The Price Elasticity of Comfort

Assessing energy poverty by utilizing the effects of energy price increases on energy usage and thermal comfort

Building Technology Graduation Studio (AR3B025)

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24-06-2025
Number of words: 44300

Abstract

Energy price fluctuations have been occurring more frequently as global insecurity rises and the energy transition continues. Households have reacted to these energy price increases in diverse ways, many by reducing their home energy consumption habits. Depending on factors like household income, construction date, quality of dwelling and the significance of the price increase, these energy consumption reductions range in severity. Severe energy price increases can result in energy poverty, a situation where a households' permittable energy consumption is too little to suffice the households' needs. Effects of energy poverty on the indoor temperatures of dwellings can be quite drastic, with indoor temperatures as low as 13 degrees becoming a reality for households which are affected heavily. Current strategies and interventions which aim towards reducing energy poverty have been inefficient, as they fail to structurally solve the issue and focus too much on temporary financial aid. In order to increase the effectiveness of these strategies, a clear definition of energy poverty is needed, and focus should shift towards providing case-level assessments of energy poverty within buildings. At the same time, energy efficiency interventions applied in these strategies need to be reviewed under different criteria. Not just energy efficiency, but also thermal comfort and financial efficiency are crucial in identifying the optimal interventions for a given case. The research provides a framework for the assessment of energy poverty within a building case. Besides this, review criteria are constructed to analyse interventions on their effectiveness in reducing energy poverty. With the use of the Poptahof Noord case study, the effectiveness of different existing interventions is simulated. The research discusses the factors which influence the effectiveness of these interventions and provides examples of how the proposed assessment method can be used to successfully assess and decrease energy poverty in cases.

Key words – Energy efficiency interventions, Energy policy, Energy poverty, Energy prices, Renovation, Thermal comfort.

Acknowledgements

Firstly, I would like to thank those who have helped me in writing my graduation research paper:

I would like to thank Regina Bokel and Arie Bergsma, who guided me throughout the research process and kept encouraging me to dive deeper and learn more.

I would like to thank my colleagues at moBius Consult, who provided me with a place to work on my research and were always available to help and discuss different hurdles with me.

Lastly, I would like to thank all others who have encouraged me in different ways during my academic career and graduation research:

My parents and sister, who have always encouraged and facilitated me to achieve my full potential during my study, during both the enjoyable and stressful times.

Ben and Denise, who have accompanied me in my time at the Delft faculty of Architecture since year one and have made this time very enjoyable.

Chantal, who has supported me whenever and wherever possible throughout the last years.

Mark, Valentijn and Sarah, who made the Building Technology master even more exciting.

And lastly, all my friends back home who were always interested in what I'd been up to and allowed me to rest and recharge; Wies, Merel, Sjoerd, Siem, Mark, Kim, Josien, Fabienne, Amy and of course Bram.

Contents

1 Introduction

1.1 Energy poverty

Since the introduction of domestic energy usage, households have allocated parts of their financial resources towards heating their homes and cooking their meals. As is the case with most commercially available resources, the price of this energy has fluctuated over time. With households having different financial resources and sources of income, some households have had trouble paying for energy in times of high energy prices, while other households have less trouble paying for energy during these periods. In periods of intense energy price increases where certain households will experience hardship in paying for these resources, the concept of energy poverty comes into play (Guyet, 2022).

Energy poverty is associated with different definitions, from "a situation in which a household is unable to attain adequate levels of energy use, leaving them unable to satisfy their basic needs" (Simcock, 2019, pp. 123–135) to "Households experiencing energy poverty have a low income combined with high costs for gas and electricity or a home with poor energy efficiency." (*TNO Brengt Niveau Energiearmoede in Kaart | TNO*, n.d.). Though energy poverty doesn't have one clear definition, it has been a topic of discussion and research since the early 1970's (Primc et al., 2021, p. 2). In the 21st century, it has become more relevant in countries around the world (Halkos & Gkampoura, 2021, p. 3). The recent energy crisis has pushed the problem into more relevancy.

Energy poverty is associated with different causes. From the increase of energy prices, low household incomes to lacking building quality (Polimeni et al., 2022, p. 17). Energy poverty is also associated to cause different issues, from financial issues, health issues, to mental issues (Mulder et al., 2024, p. 8. Healy & Clinch, 2003, p. 219. Polimeni et al., 2022, p. 17).

Many households living in energy poverty have trouble getting out of this situation on their own for varied reasons. The rising energy expenditures force households to spend more money on this resource, leaving households to reduce spending on recreation, savings and other items. Next to already having increased trouble paying for their energy bills, these households often don't have the financial means to pay for home improvements which would reduce their energy expenditures. Besides this, there is a lack of knowledge in affected households on the possible improvements they can make and the financial support they can receive (Mulder et al., 2024, p. 8).

While it is known that energy price increases can negatively affect households and cause them to reduce their energy consumption by reducing their heating, not much is known about the exact relation between these 2 occurrences. Little is known about the extent to which heating is reduced in energy poverty households. Little is known about the indoor temperatures households will tolerate or be forced to live in as a result of this heating reduction. (*The Inability to Keep Home Adequately Warm Indicator: Is It Enough to Measure Energy Poverty? | Energy Poverty Advisory Hub*, n.d.).

In the Netherlands, approximately 400.000 households lived in energy poverty in 2024. This accounts for approximately 5% of all national households (Mulder et al., 2024, p. 7). From the 2020's onward, the topic has garnered more attention in governmental organizations through data analysis and policy creation, due to the significant financial and health effects (Centraal Bureau voor de Statistiek, 2024a). At the same time, between 2022 and 2023 the number of households in energy poverty has increased with more than 21% and energy poverty has become a reoccurring problem over the last years.

As energy poverty has been identified as a national issue in many countries, including the Netherlands, different policies and strategies have been put in place with the aim of reducing the severity of the issue. The yearly reoccurrence of energy poverty problems leads to the notion that existing policies and strategies have not been able to structurally solve the problem. Probable causes for this include the divergence of definitions and the notion that strategies focus on solving conventional energy efficiency and financial problems, instead of solving the specific energy poverty problems. Finding structural solutions for energy poverty is of importance, due to its prevalence and negative effects.

1.2 Problem statement

Not enough research has been done on what type of actions should be taken to structurally combat energy poverty. This is partly due to a lack of research on the issue of energy poverty itself. There is missing research on what energy poverty is directly caused by and what changes it causes to the energy consumption habits of households. Besides this there is research lacking into the effectiveness of current strategies as the effects of strategies which are implemented on different levels often aren't tracked.

Lastly, research is missing on how different energy efficiency interventions directly relate to energy poverty. Most energy efficiency interventions which are currently put in place with the goal of combatting energy poverty solely take the energy efficiency aspect into account, skipping over other important aspects of energy poverty. The severity of energy poverty in its presence and effects stresses the necessity of adequate research and knowledge on the subject.

1.3 Research question

With the problem statement in mind, this research focuses on creating a better understanding of energy poverty. With a focus on how price increases can change the perception of thermal comfort and energy consumption of households. Besides this, the research will focus on applying this knowledge into forming more efficient strategies for assessing energy poverty. Lastly, this better understanding of energy poverty will be used to assess the effectiveness of different interventions in combatting energy poverty. This includes interventions focused on increasing the energy efficiency, thermal comfort and/or financial efficiency of dwellings, a collection and description of interventions will be given in chapter 4.4, later in the research. These steps will answer the main question of the research:

"How can the effect of energy price increases on energy usage and the experience of thermal comfort be used to assess the effectiveness of interventions in reducing energy poverty?"

The following sub-questions are related to the main research question:

- *How much are households willing/able to pay for thermal comfort in response to rising energy costs?*
- *How much comfort are households willing/forced to sacrifice in response to rising energy costs?*
- *How effective are current strategies in dealing with energy price increases and energy poverty?*
- *What is the appropriate definition of energy poverty?*
- *How should strategies with the intent of dealing with energy price increases and energy poverty function?*
- *How can interventions be assessed on their effectiveness in reducing energy poverty?*
- *How effective are existing interventions at reducing energy poverty?*

1.4 Methodology

1.4.1 Literature review

A framework is constructed through a literature review of different peer reviewed scientific papers, professional literature, books, and governmental documents. These sources are gathered by performing search queries which use keywords such as 'energy', 'poverty' and 'Netherlands'. The literature is collected using the academic search engines: Scopus, Google Scholar and the digital and physical library of the TU Delft. The literature is stored and organized with the use of Scribbr. The technical framework focuses on providing outlines in the sections of; energy poverty and its effects, thermal comfort, financial stress, building energy efficiency and strategies aimed at reducing energy poverty.

1.4.2 Interviews

Besides the scientific literature, different interviews are held with field experts to expand the technical framework. The interviews are held with the aim of forming a better understanding of different problems, by speaking to those directly involved. These interviews will focus on the technical framework subjects of energy poverty policies and energy poverty effects.

The collection of interviews includes an interview with Suzan Mannens, who is directly involved with the energy poverty policies of the municipality of Delft. Besides this, Ir. Hans Bosch is interviewed, who performs moisture and indoor mould assessments in different social housing corporations. The Energiehulp's of Dordrecht are interviewed, who are directly involved in helping households who are living in energy poverty. Lastly, discussions will be held with different inhabitants of Delft who have experienced energy poverty.

1.4.3 Data analysis

Following this, analyses are done with data on the energy usage of households and data on fluctuations and trends in energy pricing. The aim of the data analyses is to form an understanding of the causes and effects of energy poverty, including the relation between energy usage, indoor temperature, and energy price increases, which can be used in later parts of the research. These used datasets have been constructed and published by the CBS, the official statistics bureau of the Dutch government. Data is analysed through methods such as descriptive analyses and linear regression analyses. *Descriptive analyses* can be applied on current and historic data to identify trends and relationships (Luna Navarro, 2023). *Linear regression* can be used to estimate relationships between different quantitative variables. The analyses of larger scale data are compared to the findings from the specialist interviews in order to verify the analyses.

1.4.4 Simulation analysis

In the later parts of the research different simulations will be performed, in order to apply the findings of the technical framework. This application will focus on answering the last two sub-questions surrounding the assessment of energy efficiency interventions. These simulations will focus on the subjects of domestic energy consumption, energy expenditures and thermal comfort. These simulations will be performed through the programs of VABI Elements and DesignBuilder. VABI Elements will be used to simulate the energy consumption of a chosen case study. DesignBuilder will be used for its CFD module, which allows for a precise estimate of thermal comfort within rooms.

As mentioned, the simulations will be used to analyse the effects of individual interventions, this will be done by comparing values like energy consumption and thermal comfort between a base situation and a situation with a particular intervention installed. This will be done for an energy poverty case and a regular case. Chapter 4 further explain the set-ups of these simulations. A detailed overview of the research framework can be seen in appendix 22**.**

2 Literature review

2.1 Energy poverty

2.1.1 Current definition

There is no consensus (yet) on an official definition of energy poverty, different countries and different research use different definitions. They either define the issue as energy poverty or fuel poverty, both addressing the same general issue. Table 1 shows a collection of official definitions used by different countries. With the focus of this research being on the assessment of energy poverty, it is necessary to understand how definitions are formed and how energy poverty is conceived.

UK-wide (2001-2013) and Northern Ireland, Scotland, Wales (2013-): *"A household is said to be in fuel poverty if it needs to spend more than 10% of its income on fuel to maintain an adequate level of warmth"* (Department of Energy and Climate Change, 2010: 1).
England (2013-): *"A household is considered to be fuel poor where:* • *they have required fuel costs that are above average (the national median level)* • *were they to spend that amount, they would be left with a residual income below the official poverty line" [60% median income]* (Department of Energy and Climate Change, 2013: 3).
France (2009-): A person is considered fuel poor *"if he/she encounters particular difficulties in his/her accommodation in terms of energy supply related to the satisfaction of elementary needs, this being due to the inadequacy of financial resources or housing conditions"* (translation of Plan Bâtiment Grenelle, 2009: 16).
Ireland (2007-): *"the inability to afford adequate warmth in a home, or the inability to achieve adequate warmth because of the energy inefficiency of the home"* (Office for Social Inclusion, 2007: 67).
Slovakia (2015-): *"Energy poverty under the law No. 250/2012 Coll. Of Laws is a status when average monthly expenditures of household on consumption of electricity, gas, heating and hot water production represent a substantial share of average monthly income of the household"* (Strakova, 2014: 3).

Table 1: *Summary of official definitions of fuel poverty (Thomson et al., 2016)*

Several differences can be noted between the nations' definition of energy poverty, showing the divergence of definitions. Firstly, it can be noted that countries differ in their use of fuel poverty or energy poverty, with Slovakia using energy poverty, and countries like England using fuel poverty. Besides this, countries like Slovakia and the UK put a large emphasis on the financial aspect of energy poverty, meaning that the ratio between energy costs and income spent on energy can define whether a household is in energy poverty or not. At the same time, countries like France and Ireland mention the housing aspect of energy poverty, by addressing the role of housing energy inefficiency (Thomson et al., 2016, p. 5). These differences in definitions emphasize the complexity of the problem, and the need for a better consensus on the definition.

Guevara et al. (2023) has performed research on ways to distinguish between different definitions of energy poverty and provides a framework for forming suitable definition(s). The first distinction can be made between operational and constitutive definitions. Operational definitions are formed using related measurement approaches. There are different approaches for forming operational definitions, the *access approach* defines energy poverty based on the lack of access to energy carriers or to services that these carriers enable. The *physical needs approach* defines energy poverty based on the minimum energy consumption requirements associated with energy needs. The *economic approach* defines energy poverty based on relative energy expenses compared to household income. It is important to understand that these operational approaches have a limited view of the relation between energy supply and -consumption with well-being (Guevara et al., 2022, p. 7).

Constitutive definitions aim to understand the problem in a broader sense and aim to make the connection with human personal-being (Guevara et al., 2023, p. 7). There are less definable approaches for forming constitutive definitions of energy poverty. Different examples of constitutive definitions are: *"Absence of sufficient choice in accessing adequate, affordable, reliable, high-quality, safe, and environmentally benign energy services to support economic and human development."* (Reddy, 2000) and *"An inability to realize essential capabilities as a direct or indirect result of insufficient access to affordable,* *reliable and safe energy services, and taking into account available reasonable alternative means of realizing these capabilities"* (Day et al., 2016). These definitions give insight into the various aspects of energy poverty and emphasize the many ways to approach it. The findings of the research will be used to review the existing definitions and to find a better definition.

2.1.2 History

As has been mentioned in the introduction, households have always had to pay for their energy consumption. The fuel source of this energy has changed throughout the centuries, from wood, to coal, to oil, to gas and now to renewable energy (*The 200-year History of Mankind's Energy Transitions*, 2022). While the concept of energy poverty has gained much attention during the last couple of years, it has existed for a much longer time. Differences between household incomes have always existed, and the price of energy has always fluctuated (Hirst, 1976).

The term 'fuel-poverty' was introduced in the UK in the 1970's. At this time, different community groups of the UK were asking for improved access to fuel and for the improvement of energy efficiency in their homes (Ruse et al., 2019). It was from this moment on that UK researchers started investigating the issue and started to put in place different policies to address it. From this moment on, the definition took different forms, with several aspects of the issue being addressed (Guyet, 2022). While energy poverty has existed for a longer period of time, around 2021 it became a widespread topic of discussion. The war in Ukraine which started in 2021 has caused average prices increases of 73% for electricity, 122% for natural gas and 36% for petrol (Guyet, 2022) during its peak. This has resulted in a drastic increase of households at risk of experiencing energy poverty.

2.1.3 Drivers

To effectively research energy poverty, it is necessary to understand which processes lead to it. With their logistic regression study, Primc and Slabe-Erker (2020, p. 35) showed that there are different paths and causes to energy poverty. Starting with the earliest stage, in which the combination between low household income and ineffective energy policy results in the risk of energy poverty. This energy policy is mostly aimed at liberalizing and privatizing the energy sector, which in its turn drives up energy prices. This price increase happens faster than the household pay increase, causing trouble. If the energy policy which drives the prices up stays in place, the energy prices become the bigger issue (Primc and Slabe-Erker., 2020, p. 35). The next stage shows that the combination of high energy prices and ineffective energy policy lead to energy poverty. In this stage the distinction is made between household income and energy policy. Explaining that even though a household's income might not be below or near the poverty line, if the policies in place are too ineffective, energy poverty can still be a result (Primc and Slabe-Erker., 2020, p. 35-36). Polimeni et al. (2022, p. 17) touches upon the factor of energy inefficiency. Which is one of the key factors. Even if the other driving factors are not as prevalent, energy inefficiency in homes can still cause households to experience energy poverty, as energy inefficiency increases household energy consumption, thus increasing household energy costs.

2.2 Thermal comfort

In order to explore the effects of energy poverty on the experience of thermal comfort, it is important to understand what thermal comfort is, and how it works. Thermal comfort has been a topic of research and discussion for a long time but has garnered more attention during recent decades (De Dear et al., 2013, p. 2).

2.2.1 Definition

Unlike with energy poverty, the definitions within thermal comfort are more widely accepted by the scientific community. ASHRAE (The American Society of Heating, Refrigerating and Air-Conditioning Engineers) defines it as: "the condition of mind which expresses satisfaction with the surrounding thermal environment and is assessed by subjective evaluation." (ASHRAE Terminology - Terminology.Presentation, n.d.). This definition points to the fact that thermal comfort is a personal notion and is more a state of mind than a scientific condition. The definition leaves the terms 'condition of the mind' and 'satisfaction' open to interpretation, as these will be defined differently for different people.

2.2.2 The adaptive comfort model

The foundation for the definition of thermal comfort lies withing the adaptive comfort model, which is used for assessing thermal comfort. This model stems from the classic heat-exchange method, which is the physiological method for calculating heat exchange. The adaptive comfort model incorporates field studies on the thermal comfort of people in their daily lives, besides the laboratory data of the heat-exchange method. This method is now seen as the scientific standard (P. Bluyssen, 2009, p. 103).

The basis for the adaptive approach lies, according to Humphreys and Nicol (1998), within 'the biological insight that the human being is a comfort-seeking animal who will, given the opportunity, interact with the environment in ways that secure comfort'. This points toward the adaptive approach being dependent on the context, the behaviour of occupants and their expectations (P. M. Bluyssen, 2023). The approach stems from the adaptive principle: 'If a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort' (Humphreys and Nicol, 1998, p. 2). These reactions, or adaptations, can include physiological, psychological, social, technological, cultural, or behavioural actions (P. Bluyssen, 2009, p. 104). Figure 1 shows how the adaptive thermal comfort model works. It can be seen in the figure that the human thermal sensation puts different adaptations in motion, to change the actual thermal sensation of the human body.

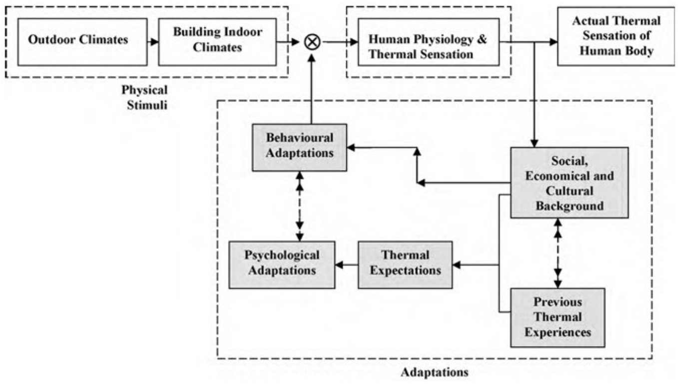


Figure 1: The thermal comfort adaptive model mechanism (Djongyang et al., 2010)

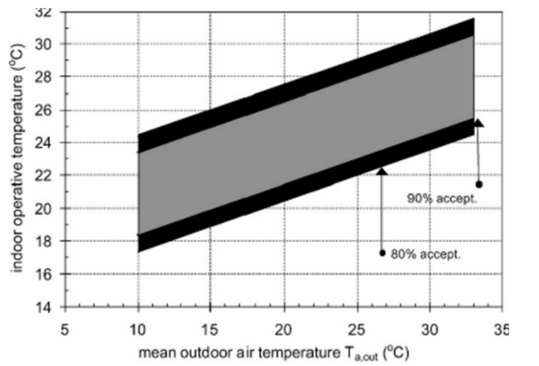


Figure 2: Proposed adaptive comfort standard (ACS) for ASHRAE Standard 55, applicable for naturally ventilated buildings (De Dear and Brager 2002)

2.2.3 Standards

The research on thermal comfort and more specifically, adaptive thermal comfort, has led to knowledge regarding the preferred indoor temperatures of individuals. While comfort temperatures remain different for different people, guidelines as shown in figure 2 give an indication on optimal indoor temperatures, in relation to outdoor temperatures. As the mean outdoor temperature rises, the indoor operative temperature and the acceptance levels rise as well. Meaning that for higher temperatures outdoors, people accept higher temperatures indoors, the same logic applies to colder temperatures. This has for example led to the notion that in Dutch households and buildings, temperatures in the range of 19 to 22 degrees Celsius are optimal in most times of the year (De Dear & Brager, 2002).

2.2.4 Psychological adaptation

One aspect of the adaptive comfort method is that of different adaptations. These adaptations come in different forms, this segment will delve into psychological adaptation. Psychological adaptation is built up out of factors which change the thermal perception of a space (Nikolopoulou & Steemers, 2002, p. 97). The researched factors which build up this psychological adaptation are for example: naturalness, expectations, experience, time of exposure, perceived control, and environmental stimulation (Nikolopoulou & Steemers, 2002, p. 97). While it is difficult to quantify the effects of these different factors, figure 3 shows the relationship between the different factors.

As a result of psychological adaptation, occupants change their neutral skin temperature and their sensitivity to temperature change (Zhuang et al., 2022, p. 10). An example of psychological adaptation is the role past, and future comfort scenarios play in changing thermal expectation (P. Bluyssen, 2009, p. 104). For example, if the outdoor temperature is 10 degrees and the indoor temperature is 19 degrees for 2 weeks, and the outdoor temperature stays the same, but the indoor temperature rises to 22 degrees, occupants might feel uncomfortably warm, even though the indoor temperature is within regular comfort levels. When this phenomenon is compared to figure 1, it can be noted that this change in thermal expectation will set behavioural adaptation into motion, with will influence the thermal sensation and eventually the actual thermal sensation of the human body. The aspect of psychological adaptation is important to understand when discussing energy poverty situations, which often result in lower indoor temperatures, this will be further explored in the coming chapters.

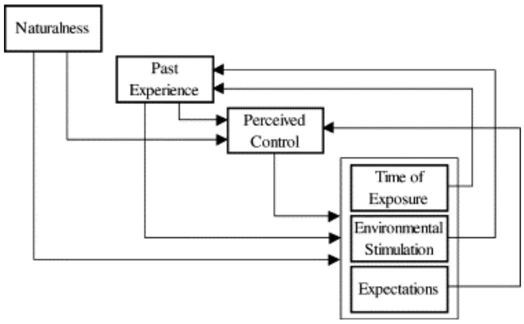


Figure 3: *Network demonstrating interrelationships between the different parameters of psychological adaptation (Nikolopoulou & Steemers, 2002)*

2.3 Financial stress

2.3.1 Definition

Financial stress is a part of the broader concept of psychological distress, which refers to: *"an emotional state of discomfort and suffering experienced by an individual with depression and/or anxiety symptoms, which could be a response to a stressor and can persist in the absence of such a stressor"* (Ryu and Fan, 2022, p. 18). Within the concept of financial stress, the driving stressor is one of financial nature. Being defined as either *"the individual's inability to meet current financial needs"*, or in a more personal way as "*an individual's subjective negative perception of their financial situation"* (Ryu and Fan, 2022, p. 18). Within energy poverty, financial stress plays a significant role and is integral to understanding energy poverty. The definition of psychological distress mentions the presence of stressors, which cause the individual's symptoms. We have identified that this stressor is of financial nature within financial stress. At the same time, because these stressors aren't defined in a restricted manner, the stressors are susceptible to be different for different individuals (Martin, 2023). This means that personal experience changes the feeling of psychological and financial distress, which is important to note within the study of energy poverty, something which differs between households, meaning that households will all have different experiences. The overarching definition of financial stress defines it as: *"A condition that is the result of financial and/or economic events that create anxiety, worry, or a sense of scarcity, and is accompanied by a physiological stress response."* (Martin, 2023).

2.3.2 Causes of financial stress within the context of energy poverty

In order to correctly understand financial stress, the different causes of financial stress need to be identified, as it isn't as simple as just 'a lack of money'. More comes into play when discussing financial stress, especially in relation to energy poverty. Financial stress, in the context of energy poverty arises when households struggle to pay their energy-related costs while managing other essential living costs. The aspect of financial stress is a result of being unable to pay for these essential means, while households are affected by other interconnected factors.

Low-income households & high energy costs

The first and most obvious driver of financial stress comes in the form of the relation between low household income and high energy costs, while this connection has been mentioned as one of the drivers of energy poverty, it is important to understand its relationship to financial stress. To understand this relation, we must define its aspects. Within the context of energy poverty in the

Netherlands, 'low income' is described as present when the standardised available household income is lower than 130% of the low-income limit (in 2021 this limit was 13.500€, with 130% being 17.550€.) (Centraal Bureau voor de Statistiek, 2024a). Besides this, within the Netherlands, 'high energy costs' have been described as present when the costs are higher than the average energy costs of an energy label C household in the year 2019 (Mulder et al., 2024, p. 20).

In the context of financial stress, the relationship between low household income and high energy costs has different implications. These costs end up consuming a large share of the household income, leaving families to cut spending in other areas, resulting in a feeling of scarcity. As energy costs are already difficult to pay for by these households, the unpredictability of these costs as they may or may not rise increases the households sense of anxiety. Lastly, while energy prices remain at a high point, low-income households are unable to save money or create a financial buffer. This leaves households on edge, as they might not be able to compensate for an increase in energy prices or unexpected costs. All these effects result in the distinct aspects of financial stress, being anxiety, worry and scarcity.

Housing conditions & energy efficiency

As has been mentioned before, housing conditions and energy efficiency play a vital role in identifying a household's risk of energy poverty. With low quality dwellings and energy efficiency leading to an increase in energy costs. The next paragraph will go more into energy (in)efficiency of buildings. Regarding financial stress, different effects on financial stress come into play when analysing housing conditions and energy efficiency.

Firstly, there is the most obvious result, with energy costs increasing when housing conditions and energy efficiency are of low value. The results of these cost increases have been explained in the previous paragraphs. Second, there is the anxiety that comes from being unable to pay for energy-efficiency upgrades. Many households will identify the need of increasing the energy efficiency of their dwelling, but these upgrades often require larger investments. Being unable to pay for these upgrades increases the sense of anxiety related to financial stress. Lastly, there is a struggle related to energy efficiency which is more specific to renters. Households who rent their home might find themselves in a dwelling of low quality, which they would like to upgrade in a variety of ways. But, as they don't own the dwelling and they might not get permission for the upgrade, it isn't installed. This increases the feeling of worry and helplessness related to financial stress and energy poverty (Mulder et al., 2024, p. 33).

2.3.3 The interplay between Energy Poverty, Financial Stress and Social Inequality

Energy poverty, financial stress and social inequality are interconnected concepts, as all individual concepts reinforce the other. For example, energy poverty can be a result of financial stress or social inequality. This connection creates a reinforcing cycle which has the most effect on the same, vulnerable group. With one of the main drivers of energy poverty being income, different aspects of social inequality are introduced which effect income. These are for example the aspects of age, gender, and education. This social inequality is therefore present in financial stress and energy poverty, with households with specific characteristics being more at risk than others. Three examples of households which are at more risk will be discussed in the next paragraphs.

Households with children

The first type of household with a larger risk and intensity of energy poverty, are 2-person households with children. On average, these households will require the most support to relieve them of their energy poverty issues. This can be explained by analysing the household composition. A larger household size results in larger energy consumption, with children taking a large part of this. Besides this, there is less ability for these households to work extra hours to increase their earnings, as they have the responsibility of children (Mulder et al., 2024, p. 31).

Elderly
The second group of people who are prone to experiencing the most effects of energy poverty, are the elderly (65+) (Mulder et al., 2024, p. 31). Within different household compositions, elderly will experience the largest problems. This can be explained by different characteristics of elders. First is their income, elders are many times reliant on their pensions to pay for their living expenses. These pensions are often fixed and a lower price than incomes of comparable households. At the same time, elders have higher energy consumption needs, which explains why the difference in income can cause problems (Zhu & Lin, 2022). Besides this, elderly often live in older homes with lower quality energy efficiency than newer homes (Vastgoedjournaal.nl, 2024).

Students
Besides these groups at risk, research has shown that students living in student housing are also at great risk of experiencing energy poverty (Van Der Veldt, 2025). There are different reasons for this, the first being their income. As students are enrolled in full-time studies, the ability to work is limited, resulting in an average low income, most of which is used to pay their rent. The absence of a financial buffer causes students to feel the effects of rising energy poverty more. Another reason for the increased risk of students is the low quality of their housing. In the questionnaire study, different statistics are reported. 71.6% of students have indicated that they experience different problems with their housing. Of this group, 45.9% indicate that insufficient insulation is a problem, besides this 20.4% report cracks in the dwelling and 21.4% report problems with heating. Besides this, problems such as leakages, mould, ventilation issues, moisture issues and how water problems are reported. Only 19% of complaints about these problems has led to improvements on energy efficiency by landlords (Van Der Veldt, 2025).

2.4 Building energy efficiency

Since the development of building construction, people have always tried to find ways to make their buildings more efficient and comfortable (Ionescu et al., 2015, p. 245). This hasn't always been done under the term 'energy efficiency', which was introduced in the 19th century. After the introduction of this term into the collective mentality, energy efficiency has become an even bigger point of interest (Ionescu et al., 2015, p. 244). The introduction of the term 'energy efficiency' during the 19th century has led to more research being done in the building field. The extensive research being done in this period allowed for researchers and designers in the 20th century to apply this research in design (Ionescu et al., 2015, p. 244).

2.4.1 Description

Energy efficiency in buildings focuses on offering a comfortable living environment with minimal energy consumption and wastage of energy. Energy efficiency concentrates on increasing the efficiency of resources use such as energy, water and materials. It concentrates on this to reduce the negative impacts of the building on human health, the environment and household finances (Gupta & Chakraborty, 2020, p. 457). Energy efficiency takes form in many ways, an energy efficient building balances several aspects such as lighting, space conditioning, ventilation and the building envelope.

Before the acceptance of energy efficiency standards during, it wasn't taken much into account during building design. This shift has happened in areas around the world, as well as the Netherlands. This has resulted in an exceptionally large number of Dutch dwellings being of low energy efficiency, as they were built before the period of efficiency standards (*Inkomenseffecten Van Woningisolatie Naar De Isolatiestandaard*, n.d.). This average low energy efficiency of Dutch dwellings has led to many dwellings having higher average energy consumptions and costs than similar dwellings built under modern standards. To increase the energy efficiency of older dwellings, households have gravitated towards implementing energy efficiency interventions. These energy efficiency interventions aim towards improving aspects of energy efficiency as mentioned before. The main improvement focus is often on the building envelope (Van Der Linden et al., 2016).

2.4.2 Heat balance of buildings

As mentioned in the previous chapter, the main improvement focus of energy efficiency interventions is often on the building envelope. This is because the energy efficiency is strongly determined by the building envelope, and many improvements are possible to be made to this parameter. The building envelope contains a collection of building elements which separate the interior from the exterior environment, this includes elements such as wall, roofs, windows and doors. These elements have a central role in the energy balance of a building. The energy balance describes the relationship between energy gains and energy losses. Within a stationary situation this balance is defined with: $\dot{Q}_{in} = \dot{Q}_{out}$. This energy balance is built up out of different energy flows, an overview of these flows can be seen in table 2, and figure 4. (Itard & van den Brom, 2023). Table 3 shows how the different flows are calculated.

Energy flow	Description
Transmission	Heat transfer through the building envelope
Ventilation	Air exchange of rooms
Infiltration	Airflow through cracks and gaps
Solar radiation	Radiation from sun entering through transparent surfaces
Internal heat load	Heat produced inside rooms by people, equipment and lighting
Energy demand	Supplied energy for space heating and usage

Table 2: Overview of energy flows within building heat balance (Itard & van den Brom, 2023)

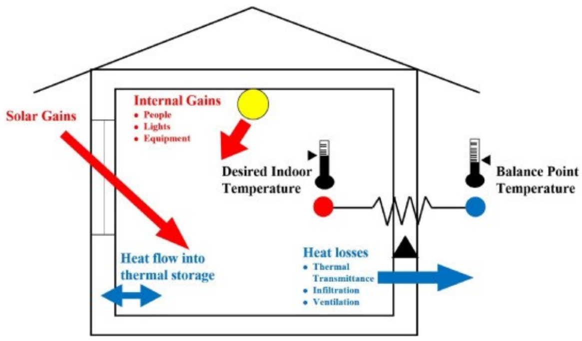


Figure 4: Energy flows between a heated building and its surroundings (Hao et al., 2022)

Energy flow	Formula	Inputs
Transmission	$\dot{Q}_{trans} = U * A * (T_e - T_i)$ [W]	U = heat transfer coefficient (W/m^{2}K)
		A = surface area of building element(s) (m^2)
		T_e = outdoor temperature (°C)
		T_i = indoor temperature (°C)
Ventilation and infiltration	$\dot{Q}_{ventilation} = \dot{V}_{ventilation} * \rho * c_p * (T_e - T_i)$ [W] $\dot{Q}_{infiltration} = \dot{V}_{infiltration} * \rho * c_p * (T_e - T_i)$ [W]	$\dot{V}$ = air volume flow rate (m^3/s)
		P = density of air (approximately 1,2 kg/m^3)
		c_p = the specific heat capacity of air (approximately 1000 J/kg.K)
		T_e = outdoor temperature (°C)
		T_i = indoor temperature (°C)
Solar radiation	$\dot{Q}_{solar} = A_{glass} * q_{solar} * ZTA$ [W]	A_{glass} = glazing surface (m^2)
		q_{solar} = intensity of solar radiation on glazing surface (W/m^2)
		ZTA = solar gain factor of glazing
Internal heat load	$\dot{Q}_{internal} = \dot{Q}_{people} + \dot{Q}_{appliances} + \dot{Q}_{lighting}$	$\dot{Q}_{people}$ = heat production of people
		$\dot{Q}_{appliances}$= heat production of appliances
		$\dot{Q}_{lighting}$= heat production of people
Stationary energy balance	$\dot{Q}_{transmission} + \dot{Q}_{ventilation} + \dot{Q}_{infiltration} + \dot{Q}_{solar} + \dot{Q}_{internal} + \dot{Q}_{demand} = 0$	$\dot{Q}_{transmission}$= transmission heat flows
		$\dot{Q}_{ventilation}$= ventilation heat flows
		$\dot{Q}_{infiltration}$= infiltration heat flows
		$\dot{Q}_{solar}$= solar radiation heat flows
		$\dot{Q}_{internal}$= internal heat flows
		$\dot{Q}_{demand}$= energy demand of dwelling

Table 3: Overview of formula and inputs for calculation of energy flows (Itard & van den Brom, 2023)

Transmission and insulation values

As can be seen in the formula used to calculate transmission losses, the amount of transmission losses of the building is determined by the temperature difference between the indoor and outdoor temperature, alongside the quality of the materials used. The material quality is represented by the heat transfer coefficient (U) in W/m²K. For transparent elements like windows and window frames, this U value is provided directly. For example, 4mm single glazing has an U value of 5,2 W/m²K (Van Der Linden et al., 2016). For opaque elements such as roofs and floors, a thermal resistance value (R) is more commonly used, which is expressed in m²K/W. The relationship between the U value and R value is defined as: $U = \frac{1}{R}$. The Dutch Building Decree (Bouwbesluit) outlines minimum thermal performance standards for building components. These standards are the following for different constructions (Mijzen, 2024):

- Ground floors: $Rc \geq 3.5$ m²K/W;
- External walls (façades): $Rc \geq 4$ m²K/W;
- Roofs: $Rc \geq 6.0R$ m²K/W;

2.4.3 Types of energy efficiency interventions

Energy efficiency interventions exist in countless forms. Research within the European Commission identifies approximately 250 energy efficiency interventions and has proposed a classification of these interventions. The interventions can be divided into short- and long-term interventions. Short-term classifying those with a low to medium required investment and which are able to be implemented by inhabitants. And long-term interventions require significant investments in time, money, and effort. 6 properties which interventions influence have been identified and include (CIRCE, 2015);

1. Envelope: The envelop consists of all building elements which protect inhabitants from the outer elements. Like roofs, walls, windows, floors, and windows. Examples of envelope interventions are the installation of insulation and the placement of efficient windows.
2. Heating, ventilation, and Air-Conditioning (HVAC) system: HVAC installations allow inhabitants to create optimized and comfortable areas in the building. Examples of interventions on HVAC systems are the installation of efficient systems such as radiant floor heating and the installation of condensing boilers.
3. Domestic hot water (DHW): DHW installations allow inhabitants to live comfortably in their homes and to use different appliances. At the same time, water comes at a cost, especially in heating it. Examples of interventions on DHW systems are installing water saving shower heads and installing heat pumps.
4. Lighting: Lighting provides inhabitants with comfortable living spaces. Examples of interventions on lighting are installation of LED lighting and the installation of motion-based lighting switches.
5. Electrical devices: Humans use different electrical devices for their comfort and entertainment. Examples of interventions on electrical devises are using more energy efficient devices and optimizing the battery use of devices.
6. Other.

2.4.4 The energy efficiency improvements of interventions

Research has been done on the efficiency and applicability of these different energy efficiency interventions. Santin et al. (2009) concluded that the most influential parameters which influence energy efficiency are: the thermal quality of buildings, building types, occupant behaviour and climate. Considering energy efficiency interventions, the thermal quality and occupant behaviour are the best subject for optimization. Figure 5 shows the effect of certain parameters on the energy usage of buildings. Most notably are the positive effects of insulation and efficient glazing, as these interventions drastically reduce the energy use of a building. As well as the negative effects of thermostat presence and people presence, as the thermostat results in people realizing a more consistent, but higher, heating level. And energy price being included in the rent results in people being less aware of their energy use (Santin et al., 2009, p. 1229).

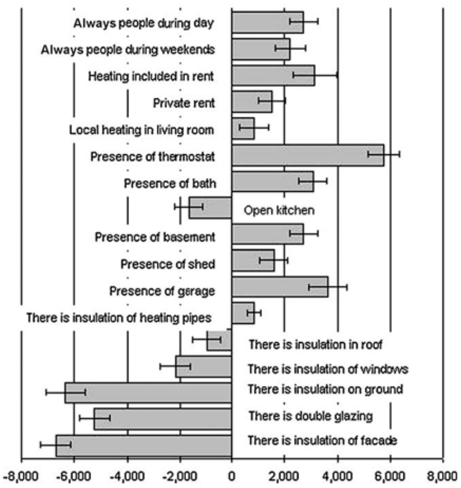


Figure 5: *Energy saved or spent when a variable is present, in comparison to cases when the variable is not present (Santin et al., 2009)*

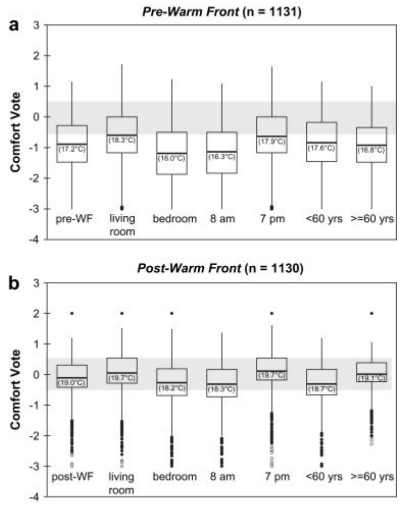


Figure 6: *Impact of efficiency measures on thermal comfort (Comfort Vote) disaggregated by room type, time of day and age of vulnerable householder. (Hong et al., 2008)*

2.4.5 The thermal comfort improvements of interventions

Within the context of this research, the energy savings of different interventions should not be the only factor which is reviewed. With thermal comfort being a large factor in energy poverty, the interventions which affect thermal comfort the most should also be reviewed. This has been researched by Hong et al. (2008), who reviewed changes in comfort vote, after energy efficiency interventions were applied.

The interventions which were reviewed are specific for the English 'Warm Front' energy efficiency scheme. This program focuses specifically on tackling energy poverty across vulnerable households (Hong et al., 2008, p. 1229). Within the program, households could apply for grants to become equipped with different interventions, either alone or in combinations. The interventions which were covered by the grant were cavity wall insulation, loft insolation, draft proofing, and central heating systems (Hong et al., 2008, p. 1229). The research analysed the effects of the different interventions on thermal comfort and concluded the following: The combination of insulation and central heating had the most effect, followed by central heating alone, followed by insulation alone. Besides the comfort votes, indoor temperature increases were also monitored. The insulation and heating combination allowed for indoor temperatures to be increased by 2.8 degrees, central heating alone increased it by 1,9 and insulation alone increased it by 1,2 (Hong et al., 2008, p. 1232). The change in thermal comfort can be seen in figure 6.

2.4.6 The financial efficiency of interventions

Besides the efficiency in both energy usage and thermal comfort, the financial efficiency of different interventions is also important in the context of energy poverty (Pombo et al., 2015). This combination of financial efficiency factors is for example represented in the research of Asadi et al. (2011), who developed a multi object optimization tool for building retrofitting. This tool compares both financial costs and energy gains, visualizing the combination of parameters (Asadi et al., 2011, p. 85). The research of Belaïd et al. (2021) reviewed different interventions and compared their financial efficiency. The interventions were compared on the indicators of; Net Present Value (NPV), Internal Profitability Rate (NPR) and the Payback Period (PP). The results of the research can be seen in figure 7, with higher NPV's indicating a more profitable energy efficiency solution. Within the concluding figure, it can be seen that condensing boilers, insulation and glazing replacement perform exceptionally well.

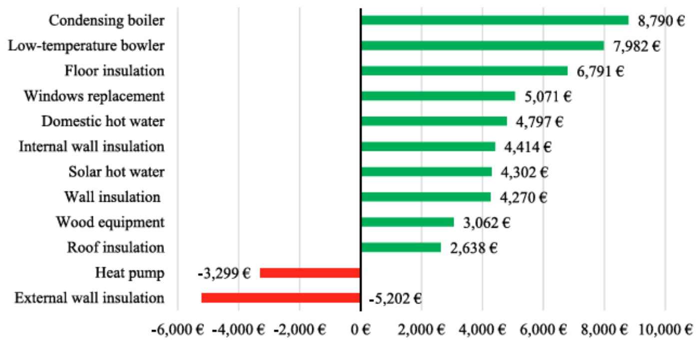


Figure 7: *Ranking of the energy efficiency measures according to their NPV (4%-discount rate and 30-year lifespan (Belaïd et al., 2021)*

2.5 Human-level effects of energy poverty

Throughout the research, the complexity of energy poverty has been addressed. For example, within its definition, origin, and drivers. The same complexity can be seen in the effects of energy poverty. This complexity is due to the different forms energy poverty takes as a problem. As discussed, it is for example a financial, thermal comfort and social problem, this makes it difficult to trace the direct effects of energy poverty. To narrow down the search for energy poverty effects, effects will be examined through different dimensions of human health, being physical health and mental health (Wang et al., 2023). Besides this, the effects energy poverty has on human behaviour and thermal comfort will also be examined, as these aspects will give a better understanding of the problem and will help in finding better solutions.

2.5.1 Physical health effects

Financial stress through energy poverty can have several similar effects on people as other forms of stress. The first relation which is to be considered is that between stress and immune system functions. When under stress, stress mediators which flow through blood streams can affect various parts of the immune system (Yaribeygi et al., 2017). This can lead to individuals being more perceptive of catching different diseases and having trouble in combatting these diseases. The second relationship is that between stress and the cardiovascular system. Stress is prone to cause activation of the autonomic nervous system which directly affects cardiovascular function. This can result in an increase in heart rate, the narrowing of veins and the contraction of arteries. Over longer periods of time, this can lead to cardiovascular problems.

A more direct effect of energy poverty that should be analysed is the effect that living in sub-optimal temperatures has on human health. It is known that increasingly cold indoor environments can lead to increased mortality rates (Analitis et al., 2008). Increasingly cold indoor temperatures as a result of energy poverty often lead to an increased risk of diseases such as influenza, pneumonia, asthma, and arthritis (Liddell & Morris, 2010, p. 2988). Another effect of energy poverty which worsens this increased risk of diseases, is the negative effect it has on nutrition. When poorer households fall into energy poverty, they reduce their food expenditures, while they physically require more nutrition when living in lower temperatures. This leads to negative nutritional and health effects (Bhattacharya et al., 2003) (Fisk et al., 2007).

These findings on the negative effects of energy poverty can be substantiated using the study of Liddell and Morris (2010, p. 2990). This study shows that when energy efficiency improvements are applied, such as heating and insulation improvements, life expectancy increases with an average of 8 days. This might not sound like much, but when this knowledge is applied to all low efficiency housing which could be improved, this number grows substantially.

2.5.2 Mental health effects

The research of Grey et al. (2015, p.36) shows that the financial stress associated with energy poverty can cause mental health to be negatively affected. This is also reflected in other research from the UK, which showed that energy poverty can result in mental health disorders. It was researched that for every

10.000 properties affected by energy poverty, 3000 residents would feel the effects of energy poverty in the form of anxiety or depression (CRESR, n.d.).

Besides these direct negative effects, more indirect effects are caused by energy poverty. Energy poverty can cause family relations to worsen. As energy poverty often results in households choosing which rooms to heat and which rooms to keep cold, families gather and spend more time in these heated rooms. This puts more pressure on the living room of dwellings, as households might choose to heat this room, instead of individual bedrooms. This results in more concentrated living space and less privacy. Both of which account for mental stress and have negative mental health effects (Liddell and Morris, 2010, p. 2993).

2.5.3 Behavioural effects

Next to these health effects of financial stress and energy poverty, are the cognitive and behavioural effects of financial stress. Research shows that periods of financial stress can have negative effects of cognitive functioning (De Almeida et al., 2024, p. 14). What can be perceived as even more pressing, are the effects financial stress can have on decision making. Hilbert et al. (2024) researched the change in decision making, because of financial stress. What resulted from this research is the notion that individuals experiencing financial stress often shift their decision-making timeframe to focus more on short term decisions and tend to procrastinate. This research leads to the notion of the ‘poverty trap’ which leads individuals to poverty and keeps them there.

In the context of energy poverty, the decision-making effects of financial stress are important. The notion on the poverty trap leads to concerns about the reoccurrence of energy poverty and its different negative effects. Besides this, the focus on short-term decision making explains why many households have trouble getting out of energy poverty. The research shows that investments in energy efficiency are necessary to escape energy poverty, but these investments require up-front money and will prove themselves effective over a longer time span. The combination of lacking financial means and the focus on short-term decision making explains why many households stay in energy poverty and don’t make the necessary improvements. This is confirmed in the interviews of Van Ooij et al. (2024). Different interviews mention the consideration some poorer households make on what ‘comfort’ they should save money. As some households perhaps save money on their energy bill, to still be able to go on holiday. While these households are aware that this has a negative influence on their thermal comfort, they weigh other types of comfort, such as recreational comfort, over thermal comfort.

2.5.4 Thermal comfort effects

When analysing the effects of financial stressors on human thermal comfort, it is important to make a distinction between an acceptance of decreased temperatures and actual thermal comfort. Chen et al. (2017, p. 63) describes how ‘bill consciousness’ is one of the main motivations for energy reduction. With low-income households being willing to conserve energy through the acceptance of lower comfort (Chen et al., 2017, p. 64). This theory explains the findings of the research by Grey et al. (2015, p. 22), which states that households in energy poverty will put up with feeling cold to save on heating costs. This can be seen as a form of emotion-focused coping. With emotion-focused coping, emotional distress is managed, in this case the distress of thermal discomfort (Anderson et al., 2010, p. 6).

Similar to the research of Grey et al. (2015), Cuerdo-Vilches et al. (2021, p. 12) also note that households in energy poverty will live in more thermal discomfort than households outside energy poverty. While at the same time, these households do still indicate that they prefer more comfortable temperatures (Cuerdo-Vilches et al., 2021, p. 13). What is also noted in this research, is that households in energy poverty will access other methods of achieving more thermal comfort than households that have more financial means. Households with the financial means tend to first change the set temperature of their heating system to achieve comfort. While households in energy poverty will first resort to, for example, changing their clothes or using alternative heating methods (Cuerdo-Vilches et al., 2021, p. 12).

This emphasizes the severity of energy poverty, as poorer households will do more alternative actions, instead of raising their energy usage and thus their energy costs.

The interviews of Van Ooij et al. (2024) confirm these findings, the interviews mention that households experience an increase in cold, heat and mould in their dwelling. They mention that this is a result of both their dwelling quality (cracks, draft & heating installation) and their new heating habits (less heating and partial heating of home). Households note that because of this, they experience negative effects on their physical health and pre-existing health conditions are worsened. Households admit that many of these problems are caused by their cost reducing energy saving habits but mention that they see no alternative. The households mention that when the opportunity presents itself, their most intensely and commonly used rooms, such as their living room, will receive the first heating increase.

2.6 Building-level effects of energy poverty

As has been discussed in previous chapters, energy poverty and financial stress can drive households to significantly reduce their energy usage through heating, in order to save on energy costs. When significant enough, this saving can have implications on the indoor temperatures of households, meaning that indoor temperatures will reduce. Part of the effects of these energy consumption reductions have been discussed in the previous chapter, focussing on the effects on humans. This chapter will focus on the effects energy poverty has on buildings.

2.6.1 Energy poverty and indoor mould

With regards to the impact energy poverty has on buildings, it has been noted that indoor mould is one of the most prevalent. The study of Ginestet et al. (2019) notes that though indoor mould is caused by several factors, the presence of energy poverty is a key factor when assessing the probability of indoor mould growth. Similar to this study, Sharpe et al. (2015) note the same presence of indoor mould within energy poverty households. Besides this, Sharpe et al. (2015) notes that factors which usually reduce indoor mould growth, such as increased risk perception and mechanical ventilation usage, did not change the risk of mould in energy poverty homes. It is noted that existing ventilation and heating strategies are ineffective in these situations since energy poverty significantly changes the situations of these households. This is similar to the conclusion Ginestet et al. (2019) draws, who states that there is need for better coherence between thermal regulation and indoor mould growth, since existing regulations don't apply effectively to energy poverty households. Lastly, the driver of missing education and knowledge on indoor mould growth is closely connected to energy poverty. As a result of energy poverty households often being poorer and of lower education, there is less knowledge on indoor mould growth within the households that need this knowledge (Ginestet et al., 2019). To understand the importance of indoor mould growth with regards to energy poverty, it is important to understand the effects indoor mould growth can have on households. These effects take place on a human and building level.

2.6.2 Indoor mould effects on human health

Bluyssen (2013, p. 331) mentions the different effects of indoor mould, in causing asthma and other respiratory diseases. An additional risk to this is the endangerment of children's health. Due to the increased times children spend in homes, their underdeveloped bodily functions and their increased inhalation rate, children are at greater risk of developing asthma. Bluyssen (2013, p. 327) also addresses the risk of occupant health, as these mould problems oftentimes present itself in residential homes. This risk is regarded in combination with households' lacking knowledge and inability to effectively solve these mould problems on their own.

2.6.3 Indoor mould effects on construction health

Besides these human health effects, construction health can also be negatively affected by indoor mould growth. As indoor mould is closely related to indoor humidity and water in buildings, water-related damage is often connected to indoor mould growth. These damages can take form in cracks, bulges, crumbling, peeling off wallpaper, blistering of paint and corrosion of metals (Du et al., 2020). These effects can have significant implications for buildings, as structural damages can be a result if these damages aren't fixed early. Fixing these damages in later stages can require large efforts and can be costly. The study of Annila et al. (2017) shows that when mould problems aren't assessed in an early stage, the problems add up and require repairs later down the line.

2.6.4 Indoor mould origin

Van Der Linden et al. (2016) discusses the factors which are the main drivers for the emergence of mould. These factors are environmental temperature, moisture, substrate, and exposure time. With other influencing factors being oxygen, pH values, light, and material surface roughness. Figure 8 shows the relationship between the 2 most determining factors for indoor mould growth, surface temperature and relative humidity. As can be seen in the figure, for average indoor temperatures around 18 to 20 degrees, a relative humidity value higher than 80% will likely result in mould growth issues (Viitanen, 2011).

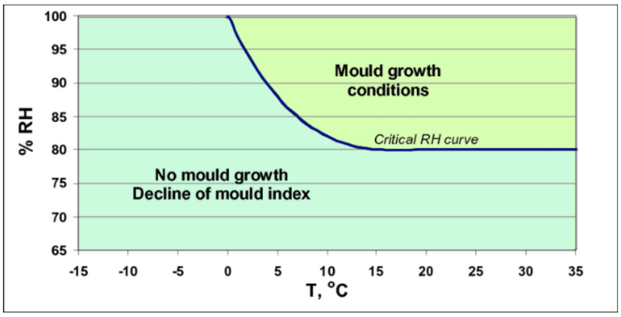


Figure 8: *The regimes for the favourable and unfavourable conditions for mould growth (Viitanen, 2011)*

Some of these factors are closely related to building characteristics. Du et al. (2020, p. 5) mentions larger scale building characteristics that have an effect on mould growth being insufficient design, low-quality constructions and lacking maintenance. With examples of this being water leakages due to insufficient maintenance or stagnant air zones due to suboptimal design. Notable is the connection between this insufficiency of building characteristics and the construction period. With older buildings experiencing more mould problems than newer buildings (Du et al., 2020).

Besides these building technical factors, factors surrounding occupant behaviour are also of importance. Du et al. (2020) notes that insufficient ventilation through the opening of windows in winter times will lead to lower ventilation rate, instigating mould growth. Besides this, cold indoor surfaces such as walls and windows, as a result of little indoor heating, are also noted to be instigators of mould growth. These behavioural factors are important to note regarding energy poverty.

2.6.5 Indoor mould combatting

While the building characteristics discussed in the previous paragraph which predict mould growth are present and established during construction, some of these can be altered later in the building's life. This comes in the form of different interventions and building retrofits, which can reduce energy demands and can improve the air and watertightness of buildings. In general, these interventions also diminish the risk of mould growth (Du et al. 2020, p. 5). Fisk et al. (2020, p.5) mentions energy efficiency interventions which have positive effects on preventing indoor mould, including the adding of thermal insulation, replacing windows, sealing leaks in buildings, and improving the air conditioning systems. Besides the effect on the energy efficiency and thermal quality of the building, a decrease in indoor dampness and mould is a result of these interventions.

At the same time, these interventions don't come without their risk. For example, when additional insulation interventions are applied, air tightness increases, the buildings air volume reduces and the risk for insufficient indoor ventilation increases. In its turn, this results in an increased risk for mould growth (Du et al. 2020, p. 5). Pihelo and Kalamees (2016) discusses this risk, in relation to a common energy efficiency measure, insulation. It is concluded that while the risk of mould growth in combination with insulation interventions exists, it can be limited. The main risk is formed when the only design variable is the thickness of the insulation, in these cases thicker insulation results in more risk of mould growth. This can be limited through the proper design of different elemental barriers, i.e. wind, water, and vapour barriers. Besides this, the sufficient natural ventilation of households remains of high importance in preventing indoor mould. This is something that isn't addressed properly to households, especially those in energy poverty. Increasing information and training on mould prevention in households would aid greatly in preventing mould growth (Ginestet et al., 2019).

2.7 Current strategies for combatting energy poverty

To reach their energy poverty, energy efficiency and sustainability goals, government actions have been implemented. These government actions mostly focus on providing financial support to energy poverty households and on implementing energy efficiency interventions in households (Dolšak, 2023). This chapter will go into discussing the implemented strategies of the Netherlands and Delft.

2.7.1 Strategies in The Netherlands

Similarly to other European countries, the Netherlands has addressed the importance of tackling energy poverty in their National Energy and Climate Plan, though this means the Netherlands doesn't consider energy poverty as a distinct phenomenon. Therefore, energy poverty is addressed via general social policy. Within the Netherlands, the following measures have been announced and/or adopted from 2021-2022 (Van Ooij et al., 2023, p. 32):

- A total of €300 million for municipalities to support energy poor households (first €150 million was announced in 2021).
- Lowering of the energy tax on electricity.
- Energy tax refund introduction of €560, which was later increased to €785.
- Increase of the energy surcharge to €1300 for welfare recipients and people earning less than 120% of the social minimum (earlier measures announced an increase of €200 and €800).
- Lowering of the energy VAT from 21% to 9% (natural gas, electricity, and city heating).
- Price cap starting in January 2023: 40 cent/kWh and €1,45 m3 gas, for a use below 2900 kilowatts hours and 1200 m3 gas. Households using more electricity and/or gas pay the higher electricity price.
- All households received €190 in November and December of 2022 to bridge the months before the price caps would be active.

2.7.2 Strategies in Delft

As mentioned in the previous paragraph, the Dutch government has been allocating money to municipalities around to country, which they must use to combat energy poverty in their region. This leaves municipalities to form their own specific strategies for the problems they encounter in their communities. Research on policies on different scales has shown that energy poverty policies are more effective, the smaller the scale they're applied on (Bouzarovski et al., 2021, p. 6), which might explain the choice to shift responsibility to individual municipalities. In order to understand what these specific policies look like, the policies for tackling energy poverty within the municipality of Delft will be discussed.

As has also been mentioned in the previous chapters, one reoccurring fact is that energy poverty isn't seen as a separate issue but falls between the wider poverty policy guidelines. This is also true for the municipality of Delft. In their poverty guidelines, energy poverty is talked about within poverty as a whole. The municipality chooses to define energy poverty as: 'someone who spends 10% of their income on energy to keep their household comfortable' (Gemeente Delft, 2023, p. 11). The municipality has formed both long term and short-term actions for fighting energy poverty. The long-term actions being the energy transition as a whole, which aims at resolving issues surrounding energy costs and energy efficiency. The short-term actions require more specification. An overview of which can be viewed in *Hulp Bij Energie En Geldzaken Gemeente Delft – Vidomes*. (n.d.) and consists of:

Financial compensation: Similar to the national government, the municipality of Delft focuses on providing direct financial compensation to the households who need it the most. The precise amount of this compensation differs per situation, as there are different compensations available, in this way the households who need it the most receive additional support.

The '*Energieloket'* (Energy counter) is a digital information point for citizens of Delft. The website allows for users to get information on improvements users can make on their homes, and the different subsidies users can apply for that allow the implementation of these improvements (*Gemeente Delft | Regionaal Energieloket*, n.d.).

'Energiehulp 015Duurzaam' is a platform where citizens of Delft in poverty can book appointments to get individual help for making their homes more energy efficient for free. This includes a visit of the 'energy helper', who installs different smaller interventions (radiator reflectors, draft strips, etc.) and who gives specific tips for the situation at hand (*Energiehulp | 015 Duurzaam*, n.d.).

The *'Energiecoach'* (Energycoach) is an organisation of advisors with knowledge on making households more energy efficient. Citizens of Delft can receive a free consulting session from these advisors on what they can do to improve their homes (*Bespaar Mee! | 015 Duurzaam*, n.d.).

The *'Informatiepakket energie besparen'* (information package on saving energy) is a document which outlines the different interventions households can make to improve their energy efficiency. It also gives outlines on how to get and implement certain interventions. This is explained for radiator foil, led lighting and draft improvements (Gemeente Delft & Regionaal Energieloket, n.d.).

Lastly, the '*Energiecafé'* (Energycafe) is an information point for those interested in energy efficiency. In a café in delft, once a week there is an energycoach available for all questions regarding sustainability and energy (*Energiecafé - Delft4GlobalGoals*, 2024).

3 Energy poverty analysis

3.1 Energy poverty in The Netherlands

3.1.1 Energy poverty on a national scale

While energy poverty has been an existing problem in European countries since the previous century, the Netherlands has been one of the countries where it has had a smaller effect (Halkos & Gkampoura, 2021, p. 6). At the time of the writing of this research (2025), energy poverty in the Netherlands should still be seen as a severe problem, though it remains a manageable problem, as Mulder et al. (2022, p. 14) argues. For better insight, in the Netherlands, energy poverty is defined in most research as *"households who are dealing with low income in combination with a high energy bill, or a dwelling with low energy efficiency".* It is estimated that in 2019, before the price spikes of 2021-2022, an estimated 8,6% of Dutch households were living in energy poverty. This changed to 6,4% in 2020, 6,3% in 2021 and 4% in 2022. The most recent available data is on the year 2023, it shows that in that year approximately 4,8% of households (396.000) were in energy poverty (Mulder et al., 2024). While this data shows promising reduction in the amount of energy poverty households, the data doesn't explain the entire picture.

From 2022 onwards, the Dutch government put different financial compensations in place to alleviate households in energy poverty. This has resulted in substantial amounts of households being 'saved' from energy poverty, this can be seen in figure 9. The policies have resulted in 2,2% of households in 2022 and 5,9% of households in 2023 being 'saved' (CBS, 2024). This means that without the government's support, 10,7% of households (885.000) would be in energy poverty in 2023 (TNO et al., n.d. p. 12).

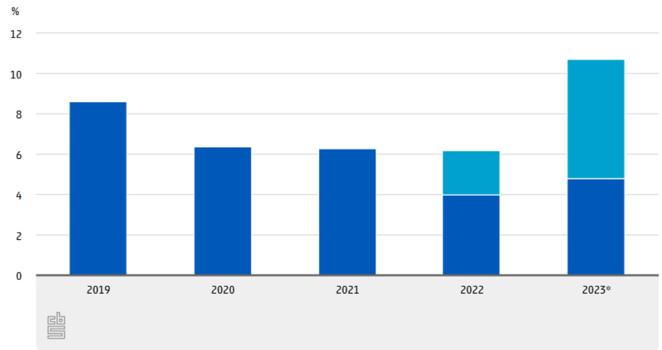


Figure 9: *Number of households in energy poverty (CBS, 2024) Dark blue = Energy poor household. Light blue = Not energy poor due to compensation*

Though the estimated total amount of households living in energy poverty is limited, there is reason to believe this amount could rise. As Mulder et al. (2022, p. 14) shows, approximately 3,8 million households in the Netherlands are on the border of energy poverty. This means that these households don't have the means to implement energy efficiency interventions. Besides this, the further rising of energy prices would force these households into energy poverty.

With the aforementioned definition of energy poverty, one important aspect of energy poverty is disregarded. These are the households who have significantly reduced their energy consumption to levels way under their actual energy consumption needs. These are households who lowered their use of indoor heating or limit the amount of cooking with gas. As these households reduce their energy consumption, their energy bill remains under the noticeable level, these households can be classified as being in 'hidden energy poverty' (TNO et al., 2019/2024, p. 13). In 2022, the number of households in this hidden energy poverty was approximately 1,4% (116.000) of all households in The Netherlands. This makes figure 9 paint an unrealistic picture, as the 'saved' and bordering households aren't taken into account.

