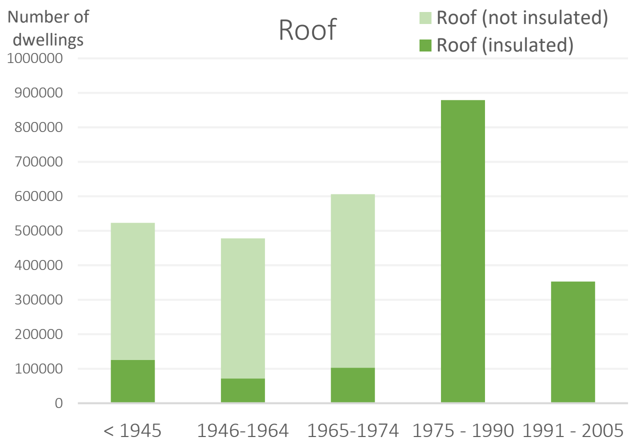
Figure B.5: Floor insulation per building period



Roof

Figure B.6 shows that dwellings built after 1975 all have roof insulation (Agentschap NL, 2011). The roof insulation of dwellings built in the period between 1975 and 1990 might be outdated.

Most of the dwellings built before 1975 do not have roof insulation, ranging from 15% to 24% of the dwellings in different building periods.



Case study building type

Dutch building regulations have changed a lot in the past century, from no laws before 1900 to building energy-neutral dwellings in 2021. A significant transition took place in 1975 because since then thermal insulation was obligated in newly constructed buildings (Bone, 2009). The most common building type in the Netherlands is terraced housing. The part of it built before 1975, with originally no thermal insulation, makes up 23,7% of the total building stock (Agentschap NL, 2011).

To determine which case study building is suitable for this graduation project, two requirements were set up:

- It should represent a large part of the building stock because he determined renovation solutions in this graduation project can widely be applied.
- It should have a poor energy level because the energy performance and thermal comfort can be improved

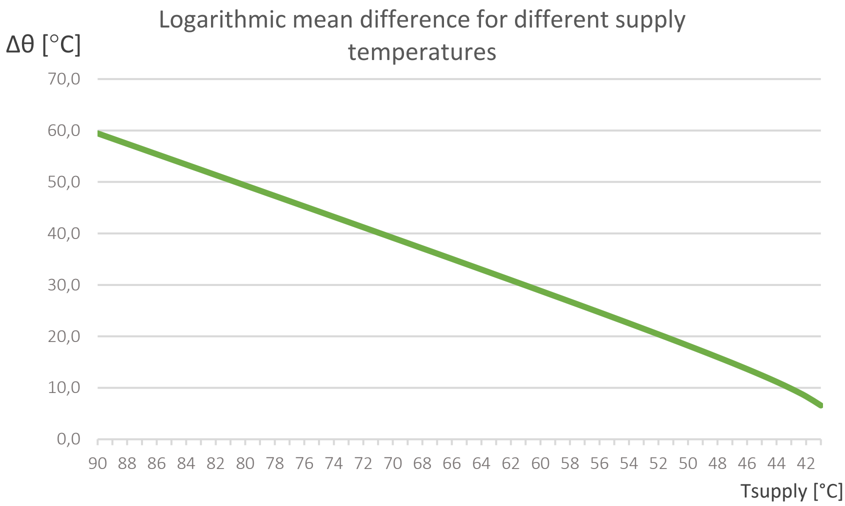
Therefore, a relevant case study building type can be *a terraced house built between in the period between 1920 and 1975.*

The current energy level of this building type varies from label G to E. It can also be concluded that common maintenance that is already be done is a replacement of the window. A reason for this is that the lifespan is windows is about 30 years (Brand & Svendsen, 2013). Other measures to upgrade the energy level regarding the building envelope, have not been performed yet. These measures include wall insulation, floor insulation, and roof insulation. From these three, floor insulation is the less performed. This all together shows potential in renovating the building envelope.