3.1.2 National policy review

Is seems as if the policy actions of the Dutch government have been effective in reducing the number of households in energy poverty. Specifically, the effects of the energy allowance for low-income households, along with the price cap for energy prices in 2023. These financial measures resulted in 500 thousand households staying below the energy poverty line (CBS, 2024). But it has done so by the wrong definition. With the energy poverty definition of: 'someone who spends 10% of their income on energy to keep their household comfortable', the problem is able to be solved with only financial support. The wrong image created by this definition, is similar to what Bouzarovski et al. (2021, p. 8) mentions. His research mentions that the fact that a nationwide definition is missing, results in policies in different countries focussing on various aspects of energy poverty and that this can lead to these wrong impressions. This confusion can be seen as different governmental research apply different definitions. This doesn't mean the governments financial support is ineffective, as with all definitions of energy poverty, the financial situation and energy prices play significant roles. At the same time, the way in which these supports are structured does not provide a permanent solution. The risk of energy prices rising to more drastic heights is still prevalent. If this were to happen, most of these financial policies would need to be kept in place, reintroduced and/or increased. The government has structured and has communicated about these policies as temporary policies, meaning that problems will arise when the policies disappear and energy prices were to rise.

While the national government implemented many financial policies surrounding energy poverty, it can be noted that the government does not directly address problems regarding the dwellings of individuals. This is instead done through the €300 million directed towards the municipalities. This choice can be explained by the logistical challenges surrounding a national plan to improve the dwelling quality of all households at risk of energy poverty. Besides the logistical challenges, there are too many variables at play to make certain claims and suggestions on a national level. The effectiveness of redirecting the policies to a smaller scale approach has been explained by Bouzarovski et al. (2021, p. 6).

At the same time, by handing all responsibilities on what to do with this money over to the municipalities, different challenges come up. As has been discussed in the detailed interview with Suzan Mannens in appendix 4, this strategy left municipalities alone in forming their own policies and choosing their own definitions. As has been stated by Bouzarovski et al. (2021), this fragmentation of policies and definitions results in a less efficient combatting of energy poverty.

The result of all municipalities implementing different strategies, is that there is less knowledge on which strategies actually work in combatting energy poverty. The unclear nature of the effect of energy poverty strategies is mentioned by Van Ooij et al. (2023, p. 35). The focus should be on which strategies have an effect and on which households, as all measures and households are different. This was also mentioned by Suzan Mannens, Van Ooij et al. (2023), and the interviews in appendix 2. Similar to what was discussed in the previous paragraph, there is a lack of research on which individual interventions within the strategies enable households to escape and stay out of energy poverty. The little research which is done focuses on outcomes in physical- and mental health, energy use, or financial stress (Van Ooij et al., 2023, p. 35). While there is no widespread investigation into the effect of strategies and interventions, it will be more difficult to create effective strategies.

As for the financial support the government has put in place, interviewees mention that the received support have partially relieved them from different burdens. The financial stress of these households has been lessened by this support, because oftentimes the financial support wasn't always used to directly pay the energy bill but more to reduce other expenses or to build up a buffer. This relates to what chapter 2.3 mentions about financial stress. For example, the support mostly wasn't used to install energy efficiency interventions, it was put into savings accounts, to provide stability. One worry households do note, is the temporary nature of the support, as the government stresses that these measures will disappear over time, many households fear the results this will have for them, as they've come to rely on them separate from their energy costs (Van Ooij et al., 2024) (appendix 2).

3.1.3 Energy poverty on the municipal scale of Delft

As has also been mentioned before in the research, one reoccurring fact is that energy poverty isn't seen as a separate issue but falls under broader poverty policy guidelines. This is also true for the municipality of Delft. In their poverty guidelines, energy poverty is talked about within poverty as a whole. The municipality defines energy poverty as: 'someone who spends 10% of their income on energy to keep their household comfortable' (Gemeente Delft, 2023, p. 11). It can be immediately noted that this definition differs from previously mentioned definitions.

Delft can be classified as one of the larger municipalities of Zuid-Holland and The Netherlands, with a population of 106.000 and 60.500 households as of 2023 (*Gemeente Delft - KadastraleKaart.com*, n.d.). Within Delft, 8200 individuals live in poverty. With their income being below 110% of the social minimum income. The largest group of individuals is that of the ages 45-65, with them accounting for 37% of individuals. Regarding energy poverty, 10,6% of households have been identified as having a low income and/or high energy cost or having a house of low energy efficiency in 2019. It is important to relate this percentage to the correct definition, in this instance the number is connected to the research of Mulder et al. (2024), instead of the definition the municipality itself accepts. Even though the municipality has adopted this percentage. This can logically lead to earlier mentioned confusions.

The amount of households with a low income and/or high energy cost or having a house of low energy efficiency has reduced from 2019 onwards. With this number being 10,6% in 2019, 8,4% in 2020, 8,6% in 2021, 5,3% in 2022 and 6,4% in 2023 (*TNO Energiearmoede Kaart Nederland*, n.d.). Within both regular poverty and energy poverty, there is discrepancy between regions of the municipality, with poverty as whole being concentrated in specific areas of Delft (Gemeente Delft, 2023, p. 13).

3.1.4 Municipal policy review
When reviewing the energy poverty policy of the municipality of Delft, one thing becomes apparent quickly, which is that the fact that no research is done on the effects of the energy poverty policy makes it exceedingly difficult to track its effects. The importance of reviewing the effects of energy poverty policy was stressed before on the national level by Van Ooij et al. (2023) but is once again stressed on this scale.

One thing Delft does well, is the implementation of the Energiehulp's. This is the only measure that undertakes direct action in making small improvements to households. In the aspect of thermal comfort, some of these improvements come a long way. As for example cold air draft has a negative impact on thermal comfort, and implementing draft strips will help in resolving this. The Energiehulp's also introduce households to the information and effects of energy efficiency interventions. With these first energy efficiency steps being taken for free, households will be more open to other energy efficiency interventions which will require larger investments. One aspect of Delft's strategy which has been deemed as negative by the inhabitants of Delft, is the placement of the strategy within the broader context of poverty and the energy transition. As mentioned in the detailed interview of appendix 1, this negatively influences the citizens' openness to energy efficiency interventions and their involvement with combatting energy poverty.

Similar findings are concluded in the interviews of Van Ooij et al. (2024), interviewees mention that they appreciate the support they receive, but that it is not efficient enough in solving their problems. For example, the energy coaches who visited households. The interventions they install, like draft improvements, have increased the indoor thermal comfort of certain households. The households do note that these interventions do help, but not for the long term or to constructively solve the problem as they can't see significant effects on their energy bills. With this in mind, the information providing measures of Delft will have negligible effect for the households in severe energy poverty.

3.2 Energy consumption analysis
Data analyses can be used to understand different relations surrounding energy poverty, energy price fluctuations and building characteristics. The aim of the data analyses is to relate small-scale problems of individual homes and occupants to the larger scale-built environment and population.

3.2.1 Data samples
In order to execute the necessary analyses, different datasets were collected, these datasets are combined to form one collective dataset on which the different analyses can be performed. This dataset collection

contains the following information: The postal codes of Delft and the number of dwellings in this postal code (Centraal Bureau voor de Statistiek, n.d.-a), the construction date of dwellings and if they are rented or owned (Centraal Bureau voor de Statistiek, n.d.-b), the average yearly natural gas supply to individual dwellings (Centraal Bureau voor de Statistiek, 2023b), the yearly prices of natural gas contracts, both fixed and flexible (*CBS Statline*, n.d.) and the average yearly natural gas supply to groups of different dwelling characteristics (Centraal Bureau voor de Statistiek, 2024c).

The used datasets contain information on these factors in the years 2018, 2019, 2020, 2021 and 2022. This is the most recent available data, data from 2023 and 2024 is not yet available. The following analyses will give insight into certain trends and correlations, such as the reaction to rising energy costs, the correlation between energy consumption and energy prices, the correlation between energy consumption and construction year, the correlation between energy consumption and postal code and the correlation between energy consumption and indoor temperature.

3.2.2 Reaction to rising energy costs

To get an overview of how different aspects of the dataset have changed over time, descriptive analyses are applied. These descriptive analyses are applied on the set and flexible prices of natural gas and on the average energy usage. With the yearly dates, percentual changes can be calculated. Table 4 shows how the prices of flexible gas contracts have changed. Most notable is the high increase in price from 2021 to 2022, the rise of 329% is unprecedented. The increase in flexible contract price is due to the costs of gas supply rising, due to the weaponization of natural gas supplies during the Ukraine-Russia war (*Reasons Behind the 2022 Energy Price Increases and Prospects for Next Year*, 2023).

Year	Flexible contract price (Euro/m3)	Price change (%)
2018	0,33	-
2019	0,35	+5
2020	0,28	-19
2021	0,42	+46
2022	1,78	+329

Table 4: *Fluctuation of flexible natural gas contract prices in The Netherlands (Own work, 2024)*

One thing that should be kept in mind when assessing the increase of energy prices from 2021 to 2022, are the additional financial supports which were also granted during this period. This came in the form of a tax deduction on energy of approximately 417€ more than a year earlier per household. Besides this tax deduction, an additional tax credit of 266€ more than the year before was also granted for each household (Centraal Bureau voor de Statistiek, 2022).

Table 5 gives an overview of how the prices of fixed natural gas contracts have changed from 2018 through 2022. What is notable is that the prices of these fixed contracts haven't increased from 2021 to 2022, like the flexible contracts have. This can be explained through the fact that gas suppliers have significantly lowered the number of fixed contracts they provide (Centraal Bureau voor de Statistiek, 2022). This can be seen in figure 10. The uncertainty surrounding gas prices has caused many to prefer the fixed contracts. This also means that households who entered a -multiple year- fixed contract at the correct time were not affected by the increases of energy prices. At the same time, they did receive the same financial support as households with flexible contracts, meaning that their situation could have actually improved during the energy crisis.

Year	Fixed contract price (Euro/year)	Price change (%)
2018	236	-
2019	224	+3
2020	253	+4
2021	259	+2
2022	251	-3

Table 5: *Fluctuation of fixed natural gas contract prices (Own work, 2024)*

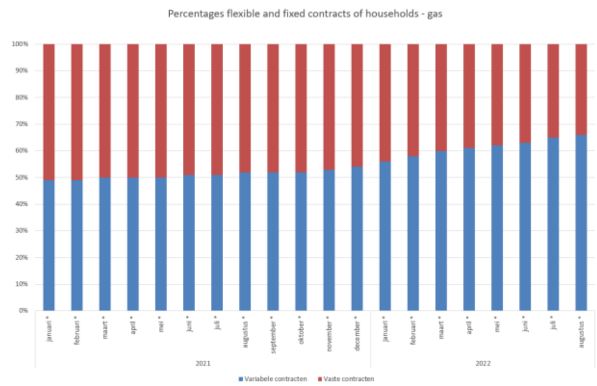


Figure 10: *Ratio of flexible and fixed price gas contracts issued in The Netherlands (Blue = flexible, Red = fixed) (Centraal Bureau voor de Statistiek, 2022)*

Table 6 visualises how the average energy usage of Delfts' households has changed over the years 2018 through 2022. While the energy consumption is different for all individual households, this average is able to show the larger scale trend. Most notable is the large negative change of energy usage from 2021 to 2022 of 12%.

Year	Average energy usage (m3)	Usage change (%)
2018	1132	-
2019	1112	-1
2020	1120	+0
2021	1126	+1
2022	990	-12

Table 6: *Fluctuation of energy usage in Delft (Own work, 2024)*

3.2.3 Energy consumption & energy price relation

In order to get insight into how natural gas usage changes when energy prices change, a descriptive analysis is done on the yearly natural gas use and the yearly flexible contract energy prices. The analysis, which can be seen in figure 11, shows a clear relationship between the increase of average variable gas prices and the reduction of gas usage per dwelling. At the same time, there is a less strong relation between the yearly natural gas use and the yearly set contract energy prices. This can be explained by the knowledge mentioned in the previous paragraph, which noted different changes of the prices and less extracted contracts. Figure 12 shows how the gas usage reacts to the pricing change in fixed energy contracts.

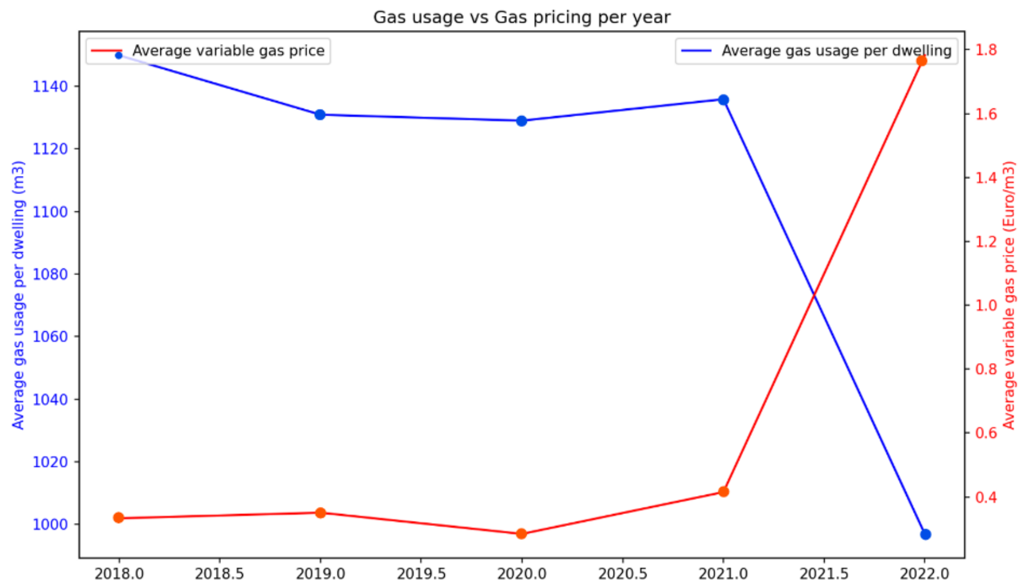


Figure 11: *Correlation between flexible contract prices and energy usage in Delft (Own work, 2024)*

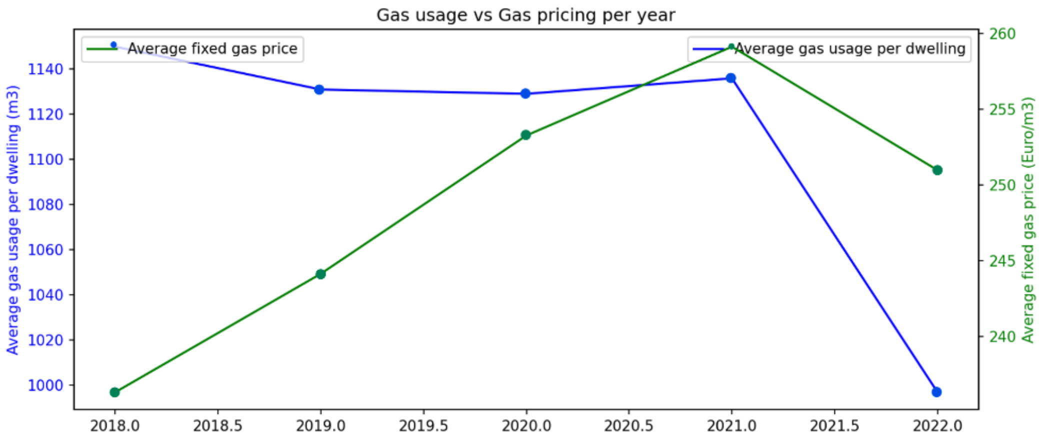


Figure 12: Correlation between fixed contract prices and energy usage in Delft (Own work, 2024)

3.2.4 Influences on energy consumption change

As has been explored in chapter 2.1, energy usage and energy poverty are concepts which are influenced by a range of factors, from income, to building characteristics, to energy policy. To understand which factors function in relation to energy poverty in Delft, it should be analysed first how the average construction year of a postal code influences the change in energy consumption from 2021 to 2022. The used dataset notes per postal code how many buildings have been built in specific time frames. The time frames being before 1945, 1945 to 1965, 1965 to 1975, 1975 to 1985, 1985 to 1995, 1995 to 2005, 2005 to 2015 and after 2015.

For example, postal code 2611AN has 40 homes built before 1945 and 10 homes built between 1945 and 1965. Using this data, the average construction year is calculated per postal code. This works as a sufficient representation, as most postal codes have solely buildings from the same construction year. One difficulty does come in the classification of buildings built before 1945, since there is no specific year to attach to these dwellings. For the sake of this analysis, the value of 1900 is assigned to these dwellings.

The goal of this analysis is to analyse the notion that construction year can be related to the presence of energy poverty and that older homes result in a larger risk of energy poverty. This notion relates to the knowledge of chapter 2.1 that energy inefficiency of buildings is one of the main drivers of energy poverty. While data on the energy efficiency of all dwellings is not something that is available, data on the construction year is and older homes are often less energy efficient than newly built homes (Van Der Linden et al., 2016). This means that if this notion is true, construction year can be used as an identifier for energy poverty risk and presence. The average construction years are compared to the decrease in energy consumption per postal code, with high decreases relating to energy poverty. This results in in figure 13, most notably are the high decreases in energy use for buildings from before 1945.

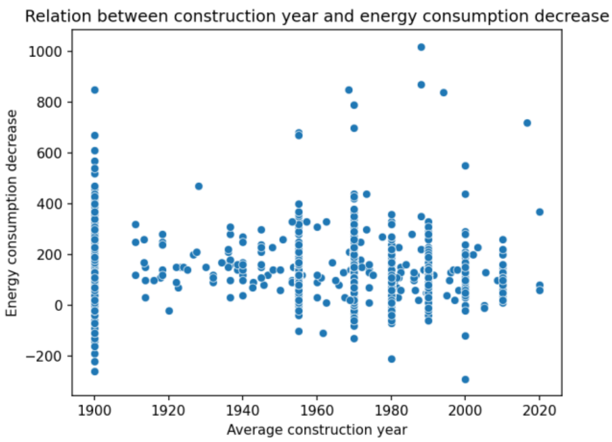


Figure 13: Relation between average construction year and energy consumption decrease (Own work, 2024)

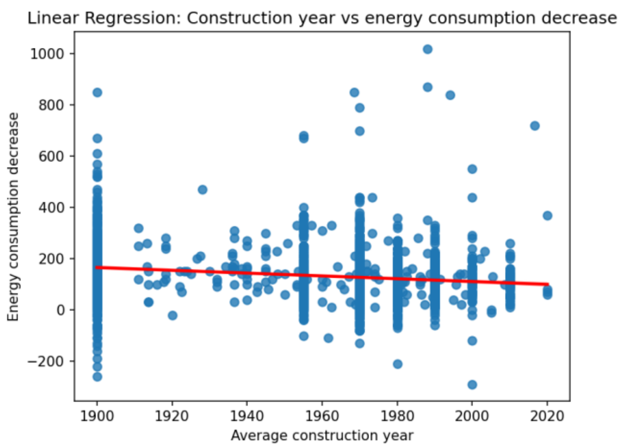


Figure 14: Linear regression analysis between average construction year and energy consumption decrease (Own work, 2024)

Following this, a linear regression analysis is performed on this data set, to identify a correlation. The result of this can be seen in figure 14. When applied to the dataset, a regression coefficient of -0,6 is the result. Meaning that there is a negative relation between the average construction year and energy consumption decrease. In other words, dwellings built more recently had on average a smaller decreases in energy consumption than older dwellings, proving the constructed hypothesis. While this coefficient doesn't explain the full picture, as the value isn't decisively negative enough for this, it does point towards a relation between the factors. This is confirmed by the R2 value of 0,034, which is quite low, meaning that there are other characteristics that also play an influential role.

The conclusions from the linear regression analysis between construction year and energy consumption change, which show the strength of this relation and the presence of other factors, are confirmed with the use of a different dataset. The CBS (Central bureau of statistics) has monitored the average temperature corrected natural gas delivery to different building categories. This dataset shows the average change in energy use per household category. With categories existing of different household sizes, construction year and dwelling sizes. The dataset of appendix 5.1 details how different household categories experience different energy consumption changes. The dataset shows a similar energy consumption decrease as the previous analyses. It also confirms the findings that older homes having larger energy consumption decreases than newer homes. This difference is best shown between data of the 1 occupant post 1992 small apartment and the data of the 1 occupant pre 1992 small apartment. With the newer homes having a decrease of 12%, and the older having a decrease of 14%. At the same time, factors such as the dwelling typology, number of occupants and dwelling size also have notable effects. With larger homes and homes with more occupants having larger decreases. This can be explained by the fact that these households have a higher average energy consumption, as larger homes take more energy to heat, and a larger number of occupants resulting in more energy usage. This means that these households will more heavily experience the effects of energy price increases. These are just some of the factors which explain the regression coefficient of -0,6 between construction year and energy consumption decrease. But these aren't the only factors which will influence the energy consumption decrease. As discussed in chapter 2.1, household income also has a large effect on the decrease.

The energy consumption decrease data coupled with the construction year and postal code of these dwellings allows for the localisation of households which are likely to be in energy poverty. With this information, alongside the average income of the postal code, an estimation can be made whether the decrease is related to energy poverty, or if there are other factors at play. The presence of other factors makes it more difficult to form the correlation between energy consumption changes and energy poverty. Because there could be other explanations for the change in energy consumption, like energy efficiency interventions, temporary vacancy of dwellings or changes in house occupancy.

3.2.5 Energy price and indoor temperature correlation

With the available energy consumption data, a general estimation for the change in indoor temperature can be made per postal code. This estimation is made using the following formula:

$$T_{indoor,2022} = T_{indoor,2018} * \frac{Q_{2022}}{Q_{2019}}$$

With:

- $T_{indoor,2022}$ = Estimated maintained indoor temperature in 2022
- $T_{indoor,2018}$ = General standard maintained indoor temperature in 2018 (20 °C)
- Q_{2022} = Gas usage in 2022, corrected for temperature fluctuations
- Q_{2019} = Gas usage in 2019, corrected for temperature fluctuations

This method allows for a general estimation, while it does contain flaws and generalisations. One is the reference year that is used, it could be that 2019 is an outlier year for some postal codes. To combat this, the average usage of 2018, 2019, 2020 and 2021 can be used. This changes the formula to:

$$T_{indoor,2022} = T_{indoor,2018} * \frac{Q_{2022}}{Q_{2018,19,20,21}}$$

Using this calculation on the example postal codes, example results can be generated, which can be seen in table 7.

Postal code	2613AP	2625LR	2611XH
Av. 2018/2021 gas usage (m^3)	3723	3798	2438
2022 gas usage (m^3)	2650	2960	2020
Initial estimated 2022 indoor temperature (^0C)	14,2	15,6	16,6
Temperature decrease (%)	28,8	22,1	17,1

Table 7: *Example postal codes indoor temperature estimation results (Own work, 2024)*

This method does not consider the personal temperature preference of households. As has been explained in chapter 2.2, thermal comfort is different for every person and household. The indoor temperature of 20 degrees is the average indoor temperature and is for that reason used in these calculations (*hier.nu*, n.d.).

The described methods allow for the estimation of indoor temperatures of specific postal codes. To give an estimation of the average maintained indoor temperature of households in Delft as a whole, the total energy use of Delft is compared from 2022 to the average of 2018, 19, 20 and 2021. Alongside the estimated indoor temperature of 20 degrees. This results in an estimated indoor temperature in 2022 of 17,5 °C. While this value gives an insight into the effect of energy pricing, it is overgeneralised, as different income classes and building characteristics are combined. Within the negative changes in indoor temperature, most values of the temperature difference lie between -4 and -1 °C between 2022 and 2018 through 2021. Appendix 5.2 details the data on the new indoor temperatures of the dwellings which experienced the largest decrease in indoor temperature in Delft.

Different things can be noted in this dataset. Most obvious is the large drop in indoor temperatures, down to extreme lows of around 12 degrees. Next, there is a variety of average construction years in the dataset, while most of these construction years are before or around 1970, there is no one on one linearity. This shows that there seems to be a relationship between construction year and energy poverty, but it isn't fully correlating. At the same time, the spread of areas and average yearly personal incomes points towards the importance of income when assessing energy poverty. Areas with lower average incomes are represented more in the largest decrease dataset than richer areas. Appendix 5.3 shows an overview of the different areas of Delft and their respective average incomes.

Though this method is generalized and provides only a calculated estimation, it does provide insight into occurring trends. While accurate data of maintained indoor temperatures of dwellings is not widely available, field experts can provide their review of these findings. The research on financial stress of chapter 2.3, the interview with ir. Hans Bosch in appendix 3 and the interview with the Energiehulp of appendix 2 provides additional information on this subject and have been assessed. During the moisture assessments Mr Bosch makes, often to energy poverty households, he notes an average indoor temperature of between 12 and 14 degrees. This aligns with the findings of several individual postal codes, but not with the temperature estimation of Delft as a whole. This be explained through the dwellings Mr Bosch visits, which are often energy poverty households of lower quality. The Energiehulp's of Dordrecht confirm the general findings. They note an average indoor temperature of 14 to 16 degrees in the severe cases of energy poverty they visit. As mentioned, the calculation method mainly allows for estimations to be made, this capability is due to different factors, which will be elaborated on in chapter 6. More detailed assessments will require careful case review and additional research.

3.2.6 Indoor mould and energy poverty

The notions of Mr. Bosch, as discussed in detail in appendix 3, become clear when compared to the methods of predicting indoor mould. As Mr. Bosch mentions and as has been researched in chapters 2.5.4 and 3.2.5, households living in energy poverty tend to accept much lower indoor temperatures than usual.

With this knowledge, a comparison between situations can be made to analyse the changes to mould growth risks. Viitanen (2011) related mould growth conditions to relative humidity values higher than 80% for temperatures in the range between 10 and 35 degrees, as discussed in chapter 2.6.4.

In order to analyse how the situations change under different indoor temperatures, relating to relative humidity, a psychometric chart is used. Psychometric charts represent the physical and thermal properties of air and allow for estimations to be made on relative humidity values (Legg, 2017). In this comparison, the position of the standard situation on the chart can be estimated. With an indoor temperature of around 18 ^{0}C, an average relative humidity will be around 50% (*What Are the Regulations on Indoor Humidity?*, n.d.). With this position localized on the chart, the position of one severe energy poverty situation can be estimated. With a reduction of indoor temperature to 12 ^{0}C, while the value for the absolute humidity remains the same, a new average relative humidity of around 75/80% can be noted. When this is compared to figure 8 and the research of Viitanen (2011), it can be seen that this relative humidity level is much closer to the indoor mould growth risk. Figure 15 shows the relation between temperatures on the psychometric chart, this figure also shows the critical humidity levels.

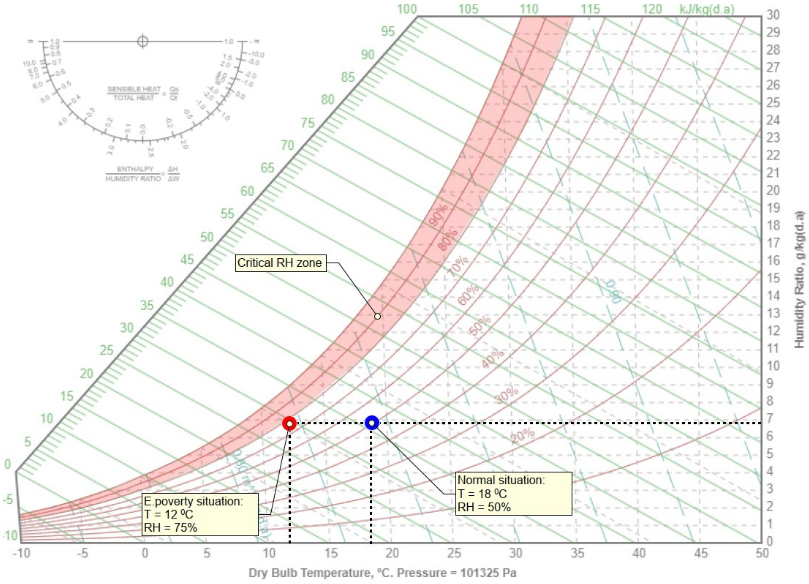


Figure 15: *Relation between indoor temperatures and relative humidities (Own work, 2024)*

The observations on the relationship between energy poverty and indoor mould can be summarized in the following statement: less or localized heating, with the same moisture production and ventilation behaviour results in; higher indoor relative humidity, higher relative humidity on the façade, increased risk of indoor mould growth and an increased risk of indoor mould growth behind objects placed along the façade (couches or other furniture). (*Energie-armoede*, 2024):

With important observations connected to this being that: The worse the dwelling is insulated, the more problematic the problem of reduced heating is. A lower indoor space temperature leads to the earlier observation of draft, which leads to less ventilation, increasing the risk of indoor mould growth. Short heating bursts will increase the air temperature, but the façade, especially if it is a brick wall façade, will stay cold, increasing the relative humidity on the façade.

The most important notion of this segment is that the amount in which indoor temperatures of households have changed during energy price increases, can be used to identify the severity of energy poverty in a certain building. As homes with lower indoor temperatures are at greater risk of mould growth and the health risks mould brings with it. The notion that the average indoor temperature has decreased significantly during the energy crises raises concerns about the growth of indoor mould across different households, a problem which already existed before the energy crisis (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024).

3.2.7 Identifying energy poverty households
As mentioned in this chapter, the data on changes in energy consumption, alongside construction year of the dwelling and household income allows for the identification of households at risk of energy poverty. This can be done with the following steps:

1. Comparison of energy consumption changes
Which households in a certain area (i.e. Delft) have experienced the largest decrease in energy consumption from 2021 to 2022? This comparison should consider faults in data and calculations, filtering out miscalculations due to changes in for example occupancy.

2. Comparison of indoor temperature changes
The changes in indoor temperature, as explained in chapter 3.2.5 should also be compared. With this comparison, the severity of the problem can be assessed. This can be done by comparing the new indoor temperature to the 'standard' indoor temperature of 20 degrees Celsius. The further the new indoor temperature is from the standard, the more prevalent the risk of mould and energy poverty.

3. Assessment of average household income
With the change in energy consumption in mind, one of the main drivers of energy poverty needs to be assessed, household income. Because if this average income is much higher than the poverty limit, there is a larger chance the reduction in energy consumption is of other nature. In these cases, it is more likely to due to energy efficiency interventions or because of a conscious change in energy consumption.

4. Assessment of average construction year & energy label
As has been discussed in chapter 3.2.4, construction year is one of the more influential factors which has an effect on the risk of energy poverty. With energy poverty households often living in older dwellings. In order to confirm the findings of the previous steps, it is helpful to assess the average construction year of the dwelling. For example, if a household with low income and low indoor temperature lives in an older home, built before conscious energy efficiency standards, they are likely to be experiencing energy poverty. At the same time, if a household with high income and lower new indoor temperatures lives in an 'older' home, they are more likely to have invested in energy efficiency interventions, explaining the change in energy consumption. Another way in which building properties can be taken into account, is through the buildings' energy label. Using this method of previously described steps, the areas, and dwellings in Delft with a large probability of energy poverty can be identified, a collection of these can be seen in appendix 5.4**.**

3.3 Redefining energy poverty and its assessment
3.3.1 Redefining energy poverty
The chapters so far have discussed many aspects of energy poverty, with the main conclusions being that rising energy prices directly influence households' energy usage. With higher energy prices resulting in lower energy usage across households. The rising of energy prices results in lower handled indoor temperatures in households living with low incomes, especially in older dwellings. This leads to different physical, mental and construction problems. Energy poverty can't solely be seen as a financial problem, it is a combination of regulatory, financial, personal, and building aspects. Current policies focus too much on the financial aspects of energy poverty and provide mostly short-term solutions.

With these conclusions in mind, redefining energy poverty becomes important, as different definitions relate to different actions. This relation can be seen in the definition which has been deemed the standard definition. This definition mostly focussed on the financial side of energy poverty, leading to the belief that financial reliefs would successfully solve or diminish the problem. This can be seen in the actions by the Dutch government, discussed in chapters 2.7 and 3.1. The financial allowances and price caps have been presented as the reason for 500 thousand households being 'saved' from energy poverty. While this is true, when no improvements are made to these households' homes, as soon as this financial action is halted these households will fall back into energy poverty. This notion was also presented in the report of Mulder et al. (2022), who notes there are approximately 3,8 million households living on the brink of energy poverty. As they don't have the financial means to improve their home energy efficiency, if the energy prices were to rise again, they would need to spend more of their income on energy, categorizing them as energy poverty households.

The notions on the intertwining of drivers of energy poverty has led to a better understanding of the concept. While constructing a perfect definition is impossible, new relations can be identified using the research thus far. The different relationships between factors can be seen in figure 16. This description of relations surrounding energy poverty points towards an adaptation of earlier mentioned definitions, with different adjustments. A proposal of this better definition is: 'A person is considered energy poor *"if he/she encounters particular difficulties in his/her accommodation in terms of energy supply related to the satisfaction of thermal comfort and health needs, this being due to the inadequacy of financial resources and housing conditions, alongside a significant rise of energy costs".*

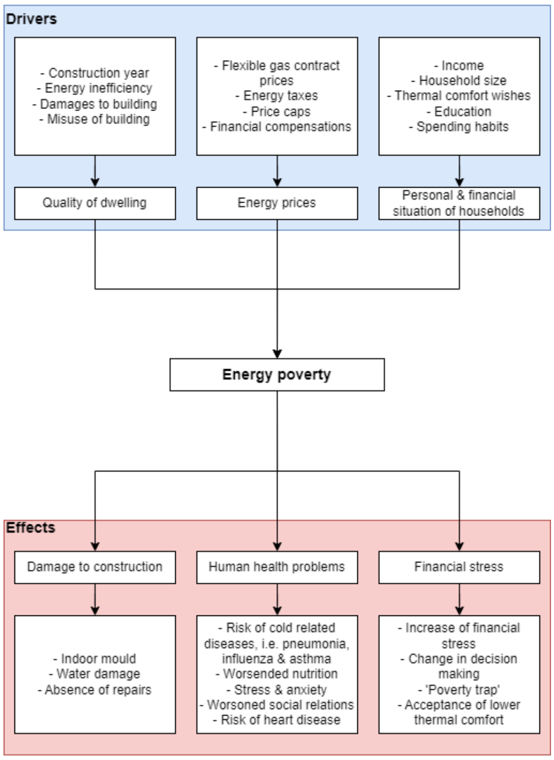


Figure 16: *Energy poverty definition relations (Own work, 2025)*

3.3.2 Assessing and combatting energy poverty

The newly formed definition, alongside the research of the previous chapters, allows for more effective strategies for combatting energy poverty to be formed. This chapter will go into developing such an approach for assessing and reducing energy poverty problems.

Figure 18 visualises an outline of this approach, consisting out of different segments. The goal of this approach is to shift the assessment of energy poverty from purely a financial and large-scale problem to a multidimensional and smaller scale problem. In this way, more effective countering strategies will be found, these strategies will work in a longer term and constructive manner which addresses the core of the problem. The outline can be viewed in more detail in appendix 24. The approach is conceptually based on the investment decision process of figure 17. This figure visualised how investment decisions are made for residential energy efficiency improvements. The developed assessment method consists of the following segments:

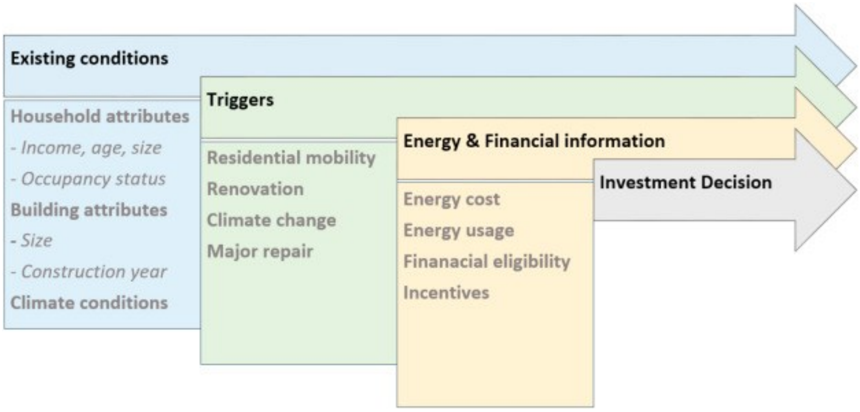


***Figure 17:** Residential energy efficiency investment decision process (Belaïd et al., 2021)*

1. Concern:

For the assessment process to start, there must be concern to believe that energy poverty is a substantial problem in a certain subject pool. This subject pool could be of different sizes, from a city-wide level to a neighbourhood level. This cause can be identified in different ways. There could have been complaints by occupants of a certain building. These occupants could have either admitted their problems while paying their energy bills, or they could have mentioned mould problems they're experiencing, leading to the suspicion of energy poverty presence. Besides this, accessible data can also lead to suspicions of energy poverty problems, similar to the data analyses. If significant reductions of energy consumptions are noted during energy price increases, without retrofitting taking place, this can be a sign of energy poverty.

2. Review:

After the building in question has been identified, relevant data needs to be gathered in order to assess the severity of the problem. This data is similar to the data used in the research so far and which will be used in the continuation of the research. Part of this data is publicly accessible, but more specific data will also be necessary to be gathered. The data which need to be gathered for a complete review is:

2.1 Heating energy usage:

Data on the heating energy usage of the case over the last years is one of the first information elements which should be gathered. This energy can consist of either solely heating energy usage or complete gas usage. The data should contain information on the energy consumption during regular times and the consumption during energy price increase periods. This data can be used to make estimations of the handled indoor temperatures during these energy price increases. If more precise measurements are available for these indoor temperatures, these should be used.

2.2 Building characteristics:

Different building characteristics have been noted to influence the presence of energy poverty in buildings. Information will be needed on the buildings' construction year, the buildings' quality (i.e. thermal quality, ventilation system quality, water proofness) and on possible bottlenecks of the building which worsen the effects of energy poverty. Perhaps, issues with the ventilation system are known or defects in the heating system have reoccurred. For a more thorough analysis and possible simulation, properties of the existing constructions are needed.

2.3 Target group:

For the successful energy poverty assessment, information is needed on the occupants of the given building. Data will be needed on their average age, their background (i.e. educational, professional, and geographical) and on their income. These factors will help direct the approaches to the specific target group and discover the severity of the energy poverty issue.

2.4 Personal factors:

To get a complete overview of energy poverty in a given building, it is important to speak to the occupants. These occupants will provide a good description of the situation they and others are living in. Besides this, by directly talking to occupants, more insights can be gained to the different causes of the problem. Perhaps they have experienced building defects (i.e. draft). Lastly, talking to occupants will provide insights into the ways they have dealt with their energy poverty situation up to that moment, perhaps giving some smart examples. Appendices 1, 2 and 3, alongside the study of Van Ooij et al. (2024) give examples of personal discussions and the information which can be extracted from these discussions.

3. **Review conclusions**

The review of the building will lead to different conclusions on the problems and possibilities at play within the building. These conclusions will be used to decide further actions for combatting the problem. These review conclusions will consist of conclusions on the severity of the problem, possible causes within the building, improvement possibilities which the building presents and key points specific to the situation. These conclusions will be different for each case.

4. **Suggested approaches**

The previously discussed review conclusions will lead to the suggestion of interventions for combatting energy poverty in the given situation. The suggested approaches will consist out of interventions on distinct levels in which energy poverty can be addressed. The levels and examples of common interventions will be discussed in chapter 4.4.

5. **Implementation**

The assessment will conclude by providing guidelines on what the most effectives ways are for implementing the approaches. This will include guidelines on how to approach the levels of communication and finances. This step is crucial, as previous chapters and the interviews have shown that correct implementation of solutions is critical to their success.

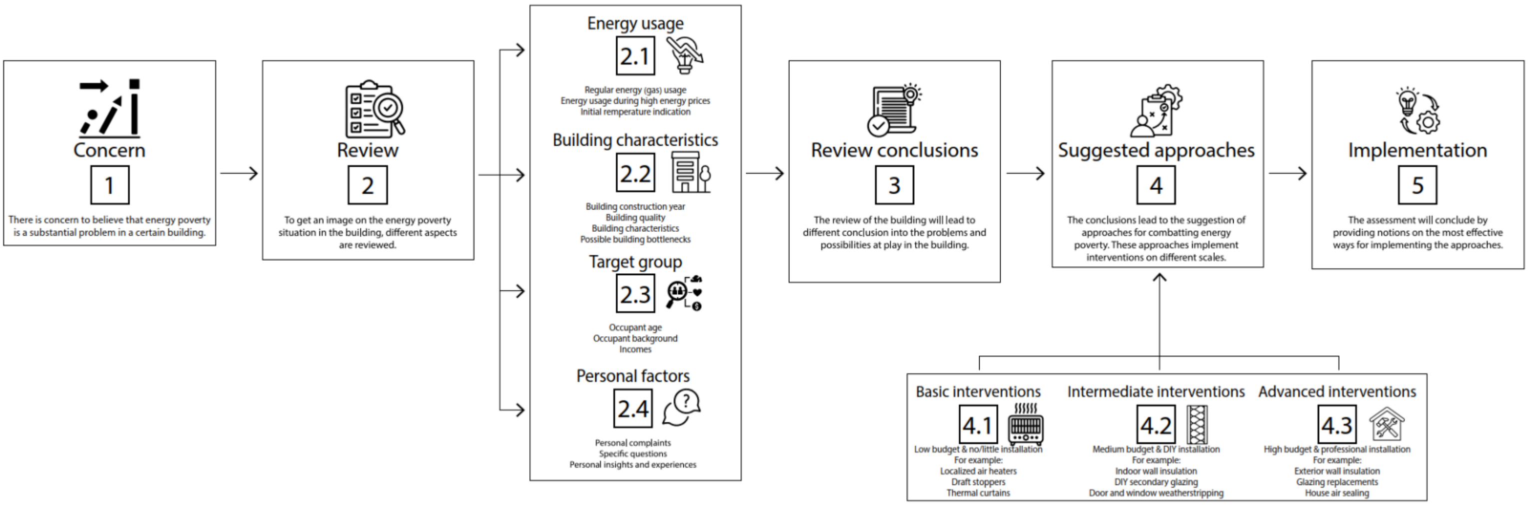


Figure 18: *Energy poverty assessment outline (Own work, 2025)*

4 Simulation research

4.1 Test case

In order to perform simulations which test the effectiveness of interventions, an applicable situation is needed in the form of a test case. The chosen test case should function both as a case for testing interventions, visualising the assessment outline and should be representative enough for the testing results to be applied on other subjects.

4.1.1 Possible cases

As mentioned, a base situation is needed to review the individual interventions. With the focus of the research being on the problem of energy poverty in The Netherlands and more specifically Delft, the test case will be situated in Delft. In order to pick a fitting test case, the method of chapter 3.2.7 is used. This method allows for the identification of energy poverty situations by identifying the dwellings with the biggest reduction in energy consumption as a result of energy price increases. Besides their identification as energy poverty affected dwellings, other criteria need to be considered when deciding if they will be the test case for this research.

Firstly, the building needs to represent a larger category of energy poverty affected buildings in Delft. This will increase the applicability of the study onto other subjects. This representation should come through the characteristics of the building. Characteristics include the construction properties, occupant characteristics and the energy consumption data.

Secondly, the building needs to be of 'low' enough quality. This means that the cause of energy poverty in the dwelling needs to be able to be traced back mainly to the quality of the dwelling and the household characteristics. This is important, as interventions could be of most aid where the dwelling quality is the main energy poverty driver. This means that applicable cases need to be reviewed on whether renovations have taken place there, besides solely the construction year. This needs to be done individually per case, but another assessment method for this is the energy label of the building. Energy labels can range from A++++ to G and represent the energy efficiency of the building. If the energy label is higher than C, it is a solid reason to believe building quality isn't the main cause of energy poverty in the building. Within buildings with an energy label lower than or equal to C the main cause of energy poverty shifts to the building quality.

Lastly, there needs to be adequate data on the building and its characteristics. While different properties of the dwelling can be manually estimated to form a comprehensive case, it is still important that enough documentation is available on the building's characteristics. The applicability of intervention tests reduces when too many assumptions need to be made. These criteria have led to the cases in table 8 being determined as applicable for the case study:

Postal code	Area	Adress	Average construction year	Energy label of building	Building
2624RD	Voorhof	Poptahof Noord	1955	E	
2612VT	Vrijenban	Gouden-regenlaan	1988	D	

2624KW	Voorhof	Guido Gezellelaan	1970	C	

Postal code	Area	Adress	Avg. Gas consumption 2018/2021 (m3)	Gas consumption 2022 (m3)	Initial indoor temperature estimations (°C)
2624RD	Voorhof	Poptahof Noord	627	350	11,2
2612VT	Vrijenban	Gouden-regenlaan	637	370	11,6
2624KW	Voorhof	Guido Gezellelaan	1320	820	12,4

Table 8: *Possible cases in Delft (Own work, 2025)*

4.1.2 Chosen case

Out of these applicable cases, the case of Poptahof Noord will be simulated. This case will be simulated due to the severity of energy poverty, the old construction year, the low average yearly personal income and the low energy label being more problematic than the other possible cases. The chosen case is situated in the Voorhof area of Delft, and the building group is also known as Poptahof. It consists of different post-war buildings with an average construction year of 1955. Poptahof consists out of 3 types of housing complexes. In this research, the 12-level apartment buildings of Poptahof Noord will be analysed. These 12 level apartment buildings are common post-war gallery apartment buildings. The complex is built up of a concrete framework, uninsulated cavity walls, outdated asbestos insulation panels and consists of single and outdated double glazing. The heating of the complex is provided through individual radiators connected to a central system. The complex is ventilated passively for the most part, with mechanical extraction being present in the bathrooms and other wet rooms. The layout of Poptahof and the documentation on Poptahof Noord can be seen in appendix 6.

4.2 Simulation set-up

In order to test the interventions, an energy consumption model of the case will be set-up. This model will simulate the energy consumption of the case. Following this, different parameters will be altered, which resemble the intervention which will be tested, and the energy consumption simulation will be performed again. After this is completed, both simulations will be compared to each other and the results and differences will be logged. The simulations will be performed through the program “VABI Elements”. This program allows for the detailed modelling and simulation of building energy usage and thermal regulation (*Vabi Elements - 3D Rekensoftware Voor Installateur & Adviseur*, n.d.). VABI Elements allows for different simulations to be done on projects, Withing this research, the simulations of ‘Building Simulation’ and ‘Building Simulation: Energy & Costs’ will be performed.

4.2.1 Input

In order to successfully set-up the simulations, different inputs are needed. The most important inputs are listed below. The input variables are noted in detail in appendix 7.

<u>Library input</u>

Constructions: How are the different constructions of the building built up. ***Internal Heat Production (IHP) of persons***: What type of human room usage is present in the building? Within this building usage, how many humans are present, how are they clothed in the summer and winter and what intensity of activity are they practicing? ***Time schedule of installations***: At what times on the different days of the week are the different installations (i.e. heating) used and in what intensity? ***Time schedule of rooms***: At what times on the different days of the week are the different aspects of rooms used (persons, devices, lighting)? ***Heat generation***: With what device(s) are cold, heat and hot water generated in the project & what are the specifications of this generation method?

Room templates input
Room demands: What comfort class should be applied to which room and what are the design temperatures of these rooms? ***Room usage***: What are the usage profiles of the different rooms in terms of the present IHP's and their time schedules? ***Room ventilation***: In what intensity are the individual rooms ventilated & what intensity of infiltration is present? ***Heat delivery***: How is heat delivered to the individual rooms, at what times is this heating available & what are the specifications of the present heating system?

4.2.2 Output
After these simulations are completed, different result data can be accessed and analysed. The result data which will be analysed from both simulation models to assess the effectiveness of different interventions are:

Energy statistics: Total heating energy (kWh), total cooling energy (kWh), the dates of the maximum heat and cold delivery. All these statistics are also available on a room level. ***Comfort charts***: What are the over- and underheating hours for different temperature classes for the different rooms? ***Daily result charts***: What are the daily energy flows within the different rooms within the building for the individual days of the year? Elements which are present within the daily charts include temperature statistics, cooling and heating energy, solar radiation, internal heating loads & ventilation statistics. ***Temperature frequency***: For how many hours is what temperature measured within a specific room? ***Energy carrier statistics***: What is the total energy usage, specific energy usage, energy costs & usage of different energy carriers of the building? These statistics include the cases gas usage. ***Monthly charts***: What are the values of the different statistics per month? ***Yearly charts***: How do the energy statistics compare to each other over an entire year?

4.3 Modelled situations
After the library and room templates are set up, the next step is to define the building geometry and individual room geometry of the project which will be simulated. The geometry can be modelled by adding volumes in the geometry modelling tool in VABI Elements, or by importing 2D or 3D digital model data. Besides modelling the exterior and interior walls of the project, all window and door openings within the building are also modelled. Besides the geometric modelling, possible overhangs can be modelled, and the orientation of the project is also defined. After the geometry and individual rooms are modelled, the predefined templates are assigned to all different aspects of the model. The modelling process of the previous paragraphs has been carried out for the case of Poptahof, figure 19 gives an overview of the modelled project.

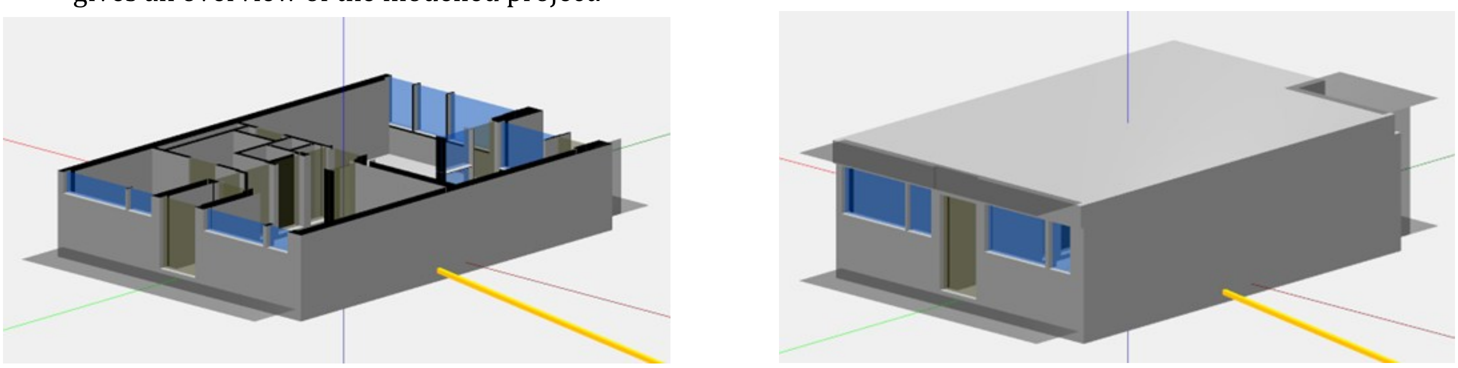


Figure 19: *Modelled situation in VABI Elements (Own work, 2025)*

4.3.1 Base situation
The purpose of the base situation is to represent the energy consumption of the household who uses the dwelling as realistically as possible. This is done by applying research on household usage to the

model. The ISSO publication on thermal comfort of dwellings translates research on household energy consumption to variables on room usage and heat production (ISSO, 2018). This publication lists and substantiates the inputs required for the simulation. Besides this, the knowledge on this subject of different energy usage advisors who frequently perform these simulations is implemented. These different inputs of information are used to model a simulation as realistically as possible. The data on the average energy consumption of the dwelling between the years 2018 to 2021, mentioned in chapter 3.2 is used as a reference point for the total amount of gas usage of the case study simulation. Table 9 shows the comparison between the retrieved gas consumption data and the representative model. It can be seen that the total gas consumption data is representative to the data from chapter 3.2 within a range of 5%.

Situation	**Energy consumption (kWh)**					**Total Gas consumption (m^3)**	**Total energy consumption (kWh)**
	Heating	**Domestic hot water**	**Appliances**	**Other**	**Total**		
Average situation 2018/21 – ch. 11	No individual information available from dataset					627	-
Modelled average situation 2018/21	3467	2878	1953	434	8732	657	8732

Table 9: *Modelled normal energy consumption situation (Own work, 2025)*

4.3.2 Energy poverty situation

With the base situation set-up, the energy poverty situation can be modelled. This situation is set up with different information inputs in mind. The first being the information of the research so far, on how the energy consumption of households changes under energy poverty. This includes the literature research of chapter 2, the data analysis of chapter 3 and the interviews of appendices 1 through 3. This information goes into how different aspects of energy consumption change under energy poverty. This includes the aspects of domestic hot water usage, the internal heat production of people, the time schedules of heating and heating setpoints which households apply to their dwelling. With this in mind, the parameters regarding these aspects of energy consumption were altered to represent the usage of an energy poverty household. For example, the estimated new indoor temperatures of chapter 3.2.5 were combined with the literature study and field experts to come to estimations of temperature setpoints between 11 and 14 degrees. Next to this, the research showed that rooms are heated for less time, only when necessary and when they are used most intensely, this had led to changes in heating schedules. An overview of the changes can be seen in table 10. The data on the average energy consumption of the dwelling in 2022, mentioned in chapter 3.2 is used as a reference point for the total amount of gas usage of the case study simulation. Table 11 shows the comparison between the retrieved gas consumption data and the representative model. It can be seen that the total gas consumption data is representative to the data from chapter 3.2 within a range of 5%.

Element	**Base situation**	**Change**	**Energy poverty situation**
Domestic hot water	House usage: 3 persons Water usage: 30 L/person/day Building usage: 340 days/year Efficiency of heating system: 0,85	In energy poverty, households shorten their showering time and other forms of water heating.	House usage: 3 persons Water usage: 20 L/person/day Building usage: 340 days/year Efficiency of heating system: 0,85
Internal heat production of people	Summer clothing: 0,5 CLO Winter clothing: 0,8 CLO Activity level: 0,8/1,2 MET	In energy poverty, households increase the amount of insulating clothing they wear so heat demands decrease.	Summer clothing: 0,5 CLO Winter clothing: 1,2 CLO Activity level: 0,8/1,2 MET
Time schedule of heating	Kitchen: 06:00 – 08:00 / 15:00 – 20:00 Bedroom: 17:00 – 23:00 Living room: 06:00 – 09:00 / 16:00 – 22:00	In energy poverty, households become more selective in the rooms they heat, and for which times they are heated.	Kitchen: 18:00 – 20:00 Bedroom: 19:00 – 23:00 Living room: 06:00 – 08:00 / 18:00 – 22:00
Heating setpoints	Daytime usage: 19^{0}C Nighttime / base usage: 14^{0}C	In energy poverty, households significantly lower their temperature standards to values between 11 and 14 degrees.	Daytime usage: 13.5^{0}C Nighttime / base usage: 11.5^{0}C

Table 10: *Applied changes to model energy poverty situation (Own work, 2025)*

Situation	Energy consumption (kWh)					Total Gas consumption (m^3)	Total energy consumption (kWh)
	Heating	Domestic hot water	Appliances	Other	Total		
Average situation 2022 – ch. 11	No individual information available from dataset					350	-
Modelled average situation 2022	1467	346	1953	434	5773	346	5773

Table 11: *Modelled energy poverty energy consumption situation (Own work, 2025)*

4.3.3 Simulation review

To effectively review the different energy poverty interventions, a review framework has been set up. This review framework can be seen in table 12. This review framework takes the most important aspects of energy poverty into account. The first aspect is that of energy efficiency, this is measured by comparing the energy consumption of the case under the same usage, with the intervention. The second aspect is that of thermal comfort, this is measured by noting how the heating setpoint of the most intensely used rooms (living room and kitchen) can be increased without increasing the energy usage and bill. This review method represents the consideration of energy poverty households between (local) thermal comfort and energy costs, as has been discussed in chapter 2.5.4 and the different interviews. The last aspect is that financial efficiency, this is measured by noting the cost, yearly gas savings, yearly gas bill savings, the interventions' payback period and the investing efficiency (the ratio between intervention cost and yearly savings). These financial effects are noted using the peak gas prices during the energy crisis of 1,5€. These review criteria are based on the definition of energy poverty of chapter 3.3.1. Besides these review criteria, the interventions will be assessed on different pros and cons within the context of energy poverty.

Parameter	Normal usage profile	Energy poverty usage profile
Energy Efficiency		
Gas consumption without intervention (m^3)	657	346
Gas consumption with intervention and same temperature settings (m^3)		
Improvement (%)		
Thermal comfort		
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)		
Improvement (°C)		
Financial efficiency		
Approximate cost of intervention (€)		
Gas consumption savings with same temperature settings (m^3)		
Gas pricing (€)		
Yearly savings with same temperature settings (€)		
Payback period (years)		
Old gas bill (€)		
New gas bill (€)		
Investing efficiency (%)		
Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's		
Intervention cons		

Table 12: *Individual intervention review framework (Own work, 2025)*

4.4 Intervention library

As has been described in chapter 2.4.3, different types of interventions exist with the goal of increasing the energy efficiency and thermal comfort within buildings. These types of interventions function on different building aspects, from the building envelope to lighting. Next to this a classification is given between short- and long-term interventions. With short-term classifying those with a low to medium required investment and which are able to be implemented by inhabitants. And long-term interventions require significantly more investments in time, money, and effort.

Within the context of energy poverty, another group of interventions can be classified. This includes interventions which present no permanent changes to the dwelling, and which require a low budget. These interventions can be classified as basic interventions. This group of interventions is important to identify within the context of energy poverty, as it relates to the households who want to install their own interventions.

Within the context of this research, the short-term interventions of the European Commission's research are split up into basic and intermediate interventions. With intermediate interventions presenting permanent changes to the dwelling and requiring a larger budget than basic interventions. The classification of long-term interventions is kept but will be renamed as advanced interventions (CIRCE, 2015). An overview of defined intervention groups can be seen in table 13.

Intervention group	Characteristics	Examples
Basic interventions	Non-permanent changes to dwelling, low budget, low required labour	Portable space heaters, draft stoppers
Intermediate interventions	Both permanent and non-permanent changes to dwelling, low to medium budget, medium required labour	Indoor wall insulation, weatherstripping
Advanced interventions	Permanent changes to dwelling, high budget, high required labour	External wall insulation, glazing replacement

Table 13: *Overview of intervention groups (Own work, 2025)*

An overview of the most widely available and researched interventions on these scales can be seen in appendix 8, this overview provides additional information regarding costs, pros and cons and effected properties. These interventions have an impact on different aspects of building use. As has been mentioned in chapter 4.3.3, the simulation research will work towards reviewing the interventions on the three most important aspects of energy poverty, energy efficiency, thermal comfort, and finances.

While deciding which interventions would be tested and which interventions wouldn't be tested, different factors were considered. Chapters 2.4, 2.6 and 3.2 address the importance of building characteristics for assessing the risk of energy poverty. This leads to the notion that interventions should aim at improving some aspect of the buildings' characteristics, in order to provide a constructive solution. Certain building characteristics these interventions could aim to improve are the thermal quality, energy efficiency or heating system efficiency of the dwelling. Next to this, the intervention should be able to be modelled into the simulation program and the case study should allow the application of the intervention. These considerations have led to a selection of interventions to be researched in the following chapters, this can also be seen in appendix 8. Within the subject of improvements to building characteristics, the interventions can be categorized by the building characteristic they influence, this can be seen in table 14. The following segments will provide descriptions of these different interventions and will summarize how they work and what parameters they aim to influence. Appendix 9 provides more information, besides this, the manner in which they have been modelled into the simulation program is explained in detail in this appendix. While certain interventions require more explanation, for most of the interventions it translates to an improvement of the property they influence. For example, indoor wall insulation is modelled by adding constructive layers which influence the R value of the existing construction.

<table>
<tr><th>R value</th><th>U value</th><th>Qv10 value (Infiltration)</th><th>Heating system</th></tr>
<tr><td colspan="2">Thermal curtains</td><td rowspan="2">Draft stoppers</td><td rowspan="2">Infrared heating panels</td></tr>
<tr><td>Indoor wall insulation</td><td>Window insulation film</td></tr>
<tr><td>Insulated door panels</td><td>Radiator foil</td><td rowspan="2">House air sealing</td><td>Portable space heaters</td></tr>
<tr><td>External wall</td><td>DIY secondary glazing</td><td>Warm air circulators</td></tr>
<tr><td>Floor insulation</td><td>Glazing replacement</td><td>Weatherstripping</td><td>Radiator foil</td></tr>
<tr><td>Ceiling insulation</td><td></td><td></td><td></td></tr>
<tr><td>Rug floor insulation</td><td></td><td></td><td></td></tr>
</table>

Table 14: *Overview of intervention scales and individual tested interventions (Own work, 2025)*

4.4.1 Portable space heaters

Portable space heaters (figure 20) operate similar to central heating systems but on a much smaller scale, providing targeted warmth to specific areas instead of heating an entire home. This targeted warmth is supplied to the room through the spread of warm air. Most portable space heaters come with two heating stances, the first supplying mild heat and second supplying more intense heat. Portable space heaters are most commonly used in rooms that are difficult to heat or in households looking to reduce reliance on central heating. They can be particularly useful in older homes with poor insulation, where they help in providing local comfort, instead of requiring heating the entire dwelling. In apartment buildings, space heaters are often used for supplemental heating, especially in rooms that receive less heat from central systems. The energy efficiency of portable space heaters is dependent on the usage habits of occupants. Due to their energy demand being higher than centralized heating systems, long term and intensive use can lead to higher electricity consumption. Most portable space heaters are commercially available and can be ordered online (*Amazon.com : Space Heater*, n.d.) or bought in store (*Ventilatorkachels*, n.d.) for around 30€.

Figure 20: *Portable space heater (bol.com, n.d.)*

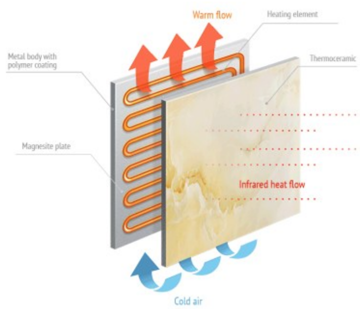


Figure 21: *Infrared heating panels (Infralia.com, 2025)*

4.4.2 Infrared heating panels

Infrared heating panels (figure 21) are an energy-efficient heating solution that uses infrared rays to directly warm objects and people in a room, rather than heating the air. This is where infrared heating panels differ from standard heating radiators. Standard heating radiators rely on heating up air and having that warm air spread throughout the room. Infrared heating panels skip this step and emit heat waves which are absorbed directly by objects in the trajectory of these heat waves. These panels are typically thin and are often mounted on walls or ceilings. The panels heat up quickly, require little maintenance, and are highly efficient since they minimize heat loss through the indoor air. Most infrared heating panels are commercially available and can be installed without professional help. There are many systems available on the market, most can be purchased within a price range between 100€ and 200€ (*Bol Infrarood Kachels*, n.d.).

4.4.3 Radiator foil

Radiator foil (figure 22) is a thin and reflective material which is placed directly behind radiators, or on the inside of façade walls behind radiators. The goal of radiator foil is to reduce heat losses and improve the efficiency of heating systems. It aims to do so by reflecting radiant heat from the radiator back into the room, instead of directly sending it to the external wall. Because by directly sending it to the external wall, there is risk of the warmth being absorbed by the wall and lost to the exterior. Radiator foil is an easy intervention to install, as it just involves attaching the foil to the back of the radiator or wall. It claims to be especially effective in older homes, as facades in these homes allow for larger amounts of heat to be lost than newer homes. Besides this, older radiators can profit more from increased efficiency than newer radiators. Radiator foil is relatively cheap and commercially available at around 10€ for a 6-meter roll at common construction material shops (Gamma NL, n.d.-a).