C. Logarithmic mean difference for different supply temperatures (Δθ)

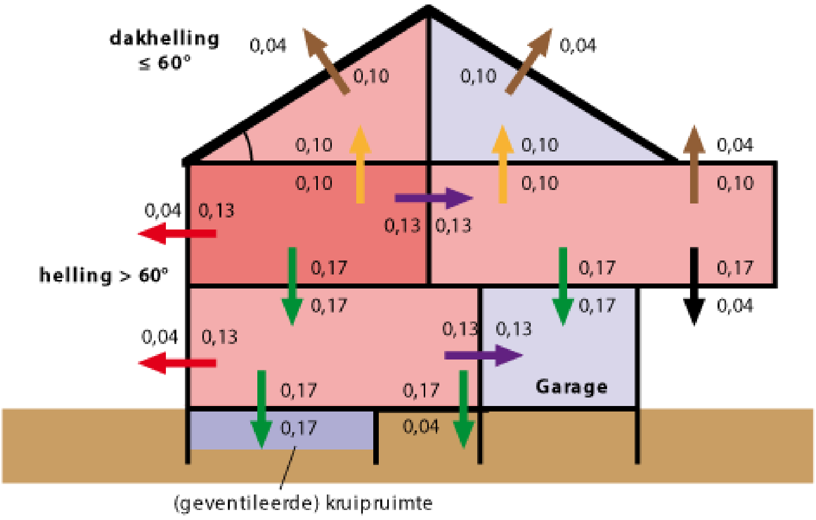
T_{supply}	T_{return}	Δθ
90	70	59.4
89	69	58.4
88	68	57.4
87	67	56.4
86	66	55.4
85	65	54.4
84	64	53.4
83	63	52.4
82	62	51.4
81	61	50.3
80	60	49.3
79	59	48.3
78	58	47.3
77	57	46.3
76	56	45.3
75	55	44.2
74	54	43.2
73	53	42.2
72	52	41.2
71	51	40.2
70	50	39.2
69	49	38.1
68	48	37.1
67	47	36.1
66	46	35.1
65	45	34.0
64	44	33.0
63	43	32.0
62	42	30.9
61	41	29.9
60	40	28.9
59	39	27.8
58	38	26.8
57	37	25.7
56	36	24.7
55	35	23.6
54	34	22.5
53	33	21.5
52	32	20.4
51	31	19.3

T_{indoor}	20 °C
T_{return}	T_{supply} -20 °C



T_{supply}	T_{return}	Δθ
50	30	18.2
49	29	17.1
48	28	16.0
47	27	14.8
46	26	13.6
45	25	12.4
44	24	11.2
43	23	9.8
42	22	8.3
41	21	6.6

D. R_{se} and R_{si} values per building envelope part



Derived from: Kennisbank ISSO. (n.d.). EnergieVademecum Energiebewust ontwerpen van nieuwbouwwoningen. Retrieved from:

https://www.kennisid.nl:443/retrievetoken?returnurl=https%3A%2F%2Fkennisbank.isso.nl%3A443%2Fpublicatie%2Fenergievademecum-energiebewust-ontwerpen-van-nieuwbouwwoningen%2F2020%2Fbijlage-1%3Fkennisidtoken%3D%7B0%7D

E. Construction data

■ Renovated situation ■ Original situation ■ Renovation measures

External Walls

External wall (renovated situation)		
Category		Walls
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Brickwork outer
	Thickness (m)	0.100
2	Material	Airofill
	Thickness (m)	0.070
3	Material	Brickwork inner
	Thickness (m)	0.100
4	Material	Gypsum plastering
	Thickness (m)	0.002
Inner layer		
Average thickness (m.)		0.275
R-Value (calculated)		2.796

External wall (original situation)		
Category		Walls
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Brickwork outer
	Thickness (m)	0.100
2	Material	Cavity
	Thickness (m)	0.070
3	Material	Brickwork inner
	Thickness (m)	0.100
4	Material	Gypsum plastering
	Thickness (m)	0.002
Inner layer		
Average thickness (m.)		0.275
R-Value (calculated)		0.695

External wall, cavity wall insulation		
Category		Walls
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Brickwork outer
	Thickness (m)	0.100
2	Material	EPS
	Thickness (m)	0.070
3	Material	Brickwork inner
	Thickness (m)	0.100
4	Material	Gypsum plastering
	Thickness (m)	0.002
Inner layer		
Average thickness (m.)		0.275
R-Value (calculated)		1.662

External wall, exterior wall insulation		
Category		Walls
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Brickwork outer
	Thickness (m)	0.020
2	Material	Mineral wool
	Thickness (m)	0.100
3	Material	Brickwork inner
	Thickness (m)	0.100
4	Material	Airofill
	Thickness (m)	0.070
5	Material	Brickwork inner
	Thickness (m)	0.100
6	Material	Gypsum plastering
	Thickness (m)	0.005
Inner layer		
Average thickness (m.)		0.374
R-Value (calculated)		3.371

External wall, interior wall insulation *light*		
Category		Walls
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Brickwork outer
	Thickness (m)	0.100
2	Material	Air
	Thickness (m)	0.070
3	Material	Brickwork inner
	Thickness (m)	0.100
4	Material	Mineral wool
	Thickness (m)	0.054
	Bridged [%]	10
	Material	Plywood
4	Material	Gypsum board
	Thickness (m)	0.0125
Inner layer		
Average thickness (m.)		0.337
R-Value (calculated)		1.904

External wall, interior wall insulation		
Category		Walls
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Brickwork outer
	Thickness (m)	0.100
2	Material	Air
	Thickness (m)	0.070
3	Material	Brickwork inner
	Thickness (m)	0.100
4	Material	Mineral wool
	Thickness (m)	0.102
	Bridged [%]	10
	Material	Plywood
4	Material	Gypsum board
	Thickness (m)	0.0125
Inner layer		
Average thickness (m.)		0.385
R-Value (calculated)		2.907

Floors

Ground floor (renovated situation)		
Category		Floors
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	EPS
	Thickness (m)	0.150
	Bridged [%]	10
	Material	Hardwood
2	Material	Timber flooring
	Thickness (m)	0.020
Inner layer		
Average thickness (m.)		0.170
R-Value (calculated)		3.256

Separation floor / Ground floor original situation		
Category		Floors
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Gypsum board
	Thickness (m)	0.0125
	Bridged [%]	10
	Material	Hardwood
2	Material	Air gap
	Thickness (m)	0.130
3	Material	Timber flooring
	Thickness (m)	0.020
	Bridged [%]	10
	Material	Hardwood
Inner layer		
Average thickness (m.)		0.1625
R-Value (calculated)		0.638

Ground floor, insulated below floor		
Category		Floors
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Mineral wool
	Thickness (m)	0.160
	Bridged [%]	10
	Material	Hardwood
2	Material	Timber flooring
	Thickness (m)	0.020
Inner layer		
Average thickness (m.)		0.180
R-Value (calculated)		3.631

Ground floor, insulated above floor		
Category		Floors
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Gypsum board
	Thickness (m)	0.0125
	Bridged [%]	10
	Material	Hardwood
2	Material	Air gap
	Thickness (m)	0.130
3	Material	Timber flooring
	Thickness (m)	0.020
	Bridged [%]	10
	Material	Hardwood
4	Material	Mineral wool
	Thickness (m)	0.075
5	Material	Timber flooring
	Thickness (m)	0.020
Inner layer		
Average thickness (m.)		0.256
R-Value (calculated)		2.754

Attic floor insulation		
Category		Floors
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Gypsum board
	Thickness (m)	0.0125
	Bridged [%]	10
	Material	Hardwood
2	Material	Air gap
	Thickness (m)	0.130
3	Material	Timber flooring
	Thickness (m)	0.020
	Bridged [%]	10
	Material	Hardwood
4	Material	Mineral wool
	Thickness (m)	0.155
Inner layer		
Average thickness (m.)		0.312
R-Value (calculated)		4.717

Roof

Roof (renovated situation)		
Category		Roof
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Clay tile
	Thickness (m)	0.025
2	Material	Air gap
	Thickness (m)	0.020
3	Material	Roofing felt
	Thickness (m)	0.005
4	Material	Mineral wool
	Thickness (m)	0.200
5	Material	Gypsum board
	Thickness (m)	0.0125
Inner layer		
Average thickness (m.)		0.2625
R-Value (calculated)		5.683

Roof (original situation)		
Category		Roof
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Clay tile
	Thickness (m)	0.025
2	Material	Air gap
	Thickness (m)	0.020
3	Material	Roofing felt
	Thickness (m)	0.005
4	Material	Mineral wool
	Thickness (m)	0.050
5	Material	Gypsum board
	Thickness (m)	0.0125
Inner layer		
Average thickness (m.)		0.1125
R-Value (calculated)		1.735

Roof, inside insulation *light*		
Category		Roof
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Clay tile
	Thickness (m)	0.025
2	Material	Air gap
	Thickness (m)	0.020
3	Material	Roofing felt
	Thickness (m)	0.005
4	Material	Mineral wool
	Thickness (m)	0.155
5	Material	Gypsum board
	Thickness (m)	0.0125
Inner layer		
Average thickness (m.)		0.2176
R-Value (calculated)		4.501

Roof, inside insulation *medium*		
Category		Roof
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Clay tile
	Thickness (m)	0.025
2	Material	Air gap
	Thickness (m)	0.020
3	Material	Roofing felt
	Thickness (m)	0.005
4	Material	Mineral wool
	Thickness (m)	0.2270
5	Material	Gypsum board
	Thickness (m)	0.0125
Inner layer		
Average thickness (m.)		0.2895
R-Value (calculated)		6.393

Crawling space

Crawling space		
Category		Roof
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Sand
	Thickness (m)	0.200
Inner layer		
Average thickness (m.)		0.200
R-Value (calculated)		0.310

Crawling space		
Category		Roof
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Sand
	Thickness (m)	0.200
2	Material	EPS
	Thickness (m)	0.160
Inner layer		
Average thickness (m.)		0.360
R-Value (calculated)		4.310