Figure 22: *Radiator foil (ecommerce development agency, 2025)*

Figure 23: *Draft stoppers (Walmart.com, 2025)*

4.4.4 Draft stoppers

Draft stoppers (figure 23) are simple but effective devices designed to block cold air from entering and warm air from escaping through gaps under doors. They come in various forms, including fabric tubes filled with insulating material and brush or rubber door sweeps. By blocking these gaps, draft stoppers prevent heat loss and reduce cold drafts. The goal of draft stoppers is to improve indoor comfort and decrease energy bills. They are an affordable and easy-to-install solution that can be used in any room, particularly in older buildings with poorly sealed doors. Their flat centre design allows for draft stoppers to be placed under almost all door types, as they don't require much space to be placed. Draft stoppers are commercially available in common construction stores (Gamma NL, n.d.-b) and online (Shop Amazon.com | Draft Stoppers, n.d.) and are relatively cheap at a price around 5€ per door.

4.4.5 Thermal curtains

Thermal curtains (figure 24) are designed like regular curtains, but they are made from heavy, insulating materials and contain built-in thermal linings. Thermal curtains aim to improve the thermal quality of the building skin by increasing the U value of façade openings and the R value of closed façade parts. The curtains aim to reduce heat losses in the winter by not allowing warmth to escape and cold air to enter. This effect is reversed in the summer. Thermal curtains are an easy to install intervention, as it only involves replacing existing curtains. Thermal curtains are available for purchase at a price range around 20€ per meter in different hardware stores (*Geld Besparen Met Isolerende Gordijnen En Raamdecoratie? | Kwantum, n.d.*). If preferred, thermal curtains can also be made in a DIY fashion by lining existing curtains with thermal materials. While thermal curtains seem like an effective intervention as it functions similarly to a cavity wall, concerns arise around the practicality of their usage. As for this intervention to function, the curtains will need to be closed at all times. This trade-off can be quite significant for the living quality of dwellings and will be researched in a later segment.

Figure 24: *Thermal curtains (Amazon.nl: Home & Kitchen, 2025)*

Figure 25: *Indoor wall insulation (cmostores.com limited, 2025)*

4.4.6 Indoor wall insulation
Indoor wall insulation (figure 25) is a more conventional method of improving energy efficiency as a small-scale renovation. It involves adding an insulation layer such as mineral wool or insulating foam boards to the interior side of façade walls. The aim of indoor wall insulation is to improve the matter in which walls contain indoor temperatures and block outdoor temperatures. It states to be particularly useful in older homes, as in these homes, the walls are often of low insulating quality and external insulation is not an option. With the correct tools and materials, indoor wall insulation can be placed by occupants themselves. The placement of indoor wall insulation does come with the downsides of a reduction of free indoor space and risks of moisture buildup. Indoor wall insulation can be installed by occupants themselves by ordering the individual materials. The actual price of these materials differs depending on the quality of insulation material, it averages at around 30€ per square meter wall, these materials can be acquired through online insulation shops (De Isolatieshop, n.d.) or hardware stores (Gamma NL, n.d.).

4.4.7 Floor insulation
Floor insulation (figure 26) works similar to other forms of insulation, such as internal and external wall insulation. The aim of floor insulation is to reduce the amount of cold which enters the dwelling from the space below and reduce the amount of heat lost to the space below. Floor insulation differentiates itself in the types of temperatures it is trying to wear off. In most applications of floor insulation in existing homes, cold temperatures from the crawl space below the floor are attempted to be blocked. When floor insulation is applied in newer dwellings, it can be proactively placed below the floor finishing. In apartment buildings, floor insulation is applied to prevent heat losses between apartments and to function as sound insulation between apartments. While this is true, floor insulation is considered less important in apartment buildings, as the space below the floor insulation is often a heated room. This could mean that when floor insulation is applied, heat is blocked from entering the apartment, which isn't desired. With apartments being heated less during energy poverty, this floor insulation could still prove itself to be of use. Floor insulation can be installed by occupants themselves, it does require significant efforts to ensure proper connection to floor and door systems. The price of floor insulation differs depending on the quality of insulation material, it averages at around 20€ per square meter. Specific floor insulating materials can be ordered online (De Isolatieshop, n.d.-b).

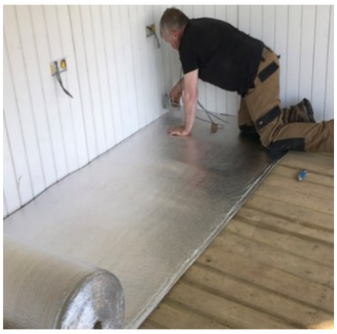


Figure 26: *Floor insulation (B&Q, 2025)*

Figure 27: *Window insulation film (Amazon.nl: Home & Kitchen, 2025)*

4.4.8 Window insulation film
Window insulation film (figure 27) is a transparent foil which is directly applied to glass surfaces. The aim of this film is to improve the thermal performance of glass by increasing its U value. This means that external cold temperatures are blocked more effectively. At the same time, other properties of the glass aren't altered significantly. This means that for example, a similar amount of heating energy through sunlight enters the dwelling, if this would be reduced it would have effects on the required heating energy of the dwelling. Next to the thermal quality effects the film claims to have, it also claims to reduce condensation which is often present in older dwellings with older windows. Window insulation film is an easy to place intervention as the film is directly applied to the glazing or the window frame. The film can be ordered online at around 10€ per window (*Amazon.nl: Window Insulation Kits: DIY & Tools,* n.d.).

4.4.9 Weatherstripping

Weatherstripping (figure 28) is a method for reducing heat loss around doors and windows. It involves applying sealing materials like rubber or foam around doors and windows to block air leaks and reduce heat losses. The purpose of weatherstripping is to improve indoor temperature by preventing drafts and reduce energy costs as these drafts wouldn't need to be compensated with additional heating. This intervention is particularly useful in older homes, where gaps around doors and windows are more common. It is an affordable and straightforward solution that can be applied by homeowners without professional assistance. At the same time, the installation does require precision to access its full potential. The weatherstrips do need to be maintained regularly and replaced after some time. Weatherstrips can be ordered online, it is important to select the correct product for the window type & measures. The price averages at around 15€ per window (*Alle Tochtstrips Online | Bol, n.d.*).

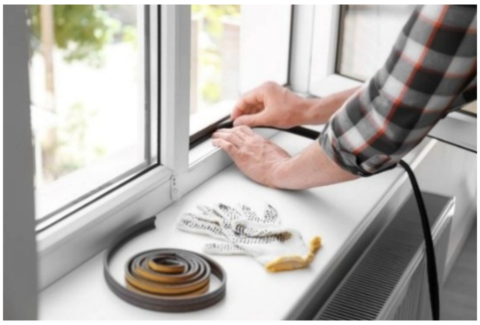


Figure 28: *Weatherstripping (Tochtstripdeur.nl, 2025)*

Figure 29: *Ceiling insulation (Certified Applicator Extend Roofing Lifespan | Kohls Foam Systems INC., 2022)*

4.4.10 Ceiling insulation

Ceiling insulation (figure 29) functions similarly to insulation methods like floor insulation. However, it specifically targets heat transfer between the ceilings and floors of apartments or between indoor spaces and attics. In most applications, ceiling insulation is used to prevent warm indoor air from escaping into the unheated attic. Ceiling insulation is commonly installed in newer homes during construction, allowing it to be placed efficiently between the ceiling construction. However, it can also be added as a renovation measure, particularly in older homes with inadequate insulation. In apartment buildings, ceiling insulation is primarily used to minimize heat loss between units and to serve as sound insulation, reducing noise transmission between floors. The importance of ceiling insulation increases in situations where upper floors are unheated or poorly insulated, as it helps maintain stable indoor temperatures and aims to improves overall energy efficiency. Ceiling insulation is one of the more difficult interventions to install without professional help, but it is possible. In terms of costs, it requires insulation material and construction material to be purchased. Different options are available for these materials, averaging around 15€ to 20€ per square meter (De Isolatieshop B.V., n.d.). The materials can either be ordered online or bought at hardware stores, as additional material for framing is also required.

4.4.11 Insulated door panels

Insulated door panels (figure 30) are specifically designed panels, or manually made panels, which aim to increase the thermal insulation of doors. The panels are constructed using framing material and insulating materials. After the panel is constructed, it is attached to the inside of the door and finished. While newly made doors are already equipped with insulating materials, oftentimes older external doors aren't. Insulated door panels present themselves as a method of uplifting the effectiveness of these external doors. In order to get the most usage out of the insulated door panels, frames need to be constructed with high quality insulating materials, this can be done by occupants themselves, though it does require precise DIY skills. The costs of these materials averages around 30€ per square meter, as these more efficient insulating materials are also more expensive (Isoleren: Paneel Van Je Deur Isoleren, n.d.). These highly efficient materials can be ordered online and the required framing material can be bought at different hardware stores.

__Figure 30:__ Insulated door panels (Amazon.nl: DIY & Tools, 2025)

__Figure 31:__ Floor rug insulation (Amazon.com, n.d.)

4.4.12 Floor rug insulation

Floor rug insulation (figure 31) works similarly to standard floor insulation by helping to reduce heat loss and improve thermal comfort. However, instead of being installed beneath the flooring, like in newly built dwellings, floor rug insulation acts as an insulating layer on top of hard surfaces. Floor rug insulation can be either installed disconnected from the floor or it can be attached to the floor. Its primary function is to prevent heat from escaping through uninsulated floors and to provide a warmer surface underneath the feet of occupants. Floor rug insulation aims to be most effective in homes with drafty floors or minimal existing insulation, where it can serve as an easy and cost-effective solution for reducing cold spots. While not a substitute for full floor insulation, rugs and carpets offer a practical and easy way to improve comfort and energy efficiency with minimal effort. The intervention can be installed by occupants themselves by purchasing materials, from specific online shores which specialize in floor rug insulating materials. The price averages at around 15€ per square meter (vloerbedekkingwebwinkel.nl, n.d.).

4.4.13 DIY secondary glazing

DIY secondary glazing (figure 32) involves installing polycarbonate sheets, or insulating foil, over low-quality windows by using a constructed extra window frame. The aimed effect of this intervention is to create an insulating air gap between the original window frame and the DIY secondary glazing. This air gap aims to reduce heat losses, similar to regular double or triple glazing systems. The system allows for the window to function similar to a double-glazing system, through an air cavity. The system claims to be especially effective when applied to single-glazing panes and less effective when applied to double-glazing panes. The secondary glazing system can be made and placed by occupants themselves, while this does require manual skills and different parts. The cost sums up to around 40€ per frame (*Brains4neighbourhoods Isolatie Doe Het Zelf Voorzetraam*, n.d.). Most of the materials can be found at hardware stores, including the required window film, which can also be ordered online (*Amazon.nl: Window Insulation Kits: DIY & Tools,* n.d.).

__Figure 32:__ DIY secondary glazing (Theeuwen & Theeuwen, 2022)

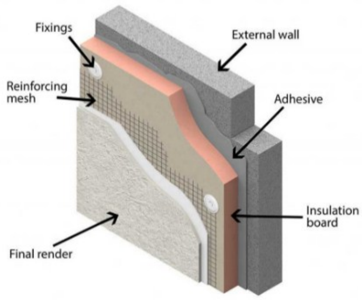


__Figure 33:__ External wall insulation (cmostores.com limited, 2025)

4.4.14 External wall insulation

External wall insulation (figure 33) works in a similar manner as internal wall insulation, with the main difference being the placement of the insulation. In this case the insulation is added to the external side of the wall. It claims to be more effective than internal wall insulation, as the cold temperature is blocked in an earlier stage than with internal wall insulation. External wall insulation requires a higher investment and implementation effort than internal wall insulation, as more changes are made to the façade. This installation can be quite disruptive and can require different permissions in order to be placed. The costs of the placement of external wall insulation will differ per project and per contractor, an average price estimation is around 250€ per square meter of façade (Solvari & Solvari, 2025).

4.4.15 Glazing replacement

Glazing replacement (figure 34) consists of changing low quality glazing for higher quality glazing. Existing glazing systems, often consisting out of single panes without thermal quality improvements can be changed with effective glazing systems which reduce heat losses. The low-quality glass can be replaced for higher quality glazing like double, triple, or HR+ glazing. In case the existing window frame doesn't allow for this new glass to be installed, the frame will need to be replaced as well. Similar to external wall insulation, this intervention requires a high investment and professional installation. The price of installation is dependent on the situation, the contractor and the chosen material, an average estimation is of a price around 130€ per square meter (*Kosten Ruit Vervangen - Kostenoverzicht in 2025 - Zoofy*, n.d.).

Figure 34: *Glazing replacement (Sadler, 2025)*

Figure 35: *House air sealing (PCC Group, 2025)*

4.4.16 House air sealing

House air sealing (figure 35) involves identifying and sealing gaps, cracks, and leaks within the building envelope. The aim of this intervention is to prevent the unwanted airflow of cold temperatures. Different areas in which air leakage is common include windows, doors, plumbing and attics. By sealing these leaks with sprays, weatherstripping and caulk, drafts are reduced. Besides reducing heat losses, house air sealing aims to improve the air quality and thermal comfort within a dwelling. The price of house air sealing is dependent on the situation, the contractor and the chosen material, an average estimation is of a price starting at 400€ per dwelling (Energiekeurplus, 2025).

4.5 Modelling inputs

Table 15 shows a summary of the changes which were made to different properties within VABI elements, to model each intervention. Within appendix 9, the detailed intervention library can be seen where each change is substantiated with associated research. It can be seen in table 15 that two modelling options have been simulated and logged for the intervention of radiator foil, as appendix 9.1 discusses, there are multiple modelling options for this intervention.

Intervention	Property	Old situation	Change	New situation
Thermal curtains	U value of façade opening 1	5,37 W/m²K	Addition of heavy curtains (R=0,16)	2,89 W/m²K
	U value of façade opening 2	3,20 W/m²K	Addition of heavy curtains (R=0,16)	2,12 W/m²K
	R value around façade opening	2,75 m²K/W	Addition of 50mm cavity and heavy curtains	3,1 m²K/W
	Solar shading	No relevant solar shading prevalent	Addition of heavy curtains (R=0,16)	Medium quality indoor shading, always closed

Intervention	Property	Old situation	Change	New situation
Infrared heating panels	Heating method	Convection radiator	Replacement of traditional heating system with infrared heating panel	Infrared panel
	Heating system effectiveness	50 W/m²		400W
Draft stoppers	Wind-dependent infiltration (1/h)	0,40	Moderate improvement of air tightness	0,35
Indoor wall insulation	Insulation (R) value (m²K/W) of exterior wall type 1	0,5	Addition of wooden framework and 70mm Kooltherm K17	4,09
	Insulation (R) value (m²K/W) of exterior wall type 2	2,75		6,31
	Insulation (R) value (m²K/W) of exterior wall type 3	1,5		5,07
Window insulation film	Effective U value of glass type 1 (W/m²K)	5,37	Addition of insulation foil, reduction of 28% of surface heat losses	3,9
	Effective U value of glass type 2 (W/m²K)	3,20	Addition of insulation foil, reduction of 13% of surface heat losses	2,8
Insulated door panels	Insulation (R) value (m²K/W) of external doors	70mm Hardwood R = 0,41	Addition of 30mm XPS and 10mm wood finishing	1,53
	Insulation (R) value (m²K/W) of internal doors	40mm Triplex wood R = 0,24		141
DIY secondary glazing	Effective U value of glass type 1 (single glazing) (W/m²K)	5,37	Application of DIY secondary glazing (35% reduction)	3,5
	Effective U value of glass type 2 (double glazing) (W/m²K)	3,2	Application of DIY secondary glazing (20% reduction)	2,6
External wall insulation	Insulation (R) value (m²K/W) of exterior wall type 1	0,5	Addition of 80mm Kooltherm K5	4,37
	Insulation (R) value (m²K/W) of exterior wall type 2	2,75		6,5
	Insulation (R) value (m²K/W) of exterior wall type 3	1,5		5,35
Glazing replacement	Effective U value of glass type 1 (W/m²K)	5,37	Change from single to HR double glazing	2
	Effective U value of glass type 2 (W/m²K)	3,2	Change from double to HR double glazing	2
House air sealing	Wind-dependent infiltration (1/h)	0,40	Improvement of air tightness of rooms and doors	0,2
Floor insulation	Insulation (R) value (m²K/W) of floor	0,21	Addition of 70mm Kooltherm K5	3,60
Weatherstripping	Wind-dependent infiltration (1/h)	0,40	Improvement of air tightness of rooms and doors	0,3
Ceiling insulation	Insulation (R) value (m²K/W) of ceiling	0,21	Addition of 70mm Kooltherm K5	3,60
Floor rug insulation	Insulation (R) value (m²K/W) of floor	0,21	Addition of 10mm rug insulation	0,5
Portable space heaters	Heating method	Convection radiator	Replacement of traditional heating system with portable space heater	Localized air heating
	Heating system effectiveness (W/m²)	50		1500W
Radiator foil (modelling method 1 (heating system))	Convection factor	0,7	Radiator foil reduces the radiant heat losses to walls, increasing the convection of the system slightly	0,75
	Heating capacity (W/m²)	50	Radiator foil reduces heat losses to the wall from the backside, increasing the capacity of the system	55
Radiator foil (modelling method 2 (wall properties))	Emissivity of wall behind radiator	0,9	Addition of reflective foil reduction in emissivity from 0,9 to 0,05	0,05
	Effective U value behind radiator (W/m2K)	0,36	Addition of reflective foil (57% decrease in U value)	0,15

***Table 15:** Overview of modelling inputs for individual interventions (Own work, 2025)*

5 Results

5.1 Results of individual interventions

The detailed comparison of interventions in appendix 11 shows the ranking in which the tested interventions perform on the levels of energy efficiency, thermal comfort, yearly savings, payback period and investing efficiency. The rankings are based on the individual results of the simulated interventions, which can be seen in appendix 10. The rankings show the effects on the normal usage profile and on the energy poverty usage profile. The rankings visualise the effectiveness of different interventions, the following chapters will go into explaining the different findings.

5.1.1 Energy efficiency

The comparison of interventions on energy efficiency shows that the interventions of glazing replacement, thermal curtains and external wall insulation perform the best. When this is compared to the comparison framework of the previous chapter it can be seen that these interventions lie on the higher side of R and U value improvements and have thus improved the energy efficiency more than others. Meanwhile, the interventions of floor insulations, ceiling insulation and draft stoppers have smaller effects on the energy efficiency of dwellings. This can be explained by the small level of improvements these interventions apply to building properties. Besides this, insulations on the floor and ceiling insulate the parts of the dwelling which allow for less improvements, this will be further explored in chapter 5.3.3. The detailed ranking can be seen in table 16.

5.1.2 Thermal comfort

When the interventions are compared on their effect on thermal comfort, meaning the number of degrees the heating in the most intensely used rooms can be improved without increasing energy expenditures, different findings can be noted. The first being that the distribution of the best and worst performing interventions is similar to that of energy efficiency. With again, glazing replacement performing the best and different insulation types performing worse. The matter in which glazing replacement outperforms the other interventions is quite significant. with glazing replacement providing 4,6 degrees of improvement, and the next best intervention of indoor wall insulation providing 2,2 degrees of improvement. The detailed ranking can be seen in table 16.

5.1.3 Yearly savings

The rankings of yearly savings are similar to the ranking of energy efficiency, as these are directly correlated to each other. Similar to the thermal comfort rankings, the disproportionality between results becomes clear when interventions are compared. With the best performing intervention of glazing replacement providing yearly savings of 101,7 euros, and the worst performing intervention of ceiling insulation providing yearly savings of only 1,4 euros, both in normal usage scenarios. The detailed ranking can be seen in table 16. Similar to energy efficiency, there is a large difference between the number 1 intervention and the interventions beneath. The difference between glazing replacement (number 1) and thermal curtains (number 2) is 44 euros for normal usage and 24 euros for energy poverty usage. For comparison, the difference between numbers 2 and 3 (thermal curtains and external wall insulation) is 12 and 9 euros respectively for normal and energy poverty usage.

5.1.4 Payback period

When the payback periods of different interventions are compared to each other, the rankings differ than those of the review criteria previously discussed. This is due to one factor which is important for households choosing how to tackle energy efficiency renovations: investment costs. Especially within the context of rising energy prices and energy poverty, households take the financial aspects of their investments in high regard. When reviewing the payback period of interventions, the interventions of window insulation film, insulated door panels, thermal curtains and radiator foil rank highly, meaning that they have relatively short payback periods between 1 and 4 years for normal usage and 2 and 6 years for energy poverty usage. Meanwhile, the interventions which resulted in the highest energy efficiency improvements have much longer payback periods. With glazing replacement, internal wall insulation and external wall insulation having payback periods of 18, 21 and 102 for normal usage and 28, 33 and 152 for energy poverty usage. Lastly, there are also interventions which scored so low on energy efficiency, that their relatively low investment costs aren't compensated or are compensated over unreasonable timeframes. This includes interventions like ceiling insulation, floor insulation and floor rug insulation. These interventions result in outlandish payback periods from 357 to 2190 years, as a result of their next to no efficiency improvements, some interventions even display negative payback periods, as they are unprofitable. The payback period review criterium allows for households to make estimations on the timespan of their energy efficiency investment. The detailed ranking can be seen in table 16.

5.1.5 Investing efficiency

The last review criterium is investing efficiency, which shows the relation between yearly savings and investment cost. Investing efficiency visualizes how much savings you get for what investment is made. The distribution of the investing efficiency ranking resembles the same ranking as payback period, as it follows a similar approach. The ranking shows that while effective interventions such as glazing replacement might save much money on a yearly basis (€ 101,7), their efficiency as an investment for households might be of lower value (5,6%). At the same time, interventions which save less money like insulated door panels (€ 20,7) have a higher investing efficiency (59.6%) due to their low cost. The detailed ranking can be seen in table 16.

Intervention	Energy Efficiency improvement		Thermal Comfort improvement (0C)		Yearly savings (€)		Intervention	Payback period (years)		Investing efficiency	
	Normal usage	Energy poverty usage	Normal usage	Energy poverty usage	Normal usage	Energy poverty usage		Normal usage	Energy poverty usage	Normal usage	Energy poverty usage
Glazing replacement	10,3%	12,4%	4,6	3,5	101,7	64,4	Radiator foil (method 1)	1,0	179,5	102,9%	0,6%
Thermal curtains	5,8%	7,7%	2,2	2,1	57,6	39,8	Window insulation film	1,4	2,2	69,4%	45,6%
Secondary glazing DIY	5,7%	7,0%	2,0	1,9	55,9	36,4	Insulated door panels	1,7	2,5	59,6%	40,2%
External wall insulation	4,7%	5,9%	2,0	1,7	45,9	30,7	Radiator foil (method 2)	2,8	4,3	35,2%	23,4%
Indoor wall insulation	4,6%	5,5%	2,0	1,7	45,1	28,7	Thermal curtains	4,3	6,3	23,0%	15,9%
Window insulation film	3,9%	4,9%	1,6	1,2	38,9	25,5	Secondary glazing DIY	5,7	8,8	17,5%	11,4%
Radiator foil (method 1)	3,7%	0,0%	2,0	0,0	36,0	0,2	Weatherstripping	6,7	10,1	14,9%	9,9%
House air sealing	2,4%	3,1%	1,0	0,9	23,9	15,9	Draft stoppers	7,2	9,4	13,9%	10,7%
Insulated door panels	2,1%	2,7%	0,9	0,8	20,7	13,9	House air sealing	16,7	25,2	6,0%	4,0%
Weatherstripping	1,8%	2,3%	0,7	0,7	17,8	11,9	Glazing replacement	17,7	27,9	5,6%	3,6%
Radiator foil (method 2)	1,2%	1,6%	0,5	0,5	12,3	8,2	Indoor wall insulation	21,1	33,1	4,7%	3,0%
Draft stoppers	0,7%	1,0%	0,3	0,3	6,7	5,1	External wall insulation	101,6	152,3	1,0%	0,7%
Floor insulation	0,3%	-0,1%	0,1	0,0	2,7	-0,3	Floor rug insulation	357,1	2187,5	0,3%	0,0%
Floor rug insulation	0,2%	0,1%	0,0	0,0	2,2	0,4	Ceiling insulation	414,4	1789,4	0,2%	0,1%
Ceiling insulation	0,1%	0,1%	0,0	0,0	1,4	0,3	Floor insulation	439,9	-3578,8	0,2%	0,0%

***Table 16:** Overview of individual intervention results and rankings (Own work, 2025)*

5.2 Comparisons of interventions

5.2.1 Comparison frameworks

To effectively visualize how improvements to different building properties of the dwelling affect the energy poverty review criteria (energy efficiency, thermal comfort & energy costs), comparison frameworks have been set-up. The building parameters for which the comparison frameworks have been set up are the R value, U value and Qv10 (infiltration) value. The energy efficiency aspect of energy poverty is related to the energy consumption (kwh/m2) of the dwelling or space. The thermal comfort aspect of energy poverty is related to the percentage of total hours in a living area in which the indoor temperature is under a certain level (class D) compared to all 8590 yearly measured hours. With class D being the lowest comfort demand of the Dutch regulatory guidelines (Vabi Software B.V., 2015). Lastly, the financial criterium is related to the gas bill of the total dwelling.

The comparison frameworks have been set up with the following steps:

1. The average existing R, U or qv10 value for each façade is determined.
2. The energy simulation is performed with this existing situation and the values of the three review criteria are logged, both the values for the entire dwelling and for the individual rooms.
3. The building parameter at hand (R, U or Qv10) is incrementally increased and the new simulation results are logged.
    - For the frameworks of the total dwelling, the parameter is altered across all facades, and the simulation results on the scale of the total dwelling are logged.
    - For the frameworks of the individual rooms, the parameter is altered across one façade, and the simulation results on the neighbouring room are logged.
4. Steps 2 and 3 are performed with both the energy poverty and normal usage profile.
5. Using these simulation results and building parameter values, the comparison framework graphs are formed in which the course of the effects of parameter changes can be seen.
6. Within these graphs, the existing façade conditions are determined and indicated with red bars.
7. In the following chapters the individual interventions will be placed on the graphs using the improved building parameter linked to each individual intervention.

An example review framework can be seen in figure 36. This figure shows the review framework for R value changes and its effects on energy consumption, on an individual façade and room scale. The red bar indicates the original building parameter and simulation results, the individual dots along each graph indicate the incrementally increased parameter values. The following segments will discuss the review frameworks and what they imply for the effectiveness of interventions on different building parameters.

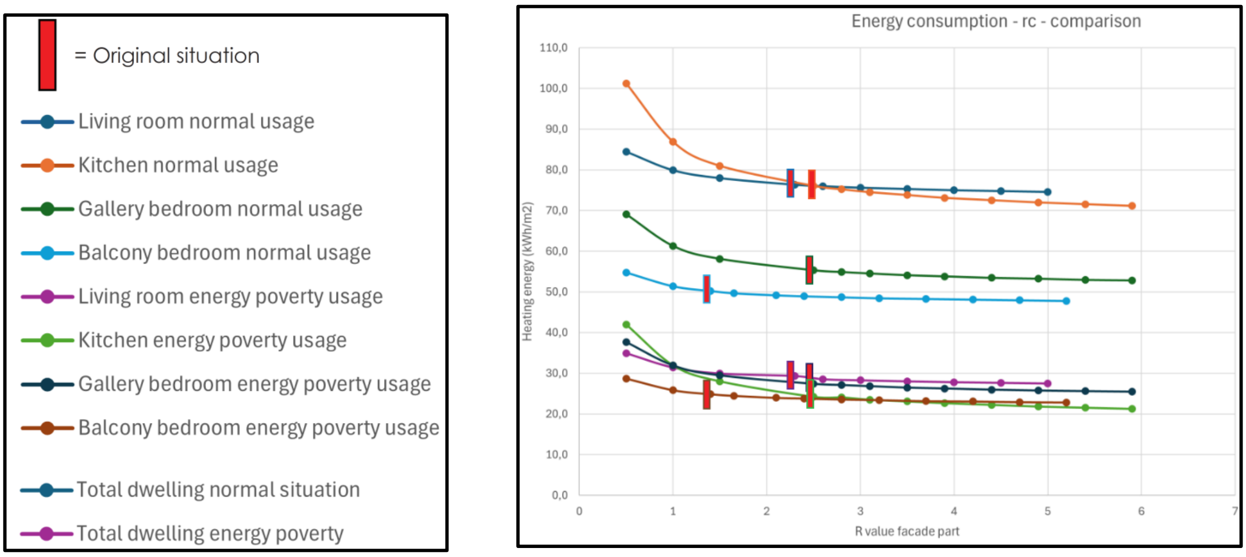


Figure 36: Example review framework: influence of R values on energy consumption (Own work, 2025)

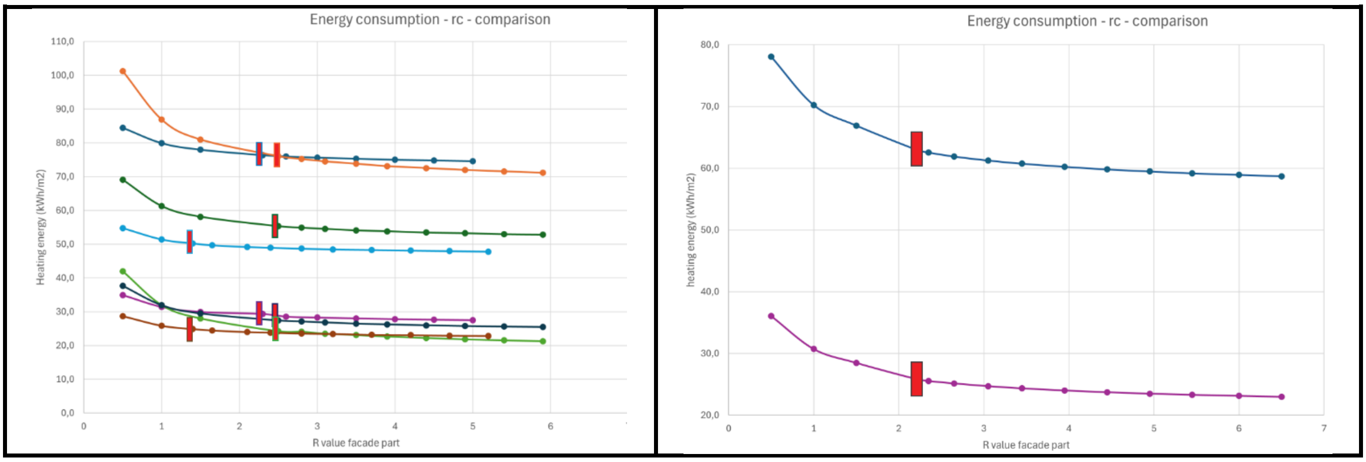
R value:

The first comparison framework which has been set up and will be analysed, is that of changes to the R value. The graphs of the effects of changing R value of gives insights on energy efficiency, thermal comfort and energy bills;

Energy efficiency (figures 37 and 38):

- Increases in R value can have significant effects in reducing the required kWh per square meter of heated rooms, the improvements are most noticeable in facades with lower base R values.
- The largest effects can be seen in the normal usage profile.

- Differences in effects can be seen between rooms which are used differently, for example a bigger reduction can be noted in the living room, than in the bedrooms.
- Lastly, the exponential nature of energy use reduction can be seen by the curve, which flattens out the higher the R value becomes and steepens the lower the R value gets, this can be seen especially well in the total dwelling framework.
- R value improvements have significantly larger energy savings possibilities when they are applied to all facades, instead of being applied to individual facades. This difference can be seen by comparing figures 37 and 38.



Figures 37 & 38: Review frameworks: influence of R values on energy consumption, specific facades (left) and entire dwelling (right) (Own work, 2025)

Thermal comfort (figure 39):

- Changes in R value show to have negligible effects on thermal comfort, especially in the energy poverty situations.
- At the same time, some effects can be seen in the intensively used rooms during the normal situation. While effects in other rooms are difficult to be seen, the living spaces do show effects. Leading to the notion that R value increases do have an effect on the amount of comfort hours in these rooms.
- Similar to the changes in energy consumption, the effects show themselves to be of exponential nature, this is most notable for R values between 0 and 2, after this, the effects flatten.

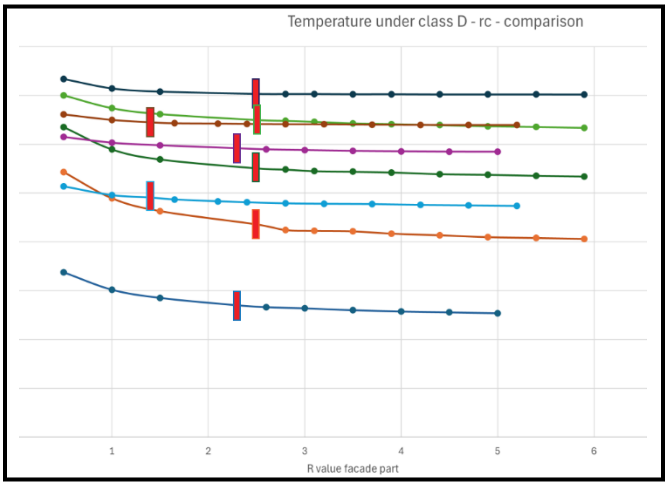
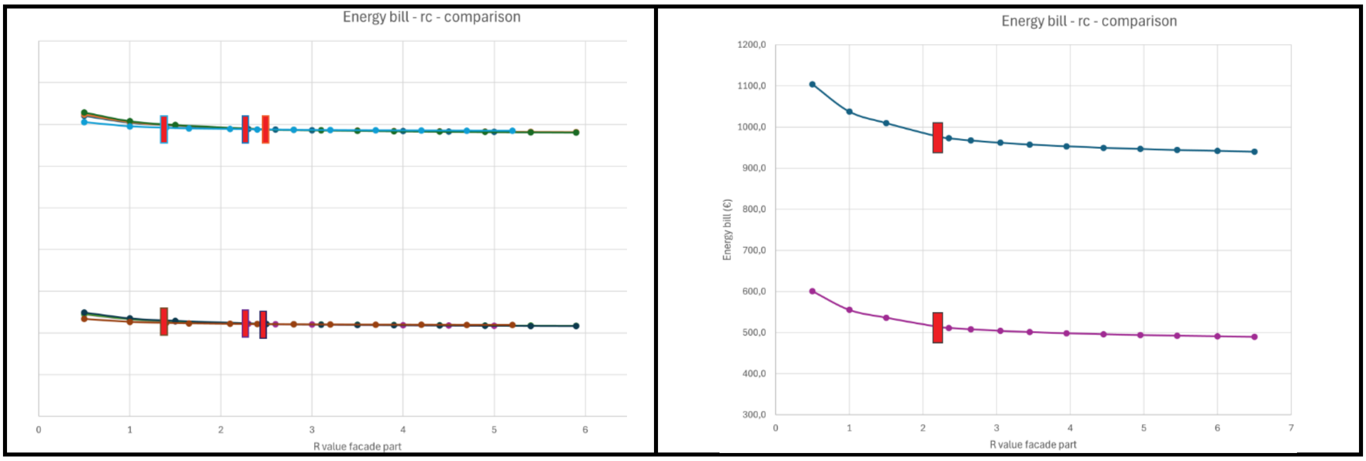


Figure 39: Review framework: influence of R values on thermal comfort, specific facades (Own work, 2025)

Energy bills (figures 40 and 41):

- The increase of R values of individual facades shows to have little to no effects on energy expenditures. Once these R value improvements are combined and applied to all facades, significant results start to show.

- These increases of R values across the dwellings show to have exponential effects on the energy bills. This becomes increasingly noticeable when R values lower than the base situation are regarded. This means that cases with poorer R values would have larger gains from these improvements.



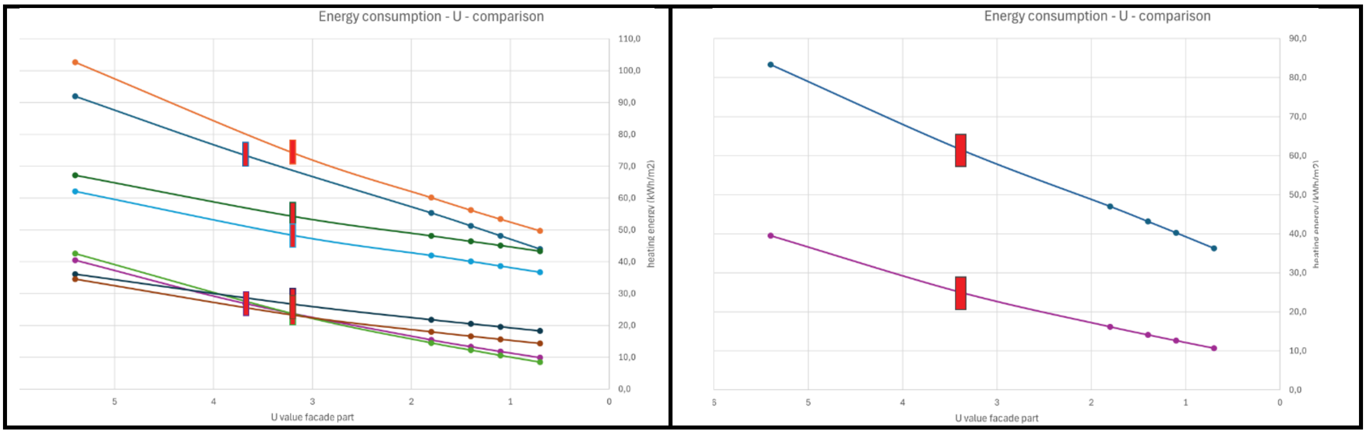
Figures 40 & 41: Review frameworks: influence of R values on energy bills, specific facades (left) and entire dwelling (right) (Own work, 2025)

U value:

The second comparison framework which has been set up and will be analysed, is that of changes to the U value. Different conclusions can be drawn on the individual criteria.

Energy efficiency (figures 42 and 43):

- Similar to the R value analyses, improvements in U values have the most effects under regular usage circumstances, and in rooms which are more intensively used.
- While the course of effects is nearly similar for both the balcony bedroom and gallery bedroom, their placement on the graph differs. This means that there is something which makes the gallery bedroom energy usage higher than the balcony bedroom energy usage. The main difference between these rooms which could be the cause of this difference is their orientation. This would explain why the southern balcony bedroom would require less heating energy, due to the solar energy which enters.
- Overall, U value improvements result in significant improvements of energy efficiency, especially when the entire façade is regarded, reductions of 30 kWh/m2 are noted in the normal situation for U improvements from 3,5 to 0,75 W/m2k.



Figures 42 & 43: Review frameworks: influence of U values on energy consumption, specific facades (left) and entire dwelling (right) (Own work, 2025)

Thermal comfort (figure 44):

- Much larger improvements of thermal comfort are noticeable when compared to the improvements through R value increases.
- Again, the largest increases are noticeable in the most intensely used rooms, under the normal usage profile. Less significant effects can be noted under the energy poverty usage profiles.
- While the thermal comfort improvements under R value increases showed to have some exponential effects, the effects show to be linear under U value improvements. Except for the latest measuring step from 1,2 to 0,4, where there are visible exponential reductions.

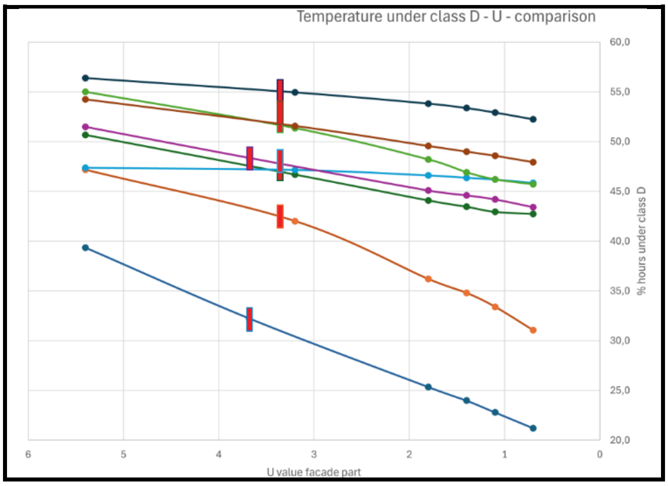
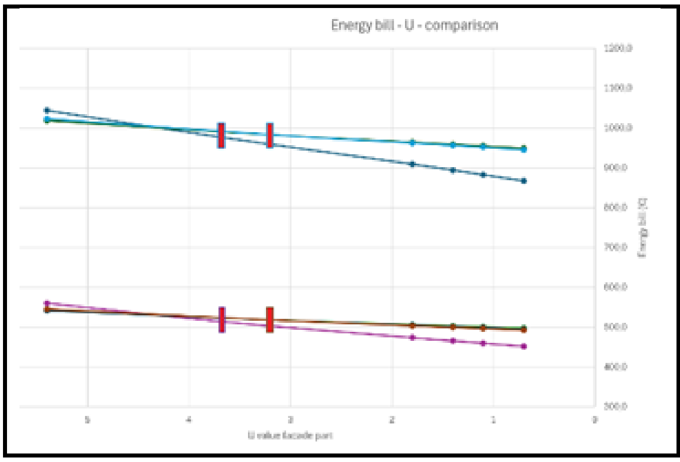
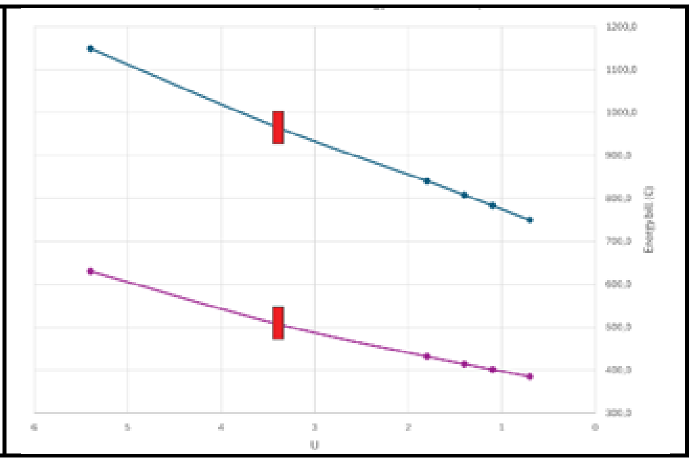


Figure 44: Review framework: influence of U values on thermal comfort, specific facades (Own work, 2025)

Energy bills (figures 45 and 46):

- U value improvements seem to have little effects on energy bills when they are applied to singular facades. When the improvements are applied to all façades, the effects become more significant. While this is true, improvements to the living room façade do have significant effects on the dwelling wide energy bill.
- The incremental improvements of U values can result in higher energy bill savings than R value improvements are able to.





Figures 45 & 46: Review frameworks: influence of U values on energy bills, specific facades (left) and entire dwelling (right) (Own work, 2025)

U and R value differences:

Within the different analyses, distinctions have become visible between the effects of changes in either the R- or U value. While both parameters influence the same review criteria, the changes differ in scope. These differences can be explained in different ways.

First, it is important to understand the scope of the application. The R-value is used for opaque constructions of the walls (i.e. concrete and masonry) and reflects the thermal resistance (m2K/W). The U-value applies to transparent elements (i.e. glazing) and represents the inverse of thermal resistance (W/m2K). As a result of this, R value interventions typically affect larger surface areas and well-insulated construction layers, while U value interventions typically target specific surfaces which are more heat vulnerable and form more weak thermal spots of the facades. As has been noted in chapter 2.4.2.

Besides this, it is important to understand the difference between the exponential behaviour of R value changes and the linear behaviour of U value changes. As has been explained in chapter 2.4.2, the transmission heat flow, which is affected by R and U value changes, works through the following formula: $\dot{Q}_{trans} = U * A * (T_e - T_i)$ [W], with $U = \frac{1}{R}$. Using this formula, it becomes clear that higher R values will result in lower heat losses. But when the incremental increase of R values is regarded, it can be noted that the effects of these increases reduce the higher the R value becomes, this can be seen in table 17. From this formula and table, the linearity regarding U value increases can also be explained, in regard to the direct effect it has on $\dot{Q}_{trans}$.

R value	**1**	**2**	**3**	**4**	**5**	**6**
U value ($U = \frac{1}{R}$)	1	0,5	0,33	0,25	0,2	0,16

Table 17: *Overview of incremental R & U value increases (Own work, 2025)*

Infiltration value:

The last comparison framework which has been set up and will be analysed, is that of changes to the infiltration value. Unlike R and U value changes, infiltration values act on the level of the entire dwelling, instead of on singular façades. This is due to the fact that infiltration values reflect the air quality and air tightness of the dwelling as a whole, instead of singular rooms and facades. It is for this reason that the comparison framework for the infiltration value only takes the effects on the energy expenditures of the entire dwelling into account. This can be seen in figure 47. It can be seen that changes to the infiltration value of the dwelling have limited results to the energy expenditures of the entire dwelling and that the maximum effect of these improvements is quickly realised. The effects are more significant in regular usage cases, and the most improvements can be made in the initial improvements of infiltration. Chapter 2.4.2 mentioned the role of infiltration values in the heat balance of buildings and can be used to understand the review framework. While these improvements provide limited effects on energy bills, chapter 2.4.5 discussed that infiltration improvements can have significant effects on the sensation of thermal comfort, through draft reductions.

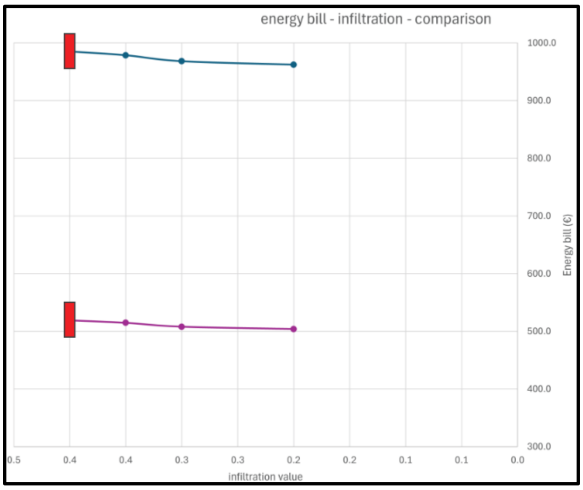


Figure 47: *Review framework: influence of infiltration values on energy bills, entire dwelling (Own work, 2025)*

5.2.2 Comparison of interventions on different comparison frameworks

The previously discussed comparison frameworks give a general overview of how gradual changes to the R, U and Qv10 value of facades will affect the cases' energy poverty review criteria. As has been discussed in chapter 4.4, different interventions have been identified which all influence a specific façade aspect. The comparison frameworks allow for an assessment and comparison of these interventions. By comparing the detailed simulation results, more specific assessments and comparisons can be made. Appendices 23.7 through 23.9 give overviews of the placements of different interventions on the different review frameworks. Appendices 23.1 through 23.5 give overviews of the simulation results on the individual criteria. Within these appendices and this chapter, R value interventions which don't improve the R value of the façade, but instead of the floor or ceiling aren't regarded, an overview of the results which do contain these interventions (i.e. ceiling insulation), can be seen in appendix 12. In the following segments, the placement of the interventions will be discussed, an overview of interventions and the colour, which is used for their placement on the frameworks, can be seen on the right.

Energy efficiency

When the effects of interventions on the energy efficiency of the dwelling are compared, different things can be noted. By comparing the difference in energy efficiency between the base situation and the situation with an intervention of figure 48, it can be seen that on average, U improvements have a larger effect than R value improvements and Qv10 improvements. This assumption is confirmed by the detailed findings, a summary of which can be seen in table 18. These findings show an average energy efficiency increase of 7,2% for U value improvements, 4,9% for R value improvement and 1,9% for Qv10 value improvements. Within the different frameworks there are significant differences between the effects of interventions. This is especially notable for the U value. The most effective intervention of glazing replacement comes with an improvement of 11,4% and the least effective intervention of window insulation film comes with an improvement of 4,4%. The large effects of R and U value improvements are comparable to the findings of chapter 2.4.4.

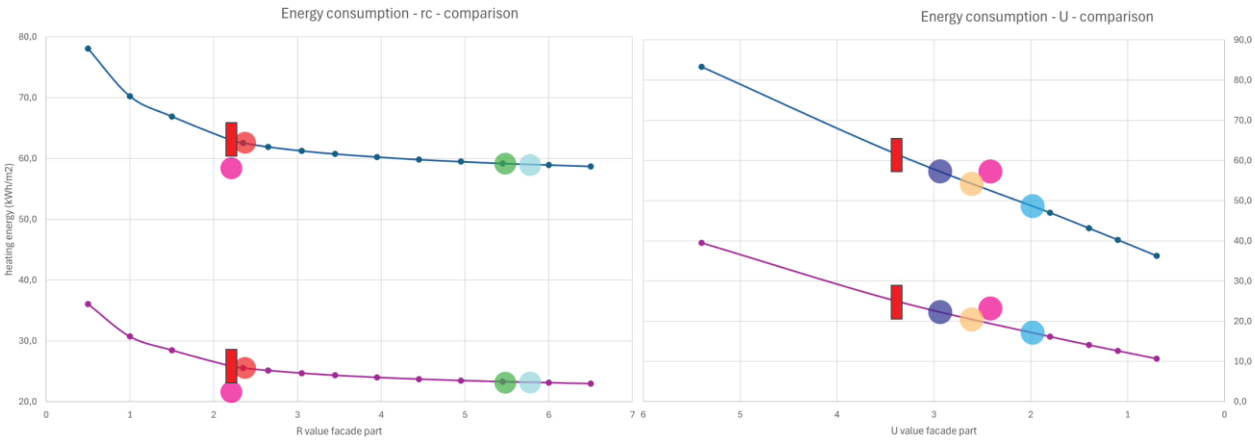


__Figure 48:__ Comparison of energy consumption frameworks (Own work, 2025)

Energy efficiency improvements		
R value improvements		
	Intervention	Result average of usage profiles
Best performing intervention	Thermal curtains	6,8%
Worst performing intervention	Insulated door panels	2,4%
Average of all interventions	4,9%	
	U value improvements	
Best performing intervention	Glazing replacement	11,4%
Worst performing intervention	Window insulation film	4,4%
Average of all interventions	7,2%	
	Qv10 value improvements	
Best performing intervention	House air sealing	2,8 %
Worst performing intervention	Draft stoppers	0,9%
Average of all interventions	1,9%	

Table 18: *Overview of best & worst energy efficiency improvement interventions on different frameworks (Own work, 2025)*

Thermal comfort

Similar to energy efficiency, the comparison of the effects interventions on different frameworks have on thermal comfort leads to the notion that U value interventions have the largest effects, followed by R and Qv10 values. A summarized overview of the results can be seen in table 19. The surpassing effect of U value interventions points towards a direct relation between heat transfer through glazing and thermal comfort, a relation which will be explored further in chapter 5.2.7. Within R value improvements, thermal curtains outperform the other interventions, an important sidenote regarding thermal curtains is the fact that they don't just alter the R value, but also the U value. With this in mind, the next best interventions are both indoor and external insulation, with an improvement of 1,9 degrees. The total average of R value improvements, 1,7, is similar to what has been discussed in chapter 2.4.5. The Qv value improvement have smaller average effects, while the most significant intervention of house air sealing does provide a 1-degree improvement, which is similar to different R and U value interventions. The performance of house air sealing addresses the impact of air speeds on thermal comfort, similar to what has been discussed in chapter 2.2 and 2.4.5.

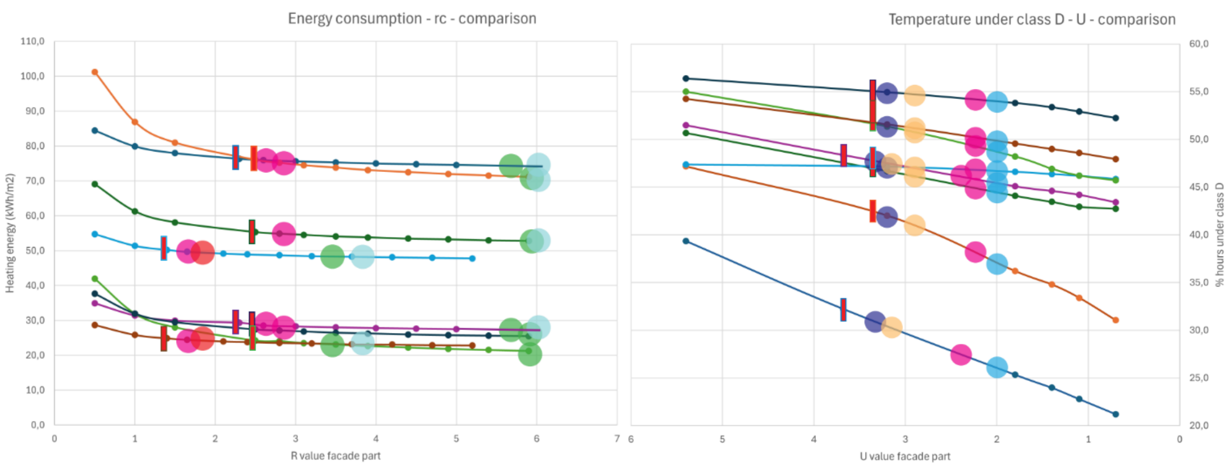


Figure 49: *Comparison of thermal comfort frameworks (Own work, 2025)*

Thermal comfort improvements		
R value improvements		
	Intervention	Result average of usage profiles
Best performing intervention	Thermal curtains	2,1 ^{0}C
Worst performing intervention	Insulated door panels	0,9 ^{0}C
Average of all interventions	1,7 ^{0}C	
	U value improvements	
Best performing intervention	Glazing replacement	4 ^{0}C
Worst performing intervention	Window insulation film	1,4 ^{0}C
Average of all interventions	2,4 ^{0}C	
	Qv10 value improvements	
Best performing intervention	House air sealing	1 ^{0}C
Worst performing intervention	Draft stoppers	0,3 ^{0}C
Average of all interventions	0,7 ^{0}C	

***Table 19:** Overview of best & worst thermal comfort improvement interventions on different frameworks (Own work, 2025)*

Yearly savings

Within the topic of yearly savings, U value improvements perform the best on average and with the best performing intervention. At the same time, there is a large range of performances within the U value interventions as for example window insulation film generates much smaller savings at around 32,2€ when compared to the glazing replacement savings of 83,1€. This range of performances is smaller for R and Qv10 value improvements. These ranges and a general summary of results can be seen in table 20. Figure 50 visualizes how individual interventions on the different frameworks compare to each other, in the total energy bill they result in. The ranking of frameworks and interventions is similar to those of energy efficiency and thermal comfort.

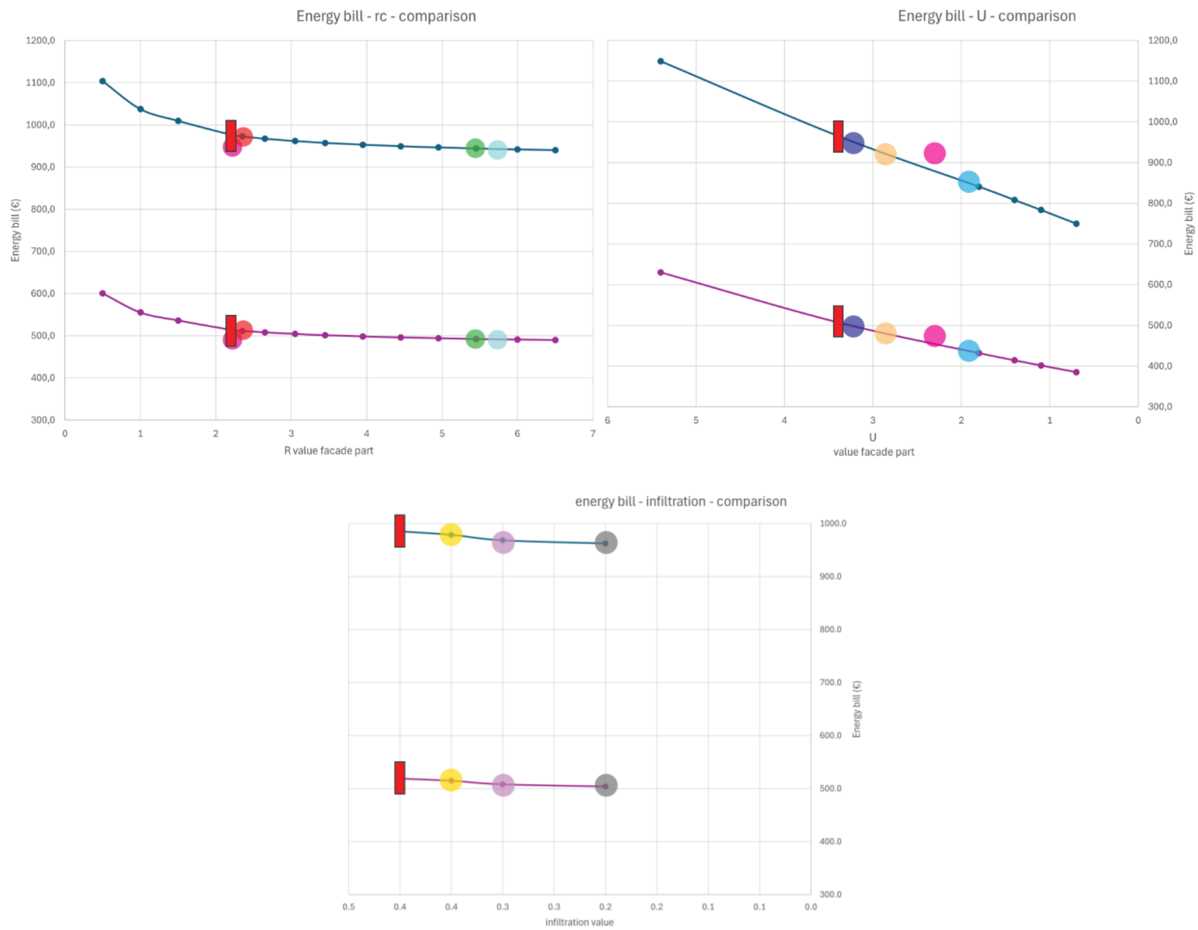


***Figure 50:** Comparison of energy bill frameworks (Own work, 2025)*

Yearly savings		
R value improvements		
	Intervention	Result average of usage profiles
Best performing intervention	Thermal curtains	49,4€
Worst performing intervention	Insulated door panels	17,3€
Average of all interventions	35,3€	
	U value improvements	
Best performing intervention	Glazing replacement	83,1€
Worst performing intervention	Window insulation film	32,2€
Average of all interventions	52,6€	
	Qv10 value improvements	
Best performing intervention	House air sealing	19,9€
Worst performing intervention	Draft stoppers	5,9€
Average of all interventions	13,6€	

***Table 20:** Overview of best & worst yearly savings interventions on different frameworks (Own work, 2025)*

Payback period

Within the topic of payback periods, the performance of interventions changes. This is due to the fact that another parameter of interventions is regarded with this criterion, that being the investment costs. While U value improvements still perform the best on this criterium, it is now followed with close margins by the Qv10 value and lastly, the R value. This shift in performance and rankings is due to the investment costs of interventions. While the effects of for example, glazing replacement and external wall insulation outperform others on energy efficiency and thermal comfort, their investment prices are also much higher. This results in significantly larger payback periods of the most effective interventions, when compared to the other interventions. Within the Qv10 value improvements, the interventions have a lower average investment cost, positively influencing their payback periods. A summary of results can be seen in table 21.

Payback period		
R value improvements		
	Intervention	Result average of usage profiles
Best performing intervention	Insulated door panels	2,1 years
Worst performing intervention	External wall insulation	127 years
Average of all interventions	40.4 years	
	U value improvements	
Best performing intervention	Window insulation film	1,8 years
Worst performing intervention	Glazing replacement	22,8 years
Average of all interventions	9,3 years	
	Qv10 value improvements	
Best performing intervention	Draft stopper	8,3 years
Worst performing intervention	House air sealing	21 years
Average of all interventions	12,6 years	

***Table 21:** Overview of best & worst payback period interventions on different frameworks (Own work, 2025)*

Investing efficiency

The investing efficiency of interventions addresses the relation between investment cost and yearly savings. The rankings of frameworks and interventions are similar to those of payback periods. The interventions with low investment costs, which generate proportionally savings result in high investing efficiency. When the different improvements are compared, it can be seen that U value improvements have the highest investing efficiency, followed by R value and Qv10 value improvements. The average efficiency of frameworks is largely influenced by the top performing interventions. For example, insulated door panels outperform external wall insulation by a far margin. A summary of results can be seen in table 22.

Investing efficiency		
R value improvements		
	Intervention	Result average of usage profiles
Best performing intervention	Insulated door panels	49,9%
Worst performing intervention	External wall insulation	0,9%
Average of all interventions	18,6%	
	U value improvements	
Best performing intervention	Window insulation film	57,5%
Worst performing intervention	Glazing replacement	4,6%
Average of all interventions	24,0%	
	Qv10 value improvements	
Best performing intervention	Draft stopper	12,3%
Worst performing intervention	House air sealing	5%
Average of all interventions	9,9%	

Table 22: *Overview of best & worst investing efficiency interventions on different frameworks (Own work, 2025)*

5.2.3 Comparison of interventions on intervention scales

The second categories of interventions which can be compared with each other are the basic, intermediate, and advanced interventions. As has been mentioned in chapter 4.4, these groups categorize interventions based on their investing cost, timespan of effectiveness and difficulty of installation. Appendix 13 gives the detailed results on all review criteria.

Energy efficiency

Regarding energy efficiency improvements, it can be noted that on average, the effectiveness of intervention groups decreases in the sequence of advanced interventions, basic interventions and basic intermediate. This can be seen in table 23. The main reasons for this being the outliers of the basic group, thermal curtains, and the outliers of the advanced group, glazing replacement. When all intermediate interventions are compared it can be seen that indoor wall insulation and secondary glazing DIY have higher results than the average of the group. The average of the group is diminished by the different interventions which have little to no effect (i.e. ceiling insulation and floor insulation).

Energy efficiency improvements			
Basic interventions			
Example interventions		Example interventions	
Intervention	Result	Intervention	Result
Draft stoppers	0,7%	Draft stoppers	1,0%
Thermal curtains	5,8%	Thermal curtains	7,7%
Average	2,6%	Average	3,4%
Intermediate interventions			
DIY secondary glazing	5,7%	DIY secondary glazing	7,0%
Ceiling insulation	0,1%	Ceiling insulation	0,1%
Average	2,3%	Average	2,8%
Advanced interventions			
Glazing replacement	10,3%	Glazing replacement	12,4%
House air sealing	2,4%	House air sealing	3,1%
Average	5,8%	Average	7,1%

Table 23: *Overview of best & worst energy efficiency improvement interventions on different scales (Own work, 2025)*

Thermal comfort

A similar sequence of effectiveness between groups is present on the criteria of thermal comfort. This can be seen in table 24. At the same time, the highest performing interventions of the basic and intermediate intervention have comparable results. Thermal curtains provide an average improvement of 2,2 degrees and indoor wall insulation provide an average improvement of 2,0 degrees. Similar to the energy efficiency of interventions, different interventions provide little to no improvement. For example, the intermediate intervention of ceiling insulation provides no measurable improvement.