Windows

Double glazing	
Category	Window
Solar transmission	0.700
Light transmission	0.750
U-value	**2.400**

HR++ glazing	
Category	Window
Solar transmission	0.700
Light transmission	0.750
U-value	**1.100**

Triple glazing	
Category	Window
Solar transmission	0.700
Light transmission	0.750
U-value	**0.800**

Other

Internal door		
Category		Door
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Painted oak
	Thickness (m)	0.035
Inner layer		
Average thickness (m.)		0.035
R-Value (calculated)		0.354

External door		
Category		Door
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Painted oak
	Thickness (m)	0.035
Inner layer		
Average thickness (m.)		0.035
R-Value (calculated)		0.354

Seperation wall		
Category		Walls
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Brickwork outer
	Thickness (m)	0.100
2	Material	Air gap
	Thickness (m)	0.020
3	Material	Brickwork inner
	Thickness (m)	0.100
4	Material	Gypsum plastering
	Thickness (m)	0.005
Inner layer		
Average thickness (m.)		0.225
R-Value (calculated)		0.700

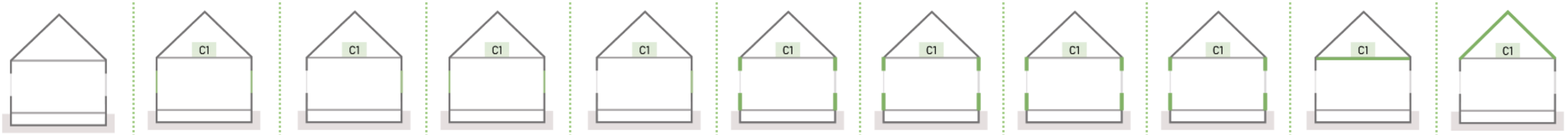
Kitchen roof		
Category		Roof
Region		Netherlands
Definition method: Layers		
Outer layer		
1	Material	Asphalt
	Thickness (m)	0.010
2	Material	Cast concrete
	Thickness (m)	0.020
3	Material	Gypsum board
	Thickness (m)	0.0125
Inner layer		

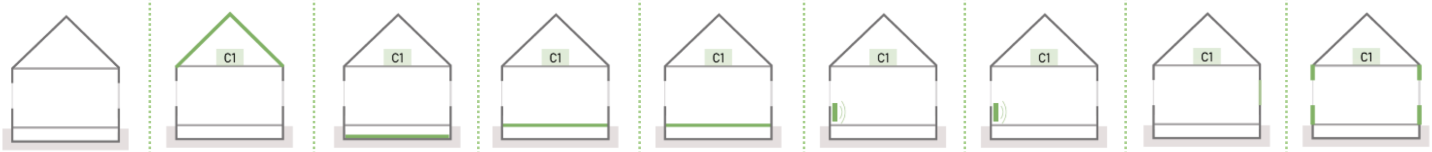
F. Simulation results

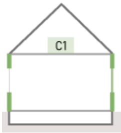
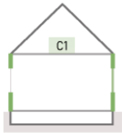
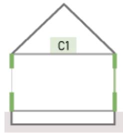
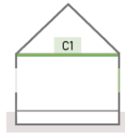
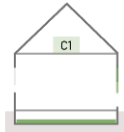
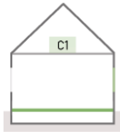
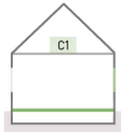
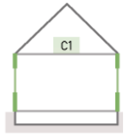
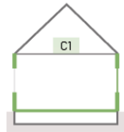
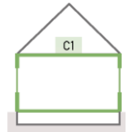
Renovation combinations: results per ventilation type

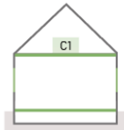
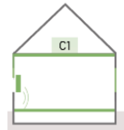
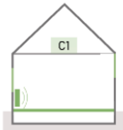
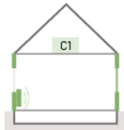
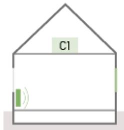
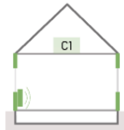
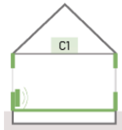
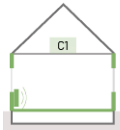
Ventilation type C1

Results for ventilation type C1 + 1 additional measure

Option	Original	C1.1a	C1.1b	C1.1c	C1.1d	C1.2a	C1.2b	C1.2c	C1.2d	C1.3a	C1.3b
											
Budget	€ 0	€ 5260	€ 3870	€ 6019	€ 4170	€ 4099	€ 4586	€ 5174	€ 7789	€ 3601	€ 5760
Hours too cold	144	402	408	352	359	320	340	286	218	535	537
Energy demand (kWh/m²)	147.4	128.3	132.8	130.8	124.7	112.0	106.5	100.1	99.6	131.3	131.4
LT-Ready		No	No	No	No	No	No	No	No	No	No
Windows	Double gl.	HR++ (all)	HR++ (living)	Triple gl. (all)	Triple gl. (living)	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.
Wall	Original	Original	Original	Original	Original	Cavity	Interior (R_c=1.4)	Interior (R_c=2.8)	Exterior	Original	Original
Roof	Original	Original	Original	Original	Original	Original	Original	Original	Original	Attic	Inside (R_c=2.8)
Floor	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original
Heating system	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original
Heating capacity	9204 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W
Additional measures	-	-	-	-	-	-	-	-	-	-	-

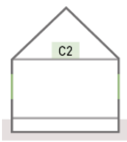
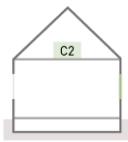
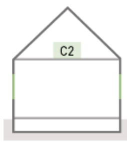
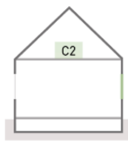
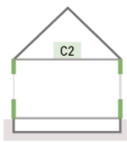
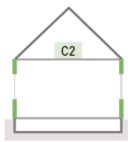
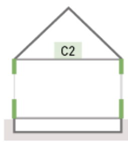
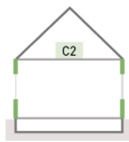
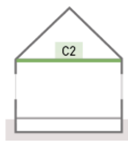
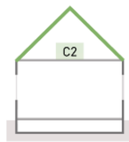
Option	Original	C1.3c	C1.4a	C1.4b	C1.4c	C1.5a	C1.5b	C1.6a	C1.6b
									
Budget	€ 0	€ 7789	€ 4030	€ 5296	€ 4252	€ 3868	€ 3159	€ 4470	€ 4764
Hours too cold	144	532	572	483	484	131	431	252	334
Energy demand (kWh/m²)	147.4	129.8	138.6	132.7	133.0	142.5	142.5	142.5	142.5
LT-Ready		No	No	No	No	Yes	No	No	No
Windows	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.
Wall	Original	Original	Original	Original	Original	Original	Original	Cavity	Cavity
Roof	Original	Inside (R_c=4.5)	Original	Original	Original	Original	Original	Original	Original
Floor	Original	Original	Crawling space	Above floor	Below floor	Original	Original	Original	Original
Heating system	Original	Original	Original	Original	Original	LT-radiator	Add-on fan	Original	Original
Heating capacity	9204 W	3737 W	3737 W	3737 W	3737 W	6119 W	3988 W	3737 W	3737 W
Additional measures	-	-	-	-	-	-	-	Radiant screen	Heat reflective paint

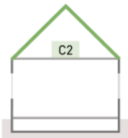
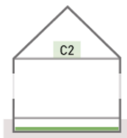
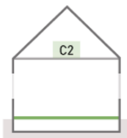
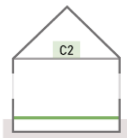
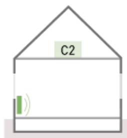
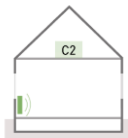
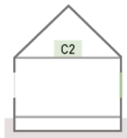
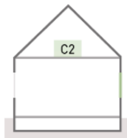
Option	Original	C1.7a	C1.7b	C1.7c	C1.7d	C1.7e	C1.7g	C1.7h	C1.7i	C1.7j	C1.7j
											
Budget	€ 0	€ 5006	€ 6082	€ 8696	€ 4509	€ 4938	€ 6204	€ 5160	€ 6396	€ 6296	€ 8325
Hours too cold	144	178	145	98	399	433	349	351	175	125	116
Energy demand (kWh/m²)	147.4	106.6	94.7	94.2	125.9	133.2	127.3	127.5	94.2	100.8	88.9
LT-Ready		No	No	Yes	No	No	No	No	No	Yes	Yes
Windows	Double gl.	HR++ (living)	HR++ (living)	HR++ (living)	HR++ (living)	HR++ (living)	HR++ (living)	HR++ (living)	HR++ (all)	HR++ (living)	HR++ (all)
Wall	Original	Cavity	Interior (R_c=2.8)	Exterior	Original	Original	Original	Original	Cavity	Cavity	Cavity
Roof	Original	Original	Original	Original	Attic	Original	Original	Original	Original	Original	Attic
Floor	Original	Original	Original	Original	Original	Crawling	Above	Below	Original	Below	Below
Heating system	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original
Heating capacity	9204 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W
Additional measures	-	-	-	-	-	-	-	-	-	-	-