Thermal comfort improvement			
Basic interventions			
Normal usage		Example interventions	
Example interventions	Result	Intervention	Result
Draft stoppers	0,3 ^{0}C	Draft stoppers	0,3 ^{0}C
Thermal curtains	2,2 ^{0}C	Thermal curtains	2,1 ^{0}C
Average	1,0 ^{0}C	Average	1,0 ^{0}C
Intermediate interventions			
Indoor wall insulation	2,0 ^{0}C	Indoor wall insulation	1,7 ^{0}C
Ceiling insulation	0,0 ^{0}C	Ceiling insulation	0,0 ^{0}C
Average	0,9 ^{0}C	Average	0,8 ^{0}C
Advanced interventions			
Glazing replacement	4,6 ^{0}C	Glazing replacement	3,5 ^{0}C
House air sealing	1,0 ^{0}C	House air sealing	0,9 ^{0}C
Average	2,5 ^{0}C	Average	2,0 ^{0}C

Table 24: *Overview of best & worst thermal comfort improvement interventions on different scales (Own work, 2025)*

Yearly savings

The comparison of groups has similar results as for the previous review criteria, as can be seen in table 25. The average performances of the basic and intermediate groups are not significantly far apart, the same can't be said for the individual performances of the best interventions of each group. As for example glazing replacement yields almost double the results than thermal curtains and secondary glazing DIY.

Yearly savings			
Basic interventions			
Example interventions		Example interventions	
Intervention	Result	Intervention	Result
Draft stoppers	6,7€	Draft stoppers	5,1€
Thermal curtains	57,6€	Thermal curtains	39,8€
Average	25,5€	Average	17,7€
Intermediate interventions			
Secondary glazing DIY	55,9€	Secondary glazing DIY	36,4€
Ceiling insulation	1,4€	Ceiling insulation	0,3€
Average	23,1€	Average	14,6€
Advanced interventions			
Glazing replacement	101,7€	Glazing replacement	64,4€
House air sealing	23,9€	House air sealing	15,9€
Average	57,2€	Average	37,0€

Table 25: *Overview of best & worst yearly savings interventions on different scales (Own work, 2025)*

Payback period

When the payback periods of interventions within the different groups are compared, different conclusions can be made than of the previous review criteria. On average, basic interventions far outperform the intermediate and advanced interventions. When the detailed results are analysed, it can be seen that both the intermediate and advanced interventions have some extreme outliers which greatly increase the group's average. When the best performing interventions are analysed, the advance intervention group still has the longest payback period. While the intermediate intervention of insulated door panels outperforms thermal curtains. This change of results regarding the payback period is a result of investment price being taken into account. As has been discussed before, basic interventions have the lowest average investment price and advanced interventions have the highest. While the advanced interventions do yield greater savings, the payback periods are still much longer. A summary of results can be seen in table 26.

Payback period			
Basic interventions			
Example interventions		Example interventions	
Intervention	Result	Intervention	Result
Radiator foil (method 2)	2,8 years	Radiator foil (method 2)	4,3 years
Draft stoppers	7,2 years	Draft stoppers	9,4 years
Average	4,8 years	Average	6,6 years
Intermediate interventions			
Window insulation film	1,4 years	Window insulation film	2,2 years
Floor rug insulation	357,1 years	Floor rug insulation	2188 years
Average	156,0 years	Average	56,8 years
Advanced interventions			
External wall insulation	101,6 years	External wall insulation	152,3 years
House air sealing	16,7 years	House air sealing	25,2 years
Average	45,4 years	Average	68,5 years

Table 26: *Overview of best & worst payback period interventions on different scales (Own work, 2025)*

Investing efficiency

Lastly, the investing efficiency is regarded, which compares the investment price to the yearly savings. It can be seen that the sequence of intervention groups is the opposite of the sequence for energy efficiency and thermal comfort. Basic interventions have the highest investing efficiency and advanced interventions the lowest. Similar to the payback periods, this is because the investment costs are taken into account, which are much lower for basic interventions. While this sequence is true for the average values, the best performing intervention is part of the intermediate intervention group and outperforms all other interventions. This intervention is the insulated door panels, which outperforms the basic interventions regarding investing efficiency. The results can be seen in table 27.

Investing efficiency			
Basic interventions			
Example interventions		Example interventions	
Intervention	Result	Intervention	Result
Radiator foil (method 2)	35,2%	Radiator foil (method 2)	23,4%
Draft stoppers	13,9%	Draft stoppers	10,7%
Average	24,0%	Average	16,7%
Intermediate interventions			
Ceiling insulation	0,2%	Ceiling insulation	0,1%
Window insulation film	69,4%	Window insulation film	45,6%
Average	20,9%	Average	13,8%
Advanced interventions			
External wall insulation	1,0%	External wall insulation	0,7%
House air sealing	6,0%	House air sealing	4,0%
Average	4,2%	Average	2,7%

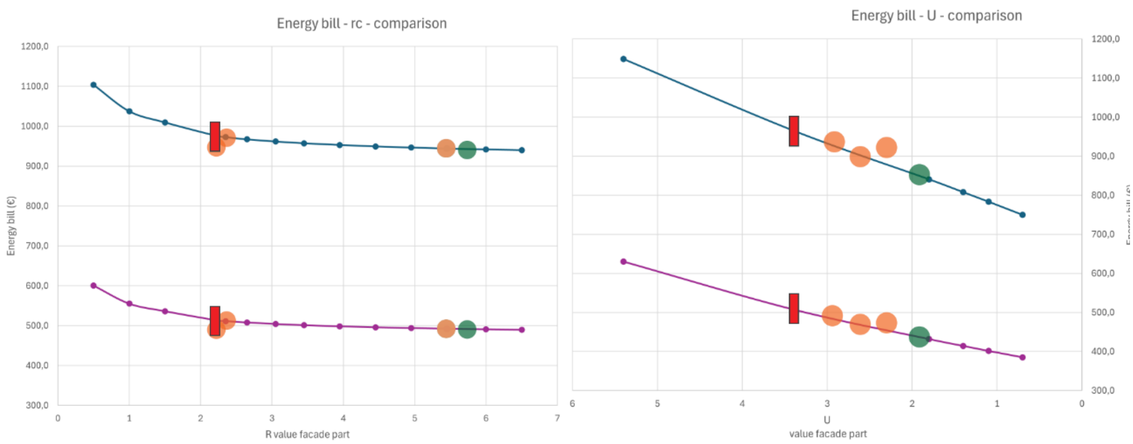
Table 27: *Overview of best & worst investing efficiency interventions on different scales (Own work, 2025)*

5.2.4 Comparison of structural and non-structural interventions

Appendix 14 gives detailed overviews on how structural interventions compare to non-structural interventions on the different review criteria. With structural interventions meaning those interventions which are placed permanently and often require professional help, such as glazing replacement and external wall insulation. Non-structural interventions are interventions which are demountable and often don't require professional help, such as DIY secondary glazing and draft stoppers. This categorization is similar to the scales of chapter 4.4, but also focusses on the dilemma posed in chapter 2.3.3, being that renting contracts prohibit occupants from placing permanent energy efficiency interventions or that they require specific approvals. In this situation, non-structural interventions would be able to be applied without certain approvals by occupants themselves. Besides the home ownership dilemma, the discussed disassociation with professionals as has been discussed in appendices 1 and 3 leads to the notion that the ability to place interventions without approval and help could be especially useful for empowering energy poverty households.

For the review criteria of energy efficiency, thermal comfort & yearly savings, in most cases the structural interventions outperform the non-structural interventions. At the same time there are some outlying non-structural interventions which outperform different structural interventions. Examples of these interventions are thermal curtains, DIY secondary glazing and window insulation film. These interventions outperform the structural interventions of house air sealing and floor insulation, on the energy efficiency improvements criteria. In regard to the review criteria of payback period and investing efficiency, the non-structural interventions outperform the structural interventions. The margin in which non-structural interventions outperform the structural interventions can be quite extensive. For example, window insulation film has an average payback period of 1,4 years while the comparable intervention of glazing replacement has an average payback period of 25 years.

The dataset shows the comparison of all review criteria. While all interventions behave differently, there are larger differences between structural and non-structural interventions for interventions which focus on increasing the U value of facades than interventions which focus on the R or Qv10 values. For example, glazing replacement provides an average energy efficiency improvement of 10,3%, while DIY secondary glazing provides an average energy efficiency improvement 5,7%. At the same time, the R value intervention of external insulation provides an average energy efficiency improvement of 4,7%, while internal insulation provides an average energy efficiency improvement 4,6%, which is a smaller difference. Lastly, interventions which influence the infiltration of buildings also have a small difference. While house air sealing provides an average energy efficiency improvement of 2,4% weatherstripping provides an average energy efficiency improvement of 1,8%. Figure 51 visualises the differences regarding the effects on energy bills. Within the comparison graphs, the orange spheres represent non-structural interventions and the green spheres represent structural interventions. The improvements non-structural interventions have on the different criteria, especially the direct financial parameters, alongside the benefits of DIY placement, make (certain) non-structural interventions quite effective.



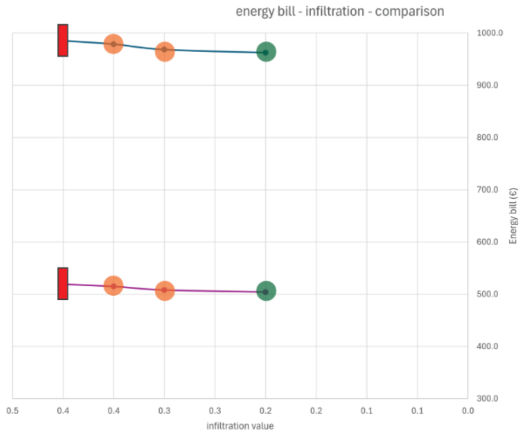


Figure 51: *Comparison of energy bill effects of structural and non-structural interventions (Own work, 2025)*

5.2.5 Comparison of financial parameters

As has been discussed in chapter 4.3.3, when assessing the effectiveness of interventions in relation to combatting energy poverty, it is crucial to take the financial aspects of interventions into account. As has been explored in chapter 2, the financial strength of households is strongly diminished when they are faced with energy poverty. They are forced to save on energy costs and other necessities. As a result of this, there is often little money available to be directed towards their savings or investments, such as energy efficiency interventions. This is one of the main reasons why households have trouble getting out of energy poverty, as they aren't capable to invest in that which will improve their situation. This relates to the 'poverty trap', which has been discussed in chapter 2.5.3.

This leads to the notion that the financial aspects of interventions are of significant importance, alongside the improvements of energy efficiency and thermal comfort. Financial aspects which need to be kept in mind, and which have been logged as part of this research include yearly savings, investment price, payback period and investing efficiency. As a starting point for reviewing the investing efficiency of interventions, people are looking for the largest amount of energy savings or thermal comfort improvement, for a low as possible price and short as possible payback period. This is the case for most investments, but is especially pressing in energy poverty situation, due to the shortage of resources and the time pressing nature of the problem. This has been discussed in chapters 2.4.6 and 3.3, an overview of this investment process can be seen in figure 52.

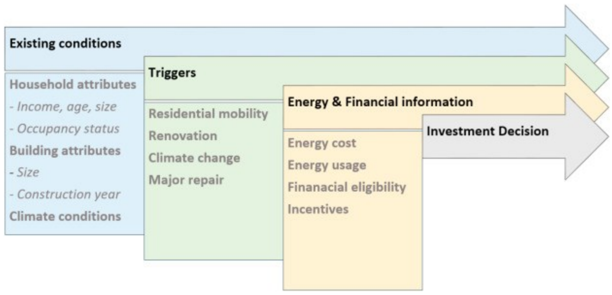


Figure 52: *Residential energy efficiency investment decision process (Belaïd et al., 2021)*

In order to assess the performance of interventions on this aspect, figures 53 and 54 visualise the relation between investment price and yearly savings of different interventions, on both usage profiles. Appendix 16.1 gives a detailed numeric overview of interventions alongside their investment price and yearly savings. The most important notion to make from this data is that there seems to be little direct correlation between the required investment of an interventions and its energy saving potential within this case study. For example, glazing replacement with an investment price of 1800€ outperforms external wall insulation which has an investment price of 4670€. Similar to this, DIY secondary glazing with an investment price of 320€ outperforms house air sealing which has an investment price of 400€. The graphs visualize this lack of correlation between the predefined criteria. These tables and figures can also be found and viewed in more detail in appendix 16.

While there is little direct correlation between visible, different notions can be made about the spread of interventions along the graph. Firstly, there is a cluster of small-scale interventions within the price range of 500€ and the savings range of 40€ for normal usage. This includes interventions such as DIY secondary glazing and insulated door panels. Besides this cluster, there is the cluster of the 3 floor- and ceiling insulation interventions, within the price range of 500€ to 1250€ who all generate neglectable savings. Lastly, there are certain outliers visible which differentiate themselves in either their investment cost, their yearly savings, or a combination of the two. These outliers are the thermal curtains, DIY secondary glazing, glazing replacement, and external wall insulation interventions. With thermal curtains performing especially well in relation to its investment cost, and external wall insulation performing especially poor in relation to its investment cost.

The relationship between investment cost and yearly savings is also visualised through the review criteria of investing efficiency and builds upon these previous notions. The investing efficiency relates the investment price and yearly savings parameters with each other and answers the question of how much savings you get per invested euro. A detailed overview of this can be seen in appendix 11.5. The spreads of figures 51 and 52 closely relate to this dataset, which shows that interventions with less savings can still be of high investing efficiency due to their low investment cost. This can be said for the interventions of radiator foil, insulated door panels and window insulation film. At the same time, the effect of high yearly savings can be held back by high investment costs and result in lower investing efficiency values, this can be said for the interventions of floor insulation and external wall insulation. Interventions with high investing efficiency pose themselves as especially useful for energy poverty households, as these interventions capitalize on their limited budgets and time pressure.

As has been discussed, the choice of energy efficiency investment searches for the largest amount of energy savings or thermal comfort improvement, for as low as possible price and payback period, this is especially pressing for energy poverty situation. An overview of the payback periods of interventions can be seen in appendix 11.4. It is important to note in regard to the financial parameters that these parameters are calculated using the average gas price peak of 2022 (1,5€). If more recent or lower gas prices are used for these estimations, the effects reduce. This is because payback periods will increase as yearly savings reduce. This notion is elaborated on in appendix 18.7.

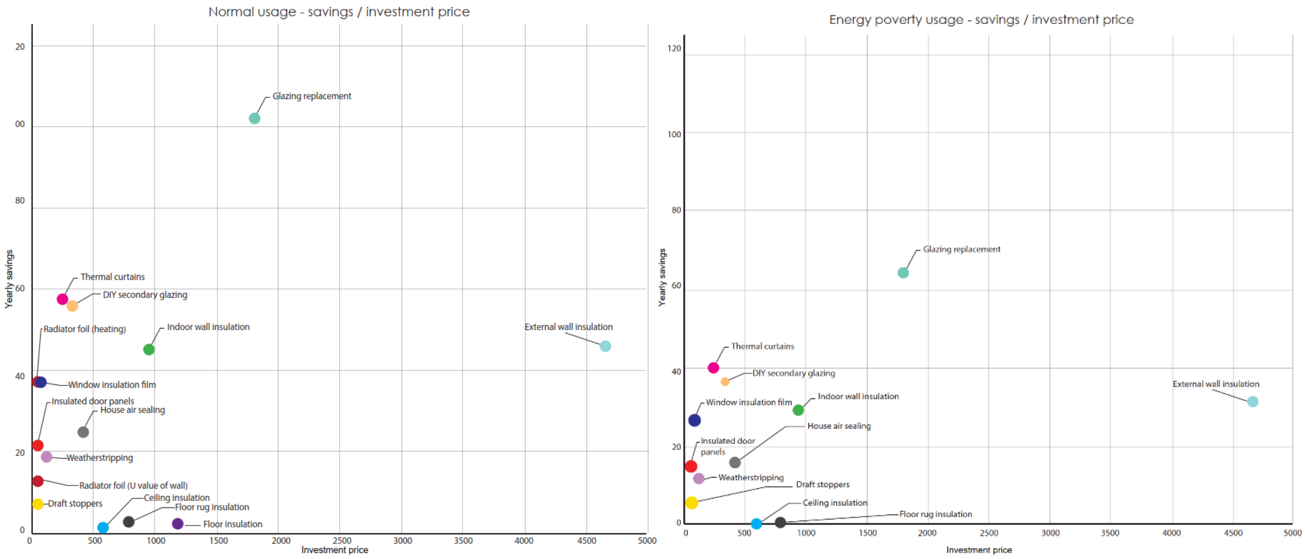


***Figure 53 & 54:** Overviews of investment prices and yearly savings of different interventions and usage scenarios (Own work, 2025)*

5.2.6 The effectiveness of combining interventions

Oftentimes households and policy makers might look towards combining different energy efficiency interventions to lower energy costs. This is an interesting thought for households looking to introduce high quality and expensive interventions, as combining them could lower these costs and possible construction times. At the same time, this combination is also interesting for households looking to introduce less effective and easy to apply interventions, as it allows for the combination of efforts and will allow for the small effects to sum up to more noticeable effects. This approach is often taken in existing energy poverty strategies, as has been discussed in chapter 2.7.

By combining the structural interventions of external insulation, glazing replacement and house air sealing, the results which are shown in table 28 are achieved. By combining the non-structural interventions of indoor wall insulation, window insulation film and draft stoppers, the results which are also shown in table 28 are achieved. This combination of interventions is similar to that which was discussed in chapter 2.7.2. Both groups of interventions differ from each other in their energy efficiency and the energy bill savings they achieve, with the group of structural interventions outperforming the group of non-structural interventions. This is especially significant in the thermal comfort improvements.

Structural combination		
	Normal usage	**Energy poverty usage**
E. efficiency improvement (%)	15,8	18,2
T. comfort improvement (C⁰)	5,7	5,5
Yearly savings (€)	155,6	94,6
Payback period (years)	44,2	72,6
Investing efficiency (%)	2,26	1,4
Non-structural combination		
	Normal usage	**Energy poverty usage**
E. efficiency improvement (%)	7,3	9,0
T. comfort improvement (C⁰)	2,5	2,2
Yearly savings (€)	72,4	46,9
Payback period (years)	14,6	22,5
Investing efficiency (%)	6,87	4,45

Table 28: *Simulation results of structural and non-structural interventions (Own work, 2025)*

The comparison of groups of table 28 shows that the structural combination outperforms the non-structural combination on all aspects, except for the payback period and investing efficiency, this falls in line with the findings of the previous chapters. Figure 55 visualise how the groups of structural and non-structural interventions compare to the interventions which were individually tested on the U, R and Qv10 value. It can be seen that both groups of interventions outperform almost all of the individual interventions on the R and Qv10 value. When the grouped interventions are compared to interventions on the U value it can be seen that different U value interventions are able to provide similar effects or outperform the effects of the non-structural combination. DIY secondary glazing, thermal curtains and glazing replacement are all individual interventions which can provide more than the non-structural interventions can. This comparison points to the fact that not all interventions within the grouped build-up have comparable results. This puts their effect relative to the effect of the group in question; does their inclusion outweigh its accompanying costs? For example, within the non-structural group, indoor wall insulation has an energy efficiency improvement average of 5% and draft stoppers of 0.9%. Within the structural group, glazing replacement has an energy efficiency improvement average of 11,4% and house air sealing of 2.7%. The effectiveness of including house air sealing can be questioned from this, as it includes significant investment costs. This approach of combining different interventions doesn’t always outperform choosing the most effective interventions for a specific case, which will be elaborated on in further chapters.

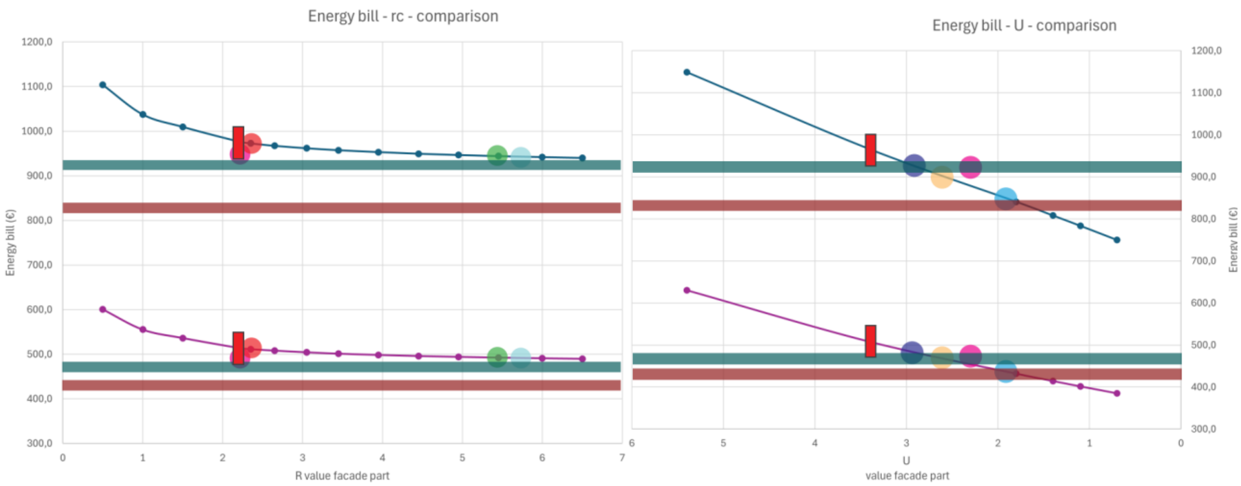


Figure 55: Relation between grouped interventions and singular interventions on different frameworks (Own work, 2025)

5.2.7 Comparison of comfort effects of interventions

The simulations and conclusions of the previous chapters take important aspects of energy efficiency interventions into account, such as their energy efficiency improvements, their financial feasibility, and the degrees of thermal comfort improvement they provide. At the same time, assessing thermal comfort through the degrees in which a temperature setpoint can be increased and through the percentage of hours below a certain comfort class can be too much of an oversimplification. While the approach to thermal comfort is sufficient, as it visualises the manner in which energy poverty households outweigh their choice of room heating, it doesn't directly translate to room temperature increase, as heating system efficiency and outdoor temperatures need to be considered in this estimation.

To elaborate on this with an example, the simulations of glazing replacement in normal usage scenarios allows for temperature setpoints of 23,6 degrees to be applied in the living room, without increasing energy costs. When this setpoint is simulated and the monthly temperatures of January are analysed, it can be noted that the indoor temperatures of the living room during its usage averages around at 22 degrees, as the extreme cold temperatures and the heating periods restrict the temperature of 23,6 degrees from being reached. When the month of February is analysed, it can be seen that outdoor temperatures rise, resulting in the indoor temperatures of the living room reaching the setpoint of 23,6 degrees. Chapter 2.2 discussed the different aspects of thermal comfort. This oversimplification and presented problem can be counteracted with specific thermal comfort simulations, known as CFD (Computational Fluid Dynamics) simulations.

Simulation set-up and review framework

The CFD simulation is a method which can be used to analyse the behaviour of fluids, such as air and water, within predefined spaces. The simulation software solves the fundamental equation of fluid motion and then allows the user to review airflows, temperatures, and pressure fields. In the case of building design, specific rooms or buildings can be modelled in this software to analyse how heat transfers itself through the design.

The simulation works by first creating a digital 3D model of the situation at hand, which the software divides into a mesh of small cells. After this, physical boundary conditions need to be added, these include conditions like heat sources, air inlets and material properties. When this is completed, the software computes the way in which air and heat move through the individual cells. Figure 56 visualises what these simulations look like when applied on the case. After these simulations are completed, different data can be assessed.

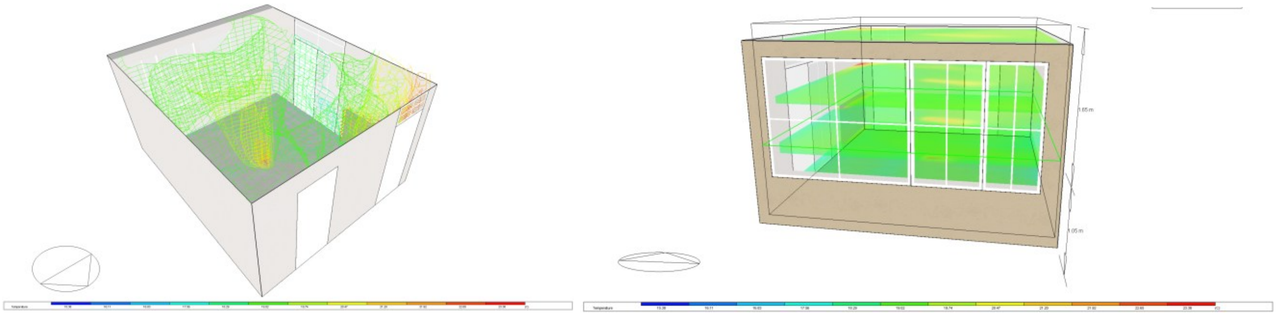


***Figure 56:** Visualizations of CFD simulations in chosen case (Own work, 2025)*

In order to review the thermal comfort of predefined positions in the simulated rooms, different values are assessed from the CFD simulations. The PMV (predicted mean vote) value is assessed. The PMV method relates thermal conditions to the seven-point thermal sensation scale of ASHRAE (cold, to cool, slightly cool, comfortable/neutral, slightly warm, warm, and hot (Heinzerling et al., 2022). Besides this, the mean radiant temperature is assessed, this value stands for the average temperature on a specific surface, it reflects how much heat a body gains or loses through thermal radiation. This radiant temperature plays an important role in assessing the comfort in a certain space. Lastly, the operative temperature is assessed. This temperature is a value which combines air temperature and mean radiant temperature in order to estimate how warm a person will feel. These values will be assessed from 4 review points, which all present different points of importance within the dwelling. Point 1 represents a seating space close to the window, point 2 represents the middle of the room which could be used as dining space, point 3 represents a possible seating area in the back of the room and point 4 represents the entrance to the room and one of the spaces close to the radiator which can influence the thermal sensation when entering the room. These review points can be seen in figure 57.

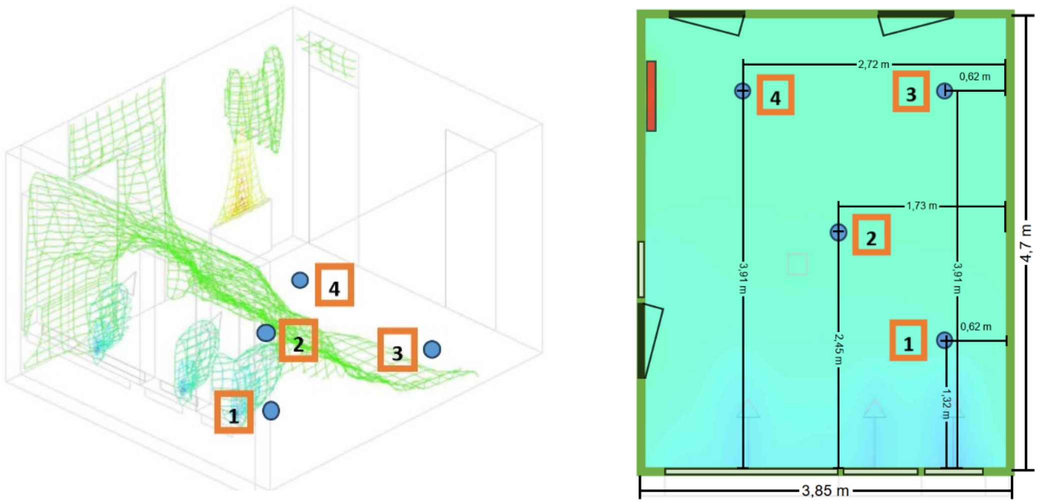


***Figure 57:** Visualizations of CFD review points (Own work, 2025)*

Different interventions will be simulated to review their effects on thermal comfort. The simulated interventions function on different review frameworks and are both structural and non-structural. The tested interventions can be seen in table 29. The constructions of the base situation and the energy usage of the energy poverty situation will lay the foundation for the analyses, comparable to what has been described in chapter 4.2. This chapter will discuss the findings of the simulation and will summarize the findings. The detailed results and simulations can be found in appendices 19 through 21.

R value	U value	Appliance
Indoor wall insulation	Window insulation film	Warm air circulators
External wall insulation	Glazing replacement	Infrared heating panels

***Table 29:** Overview of CFD tested interventions (Own work, 2025)*

Normal situation

The CFD simulation applied on the situation without interventions shows how the different physiological elements behave in the living room. This model contains the constructions of the base situation, and the space usage of the energy poverty situation. The heating of the room has been set-up to represent the modelled situations in VABI, this means that the heating power was set to the value which resulted in an operative temperature around 13,5 ^{0}C in the centre of the room. The model of the living room does not contain furnishing. This has been left out in order to analyse the direct effects of interventions. In real-life situations, furnishing will reduce the free flow of air in the dwelling, which can have positive effects in blocking colder temperatures from reaching resting positions but will also prohibit warm air flows from flowing freely throughout the dwelling.

It can be seen in the simulations of appendix 19.1 that cold temperatures enter at the position of the glazing, through the ventilation and low surface temperature at that location. Besides this, cold temperatures enter through the lower part of the façade. Due to the physiological aspects of temperature, this cold flows to the lower half of the dwelling height and warmer temperature rise up. In this upper half, colder temperatures mix with warmer temperatures generated by the radiator in the back corner of the room. Due to this discrepancy of temperatures within the dwelling, it can be seen that the mean radiant temperature, operative temperature and PMV increase the further back in the dwelling these values are analysed. The values of the different points and parameters can be seen in table 30. The detailed results can be seen in appendix 20.1.

Review point	Operative temperature (^{0}C)	Mean radiant temperature (^{0}C)	PMV
1	13,8	13,5	-2,0
2	14,5	14,0	-1,4
3	15,5	15,0	-1,1
4	15,5	15,8	-1,1

Table 30: *Overview of standard situation CFD results of different points (Own work, 2025)*

Indoor wall insulation

It can be seen that indoor wall insulation generally increases the operative and mean radiant temperatures, as the surface temperatures of the wall increase. This intervention shifts the entrance of colder temperatures more to the glazing than through the walls. The most striking difference can be seen when comparing the 3D distribution of PMV values. In the normal situation, cold enters through the top of the façade, these temperatures lower throughout the dwelling. In the new situation, this cold is reduced, preventing this 3D discrepancy of temperature, this can be seen in appendix 19.2. The results of this intervention can be seen in table 31. The detailed results can be seen in appendix 20.2.

Average improvements for all review points: Indoor wall insulation		
Operative temperature (%)	Mean radiant temperature (%)	PMV (%)
7,5	4,9	42,0

Table 31: *Overview of indoor wall insulation CFD results (Own work, 2025)*

External wall insulation

The situation where external wall insulation is applied is almost identical to the situation with indoor wall insulation, the main difference being that the added insulation improves the different parameters, throughout the dwelling more than indoor insulation. The results of this intervention can be seen in table 32. The detailed results can be seen in appendix 20.3.

Average improvements for all review points: External wall insulation		
Operative temperature (%)	Mean radiant temperature (%)	PMV (%)
8,2	5,9	49,0

Table 32: *Overview of external wall insulation CFD results (Own work, 2025)*

Window insulation film

The first improvements by window insulation film can be seen by comparing how temperature flows through the dwelling in comparison to the normal situation, it can be seen that the cold temperatures given off by the windows decreases, resulting in less cold air flows through the room. When the operative temperatures are compared, the operative temperature which borders the window is much lower and smaller than in the normal situation. The main remaining entry of cold air comes from the ventilation. When the mean radiant temperatures are compared, it can be seen that the temperature increases faster from the window than in normal situation, this is due to the increase in surface temperature. At the same time, there is still discrepancy visible between window panes, as the base characteristics are different between window panes. It can also be noted that the biggest improvement comes through the mean radiant temperature and the PMV. As the area of the window panes are quite large, in comparison to the wall area, the relatively low value glazing improvement can have large effects. Besides this, similar to what will be further discussed in chapter 5.3, the tackling of the weakest link also results in these significant effects. The results of this intervention can be seen in table 33. The detailed results can be seen in appendix 20.4.

Average improvements for all review points: Window insulation film		
Operative temperature (%)	**Mean radiant temperature (%)**	**PMV (%)**
6,7	5,1	57,2

Table 33: *Overview of window insulation film CFD results (Own work, 2025)*

Glazing replacement

Glazing replacement follows up on the positive effects of window insulation film, by improving these effects more significantly. This is due to the further improvements in U value. Another important factor of the glazing replacement intervention is the fact that glazing replacement improves the U value of all panes to the same value, this removes the differences between the U values of panes, which is present in the window insulation film simulation. The main improvements of this intervention can be seen by analysing the mean radiant temperature. This temperature increases significantly throughout the dwelling, and there is less discrepancy across the room. Glazing replacement results in large improvements of all thermal comfort parameters. The results of this intervention can be seen in table 34. The detailed results can be seen in appendix 20.5.

Average improvements for all review points: Glazing replacement		
Operative temperature (%)	**Mean radiant temperature (%)**	**PMV (%)**
7,7	19,0	64,9

Table 34: *Overview of glazing replacement CFD results (Own work, 2025)*

Warm air circulators

Warm air circulators work in a different way than the previously discussed interventions. The intended effect of the localized air heating system is to blow warm air into the room it is applied on, this air will then mix with the colder air of the room. Most warm air circulators come with 2 heating settings, 1000W and 2000W. Both settings show to greatly improve both the operative temperature and the PMV of the base energy poverty situation. The 2000W system outperforms the 1000W system. The warm air circulators have little effect on the mean radiant temperature, as it has no effect on the u value of the glazing within the situation, and its heat is transferred through the air. One of the main benefits of the system is that it has an effect on the entire room, as air spreads through the room. The large increase of PMV and operative temperature show that its method of heat transfer can be more effective than traditional radiators. The inclusion of furnishing within the model would reduce the effectiveness of the system. The furnishing would act as blockades which hinder the free flow of air throughout the room. The results of this intervention can be seen in table 35. The detailed results can be seen in appendix 21.2 and 21.3.

Average improvements for all review points: Warm air circulators 1000W		
Operative temperature (%)	**Mean radiant temperature (%)**	**PMV (%)**
8,1	3,9	34,8
Average improvements for all review points: Warm air circulators 2000W		
Operative temperature (%)	**Mean radiant temperature (%)**	**PMV (%)**
11,9	5,9	93,8

Table 35: *Overview of warm air circulators CFD results (Own work, 2025)*

Infrared heating panels

Infrared heating panels work in a much different way than traditional radiators or warm air circulators, this has been explained in chapter 4.4.2. This can be seen when the effects on the different thermal comfort parameters are compared. Infrared heating panels have little to no effect on the operative temperature within the room, it mainly influences the mean radiant temperature and PMV. The increase of mean radiant temperature can be significant, depending on the location in which it is measured. As PMV results are built up out of many different factors, an increase solely in mean radiant temperature will not result in large PMV improvements.

The placement of the panels is also crucial to its effectiveness. One simulation was performed where the panel was placed mounted on the wall, above the original location of the radiator. Another simulation was performed where the panel was mounted on the ceiling, almost above measure point 3. This difference can be seen when the individual points are analysed. The wall-mounted panel shows a PMV increase of 34,6% for point 4, but the ceiling mounted panel only shows an increase of 6,5%. At the same time, the ceiling mounted panel shows a PMV increase of 42,5% for point 1, but the wall mounted panel only shows an increase of 22%. These results show that infrared heating panels can be utilized for localized heating, but that their application for room-wide heating is limited. The effectiveness of the panels is also compromised by the existing low-quality façade, this can be seen when the 3D spread of temperatures and PMV values are compared. Lastly, the inclusion of furnishing would further diminish the effects of the panels, as with infrared heating panels direct surfaces are heated. This would mean that if a piece of furniture blocks the line of sight with a panel, those heating rays are blocked. The results of this intervention can be seen in table 36. The detailed results can be seen in appendix 21.4 and 21.5.

Average improvements per intervention: Infrared heating panels wall mounted		
Operative temperature (%)	**Mean radiant temperature (%)**	**PMV (%)**
5,5	14,7	27,1
Average improvements per intervention: Infrared heating ceiling mounted		
Operative temperature (%)	**Mean radiant temperature (%)**	**PMV (%)**
1,7	6,0	21,0

Table 36: *Overview of infrared heating panels CFD results (Own work, 2025)*

Comparison

When the different interventions are compared to each other, it becomes apparent that they function on different aspects of the dwelling and generate different results. The detailed comparisons of interventions can be seen in appendixes 20 and 21. Similar to the analyses of the previous chapters, the glazing characteristics are an important factor in evaluating the effectiveness of interventions. As was will be elaborated on in chapter 5.3, it is quite important to correctly assess which part of the façade requires interventions, as the weakest link, in this case the single glazing, can still carry negative effects while other improvements are made. When the skin interventions are compared, it can be concluded that glazing replacement works the best, followed by window insulation film, external wall insulation and internal wall insulation.

5.3 Factors influencing the effectiveness of interventions

As has been explained in chapter 3.3, different building characteristics need to be taken into account when deciding how energy poverty should be assessed within a certain case. This leads to the notion that not all strategies and not all interventions work on all cases and that case-specific characteristics influence this effectiveness. This chapter will discuss the characteristics which have influenced the results of the tested interventions, and how this should be taken into account when assessing other cases.

5.3.1 Influence of glazing percentages

One of the aspects which is both crucial for the energy efficiency and renovation of buildings and which differs between dwelling types, is the proportion between open and closed elements of the façade. The original tested case has a relatively high proportion of glazing compared to closed façade elements. This is part of the reason as to why U value improvements have more of an effect on the energy consumption of the dwelling than R value improvements, besides the proportionally larger effects of U value increases in general. This will be elaborated on by decreasing the size of glazing and increasing the sized of the closed parts and performing the simulations again.

When this original glazing area is reduced by 30%, different observations can be noted. First, the base energy consumption of the dwelling reduces from 657,5 m^3 to 616,8 m^3 in normal usage and from 346,6 m^3 to 316,4 m^3 in energy poverty usage. The effect of U value improvements decreases, this can be seen in figure 58. Besides this, it can be seen in figure 58 that the effect of R value improvements increases. When this original glazing area is reduced by 50%, resulting in a total glazing percentage of 9%, similar observations can be noted. First, the base energy consumption of the dwelling reduces from the original 657,5 m^3 to 598,6 m^3 in normal usage and from 346,6 m^3 to 304,3 m^3 in energy poverty usage. The effect of U value improvements decreases even further than the 30% reduction situation, this can be seen in figure 58. A detailed view of this figure can be seen in appendix 18.2.

These notions have significant implications for the effectiveness of interventions such as glazing replacement, external wall insulation, window insulation film and internal wall insulation. The effects will increase for the R value interventions and will decrease for U value interventions. This will significantly improve the financial feasibility of R value interventions, which is currently lacking in the case study of Poptahof Noord. At the same time, the financial feasibility of U value interventions, which outperform the other interventions in the case study of Poptahof Noord, will decrease.

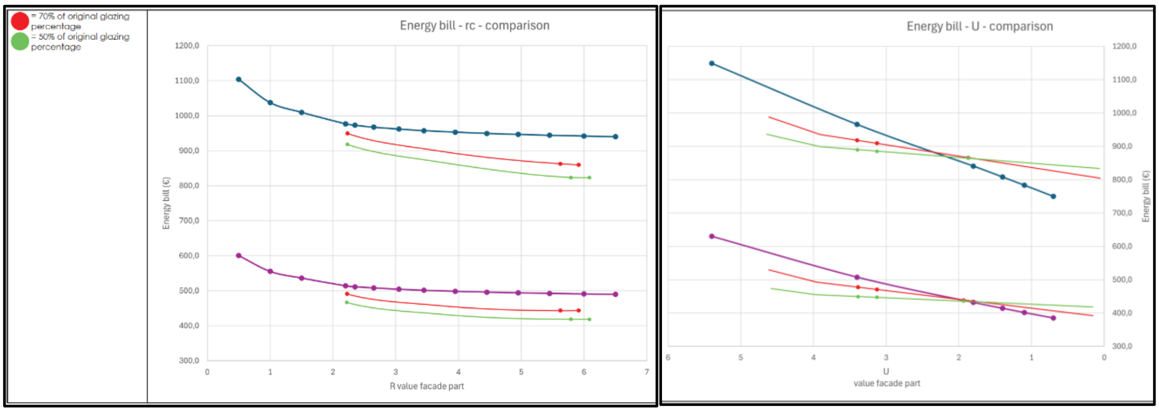


Figure 58: *Effects of changes in glazing percentages on the applicability of R or U value improvements (Own work, 2025)*

5.3.2 Influences of room-specific interventions

Most of the tested interventions assume that interventions are applied on all possible subjects in the dwelling. For example, this means that when glazing replacement is applied, it is applied on all glass panes in the dwelling. But this doesn't have to always be the case, the concept of applying interventions to individual façade parts and rooms was briefly discussed in chapter 5.2.1 but is especially interesting within the context of the lower investment budgets as a result of energy poverty. Within chapter 5.2.1 it was already noted that the effectiveness of frameworks differs between rooms. As has been explored in chapter 2.5.4, households living in energy poverty are often looking for ways to locally heat up spaces which are important for their personal living comfort. For example, households might prefer to keep their bedrooms cold, but improve their living room comfort. This way of thinking requires a change in how energy efficiency interventions are considered. For example, the effectiveness of glazing replacement on all facades reduces, when the household then chooses only to increase the heating inside the living room, as a result of their financial situation.

This way of localized heating lends itself to localized energy efficiency interventions and localized changes in heating systems and behaviour. An example of this can be seen in figure 59, which shows how interventions applied onto more intensely heated rooms, like the living room, have a larger impact on energy expenditures than the same interventions applied on lesser used rooms, like bedrooms. This notion has implications on the effectiveness of interventions. This effectiveness on the fronts of thermal comfort, energy efficiency and finances increases when it is applied to the correct room(s), it decreases when it is applied to the incorrect room(s).

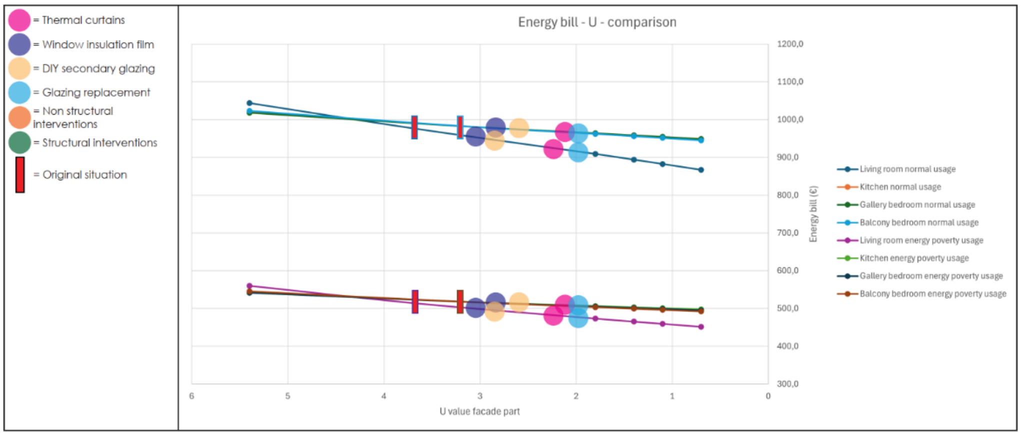


***Figure 59:** Comparison of U value improvements on individual spaces (Own work, 2025)*

Next to energy efficiency improvements, localized heating has also been a concept which has been applied in energy poverty households, this has been explored in chapters and 5.2.7. This has led to the hypothesis that localized heating sources could be of better efficiency in these situations than standard heating methods. This is based on the fact that energy poverty heating habits translate to shorter heating timespans and can be specified to provided localized thermal comfort, as has been discussed in chapters 2.5.4 and 4.3.2. An example of this is the situation where a localized air heater is used next to a couch, instead of the radiator at the end of the room. With this method, localized heating is provided to the person in the couch, instead of generalized heating which would have been provided by the radiator for the entire room. Table 37 shows the effectiveness of the usage of this heating source, showing that the overall heating energy demand worsens in normal usage profiles, but improves in energy poverty usage profiles.

Parameter	Normal usage profile	Energy poverty usage profile
Heating energy consumption without intervention (kwh)	3545,0	1467,0
Heating energy consumption with intervention and same temperature settings (kwh)	3661,2	1436,7
Improvement (%)	-3,3%	2,1%

***Table 37:** Simulation results of portable space heaters (Own work, 2025)*

This can be explained by the usage of the portable space heater in the different usage profiles and the way in which it is simulated. The used simulation program of VABI assumes that the applied heating device is used to heat the entire room, instead of a specific area like the situation previously discussed. This means that in the normal usage, the software assumes that the device is used to heat the entirety of the rooms to 19 degrees for the standard duration of time, which requires more heating energy than if this was done with the regular heating system. Meanwhile, in the energy poverty usage the rooms are heated only to 13,5 degrees, for a short amount of time. Air heating lends itself most to situations where shorter bursts of lower heating are required, than longer burst of higher energy. This is why the heating method can be deemed efficient in energy poverty situations and inefficient in normal situations.

The applied simulation method doesn't allow for the accurate consideration of changes in thermal comfort due to the application of localized air heaters, due to the problems surrounding the calculation of room temperatures. This is why additional CFD simulations were performed in chapter 5.2.7. These simulations show that localized air heaters can also improve the thermal comfort inside living spaces. Similar simulations were performed to test the effectiveness of infrared heating panels. The goal of these panels is to provide direct thermal comfort to specific areas of the dwelling. For example, a reading chair inside a room, or the couch inside a room. The simulations show that while infrared heating panels can have more of an effect on the mean radiant temperature of a certain area within a room than air heating, they don't provide higher increases of operative temperatures and thermal comfort. The difference between the increases of thermal comfort can be explained by looking at the heating both systems provide. Air heating increases the operative and air temperature gradually throughout a room, something which is perceived as comfortable by people. Infrared heating panels solely provide radiant temperature to surfaces. If this radiant surface temperature becomes disproportionate to the air temperature, or if there is too much of a difference between radiant temperatures on someone, their thermal comfort doesn't improve. These points stress the importance of analysing the energy usage situation of a specific energy poverty case, as the energy usage and thermal setpoints have implications on the effectiveness of heating interventions.

5.3.3 Influences of façade segment of intervention

The previous chapter mentioned the importance of choosing the correct space to improve, as the effectiveness of interventions reduces when they are applied to less fitting cases. Next to this, chapters 5.2.1 and 2.4.2 showed how the effectiveness of interventions depends on the base situation they are applied on. With for example interventions which influence the R value having the largest effect on facades with low R values. This chapter will discuss the importance of identifying the weakest link of the dwelling and its facades.

Where improving the rooms which are used most intensely can give disproportionate results, so can improving the elements which require the most improvement. In the simulated case, this can be seen in the application of insulated door panels in the energy poverty households. While this is a specific intervention which is only applied on 3,8m^2 of the façade, it still produces results similar to or better than interventions which are applied on a larger total surface, like window insulation film. Like window insulation film and other interventions, the effectiveness of insulated door panels relies on the energy efficiency of the existing element. The energy efficiency effects of insulated door panels are closely related to the properties of the original doors and the heat flows associated with this element. Within the case, there are 2 exterior doors, one on the balcony which is connected to the balcony bedroom. The other door is situated on the gallery and leads to a hallway connected to the kitchen and the gallery bedroom.

The direct influences of insulated door panels in reducing the required heating can be seen in the analysis of the balcony bedroom. By only insulating this door, half of the total results of the dwelling wide intervention is achieved. The application of the insulated door reduces the amount of cold which enters the dwelling from the outside and it reduces the heat lost from the heating system on the inside. To display the effects, the coldest day of the simulated year is analysed (17th of January). Table 38 shows the results for the average indoor temperature and total heating required for the balcony bedroom under different the implementation of different interventions. The heating energy reduces significantly with the application of the insulated door. At the same time, the application of solely window insulation film, which exists in a similar category of interventions, has a slightly less effect.

	No interventions	Insulated door panels	Window insulation film	Insulated door panels & window insulation film
Total heating (W)	5278	4617	4870	4216

Table 38: *Comparison of different interventions' effects on the balcony bedroom under energy poverty usage (Own work, 2025)*

The comparison of these results has different implications. It addresses the importance and benefits of a substantiated intervention choice, based on the characteristic façade build-up and lay-out of dwellings. Especially for energy poverty households, where investing efficiency is of more importance, it is important that the correct intervention choice is made. This choice is able to be made through the analysis of building characteristics and through the personal factors. For the case of Poptahof Noord, the exterior doors can be seen as the weakest link. As has been discussed in chapter 3.3 and through the study of Van Ooij et al. (2024), occupants can help in identifying this weakest link.

5.3.4 Influences of usage profiles

Chapter 5.3.2 has touched upon the fact that often, the biggest reduction in energy expenditures can be obtained by improving the rooms which are used most intensely. As these spaces consume the most energy, the overall reductions will also be the biggest here. Similar to differences in spaces inside a dwelling, there are differences between the energy consumptions habits of households which either are or aren't affected by energy poverty. As has been discussed in chapter 3.2, the energy consumption habits of households vary whether they are living in a normal or energy poverty situation. Within the most severe cases of energy poverty in Delft, energy consumption reductions of as much as 40% have been noted. As has been discussed in chapter 4.3, this reduction mostly stems from a shorter heating timespan and lower temperature setpoints, alongside lower hot water usage.

Chapter 5.3.2 touched upon the fact that interventions to rooms with high energy consumption numbers have a higher effect on energy costs than interventions to rooms with lower energy consumption numbers. This phenomenon was particularly noticeable when the living room was compared to the bedrooms, this trend is visible for both usage scenarios. The concept of interventions having the most effect on high energy consumption spaces doesn't just apply to rooms within the dwelling. This concept is also noticeable between both usage cases on a dwelling scale. As a result of lower energy consumption values, interventions have less of an effect on the energy bills of energy poverty cases than on normal cases.

While this is a logical result of factors surrounding energy efficiency interventions, it does pose a problem. This observation means that households living in energy poverty energy will gain less from energy efficiency interventions, while they need it the most due to the effects they encounter. These reduced effects lower the gains of energy efficiency interventions, a comparison of this can be seen in appendix 15. This could cause these households to dismiss these interventions altogether, as the financial benefits might not outweigh the costs for them. This results in a situation similar to the poverty trap discussed in chapter 2.5.3, meaning that households in negative situations have more trouble getting out of those situations by themselves. Figure 60 visualises how both usage profiles compare to each other regarding improvements to the U value of facades. While the actual energy bill numbers are far apart, it can be noted that the improvements have more of an effect in the normal situation than the energy poverty situation when looking at the course of the effects of U value changes. At the same time, the majority of interventions provide proportionally larger improvements of energy efficiency for energy poverty usage cases than normal usage cases. The reason for this is that, similar to chapter 5.2.1, the lower starting energy efficiency allows for improvements to be made more rapidly.

The difference of intervention effects between usage profiles stresses the notion made in the research that conventional energy efficiency measures, which focus solely on energy efficiency, can't be directly applied to energy poverty cases. If energy poverty households were to apply these interventions through their own financial means, the gains will not outweigh the costs. Because of this, the thermal comfort effects and financial parameters of interventions should be weighed more heavily. This builds upon the notion of chapter 4.3.3 which addresses the energy poverty review criteria. This leads to interventions such as thermal curtains and insulated door panels being more applicable to energy poverty cases than they would be for normal cases. As while they might now give substantial energy efficiency improvements, they do provide significant financial benefits.

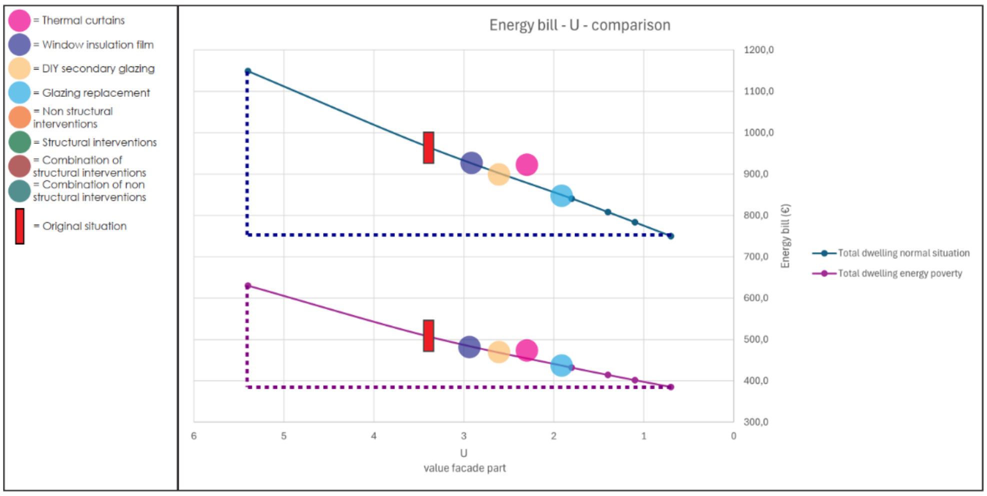


Figure 60: *Comparison of effects of U value changes on different usage profiles (Own work, 2025)*

5.4 Poptahof Noord case assessment

The case study of Poptahof Noord in Delft has provided the opportunity to apply the findings of the literature review and data analysis. The Poptahof Noord case poses itself as an average energy poverty dwelling through its different characteristics, including its typology, location, and different building attributes. This has resulted in individual interventions to be reviewed through this case study. One of the goals of the case study research is to provide more knowledge on the effectiveness of individual interventions. Besides this, the case study also allows for an assessment of viable interventions to be made to the case. This assessment of the energy poverty problems and solutions falls in line with the assessment framework of chapter 3.3 and figure 18.

5.4.1 Review

The characteristics which distinguish Poptahof Noord from other cases are its energy usage, the building characteristics of the case, the target occupant group within the dwelling and other specific notions. A good understanding of the characteristics allows for specific approaches to be suggested for Poptahof Noord, in order to reduce the energy poverty problem it is facing in the most effective manner.

Energy usage

Chapter 4.1 notes the energy usage data which made Poptahof Noord stand out as an energy poverty case. Changes in gas consumption were noted from 627 cubic meters per household during normal periods to 350 cubic meters per household during the energy crisis. This significant drop in energy consumption already raised concerns about the presence of energy poverty, as the large drop points toward a financial buffer being missing in the case. Besides this, the large decrease in gas consumption led to concerns about the average indoor temperature within the case.

Target group

The case is located in the region of Delft with the 2nd lowest average yearly personal income of the total city, with the average income being 25.000€. This exceptionally low income makes it much more difficult to finance expensive large-scale interventions. The largest group of people living in Voorhof are between 25-45 years old, with over half off all inhabitants being older than 25 years. This age is important to take into account, as older inhabitants often time have less technical knowledge of energy efficiency interventions and are more susceptible to the health risk of lower indoor temperatures. Most of the people living in Voorhof are of non-Dutch background, with over 55% having a migrant background. These observations fall in line with the observations made during the research, which point towards a misunderstanding and lacking focus on energy efficiency in dwellings. This enhances the importance of interventions which are of low cost and are easy to install.

Building characteristics

Countless building characteristics can be noted on the case of Poptahof Noord. Many of these characteristics are quite specific, like the technical properties of the constructions modelled in the simulations. While these specific characteristics allow for the precise allocation of interventions, it can't be expected that for every energy poverty assessment, all this information is gathered. The analysis of the previous chapters show that more obvious building characteristics still allow for the effective allocation of interventions. Important building characteristics of Poptahof Noord include the construction year of 1955 and the E energy label, which leads to the concern of low building quality and poor thermal properties of constructions. Other building characteristics which can be noted include the large glazing percentage of the complex. Besides this, it can be noted that the building is most likely equipped with an outdated heating system and that the rooms within the apartments are relatively compact.

Personal factors

During the assessment of energy poverty problems within the case, different specifics might come up from occupants. These specifics can be on different scales and lead to different insights. For the case study of Poptahof Noord, the personal factors for Poptahof Noords' occupants weren't taken into account. Appendices 1, 2 and 3 and the study of Van Ooij et al. (2024) provide indications of what these personal factors can be. These factors often include construction faults, additional information on the financial situation of households and the effects of earlier implemented supports and interventions.

5.4.2 Suggested approaches

The review of the case characteristics results in the following approaches being suggested to reduce the energy poverty problems in the most effective way:

Insulating door panel on bedroom door

The analyses show the importance of tackling the weakest points of the dwelling, in the case of Poptahof Noord one of these points are the exterior doors of the dwelling. The application of insulated door panels presents itself as an intervention which can be installed with relative ease and low cost but can aid much to the energy efficiency and thermal comfort of the room it is covering.

Thermal curtains on free windows

Another intervention which can be installed with ease and low cost but can generate significant savings are thermal curtains. The consideration which needs to be made with these curtains is the relation between (day)lighting quality and energy savings. As its energy savings can be generated by leaving them closed but this reduces living quality through the removal of daylight. That is why in this case thermal curtains should be applied on all windows except for those on the most intensely used living space, the living room. This sounds counterintuitive, but the energy efficiency gains won't outweigh the living quality reduction, especially since the health of energy poverty households is already at a lower level than normal households. The application of thermal curtains on the other windows still improves the thermal quality of the dwelling significantly.

Window insulation film on single glazing

To improve the thermal quality of the dwelling, one of the other weakest points of the dwelling needs to be assessed, being the single glazing panes. The poor U values of these windows have large negative effects on the dwelling's energy consumption. At the same time, the other windows are equipped with Thermopane double glazing. While this double glazing is not up to par with current standards, it does provide a reasonable buffer. The alterations which could be made to these window panes which have noticeable effects are either DIY secondary glazing or glazing replacement. These interventions either require too much installation effort or investment cost to be interesting for this specific case. For these reasons, it can be recommended that either DIY secondary glazing or window insulation film is applied to the single glazing windows, to improve their quality to near the level of the double glazing. Window insulation film will be recommended due to its lower cost and easier installation.

Localized air heating in living room

The individual analysis and CFD simulations show the possible benefits of applying localized air heating in living spaces of energy poverty households. The small bursts of heating energy can quickly heat up the room and provide better thermal comfort. The research shows the importance of not just improving energy efficiency but also taking thermal comfort into account. This is why localized air heating should be applied in the living room, which is used most intensely.

Results

With these described interventions, one of the most pressing drivers of energy poverty will be improved, the quality of the dwelling. This structural improvement of dwelling quality, through changes made to the thermal quality and heating systems of the dwelling will have lasting influences on the energy poverty situation. As changes to the building quality are able to tackle of the main energy poverty effects of construction damages, human health problems and financial stress. The direct results of the interventions can be seen in table 39. It can be seen that significant improvements in energy efficiency and thermal comfort through temperature settings can be made with the implementation of the interventions. These improvements are able to be implemented under relatively limited investment costs and payback periods. Besides these direct effects, indoor mould and other water damages within the dwelling will be reduced through an improvement of thermal quality, which raise the indoor temperature and the ventilation flows within the dwelling.

Human health problems as a result of energy poverty are also structurally reduced through the implemented interventions. The interventions allow for higher temperature setpoints to be set through the dwelling and the usage of localized air heating improves the overall thermal comfort of occupants. These increases of indoor temperature and thermal comfort will lower the risks of cold-related diseases and heart diseases. Lastly, the pressing effects of energy poverty on financial stress are also reduced through the implemented interventions. As the results show, the application of different interventions will reduce the energy expenses of the household. This reduction of energy expenses will reduce financial stress, as households gain more financial freedom. The relatively low investment costs and short payback periods add to these effects. The decrease of financial stress will lead to improvements in decision making processes and will lead households towards exiting the poverty trap.

	Normal usage	Energy poverty usage
Energy efficiency improvement (%)	5,8	7,2
Thermal comfort improvement (C^o)	2,5	2,1
Approximate cost of interventions	300	
Yearly savings with same temperature settings (€)	57,0	37,8
Payback period (years)	5,3	7,9
Investing efficiency (%)	19,0	12,6

Table 39: *Direct results of suggested approaches to Poptahof Noord (Own work, 2025)*

5.4.3 Implementation

Regarding the implementation of these approaches, different things should be kept in mind for the specific case. It should be noted that a substantial language and knowledge barrier is present between inhabitants and those who rent out the dwellings. The research has shown that an uncareful and inconsiderate approach to energy efficiency actions can lead to unsuccessful results.

The first point which needs to be discussed revolves around the responsibility of the implementation of interventions. It has been discussed in earlier parts of the research that it is often difficult for tenants to make alterations to their dwellings, as they must request and get permission for this. When the assessment process leads to structural interventions, this responsibility and permission needs to be discussed. This could lead to the notion that more influential interventions are either given installation permission to occupants or are installed by the building owners themselves. The motivation for building owners to install these interventions themselves can take different forms. It ensures a healthy living environment for tenants, reduces construction damages and increases the dwellings' value.

For the case of Poptahof Noord, most of the suggested approaches are of low investment cost and are able to be installed by occupants themselves. Most of the intervention are of a temporary nature and could also be removed by tenants themselves, this reduces the interest of building owners to install these interventions. The measure which should be more of the building owner's responsibility is the improvement of the balcony bedroom doors, these could either be replaced or financed by the building owner. In the situation where the responsibility of improving the dwelling is redirected to the occupants, the approaches need to be presented in a clear way, with emphasis on the easy installation, financial and thermal effects of the individual and combined interventions. The following elements can be used for this clear presentation: appendices 8, 9, 17 and table 39.

5.5 Applicability of assessment method

The process and results of this research allow for different applications in building design. On the one hand, it provides designers of buildings and energy systems with a better understanding of how occupants view energy usage and thermal comfort, through the lens of varying energy prices. On the other hand, it provides those who design through renovation, retrofitting or who help people struggling with energy poverty with guidelines and suggestions on how to assess these challenges. Different parameters of the performed case study influence the applicability of the simulation results to other dwellings. To allow the application of the results of this research to other cases, these parameters need to be kept in mind. These parameters have been discussed in chapter 5.3, appendix 17 provides an overview of the tested interventions and their optimal application situations. With this in mind, the proposed assessment strategy can be applied and compared between three energy poverty cases, leading to suggested interventions for each of the cases. While detailed analyses are possible, this segment will approach it with less detail, with the intent of showing the applicability of the research and assessment process.

5.5.1 Cases and concerns

The designed assessment framework starts with the selection of a case, through concerns. As has been discussed in chapter 3.3, these concerns could come from occupant outcries or significant reductions of energy consumption in periods of price increases. Within chapter 4.1.1, the case of Poptahof Noord, Goudenregenlaan and Guido Gezellelaan were identified as possible energy poverty cases and simulation subjects due to their energy consumption changes and building characteristics. These cases will be compared in this chapter. Table 40 gives an overview of these cases.