Option	Original	C1.7k	C1.7l	C1.7m	C1.7n	C1.8a	C1.8b	C1.8c	C1.8d
									
Budget	€ 0	€ 7560	€ 7757	€ 8516	€ 5203	€ 4775	€ 5004	€ 5912	€ 7201
Hours too cold	144	343	239	125	484	94	68	24	18
Energy demand (kWh/m²)	147.4	116.1	116.4	106.9	133.0	136.4	114.9	108.9	102.4
LT-Ready		No	No	Yes	No	Yes	Yes	Yes	Yes
Windows	Double gl.	HR++ (all)	HR++ (all)	Triple glaz. (all)	HR++ (living)	HR++ (living)	Original	HR++ (living)	HR++ (living)
Wall	Original	Original	Original	Original	Cavity	Original	Cavity	Cavity	Cavity
Roof	Original	Attic	Attic	Original	Original	Original	Original	Original	Original
Floor	Original	Below	Below	Above floor	Original	Original	Original	Original	Below floor
Heating system	Original	Original	Add-on fan	Add-on fan	Add-on fan	LT-radiator	LT-radiator	LT-radiator	LT-radiator
Heating capacity	9204 W	3737 W	3988 W	3988 W	3988 W	6119 W	6119 W	6119 W	6119 W
Additional measures	-	-	-	-	-	-	-	-	-

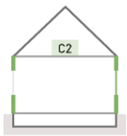
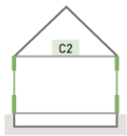
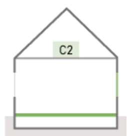
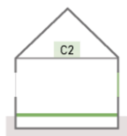
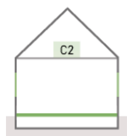
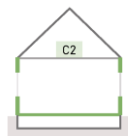
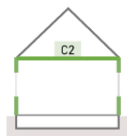
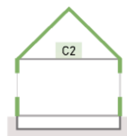
Ventilation type C2

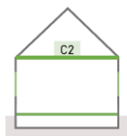
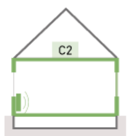
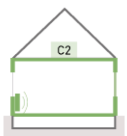
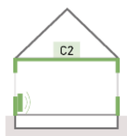
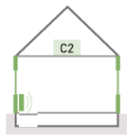
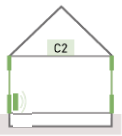
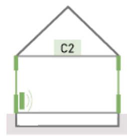
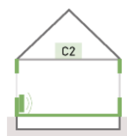
Ventilation type C2 + 1 additional measure

Option	Original	C2.1a	C2.1b	C2.1c	C2.1d	C2.2a	C2.2b	C2.2c	C2.2d	C2.3a	C2.3b
											
Budget	€ 0	€ 7049	€ 5659	€ 7808	€ 5959	€ 5888	€ 6375	€ 6963	€ 9577	€ 5390	€ 7549
Hours too cold	144	249	255	197	202	179	190	147	100	400	398
Energy demand (kWh/m²)	147.4	107.4	111.9	103.9	109.9	90.9	85.9	79.9	79.4	110.2	110.3
LT-Ready		No	No	No	No	No	No	No	Yes	No	No
Windows	Double gl.	HR++ (all)	HR++ (living)	Triple gl. (all)	Triple gl. (living)	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.
Wall	Original	Original	Original	Original	Original	Cavity	Interior (R_c=1.4)	Interior (R_c=2.8)	Exterior	Original	Original
Roof	Original	Original	Original	Original	Original	Original	Original	Original	Original	Attic	Inside (R_c=2.8)
Floor	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original
Heating system	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original
Heating capacity	9204 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W
Additional measures	-	-	-	-	-	-	-	-	-	-	-

Option	Original	C2.3c	C2.4a	C2.4b	C2.4c	C2.5a	C2.5b	C2.6a	C2.6b
									
Budget	€ 0	€ 8715	€ 5819	€ 7085	€ 6041	€ 3868	€ 4948	€ 6259	€ 6110
Hours too cold	396	6	432	347	351	96	288	124	184
Energy demand (kWh/m²)	147.4	108.8	117.7	112.3	112.3	121.6	117.4	91.1	90.4
LT-Ready		No	No	No	No	Yes	No	Yes	No
Windows	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.
Wall	Original	Original	Original	Original	Original	Original	Original	Cavity	Cavity
Roof	Original	Inside (R_c=4.5)	Original	Original	Original	Original	Original	Original	Original
Floor	Original	Original	Crawling space	Above floor	Below floor	Original	Original	Original	Original
Heating system	Original	Original	Original	Original	Original	LT-radiator	Add-on fan	Original	Original
Heating capacity	9204 W	3737 W	3737 W	3737 W	3737 W	6119 W	3988 W	3737 W	3737 W
Additional measures	-	-	-	-	-	-	-	Radiant screen	Heat reflective paint

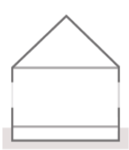
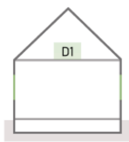
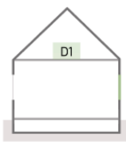
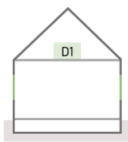
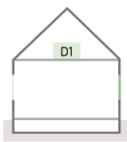
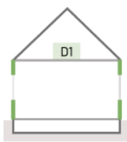
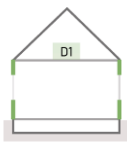
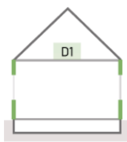
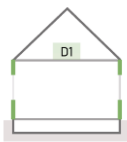
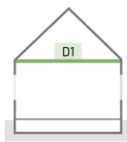
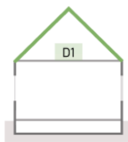
Results for ventilation type C2 + combination of measures

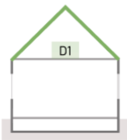
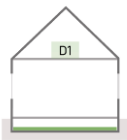
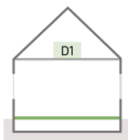
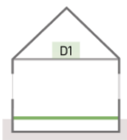
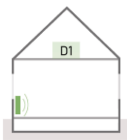
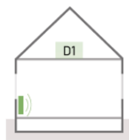
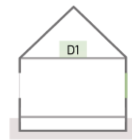
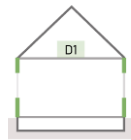
Option	Original	C2.7a	C2.7b	C2.7c	C2.7d	C2.7e	C2.7g	C2.7h	C2.7i
									
Budget	€ 0	€ 6795	€ 8185	€ 6949	€ 7249	€ 9098	€ 7178	€ 6526	€ 10005
Hours too cold	144	69	66	205	158	152	125	170	172
Energy demand (kWh/m²)	147.4	85.3	80.9	106.6	104.7	98.7	85.2	83.2	82.0
LT-Ready		Yes	Yes	No	No	No	Yes	No	No
Windows	Double gl.	HR++ (living)	HR++ (all)	HR++ (living)	Triple glaz. (living)	Triple glaz. (all)	Double gl.	Double gl.	Double gl.
Wall	Original	Cavity	Cavity	Original	Original	Original	Cavity	Cavity	Cavity
Roof	Original	Original	Original	Original	Original	Original	Original	Attic	Inside (extra Rc=4.5)
Floor	Original	Original	Original	Below	Below	Below	Below	Original	Original
Heating system	Original	Original	Original	Original	Original	Original	Original	Original	Original
Heating capacity	9204 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W
Additional measures	-	-	-	-	-	-	-	-	-

Option	Original	C2.7k	C2.7k	C2.7m	C2.8a	C2.8b	C2.8c	C2.8d	C2.8d
									
Budget	€ 0	€ 8977	€ 9174	€ 7784	€ 6877	€ 7246	€ 6084	€ 7160	€ 6572
Hours too cold	144	195	118	121	116	175	123	111	125
Energy demand (kWh/m²)	147.4	95.1	95.3	99.7	83.4	107.3	90.8	79.9	85.9
LT-Ready		No	Yes	Yes	Yes	No	Yes	Yes	Yes
Windows	Double gl.	HR++ (all)	HR++ (all)	HR++ (living)	Double gl.	HR++ (all)	Double gl.	Double gl.	Double gl.
Wall	Original	Original	Original	Original	Cavity	Original	Cavity	Interior (R_c=2.8)	Interior (R_c=1.4)
Roof	Original	Attic	Attic	Attic	Attic	Original	Original	Original	Original
Floor	Original	Below	Below	Above floor	Original	Original	Original	Original	Below floor
Heating system	Original	Original	Add-on fan	Add-on fan	LT-radiator	LT-radiator	LT-radiator	LT-radiator	LT-radiator
Heating capacity	9204 W	3737 W	3988 W	3988 W	6119 W	6119 W	6119 W	6119 W	6119 W
Additional measures	-	-	-	-	-	-	-	-	-

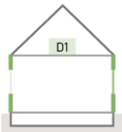
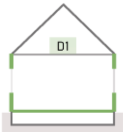
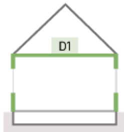
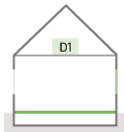
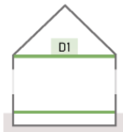
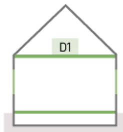
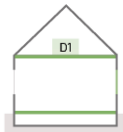
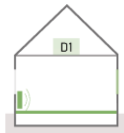
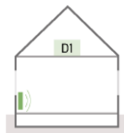
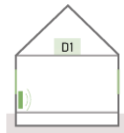
Ventilation type D1