Poptahof Noord	Goudenregenlaan	Guido Gezellelaan
		

Table 40: *Different energy poverty cases for comparison (Own work, 2025)*

5.5.2 Review

After the cases have been identified and verified, the review process can start, following the topics of energy usage, building characteristics and target group.

Energy usage

The first parameter which should be reviewed is that of energy usage, an overview of energy usage statistics can be seen in table 41. It can be seen that the cases have comparable energy consumption decreases and indoor temperature estimation. The case of Guido Gezellelaan is the less extreme case of the three. As mentioned in chapter 3.2.5, the initial indoor temperature estimations require more detailed analysis in order to specify these estimations. The results decisively show that all cases are energy poverty cases.

Review topic	Parameter	Poptahof Noord	Gouden-regenlaan	Guido Gezellelaan
Energy usage	Average gas consumption (m^3)	627	638	1320
	Energy poverty gas consumption (m^3)	350	370	820
	Decrease (%)	44,2	42,0	37,9
	Initial indoor temperature estimation (C^0)	11,2	11,6	12,4

Table 41: *Energy usage review of cases (Own work, 2025)*

Building characteristics

Following this, the different building characteristics need to be considered. This can be analysed to the extent which is preferable by the assessor, from surface level to very detailed. For this example, the building characteristics which have also been identified as some of the main influences on intervention effectiveness will be noted. An overview of this analysis can be seen in table 42.

The overview shows the construction year of the individual dwellings, with the Goudenregenlaan being built most recently. It also shows the building quality of the dwellings through the energy label, with the Guido Gezellelaan having the highest energy label, C. This C energy label could mean that renovations have taken place, or the dwelling was originally built with higher quality. Images of individual façade buildups can be seen in table 43. The overview shows the façade buildup, the buildups of Poptahof Noord and Guido Gezellelaan are quite similar. The Goudenregenlaan is quite different, it has a much larger closed surface built up of stone material, it also has a roof and floor where heat losses can take place. The findings are concluded in the possible building bottlenecks, which are noted in table 42.

Review topic	Parameter	Poptahof Noord	Goudenregenlaan	Guido Gezellelaan
Building charact-eristics	Building construction year	1955	1988	1970
	Building quality	Energy label: E	Energy label: D	Energy label: C
	Façade buildup	Apartment complex, gallery on one side, glazing and balcony on other side	'Classic' Dutch housing, smaller windows, large stone closed facade	Apartment complex, balconies on one side, horizontal glazing strips on other side
	Possible building bottlenecks	Glazing surface, balcony doors	Closed surface, roof & floor surface,	Glazing surface, large living room, many individual compact rooms

Table 42: *Building characteristics review of cases (Own work, 2025)*

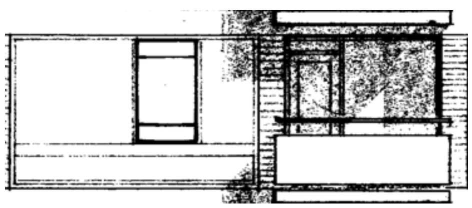
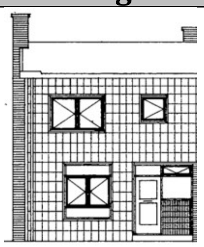
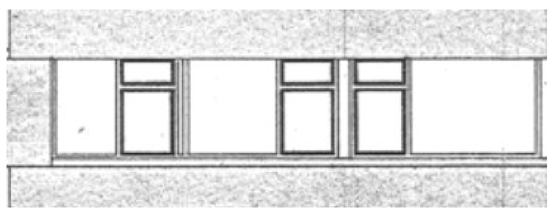
Poptahof Noord	Goudenregenlaan	Guido Gezellelaan
		

Table 43: *Façade build-ups of cases (Own work, 2025)*

Target group
After the building characteristics have been noted, the target groups of the cases can be analysed. This will result in an overview and understanding of the people who inhabit the dwellings. An overview of the target group analysis can be seen in table 44. Different things can be noted, the first being on the occupant ages. The largest group within Poptahof Noord has an age between 25 and 45, though there are similarly sized groups of elderly and youth. The Goudenregelaan has a larger group of over-45-year-olds and elderly. Lastly, the Guido Gezellelaan consists for the largest part of people between the age of 25 and 45. The majority of inhabitants of the Goudenregenlaan are of Dutch descent, the majority if inhabitants in the other regions are of migrant background. Lastly, both Poptahof Noord and Guido Gezellelaan are located within the area with the lowest average personal income of 25.000€ the Goudenregenlaan has a higher average income of 28.600€ (*Alle Wijken En Buurten in De Gemeente Delft*, 2025).

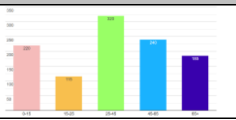
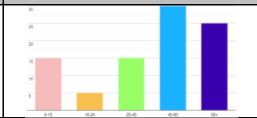
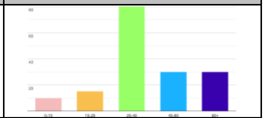
Review topic	Parameter	Poptahof Noord	Gouden-regenlaan	Guido Gezellelaan
Target group	Occupant age build-up (0-15, 15-25, 25-45, 45-65, 65+)			
	Occupant background	Majority non-Dutch	Majority Dutch	Majority non-Dutch
	Average household income	25.000€	28.600€	25.000€

Table 44: *Target group review of cases (Own work, 2025)*

5.5.3 Review conclusions
These individual reviews will lead to different review conclusions on the subjects, an overview of these conclusions can be seen in table 45. These conclusions will be used as guidelines for choosing the appropriate approaches.

Review conclusion subject	Poptahof Noord	Goudenregenlaan	Guido Gezellelaan
Energy usage	- Severe reduction in energy usage - Low base energy usage - Worrying indoor temperatures	- Severe reduction in energy usage - Low base energy usage - Worrying indoor temperatures	- Less severe reduction in energy usage - Higher base energy usage - Less worrying indoor temperatures
Building characteristics	- Low thermal building quality through energy label and construction date - Large glazing surface	- Medium thermal quality - Large closed façade surface - Additional heat loss surfaces of floor & roof	- Good thermal quality of building - Large glazing surface - Individual compact rooms
Target group	- Low personal income - Non-Dutch speaking - Different ages, bit older	- Low/medium personal income - Dutch speaking - Mostly older population	- Low personal income - Non-Dutch speaking - Predominantly 25–45-year-olds

Table 45: *Review conclusions of cases (Own work, 2025)*

5.5.4 Suggested approaches
As mentioned, the review conclusions lead to different suggested approaches, the suggested approaches for Poptahof Noord have been explained in chapter 5.4.2. These suggested approaches for the Goudenregenlaan and the Guido Gezellelaan will be briefly explained in this segment. An overview of the suggested approaches can be seen in table 46.

The Goudenregenlaan poses a situation which differs itself from Poptahof Noord and Guido Gezellelaan in different ways. It does this through its larger closed facades surface, bigger budget, and old

& Dutch population. The larger budget makes interventions to its possible bottleneck, the closed areas of the thermal skin, more attractive. Besides this, the Dutch speaking skill, larger income and older age make it more beneficial to access the services of professionals, instead of opting for a DIY solution. The Guido Gezellelaan poses a situation similar to Poptahof Noord, but with some differences. The presence of energy poverty seems to be less significant, the thermal quality of the dwelling is better, and it consists of more individual rooms. The presence of many individual rooms with large glazing surfaces makes thermal curtains, alongside localized air heating interesting interventions for this case. Besides this, the improvement of the thermal quality of the largest space in this dwelling, the living rooms, could also be beneficial. As the cost of the other interventions isn't out of the ordinary, and the age group speaks to an ability to personally install interventions, DIY secondary glazing could be a beneficial intervention for this space.

Poptahof Noord	Goudenregenlaan	Guido Gezellelaan
- Insulated door panel on balcony bedroom - Thermal curtains on free windows - Window insulation film on single glazing windows - Localized air heating in living room	- Additional insulation measures on either floor, roof, or facades	- Thermal curtains on bedroom windows - Localized air heating in compact bedrooms - DIY secondary glazing on living room window

Table 46: *Suggested approaches of cases (Own work, 2025)*

5.5.5 Implementation

Lastly, the implementation of the approach will be discussed. For the Goudenregenlaan, the implications of larger interventions should be made clear, in its costs and benefits. Due to the higher household income in this case, it might be possible to combine funding with the housing association and the occupants, and that the usage of professional parties can be combined with other dwellings. The implementation notions for the Guido Gezellelaan are similar to Poptahof Noord, as both cases are quite similar. An overview of implementation notes can be seen in table 47.

Poptahof Noord	Goudenregenlaan	Guido Gezellelaan
- Focus on individual interventions by occupants - Overview and information of suggested approaches	- Focus on larger interventions which might require professional help - Motive should come from building owner - Division of finance	- Focus on individual interventions by occupants - Overview and information of suggested approaches

Table 47: *Implementation notes of cases (Own work, 2025)*

6 Discussion

Within chapter 5.3, different aspects have been discussed which influence the effectiveness of individual interventions to different cases. This chapter will discuss different margins of the performed research as a whole which influence the applicability of the research.

6.1 Margins of data analysis

While the executed data analysis provides interesting insights into different relations and consequences between energy prices and energy usage, some sidenotes about the accuracy and further research should be made.

6.1.1 Energy usage of households

One example of this is the energy usage of households. This is an average value which has been derived from the registers of energy supply companies. While this average is correctly calculated and implemented into the dataset, several uncertainties surround this data. There could be uninhabited dwellings inside the postal codes for example, or dwellings which have changed in household size. Another example factor influencing energy usage could be home renovation. Besides these aspects, energy usage between households will vary much, due to dwelling typology, household size and personal preference. This should be kept in mind, to prevent overgeneralizations.

6.1.2 Timeframe of datapoints

Another point which could be improved is the timeframe of different datapoints. Many of the used datasets are only assessed yearly, like the energy use and the flexible energy contract pricing. To further improve the data analyses, get an insight into the effects of for example the price caps and improve the research' applicability more instances of this data would be needed.

6.1.3 Energy usage and indoor temperature

Lastly, the step between energy usage and indoor temperature that has been made in this research could be specified more. In this research, this step is made using a formula which relates the change in energy consumption to standardized indoor temperatures, as discussed in chapter 3.2.5. While this approach works for making initial estimations, more detailed estimations could be formed. These detailed estimations should take different influential factors like personal setpoints and heating system efficiency into account. Preferably, temperature meters would be placed and logged in these dwellings. This would allow for a more specific overview of new indoor temperatures and would allow for relations to be identified in more detail.

6.2 Margins of simulations

6.2.1 Resident usage

Within the energy simulations, usage profiles are used for different parameters and different rooms, these profiles include parameters like heating, ventilation, clothing and appliance use. While these usage profiles are based on research and existing standards, there are possible differences between households and their preferences. Perhaps there are households who do not use appliances as frequently as average, or perhaps there are households who prefer to increase their ventilation more than regular households. This same principle applies to the approach to thermal comfort. Within the simulations, temperature increases and PMV calculations are used to estimate the sufficiency of thermal comfort in different situations. Similar to energy usage, thermal comfort strongly differs between individuals. While PMV still provides a good estimation, individuals can also differ from this scale and be comfortable in colder or warmer environments than mentioned by these standards. These preferences play a part in the applied temperature setpoints. Within the simulations, rooms are set to a specific temperature setpoint, in the case of energy poverty this has been estimated at 13,5 ^{0}C and for normal usage this has estimated set at 19 ^{0}C. While this provides an indication for the indoor temperature situation of households and the effectiveness of interventions, these temperature setpoints can be more adaptive in reality and will differ between households.

6.2.2 Infiltration and ventilation
Ventilation is an important parameter within energy and thermal comfort simulations. Ventilation is simulated through infiltration, natural ventilation and mechanical ventilation. The parameter of mechanical ventilation is one which can be modelled in a straightforward fashion, with set flow rates. However, the parameters of infiltration and natural ventilation are more difficult to determine. Infiltration is a value which is specific to different buildings and depends on various aspects of the building, such as building age, possible damage, cracks, and air tightness. Within the simulated case study, estimations were made on the infiltration parameter and the usage of natural ventilation. These estimations were made as accurately as possible but could be measured more precisely. While the base ventilation values contain assumptions, the effects of ventilation interventions are still relevant, as these reflect a proportional improvement of ventilation values.

6.2.3 Investment costs
Another margin that has to be kept in mind is that of the investment prices for the different interventions. For the analysed interventions, this investment price has been calculated as an average of different products available on the marketplace. This has led to accurate assumptions on purchasable products such as window insulation film, draft stoppers and portable space heaters. At the same time, larger scale interventions are often priced specifically for a given project. Prices for interventions such as external wall insulation, glazing replacement and house air sealing are dependent on the size of a project, different characteristics of the project and the specific contractor. This has made it more difficult to make accurate estimations on the investment prices of these interventions. The estimations have been made by comparing different suppliers and through other available information. For specific projects, contractors should be approached in order to get accurate pricing. The specific pricing of larger scale interventions can have effects on the financial effectiveness of interventions.

6.2.4 Year-specifc parameters
Besides the previously mentioned points, there are different parameters which influence the results which are specific to the simulation, in regard to the simulated year. These parameters include the weather conditions of the simulated year and the applied gas prices. A more detailed review on the implications of these year-specific parameters can be found in appendices 18.3 through 18.7.

6.2.5 Hidden assumptions
The final simulation sidenote which should be discussed is the uncertainty that building simulations present. Within the calculations made by simulation software, different assumptions are being made. These assumptions can be the cause the possible inaccuracy of building energy simulations. While this is true, the design of the simulation software, alongside the allowance of its usage by standardization organizations, show that results are within relevant margins.

6.3 Research method
During the set-up of the research methodology of this graduation research, it became clear that this would be a challenging task. The research questions revolving around energy usage, energy poverty and thermal comfort posed themselves as topics which all required different research methods and it would be difficult to combine these topics. To solve this problem, the methodology was set-up in such a way that different research methods would be applied to the different topics, and these topics would be combined in textual pieces and simulations. This approach meant that in the first half of the research, the methods of literature review, data analysis, interviews were applied. These research methods were textually combined in chapter 3 with the use of research by design of an energy poverty assessment approach. The conclusions of this chapter were applied in the latter half of the research, by applying the research by design segment of the assessment approach on case studies. The second half of the research focused more on research through simulations and testing. This simulation research functioned both as a testing ground for the research by design conclusions and a method to test individual interventions. The research methods have proven themselves to have been sufficient in answering the main research

question posed in this research, alongside the different sub questions. At the same time, improvements could have been made to the research methods.

Firstly, the simulation research and case study could have been expanded on with more case studies, in order to further verify the findings on the effectiveness of interventions and the assessment approach. While chapters 5.3, 5.4 and 5.5 do shed light on the factors which influence the effectiveness of interventions, additional case studies could have been used to verify this. Secondly, the findings of the case study could have been translated to a real-life simulation. As has been discussed in chapter 6.2, a simulation case study does impose some limitations to the applicability of results. Some of these limitations stem from the computing nature of the case, which can differ from reality. In order to further verify the findings of the case study, interventions could have been tested in real-life test simulations, or in a physical case study, perhaps of Poptahof Noord. A real-life case study could take form through a specific case study where the effects of interventions are logged, or a case study on the building level, where interventions are applied throughout the complex and the effects are logged.

While these points of critique mostly focus on how different additions could have been beneficial to the research as a whole, there is also an argument to make on how reductions could have been beneficial to the research. As discussed in this chapter, numerous research methods were used to answer the research questions. This variety of methods was necessary to answer this elaborate question. While this is true, a less elaborate research question which would require less research methods could have resulted in a more focused research with more detailed results. For example, if the research question focused solely on understanding the effects of energy price increases on energy usage and thermal comfort, more focus could have been placed on this relation, instead of also having to include the aspect of intervention effectiveness. This could have led to the reduction of research more detailed conclusions.

6.4 Further research

Further research on the topic can add to the findings in different ways. The data analysis of chapter 3.4 could be expanded on with the use of more specific data and more elaborate data analysis methods. This will help in making the relation between price increases and energy consumption clearer and more predictable.

While this research gives a broad overview of the effectiveness of existing interventions, further research could expand on the library of interventions. Interventions which were considered but weren't tested in this research, such as electric blankets or smart heating systems, could be tested using other research methods. Besides this, the library could be expanded with other interventions, such as changes to HVAC- or DHW systems.

Lastly, further research could dive deeper into policy effects and policy creation. This research discusses energy poverty policies on different levels and expands on the policies of the municipality of Delft specifically. Further research could perhaps expand on the policies of other municipalities. Besides this, further research could explore the effects of policies in more detail than was done in this research.

7 Conclusion
7.1 The price elasticity of comfort
Following the set-up of the theoretical framework, the first part of the research focused on investigating the relationships between energy prices, energy consumption and thermal comfort. The analysis showed a clear coherence between rising energy prices and a decrease in energy consumption, this coherence can be seen through a reduction in energy usage of 12%, while gas prices increased significantly from 0,4€ to 1,8€. This points toward an affordability limit within the price range of 0,4€ to 1,8€. This sheds light on the sub question: *"How much are households willing/able to pay for thermal comfort in response to rising energy costs?"*

This reduction in energy consumption translated itself to reduction in, mostly, heating energy on a household level. The increase of gas prices led households reducing their handled indoor temperature with an average between 1 and 4°C. This has led to very pressing situations, where low indoor temperatures around 14 to 13 degrees are handled indoors. These pressing situations were discussed with field-practitioners. These indoor environments are able to be coupled to the identified negative effects of energy poverty, including health effects and indoor mould. There are different factors which influence the severity of this reduction in indoor temperature. This includes factors such as the construction year of the dwelling, number of occupants, home size, dwelling typology, household income, personal preferences and energy efficiency. These reductions in indoor temperatures lead to worries about the thermal comfort of these households. The research shows that households are dissatisfied with their indoor environment, their choice to reduce the handled indoor temperatures and heating energy are mainly of financial nature. If the price situations were different, households would increase their indoor temperatures. This understanding elaborates on the sub question: *"How much comfort are households willing/forced to sacrifice in response to rising energy costs?".*

Existing methods and strategies which aim at combatting energy poverty have shown to be inefficient, as too much focus is put on the financial aspects of energy poverty, and too little on the building related aspects. Financial support is given, which doesn't structurally solve the issue. By addressing the energy efficiency of dwellings, structural improvements can be made with the aim of reducing the energy expenditures of households. Besides this, little research is being done on the effectiveness of different existing strategies and interventions, which reduces the capability to address the issue effectively. These points work towards answering the sub question: *"How effective are current strategies in dealing with energy price increases and energy poverty?".* This misdirection of focus and lack of research is largely due to the fact that an official definition is missing and policy makers are free to choose their definition. This reduces the capability of strategies to be compared and measured. In order to form effective strategies, a definition is needed which takes the essential aspects and drivers of energy poverty into account, those being dwelling quality, household finances and energy prices. With the research in mind, the following definition is proposed: 'A person is considered energy poor *"if he/she encounters particular difficulties in his/her accommodation in terms of energy supply related to the satisfaction of thermal comfort and health needs, this being due to the inadequacy of financial resources and housing conditions, alongside a significant rise of energy costs".*

These points on the price elasticity of comfort point towards the need for an improved method for assessing energy poverty, an outline for which has been created in the research. This strategy introduces a more integrated approach on energy poverty on a building scale and works on different levels. The strategy starts with identifying the causes of energy poverty in a case by reviewing the case on the aspects of the energy usage, building characteristics, target group(s) and relevant personal factors. This review will lead to suggested approaches which implement different interventions to the case at hand. Lastly, the implementation of approaches and interventions is to be considered. This newly formed assessment method aims towards answering the sub question: *"How should strategies with the intent of dealing with energy price increases and energy poverty function?".*

7.2 The effectiveness of interventions in reducing energy poverty

The latter half of the research focused on the review of individual interventions on their effectiveness in combatting energy poverty through a review framework based on the first half of the research. This review framework identifies the main criteria for interventions which influence their effectiveness. These criteria include the provided energy efficiency improvements, thermal comfort improvements and financial aspects of interventions. This review framework has been tested and applied to different groups of individual interventions. The testing and application has been done through the energy simulation of an energy poverty case in Delft, Poptahof Noord. The simulation results show the large influences case characteristics can have on the applicability of interventions. Influential characteristics include glazing percentages, dwelling lay-outs, façade build-ups and existing technical properties. The set-up and application of this review framework answers the sub question: *"How can interventions be assessed on their effectiveness in reducing energy poverty?".*

The results of the tested interventions show that all scales of interventions can have significant effects on energy poverty, with advanced interventions having higher effects on energy efficiency, and basic interventions offering shorter payback periods and increased investing efficiency. Besides this, interventions which can be placed by occupants themselves show to have high investing efficiency, compared to interventions which require professional placement. This adds to the resilience of energy poverty households, through installing their own improvements and making changes to their own households. At the same time, the analysis shows that there is no clear correlation between investment price and energy efficiency improvements, emphasizing the importance of a case-specific review.

Another important notion to make is the reduced effects of interventions on the energy bills of energy poverty cases, in comparison to regular usage cases. This shows the trouble energy poverty households have in improving their situation, even trough the correct choice of energy efficiency interventions. The results of the analysis alongside the sidenotes on which factors influence the effectiveness of interventions answers the sub question of : *"How effective are existing interventions at reducing energy poverty?".*

When the energy poverty assessment process is caried out for the case study of Poptahof Noord, it can be concluded that interventions such as insulating door panels, thermal curtains, window insulation film and localized air heating form an optimal package of interventions. This package of interventions speaks to the characteristics of Poptahof Noord in its energy usage, building characteristics and target group. The assessment process adapts to the case at hand, as when the process is carried out for the cases of the Guido Gezellelaan and the Goudenregenlaan, which both have different characteristics, different intervention packages are suggested.

7.3 Conclusion

In conclusion, the individual segments of the research, alongside their combination, work towards answering the research question of *"How can the effect of energy price increases on energy usage and the experience of thermal comfort be used to assess the effectiveness of interventions in reducing energy poverty?"*. This has been done firstly by forming a better understanding of the effect energy price increases have on energy usage and thermal comfort. Following this, the characteristics of interventions which need to be reviewed have been identified and the case characteristics which influence the effectiveness of individual interventions have been identified. The different aspects of the research have been combined in an assessment approach, which has been tested on the energy poverty cases of Poptahof Noord, Guido Gezellelaan and Goudenregenlaan in Delft.

The results of the research provide a better understanding of the many different aspects of energy poverty. Next to this, the research shows that structural solutions to the problem of energy poverty are necessary and can be achieved through energy efficiency interventions, shifting the focus from financial support to improving the dwellings of energy poverty households. These structural improvements can be made using different energy efficiency interventions, the effects of which are both generalized and dependent on case characteristics. Importantly, this research addresses the urgency of addressing energy poverty in the correct way, not solely as a financial issue, but as a health, housing and societal issue. By moving beyond financial relief and focusing on building improvements, policymakers, practitioners and households themselves can improve the ability of households to regain control over their energy expenditures and thermal comfort. The research shows that much of this ability can come from interventions they can install themselves, including small scale interventions like window insulation film and DIY secondary glazing, aiding to the resilience of energy poverty households.

8 Reflection

8.1 Research approach

As has been discussed in chapter 6.1, the research approach consisted of segmenting the research into different topics, which individually required different research methods. This has led to the research touching upon a broad range of topics, from personal experiences with energy poverty to large-scale energy consumption data. This broad approach has different upsides, it improves the applicability and relevance of the study as it touches upon different societal aspects like. At the same time, the broad research approach can lead to risks in oversimplification and possible dilution of some conclusions.

On a personal level, the research approach has been a large positive aspect of the research. The approach allowed for different research skills to be developed and applied, which kept the research process fresh and intriguing. The data analysis of chapter 3.2 required new coding and analytic skills to be developed and used. The simulation analysis of chapters 4 and 5.2.7 allowed for the thorough usage of simulation programs and allowed me to better understand how these programs work. A possible shift of the research approach to be more focused would have increased the improvement of one of these skills and would have reduced the improvement of another skill, which can be deemed either positive or negative. In my case, I am glad I got to learn multiple new skills.

Besides this, the difference between research scales, from national energy consumption to personal energy poverty challenged me to grasp the problem of energy poverty from different points of view. It required me not to get fully lost in policy creation, but to also consider the personal experiences and requirements of people living in energy poverty. This also worked the other way around and forced me to not get stuck in personal experiences and an individual approach to energy poverty, but to try and find common ground and conclusions on a larger scale. The shift of focus to the regional scale of Delft and case study of Poptahof Noord has aided in my understanding on how to combine different research scales. It has also added a personal note to the research, due to my own connection with Delft., which is something the research could have capitalized more on.

Lastly, the application of the research into a case study has helped me develop skills on applying technical knowledge to application scenarios. It required me to model what is known about energy poverty into simulation software, as close to representing an actual household as possible. This application to a case study has aided the design of the assessment framework and helped making conclusions on individual interventions possible. This case study, alongside the discussed research methods made it possible to address the different aspects of the research question. This skill of the application of research to case studies is something which will be useful in my later work.

8.2 Research process

Similar to the discussion on the research approach, the research process has mostly been a positive experience. The process allowed for different skills to be tested and stayed captivating along the way. The frequent mentor meetings which were spread out between periods of 2 to 4 weeks made sure the approaches were always actively being questioned and that the broader picture was not lost. This was also experienced while performing the simulations and writing parts of the research at moBius consult, where colleagues were often asking questions and challenging me to rethink my choices.

Besides these positive aspects, one downside of the chosen approach and process was the continual changing of the research goals. While constructing the research approach, it was kept in mind that changes could be made to this approach during the research, depending on the outcomes of other aspects of the research. This meant that while the first half of the research was able to be carefully planned, the second half wasn't. As a result of this, the approach changed along the way and the goals of the research were often altered. For example, the DesignBuilder CFD simulations of chapter 5.2.7 was seen as an option since the start of the research but was only set at an actual goal once the VABI simulations were concluded in a shorter time period than expected. While this did allow for the research to keep developing, it sometimes felt less organized than I would have preferred.

8.3 Sustainability and societal implications

The research topics of energy poverty and the influences of price increases on energy consumption have shown during the research to be of societal importance. The research speaks to energy poverty in the Netherlands by discussing its presence and elaborating on the issue. The research also stresses the dangers of rising energy prices, on which concerns are already being raised. The research gives an indication of the effects these price increases can have, which can bring policy makers toward making better actions. Besides this, the research presents methods to assess the issue and interventions which can be applied to different situations. The societal importance of energy poverty has been a large factor during the research. On the one hand, it has made the research more complicated and elaborate, as it requires for more variables to be taken into account than more technical topics. This has for example led to more human experiences and policy implications to be researched through during the research. On the other hand, the topic has allowed for research to be done and conclusions to be made which don't solely focus on the built environment but also focusses on human and policy problems. This positioning has separated the research topic from other topics, while still allowing for different traditional building-technology research methods to be used.

A moral and societal topic like energy poverty has introduced different dilemmas across the research process. One example includes the positioning of researchers and policy makers in assessing energy poverty. A common mistake of policy makers, which has been discussed in the research, is that they are often positioned in a manner that they end up telling those with issues what to do in a commanding manner. This commanding appearance, which can be both intentional and unintentional, ends up driving people away. This had to be taken into account during the research, in the way that the research and its content did not take the position of presenting the 'perfect' solution or telling households what to do. Another example included difficulties in understanding the point of view of energy poverty victims. As has been explained, energy poverty is an issue which has the most effects on the least privileged members of society, in terms of income and education. At some times, it was difficult to position the research from the point of view of these energy poverty victims.

Lastly, both the assessment of energy efficiency interventions and the improved understanding of personal energy usage can aid in the sustainable (re)design of the built environment. A better understanding of the simulated interventions allows for more optimal interventions to be applied to the renovation of existing dwellings. The assessment framework allows for energy poverty cases to be assessed more effectively, aiding to the quality of the built environment and energy efficiency. Besides this, the improved understanding of personal energy use and thermal comfort can aid in designing smart and energy efficient systems. This understanding shows the flexibility and resilience of people when it comes to energy usage and thermal comfort. In conclusion, the research addresses different aspects of sustainability, with a large focus on the human side of sustainability through personal energy usage.

8.4 Final reflection

To sum up, I feel that I have learned much during my graduation research, both on the topic at hand and on how to perform and apply effective research. The large-scale data analysis and research has made me understand how energy prices can have large effects on different groups of people. The small-scale simulations of interventions on a case study have increased my understanding of domestic energy usage, energy efficiency interventions and on how to apply research to case studies. While I would have approached some aspects differently, I look back with content and pride on this graduation research, and I look forward to applying what I have learnt into making the built environment a better place.

9 References

Alle wijken en buurten in de gemeente Delft. (2025, May 15). AlleCijfers.nl. https://allecijfers.nl/gemeente-overzicht/delft/

Alle Tochtstrips online | bol. (n.d.). Bol. https://www.bol.com/nl/nl/l/tochtwering/28752/

Amazon.com: Non-Slip Pad for Rugheat Under Rug Heated Mat, Medium, 3 x 5 feet (fits Under a 3' x 5' Rug) Skid-Proof Pad for Heated Floor Mat Under Desk, Thermal Insulation Improves RugHeat Performance : Home & Kitchen. (n.d.). https://www.amazon.com/Non-Slip-Thermal-Insulation-RugHeat-under/dp/B08LSP1F1N?th=1

Amazon.com : space heater. (n.d.). https://www.amazon.com/space-heater/s?k=space+heater

Amazon.nl: Window insulation Kits: DIY & tools. (n.d.). https://www.amazon.nl/-/en/b?ie=UTF8&node=16419394031

Amirkhani, S., Bahadori-Jahromi, A., Mylona, A., Godfrey, P., & Cook, D. (2019). Impact of Low-E Window Films on Energy Consumption and CO2 Emissions of an Existing UK Hotel Building. *Sustainability, 11*(16), 4265. https://doi.org/10.3390/su11164265

Analitis, A., Katsouyanni, K., Biggeri, A., Baccini, M., Forsberg, B., Bisanti, L., Kirchmayer, U., Ballester, F., Cadum, E., Goodman, P. G., Hojs, A., Sunyer, J., Tiittanen, P., & Michelozzi, P. (2008). Effects of cold weather on mortality: Results from 15 European cities within the PHEWE project. *American Journal of Epidemiology*, *168*(12), 1397–1408. https://doi.org/10.1093/aje/kwn266

Anand, J., Liu, X., Anees, F., Li, Y., Eckman, B., & Malhotra, M. (2024). Assessing the impacts of air-sealing on the sizing, operation, and economic feasibility of ground-source heat pumps for electrifying single-family houses in the US. *Journal of Building Engineering*, *98*, 111149. https://doi.org/10.1016/j.jobe.2024.111149

Anderson, W., White, V., & Finney, A. (2010). *"You just have to get by" Coping with low incomes and cold homes*. University of Bristol. https://research-information.bris.ac.uk/en/publications/you-just-have-to-get-by-coping-with-low-incomes-and-cold-homes

Annila, P. J., Lahdensivu, J., Suonketo, J., Pentti, M., & Vinha, J. (2017). Need to repair moisture- and mould damage in different structures in finnish public buildings. *Journal of Building Engineering, 16*, 72–78. https://doi.org/10.1016/j.jobe.2017.12.010

Asadi, E., Da Silva, M. G., Antunes, C. H., & Dias, L. (2011). Multi-objective optimization for building retrofit strategies: A model and an application. *Energy and Buildings*, *44*, 81–87. https://doi.org/10.1016/j.enbuild.2011.10.016

ASHRAE Terminology - Terminology.Presentation. (n.d.). https://terminology.ashrae.org/?entry=thermal%20comfort

Baldinelli, G., & Asdrubali, F. (2008). Reflecting panels for radiators in residential buildings: Theoretical analysis of energy performance. *Thermal Issues in Emerging Technologies*, 449–454. https://doi.org/10.1109/theta.2008.5167195

Barrella, R., Romero, J. C., Laguillo, A., & Sevilla, E. (2023). Assessing the Impact of Shallow Renovation on Energy Poverty: A Primary Data Study. *Energies, 16*(21), 7237. https://doi.org/10.3390/en16217237

Belaïd, F., Ranjbar, Z., & Massié, C. (2021). Exploring the cost-effectiveness of energy efficiency implementation measures in the residential sector. *Energy Policy*, *150*, 112122. https://doi.org/10.1016/j.enpol.2020.112122

Bespaar mee! | 015 Duurzaam. (n.d.). 015 Duurzaam. https://www.015duurzaam.info/015-energiegesprekken

Bhattacharya, J., DeLeire, T., Haider, S., & Currie, J. (2003). Heat or eat? Cold-Weather shocks and nutrition in poor American families. *American Journal of Public Health*, *93*(7), 1149–1154. https://doi.org/10.2105/ajph.93.7.1149

Bij deze temperatuur zetten Nederlanders massaal de verwarming aan. (n.d.). HIER. https://www.hier.nu/stroom-en-gas/bij-deze-temperatuur-zetten-nederlanders-massaal-verwarming-aan#:~:text=Nederland%20stookt%20gemiddeld%20op%2019,gemiddeld%20op%2015%2C4%20graden.

Bluyssen, P. (2009). The Indoor Environment Handbook. In *Routledge eBooks*. https://doi.org/10.4324/9781849774611

Bluyssen, P. M. (2013). *The Healthy Indoor Environment: How to assess occupants' wellbeing in buildings*. http://ci.nii.ac.jp/ncid/BB1698638X

Bluyssen, P. M. (2023, November 3). *Health challenges and needs for the indoor environment* [Slide show; Powerpoint Presentation]. Msc. Building Technology Climate Design Lecture.

Bouzarovski, S., Thomson, H., & Cornelis, M. (2021). Confronting energy Poverty in Europe: A research and Policy agenda. *Energies*, *14*(4), 858. https://doi.org/10.3390/en14040858

Bol Infrarood kachels. (n.d.). Bol. https://www.bol.com/nl/nl/l/infraroodkachels/34363/54898/?rating=all

Boyacı, S., Atilgan, A., Kocięcka, J., Liberacki, D., Rolbiecki, R., & Jagosz, B. (2023). Determination of the Effect of a Thermal Curtain Used in a Greenhouse on the Indoor Climate and Energy Savings. *Energies, 16*(23), 7744. https://doi.org/10.3390/en16237744

Br*ains4neighbourhoods isolatie doe het zelf voorzetraam*. (n.d.). tno.nl/nl. https://www.tno.nl/nl/newsroom/insights/2022/06/brains4neighbourhoods-isolatie-doe/

Brambley, Kennedy, E., Romelczyk, S., & Penner, S. (1984). Field study of the effect of low-cost weatherstripping devices on energy use in single-family (San Diego) residences. *Energy*, *9*(6), 465–475. https://doi.org/10.1016/0360-5442(84)90026-4

Brambley, & Moline, B. (1986). Energy and monetary benefits of portable heaters. *Energy*, *11*(8), 797–804. https://doi.org/10.1016/0360-5442(86)90018-6

CBS. (2024, October 9). Energy poverty reduced by compensation and energy savings. *CBS Statistics*. https://www.cbs.nl/en-gb/news/2024/27/energy-poverty-reduced-by-compensation-and-energy-savings#:~:text=In%202022%20and%202023%2C%20low,percent%20of%20households%20in%202023.

CBS. (2023, December 19). *Werkenden met risico op armoede - Armoede en sociale uitsluiting 2023*. Werkenden Met Risico Op Armoede - Armoede En Sociale Uitsluiting 2023 | CBS.

https://longreads.cbs.nl/armoede-en-sociale-uitsluiting-2023/werkenden-met-risico-op-armoede/

CBS Statline. (n.d.). https://opendata.cbs.nl/#/CBS/nl/dataset/85592NED/table

Ceramic *Infrared Panel with Thermostat - Infralia .com*. (2025, February 7). Infralia. https://www.infralia.com/en/p/ceramic-infrared-panel-with-thermostat/

Centraal Bureau voor de Statistiek. (n.d.-a). *Kerncijfers per postcode*. Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/gegevens-per-postcode

Centraal Bureau voor de Statistiek. (n.d.-b). *SDG 11.1 wonen*. Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/visualisaties/monitor-brede-welvaart-en-de-sustainable-development-goals/sdg-s/sdg-11-1-wonen

Centraal Bureau voor de Statistiek. (2022, September 15). *Variabele en vaste energiecontracten jan 2021-aug 2022*. Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/maatwerk/2022/37/variabele-en-vaste-energiecontracten-jan-2021-aug-2022

Centraal Bureau voor de Statistiek. (2023a, January 27). *3. Welke huishoudens zijn energiearm?* Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/longread/aanvullende-statistische-diensten/2023/monitor-energiearmoede-in-nederland-2019-en-2020/3-welke-huishoudens-zijn-energiearm-

Centraal Bureau voor de Statistiek. (2023b, November 15). *Energielevering aan woningen en bedrijven naar postcode*. Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/maatwerk/2023/46/energielevering-aan-woningen-en-bedrijven-naar-postcode

Centraal Bureau voor de Statistiek. (2024a, July 2). *Monitor Energiearmoede 2022*. Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/maatwerk/2024/27/monitor-energiearmoede-2022

Centraal Bureau voor de Statistiek. (2024b, August 7). *1. Inleiding*. Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/longread/aanvullende-statistische-diensten/2024/methodedocument-monitor-energiearmoede-2019-2022/1-inleiding

Centraal Bureau voor de Statistiek. (2024c, August 13). *Energielevering particuliere woningen naar woningkenmerken, 2019-2023*. Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/maatwerk/2024/33/energielevering-particuliere-woningen-naar-woningkenmerken-2019-2023

Certified Applicator Extend Roofing Lifespan | Kohls Foam Systems INC. (2022, February 19). Kohls Foam Systems INC. https://kohlsfoamsystems.com/

Chen, C., Xu, X., & Day, J. K. (2017). Thermal comfort or money saving? Exploring intentions to conserve energy among low-income households in the United States. *Energy Research & Social Science*, *26*, 61–71. https://doi.org/10.1016/j.erss.2017.01.009

CIRCE. (2015). Analysis of energy efficiency measures. In *TRaIning Behaviours Towards Energy Efficiency: Play It!* (D4.1). CORDIS - European Commission. https://cordis.europa.eu/project/id/649770/results

cmostores.com limited. (2024, February 12). *How to install external wall insulation - Insulation Superstore Help & Advice. Insulation Superstore Help & Advice.*

https://www.insulationsuperstore.co.uk/help-and-advice/project-guides/insulation/how-to-install-external-wall-insulation/

Corsten, A. J. H. (2021). *A comparative performance assessment of infrared heating panels and conventional heating solutions in Dutch residential buildings* [Masterthesis]. TU Eindhoven.

CRESR. (n.d.). *Warm Front Better Health: Health Impact Evaluation of the Warm Front Scheme - Sheffield Hallam University Research Archive*. https://shura.shu.ac.uk/18167/

Cuerdo-Vilches, T., Navas-Martín, M. Á., & Oteiza, I. (2021). Behavior Patterns, Energy Consumption and Comfort during COVID-19 Lockdown Related to Home Features, Socioeconomic Factors and Energy Poverty in Madrid. *Sustainability*, *13*(11), 5949. https://doi.org/10.3390/su13115949

Day, R., Walker, G., & Simcock, N. (2016). Conceptualising energy use and energy poverty using a capabilities framework. *Energy Policy*, *93*, 255–264. https://doi.org/10.1016/j.enpol.2016.03.019

De Almeida, F., Scott, I. J., Soro, J. C., Fernandes, D., Amaral, A. R., Catarino, M. L., Arêde, A., & Ferreira, M. B. (2024). Financial scarcity and cognitive performance: a meta-analysis. *Journal of Economic Psychology*, *101*, 102702. https://doi.org/10.1016/j.joep.2024.102702

De Dear, R. J., Akimoto, T., Arens, E. A., Brager, G., Candido, C., Cheong, K. W. D., Li, B., Nishihara, N., Sekhar, S. C., Tanabe, S., Toftum, J., Zhang, H., & Zhu, Y. (2013). Progress in thermal comfort research over the last twenty years. *Indoor Air*, *23*(6), 442–461. https://doi.org/10.1111/ina.12046

De Dear, R. J., & Brager, G. S. (2002). Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings*, *34*(6), 549–561. https://doi.org/10.1016/s0378-7788(02)00005-1

De Isolatieshop. (n.d.). *De isolatieshop*. https://www.isolatiemateriaal.nl/muurisolatie/voorzetwand-isolatie

De Isolatieshop. (n.d.-b). *De isolatieshop*. https://www.isolatiemateriaal.nl/vloerisolatie/betonvloer-isolatie/xps-isolatie

De Isolatieshop B.V. (n.d.). *Plat dak van binnenuit isoleren | De Isolatieshop*. De Isolatieshop. https://www.isolatiemateriaal.nl/dakisolatie/platdak-isolatie/dakisolatie-binnenzijde

Djongyang, N., Tchinda, R., & Njomo, D. (2010). Thermal comfort: A review paper. *Renewable and Sustainable Energy Reviews*, *14*(9), 2626–2640. https://doi.org/10.1016/j.rser.2010.07.040

Dolšak, J. (2023). Determinants of energy efficient retrofits in residential sector: A comprehensive analysis. *Energy and Buildings*, *282*, 112801. https://doi.org/10.1016/j.enbuild.2023.112801

Du, C., Li, B., & Yu, W. (2020). Indoor mould exposure: Characteristics, influences and corresponding associations with built environment—A review. *Journal of Building Engineering*, *35*, 101983. https://doi.org/10.1016/j.jobe.2020.101983

ecommerce development agency - Remarkable.net. (n.d.). *Heat-Reflective Radiator Foil*. ExpertVerdict. https://www.expertverdict.com/heat-reflective-radiator-foil-372

Energie-armoede. (2024). [Slide show; Powerpoint]. bba binnenmileu.

Energiecafé - Delft4GlobalGoals. (2024, April 3). Delft4GlobalGoals. https://delft4globalgoals.nl/events/energie-cafe/

Energiekeurplus. (2025, January 29). *Blowerdoortest - luchtdichtheidsmeting | Blowerdoortest XL* |. https://www.energiekeurplus.nl/blowerdoor-luchtdichtheidstest/blowerdoortest-blowerdoor/

Energiecrisis hakt in op ons mentaal welbevinden. (n.d.). Gezond Leven. https://www.gezondleven.be/nieuws/energiecrisis-hakt-in-op-ons-mentaal-welbevinden

Energiehulp | 015 duurzaam. (n.d.). 015 Duurzaam. https://www.015duurzaam.info/energiehulp

Fisk, W. J., Lei-Gomez, Q., & Mendell, M. J. (2007). Meta-analyses of the associations of respiratory health effects with dampness and mould in homes. *Indoor Air*, *17*(4), 284–296. https://doi.org/10.1111/j.1600-0668.2007.00475.x

Fisk, W. J., Singer, B. C., & Chan, W. R. (2020). Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: A review of empirical data. *Building and Environment*, *180*, 107067. https://doi.org/10.1016/j.buildenv.2020.107067

Fitton, R., Swan, W., Hughes, T., & Benjaber, M. (2017). The thermal performance of window coverings in a whole house test facility with single-glazed sash windows. *Energy Efficiency, 10*(6), 1419–1431. https://doi.org/10.1007/s12053-017-9529-0

Gamma NL. (n.d.). *GAMMA | Isolatierollen kopen?* GAMMA. https://www.gamma.nl/assortiment/l/verwarming-isolatie-ventilatie/isolatiemateriaal/isolatierollen

Gamma NL. (n.d.-a). *GAMMA | Radiatorfolie kopen?* GAMMA. https://www.gamma.nl/assortiment/l/verwarming-isolatie-ventilatie/isolatiemateriaal/radiatorfolie

Gamma NL. (n.d.-b). GAMMA | *Tochtwering kopen?* GAMMA. https://www.gamma.nl/assortiment/l/verwarming-isolatie-ventilatie/isolatieklus/tochtwering

Gebouweisen - VaBi Support. (2025, April 8). Vabi Support. https://support.vabi.nl/support/elements/online-help/sjablonen/gebouweisen/

Geld besparen met isolerende gordijnen en raamdecoratie? | Kwantum. (n.d.). https://www.kwantum.nl/alles-over-raamdecoratie/op-maat/gordijnen-op-maat/isolerende-gordijnen#isolerendegordijnen

Gemeente Delft - KadastraleKaart.com. (n.d.). https://kadastralekaart.com/gemeenten/delft-GM0503

Gemeente Delft. (2023). Nota armoede. *Nota Armoede*, 3. https://www.delft.nl/sites/default/files/2023-05/Nota%20armoede.pdf

Gemeente Delft | Regionaal Energieloket. (n.d.). https://regionaalenergieloket.nl/delft

Gemeente Delft & Regionaal Energieloket. (n.d.). [Informatiepakket energie besparen]. In *Regionaal Energieloket*.

Ginestet, S., Aschan-Leygonie, C., Bayeux, T., & Keirsbulck, M. (2019). Mould in indoor environments: The role of heating, ventilation and fuel poverty. A French perspective. *Building and Environment, 169*, 106577. https://doi.org/10.1016/j.buildenv.2019.106577

Grey, C., Jiang, S., Poortinga, W., & Welsh School of Architecture, Cardiff University. (2015). Fuel Poverty, Thermal Comfort, and Health in Low-Income Areas in Wales: Results from the First Wave of Data Collection for the Arbed Health Impact Study. *WSA Working Paper Series*.

Guevara, Z., Espinosa, M., & López-Corona, O. (2022). The evolution of energy poverty theory: a scientometrics approach. *SocArXiv*. https://doi.org/10.31235/osf.io/xqkup

Guevara, Z., Mendoza-Tinoco, D., & Silva, D. (2023). The theoretical peculiarities of energy poverty research: A systematic literature review. *Energy Research & Social Science*, *105*, 103274. https://doi.org/10.1016/j.erss.2023.103274

Gupta, J., & Chakraborty, M. (2020). Energy efficiency in buildings. In *Elsevier eBooks* (pp. 457–480). https://doi.org/10.1016/b978-0-12-822989-7.00016-0

Guyet, B. D. R. (2022, December 1). *The Origins of energy Poverty in Europe - Australian Institute of International Affairs*. Australian Institute of International Affairs. https://www.internationalaffairs.org.au/australianoutlook/the-origins-of-energy-poverty-in-europe/

Halfens, E. (2021, December 13). *Referentieklimaatjaren vergelijken - Vabi*. Vabi. https://www.vabi.nl/engineering/klimaatjaren-vergelijken/

Halkos, G. E., & Gkampoura, E. (2021). Evaluating the effect of economic crisis on energy poverty in Europe. *Renewable and Sustainable Energy Reviews*, *144*, 110981. https://doi.org/10.1016/j.rser.2021.110981

Hao, Z., Zhang, X., Xie, J., Yin, K., & Liu, J. (2022). Balance point temperature and heating degree-days in different climate conditions for building energy efficiency applications. *Building and Environment, 216*, 109013. https://doi.org/10.1016/j.buildenv.2022.109013

Harris, D. (1995). Use of metallic foils as radiation barriers to reduce heat losses from buildings. *Applied Energy, 52*(4), 331–339. https://doi.org/10.1016/0306-2619(95)00018-6

Healy, J. D., & Clinch, J. (2003). Quantifying the severity of fuel poverty, its relationship with poor housing and reasons for non-investment in energy-saving measures in Ireland. *Energy Policy*, *32*(2), 207–220. https://doi.org/10.1016/s0301-4215(02)00265-3

Heinzerling, D., Chair, ASHRAE, & American National Standards Institute. (2022). *ANSI/ASHRAE Addendum h to ANSI/ASHRAE Standard 55-2020* (By ASHRAE Standards Committee & ASHRAE). https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/55_2020_h_20221230.pdf

Hilbert, L. P., Noordewier, M. K., Seck, L., & Van Dijk, W. W. (2024). Financial scarcity and financial avoidance: an eye-tracking and behavioral experiment. *Psychological Research*. https://doi.org/10.1007/s00426-024-02019-7

Hirst, E. (1976). Changes in retail energy prices and the consumer price index. *Energy, 1(1)*, 33–43. https://doi.org/10.1016/0360-5442(76)90055-4

Hong, S. H., Gilbertson, J., Oreszczyn, T., Green, G., & Ridley, I. (2008). A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. *Building and Environment*, *44*(6), 1228–1236. https://doi.org/10.1016/j.buildenv.2008.09.003

Hulp bij energie en geldzaken gemeente Delft - Vidomes. (n.d.). https://www.vidomes.nl/ik-huur/energie-besparen/hulp-bij-energie-en-geldzaken-gemeente-delft/

Humphreys, & Nicol, J. (1998). Understanding the adaptive approach to thermal comfort. *ASHRAE Transactions 104(1):991-1004*. https://www.osti.gov/scitech/biblio/649430

Inkomenseffecten van woningisolatie naar de isolatiestandaard. (n.d.). Centraal Planbureau. https://www.cpb.nl/inkomenseffecten-van-woningisolatie

Ionescu, C., Baracu, T., Vlad, G., Necula, H., & Badea, A. (2015). The historical evolution of the energy efficient buildings. *Renewable and Sustainable Energy Reviews*, *49*, 243–253. https://doi.org/10.1016/j.rser.2015.04.062

Isoleren: Paneel van je deur isoleren. (n.d.). Energieke Club. https://www.energieke.club/doen-en-praktisch/energiemaatregelen/isolatie/isoleren-paneel-van-je-deur-isoleren

Isoleren: isolatiegordijn. (n.d.). Energieke Club. https://www.energieke.club/doen-en-praktisch/energiemaatregelen/isolatie/isoleren-isolatiegordijn

ISSO. (2018). Kennispaper - Thermisch comfort. In *kennisbank.isso.nl*. ISSO Kennisinstituut voor installatietechniek.

ISSO kennisinstituut voor installatietechniek. (2017). ISSO-publicatie 51: Warmteverliesberekening voor woningen en woongebouwen. *In KENNISBANK.ISSO.NL* (No. 978-90-5044-303–6). KENNISBANK.ISSO.NL.

Itard, L. C. M. & van den Brom, P.I. (2023). *Energy Demand in Buildings: The Essentials, part II* [Slide show; Powerpoint Presentation]. Msc. Building Technology Climate Design Lecture.

Kosten ruit vervangen - Kostenoverzicht in 2025 - Zoofy. (n.d.). https://zoofy.nl/prijsgidsen/kosten-ruit-vervangen/

Luna Navarro, A. (2023). Introduction to experimental design. In *MSC BT - Research and Methodology*.

Large Door Draft Stopper ,36 Inch Under Door Draft Noise Blocker, Black Gap Stoppers ,Door Draft Guard for Bottom of Doors Adjustable Twin Door Sweep Draft Seal Window Sealer - Walmart.com. (n.d.). Walmart.com. https://www.walmart.com/ip/Large-Door-Draft-Stopper-36-Inch-Under-Noise-Blocker-Black-Gap-Stoppers-Door-Guard-Bottom-Doors-Adjustable-Twin-Sweep-Seal-Window-Sealer/6342950935?wmlspartner=wlpa&selectedSellerId=101671400

Liddell, C., & Morris, C. (2010). Fuel poverty and human health: A review of recent evidence. *Energy Policy*, *38*(6), 2987–2997. https://doi.org/10.1016/j.enpol.2010.01.037

Magnetic Thermal Door Curtain, Durable Oxford Fabric Heat Insulation Fly Curtain with Transparent Window, for Front Door Hands-Free Windproof Door Screen (Color : Free, Size : 0.8x2.03m/2.79x6.72 : Amazon.nl: DIY & Tools. (n.d.). https://www.amazon.nl/deurgordijn-Oxford-stof-warmte-isolatie-vliegengordijn-transparant/dp/B0CN5DSGXY

Martin, M. M. (2023). *Financial Stress and Your Health*. UNIVERSITY OF WYOMING EXTENSION. Retrieved November 29, 2024, from https://www.uwyo.edu/uwe/programs/money/saving-investing/financial-stress-and-your-health.html#:~:text=%E2%80%9CFinancial%20Stress%E2%80%9D%20is%20defined%20as,yet%20frequently%20intermittent)%20financial%20stress.

McNeil, S. (2016). The Thermal Properties of Wool Carpets. *ResearchGate*. https://doi.org/10.13140/RG.2.1.3925.1601/1

McNerney, J., Farmer, J. D., & Trancik, J. E. (2011). Historical costs of coal-fired electricity and implications for the future. *Energy Policy*, *39*(6), 3042–3054. https://doi.org/10.1016/j.enpol.2011.01.037

Mijzen, D. T. (2024, July 8). *Minimale eisen bouwbesluit/BBL | Rc-waarde verhogen | HBA B.V.* Handelbouwadvies. https://www.handelbouwadvies.nl/isolatiewaarde-minimale-eis-bouwbesluit/

Min, J. (2024, July 17). *TNO: 21 procent meer energiearme huishoudens in Nederland - metropoolregioamsterdam*. Metropoolregioamsterdam. https://www.metropoolregioamsterdam.nl/tno-21-procent-meer-energiearme-huishoudens-in-nederland/

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2023, September 8). *Bijlage Toolkit Aanpak Energiearmoede Tips energiebesparende maatregelen*. Publicatie | Home | Volkshuisvesting Nederland. https://www.volkshuisvestingnederland.nl/onderwerpen/toolkit-programma-verduurzaming-gebouwde-omgeving/documenten/publicaties/2022/09/15/bijlage-toolkit-aanpak-energiearmoede-tips-energiebesparende-maatregelen

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2024, August 22). *Het statistisch woningtekort uitgelegd*. Home | Volkshuisvesting Nederland. https://www.volkshuisvestingnederland.nl/onderwerpen/berekening-woningbouwopgave

Moghaddam, S. A., Serra, C., Da Silva, M. G., & Simões, N. (2023). Comprehensive Review and Analysis of Glazing Systems towards Nearly Zero-Energy Buildings: Energy Performance, Thermal Comfort, Cost-Effectiveness, and Environmental Impact Perspectives. *Energies, 16*(17), 6283. https://doi.org/10.3390/en16176283

Mulder, P., Dalla Longa, F., Croon, T., & TNO Publiek. (2024). De energiearmoedekloof in Nederland: Een microdata-analyse van het niveau en de ongelijkheid van energiearmoede. In *TNO Publiek* (TNO 2024 R11693; pp. 3–46). TNO. https://publications.tno.nl/publication/34643138/yulKz7av/TNO-2024-R11693.pdf

Mulder, P., Longa, F. D., & Straver, K. (2022). Energy poverty in the Netherlands at the national and local level: A multi-dimensional spatial analysis. *Energy Research & Social Science*, *96*, 102892. https://doi.org/10.1016/j.erss.2022.102892

Nikolopoulou, M., & Steemers, K. (2002). Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings*, *35*(1), 95–101. https://doi.org/10.1016/s0378-7788(02)00084-1

New in | B&Q. (n.d.). https://www.diy.com/new-in.cat

Nussbaumer, T., Bundi, R., Tanner, C., & Muehlebach, H. (2005). Thermal analysis of a wooden door system with integrated vacuum insulation panels. *Energy and Buildings, 37*(11), 1107–1113. https://doi.org/10.1016/j.enbuild.2004.11.002

PCC Group. (2025, January 23). *Thermische weerstand – een sleutelparameter bij isolatie van gebouwen*. PCC Group Product Portal. https://www.products.pcc.eu/nl/blog/thermische-weerstand-een-sleutelparameter-bij-isolatie-van-gebouwen/

Pihelo, P., & Kalamees, T. (2016). The effect of thermal transmittance of building envelope and material selection of wind barrier on moisture safety of timber frame exterior wall. *Journal of Building Engineering*, *6*, 29–38. https://doi.org/10.1016/j.jobe.2016.02.002

Polimeni, J. M., Simionescu, M., & Iorgulescu, R. I. (2022). Energy poverty and personal health in the EU. *International Journal of Environmental Research and Public Health*, *19*(18), 11459. https://doi.org/10.3390/ijerph191811459

Pombo, O., Rivela, B., & Neila, J. (2015). The challenge of sustainable building renovation: assessment of current criteria and future outlook. *Journal of Cleaner Production*, *123*, 88–100. https://doi.org/10.1016/j.jclepro.2015.06.137

Primc, K., Dominko, M., & Slabe-Erker, R. (2021). 30 years of energy and fuel poverty research: A retrospective analysis and future trends. *Journal of Cleaner Production*, *301*, 127003. https://doi.org/10.1016/j.jclepro.2021.127003

Primc, K., & Slabe-Erker, R. (2020). Social policy or energy policy? Time to reconsider energy poverty policies. *Energy Sustainable Development/Energy for Sustainable Development*, *55*, 32–36. https://doi.org/10.1016/j.esd.2020.01.001

Provincie maakt impact met 'eerlijke energietransitie.' (n.d.). Provincie Zuid-Holland. https://www.zuid-holland.nl/actueel/nieuws/juni-2024/provincie-maakt-impact-eerlijke-energietransitie/

Reasons behind the 2022 energy price increases and prospects for next year. (2023, July 20). CEPR. https://cepr.org/voxeu/columns/reasons-behind-2022-energy-price-increases-and-prospects-next-year

Reddy, A. K. N. (2000). *Energy and Social issues* (World Energy Assessment: Energy and the Challenge of Sustainability) [United Nations Development Programme, New York, NY].

Royal Swiss - Fan Heater - Ventilator Kachel - 2000W | bol. (n.d.). Bol. https://www.bol.com/nl/nl/p/royal-swiss-fan-heater-ventilator-kachel-2000w/9300000194577767/

Ruse, J., Stockton, H., & Smith, P. (2019). Social and health-related indicators of energy poverty. In *Elsevier eBooks* (pp. 143–184). https://doi.org/10.1016/b978-0-12-816952-0.00007-7

Ryu, S., & Fan, L. (2022). The relationship between financial worries and psychological distress among U.S. adults. *Journal of Family and Economic Issues*, *44*(1), 16–33. https://doi.org/10.1007/s10834-022-09820-9

Sadler, A. (2024, March 13). *How to install the most energy-efficient windows for your home*. BuildPass. https://www.buildpass.co.uk/blog/how-to-install-the-most-energy-efficient-windows-for-your-home/

Santin, O. G., Itard, L., & Visscher, H. (2009). The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings*, *41*(11), 1223–1232. https://doi.org/10.1016/j.enbuild.2009.07.002

Sharpe, R. A., Thornton, C. R., Nikolaou, V., & Osborne, N. J. (2015). Fuel poverty increases risk of mould contamination, regardless of adult risk perception & ventilation in social housing properties. *Environment International, 79*, 115–129. https://doi.org/10.1016/j.envint.2015.03.009

Shop Amazon.com | Draft stoppers. (n.d.). https://www.amazon.com/Under-Door-Draft-Stoppers/b?ie=UTF8&node=3291684011

Simcock, N. (2019). Energy. In *Elsevier eBooks* (pp. 123–135). https://doi.org/10.1016/b978-0-08-102295-5.10783-8

SK Studio Curtains Opaque Blackout Curtains with Rings Thermal Curtain Cold Protection Insulation Curtain for Bedroom Living Room 1 Piece Brown 132 x 213 cm : Amazon.nl: Home & Kitchen. (n.d.). https://www.amazon.nl/-/en/Curtains-Blackout-Thermal-Protection-Insulation/dp/B0BMGC9VG8

Solvari, & Solvari. (2025, May 6). *Buitenmuur isoleren*. Gevelrenovatie-info.nl. https://www.gevelrenovatie-info.nl/gevelisolatie/buitenmuur-isoleren

Staszczuk, A., Wojciech, M., & Kuczyński, T. (2017). The effect of floor insulation on indoor air temperature and energy consumption of residential buildings in moderate climates. *Energy*, *138*, 139–146. https://doi.org/10.1016/j.energy.2017.07.060

Taylor, P., Mathews, E., Kleingeld, M., & Taljaard, G. (2000). The effect of ceiling insulation on indoor comfort. *Building and Environment*, *35*(4), 339–346. https://doi.org/10.1016/s0360-1323(99)00025-6

Technology Networks. (2020, February 4). *The history of home energy use*. Applied Sciences From Technology Networks. https://www.technologynetworks.com/applied-sciences/articles/the-history-of-home-energy-use-330294

tesa moll Thermo Cover - Window Insulation Film, Transparent - Non-Adhesive Window Film - Insulation Film - 1.70 m x 1.5 m : Amazon.nl: DIY & Tools. (n.d.). https://www.amazon.nl/-/en/tesa-moll-Thermo-Cover-Non-Adhesive/dp/B0038JE7WW?ref_=Oct_d_obs_d_16419394031_0&pd_rd_w=L0FpJ&content-id=amzn1.sym.1434a312-8362-415e-b7d6-0a42f28f7b4e&pf_rd_p=1434a312-8362-415e-b7d6-0a42f28f7b4e&pf_rd_r=2AB3878A5J6P6Y3XB801&pd_rd_wg=uJdlA&pd_rd_r=c527ae0c-67c9-48d0-8f05-5d9ebb87d9f7&pd_rd_i=B0038JE7WW&th=1

Theeuwen, M., & Theeuwen, M. (2022, September 29). Voorzetraam van TNO dat makkelijk zelf in elkaar te zetten is moet energiearmoede helpen te bestrijden, ook in Eindhoven. *ed.nl*. https://www.ed.nl/eindhoven/voorzetraam-van-tno-dat-makkelijk-zelf-in-elkaar-te-zetten-is-moet-energiearmoede-helpen-te-bestrijden-ook-in-eindhoven~aeb0b4f5/?referrer=https%3A%2F%2Fwww.google.com%2F

The 200-year history of mankind's energy transitions. (2022, April 13). World Economic Forum. https://www.weforum.org/stories/2022/04/visualizing-the-history-of-energy-transitions/

The Inability to keep home adequately warm" indicator: Is it enough to measure energy poverty? | Energy Poverty Advisory Hub. (n.d.). https://energy-poverty.ec.europa.eu/newsroom/news/inability-keep-home-adequately-warm-indicator-it-enough-measure-energy-poverty

Thomson, H., Snell, C., & Liddell, C. (2016). Fuel poverty in the European Union: a concept in need of definition? *People Place and Policy Online*, *10*(1), 5–24. https://doi.org/10.3351/ppp.0010.0001.0002

TNO. (2022). *Toolkit aanpak energiearmoede*.