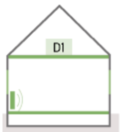
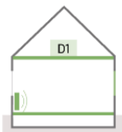
Ventilation type D1 + 1 additional measure

Option	Original	D1.1a	D1.1b	D1.1c	D1.1d	D1.2a	D1.2b	D1.2c	D1.2d	D1.3a	D1.3b
											
Budget	€ 0	€ 8868	€ 7478	€ 9627	€ 7778	€ 7707	€ 8194	€ 8782	€ 11396	€ 7209	€ 9368
Hours too cold	144	187	189	137	140	125	137	106	64	331	333
Energy demand (kWh/m^2)	147.4	98.4	102.8	95.0	100.9	81.9	77.3	71.5	71.0	101.0	101.2
LT-Ready		No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Windows	Double gl.	HR++ (all)	HR++ (living)	Triple gl. (all)	Triple gl. (living)	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.
Wall	Original	Original	Original	Original	Original	Cavity	Interior (R_c=1.4)	Interior (R_c=2.8)	Exterior	Original	Original
Roof	Original	Original	Original	Original	Original	Original	Original	Original	Original	Attic	Inside (R_c=2.8)
Floor	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original
Heating system	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original	Original
Heating capacity	9204 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W
Additional measures	-	-	-	-	-	-	-	-	-	-	-

Option	Original	D1.3c	D1.4a	D1.4b	D1.4c	D1.5a	D1.5b	D1.6a	D1.6b
									
Budget	€ 0	€ 10534	€ 7638	€ 8904	€ 7860	€ 7475	€ 7903	€ 8078	€ 7929
Hours too cold	396	328	378	290	292	84	228	81	132
Energy demand (kWh/m^2)	147.4	99.7	108.6	103.5	103.4	112.5	107.9	80.1	86.3
LT-Ready		No	No	No	No	Yes	No	Yes	Yes
Windows	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.	Double gl.
Wall	Original	Original	Original	Original	Original	Original	Original	Cavity	Cavity
Roof	Original	Inside (R_c=4.5)	Original	Original	Original	Original	Original	Original	Original
Floor	Original	Original	Crawling space	Above floor	Below floor	Original	Original	Original	Original
Heating system	Original	Original	Original	Original	Original	LT-radiator	Add-on fan	Original	Original
Heating capacity	9204 W	3737 W	3737 W	3737 W	3737 W	6119 W	3988 W	3737 W	3737 W
Additional measures	-	-	-	-	-	-	-	Radiant screen	Heat reflective paint

Results for ventilation type D1 + combination of measures

Option	Original	D1.7a	D1.7b	D1.7c	D1.7d	D1.7e	D1.7f	D1.7g	D1.7h	D1.7i	D1.7j
											
Budget	€ 0	€ 8614	€ 8997	€ 8345	€ 8768	€ 8499	€ 10796	€ 9407	€ 8965	€ 6767	€ 9065
Hours too cold	144	41	91	119	189	277	138	138	119	247	117
Energy demand (kWh/m²)	147.4	76.8	76.9	74.5	102.8	96.3	86.7	91.1	103.1	108.4	98.7
LT-Ready		Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes
Windows	Double gl.	HR++ (living)	Double gl.	Double gl.	HR++ (living)	Double gl.	HR++ (all)	HR++ (living)	HR++ (living)	Double gl.	HR++ (all)
Wall	Original	Cavity	Cavity	Cavity	Original	Original	Original	Original	Original	Original	Original
Roof	Original	Original	Original	Attic	Original	Attic	Attic	Attic	Original	Original	Original
Floor	Original	Original	Below	Original	Below	Below	Below	Below	Below	Original	Original
Heating system	Original	Original	Original	Original	Original	Original	Original	Original	Add-on fan	Add-on fan	Add-on fan
Heating capacity	9204 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3737 W	3988 W	3988 W	3988 W
Additional measures	-	-	-	-	-	-	-	-	-	-	-

Option	Original	D1.7k	D1.7l
			
Budget	€ 0	€ 10993	€ 9603
Hours too cold	144	91	92
Energy demand (kWh/m²)	147.4	86.9	91.2
LT-Ready		Yes	Yes
Windows	Double gl.	HR++ (all)	HR++ (living)
Wall	Original	Original	Original
Roof	Original	Attic	Attic
Floor	Original	Below	Below
Heating system	Original	Add-on fan	Add-on fan
Heating capacity	9204 W	3988 W	3988 W
Additional measures	-	-	-