TNO brengt niveau energiearmoede in kaart | TNO. (n.d.). tno.nl/nl. https://www.tno.nl/nl/newsroom/2024/09/niveau-energiearmoede-in-kaart/

Tochtstripdeur.nl. (2025, February 28). *Tochtstrip raam online bestellen. De ideale doe-het-zelf oplossing*. https://tochtstripdeur.nl/tochtstrip-raam/

TRADING ECONOMICS. (n.d.). *Natural gas - Price - Chart - Historical Data - News*. https://tradingeconomics.com/commodity/natural-gas

Ucl. (2025, March 11). *Ground-floor insulation can reduce floor heat loss by up to 92 per*. UCL News. https://www.ucl.ac.uk/news/2017/oct/ground-floor-insulation-can-reduce-floor-heat-loss-92-cent

UK Green Building Council. (2024, April 25). *Insulating window coating for retrofit | UKGBC*. UKGBC. https://ukgbc.org/resources/insulating-window-coating-for-retrofit/

Vabi Elements - 3D rekensoftware voor installateur & adviseur. (n.d.). Vabi. https://www.vabi.nl/producten/vabi-elements/

Vabi Elements 3.5 vanaf nu beschikbaar | Vabi Elements. (2019, July 26). Vabi. https://www.vabi.nl/nieuw-vabi-elements-3-5/

Vabi Software B.V. (2015). *Comforteisen toetsen met gebouwsimulatie*. https://www.vabi.nl/wp-content/uploads/2016/02/Open-hier-Comforteisen-toetsen-met-gebouwsimulatie.pdf

Van Der Linden, A. C., Kuijpers-van Gaalen, I. M., & Zeegers, A. (2016). *Bouwfysica* (8th ed.). ThiemeMeulenhoff.

Van Der Veldt, M. (2025, January 23). Slechte isolatie en dreigende verkoop: Delftse studenten maken zich zorgen over hun woonsituatie - Delta. *Delta*. https://delta.tudelft.nl/article/slechte-isolatie-en-dreigende-verkoop-delftse-studenten-maken-zich-zorgen-over-hun-woonsituatie

Van Ooij, C., Batenburg, A., Nguyen, N. C., Straver, K., & TNO. (2023). Energy Poverty: a science and policy state of play. In *TNO Report* (TNO 2023 P10119; pp. 2–46). https://publications.tno.nl/publication/34640524/86Phvt/TNO-2023-P10119.pdf

Van Ooij, C., Mesdaghi, B., De Vreede, C., Peuchen, R., & Straver, K. (2024). Verhalen van mensen in energiearmoede. In *TNO* (TNO 2024 R10989). TNO. Retrieved January 8, 2025, from https://www.tno.nl/nl/newsroom/insights/2024/06/energiearmoede-verhalen-mensen/

Vastgoedjournaal.nl. (2024, November 26). *'Doorstroming draagt ook bij aan verduurzaming, want ouderen verduurzamen minder'* https://vastgoedjournaal.nl/news/66111/doorstroming-draagt-ook-bij-aan-verduurzaming-want-ouderen-verduurzamen-minder

Ventilatorkachels. (n.d.). https://www.praxis.nl/verwarmingen-airco-s/bijverwarming/ventilatorkachels/he021/

Viitanen, H. (2011). Moisture and Bio-Deterioration Risk of Building Materials and Structures. In *InTech eBooks*. https://doi.org/10.5772/21184 vloerbedekkingwebwinkel.nl. (n.d.). *Ondervloer voor tapijt kopen? Vloerbedekking Webwinkel*. https://www.vloerbedekkingwebwinkel.nl/ondervloeren/tapijt?srsltid=AfmBOooKAfLF-gpBUXcdHOSiWLuWR8FudXctoWzMzaOufcqHekNHmyGN

Wang, C., Chen, S., Shao, R., & Yang, W. (2023). Redefining human health: physical wellbeing, mental wellbeing, social wellbeing, and environmental wellbeing. *Chinese Medical Journal*, *136*(20), 2395–2396. https://doi.org/10.1097/cm9.0000000000002817

What are the regulations on indoor humidity? (n.d.). https://www.condair.co.uk/industry-guidelines-and-regulations-on-indoor-humidity

*Window Insulation Film, Insulating Shrink Film For Window, Transparent Thermal Window Film, Window Insulation Film, Cold Resistant Film, Window Insulation Kit For Winter,WxH-60x80cm/24 * 31in : Amazon.nl: Home & Kitchen.* (n.d.). https://www.amazon.nl/-/en/Insulation-Insulating-Transparent-Resistant-WxH-60x80cm/dp/B0CQVH97R2

Wijk Voorhof (gemeente Delft) in cijfers en grafieken. (2025, May 1). AlleCijfers.nl. https://allecijfers.nl/wijk/wijk-24-voorhof-delft/

Yaribeygi, H., Panahi, Y., Sahraei, H., Johnston, T. P., & Sahebkar, A. (2017). The impact of stress on body function: A review. *PubMed*, *16*, 1057–1072. https://doi.org/10.17179/excli2017-480

Zhao, Q., Lian, Z., & Lai, D. (2020). Thermal comfort models and their developments: A review. *Energy and Built Environment*, *2*(1), 21–33. https://doi.org/10.1016/j.enbenv.2020.05.007

Zhuang, L., Huang, J., Li, F., & Zhong, K. (2022). Psychological adaptation to thermal environments and its effects on thermal sensation. *Physiology & Behavior*, *247*, 113724. https://doi.org/10.1016/j.physbeh.2022.113724

Appendixes

Appendix: 1 - Interview: Citizen participation in the energy policies of the municipality of Delft

In order to get a better understanding of the effects of the energy poverty and energy transition policies of the municipality of Delft, an information event was attended. This information event focussed on how the citizens of Delft are currently and should be involved in the energy policies of the municipality of Delft. This event included different presentations by the municipality and several PhD students. Besides this, a panel discussion was held, in which different actors spoke with each other.

The role of the municipality in the energy transition was explained, through the view of the municipality. It was explained that the municipality views itself as a provider of information surrounding the energy transition, and that in most cases it is up to the citizens of Delft to act on this information. It was explained that the municipality aimed through providing information and financial incentives, to hold 'a carrot on a stick' in front of citizens.

The event concluded with a panel discussion, in which one official of the municipality, the chairman of a homeowner association, and a representative of a citizen association of one of the poorer areas of Delft discussed various topics. The discussion was concluded with the representative of the citizen association of one of the poorer areas of Delft discussing the problems the common households in energy poverty experience. She mentioned the disconnect within the citizens in her area, who are living in energy poverty, and the municipality. She noted that these citizens have enormous trouble in paying their monthly bills, especially their energy bills, and that they respond negatively to officials of the municipality, who come from a different educational and financial background, telling them 'What to do'. She also mentioned how energy poverty being part of the broader poverty and energy transition policies negatively affected the adoption of energy efficiency interventions. As the victims of energy poverty were solely focused on getting through the month and lowering their energy costs, terms like; 'sustainability' and 'the energy transition' didn't attract the people who needed the help the most but instead pushed them away. She mentioned that people started opening up to potential energy efficiency interventions once the used terminology was redirected to; 'energy saving' and 'cost efficiency'. Lastly, she mentioned the importance of implementing the first step, as this was the hardest step. It was noted that once the first small interventions were adopted (draft strips, radiator foil, etc.), households were more open to adopting more impactful interventions (insulation, improved glazing, etc.).

The panel discussion showed some important relations between the citizens of Delft and the energy poverty policy of the municipality. It also showed some of the effects of this policy, and where there is room for improvement.

Appendix: 2 - Interview: Energiehulp Dordrecht

In order to get a better understanding of the current efforts of combatting energy poverty, discussions were held with the 'Energiehulpen' (Energy helpers) of Dordrecht. The Energiehulp in Dordrecht focusses on providing direct interventions to occupants who are living in energy poverty, along with giving advice on their energy usage.

How are you as Energiehulp's approached? Does this happen through the municipality, through citizen organisations or housing associations?

De Energiehulp's are on occasion approached by municipalities through energy policy. Mostly, they are directly approached as a result of their social media and printed media campaigns. They use these channels to inform households on the work they provide and how they can be contacted.

Besides these direct forms of client acquisition, indirect advertisements also bring many people to their services. The Energiehulp's are often recommended by neighbours, acquaintances, housing corporations, district organisations or events through the municipality.

What are the activities you carry out?

The Energiehulp's offer free activities which relate to energy efficiency and housing comfort of dwellings. The activities are carried out as follows:

- The Energiehulp request is entered and processed through their system.
- The request is included in their schedule.
- The Energiehulp visits, during this visit, the following activities are carried out:
    - The dwelling is examined and mapped. The quality of the dwelling and the appliances used in the household are mapped.
    - Small interventions are applied throughout the dwelling.
    - The dwelling is checked for draft, if there is draft present, this will be reduced in later steps.
    - The Energiehulp talks to the household about their situation surrounding energy usage and the problems they encounter.
    - The household receives information and advice about their energy usage and about further steps they can make to reduce their energy consumption.

The interventions which are applied throughout the dwelling are the following:

- ➢ LED lighting, which function as a replacement for inefficient light bulbs.
- ➢ Radiator foil to improve the energy efficiency of heating.
- ➢ Draft strips for underneath doors, to reduce cold air flows through the dwelling.
- ➢ Energy efficient power strips, to reduce energy losses.
- ➢ Efficient shower heads, to reduce water usage and water costs.
- ➢ Shower alarm clocks, which makes users more conscious of their shower usage and reduces this.
- ➢ Draft tape to use on window frames, to reduce the amount of cold that enters the dwelling.

In what way are you received by occupants?

The Energyhulp's recall that they are received in a friendly and open-minded manner in almost all cases. The reasons for this being the facts that people personally request their visit, that their activities are free, and that the interventions they install save the occupants money.

Are the effects of your applied interventions mapped?

No, the effects of the energy saving interventions are not mapped. Besides the report that is made on the state of the dwelling and the applied interventions, nothing is tracked.

What situations do you often encounter in households?

A large variety of situations is described to be encounter in the visited homes, due to the facts that everybody deals with energy poverty in a unique way, and because the Energiehulp's visit many different target groups. Often, very cold indoor temperatures are encountered and below average living conditions.

What are the most common building flaws of the dwellings you visit?

Building flaws which are often encountered are:

- Aged buildings, damaged by time degradation.
- Insulation which is old and of low quality.
- Bad energy efficiency of glazing.
- Ventilation grids which are inefficient and allow to much cold to enter.
- Bad air tightness of the building.
- Thermal bridges which allow a large amount of cold to enter through balconies or other places.

Where do you view a possible solution / improvement of the current solution against energy poverty?

The Energiehulp's mention the importance of extending the financial support, instead of reducing this support. With news items announcing that the financial support is soon to stop, while energy prices are still unstable, many households are in danger of entering energy poverty. The financial support will reduce this.

There need to be better ways of directing households in energy poverty to parties which can help reduce their problems. When occupants for example express their problems to their housing associations, more effective referrals should be in place to approach help.

Lastly comes the necessity of integral financial support instead of free financial support. The current financial support allows for this money to be spent on different things than what it is meant to be spent on, being energy efficiency. Often, the financial support is spent on recreation or other costs. When this support is directly attached to energy efficiency, more long-term solutions will come in place. One example of this are the vouchers as part of the national insulation plan, these vouchers can only be spent on insulation, increasing the effectiveness of this measure.

Appendix: 3 - Interview: Energy poverty consequences regarding indoor mould growth

A discussion was held with ir. Hans Bosch. Hans Bosch is a tutor at the TU Delft faculty of Architectural Engineering + Technology. He has collected much field experience in heat and moisture transport in constructions. He has worked with these fields as an advisor but has also worked more closely with occupants of these dwellings, and has helped them in solving their problems, both through construction interventions and behavioural changes. In his regular activities, he performs moisture measurements in dwellings to get information on how to combat mould.

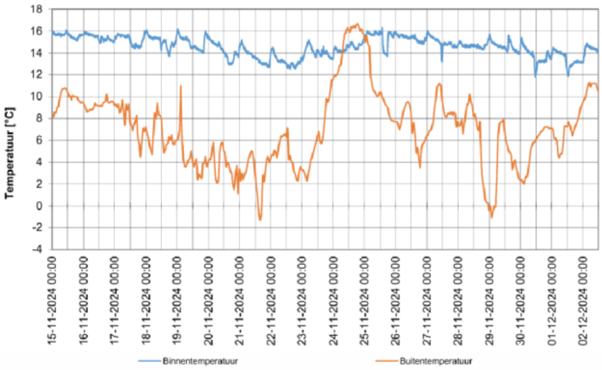
In extending the definition of energy poverty from solely a financial problem to a health and built-environmental problem, it is important to gain more knowledge of one of the most harmful effects of energy poverty, indoor mould.

What are your activities as a building physics expert?
Mr Bosch explains how he carries out indoor moisture tests. He is approached by social housing corporations, in which occupants are experiencing indoor mould. Notably, though he has done these activities for a longer period of time, the demand has increased exponentially during the last 3 years (2021/2024).

What people do you encounter most during your activities?
Mr Bosch notes that the increase in interior mould has a strong correlation with the increase of energy prices and energy poverty. The people he visits are mostly people of low income and low academic education, who are renting their home from a social housing corporation.

He mentions a substantial language and educational barrier between him as professional and the occupants he visits. Besides this barrier, he mentions the negative image occupants have of 'advisors' coming to take a look at their dwelling, which has a big negative effect on the communication between specialists and tenants. Oftentimes these occupants have filed numerous complaints to their respective social housing corporations, which has in their turn has sent different parties over to the dwellings to look at the problem. As a result, when no action and responsibility has been taken, Mr Bosch is called upon to assess the damage of the problem.

What are the most common behavioural causes of indoor mould problems?
Most importantly, the rising energy costs have led to households significantly lowering the amount of heating they apply in their homes, which leads to the growth of mould. He mentions an average indoor temperature of 14 degrees, in the homes he inspects. The figure below shows one typical example of indoor temperatures which were measured in a home struggling with energy poverty. It can be seen that indoor temperatures are consistently below 16^0 C. With the average indoor temperature in this home being $14{,}6^0$ C, with 62% of the time, the indoor temperature being below 15^0 C. These measurements were made in the winter of 2024, the low temperature during this period raises concerns for the temperatures handled in earlier years, where the energy crisis was at its peak.



Indoor temperature measurements of energy poverty household in November 2024 (Bosch, 2024)

This is one part of the mould problem; the other aspect of mould growth comes in the form of ventilation. Both heating and ventilation are the most important aspects in combatting mould growth. With energy prices rising and indoor temperatures decreasing as a result, the amount of applied ventilation also lowers, as occupants are already living in too low temperatures.

What are the most common building technical related causes of indoor mould problems?
Throughout the dwellings that Mr Bosch has visited, he has noticed clear trends. Most dwellings are of older age, before the introduction of building quality law in 1992. Most dwellings have little thermal insulation, insufficient glazing, and ineffective ventilation systems. Especially for combatting mould, Mr Bosch stressed the amplitude of the ineffective ventilation systems.

What are the most common building use related causes of indoor mould problems?
On the transition between building construction causes and behavioural causes are the building use related causes. These are causes that effect mould growth, by how occupants use and arrange their dwelling. Oftentimes, dwellings might not be of terrible quality, but because occupants make certain changes, they still get problems.

Mr Bosch mentions examples such as the placement of large furniture pieces along walls. These large furniture pieces reduce the air flow and negatively impact temperature flows. The hanging of large curtains also negatively affects the heat distribution of radiators, it also increases the risk of the sun not warming these dwellings. Another example are dwellings where frames have been built around the radiator. These frames have an aesthetic purpose but reduce the effectiveness of the radiator, as a second result this also drives up energy costs from heating.

What are the interventions you advise which reduce the health effects of occupants?
Most of the actions Mr Bosch advises to occupants are behavioural changes they can make or on the use of their dwelling. Though it is difficult, as to reduce mould growth, the advice is to increase the amount in which occupants heat their dwellings. For these occupants, this one of the last things they want to and are able to do. Mr Bosch also focuses on other behavioural changes they can make, for example when and where to heat minimally, how, and when to ventilate. In his work, Mr Bosch tries to address the responsibility occupants have on the quality of their dwelling and how they use it, as this has a large effect. Oftentimes, the blame is shifted only to the housing corporation.

What is your view of energy poverty, in relation to the work you've done in mould testing?
Mr Bosch mentions that there is a lot of contradictory thinking between housing corporations and tenants. With tenants experiencing problems, not knowing how to solve them, and the only means of solving them being through the housing corporation. At the same time, corporations with less financial means have less concern and financial incentive in solving these problems and oftentimes push responsibility off themselves or even try to push responsibilities onto the tenants. Corporations with more financial means often have more concerns in fixing the problems of their tenants and undertake more effective action.

The problems at hand are in turn increased by the growing energy poverty and energy prices. Because one of the main ways to combat mould creation, is to turn on the heating. As higher energy prices result in less indoor heating, leading to mould creation, leading to health problems, which lead to more financial problems, which leads to more energy poverty, and on and on.

Mr Bosch also relates the energy poverty issue as a building envelope issue, instead of solely a financial issue. He expresses the fact that the households most negatively influenced are living in sub-par homes. These can be both single free-standing homes, and apartments in larger complexes. If these homes aren't adequately insulated and ventilated, they require more heating which many can't afford, which increases the risk of problems.

Appendix: 4 - Interview: Energy poverty policy of the municipality of Delft

In order to get a better understanding of the municipalities policy, an interview was held with Suzan Mannens, the senior project manager energy transition of the municipality of Delft. She works for the municipality and leads the plans promoting sustainable development of the municipality, energy poverty also falls under her portfolio. This discussion led to several important insights in policy creation.

How is energy poverty policy created for the municipality of Delft?
As stated in the chapter 2.7, the Dutch government has given different municipalities a lot of freedom in choosing their approach for combatting energy poverty. The different municipalities have been given a specific budget and are told which target groups to approach. But besides these comments, municipalities remain free of instructions. She notes that this can cause confusion and can make municipalities feel lost. One example of this comes in the form of choosing a definition to act on, the municipality has for example chosen on the definition of 'a household which spends more than 10% of their income on energy'.

In their policy creation, the Delft municipality has implemented different findings of the TNO research, for example Mulder et al. (2024), to determine their policy. Besides this, the municipality uses other municipalities' experiences to alter their policy, this is done through the 'Eerlijke Energietransitie' platform of the South-Holland province (*Provincie Maakt Impact Met 'Eerlijke Energietransitie,'* n.d.).

What are the effects of Delft's energy poverty policy?
As has been mentioned in chapter 2.7 by Van Ooij et al. (2023, p. 35), research is lacking in the effect of interventions to combat energy poverty. This notion was confirmed by Ms Mannens, she mentioned that for example the Energiehulpen don't get back in touch with the households they helped. At the same time, data is tracked on the amount of people who use the provided measures, like the Energieloket and the Energiehulpen. At the same time, the use of a financial definition allows for the monitoring of the number of households in energy poverty, this can give some indication into the effects of the policies.

What are common setbacks in policy creation and implementation?
Different setbacks in forming and executing energy poverty policy were mentioned by Ms Mannens. The main setback she mentioned was in communicating with the households experiencing energy poverty, it has been difficult to both find and help households. Often, households react dismissive or negatively to contact and offered help from the municipality. Mentioned by these households are the facts that they aren't thinking about their energy usage in such nuance, that they don't have time for making improvements, or that they don't have the money to make improvements.

Next to this, financial setbacks are also common. Despite different financial aids of the municipality, for a lot of households, energy efficiency improvements are still too expensive. This is similar to what was discussed in chapter 2.7. Lastly, another setback was that of market supply of parties which can apply energy efficiency interventions. Ms Mannens mentioned that often when households are informed on what they can do, and they're willing to do the investments, they have trouble in finding a business to implement these improvements. This struggle demotivates households.

Additional setbacks / findings

- One large hurdle is the combination of small hurdles households need to overcome to implement certain measures. For one improvement, many different parties need to be accessed, with no all-in-one services. Other 'smaller' hurdles, like having to clean up the attic for interior roof insulation, can be perceived as to large of an obstacle.
- The setback of many different parties needing to be contacted is something where the municipality can't help. As the municipality isn't (easily) allowed to nominate businesses for certain assignments, due to possible conflict of interests.

The discussion was quite informative, and Ms Mannens pressed the municipalities interest in a collaboration during the research and design process of this thesis.

Appendix: 5 – Energy consumption analyses results

Appendix 5.1 – Dutch household energy consumption per household characteristics

Description	Average energy usage 2021 (m3)	Average energy usage 2022 (m3)	Change (%)
1 occupant, post 1992, small apartment	650	570	-12
1 occupant, pre-1992, small apartment	850	730	-14
2 or more occupants, pre-1992, small apartment	1060	920	-13
1 occupant, pre-1992, small, terraced house	1110	930	-16.
1 occupant, pre-1992, middle/large, terraced house	1320	1100	-17
2 or more occupants, pre-1992, small, terraced house	1280	1080	-16
2 or more occupants, post 1992, middle/large, terraced house	1130	970	-14
2 or more occupants, pre-1992, middle/large, terraced house	1450	1220	-16
2 or more occupants, pre-1992, large, terraced house	2050	1720	-1
2 or more occupants, pre-1992, large, detached house	2540	2130	-16

Appendix 5.2 – Largest decreases of indoor temperatures in Delft

Postal code	Area	Avg. Gas consumption 2018/2021 (m3)	Gas consumption 2022 (m3)	Estimated indoor temperature (°C)	Average yearly personal income 2022 (€)	Average construction year
2624RD	Voorhof	627	350	11.2	25.000	1955
2612VT	Vrijenban	637	370	11.6	28.600	1988
2625AE	Buitenhof	1257	750	11.9	23.700	1985
2614CX	Voordijkshoorn	1007	610	12.1	33.300	1955
2614AR	Voordijkshoorn	1130	690	12.2	33.300	1955
2624KW	Voorhof	1320	820	12.4	25.000	1970
2624KV	Voorhof	1300	810	12.5	25.000	1970
2624KZ	Voorhof	1300	810	12.5	25.000	1970
2614EB	Voordijkshoorn	877	550	12.5	33.300	1955
2624EA	Voorhof	2040	1280	12.5	25.000	1955
2624KT	Voorhof	1303	820	12.6	25.000	1970

2624KX	Voorhof	1300	820	12.6	25.000	1970
2613TA	Hof van Delft	1657	1050	12.7	30.500	1900
2622BB	Tanthof-Oost	1177	750	12.7	29.500	1980
2625EL	Buitenhof	783	500	12.8	23.700	1970

Appendix 5.3 – Average yearly personal incomes of 2022 in Delft

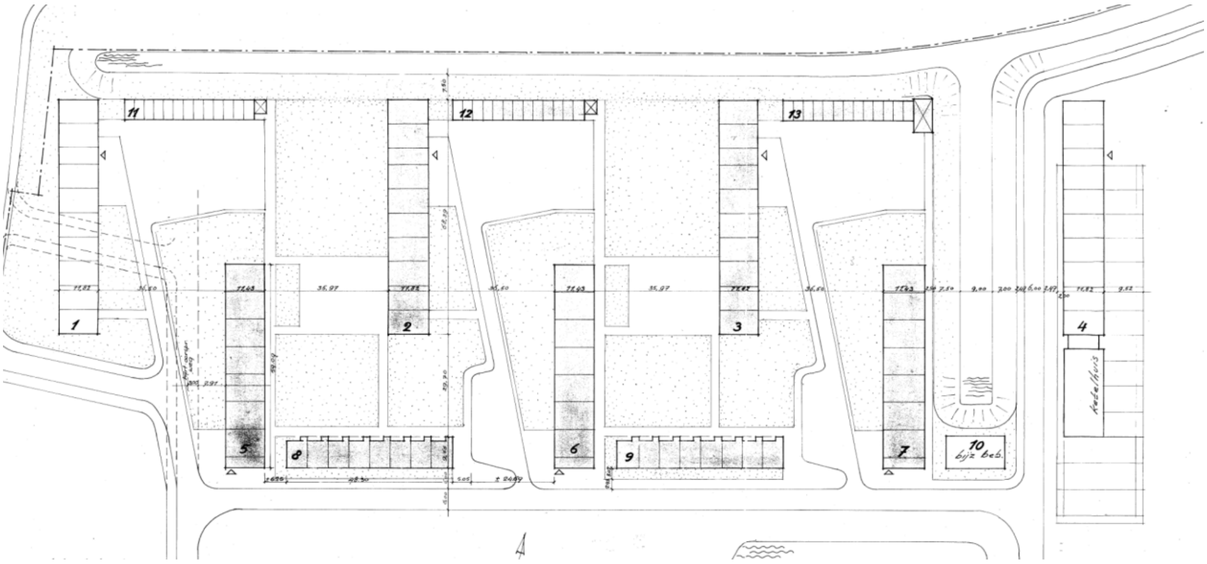
Area	Average yearly personal income 2022 (€)
Schieweg	37.700
Binnenstad	34.700
Voordijkshoorn	33.300
Tanthof-West	30.900
Hof van Delft	30.500
Tanthof-Oost	29.500
Ruiven	28.700
Vrijenban	28.600
Wippolder	26.500
Voorhof	25.000
Buitenhof	23.700

Appendix 5.4 – Identified energy poverty dwellings in Delft

Postal code	Area	Estimated indoor temperature (°C)	Average yearly personal income 2022 (€)	Average construction year	Building
2624RD	Voorhof	11,2	25.000	1955	
2612VT	Vrijenban	11,6	28.600	1988	

2625AE	Buitenhof	11,9	23.700	1985	
2624KW 2624KV 2624KZ	Voorhof	12,4	25.000	1970	
2624EA	Voorhof	12,5	25.000	1955	
2613TA	Hof van Delft	12,7	30.500	1900	
2622BB	Tanthof-Oost	12,7	29.500	1980	
2625EL	Buitenhof	12,8	23.700	1970	

Appendix: 6 – Documentation high-rise Poptahof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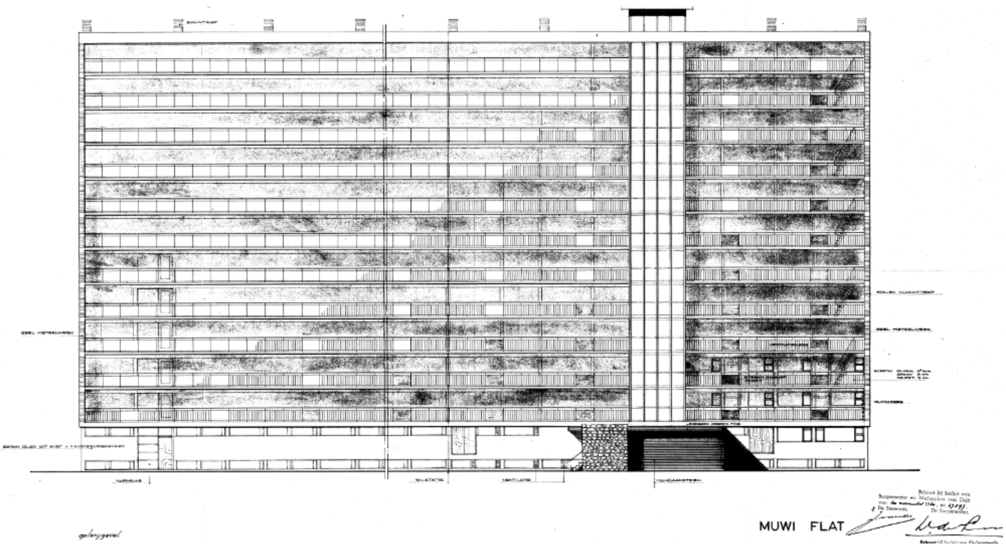
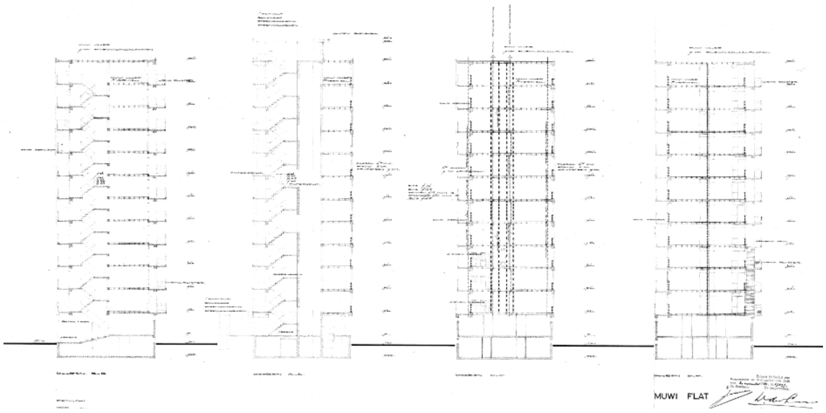

MUWI FLAT
galerijgevel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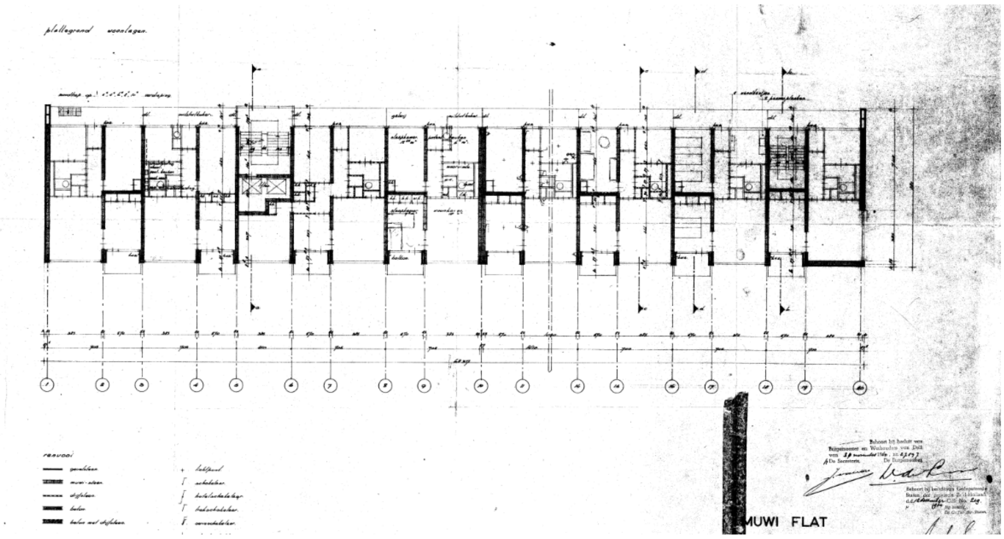
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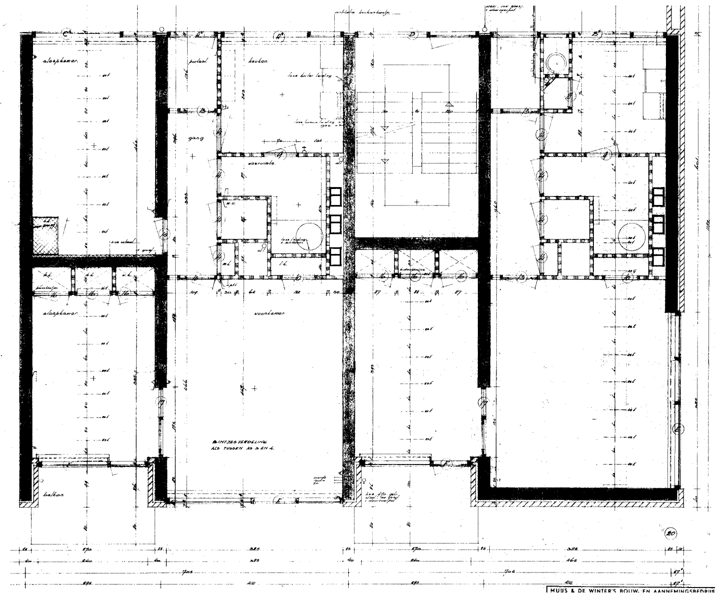


Appendix: 7 – Modelling input

Appendix 7.1 – Individual rooms within model

Room number	Room	Area (m²)
1	Kitchen	7,1
2	Entrance	2,0
3	Bedroom 1 – Galleryside	13,9
4	Bedroom 2 – Balconyside	12,3
5	Living room	19,2
6	Toilet	1,0
7	Laundry room	3,7
8	Storage	0,6
9	Installation space	0,3
10	Hallway	4,5
11	Shaft 1	0,5
12	Shaft 2	1,2

Appendix 7.2 – Domestic hot water consumption input

Domestic hot water consumption			
Number of inhabitants	Hot water demand	Building usage days	Efficiency of water heating
3	30 litres per person per day	330	0,85

Appendix 7.3 – Input of constructions within case

Construction	Buildup	R value (m^2K/W)	U value (W/m^2K)
Exterior wall 1 – Balcony side concrete	100mm masonry – 50mm cavity – 250mm concrete – 10mm plasterboard	0,5	-
Exterior wall 2 – Under windows	5mm Glasal cementpanel – 60mm Glasal insulation – 5mm Glasal cementpanel – 60mm cavity – 90mm alluvial stone – 10mm plasterboard	2,75	-
Exterior wall 3 – Upper side concrete	360mm concrete – 50mm Schewil insulation – 10mm plasterboard	1,5	-
Interior wall 1 – Alluvial stone	10mm plasterboard – 90mm alluvial stone – 10mm plasterboard	0,59	-
Interior wall 2 – Concrete	300mm concrete	0,16	-
Floors / ceilings	10mm flooring – 220mm MUWI hollow core slab floor – 10mm plasterboard	0,21	-
Windows 1 – Steel	Steel window frame – Single glazing	-	5,37
Windows 2 – Thermopane	Wood window frame – Thermopane double glazing	-	3,20
Interior windows	Wood window frame – single glazing	-	5,37
Interior doors	40mm Triplex wood	0,24	-

Exterior doors	70mm Hardwood	0,41	-

Appendix 7.4 – Internal heat production input

Internal heat production			
Type of room	**Internal heat production of people (peak)**	**Internal heat production of appliances (peak)**	**Internal heat production of lighting (peak)**
Bathroom	1 person Summer clothing: 0,5 CLO Winter clothing: 0,9 CLO Activity level: 1,2 MET	150W	5 W/m²
Kitchen		300W	
Bedroom	1 person Summer clothing: 0,5 CLO Winter clothing: 0,9 CLO Activity level: 0,8 MET	25W	
Living room	2 persons Summer clothing: 0,5 CLO Winter clothing: 0,9 CLO Activity level: 1,2 MET	100W	
Other living spaces		100W	

Appendix 7.5 – Room usage time schedule input

Time schedule of usage			
Type of room	**People**	**Appliances**	**Lighting**
Bathroom	07:00 – 09:00 ; 100% 22:00 – 23:00 ; 100% Remaining times ; 0%	07:00 – 08:00 ; 100% 18:00 – 20:00 ; 100% Remaining times ; 7%	07:00 – 09:00 ; 25% 18:00 – 20:00 ; 25% 22:00 – 23:00 ; 25% Remaining times ; 0%
Kitchen	18:00 – 20:00 ; 100% Remaining times ; 0%	07:00 – 09:00 ; 25% 09:00 – 16:00 ; 31% 16:00 –18:00 ; 38% 18:00 – 20:00 ; 100% 20:00 – 23:00 ; 38% 23:00 – 07:00 ; 19%	07:00 – 10:00 ; 15% 17:00 – 19:00 ; 35% 19:00 – 20:00 ; 75% 20:00 – 22:00 ; 100% 22:00 – 23:00 ; 75% Remaining times ; 0%
Bedroom	23:00 – 07:00 ; 100% Remaining times ; 0%	00:00 – 24:00 ; 100%	06:00 – 09:00 ; 25% 23:00 – 24:00 ; 25% Remaining times ; 0%
Living room	07:00 – 20:00 ; 50% 20:00 – 23:00 ; 100% Remaining times ; 0%	23:00 – 09:00 ; 50% 09:00 – 16:00 ; 75% 16:00 – 23:00 ; 100%	07:00 – 10:00 ; 15% 17:00 – 19:00 ; 35% 19:00 – 20:00 ; 75% 20:00 – 22:00 ; 100% 22:00 – 23:00 ; 75% Remaining times ; 0%

Other living spaces	07:00 – 19:00 ; 50% 19:00 – 22:00 ; 100% Remaining times ; 0%	22:00 – 09:00 ; 50% 09:00 – 16:00 ; 75% 16:00 – 22:00 ; 100%	07:00 – 10:00 ; 15% 17:00 – 19:00 ; 35% 19:00 – 20:00 ; 75% 20:00 – 22:00 ; 100% 22:00 – 23:00 ; 75% Remaining times ; 0%

Appendix 7.6 – Time schedule of heating input

Type of room	Time schedule of heating
Kitchen	06:00 – 08:00 15:00 – 20:00
Bedroom	17:00 – 23:00
Living room	06:00 – 09:00 16:00 – 22:00

Appendix 7.7 – Heat generation system input

Heat generation				
Configuration	**System**	**Location of generator**	**Type**	**Heat certification**
Individual system	Combi heat generator	Inside zone	Combi boiler	Improved efficiency boiler

Appendix 7.8 – Heat distribution system input

Distribution			
System	**Generation**	**Temperature level**	**Temperatures**
Hot-water net	Combiketel	High Temperature	Day = 80 degrees Night = 80 degrees

Appendix 7.9 – Input changes from base situation to energy poverty situation

Element	Base situation	Change	Energy poverty situation
Domestic hot water	House usage: 3 persons Water usage: 30 L/person/day Building usage: 340 days/year Efficiency of heating system: 0,85	In energy poverty, households shorten their showering time and other forms of water heating.	House usage: 3 persons Water usage: 20 L/person/day Building usage: 340 days/year Efficiency of heating system: 0,85
Internal heat production of people	Summer clothing: 0,5 CLO Winter clothing: 0,8 CLO Activity level: 0,8 / 1,2 MET	In energy poverty, households increase the amount of insulating clothing they wear so heat demands decreases.	Summer clothing: 0,5 CLO Winter clothing: 1,2 CLO Activity level: 0,8 / 1,2 MET
Time schedule of heating	Kitchen: 06:00 – 08:00 / 15:00 – 20:00 Bedroom: 17:00 – 23:00 Living room: 06:00 – 09:00 / 16:00 – 22:00	In energy poverty, households become more selective in the rooms they heat, and for which times they are heated.	Kitchen: 18:00 – 20:00 Bedroom: 19:00 – 23:00 Living room: 06:00 – 08:00 / 18:00 – 22:00

Heating setpoints	Daytime usage: 19^0C Nighttime / base usage: 14^0C	In energy poverty, households significantly lower their temperature standards to values between 11 and 14 degrees.	Daytime usage: 13.5^0C Nighttime / base usage: 11.5^0C

Appendix 7.10 – Simulation review criteria

Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657	346
Gas consumption with intervention and same temperature settings (m^3)		
Improvement (%)		
Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (^{o}C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(^{o}C)		
Improvement (^{o}C)		
Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)		
Gas consumption savings with same temperature settings (m^3)		
Gas pricing (€)		
Yearly savings with same temperature settings (€)		
Payback period (years)		
Old gas bill (€)		
New gas bill (€)		
Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's		
Intervention cons		

Appendix 7.11 – Rc value calculations of constructions

Vestiging Driebergen
Patrimoniumstraat 1
3971 MR Driebergen
T 0343 51 28 86

Vestiging Delft
Mijnbouwstraat 110
2628 RX Delft
T 015 215 96 00

mail@moBiusconsult.nl · www.moBiusconsult.nl

Exterior wall 1 – Balcony side concrete

Thermal protection

R = 0,533 m²K/W

Bouwbesluit 2015*: Rc> m²K/W

excellent insufficient

Moisture proofing

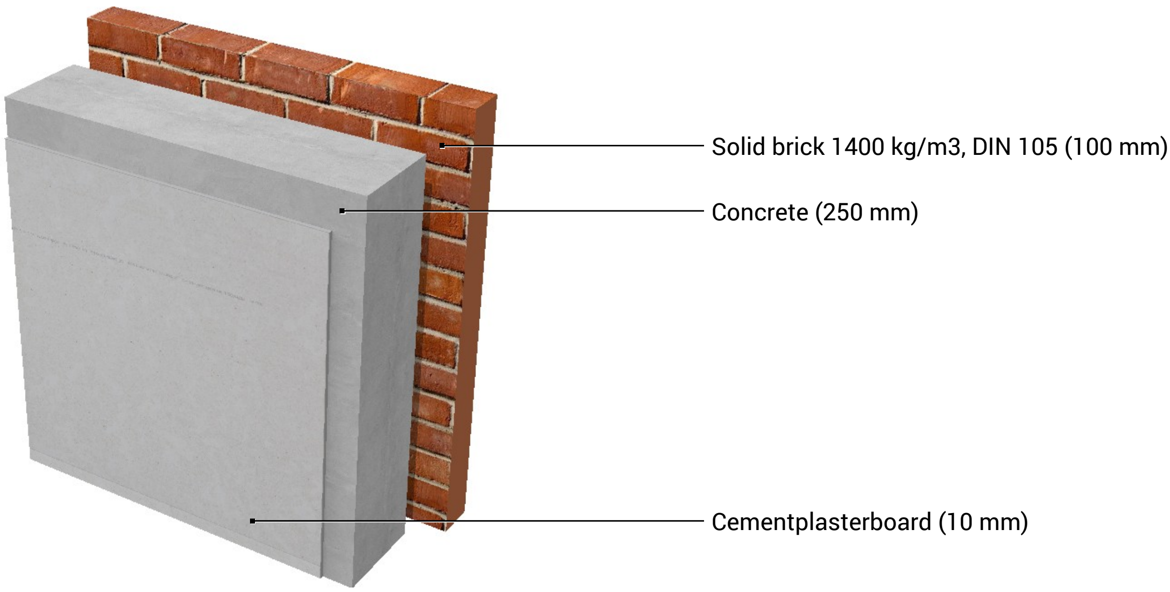
No condensate

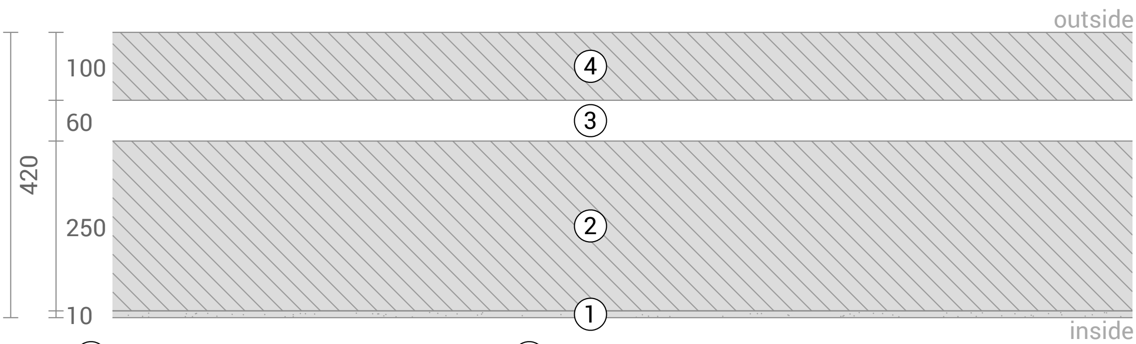
excellent insufficient

Heat protection

Temperature amplitude damping: 21
phase shift: 11,0 h
Thermal capacity inside: 346 kJ/m²K

excellent insufficient





1. Cementplasterboard (10 mm)
2. Concrete (250 mm)
3. Vertical cavity (60 mm)
4. Solid brick 1400 kg/m3, DIN 105 (100 mm)

Inside air :	20,0°C / 50%		Thickness:	42,0 cm
Outside air:	-5,0°C / 80%	sd-value: 21,1 m	Weight:	747 kg/m²
Surface temperature.:	12,4°C / -3,8°C		Heat capacity:	716 kJ/m²K

☐ Bouwbesluit 2015 ☐ BEG Einzelmaßn. ☐ GEG 2020/24 Bestand ☐ GEG 2023/24 Neubau

*Comparison of the U-value with grenswaarde volgens Bouwbesluit 2015; den techn. Mindestanforderungen für BEG Einzelmaßnahmen; den Höchstwerten aus GEG Anlage 7 (GEG 2020-2024 Bestand); 70% des U-Werts der Referenzausführung aus GEG 2023/2024 Anlage 1 (GEG Neubau)

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Exterior wall 1 – Balcony side concrete external insulation

Thermal protection

R = 4,37 m²K/W

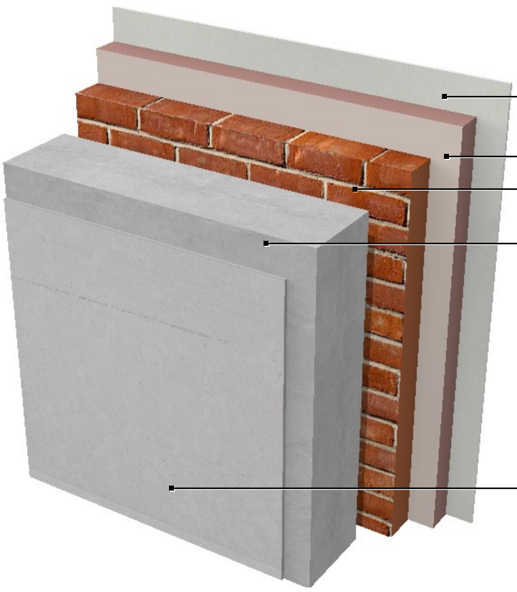
Bouwbesluit 2015*: Rc> m²K/W

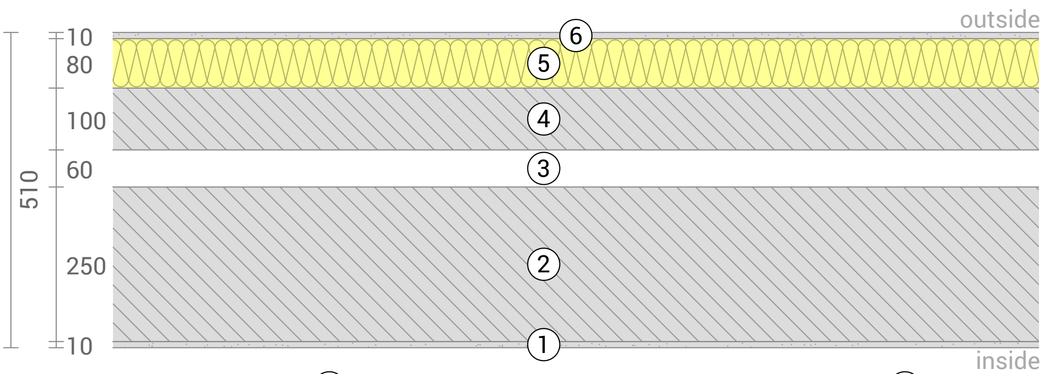
excellent insufficient

Heat protection

Temperature amplitude damping: >100
phase shift: non relevant
Thermal capacity inside: 653 kJ/m²K

excellent insufficient





1. Cementplasterboard (10 mm)
2. Concrete (250 mm)
3. Vertical cavity (60 mm)
4. solid brick 1400 kg/m3, DIN 105 (100 mm)
5. Kooltherm® K5 (80 mm)
6. Plaster (10 mm)

Inside air :	20,0°C / 50%	Thickness:	51,0 cm
Outside air:	-5,0°C / 80%	Weight:	760 kg/m²
Surface temperature.:	18,7°C / -4,8°C	Heat capacity:	731 kJ/m²K

☐ Bouwbesluit 2015 ☐ BEG Einzelmaßn. ☑ GEG 2020/24 Bestand ☐ GEG 2023/24 Neubau

*Comparison of the U-value with grenswaarde volgens Bouwbesluit 2015; den techn. Mindestanforderungen für BEG Einzelmaßnahmen; den Höchstwerten aus GEG Anlage 7 (GEG 2020-2024 Bestand); 70% des U-Werts der Referenzausführung aus GEG 2023/2024 Anlage 1 (GEG Neubau)

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Exterior wall 1 – Balcony side concrete indoor insulation

Thermal protection

R = 4,09 m²K/W

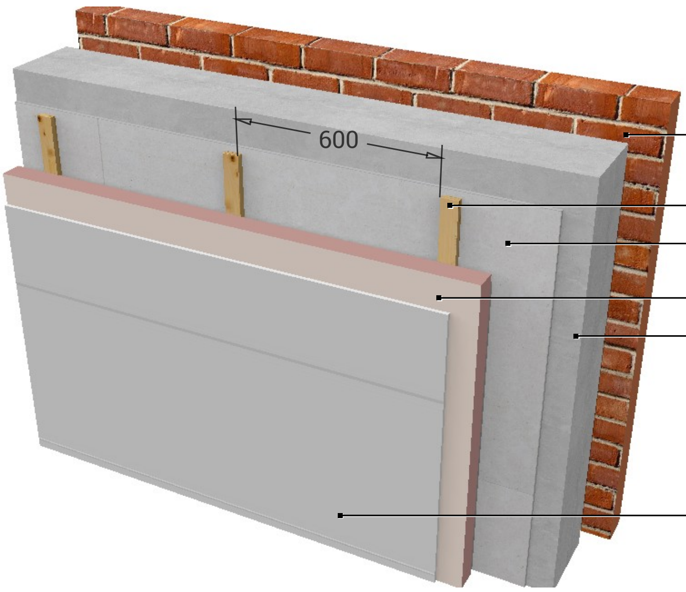
Bouwbesluit 2015*: Rc> m²K/W

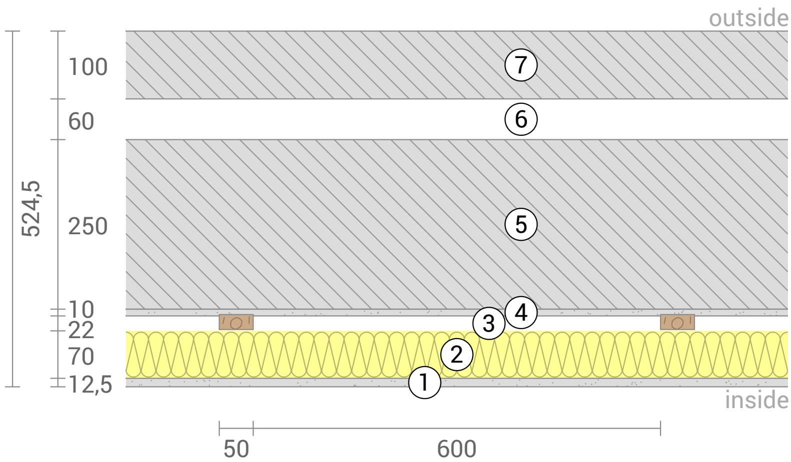
excellent insufficient

Heat protection

Temperature amplitude damping: 65
phase shift: 16,0 h
Thermal capacity inside: 75 kJ/m²K

excellent insufficient





1. Gypsum board (12,5 mm)
2. Kooltherm K17 (70 mm)
3. Vertical cavity (22 mm)
4. Cementplasterboard (10 mm)
5. Concrete (250 mm)
6. Vertical cavity (60 mm)
7. solid brick 1400 kg/m3, DIN 105 (100 mm)

Inside air :	20,0°C / 50%
Outside air:	-5,0°C / 80%
Surface temperature.:	18,6°C / -4,8°C

Thickness:	52,5 cm
Weight:	759 kg/m²
Heat capacity:	729 kJ/m²K

☐ Bouwbesluit 2015 ☐ BEG Einzelmaßn. ☐ GEG 2020/24 Bestand ☐ GEG 2023/24 Neubau

*Comparison of the U-value with grenswaarde volgens Bouwbesluit 2015; den techn. Mindestanforderungen für BEG Einzelmaßnahmen; den Höchstwerten aus GEG Anlage 7 (GEG 2020-2024 Bestand); 70% des U-Werts der Referenzausführung aus GEG 2023/2024 Anlage 1 (GEG Neubau)

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Exterior wall 2 – Under windows

Thermal protection

R = 2,75 m²K/W

Bouwbesluit 2015*: Rc> m²K/W

excellent insufficient

Moisture proofing

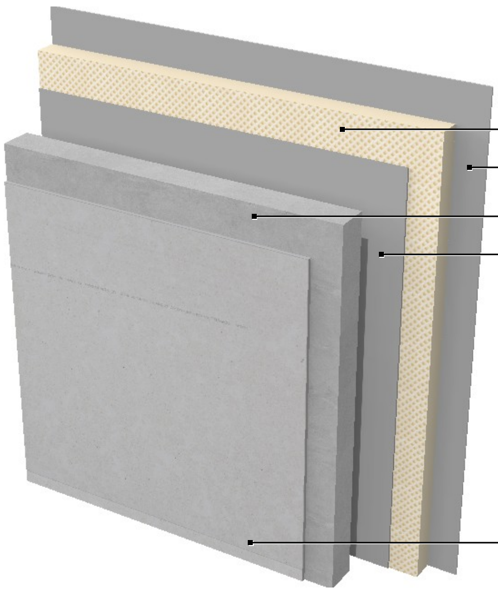
No condensate

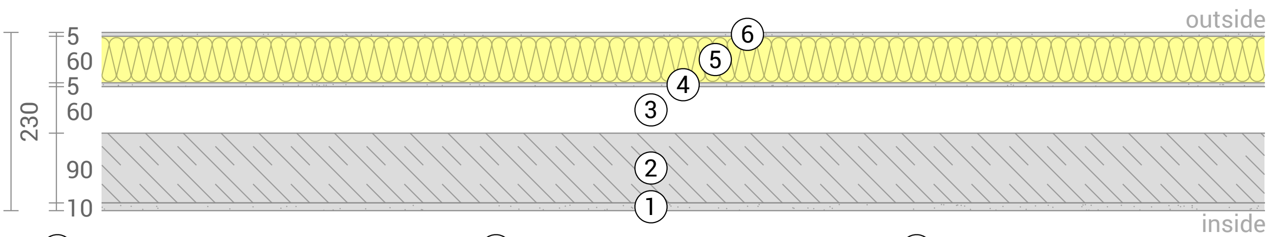
excellent insufficient

Heat protection

Temperature amplitude damping: 12
phase shift: 8,3 h
Thermal capacity inside: 58 kJ/m²K

excellent insufficient





1. Cementplasterboard (10 mm)
2. Drijfsteen (90 mm)
3. Vertical cavity (60 mm)
4. Glasal Cementpanel (5 mm)
5. Glasal insulation (60 mm)
6. Glasal Cementpanel (5 mm)

Inside air :	20,0°C / 50%	Thickness:	23,0 cm
Outside air:	-5,0°C / 80% sd-value: 5,7 m	Weight:	93 kg/m²
Surface temperature.:	17,9°C / -4,7°C	Heat capacity:	81 kJ/m²K

☐ Bouwbesluit 2015 ☐ BEG Einzelmaßn. ☐ GEG 2020/24 Bestand ☐ GEG 2023/24 Neubau

*Comparison of the U-value with grenswaarde volgens Bouwbesluit 2015; den techn. Mindestanforderungen für BEG Einzelmaßnahmen; den Höchstwerten aus GEG Anlage 7 (GEG 2020-2024 Bestand); 70% des U-Werts der Referenzausführung aus GEG 2023/2024 Anlage 1 (GEG Neubau)

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Exterior wall 2 – Under windows external insulation

Thermal protection

R = 6,58 m²K/W

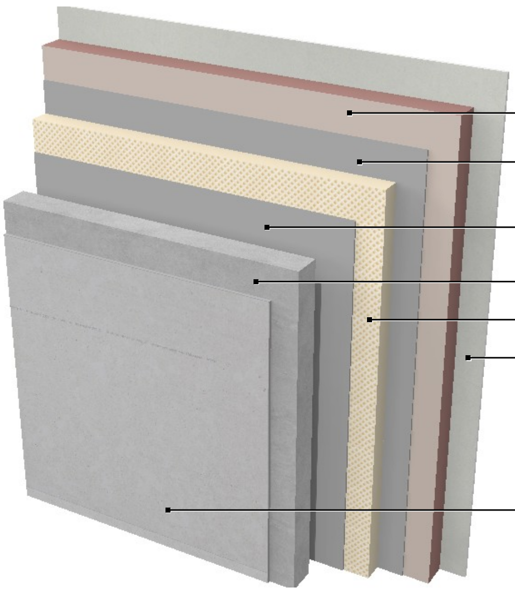
Bouwbesluit 2015*: Rc> m²K/W

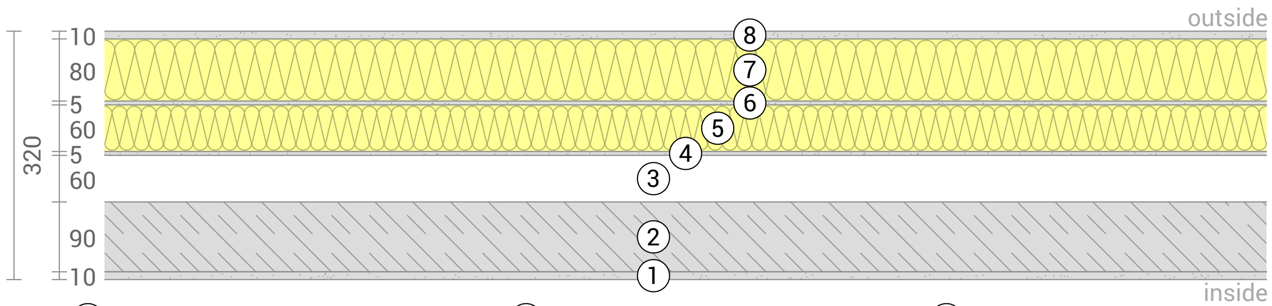
excellent insufficient

Heat protection

Temperature amplitude damping: 51
phase shift: 12,3 h
Thermal capacity inside: 72 kJ/m²K

excellent insufficient





1. Cementplasterboard (10 mm)
2. Drijfsteen (90 mm)
3. Vertical cavity (60 mm)
4. Glasal Cementpanel (5 mm)
5. Glasal insulation (60 mm)
6. Glasal Cementpanel (5 mm)
7. Kooltherm K5 (80 mm)
8. Plaster (10 mm)

Inside air :	20,0°C / 50%
Outside air:	-5,0°C / 80%
Surface temperature.:	19,1°C / -4,9°C

Thickness:	32,0 cm
Weight:	106 kg/m²
Heat capacity:	95 kJ/m²K

☑ Bouwbesluit 2015 ☑ BEG Einzelmaßn. ☑ GEG 2020/24 Bestand ☑ GEG 2023/24 Neubau

*Comparison of the U-value with grenswaarde volgens Bouwbesluit 2015; den techn. Mindestanforderungen für BEG Einzelmaßnahmen; den Höchstwerten aus GEG Anlage 7 (GEG 2020-2024 Bestand); 70% des U-Werts der Referenzausführung aus GEG 2023/2024 Anlage 1 (GEG Neubau)

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Exterior wall 2 – Under windows indoor insulation

Thermal protection

R = 6,31 m²K/W

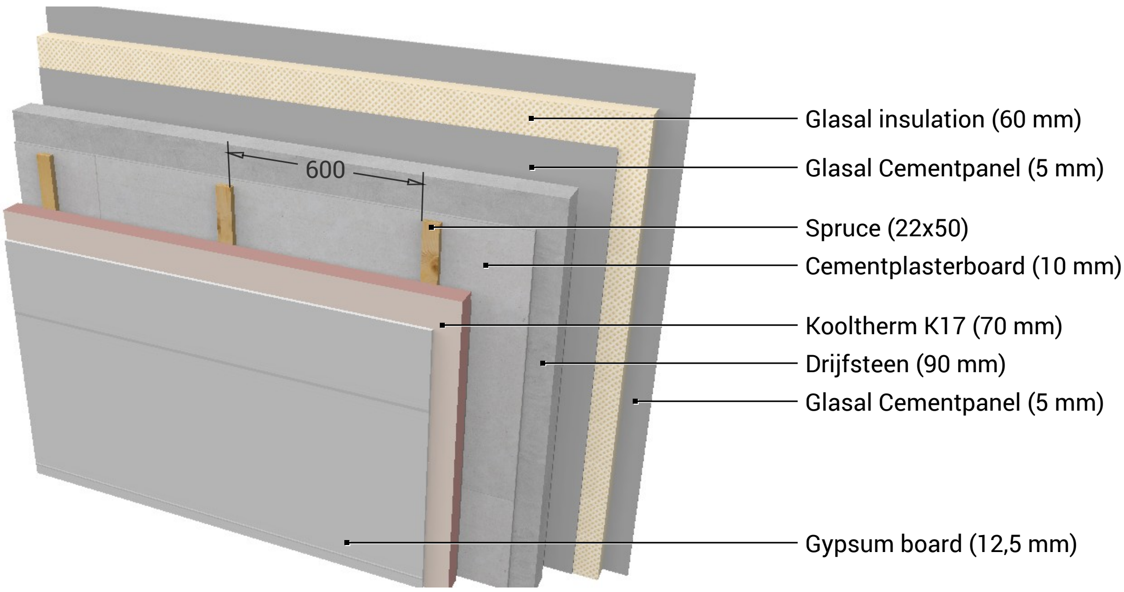
Bouwbesluit 2015*: Rc> m²K/W

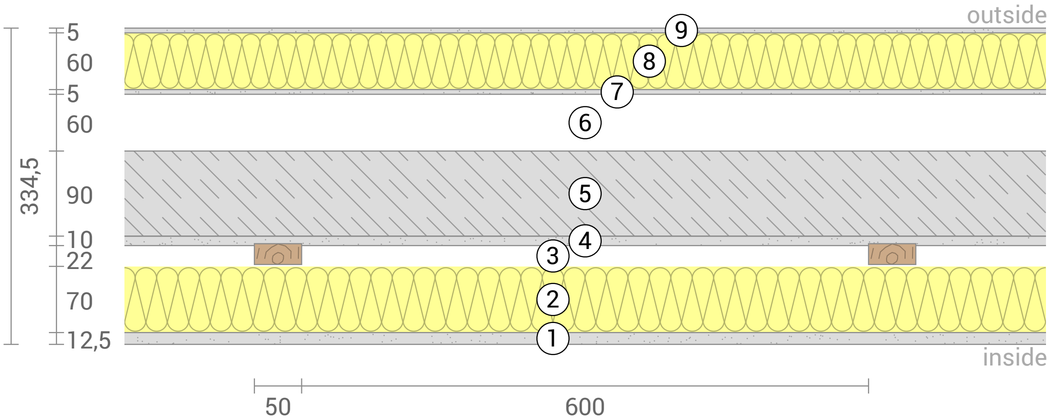
excellent insufficient

Heat protection

Temperature amplitude damping: 36
phase shift: 13,2 h
Thermal capacity inside: 38 kJ/m²K

excellent insufficient





1. Gypsum board (12,5 mm)
2. Kooltherm K17 (70 mm)
3. Vertical cavity (22 mm)
4. Cementplasterboard (10 mm)
5. Drijfsteen (90 mm)
6. Vertical cavity (60 mm)
7. Glasal Cementpanel (5 mm)
8. Glasal insulation (60 mm)
9. Glasal Cementpanel (5 mm)

Inside air :	20,0°C / 50%
Outside air:	-5,0°C / 80%
Surface temperature.:	19,1°C / -4,8°C

Thickness:	33,5 cm
Weight:	105 kg/m²
Heat capacity:	93 kJ/m²K

☑ Bouwbesluit 2015 ☑ BEG Einzelmaßn. ☑ GEG 2020/24 Bestand ☑ GEG 2023/24 Neubau

*Comparison of the U-value with grenswaarde volgens Bouwbesluit 2015; den techn. Mindestanforderungen für BEG Einzelmaßnahmen; den Höchstwerten aus GEG Anlage 7 (GEG 2020-2024 Bestand); 70% des U-Werts der Referenzausführung aus GEG 2023/2024 Anlage 1 (GEG Neubau)

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Exterior wall 3 – Upper side concrete

Thermal protection

R = 1,51 m²K/W

Bouwbesluit 2015*: Rc> m²K/W

excellent insufficient

Moisture proofing

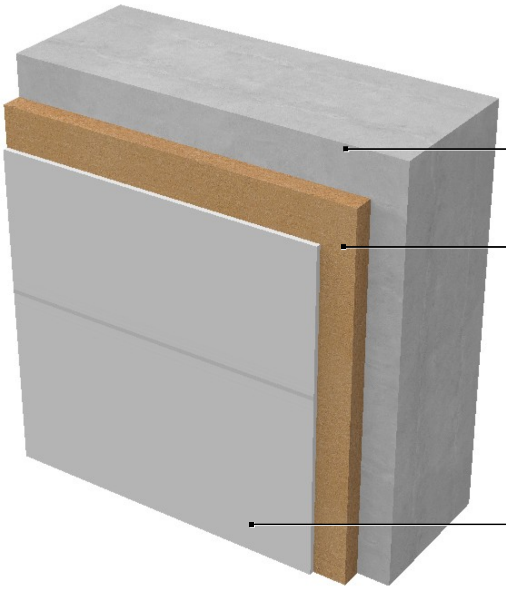
Condensate: 5,05 kg/m²
Dries 121 days

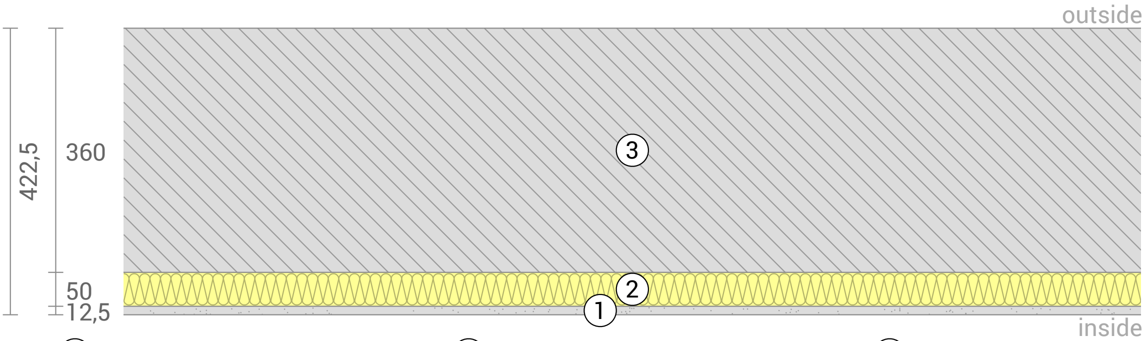
excellent insufficient

Heat protection

Temperature amplitude damping: 8,4
phase shift: 12,7 h
Thermal capacity inside: 76 kJ/m²K

excellent insufficient





① Gypsum board (12,5 mm) ② Schewill insulation (50 mm) ③ Concrete (360 mm)

Inside air :	20,0°C / 50%		Thickness:	42,2 cm
Outside air:	-5,0°C / 80%	sd-value: 47,0 m	Weight:	878 kg/m²
Surface temperature.:	16,5°C / -4,4°C		Heat capacity:	841 kJ/m²K

☐ Bouwbesluit 2015 ☐ BEG Einzelmaßn. ☐ GEG 2020/24 Bestand ☐ GEG 2023/24 Neubau

*Comparison of the U-value with grenswaarde volgens Bouwbesluit 2015; den techn. Mindestanforderungen für BEG Einzelmaßnahmen; den Höchstwerten aus GEG Anlage 7 (GEG 2020-2024 Bestand); 70% des U-Werts der Referenzausführung aus GEG 2023/2024 Anlage 1 (GEG Neubau)

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Exterior wall 3 – Upper side concrete indoor insulation

Thermal protection

R = 5,07 m²K/W

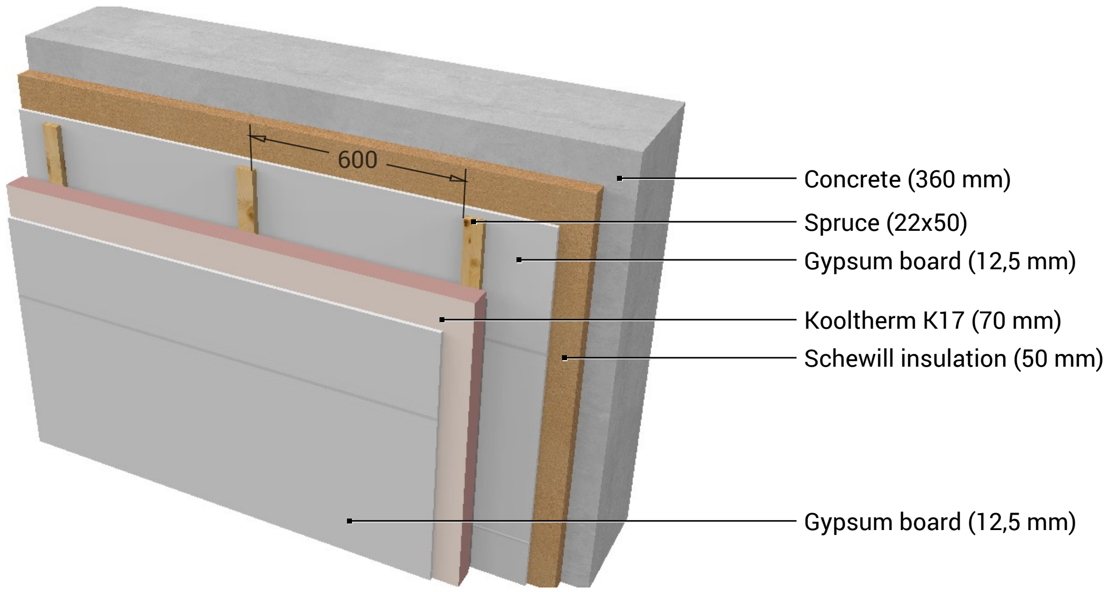
Bouwbesluit 2015*: Rc> m²K/W

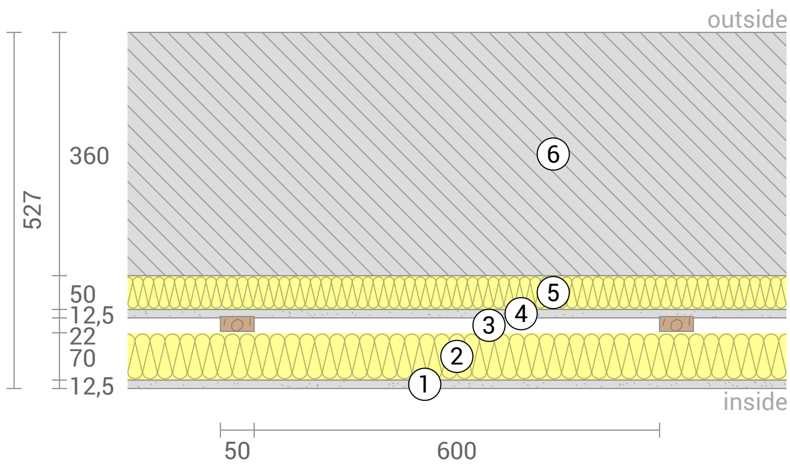
excellent insufficient

Heat protection

Temperature amplitude damping: 31
phase shift: 17,3 h
Thermal capacity inside: 36 kJ/m²K

excellent insufficient





1. Gypsum board (12,5 mm)
2. Kooltherm K17 (70 mm)
3. Vertical cavity (22 mm)
4. Gypsum board (12,5 mm)
5. Schewill insulation (50 mm)
6. Concrete (360 mm)

Inside air :	20,0°C / 50%
Outside air:	-5,0°C / 80%
Surface temperature.:	18,8°C / -4,8°C

Thickness:	52,7 cm
Weight:	890 kg/m²
Heat capacity:	853 kJ/m²K

☑ Bouwbesluit 2015 ☑ BEG Einzelmaßn. ☐ GEG 2020/24 Bestand ☑ GEG 2023/24 Neubau

*Comparison of the U-value with grenswaarde volgens Bouwbesluit 2015; den techn. Mindestanforderungen für BEG Einzelmaßnahmen; den Höchstwerten aus GEG Anlage 7 (GEG 2020-2024 Bestand); 70% des U-Werts der Referenzausführung aus GEG 2023/2024 Anlage 1 (GEG Neubau)

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Exterior wall 3 - Upper side concrete external insulation

Thermal protection

R = 5,35 m²K/W

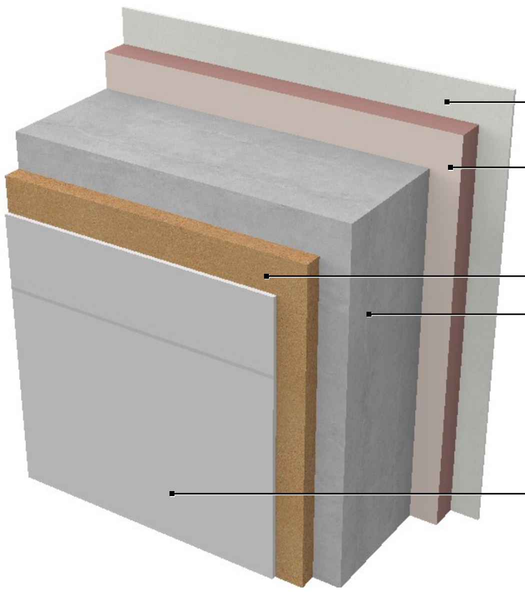
Bouwbesluit 2015*: Rc> m²K/W

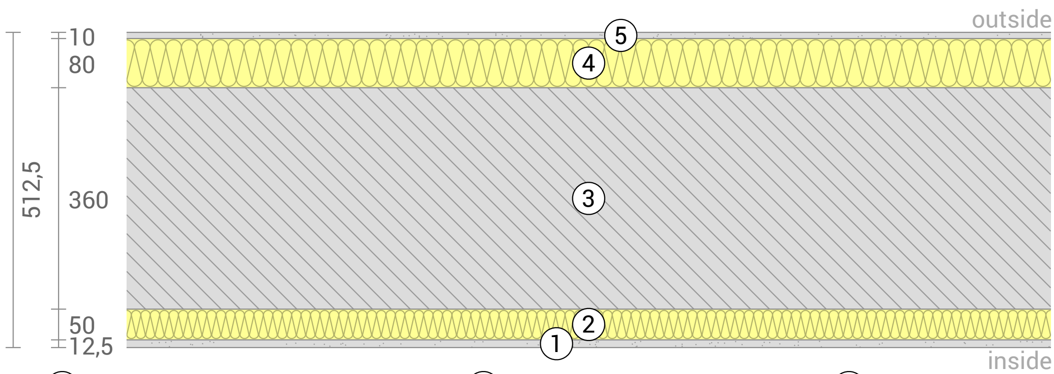
excellent insufficient

Heat protection

Temperature amplitude damping: >100
phase shift: non relevant
Thermal capacity inside: 598 kJ/m²K

excellent insufficient





1 Gypsum board (12,5 mm)
2 Schewill insulation (50 mm)
3 Concrete (360 mm)
4 Kooltherm K5 (80 mm)
5 Plaster (10 mm)

Inside air :	20,0°C / 50%
Outside air:	-5,0°C / 80%
Surface temperature.:	18,9°C / -4,8°C

Thickness:	51,2 cm
Weight:	891 kg/m²
Heat capacity:	855 kJ/m²K

☑ Bouwbesluit 2015 ☑ BEG Einzelmaßn. ☑ GEG 2020/24 Bestand ☑ GEG 2023/24 Neubau

*Comparison of the U-value with grenswaarde volgens Bouwbesluit 2015; den techn. Mindestanforderungen für BEG Einzelmaßnahmen; den Höchstwerten aus GEG Anlage 7 (GEG 2020-2024 Bestand); 70% des U-Werts der Referenzausführung aus GEG 2023/2024 Anlage 1 (GEG Neubau)

Appendix 7.12 – Qv10 calculations of constructions

Collection of room and façade specifications

Information	Buildup
1. Room type 2. Volume 3. Sealing indication 4. Façade surface 5. Rooms & doors	Bedroom 1 (facing gallery) 39 m^3 Dwelling from 1960, so it is not very well insulated or airtight (same for all rooms) Total exterior surface area: 8 m^2 2.4 m^2 of this consists of double-glazed windows in wooden frames, also from the same time period and therefore not of very high quality.
1. Room type 2. Volume 3. Sealing indication 4. Façade surface 5. Rooms & doors	Kitchen: 19.8 m^3 Dwelling from 1960, so it is not very well insulated or airtight (same for all rooms) Total exterior surface area: 7.7 m^2 2.6 m^2 of this consists of double-glazed windows in wooden frames, also from the same time period and therefore not of very high quality.
1. Room type 2. Volume 3. Sealing indication 4. Façade surface 5. Rooms & doors	Living room 53.6 m^3 Dwelling from 1960, so it is not very well insulated or airtight (same for all rooms) Total exterior surface area: 10.7 m^2 6 m^2 of this consists of double-glazed windows in wooden frames, also from the same time period and therefore not of very high quality.
1. Room type 2. Volume 3. Sealing indication 4. Façade surface 5. Rooms & doors	Bedroom 2 (facing balcony): 34.4 m^3 Dwelling from 1960, so it is not very well insulated or airtight (same for all rooms) Total exterior surface area: 8 m^2 2.6 m^2 of this consists of double-glazed windows in wooden frames, also from the same time period and therefore not of very high quality. 1.5 m^2 is a door.

The characteristic infiltration flow (*Gebouweisen - VaBi Support*, 2025) has been calculated through the use of ISSO-publication 51, which provides guidelines on how to set-up heat loss calculations for dwellings and is used in Dutch regulation (ISSO kennisinstituut voor installatietechniek, 2017). It has been done through the following steps:

Step	Element	Formula / explanation	Value(s)	Source/comment
1	Building dimensions	The building dimensions are needed to estimate the correctionfactor due to wind.	L = 68m W = 12m H = 35m	Extracted from drawings
2	Correctionfactor: f_{wind}	$f_{wind} = \max\left[1; \left\{0{,}01 \cdot \left(24 + 0{,}555 \cdot \sqrt{(L^2 + B^2)} + 4{,}5 \cdot H\right)\right\}^{0{,}65}\right]$	1,14	
3	Correctionfactor: f_{type}	The f_{type} correctionfactor relates to the characteristic infiltration of the building type.	0,51	Table 4.5
4	Correctionfactor: f_{inf}	The f_{inf} correctionfactor relates to the characteristic infiltration of the ventilation system.	1,0	Table 4.6
5	Specific infiltration flow: $q_{i,spec}$	The $q_{i,spec}$ infiltration flow relates to the characteristic infiltration of the building type.	0,0022 $m^3/s/m^2$	Table 4.7
6	Calculation of q_{is}	$q_{is} = f_{wind} \cdot f_{type} \cdot f_{inf} \cdot (0{,}23 \cdot q_{i,spec})$	0,000295 $m^3/s/m^2$	

7	Usage surface ag		65m²	Extracted from drawings
8	Infiltration volume flow	$q_i = q_{is} \cdot A_g$	0,0192 m³/s	
9	Air changes per hour (ACH)	$\frac{q_i \cdot 3600}{V}$	0.37 -> 0.4 1/h	

Table 4.5

Gebouwtype			f_{type}
Gebouwen met kap	Grondgebonden, één laag, gebouweenheden met verscheidene bouwlagen in open verbinding	Grondgebonden eengezinswoningen of kantoorvilla's	1,0
		Bij elkaar horende topverdiepingen van gestapelde laagbouw	
Gebouwen met plat dak	Grondgebonden, één laag, categorie utiliteitsbouw, gebouweenheden met verscheidene bouwlagen in open verbinding	Grondgebonden eengezinswoningen of kantoorvilla's	0,77
		Bij elkaar horende verdiepingen van gestapelde laagbouw	
Gebouwen met meer lagen	Etages van gebouwen met meer lagen uit de categorie flat- of portiekwoningen met geveltype[1)]	Standaard	0,51
		Volgevel binnengalerij aan één zijde	0,48
		Dubbele huidgevel met onderbroken tussenruimte	0,46
		Dubbele huidgevel met doorlopende tussenruimte	0,15
1) Het onderscheid in de factoren f_{type} naar geveltype geldt uitsluitend indien de tussenruimten per etage (dus in verticale zin) luchttechnisch zijn gescheiden. Indien dit niet het geval is, geldt voor alle geveltypen van deze flatwoningen of kantooretages de standaardwaarde f_{type} = 0,51.			

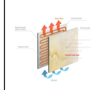
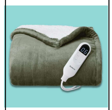
Table 4.6

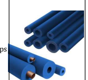
Ventilatiesysteem		f_{inf}
A	Systemen met natuurlijke toe- en afvoer	0,80
B	Systemen met mechanische toevoer en natuurlijke afvoer	0,85
C	Systemen met natuurlijke toevoer en mechanische afvoer	1,0
D	Systemen met mechanische toe- en afvoer; gebalanceerde ventilatie	1,15
E.1	Zones met natuurlijke toevoer en mechanische afvoer en zones met lokale WTW, CO_2-sturing op afvoer van ruimtes met lokale WTW	1,08

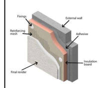
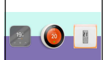
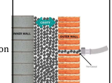
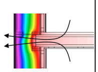
Table 4.7

Gebouwtype			Bouwjaar/renovatiejaar		
			< 1970	1970-1980	1980-1992
Grondgebonden woningen	Eénlaags met een kap	Tussenwoning	0,0043	0,0028	0,0019
		Hoekwoning	0,0052	0,0034	0,0023
		Vrijstaande woning, puntdak	0,0060	0,0039	0,0027
		Vrijstaande woning, half plat dak	0,0052	0,0034	0,0023
	Eénlaags met een plat dak	Tussenwoning	0,0030	0,0020	0,0013
		Hoekwoning	0,0036	0,0024	0,0016
		Vrijstaande woning	0,0042	0,0027	0,0019
Meerlaagse woningen	Etage van flat-/portiekwoning	Tussenligging op onderste of tussenverdieping	0,0022	0,0014	0,0010
		Kop-, eind- of hoekligging op onderste of tussenverdieping	0,0028	0,0018	0,0012
		Tussenligging op bovenste verdieping	0,0026	0,0017	0,0011
		Kop-, eind- of hoekligging op bovenste verdieping	0,0030	0,0020	0,0013

Appendix: 8 – Intervention library overview

Scale	Method / appliance	Image	Short description	Effect through	Effected propery	Price	Source of price	Source of research	Pro's	Cons	Hypothesis of effectiveness	Choice of modelling and modelling method
Basic interventions	Portable space heaters		Compact electric or gas heaters designed to warm small areas quickly	Thermal comfort through warm air heat flow. Portable space heaters cause air to heat up and start flowing.	Heating efficiency	20/30,-	www.amazon.com/space-heater/s?k=spac	Ali, A. H. H., & Morsy, M. G. (2010). Energy efficiency and indoor thermal perception: a comparative study between radiant panel and portable convective heaters. Energy Efficiency, 3(4), 283–301. https://doi.org/10.1007/s12053-010-9077-3	Targeted and localized heating, portable and flexible, fast heating time	High energy consumption, dries out air, ineffective in larger spaces	Portable space heaters seem like an effective manner to achieve more local heating. This would mean that these heaters would aid in providing local thermal comfort, which is of aid when it comes to energy poverty. At the same time, unless there is a large discrepancy between gas en electricity prices, heatings costs don't seem to reduce significantly. Besides this, portable space heaters don't present themselves as a long-term solution for thermal comfort.	CFD/VABI
	Infrared heating panels		Wall- or ceiling-mounted panels that provide radiant heat.	Infrared heating panels provide direct personal comfort. Due to the radiative heat, concentrated areas can be heated with good controll.	Heating efficiency	100/200,-	https://www.bol.com/nl/nl/s/?searchtext=infrarood%20verwarmingspaneel&suggestFragment=infrarood%20v	Rugani, R., Bernagozzi, M., Picco, M., Salvadori, G., Marengo, M., Zhang, H., & Fantozzi, F. (2023). Thermal comfort and energy efficiency evaluation of a novel conductive-radiative Personal Comfort System. Building and Environment, 244, 110787. https://doi.org/10.1016/j.buildenv.2023.110787	Efficient and direct heating, silent operation, low maintenance, aesthetical options	Limited range, requires precise positioning, higher investment costs	Infrared heating panels aim toward providing local comfort, at a higher efficiency than standard radiators. The research on the effects of infrared heating panels discuss the succes these panels have in achieving this through radiation. Unlike other heating methods, these panels don't rely on heating the entire air of a room, but only focus on concentrated areas. This, alongside the long-term implication of mounting these panels point towards the potential in fighting energy poverty.	CFD/VABI
	Electric blankets		Energy-efficient blankets with adjustable heat settings.	Electric blankets provide full body warmth with its controls. It doesn't provide space heating. It does provide thermal comfort in stationairy positions.	Heating efficiency	30/70,-	https://www.bol.com/nl/nl/l/elektrische-dekens/14204/?psafe_param=1&Referrer=ADVNLGOO002028-S--&gad_source=1&gclid=Cj0KCQiAqL28BhCrARIsACYJvke2DHl8PIO4PMz_sCkfM6dPq8wQBWS2wXpzF8TzqbUcGfn3UqD2L_waAlfREALw_wcB		High heating efficiency, fast heating time, lightweight and portable	Short lifespan, very local heating, safety concerns	Electrical blankets function in a similar way as portable space heaters and infrared heating panels, in providing thermal comfort. But unlike these methods, these blankets are even more localized and don’t provide a longer term solution.	Will not be simulated due to simulation program limitations
	Radiator foil		Foil placed behind radiators to reflect heat back into the room.	Radiator foil is used to reduce energy costs and to improve the effectiveness of radiators.	Radiator efficiency and U value of wall	5/20,-	https://www.gamma.nl/assortiment/l/verwarming-isolatie-ventilatie/isolatiemateriaal/radiatorfolie	Harris, D. (1995). Use of metallic foils as radiation barriers to reduce heat losses from buildings. Applied Energy, 52(4), 331–339. https://doi.org/10.1016/0306-2619(95)00018-6	Reduces heat losses, cheap and easy to install, effective in older buildings	Limited impact, effectiveness depends on wall type, not suitable on other heat sources	Radiator foil is considered a wide-spread applied intervention against energy poverty. It presents itsself as a low cost energy efficiency measure, which reduces energy consumption and reduces energy costs. Besides this, it is easy to apply and claims to work especially well on badly insulated walls. These characteristics make it an attractive intervention against energy poverty.	VABI
	Draft stoppers		Placed at the base of doors and windows to reduce cold air intrusion and improve thermal comfort.	Draft stoppers are used to prevent cold air from flowing through dwellings. The reduction of draft reduces energy costs through heating, it also increases thermal comfort, by removing cold air flows.	Air tightness of building	5/10,-	https://www.gamma.nl/assortiment/l/verwarming-isolatie-ventilatie/isolatieklus/tochtwering	Barrella, R., Romero, J. C., Laguillo, A., & Sevilla, E. (2023). Assessing the Impact of Shallow Renovation on Energy Poverty: A Primary Data Study. Energies, 16(21), 7237. https://doi.org/10.3390/en16217237	Inmediate effect on thermal comfort, portable and reusable, no energy consumption	Requires regular adjustment, not suitable for all door types, not aesthetically pleasing	Draft stoppers are also considered a low-effort and low-cost method for improving the energy efficiency and thermal comfort within energy poverty households. The effects they present, in preventing cold air flows through dwellings. All these factors make draft stoppers an interesting intervention against energy poverty.	VABI
	Warm air circulators		Fans that work with heating sources to evenly distribute warm air.	Warm air circulators work similar to portable space heaters, they increase air flows through rooms by blowing out warm air.	Heating efficiency	40,-	https://www.praxis.nl/verwarmingen-airco-s/bijverwarming/ventilatorkachels/he021/	Warthmann, A., Wölki, D., Metzmacher, H., & Van Treeck, C. (2018). Personal Climatization Systems—A review on existing and upcoming concepts. Applied Sciences, 9(1), 35. https://doi.org/10.3390/app9010035	Even heat distribution, works with existing heating system	Doesn't generate heat, electricity need, may create unwanted airflows	Warm air circulators present similar characteristics as portable space heaters. They claim to improve local thermal comfort through warm air circulation. Just like portable space heaters, their efficiency and short term-implications make them a lesser interesting method for combatting energy poverty.	CFD
	Thermal curtains		Heavy, insulated curtains or blinds.	Thermal curtains are regular curtains layered with foils or insulation material. These reduce cold infiltration from the outside, while keeping warmth indoors.	U value of window	20,- / meter	https://www.kwantum.nl/alles-over-raamdecoratie/op-maat/gordijnen-op-maat/isolerende-gordijnen#isolerendegordijnen	Isoleren: Isolatiegordijn. (n.d.). Energieke Club. https://www.energieke.club/doen-en-praktisch/energiemaatregelen/isolatie/isoleren-isolatiegordijn	Blocks cold and drafts, effects on consumption and thermal comfort, easy to install	Only effective near windows, blocks sunlight when used	Thermal curtains claim to act similarly like indoor insulation or glazing improvements, in their improvement of the thermal quality of the dwelling. This would increase the energy efficiency and thermal comfort of the dwelling. Besides this, the method presents itsself like a long term solution, as most dwellings contain curtains, and the intervention isn't visible. The intervention is also able to placed by occupants themselves, lowering costs. All these factors make thermal curtains an interesting method to study.	VABI

Scale	Method / appliance	Image	Short description	Effect through	Effected propery	Price	Source of price	Source of research	Pro's	Cons	Hypothesis of effectiveness	Choice of modelling and modelling method
Intermediate interventions	Indoor wall insulation		Install foam or fiberboard insulation panels on interior walls to reduce heat loss and improve thermal comfort.	Indoor insulation reduces the heat loss from the interior of the building and keeps cold outside the building. The insulation being placed indoors makes the placement easier.	R value of wall	divers, ligt aan materiaal, +- 30,- / m2	https://www.isolatiemateriaal.nl/muurisolatie/voorzetwand-isolatie	cmostores.com limited. (2024b, February 15). *What is solid wall insulation? - Insulation Superstore Help & Advice*. Insulation Superstore Help & Advice. https://www.insulationsuperstore.co.uk/help-and-advice/product-guides/insulation/what-is-solid-wall-insulation/	Significant reduction in heat losses, improves thermal comfort, doesn't alter exterior, can be installed in older homes	Reduces interior space, can be disruptive to install, risk of moisture buildup	Indoor insulation is one of the proven methods for improving the thermal quality of a dwelling. Especially the lower quality dwellings of energy poverty households could benefit from indoor insulation. Next to this, indoor wall insulation is a relatively easy intervention to install by occupants themselves, it also presents itsself as an affordable option.	CFD/VABI
	Floor insulation		Place rigid foam or underlayment mats beneath flooring.	Floor insulation ensures that heat doesn't transfer to the crawlspace beneath. Floor insulation can preferable be placed beneath the floor in the crawl space. It can also be placed on top of the floor, requiring more work.	R value of floor	divers, ligt aan materiaal, +- 20,- / m2	https://www.isolatiemateriaal.nl/vloerisolatie/betonvloer-isolatie/xps-isolatie	Staszczuk, A., Wojciech, M., & Kuczyński, T. (2017). The effect of floor insulation on indoor air temperature and energy consumption of residential buildings in moderate climates. Energy, 138, 139–146. https://doi.org/10.1016/j.energy.2017.07.060	Prevents heat losses through crawling space, long lifespan, improves thermal comfort	Disruptive installation, not always possible in existing buildings, limited benefits	Floor insulation works in a smilar way as indoor wall insulation, but there are several differences. The first being that heat losses through the floor are often less significant and don't add up as much as heat losses through the façade. Also, floor insulation is a more labour intensive intervention than indoor wall insulation, as it requires alterations to doors and flooring systems. This makes it less of an attractive method against energy poverty.	VABI
	Window insulation film		Transparent films that reduce heat loss through windows while allowing sunlight to enter.	This film improves the insulation values of the glazing. Allowing less cold to enter and less heat to escape during colder periods. It is most effective for lower value windows.	U value of glazing	10/20,-	https://www.amazon.nl/-/en/b?ie=UTF8&node=16419394031	Amirkhani, S., Bahadori-Jahromi, A., Mylona, A., Godfrey, P., & Cook, D. (2019). Impact of Low-E Window Films on Energy Consumption and CO2 Emissions of an Existing UK Hotel Building. Sustainability, 11(16), 4265. https://doi.org/10.3390/su11164265	Affordable, DIY solution, can help reduce condensation	May reduce window clarity, temporary solution, limited impact on drafts	Window insulation film is another widely implemented measures by households aiming to make their dwelling more energy efficient. It poses to be an affordable and easy to implement measure for energy efficiency of glazing. This method is more interesting for energy poverty households, as existing glazing is often of lower quality. These factors make it an interesting intervention to research.	CFD/VABI
	Door and window weatherstripping		Use adhesive foam, silicone strips, or rubber seals.	Weatherstripping allows for air gaps to be sealed. This results in less cold air flowing into the dwelling. This reduces energy usage and improves thermal comfort, as cold draft is elminated	Air tightness of window frame	10/20,-	https://www.bol.com/nl/nl/l/tochtstrips/28760/	Croon, T., Nia, E. M., He, S., Qian, Q., Elsinga, M., Hoekstra, J., Van Ooij, C., & Van Der Wal, A. (2024). Energy coaching and 'fix team' retrofitting to mitigate energy poverty: An ex-post analysis of treatment and interaction effects. Energy Research & Social Science, 119, 103807. https://doi.org/10.1016/j.erss.2024.103807	Reduces drafts, easy and cheap installation, improved heating efficiency	Regular maintenance, not as effective for larger gaps, can be tricky to install correctly	While weatherstripping aims to have similar effects such as draft stoppers, their effects look appear to have less of an impact on energy consumption and thermal comfort. While their price is in a similar range, their energy consumption seems to be less, as weatherstripping doesn't stop draft in the same way draft stoppers do. While the cold weatherstripping stops could be noticeable in energy consumption, it likely won't be enough to make significant changes in energy costs and thermal comfort.	VABI
	Insulating pipe wraps		Wrap hot water pipes with insulating foam.	Pipe insulation reduces the energy loss through water pipes. When these pipes are heated, much energy can be lost. By insulating these pipes, warm water can be accessed sooner, and energy costs are reduced.	Heat retention of water pipes	5,- / 2m	https://www.isolatiemateriaal.nl/buisisolatie		Reduces heat losses through pipes, prevents freezing pipes, cheap and easy to install	Limited impact, only works for exposed pipes, periodic replacement	Insulating pipe wraps claim to help in lowering energy costs by reducing heat losses of hot water pipes. While this is an interesting measure, it is less applicable to energy poverty. This is because insulating pipe wraps do nothing for the thermal comfort of households in a direct manner.	Will not be simulated due to simulation program limitations
	Ceiling insulation		Add insulating materials (like foam boards or fiberglass rolls) to the underside of accessible ceilings or attic spaces.	Indoor insulation reduces the heat loss from the interior of the building and keeps cold outside the building. It can also be used inside the building, around spaces like attics.	R value of ceiling	10,- / m2	https://www.isolatiemateriaal.nl/dakisolatie/platdak-isolatie/dakisolatie-binnenzijde/glaswol-isolatie/glaswolplaten	Taylor, P., Mathews, E., Kleingeld, M., & Taljaard, G. (2000). The effect of ceiling insulation on indoor comfort. Building and Environment, 35(4), 339–346. https://doi.org/10.1016/s0360-1323(99)00025-6	Reduces energy costs, long lifespan	Costly, requires professional installation, difficult to place, may cause moisture problems	Ceiling insulation works in a similar way as indoor wall insulation and floor insulation. But, the effects of ceiling insulation are likely to be even less, since it doesn't reduce energy losses to the exterior to the dwelling, but only to the interior of the dwelling. As these interior heat losses are often less significant than exterior losses, the benefits of ceiling insulation will likely be insufficient. Besides this, the placement of this intervention seems to be quite labour intensive and might require professional help, while most interventions on this method don't need this.	VABI
	Insulated door panels		Attach rigid foam or fabric panels to the inside of external doors.	Insulated door panels will improve the insulation value of exterior doors and the exterior of the dwelling as a whole. It is most effective in low-quality doors, or doors with much glazing.	R value of doors	divers, ligt aan materiaal, +- 30,- / m2	https://www.isolatiemateriaal.nl/muurisolatie/voorzetwand-isolatie	Isoleren: Paneel van je deur isoleren. (n.d.). Energieke Club. https://www.energieke.club/doen-en-praktisch/energiemaatregelen/isolatie/isoleren-paneel-van-je-deur-isoleren	Improves insulation, can be added to existing doors, cost-effective compared to buying new doors	Limited impact, alters door aesthetics, precise installation	Insulating door panels aim to improve the thermal quality of an often overlooked aspect of the façade, doors. The increased risk of doors of energy poverty households being of low quality makes this an interesting intervention. The cost of this intervention is similar to that of indoor wall insulation, and it is also able to be placed by occupants themselves.	VABI
	Rug floor insulation		Insulating underlays beneath rugs.	Insulating underlays placed beneath area rugs prevent heat loss through floors, especially over uninsulated basements or slabs.	R value of floor	15,- / m2	https://www.vloerbedekkingwebwinkel.nl/ondervloeren/tapijt?srsltid=AfmBOooKAfLF-gpBUXcdHOSiWLuWR8FudXctoWzMzaOufcqHekNHmyGN	McNeil, S. (2016). The Thermal Properties of Wool Carpets. ResearchGate. https://doi.org/10.13140/RG.2.1.3925.1601/1	Heat insulation, hidden, cheap	Limited effect, tricky placement	Under-rug floor insulation works in a similar way as regular floor insulation. Unlike floor insulation, under-rug insulation doesn't require significant altercations to the floor contruction of the dwelling. At the same time, under-rug insulation will also not achieve the same thermal quality benefits as regular floor insulation.	VABI
	Secondary glazing		Make a diy insulating window frame	Temporary acrylic or polycarbonate sheets installed over single-pane windows create an insulating air gap. This increases the insulation values of glazing frames, preventing temperature losses.	U value of glazing	Wood + screws + foil	Gamma NL. (2022a, January 22). Raamhoek Verzinkt 250x250 mm | GAMMA. GAMMA. https://www.gamma.nl/assortiment/raamhoek-verzinkt-250x250-mm/p/B123874	Brains4neighbourhoods isolatie doe het zelf voorzetraam. (n.d.). tno.nl/nl. https://www.tno.nl/nl/newsroom/insights/2022/06/brains4neighbourhoods-isolatie-doe/	Cheap alternative to double glazing, DIY installation, reversible for rental homes	Can reduce window visibility, not very durable for long term, condensation risks	The DIY secondary glazing solution aims to be a very effective interventions for energy poverty households. The research on the interventions show significant reductions in energy consumptions and increases in thermal comfort. The presentation and research on this method as a DIY intervention make it one worth researching. Besides this, the method is low-cost and can be easily demounted, which is of added use to renting households.	VABI

Scale	Method / appliance	Image	Short description	Effect through	Effected propery	Price	Source of price	Source of research	Pro's	Cons	Hypothesis of effectiveness	Choice of modelling and modelling method
Advanced interventions	External wall insulation		Insulating material is added to the outside of the dwelling, on the façade.	Insulating materials on the exterior walls, then covered with a protective render or cladding enhance the thermal performance of the dwelling. Blocking environmental cold effectively.	R value of walls	250,- / m2	Solvari, & Solvari. (2024, May 13). Buitenmuur isoleren. Gevelrenovatie-info.nl. https://www.gevelrenovatie-info.nl/gevelisolatie/buitenmuur-isoleren	Croon, T., Hoekstra, J., & Dubois, U. (2024). Energy poverty alleviation by social housing providers: A qualitative investigation of targeted interventions in France, England, and the Netherlands. Energy Policy, 192, 114247. https://doi.org/10.1016/j.enpol.2024.114247	Highly effective for heat losses, energy efficiency, long term solution, can improve external aesthetics	Expensive, requires professional installation, disruptive installation, potential planning restrictions	Researched has shown that external wall insulation is the most effective way of increasing the thermal quality of dwellings through insulation. It blocks the cold temperatures the furthest from the interior environment. It has also shown that external wall insulation is a quite costly and labor intensive method, as it requires significant changes to the facade of dwellings. This makes external wall insulation an intervention worth looking at in regards to energy poverty.	CFD/VABI
	Glazing replacement		Glazing replacements improves efficiency while keeping visual aesthetics.	Replacing single-pane windows with double- or triple-glazed units improve thermal insulation and reduce heat loss through windows.	U value of glazing	115 - 130,- / m2	Kosten ruit vervangen - Kostenoverzicht in 2025 - Zoofy. (n.d.). https://zoofy.nl/prijsgidsen/kosten-ruit-vervangen/	Croon, T., Hoekstra, J., & Dubois, U. (2024). Energy poverty alleviation by social housing providers: A qualitative investigation of targeted interventions in France, England, and the Netherlands. Energy Policy, 192, 114247. https://doi.org/10.1016/j.enpol.2024.114247	Significantly improves insulation, long life span, property value increases	High cost, may require frame modifications, long payback period	Similar to external wall insulation, glazing replacements are also a well researched method for improving the thermal quality of dwellings. Especially for dwellings which have low quality glazing to begin with, replacing this glazing can have large effects on energy consumptions and costs. At the same time, this method can be quite costly, especially if the existing windo frames need to be replaced as well.	CFD/VABI
	Roof external/ replacement insulation		Replace the roof with modern materials. Replacing the exterior and enhancing efficiency.	By insulating the exterior of the roof with insulating materials, the energy efficiency of the dwelling is improved by reducing temperature losses. This also increases the liveability of attics.	R value of roof	100 - 150,- / m2	Myrthe. (2024, December 31). Dakisolatie kosten. Homedeal NL. https://www.homedeal.nl/isolatie/dakisolatie-prijzen/		Prevents heat losses, improves home energy efficiency	Expensive, complex installation, not always possible in older homes	External roof insulation can be of great benefit for houses which have older roofs with insufficient insulation. External insulation allows for more effective blocking of cold than internal insulation, but it's a more intensive and costly intervention, as large parts of the roof will need to be stripped. Roof insulation is also most impactfull for individual houses, this makes it less applicable for energy poverty households, who are often living in social housing complexes.	Will not be simulated since it is not applicable to case
	Smart heating systems		Invest in a smart home heating system with zoned controls and learning thermostats.	By installing smart home heating systems, consistent indoor temperatures can be retained. Reducing the energy usage through spikes in heating energy.	Efficiency of heating	from 300,-	Coolblue. (n.d.). Buy smart thermostat? - Coolblue - Before 23:59, delivered tomorrow. https://www.coolblue.nl/en/thermostats/smart-thermostats		Optimizes energy use, remote control & automation, zoned heating, can learn user habits	High costs, requires technical knowledge, limited effectiveness in poorly insulated homes, compatibility issues	Smart heating systems aid towards the conscious use of heating, thereby aiding towards reducing the energy consumption of households. These systems are often implemented in newly built dwellings, as it allows for smart systems to be the most effective. Older dwellings often don't allow the integration of these systems, besides this, the thermal quality is often of such low quality that these systems won't lead to energy consumption decreases.	Will not be simulated due to simulation program limitations
	Whole-house air sealing		Conduct a blower door test and seal all leaks.	The blower test will reveal all leaks inside a dwelling, around windows, doors and other construction parts. By sealing this, thermal comfort and energy use will be improved.	Air tightness of dwelling	from ,- 395	Energiekeurplus. (2025, January 29). Blowerdoortest - luchtdichtheidsmeting | Blowerdoortest XL |. https://www.energiekeurplus.nl/blowerdoor-luchtdichtheidstest/blowerdoortest-blowerdoor/	Anand, J., Liu, X., Anees, F., Li, Y., Eckman, B., & Malhotra, M. (2024). Assessing the impacts of air-sealing on the sizing, operation, and economic feasibility of ground-source heat pumps for electrifying single-family houses in the US. Journal of Building Engineering, 98, 111149. https://doi.org/10.1016/j.jobe.2024.111149	Reduces heat losses through cracks, improves air quality, enhances home thermal comfort, works well in combination with insulation	Requires professional help, expensive, risk of poor ventilation	Whole-house air sealing presents itsself as large scale draft prevention. With many energy poverty households being of lower quality and having significant damages to the construction, this can be an interesting method for reducing energy losses and thermal discomfort. At the same time, it is important to take the needed investment into account, as whole-house air sealing is a more technical and costly solutions.	VABI
	Wall cavity insulation		Fill wall cavities with insulating materials such as foam, fiberglass, or cellulose.	Many dutch dwellings are constructed with masonry wall, including their cavities. The thermal insulation of the cavities can be increased by placing insulating material in there.	R value of walls	38,- / m2	De kosten van spouwmuurisolatie | Nederland Isoleert. (n.d.). https://www.nederlandisoleert.nl/kenniscentrum/financieel/spouwmuurisolatie-kosten		Improvement in thermal efficiency, can be installed in existing homes, reduces heat costs	Professional installation, potential for moisture buildup, not applicable in all homes	Wall cavity insulation presents the middle ground between internal and external wall insulation. It is an intervention which isn't visible from the outside or the inside, but can be visible through reductions in energy consumption. Wall cavity does place itsself in a niche, as it is an intervention which is nearly only applicable to masonry buildings and lower-level buildings.	Will not be simulated since it is not applicable to case
	Thermal bridge elimination		Retrofit and insulate thermal bridges.	By identifying and retrofitting areas prone to thermal bridging, such as corners and junctions, by adding insulation or specialized thermal breaks, the risk of heat loss is reduced.	Thermal quality of building exterior	Dependent on project			Prevents heat loss, increases effectiveness of insulation, reduces risk of condensation and mould, improves thermal comfort	Complex and costly to adress, requites expert assessment and design, difficult to retrofit in older buildings	Thermal bridge elimination can be an interesting intervention to reduce cold flows through thermal bridges. These thermal bridges are often found in energy poverty households through concrete balconies or floors. While it can significantly reduce energy consumption, it will have less of an effect as for example, wall insulations. Besides this, thermal bridge elimination is labour intensive and requires more interventions on the facade, which can become quite costly.	Will not be simulated due to simulation program limitations
	High-efficiency boiler or furnace		Replace old heating systems with modern, high-efficiency systens.	By replacing old heating systems with modern, high-efficiency condensing boilers or furnaces, energy waste is reduced.	Efficiency of energy systems	Dependent on household			Reduces fuel consumption, more consistent and powerful heating, long lifespan	High investment, requires professional installation, may need additional upgrades, limited benefits if home insulation is poor	High-efficiency boilers or furnaces have replaced the older systems in modern dwellings. These devices are of higher efficiency than older systems, posing them interesting for households looking to recude their energy consumption. But, the reason that these devices are now placed in newer dwellings is because the thermal quality of newer dwellings allows for it. If these devices were to be placed in existing, lower quality dwellings, their effectiveness will be significantly less. This makes it hard to justify this intervention in regards to energy poverty, as the high investment will be more difficult to return itsself.	Will not be simulated due to simulation program limitations

Appendix: 9 – Detailed intervention library

Appendix 9.1 Radiator foil

Description

Radiator foil (figure a) is a thin and reflective material which is placed behind radiator, on the inside of façade walls. The goal of radiator foil is to reduce heat loss. It aims to do so by reflecting radiant heat from the radiator back into the room, instead of directly sending it to the external wall. Because by directly sending it to the external wall, there is risk of the warmth being absorbed by the wall and lost to the exterior. Radiator foil is an easy intervention to install, as it just involves attaching the foil to the back of the radiator. It claims to be especially effective in older homes, as facades in these homes allow for larger amounts of heat to be lost than newer homes.

Figure a: *Radiator foil (ecommerce development agency, 2025)*

Envisioned effects

The study of Harris (1995) performs experiments with radiators and different metallic foils as radiation barriers. The aim of the study is to determine the effects of these foils on the effectiveness of radiators and the changes in energy usage. In the experiment, a radiator is placed within a 3x3x3 meter room constructed out of a timber frame with insulation. The average U value of the walls in the experiment setup was calculated to be 0.63 W/m^2 ^{0}C. The study led to the following results:

	Without foil (base)	With insulation	With foil	With foil and insulation
Heat flux through wall (W/m^2)	7,1	4,1	3,1	2,1
Effective U value behind radiator (W/m^{2}K)	0,63	0,29	0,27	0,24
Reduction in energy consumption of room (%)	X	2,4	3,7	4,4
Emissivity of wall	0,9	0,9	0,05	0,05

Table a1: *Effects of radiator foil (Harris, 1995)*

Similar to the study of Harris (1995), Baldinelli and Asdrubali (2008) perform a theoretical analysis of energy performance in residential buildings with the use of reflecting panels. An analysis is made on the effect of reflective foils on radiators in 3 Italian cities. An important insight is noted in this research, being that reflective foils have the most effect on walls of lower insulation value. With higher insulation values, the foils have less effect. The following results are noted with regards to the power saved on average:

Wall type	Power saved (%)
Without insulation	8,4
With light insulation	3,1
With high insulation	0,7

Table a2: *Perceived effects of radiator foil (Asdrubali, 2008)*

Simulation
To test the effects of radiator foil, different approaches were taken, both to the used heating system and other building elements. Within the base situation, the dwelling is equipped radiators inside the rooms which are heated. This includes rooms like the living room and bedrooms. The first test consisted of changing different characteristics of the used radiator. The heating system has different values which can be changed to increase the effectiveness of the radiator. These values and the modelled changes can be seen in table a3.

Property	Description	Old situation	Change	New situation
Convection factor	The amount of heat which is transferred via convection (air currents)	0,7	Radiator foil reduces the radiant heat losses to walls, increasing the convection of the system slightly.	0,75
Heating capacity	The heating capacity accounts for the amount of heat the system can give to the environment	50 W/m2	Radiator foil reduces heat losses to the wall from the backside, increasing the capacity of the system	55 W/m2

Table a3: *Simulation properties of heating system with radiator foil (simulation method 1) (Own work, 2025)*

The second test consisted of making changes to the building physical characteristics of the construction. The effectiveness of these alterations is more difficult to assess than direct changes to the heating system, because the exact location of the radiators is unable to be modelled in VABI Elements. These tests were done with an approach similar to the study of Harris (1995). While these changes allow for the reflection of radiator foil to be simulated, the modelling method becomes questionable, when it is noted that the U value changes don't just alter the reflection, but the entire heat transport of that wall part. With this in mind, the simulation method which focusses on changes to the heating system is regarded as most realistic.

Property	Old situation	Change	New situation
Emissivity of wall behind radiator	0,9	Addition of reflective foil reduction in emissivity from 0.9 to 0.05	0,05
Effective U value behind radiator (W/m²K)	0,36	Addition of reflective foil (57% decrease in U value)	0,15

Table a4: *Simulation properties of walls with radiator foil (simulation method 2) (Own work, 2025)*

Results
The simulation set-up which changes the U value of the wall behind the radiator gives small values for energy efficiency and thermal comfort improvements. The results can be seen in table a5. Meanwhile, the simulation set-up which changes the effectiveness of the radiator settings provides significantly different results. The most important notions about the effects of this set-up of radiator foil are the differences between the normal and energy poverty usage profiles. The results can be seen in table a6.

At first glance these results might seem unrealistic, but when the difference in radiator usage and the process in which the intervention works is considered, the results make more sense. This simulation set-up favours radiators which are intensely used, as it becomes easier for the system to reach and maintain desired temperatures. Within the energy poverty usage, the radiators are used to such low intensity, that the intervention has little chance to have an effect. At the same time, the thermal comfort improvements within this intervention comes from the energy saved specifically by the heating system. In the energy poverty situation, the system is used so little, that there is no energy usage reduction to profit from. When this simulation set-up is compared to the changes in wall construction, the difference in effects for the energy poverty situation can be explained. The changes in wall construction actively reduce the heat loss through the walls, which is beneficial weather the heating system is working or not. This has been discussed in chapter 2.4.2. The heating system changes only work when the system is used above a certain level.

Besides its operational benefits, radiator foil proves itself useful for the energy efficiency of normal and energy poverty households through other characteristics of the intervention. The easy applicability, cheap investment price and increased effectiveness in older buildings makes radiator foil especially useful for energy poverty households. Within the continuation of the research, both simulation results will be used to analyse the effects of radiator foil. The conclusions from both modelling methods will be used. For example, the difference between usage profiles of method 1 will be used and the investing efficiencies of method 2 will be used. An important sidenote to make is that for more accurate results, radiator foil needs to be researched either through real-life simulations or detailed CFD simulations.

Radiator foil (Method 1)	Normal usage	Energy poverty usage
E. efficiency improvement (%)	3,65	0,04
T. comfort improvement (C^0)	2	0
Yearly savings (€)	36,02	0,19
Payback period (years)	1	179,5
Investing efficiency (%)	102,90	0,56

Table a5: *Simulation results of radiator foil (Method 1) (Own work, 2025)*

Radiator foil (Method 2)	Normal usage	Energy poverty usage
E. efficiency improvement (%)	1,25	1,58
T. comfort improvement (C^0)	0,5	0,5
Yearly savings (€)	12,32	8,20
Payback period (years)	2,8	4,3
Investing efficiency (%)	35,19	23,44

Table a6: *Simulation results of radiator foil (Method 2) (Own work, 2025)*

Appendix 9.2 Thermal curtains

Description

Thermal curtains (figure b) are designed like regular curtains, but they are made from heavy, insulating materials and contain built-in thermal linings. The thermal curtains aim to provide similar effects as insulated walls. The curtains aim to reduce heat losses in the winter by not allowing warmth to escape and cold air to enter. This effect is reversed in the summer. Thermal curtains are an easy to install intervention, as it simply involves replacing existing curtains. If desired, thermal curtains can even be made in a DIY fashion.

Figure b: *Thermal curtains (Amazone.nl: Home & Kitchen, 2025)*

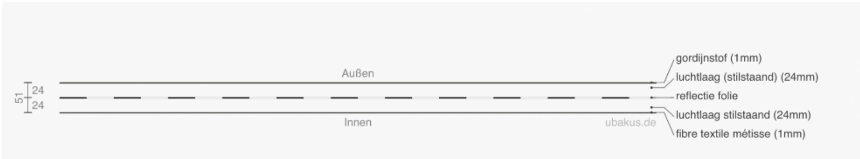


Figure c: *Thermal curtains buildup (Isoleren: Paneel Van Je Deur Isoleren, n.d.)*

Envisioned effects

Fitton et al. (2017) has done research on the effects curtains can have on energy losses within buildings. This research has taken place partly through literature review and partly through experiments in house testing facilities. Different factors are noted regarding the relationship between heat transfer and indoor curtains. A 38% reduction in heat transfer is noted with the usage of curtain window coverings. Besides this, a significant difference is noted in the heat transfer reduction between sealed and loose edge curtains, with sealed edge curtains providing 19% better results than loose edge curtains. Similar to these results, in greenhouses heat energy savings of 21% on average were noted by Boyacı et al. (2023). Lastly, using the findings of similar research, a formula is noted which can be used to calculate the thermal transmittance (U) values of windows with curtains or blinds. This can be done using the formula stated below. The formula considers the U_w value of the window and the thermal resistance (R_{bi}) of the internal blind or curtain. An example build-up of a thermal curtain can be seen in figure c

$$U_{wb}' = [(1/U_W) + R_{bi}]^{-1}$$

To allow for effective usage of the formula Fitton et al. (2017, p. 5) has stated different thermal resistance values of covering layers, these can be seen in table a7.

Description	Thermal resistance (R) of covering layer (m2 K/W)
Roller blind	0,14
Heavy curtains	0,16
Secondary glazing	0,18
Honeycomb insulated blind	0,24
Roller blind with low emissivity film	0,3
Low emissivity secondary glazing	0,32
Well-fitting shutters	0,33
Low emissivity secondary glazing and shutters	0,39

Table a7: *R values of window covering layers (Fitton et al., 2017)*

Simulation

To simulate the effects of thermal curtains, changes were made to the wall build-up of specific parts. Segments around the windows were altered to consist of an additional air gap and a thin insulated material. For the window itself, this was changed to consist of an air gap and the same insulated material, with the outer layer being glass. The following changes were made:

Property	Old situation	Change	New situation
U value of façade opening 1	5,37 W/m²K	Addition of heavy curtains (R=0,16)	2,89 W/m²K
U value of façade opening 2	3,20 W/m²K	Addition of heavy curtains (R=0,16)	2,12 W/m²K
R value around façade opening	2,75 m²K/W	Addition of 50mm cavity and heavy curtains	3,1 m²K/W

Table a8: *Simulation properties of thermal curtain windows (Own work, 2025)*

While these direct values can be altered, the modelling of thermal curtains becomes tricky when assessing the usage of the curtains themselves. While the U value of the window opening can be altered, this would still allow for sunlight to pass through entirely into the space behind it, which isn't the case when thermal curtains are closed. The modelling of the shading is open or closed is critical. During their closed usage, the thermal curtains restrict cold temperatures from entering the space and heat from exiting the space, meaning that the curtains should preferably be closed during these usage times. This would mean though, that these rooms would not be granted daylight during their usage, and that the entering solar heat would also be reduced, which could in turn increase the systems energy usage. This raises questions about the practicality of this usage system. In order to assess the functioning of thermal curtains as both an energy efficiency measure and solar shading system, an additional simulation is performed. The changes in this simulation can be seen in table a9.

Property	Old situation	Change	New situation
Solar shading	No relevant solar shading prevalent	Addition of heavy curtains (R=0,16)	Medium quality indoor solar shading, always closed

Table a9: *Simulation properties of solar shading under the influence of thermal curtains (Own work, 2025)*

Results

The first simulation, which only changes the U and R value of the façade parts show positive effects in the different review criteria. The results can be seen in appendix 10.3. These positive effects can be explained by the high value changes the intervention applies to R and U values, and the low investment cost. The second simulation, which takes the solar shading into account changes these results quite significantly. The changes can be seen in appendix 10.4. While these are negative changes, the thermal curtains are still able to be deemed as an efficient measure. The reason for these changes is a result of solar energy being blocked from entering the rooms behind the curtains. During winter times, this energy is partly used to heat up the room, the thermal curtain reduces the amount of energy that can enter. This negative effect is significantly more noticeable in rooms situated on the southern façade than rooms situated on the northern façade. The comparison between entered solar heating with and without shading can be seen in appendix 10.4. What can be concluded from this comparison of simulation methods, is that the personal usage of the thermal curtains is crucial to its success, and that an effective application of thermal curtains means that little to no daylight will enter the rooms behind them. Which greatly reduces their realistic usage. A overview of results can be seen in table a10.

Thermal curtains	Normal usage	Energy poverty usage
E. efficiency improvement (%)	5,8	7,66
T. comfort improvement (C⁰)	2,2	2,1
Yearly savings (€)	57,6	39,8
Payback period (years)	4	6
Investing efficiency (%)	23,04	15,94

Table a10: *Simulation results of thermal curtains (Own work, 2025)*

Appendix 9.3 Infrared heating panels

Description

Infrared heating panels (figure d) are an energy-efficient heating solution that uses infrared rays to directly warm objects and people in a room rather than heating the air. This is where infrared heating panels differ from standard heating radiators. Standard heating radiators rely on heating up warm air and having that warm air spread throughout the rooms. Infrared heating panels skip over this step and emit heat waves which are absorbed by the room and occupants. These panels are typically thin and are often mounted on walls or ceilings. The panels heat up quickly, require little maintenance, and are highly efficient since they minimize heat loss through the indoor air.

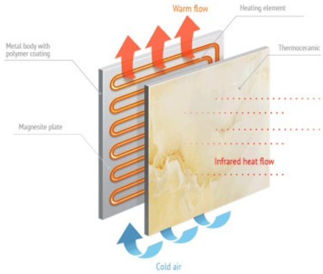


***Figure d:** Infrared heating panels (Infralia.com, 2025)*

Envisioned effects

Corsten (2021, p. 4) has performed similar research looking into the effectiveness of infrared heating panels, when compared to conventional heating methods, like floor heating. It is noted that the applicability of infrared heating panels is influenced a lot by the scenario it is applied to. The panels are often perceived as more comfortable in well-insulated and high-quality homes than in homes of lower thermal quality. Besides this, it is noted that infrared panels are able to maintain set indoor temperatures and that this works especially well when using a lower temperature setting. Infrared panels are also proven to work in a quick manner, with the form of heating being useful for quickly providing heat to humans. Lastly, it is noted that infrared heating panels aren't as useful for providing constant high indoor operative temperatures than conventional heating methods and that there are valid concerns surrounding the peak load and operative costs of these panels.

Some of these findings are questionable for the overall usefulness of infrared heating panels but do point toward the effectiveness regarding energy poverty. For example, the point that heating panels are less useful for proving constant indoor operative temperatures. This might be a concern for regular households, but energy poverty households might not be looking to heat their whole house, but are perhaps only aiming to heat areas they spend time in.

Next to this, the improved efficiency with lower temperature settings is noted as a being inapplicable to regular households, as regular households maintain a higher heating temperature on average. At the same time, this could be of benefit for energy poverty households. The research has showed that these households often maintain lower indoor temperatures, due to the connection between energy costs and high indoor temperatures. This means that energy poverty households would be able to benefit from this increased efficiency with lower temperatures.

Simulation

Infrared heating panels can be directly modelled into VABI elements. The heating system of the room is changed from the standard radiator to infrared heating panels. The panels have the following specifications:

Property	Old situation	New situation
Heating method	Convection radiator	Infrared panels
Heating system effectiveness	50 W/m^2	400W

***Table a11:** Simulation properties of infrared heating panels (Own work, 2025)*

Results

The used simulation software provides questionable results regarding infrared panels for different reasons, the most important one being that VABI is unable to model local comfort. Instead of modelling the localized usage of infrared panels, it models infrared panels as a method of heating the entire space, which isn't how they are used. While this modelling method does provide improvements in energy efficiency, which can be seen in appendix 10.5, this gives the wrong impression of the efficiency of infrared panels. To assess the thermal comfort effectiveness of infrared heating panels, CFD calculations with infrared heating panels have been made and discussed in chapter 5.2.7.

The research and simulation show that infrared heating panels can provide localized heating to occupants of both regular and energy poverty households. At the same time, questions arise surrounding the thermal comfort effectiveness of the intervention. While it is able to provide localized heating, the transition from these temperatures to the low average room temperatures of energy poverty households through radiant temperatures results in lower thermal comfort results than heating methods such as localized air heating.

Besides this, while infrared heating panels can provide localized heating, heating is only one aspect of energy poverty which needs to be considered when reviewing interventions. Firstly, as has been discussed in chapter 3.2, one of the negative effects of rising energy prices and energy poverty is the resurgence of indoor mould. This indoor mould is fueled by insufficient ventilation, and low temperatures. This means that to reduce indoor mould in energy poverty households, average household temperatures need to increase, which is not the effect infrared heating panels have. Secondly, infrared heating panels are an expensive intervention, with a relatively high investment price for the low and uncertain energy savings they provide.

Appendix 9.4 Draft stoppers

Description

Draft stoppers (figure e) are simple but effective devices designed to block cold air from entering and warm air from escaping through gaps under doors. They come in various forms, including fabric tubes filled with insulating material and brush or rubber door sweeps. By sealing these gaps, draft stoppers prevent heat loss, reduce cold drafts, and improve indoor comfort, leading to lower energy bills. They are an affordable and easy-to-install solution that can be used in any room, particularly in older buildings with poorly sealed doors.

Figure e: *Draft stoppers (Walmart.com, 2025)*

15.5.2 Envisioned effects

Indoor draft is described by P. Bluyssen (2009) and Van Der Linden et al. (2016) as an important cause of thermal discomfort in dwellings. This is caused by both differences in air temperatures but just as important, differences in air velocities. Van Der Linden et al. (2016, p. 102) notes that the risk of draft problems is increased in smaller spaces where the average area per person is smaller, like meeting rooms or living rooms. The cause of draft problems in naturally ventilated buildings is a result of the exterior cold air not mixing with warmer air and flowing through the dwelling at a high speed. Measures noted by Van Der Linden et al. (2016, p. 102) to minimize this risk are, placing windows above heating elements, placing ventilation entrances as high as possible and provide space for increasing the mixing of ventilation air. In the cases of energy poverty dwellings, most of these points can't be improved. As the heating is of lower temperature in these dwellings and the construction of the dwelling is set.

Besides these aspects of draft comfort, P. Bluyssen (2009, p.103) and Van Der Linden et al. (2016, p. 98) note the importance of indoor air velocity. Too big of a difference in air velocities, or too high air velocities under certain air temperatures could cause thermal discomfort. This is where draft stoppers come into play. As the aim of draft stoppers is to reduce the air velocity, thus giving ventilation air a better chance of mixing correctly with the indoor air.

15.5.3 Simulation

Draft stoppers are simulated by altering the infiltration values of the dwelling. These infiltration values are slightly improved by draft stoppers, but draft stoppers don't have much of an effect on outdoor air infiltration, especially at higher wind speeds. Due to the lack of research on the effects of draft stoppers on the air tightness of buildings, an estimation has been made in comparison to the effects of the other infiltration value interventions. The calculations of the original infiltration values can be found in appendix 7.12.

Property	Old situation	Change	New situation
Wind-dependent infiltration (1/h)	0,40	Moderate improvement of air tightness of rooms and doors	0,35

Table a12: *Simulation properties of draft stoppers (Own work, 2025)*

15.5.4 Results

The results of the draft stoppers simulations show the limited effects of the intervention, The results can be seen in table a13. While draft stoppers have limited financial effects, they are an inexpensive intervention and immediately influence thermal comfort through the prevention of draft. This is a benefit which is especially useful for energy poverty households and the cold indoor temperatures in these households. The small outperformance of energy efficiency improvements for energy poverty situations in comparison to normal situations show that the intervention is aimed more at the energy poverty target group.

Besides the energy efficiency working of the intervention, it should be noted that draft stoppers are an easy to apply interventions which provides immediate noticeable effects through thermal comfort. Draft stoppers are portable, reusable and can be specifically used in the critical areas of dwellings. At the same time, the intervention does require regular adjustment, it is not suitable for all door types, and it isn't an aesthetically pleasing intervention.

Draft stoppers	Normal usage	Energy poverty usage
E. efficiency improvement (%)	0,68	0,98
T. comfort improvement (C^0)	0,3	0,3
Yearly savings (€)	6,66	5,11
Payback period (years)	7,2	9,4
Investing efficiency (%)	13,88	10,66

Table a13: *Simulation results of draft stoppers (Own work, 2025)*

Appendix 9.5 Indoor wall insulation
Description
Indoor wall insulation (figure f) is a more conventional method for improving energy efficiency. It involves adding an insulation layer like mineral wool or insulating foam boards to the interior side of external walls. The aim of indoor wall insulation is to improve the matter in which walls contain indoor temperatures and block outdoor temperatures. It aims to be particularly useful in older homes. As in these homes, the walls are often of low insulating quality and external insulation is often not an option. With the correct tools and materials, indoor wall insulation can be placed by occupants themselves.

Figure f: *Indoor wall insulation (cmostores.com limited, 2025)*

Envisioned effects
Van Der Linden et al. (2016, p. 54) discusses the possible effects of indoor wall insulation in providing a more comfortable indoor environment. Like all forms of insulation, the insulating materials slows down the travel of cold exterior temperatures to the indoor environment. This results in less cooling of the indoor environment. When comparing insulating methods, indoor insulation is often the least preferable option, this is because it diminishes the heat accumulation effect. This points toward the phenomenon that the walls of a dwelling are heated, as the indoor environment is heated, this buffer will slow down the cooling from exterior temperatures. Indoor insulation negates this effect, as the indoor insulation hasn't got enough mass to replicate this. At the same time, this means that spaces with indoor insulation are able to be heated quicker, pointing towards benefits in energy costs.

Simulation
To simulate the effectiveness of indoor wall insulation, changes were made to the wall build-up of the exterior walls of the dwellings. These walls were kept in their original state, except for the interior. The interior was equipped with an indoor insulation system and wall finishing. The buildup of elements and R value calculations can be seen in appendix 7.3 and 7.11. An example of the buildup of wall type 1 with indoor insulation can be seen in figure g

Property	Old situation	Change	New situation
Insulation (R) value (m^2K/W) of exterior wall type 1	0,5	Addition of wooden framework and 70mm Kooltherm K17	4,09
Insulation (R) value (m^2K/W) of exterior wall type 2	2,75		6,31
Insulation (R) value (m^2K/W) of exterior wall type 3	1,5		5,07

Table a14: *Simulation properties of indoor wall insulation (Own work, 2025)*

Results

The results of indoor wall insulation simulations can be seen in table a15. Because of the relatively high investment cost, the yearly savings of 45 or 28,7 euros get overshadowed and result in savings efficiencies of 4,7% for normal situations and 3,0% for energy poverty situations.

Besides the direct improvements indoor wall insulation provides, there are other upsides to the intervention. The first being that it is one of the more impactful interventions which can still be applied by homeowners themselves. This greatly improves the financial feasibility of the intervention and shortens the period required for the intervention to be installed. It is also an intervention which is demountable, while this does take a bit more effort than with other interventions. Other positive aspects surrounding the installation of the measure include the fact that it doesn't impact the exterior of the dwelling and the fact that it can be installed in older homes.

There are also practical downsides to the intervention, the first being that an effective insulation thickness can significantly reduce the liveable area of the room it is applied in. While indoor wall insulation can be installed buy homeowners, its installation can be disruptive to the interior of the dwelling and to existing technicalities of the wall construction. Lastly, the risks of moisture build-up need to be carefully assessed before installation and should be dealt with effectively during installation.

Indoor wall insulation	Normal usage	Energy poverty usage
E. efficiency improvement (%)	4,57	5,54
T. comfort improvement (C⁰)	2	1,7
Yearly savings (€)	45,06	28,74
Payback period (years)	21,1	33,1
Investing efficiency (%)	4,74	3,03

Table a15: Simulation results of indoor wall insulation (Own work, 2025)

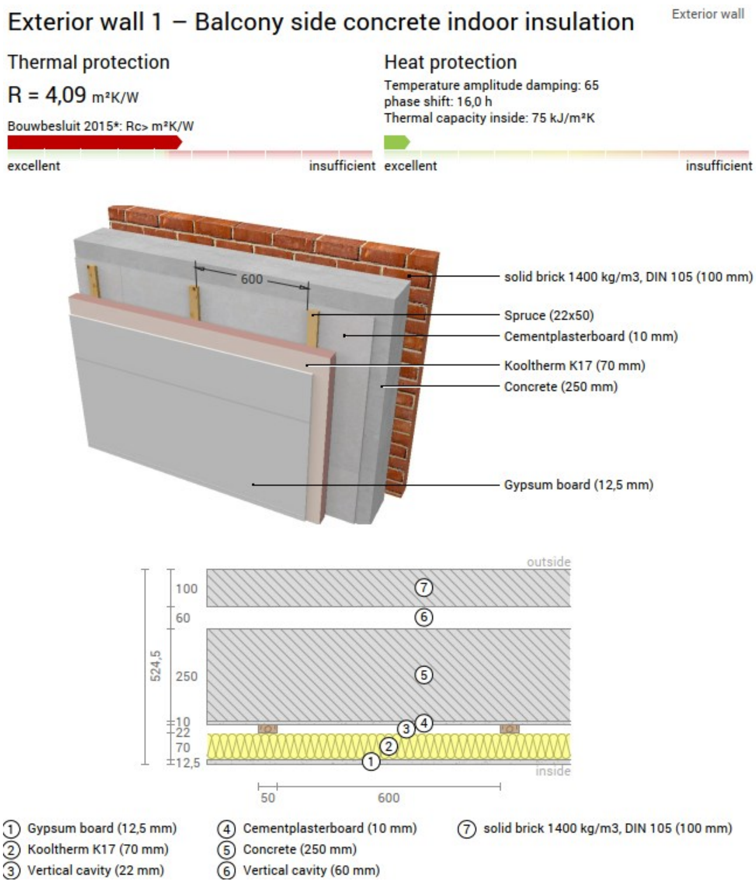


Figure g: Example wall buildup with indoor insulation (Own work, 2025)

Appendix 9.6 Window insulation film
Description
Window insulation film (figure h) is a transparent sheet which is directly applied to glass surfaces. The aim of this film is to improve the thermal performance of the glass. Meaning that external cold temperatures are blocked more effectively. At the same time, other properties of the glass are upheld, like its ability to allow sunlight to enter.

Figure h: *Window insulation film (Amazone.nl: Home & Kitchen, 2025)*

Envisioned effects
In their research, Amirkhani et al. (2019) note the different positive effects Low-w window insulation films can have on the energy consumption of buildings. The usage of Low-E film is dependent on the glazing it is placed on, Amirkhani et al. (2019) notes that the most significant energy usage decreases are noticed on single-pane glazing, with a decrease in heat loss of 40%. Besides this, Barrella et al. (2023) also note a reduction in heating demand with the use of Thermocover insulation films. An average reduction in heat dissipation/transfer of 28% for single glazing window panes and 13% for double glazing window panes is noted. With regards to the properties of the glass itself, a study of Nottingham Trent University (UK Green Building Council, 2024) discovered a U-value reduction of 1,09 W/m^2K when insulating film is used on lower quality existing glass, similar to the research of Barrella et al. (2023).

Simulation
To simulate window insulation film, changes were made to the thermal properties of the glazing within the project. The glazing originally consisted out of single or Thermopane double glass panes. The properties of this material were altered with the improvements noted by Barrella et al. (2023), as this study mentioned the usage of a specific window insulation film product.

Property	Old situation	Change	New situation
Effective U value of glass type 1 (W/m^2K)	5,37	Addition of insulation foil, reduction of 28% of surface heat losses.	3,9
Effective U value of glass type 2 (W/m^2K)	3,20	Addition of insulation foil, reduction of 13% of surface heat losses.	2,8

Table a16: *Simulation properties of window insulation film (Own work, 2025)*

Results
Window insulation film can be summed up as an intervention which has relatively little effect on energy The results of the simulations can be seen in table a17.

Window insulation film can be classified as another cheap and easy to install energy efficiency interventions, which generate significant energy savings in relation to the investment cost. Especially for energy poverty households living in a dwelling with low quality glazing, who don't have the means to completely replace the glazing, window insulation film is an interesting intervention.

At the same time, the low investment cost of the intervention does show itself during the application and usage of the film. In many cases, the insulation film causes the clarity of the window it is applied on to reduce. Besides this, after it has been applied, the film starts to loosen and fall of the window, this means that the film needs to be replaced after some time.

Window insulation film	Normal usage	Energy poverty usage
E. efficiency improvement (%)	3,9	4,9
T. comfort improvement (C^0)	1,6	1,2
Yearly savings (€)	38,9	25,5
Payback period (years)	1,4	2,2
Investing efficiency (%)	69,4	45,6

Table a17: *Simulation results of window insulation film (Own work, 2025)*

Appendix 9.7 Insulated door panels

Description

Insulated door panels (figure i) are specifically designed panels, or manually made panels, which aim to increase the thermal insulation of doors. The panels are constructed using framing material and insulating materials. After the panel is constructed, it is attached to the inside of the door. While some doors already have insulating materials, insulated door panels present themselves as a method of uplifting the effectiveness of other external doors.

Figure i: *Insulated door panels (Amazon.nl: DIY & Tools, 2025)*

Envisioned effects

The effects of insulated door panels work in similar fashion as the indoor wall insulation (Isoleren: Paneel Van Je Deur Isoleren, n.d.). The research of Nussbaumer et al. (2005) discusses an example of door insulation using a specific type of insulation material, besides this, different thermal aspects of the intervention are discussed, such as thermal bridging.

Simulation

To simulate the effects of insulated door panels, the materiality of exterior and interior doors was altered. The exterior doors, which focus on keeping cold outside, were equipped with additional insulation on the inside. In addition to this, different indoor doors were equipped with similar insulation. This was applied on indoor doors which were bordering rooms which weren't heated and would likely be cold. For example, indoor doors which were bordering hallways, which typically get quite cold .

Property	Old situation	Change	New situation
Insulation (R) value (m^2K/W) of external doors	70mm Hardwood R = 0,41	Addition of 30mm XPS and 10mm wood finishing	1,53
Insulation (R) value (m^2K/W) of internal doors	40mm Triplex wood R = 0,24		141

Table a18: *Simulation properties of insulated door panels (Own work, 2025)*

Results

The simulation results of insulated door panels show that insulated door panels have limited effects when the scale of the entire dwelling is regarded, with energy efficiency values of 2,1% and 2,7% and thermal comfort improvements of 0,9 and 0,8 degrees. At the same time, when the scale of the intervention and the room it is applied in is regarded, insulated door panels can be regarded as quite an effective intervention. With its short payback period and high investing efficiency for normal households (1,7 years and 59,6%) and energy poverty households (2,5 years and 40,18%) the financial aspects of the intervention are of higher quality. An overview of these results can be seen in table a19.

Besides these positive results, insulated door panels is an intervention which can be installed by occupants themselves, while it does require some accuracy and technical skills. And like indoor wall insulation, the installation of the panels will alter the aesthetic of the existing element and will imply small changes to the room area. The effects of insulated door panels can also be achieved by replacing the existing door with a high-quality insulated door, but this will cost more than installing insulated door panels.

Insulated door panels	Normal usage	Energy poverty usage
E. efficiency improvement (%)	2,09	2,68
T. comfort improvement (C^0)	0,9	0,8
Yearly savings (€)	20,66	13,92
Payback period (years)	1,7	2,5
Investing efficiency (%)	59,63	40,18

Table a19: *Simulation results of insulated door panels (Own work, 2025)*

The panels are constructed using framing material and insulating materials. After the panel is constructed, it is attached to the inside of the door and finished. An example of this workflow can be seen in figure j. While newly made doors are already equipped with insulating materials, oftentimes older external doors aren't. Insulated door panels present themselves as a method of uplifting the effectiveness of these external doors.

Figure j: *Insulated door panels DIY set-up (Isoleren: Paneel Van Je Deur Isoleren, n.d.)*

Appendix 9.8 DIY secondary glazing
Description
DIY secondary glazing (figure k) involves installing acrylic or polycarbonate sheets, or insulating foil, over low-quality windows. The aimed effect of this intervention is to create an insulating air gap between the original window frame and the DIY secondary glazing. This air gap aims to reduce heat losses, similar to regular double or triple glazing systems.

Figure k: *DIY secondary glazing (Theeuwen & Theeuwen, 2022)*

Envisioned effects
The envisioned effects of this intervention function in a similar way as standard insulation film. This method differs itself from standard insulation film by also introducing an air gap between the film and the existing window through a wooden frame. The research on the intervention notes a reduction in heat transfer loss of 35% on single pane windows and 20% on double pane windows (*Brains4neighbourhoods Isolatie Doe Het Zelf Voorzetraam*, n.d.). Figure l shows the perceived changes in the U value of single glazing with a U value of 6 W/m^{2}k when the secondary glazing system is applied.

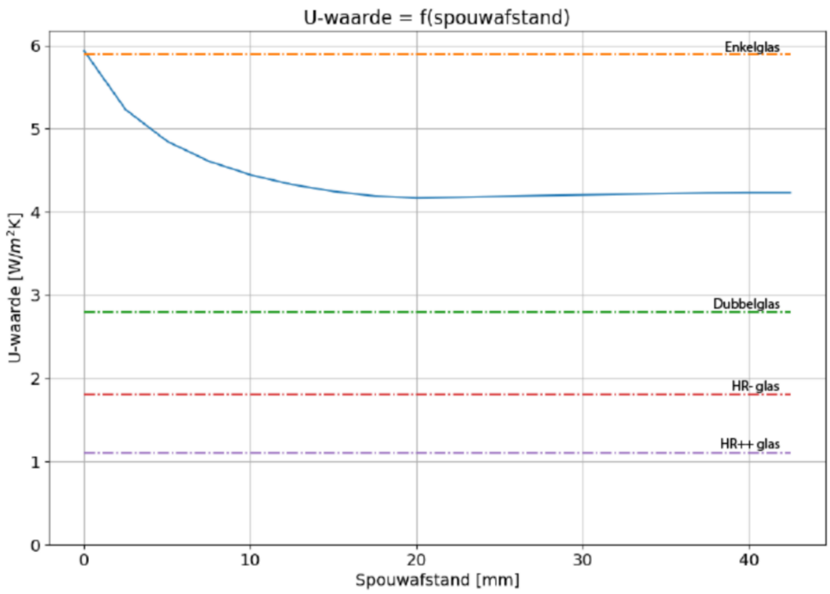


Figure l: *Changes to U value with DIY secondary glazing (Brains4neighbourhoods Isolatie Doe Het Zelf Voorzetraam, n.d)*

Simulation
To simulate this DIY secondary glazing, the thermal qualities of the glass within the base situation was altered. To represent this DIY secondary glazing, the U values and glass composition was altered. Since the simulation program doesn't allow this detail of material modelling, the envisioned effects were reached by modelling the window as a 'preset window'. With a preset window being an additional window placement, which forms a cavity. The U value of the new preset window has been gathered from the previously mentioned study, which noted changes in surface heat transfer.

Property	Old situation	Change	New situation
Effective U value of glass type 1 (single glazing) (W/m²K)	5,37	Application of DIY secondary glazing, 35% reduction of surface heat loss	3,5
Effective U value of glass type 2 (double glazing) (W/m²K)	3,2	Application of DIY secondary glazing, 20% reduction of surface heat loss	2,6

Table a20: *Simulation properties of DIY secondary glazing (Own work, 2025)*

Results

DIY secondary glazing has proven itself as an effective energy efficiency intervention regarding its application and the results it generates. The results can be seen in table a21.

Besides these direct results, DIY secondary glazing has proven itself as a cheap alternative to double glazing, an intervention which is normally both expensive and labour intense in its installation. DIY secondary glazing has shown itself to be especially useful in older homes with lower quality existing glazing, a target group where energy poverty is present. Lastly, the secondary glazing system allows itself to be removed, when necessary, this also improves the applicability of the intervention in energy poverty households, who are often rental owners of their dwelling.

There are also different downsides to the intervention, as it can reduce window visibility with the framing and disturbances of the foil, similar to window insulation film. The intervention also isn't very suitable for longer term use, as the materials are prone to deteriorate, and the functioning of the window will damage the framing over time. Lastly, condensation risks need to be considered and assessed when considering the application of DIY secondary glazing.

DIY secondary glazing	Normal usage	Energy poverty usage
E. efficiency improvement (%)	5,7	7,0
T. comfort improvement (C^0)	2	1,9
Yearly savings (€)	55,9	36,4
Payback period (years)	5,7	8,8
Investing efficiency (%)	17,47	11,39

Table a21: *Simulation results of DIY secondary glazing (Own work, 2025)*

Appendix 9.9 External wall insulation
Description
External wall insulation (figure m) works in a similar manner as internal wall insulation, with the main difference being the placement of the insulation. In this case the insulation is added to the external side of the wall. It aims to be more effective than internal wall insulation, as the cold temperature is in an earlier stage than with internal wall insulation. External wall insulation requires a higher investment and implementation effort than internal wall insulation, as more changes are made to the façade.

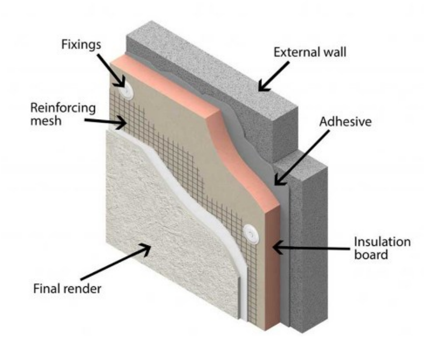


Figure m: *External wall insulation (cmostores.com limited, 2025)*

Envisioned effects
Van Der Linden et al. (2016, p. 54) discusses why external wall insulation is the most preferable method for improving the thermal quality of dwellings through insulation. By adding insulation to the outside of the dwelling, less cold is able to enter the dwelling. Besides this, the heat accumulation effect of the walls is kept intact, adding to the indoor environment. Besides these effects, external insulation is also effective in preventing thermal bridges from the exterior of the building into the interior of the building, for example through concrete. Indoor wall insulation is less effective in this regard and can even add negatively to these thermal bridges.

Simulation
External wall insulation was modelled similarly to indoor wall insulation. The base of the wall build-up was kept the same, only was there insulation added on the exterior of façades. The buildup of elements and R value calculations can be seen in appendix 7.3 and 7.11.

Property	Old situation	Change	New situation
Insulation (R) value (m^2K/W) of exterior wall type 1	0,5	Addition of 80mm Kooltherm K5	4,37
Insulation (R) value (m^2K/W) of exterior wall type 2	2,75		6,5
Insulation (R) value (m^2K/W) of exterior wall type 3	1,5		5,35

Table a22: *Simulation properties of external wall insulation (Own work, 2025)*

Results
External wall insulation is an energy efficiency intervention which has been researched and applied a lot since the growing importance of energy efficiency movement in buildings. Its applicability differs between housing typologies. Within the simulated case the results of external wall insulation remain limited and are comparable to the results of indoor wall insulation. The results can be seen in table a23.

Besides the financial performance, external wall insulation also comes with some more practical downsides than internal wall insulation. External wall insulation does require professional installation which can be quite disruptive and time consuming. Because external wall insulation will alter the exterior of the dwelling, approval from governance institutions will be required, which can add up to the time span and costs of the intervention. While this is a negative factor, it also provides chances for improving the quality of the building's exterior.

External wall insulation	Normal usage	Energy poverty usage
E. efficiency improvement (%)	4,66	5,9
T. comfort improvement (C^0)	2	1,7
Yearly savings (€)	45,95	30,66
Payback period (years)	101,6	152,3
Investing efficiency (%)	0,98	0,66

Table a23: *Simulation results of external wall insulation (Own work, 2025)*

Appendix 9.10 Glazing replacement

Description

Glazing replacement (figure n) consists of changing low quality glazing for higher quality materials. Existing glazing systems, often consisting out of single panes without thermal quality improvements can be changed with effective glazing systems which reduce heat losses. This is, like external wall insulation, an intervention which requires a higher investment and professional help.

Figure n: *Glazing replacement (Sadler, 2025)*

Envisioned effects

In chapter 2.4 the effects of different types of insulation were discussed, but these aren't the only segments of the façade which influence heat transfer, another integral part of the façade is the glazing. In calculating the effectiveness of insulation, the R value (heat resistance) is often used, but when calculating the overall thermal quality of the building the U value (heat transfer coefficient) is used more often (Van Der Linden et al., 2016, p. 12). This value describes the amount of heat which transfers through a specific construction, this distinction is important to understand when glazing is discussed.

Older glazing types, like single pane glazing, often have a U value of around 5,7 W/(m^{2}K). Newer types of glazing, like double pane glazing, already have U values of around 3,0 W/(m^{2}K), giving the indication that these types of glazing can restrict more cold from entering the dwelling. In their research, Moghaddam et al. (2023) provides an overview of U values of types of glazing, with lower U values resulting in improved energy efficiency and thermal comfort, this can be seen in figure o.

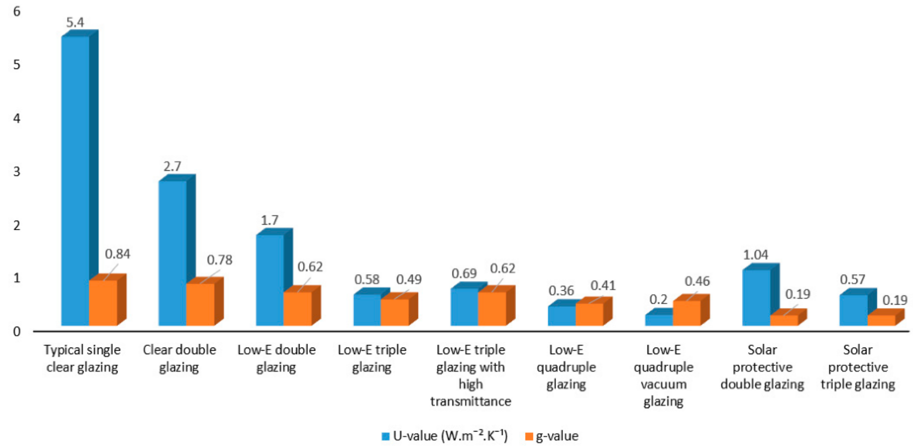


Figure o: *U-value and g-value of commercially available glazing systems (Moghaddam et al., 2023)*

Simulation

The glazing replacement was directly simulated by changing the glazing from double or single glass to HR glass. This was chosen to present a lower investment cost of glazing replacement, the effects of changes to lower U values were discussed in chapter 5.2.1. Within this case study, the glazing replacement is viewed separately from window frame replacement and accompanying improvements of infiltration values. The improvement of infiltration values as a result of glazing replacement is not taken into account, as this will differ per contractor, existing window frame and applied materials. Comparable improvements to infiltration values as a result of glazing replacement can be regarded through the simulation of weatherstripping.

Property	Old situation	Change	New situation
Effective U value of glass type 1 (W/m^2K)	5,37	Change from single to HR double glazing	2
Effective U value of glass type 2 (W/m^2K)	3,2	Change from double to HR double glazing	2

***Table a24:** Simulation properties of glazing replacement (Own work, 2025)*

Results

Glazing replacement achieves some of the most positive results out of all the tested interventions. The results can be seen in table a25. The results show glazing replacement to a very effective intervention for improving the energy efficiency of dwellings. Next to the simulated results, glazing replacement has a long life span with low maintenance efforts, and it can significantly increase the value of property and dwellings. At the same time, the high investment cost and long payback period reduce the interventions effectiveness in helping energy poverty households. As the installation might require frame modifications and intrusive façade modifications, it is also an intervention which only lends itself to homeowners instead of households who are renting their dwelling.

Glazing replacement	Normal usage	Energy poverty usage
E. efficiency improvement (%)	10,31	12,39
T. comfort improvement (C^0)	4,6	3,5
Yearly savings (€)	101,66	64,41
Payback period (years)	17,7	27,9
Investing efficiency (%)	5,65	3,58

***Table a25:** Simulation results of glazing replacement (Own work, 2025)*

Appendix 9.11 House air sealing
Description
House air sealing (figure p) involves identifying and sealing gaps, cracks, and leaks in the building envelope. The aim of this method is to prevent unwanted airflow of cold temperatures. Different areas in which air leakage is common include windows, doors, plumbing or attics. By sealing these leaks with sprays, weatherstripping or caulk, drafts are reduced. Besides reducing heat losses, air quality is another positive effect of house air sealing. House air sealing requires professional help who have thermal cameras. This is done to detect air leaks within the dwelling, which can't be noticed with the naked eye. Besides this, blowerdoor tests can be applied by professionals to detect leaks.

Figure p: *House air sealing (PCC Group, 2025)*

Envisioned effects
Anand et al. (2024) has provided research on the effects air-sealing can have on the thermal loads of single-family houses in America. The aim of the study was to investigate the benefits of combining air sealing with the installation of ground source heat pumps, as air sealed houses were hypothesized to need smaller heat pumps. The study showed that by reducing the outdoor air infiltration of the homes from 0,85 air changes per hour (ACH) to the minimal requirement of 0,35 ACH, the total heating electricity could be reduced up to 44%.

Air sealing showed to be most applicable for reducing heating energy in colder climates. The Netherlands has an average ground temperature of around 11 degrees Celsius, similar to the cities of Chicago and Helena. Chicago test subjects show a 43% reduction in heating energy and Helena test subjects show a 41% reduction.

Simulation
House air sealing was simulated by improving the wind-dependent infiltration rates within the simulation model. Because there is no direct research available on the improvements house air sealing makes to the infiltration values of a dwelling, an estimation was made. This estimation was made by following the calculation steps of ISSO 51-2017 (ISSO kennisinstituut voor installatietechniek, 2017) of appendix 7.12. By changing the value for the characteristic specific infiltration flow to that of a renovated dwelling, the calculations changed and resulted in a new infiltration value which can be seen in table a26. House air sealing significantly improves these infiltration values, as all possible leakage spots of the dwelling are considered. Besides this, these spots are professionally sealed and there is meticulous control to check whether all spots have been handled. The calculations of the original infiltration values can be found in appendix 7.12.

Property	Old situation	Change	New situation
Wind-dependent infiltration (1/h)	0,40	Improvement of air tightness of rooms and doors	0,2

Table a26: *Simulation properties of house air sealing (Own work, 2025)*

Results
Depending on the existing situation in which the intervention is applied, house air sealing can have significant effects on the energy efficiency and thermal comfort of dwellings. The results can be seen in table a27.

While the intervention introduces different improvements in energy efficiency and thermal comfort setpoints, house air sealing introduces more relevant improvements to the dwelling. The air quality of the dwelling is improved, as low-quality air from cracks and cavities is obstructed from entering the dwelling. The direct thermal comfort of the dwelling is also improved, as drafts and cold air flows are reduced by the intervention. Lastly, house air sealing is an intervention which lends itself well to be combined with other energy efficiency interventions like indoor wall insulation or improvements to the U value of walls.

While there are many upsides to the usage of house air sealing, it is a labour-intensive intervention in its installation and requires professional help to effectively detect leaks. Another potential downside to house air sealing is that it might reduce the ventilation rate of dwellings. As households without house air sealing indirectly profit from the ventilation rate due to infiltration, will be left with a reduced ventilation rate as this is obstructed by house air sealings. If households don't compensate for this loss of ventilation by increasing their natural or mechanical ventilation, the ventilation quality could worsen and cause negative effects, such as mould.

House air sealing	Normal usage	Energy poverty usage
E. efficiency improvement (%)	2,42	3,05
T. comfort improvement (C^0)	1	0,9
Yearly savings (€)	23,9	15,87
Payback period (years)	16,7	25,2
Investing efficiency (%)	5,97	3,97

Table a27: *Simulation results of house air sealing (Own work, 2025)*

Appendix 9.12 Floor insulation

Description

Floor insulation (figure q) works similar to other forms of insulation, such as internal and external wall insulation. Floor insulation differentiates itself in the types of temperatures it is trying to wear off. In most applications of floor insulation, cold temperatures from the crawl space below the floor are attempted to be blocked. Floor insulation is often applied in newer dwellings in which it can be proactively placed below the floor finishing. But it is also able to be applied as a renovation measure. In apartment buildings, floor insulation is still applied to prevent heat losses from the single apartments and to function as sound insulation. But there is less emphasis on this floor insulation, as the individual rooms will heat each other up, if they are individually heated. With apartments being heated less during energy poverty, this floor insulation could be of more importance.

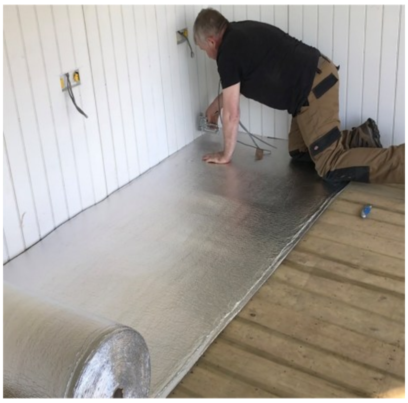


Figure q: *Floor insulation (BQ, 2025)*

Envisioned effects

The research on the effects of floor insulation shows the great effect it has in older dwellings. Especially dwellings with suspended timber floors, with space for air to circulate. Research of the UCL showed a reduction in heat losses through the floor between 65 and 92 percent (Ucl, 2025). Similar research investigated the effect floor insulation had on the overheating of dwellings, looking into how removing floor insulation would reduce this overheating. The research showed that removing this insulation would aid in preventing this overheating but would significantly increase the necessary heating energy (Staszczuk et al., 2017). As has been discussed in this research, insulation is most useful when applied to the coldest neighbouring temperature. This causes the effects of floor insulation in apartment buildings to be questioned.

Simulation

To simulate the addition of floor insulation in the existing dwelling, a relatively thin layer of insulation was added to the floor construction, increasing the R value of this construction.

Property	Old situation	Change	New situation
Insulation (R) value (m^2K/W) of floor	0,21	Addition of 70mm Kooltherm K5	3,60

Table a28: *Simulation properties of floor insulation (Own work, 2025)*

Results

The simulation results of floor insulation are remarkably limited and are even perceived as negative within the energy poverty situation. The results can be seen in table a29. These results raise many different questions about floor insulation and its ineffectiveness, common knowledge on energy efficiency interventions lead to the notion that it should be impossible for interventions to have negative effects on households. But there are different explanations for the simulation results.

The first being that floor insulations most common usage is in ground floor dwellings which have cold crawl spaces underneath the floors of living areas. Floor insulation aims toward blocking these colder temperatures, similar to other forms of insulation. But in the realistic and simulated situation, the floor insulation is applied on floors which are connected to living spaces of the dwellings of the downstairs neighbour. The dwelling of the downstairs neighbour emits much higher temperatures than the crawlspaces the intervention is intended to be used on. This difference results in warm temperatures being blocked from entering the dwelling, which causes the heating demand to rise for energy poverty households, this explains the negative effect on energy efficiency in energy poverty households. Meanwhile, for normal households the pros of floor insulation can outweigh its previously mentioned cons. As normal households are heated to a higher extend, the heating energy can be lost through the floor to the dwelling below. In these cases, floor insulation can aid in reducing the amount of heat energy which is lost through the floor.

Floor insulation	Normal usage	Energy poverty usage
E. efficiency improvement (%)	0,27	0
T. comfort improvement (C^0)	0,1	0
Yearly savings (€)	2,68	0
Payback period (years)	439,9	Unprofitable
Investing efficiency (%)	0,23	0

Table a29: *Simulation results of floor insulation (Own work, 2025)*

Appendix 9.13 Weatherstripping
Description
Weatherstripping (figure r) is a practical method for reducing heat loss around doors and windows. It involves applying sealing materials like rubber or foam to gaps where air can escape or enter. The purpose of weatherstripping is to improve indoor temperature and limit energy waste by preventing drafts. This method is particularly useful in older homes, where gaps around doors and windows are more common. By blocking these air leaks, weatherstripping helps lower heating and cooling costs while enhancing indoor comfort. It is an affordable and straightforward solution that can be applied by homeowners without professional assistance. Unlike house air sealing, weatherstripping only focusses on cracks through windows and doors, instead of also through constructive elements.

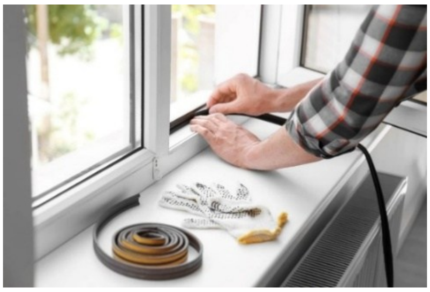


Figure r: *Weatherstripping (Tochtstripdeur.nl, 2025)*

Envisioned effects
The research of Brambley et al. (1984) investigates the effects of weatherstripping on the energy consumption in single-family residences in San Diego. The research shows that the effects of weatherstripping are heavily dependent on the energy consumption habits of the household, and the energy efficiency of the dwelling as a whole. An average energy saving of between 0 and 5% is noted.

Simulation
Weatherstripping improves the air tightness of windows and door frames, which accounts for a large amount of wind infiltration. The research of Brambley et al. (1984) notes an reduction in infiltration of around 30% as a result of weatherstripping. This conclusion was used to alter the wind-dependent infiltration value from 0,4 to 0,3. The calculations of the original infiltration values can be found in appendix 7.12.

Property	Old situation	Change	New situation
Wind-dependent infiltration (1/h)	0,40	Improvement of air tightness of rooms and doors	0,3

Table a30: *Simulation properties of weatherstripping (Own work, 2025)*

Results
Weatherstripping works similar to the interventions of draft stoppers and house air sealing, as it improves the air tightness of the dwelling. The effects of weatherstripping are like those of draft stoppers, but slightly better. The results can be seen in table a31. Similar to draft stoppers and house air sealing, the largest improvement weatherstripping provides is in its improvement of thermal comfort, by preventing cold drafts from entering the dwelling. It is a cheap investment which is easy to apply but can be tricky to apply in more complicated situations. It is also an intervention which requires regular maintenance and is less effective for larger air gaps.

Weatherstripping	Normal usage	Energy poverty usage
E. efficiency improvement (%)	1,81	2,28
T. comfort improvement (C^0)	0,7	0,7
Yearly savings (€)	17,82	11,87
Payback period (years)	6,7	10,1
Investing efficiency (%)	14,85	9,89

Table a31: *Simulation results of weatherstripping (Own work, 2025)*

Appendix 9.14 Ceiling insulation

Description

Ceiling insulation (figure s) functions similarly to other insulation methods, such as wall and floor insulation. However, it specifically targets heat transfer between floors or between indoor spaces and the attic. In most applications, ceiling insulation is used to prevent warm indoor air from escaping into unheated attic. Ceiling insulation is commonly installed in newer homes during construction, allowing it to be placed efficiently between ceiling joists. However, it can also be added as a renovation measure, particularly in older homes with inadequate insulation. In apartment buildings, ceiling insulation is primarily used to minimize heat loss between units and to serve as sound insulation, reducing noise transmission between floors. The importance of ceiling insulation increases in situations where upper floors are unheated or poorly insulated, as it helps maintain stable indoor temperatures and improves overall energy efficiency.

***Figure s:** Ceiling insulation (Certified Applicator Extend Roofing Lifespan | Kohls Foam Systems INC., 2022)*

Envisioned effects

Not much research has been done on the possible effects and applications of ceiling insulation, the overarching understanding of surface insulation would lead to believe that it works similarly to floor insulation. In theory, ceiling insulation would lead to generated heat being obstructed from leaving the dwelling, and colder temperatures being prevented from entering the dwelling. Like floor insulation, ceiling insulation mains application is on roofs or ceilings which are neighbouring the outdoor air.

Research by Taylor et al. (2000) on the application of ceiling insulation within South-African households showed that winter savings were caused by ceiling insulation. At the same time, these winter savings were of such low value that it would not be an attractive intervention for households. To broaden the application of ceiling insulation, research was done on the thermal comfort improvement the intervention generates. The research showed that summer comfort would improve significantly under the application of ceiling insulation.

Simulation

To simulate the addition of ceiling insulation in the existing dwelling, a relatively thin layer of insulation was added to the ceiling construction, increasing the R value of this construction.

Property	Old situation	Change	New situation
Insulation (R) value (m^2K/W) of ceiling	0,21	Addition of 70mm Kooltherm K5	3,60

***Table a32:** Simulation properties of ceiling insulation (Own work, 2025)*

Results

The results on the application of ceiling insulation are like those of floor insulation, ceiling insulation does show itself to be slightly less effective. The results can be seen in table a33.

These results show that the intervention is quite ineffective, which can be explained by analysing the changes the intervention applies. Ceiling insulation would aim toward obstructing indoor heating from leaving the room, but when there is another heated room above, these existing heat losses are minimal. Because the existing heat losses are already minimal, insulating this area has little effect.

Because of these results, ceiling insulation can be deemed as an ineffective method in the simulated case. On top of this, ceiling insulation has other downsides like the cost of the intervention, the requirement of professional placement, its difficulty of installation and the risk of moisture.

Ceiling insulation	Normal usage	Energy poverty usage
E. efficiency improvement (%)	0,14	0,06
T. comfort improvement (C^0)	0	0
Yearly savings (€)	1,43	0,33
Payback period (years)	414,4	1789,4
Investing efficiency (%)	0,24	0,06

Table a33: *Simulation results of ceiling insulation (Own work, 2025)*

Appendix 9.15 Floor rug insulation

Description

Floor rug insulation (figure t) works similarly to standard floor insulation by helping to reduce heat loss and improve thermal comfort. However, instead of being installed beneath the flooring, rugs and carpets act as an insulating layer on top of hard surfaces. Their primary function is to prevent heat from escaping through uninsulated floors and to provide a warmer surface underfoot. Floor rug insulation is most effective in homes with drafty floors or minimal existing insulation, where it can serve as an easy and cost-effective solution for reducing cold spots. While not a substitute for full floor insulation, rugs and carpets offer a practical and easy way to improve comfort and energy efficiency with minimal effort.

Figure t: *Floor rug insulation (Amazon.com, n.d.)*

Envisioned effects

The research of McNeil (2016) looks into the effects wool carpets can have on the energy consumption of households. Many parameters are noted which influence the effectiveness of floor rug insulation, such as the underlying material and the material of the rug itself. For a 10mm thick floor rug, a heating energy saving of 10% is noted. This energy saving is not only due to the thermal performance of the rug, but also the way in which it provides comfort for those living in the dwelling. The added warmth to the feet results in less heating being necessary.

Simulation

Floor insulation is simulated by adding a carpet insulation layer onto the existing concrete floor. This new flooring is applied to the discussed living spaces.

Property	Old situation	Change	New situation
Insulation (R) value (m^2K/W) of floor	0,21	Addition of 10mm rug insulation	0,5

Table a34: *Simulation properties of floor rug insulation (Own work, 2025)*

Results

The results of floor rug insulation are similar to those of regular floor insulation, in the observation that the effects are very limited and aren’t financially attractive. Where floor rug insulation differs from regular floor insulation, is in the result that it is a profitable intervention for energy poverty situations, while only slightly, unlike normal floor insulation. This is likely due to the thickness of floor rug insulation being so little that not all the heat of the dwelling below is blocked. Where floor rug insulation does stand out, Is in its ease of application and its cheap investment price.

Floor rug insulation	Normal usage	Energy poverty usage
E. efficiency improvement (%)	0,22	0,07
T. comfort improvement (C^0)	0	0
Yearly savings (€)	2,21	0,36
Payback period (years)	357,1	2187
Investing efficiency (%)	0,28	0,05

Table a35: *Simulation results of floor rug insulation (Own work, 2025)*

Appendix 9.16 Portable space heaters

Description

Portable space heaters (figure u) operate similarly to central heating systems but on a much smaller scale, providing targeted warmth to specific areas instead of heating an entire home. Portable space heaters are most commonly used in rooms that are difficult to heat or in households looking to reduce reliance on central heating. They can be particularly useful in older homes with poor insulation, where they help in providing local comfort, instead of needing to heat the entire dwelling. In apartment buildings, space heaters are often used for supplemental heating, especially in rooms that receive less heat from central systems. However, their efficiency depends on usage habits, as prolonged operation can lead to higher electricity consumption.

Figure u: *Portable space heater (bol.com, n.d.)*

Envisioned effects

Research by Brambley and Moline (1986) notes that the effectiveness of portable space heaters is heavily dependent on the situation in which it is used, and that its benefits can vary heavily. For example, portable space heaters show to be effective in poorly insulated homes. Because the required energy for entirely heating these rooms with regular radiators is much higher.

Simulation

Portable space heaters are simulated by changing the heating system from convection radiators to localized air heating.

Property	Old situation	New situation
Heating method	Convection radiator	Localized air heating
Heating system effectiveness	50 W/m^2	1500W

Table a36: *Simulation properties of portable space heaters (Own work, 2025)*

Results

In order to correctly interpret the results of the simulation with portable space heaters, different testing criteria need to be considered. The results of the intervention can be seen in table a37.

Floor rug insulation	Normal usage	Energy poverty usage
Heating energy efficiency improvement (%)	-3,33	2,1
T. comfort improvement (C^0)	-0,4	0,3
Yearly savings with energy priced at 0,78€(€)	-90,6	61
Payback period (years)	Unprofitable	1
Investing efficiency (%)	-66%	98%

Table a37: *Simulation results of portable space heaters (Own work, 2025)*

Appendix: 10 – Individual analyses detailed results

Appendix 10.1 – Radiator foil method 1 (heating system)

Radiator foil method 1 (heating system) - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	633,5	346,5
Improvement (%)	3,7	0,04
Radiator foil method 1 (heating system) - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	21	13,5
Improvement (°C)	2	0
Radiator foil method 1 (heating system) - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	35	
Gas consumption savings with same temperature settings (m^3)	24	0,1
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	36	0,2
Payback period (years)	1	179
Old gas bill (€)	986,2	519,9
New gas bill (€)	950,2	519,7
Investing efficiency (%)	102,9	0,56
Radiator foil method 1 (heating system) - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Reduces heat losses relative to price • Cheap and easy to install • Effective in older buildings • Easy upgrade to existing systems	
Intervention cons	• Limited impact • Effectiveness depends on wall type • Not suitable on other heat sources	

Appendix 10.2 – Radiator foil method 2 (wall properties)

Radiator foil method 2 (wall properties) - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	649,3	341,1
Improvement (%)	1,2	1,6
Radiator foil method 2 (wall properties) - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	19,5	14
Improvement (°C)	0,5	0,5
Radiator foil method 2 (wall properties) - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	35	
Gas consumption savings with same temperature settings (m^3)	8,2	5,5
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	12,3	8,2
Payback period (years)	2,8	4,3
Old gas bill (€)	986,2	519,9
New gas bill (€)	973,9	511,7
Investing efficiency (%)	35,19	23,44
Radiator foil U value - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Reduces heat losses relative to price • Cheap and easy to install • Effective in older buildings • Easy upgrade to existing systems	
Intervention cons	• Limited impact • Effectiveness depends on wall type • Not suitable on other heat sources	

Appendix 10.3 – Thermal curtains (no changes in solar shading)

Thermal curtains (without changes in solar shading) - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	592,0	305,5
Improvement (%)	10	11,85
Thermal curtains - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	23,6	16,9
Improvement (°C)	4,6	3,4
Thermal curtains - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	250	
Gas consumption savings with same temperature settings (m^3)	65,5	41,1
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	98,2	61,6
Payback period (years)	3	4
Old gas bill (€)	986,2	519,9
New gas bill (€)	888,0	458,3
Investing efficiency (%)	39,29	24,64
Thermal curtains - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Blocks cold and drafts • Large effects on consumption and thermal comfort • Easy to install • Not expensive • DIY optional	
Intervention cons	• Only effective near low quality windows and walls • Only useful when consistently closed • Blocks sunlight when used	

Appendix 10.4 – Thermal curtains (with changes in solar shading)

Thermal curtains (with changes in solar shading) - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	619,1	320
Improvement (%)	5,8	7,66
Thermal curtains - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	21,2	15,6
Improvement (°C)	2,2	2,1
Thermal curtains - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	250	
Gas consumption savings with same temperature settings (m^3)	38,4	26,2
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	57,6	39,8
Payback period (years)	4	6
Old gas bill (€)	986,2	519,9
New gas bill (€)	928,6	480
Investing efficiency (%)	23,04	15,94
Thermal curtains - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Blocks cold and drafts • Large effects on consumption and thermal comfort • Easy to install • Not expensive • DIY optional	
Intervention cons	• Only effective near low quality windows and walls • Only useful when consistently closed • Blocks sunlight when used	

	Thermal curtains – no change in solar shading		Thermal curtains – solar shading always closed	
Parameter	**Normal usage**	**Energy poverty usage**	**Normal usage**	**Energy poverty usage**
Energy efficiency improvement	10,0%	11,85%	5,8%	7,66%
Thermal comfort improvement	4,6 °C	3,4 °C	2,2 °C	2,1 °C
Yearly savings	98,2€	61,6€	57,6€	39,8€
Payback period	3	4	4	6
Investing efficiency	39,29%	24,64%	23,04%	15,94%

Energy flows on the coldest day	Required heating energy (W)	Entered solar heating energy (W)
Room 4: balcony side bedroom – no interventions	5278	1588,6
Room 4: balcony side bedroom – thermal curtains	4063	1588,5
Room 4: balcony side bedroom – thermal curtains & solar shading	5245	806,7
Room 5: living room – no interventions	11127,0	5185,4
Room 5: living room – thermal curtains	8109,5	5185,6
Room 5: living room – thermal curtains & solar shading	8827,8	3588,3
Room 3: gallery side bedroom – no interventions	7453,6	1008,0
Room 3: gallery side bedroom – thermal curtains	6444,8	1008,0
Room 3: gallery side bedroom – thermal curtains & solar shading	6789,7	651,5
Room 1: kitchen – no interventions	5196,2	1165,0
Room 1: kitchen – thermal curtains	4816,8	1165,0
Room 1: kitchen – thermal curtains & solar shading	4946,4	757,1

Appendix 10.5 – Infrared heating panels

Infrared heating panels - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Heating energy consumption without intervention (kwh)	3545	1467
Heating energy consumption with intervention and same temperature settings (kwh)	2967	1384
Improvement (%)	16,3	5,7
Infrared heating panels - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	400	
Electricity consumption savings with same temperature settings (kwh)	-1626	-887
Energy pricing (€)	0,32	0,32
Yearly savings with same temperature settings (€)	-520,3	-283,8
Payback period (years)	X	X
Old energy bill (€)	763,8	763,8
New energy bill (€)	1.284,2	1.047,7
Investing efficiency (%)	-130,08	-70,96
Infrared heating panels - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Significantly improves insulation • Long life span • Property value increase	
Intervention cons	• High cost • May require frame modifications • Long payback period, if it is profitable	

Appendix 10.6 – Draft stoppers

Draft stoppers - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	652,6	343,2
Improvement (%)	0,7	1,0
Draft stoppers - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	19,3	13,8
Improvement (°C)	0,3	0,3
Draft stoppers - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	48	
Gas consumption savings with same temperature settings (m^3)	4,4	3,4
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	6,7	5,1
Payback period (years)	7,2	9,4
Old gas bill (€)	986,2	519,9
New gas bill (€)	978,8	514,8
Investing efficiency (%)	13,88	10,66
Draft stoppers - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Immediate noticeable effect through draft stopping • Effects on both energy consumption and thermal comfort • Portable and reusable • No energy consumption	
Intervention cons	• Requires regular adjustment • Not suitable for all door types • Not aesthetically pleasing	

Appendix 10.7 – Indoor wall insulation

Indoor wall insulation - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	627,0	326,8
Improvement (%)	4,6	5,5
Indoor wall insulation - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	21	15,2
Improvement (°C)	2	1,7
Indoor wall insulation - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	950	
Gas consumption savings with same temperature settings (m^3)	30,0	19,2
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	45,1	28,7
Payback period (years)	21,1	33,1
Old gas bill (€)	985,5	519,0
New gas bill (€)	940,4	490,3
Investing efficiency (%)	4,74	3,03
Indoor wall insulation - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Significant heat loss reduction • Significant thermal comfort improvement • No altering of exterior • Installation possible in older homes	
Intervention cons	• Reduces interior space • Installation can be disruptive of existing situation • Risk of moisture buildup	

Appendix 10.8 – Window insulation film

Window insulation film - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	631,6	329,6
Improvement (%)	3,9	4,9
Window insulation film - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	20,6	14,7
Improvement (°C)	1,6	1,2
Window insulation film - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	56	
Gas consumption savings with same temperature settings (m^3)	25,9	17,0
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	38,9	25,5
Payback period (years)	1,4	2,2
Old gas bill (€)	986,2	519,9
New gas bill (€)	947,4	494,4
Investing efficiency (%)	69,4	45,6
Window insulation film - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Affordable • DIY solution • Can help reduce condensation	
Intervention cons	• May reduce window clarity • Temporary solution • Limited impact on drafts • Only effective on existing low window quality	

Appendix 10.9 – Insulated door panels

Insulated door panels - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	643,7	337,3
Improvement (%)	2,1	2,7
Insulated door panels - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	19,9	14,3
Improvement (°C)	0,9	0,8
Insulated door panels - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	34,64	
Gas consumption savings with same temperature settings (m^3)	13,8	9,3
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	20,7	13,9
Payback period (years)	1,7	2,5
Old gas bill (€)	986,2	519,9
New gas bill (€)	965,6	506,0
Investing efficiency (%)	59,63	40,18
Insulated door panels - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Improves insulation • Can be added to existing doors • Cost-effective compared to buying new doors	
Intervention cons	• Limited impact • Alters door aesthetics • Precise installation	

Appendix 10.10 – DIY secondary glazing

DIY secondary glazing - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657	346
Gas consumption with intervention and same temperature settings (m^3)	620,2	322,3
Improvement (%)	5,7	7,0
DIY secondary glazing - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	21,0	15,4
Improvement (°C)	2	1,9
DIY secondary glazing - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	320	
Gas consumption savings with same temperature settings (m^3)	37,3	24,3
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	55,9	36,4
Payback period (years)	5,7	8,8
Old gas bill (€)	986,2	519,9
New gas bill (€)	930,3	483,4
Investing efficiency (%)	17,47	11,39
DIY secondary glazing - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Cheap alternative to double glazing • DIY installation • Reversable, useful for rental homes	
Intervention cons	• Can reduce window visibility • Not very durable for long term • Condensation risks • Limited effectiveness for more efficient glazing types	

Appendix 10.11 – External wall insulation

External wall insulation - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	626,9	326,2
Improvement (%)	4,7	5,9
External wall insulation - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (^oC)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(^oC)	21	15,2
Improvement (^oC)	2	1,7
External wall insulation - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	4670	
Gas consumption savings with same temperature settings (m^3)	30,6	20,4
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	45,9	30,7
Payback period (years)	101,6	152,3
Old gas bill (€)	986,2	519,9
New gas bill (€)	940,3	489,2
Investing efficiency (%)	0,98	0,66
External wall insulation - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Highly effective for heat losses • Energy efficiency • Long term solution • Can improve external aesthetics	
Intervention cons	• Expensive • Requires professional installation • Disruptive installation • Potential planning restrictions	

Appendix 10.12 – Glazing replacement

Glazing replacement - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	589,7	303,7
Improvement (%)	10,3	12,4
Glazing replacement - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	23,6	17
Improvement (°C)	4,6	3,5
Glazing replacement - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	1800	
Gas consumption savings with same temperature settings (m^3)	67,8	42,9
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	101,7	64,4
Payback period (years)	17,7	27,9
Old gas bill (€)	986,2	519,9
New gas bill (€)	884,6	455,5
Investing efficiency (%)	5,65	3,58
Glazing replacement - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Significantly improves insulation • Long life span • Property value increase	
Intervention cons	• High cost • May require frame modifications • Long payback period	

Appendix 10.13 – House air sealing

House air sealing - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	641,6	336,2
Improvement (%)	2,4	3,1
House air sealing - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	20	14,4
Improvement (°C)	1	0,9
House air sealing - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	400	
Gas consumption savings with same temperature settings (m^3)	15,9	10,6
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	23,9	15,9
Payback period (years)	16,7	25,2
Old gas bill (€)	986,2	519,9
New gas bill (€)	962,3	504
Investing efficiency (%)	5,97	3,97
House air sealing - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Reduces heat losses through cracks • Improves air quality • Enhances home thermal comfort • Works well in combination with insulation	
Intervention cons	• Requires professional installation • Expensive • Risk of ventilation decrease	

Appendix 10.14 – Floor insulation

Floor insulation - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	655,7	346,8
Improvement (%)	0,3	-0,1
Floor insulation - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (^oC)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(^oC)	19,1	13,5
Improvement (^oC)	0,1	0
Floor insulation - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	1181	
Gas consumption savings with same temperature settings (m^3)	1,8	-0,2
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	2,7	-0,3
Payback period (years)	439,9	-3578,8
Old gas bill (€)	986,2	519,9
New gas bill (€)	983,6	520,2
Investing efficiency (%)	0,23	-0,03
Floor insulation - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Prevents heat losses through crawling space or cold lower neighbours • Long lifespan	
Intervention cons	• Disruptive installation • Not always possible in existing buildings • Limited to negative benefits	

Appendix 10.15 – Weatherstripping

Weatherstripping - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	645,6	338,7
Improvement (%)	1,8	2,3
Weatherstripping - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (^oC)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(^oC)	19,7	14,2
Improvement (^oC)	0,7	0,7
Weatherstripping - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	120	
Gas consumption savings with same temperature settings (m^3)	11,9	7,9
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	17,8	11,9
Payback period (years)	6,7	10,1
Old gas bill (€)	986,2	519,9
New gas bill (€)	968,4	508
Investing efficiency (%)	14,85	9,89
Weatherstripping - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Reduces drafts • Easy and cheap installation • Improved heating efficiency	
Intervention cons	• Regular maintenance needed • Not as effective for larger gaps • Can be difficult to install correctly	

Appendix 10.16 – Ceiling insulation

Ceiling insulation - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	656,5	346,4
Improvement (%)	0,1	0,1
Ceiling insulation - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	19	13.5
Improvement (°C)	0	0
Ceiling insulation - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	590,5	
Gas consumption savings with same temperature settings (m^3)	1,0	0,2
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	1,4	0,3
Payback period (years)	414,4	1789,4
Old gas bill (€)	986,2	519,9
New gas bill (€)	984,8	519,6
Investing efficiency (%)	0,24	0,06
Ceiling insulation - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Long lifespan • No visible obstruction	
Intervention cons	• Limited effects • Costly • May require professional installation • Can cause moisture problems	

Appendix 10.17 – High efficiency boiler

High efficiency boiler - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	632,2	329,7
Improvement (%)	3,9	4,9
High efficiency boiler - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (^oC)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(^oC)	19	13,5
Improvement (^oC)	0	0
High efficiency boiler - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	1500	
Gas consumption savings with same temperature settings (m^3)	25,3	16,9
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	38	25,3
Payback period (years)	39,5	59,2
Old gas bill (€)	986,2	519,9
New gas bill (€)	948,2	494,6
Investing efficiency (%)	2,53	1,69
High efficiency boiler - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Reduces fuel consumption • More consistent and powerful heating • Long lifespan	
Intervention cons	• High investment • Requires professional installation • May need additional upgrades • Limited benefits if home insulation is poor	

Appendix 10.18 – Rug floor insulation

Rug floor insulation - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	656,0	346,4
Improvement (%)	0,2	0,1
Rug floor insulation - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	19	13,5
Improvement (°C)	0	0
Rug floor insulation - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	787,5	
Gas consumption savings with same temperature settings (m^3)	1,5	0,2
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	2,2	0,4
Payback period (years)	357,1	2187,5
Old gas bill (€)	986,2	519,9
New gas bill (€)	984	519,5
Investing efficiency (%)	0,28	0,05
Rug floor insulation - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Hidden placement • Cheap installation • No taking up space	
Intervention cons	• Limited effects • Requires rugs to be present	

Appendix 10.19 – Portable space heaters

Portable space heaters - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Heating energy consumption without intervention (kwh)	3545	1467
Heating energy consumption with intervention and same temperature settings (kwh)	3661,2	1436,7
Improvement (%)	-3,3	2,1
Portable space heaters - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (ᵒC)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(ᵒC)	18,6	13,8
Improvement (ᵒC)	-0,4	0,3
Portable space heaters - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	60	
Heating energy consumption savings with same temperature settings (kwh)	-116,2	78,2
Energy pricing (€)	0,78	0,78
Yearly savings with same temperature settings (€)	-90,6	61
Payback period (years)	-0,7	1
Old gas bill (€)	512,8	270,3
New gas bill (€)	340,9	209,4
Portable space heaters - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Targeted and localized heating • Portable and flexible • Fast heating time	
Intervention cons	• High energy consumption • Dries out air • Ineffective in larger spaces	

Appendix 10.20 – High value interventions (External wall insulation, glazing replacement, house air sealing)

High value interventions - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	553,8	283,5
Improvement (%)	15,8	18,2
High value interventions - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	24,7	19
Improvement (°C)	5,7	5,5
High value interventions - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	6870	
Gas consumption savings with same temperature settings (m^3)	103,7	63,1
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	155,6	94,6
Payback period (years)	44,2	72,6
Old gas bill (€)	986,2	519,9
New gas bill (€)	830,6	425,3
Investing efficiency (%)	2,26	1,38
High value interventions - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• High energy efficiency • High quality and lifespan • Large comfort improvement	
Intervention cons	• High investment costs • Long payback period • Professional help required	

Appendix 10.21 – Low value interventions (Insulation film, draft stoppers, indoor wall insulation)

Low value interventions - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	609,3	315,4
Improvement (%)	7.3	9,0
Low value interventions - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (^oC)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(^oC)	21,5	15,7
Improvement (^oC)	2,5	2,2
Low value interventions - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	1054	
Gas consumption savings with same temperature settings (m^3)	48,2	31,2
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	72,4	46,9
Payback period (years)	14,6	22,5
Old gas bill (€)	986,2	519,9
New gas bill (€)	913,9	€ 473,0
Investing efficiency (%)	6,87	4,45
Low value interventions - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Low investment costs • DIY'able • Easy removal	
Intervention cons	• Lower energy and thermal comfort efficiency • Short lifespan	

Appendix 10.22 – Poptahof noord interventions (Insulating door panels, thermal curtains & window insulation film)

Low value interventions - Energy Efficiency (What is the impact on energy savings?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Gas consumption without intervention (m^3)	657,5	346,6
Gas consumption with intervention and same temperature settings (m^3)	621,5	322,6
Improvement (%)	5,8%	7,2%
Low value interventions - Thermal comfort (What is the impact on indoor temperature?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Temperature setpoint without intervention (°C)	19	13,5
Temperature setpoint with intervention under same energy usage & bill(°C)	21,3	15,4
Improvement (°C)	2,5	2,1
Low value interventions - Financial efficiency (What is the impact on energy bills?)		
Parameter	**Normal usage profile**	**Energy poverty usage profile**
Approximate cost of intervention (€)	300	
Gas consumption savings with same temperature settings (m^3)	37,9	25,2
Gas pricing (€)	1,5	1,5
Yearly savings with same temperature settings (€)	57,0	37,8
Payback period (years)	5,3	7,9
Old gas bill (€)	€ 986,2	€ 519,9
New gas bill (€)	€ 929,3	€ 483,9
Investing efficiency (%)	18,97%	12,60%
Low value interventions - Overall efficiency (What is the conclusion on the intervention?)		
Intervention pro's	• Specific to Poptahof Noord • Combines energy efficiency with thermal comfort • All interventions can be installed without professional help • Demountable interventions	
Intervention cons	• Lower energy and thermal comfort efficiency than more expensive interventions • Extensive installation work	

Appendix: 11 – Comparison of individual interventions

Appendix 11.1 – Energy efficiency improvements

Energy efficiency improvements				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	Glazing replacement	10,3%	Glazing replacement	12,4%
2	Thermal curtains	5,8%	Thermal curtains	7,7%
3	Secondary glazing DIY	5,7%	Secondary glazing DIY	7,0%
4	External wall insulation	4,7%	External wall insulation	5,9%
5	Indoor wall insulation	4,6%	Indoor wall insulation	5,5%
6	Window insulation film	3,9%	Window insulation film	4,9%
7	Radiator foil (Method 1)	3,7%	House air sealing	3,1%
8	House air sealing	2,4%	Insulated door panels	2,7%
9	Insulated door panels	2,1%	Weatherstripping	2,3%
10	Weatherstripping	1,8%	Radiator foil (Method 2)	1,6%
11	Radiator foil (Method 2)	1,2%	Draft stoppers	1,0%
12	Draft stoppers	0,7%	Floor rug insulation	0,1%
13	Floor insulation	0,3%	Ceiling insulation	0,1%
14	Floor rug insulation	0,2%	Radiator foil (Method 1)	0,0%
15	Ceiling insulation	0,1%	Floor insulation	-0,1%

Appendix 11.2 – Thermal comfort improvements

Thermal comfort improvements				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	Glazing replacement	4,6	Glazing replacement	3,5
2	Thermal curtains	2,2	Thermal curtains	2,1
3	Indoor wall insulation	2,0	Secondary glazing DIY	1,9
4	External wall insulation	2,0	Indoor wall insulation	1,7
5	Radiator foil (Method 1)	2,0	External wall insulation	1,7
6	Secondary glazing DIY	2,0	Window insulation film	1,2
7	Window insulation film	1,6	House air sealing	0,9
8	House air sealing	1,0	Insulated door panels	0,8
9	Insulated door panels	0,9	Weatherstripping	0,7
10	Weatherstripping	0,7	Radiator foil (Method 2)	0,5
11	Radiator foil (Method 2)	0,5	Draft stoppers	0,3
12	Draft stoppers	0,3	Floor insulation	0,0
13	Floor insulation	0,1	Ceiling insulation	0,0
14	Ceiling insulation	0,0	Floor rug insulation	0,0
15	Floor rug insulation	0,0	Radiator foil (Method 1)	0,0

Appendix 11.3 – Yearly savings

Yearly savings				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	Glazing replacement	101,7	Glazing replacement	64,4
2	Thermal curtains	57,6	Thermal curtains	39,8
3	Secondary glazing DIY	55,9	Secondary glazing DIY	36,4
4	External wall insulation	45,9	External wall insulation	30,7
5	Indoor wall insulation	45,1	Indoor wall insulation	28,7
6	Window insulation film	38,9	Window insulation film	25,5
7	Radiator foil (Method 1)	36,0	House air sealing	15,9
8	House air sealing	23,9	Insulated door panels	13,9
9	Insulated door panels	20,7	Weatherstripping	11,9
10	Weatherstripping	17,8	Radiator foil (Method 2)	8,2
11	Radiator foil (Method 2)	12,3	Draft stoppers	5,1
12	Draft stoppers	6,7	Floor rug insulation	0,4
13	Floor insulation	2,7	Ceiling insulation	0,3
14	Floor rug insulation	2,2	Radiator foil (Method 1)	0,2
15	Ceiling insulation	1,4	Floor insulation	-0,3

Appendix 11.4 – Payback period

Payback period				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	Radiator foil (Method 1)	1,0	Window insulation film	2,2
2	Window insulation film	1,4	Insulated door panels	2,5
3	Insulated door panels	1,7	Radiator foil (Method 2)	4,3
4	Radiator foil (Method 2)	2,8	Thermal curtains	6,3
5	Thermal curtains	4,3	Secondary glazing DIY	8,8
6	Secondary glazing DIY	5,7	Draft stoppers	9,4
7	Weatherstripping	6,7	Weatherstripping	10,1
8	Draft stoppers	7,2	House air sealing	25,2
9	House air sealing	16,7	Glazing replacement	27,9
10	Glazing replacement	17,7	Indoor wall insulation	33,1
11	Indoor wall insulation	21,1	External wall insulation	152,3
12	External wall insulation	101,6	Radiator foil (Method 1)	179,5
13	Floor rug insulation	357,1	Ceiling insulation	1789,4
14	Ceiling insulation	414,4	Floor rug insulation	2187,5
15	Floor insulation	439,9	Floor insulation	-3578,8

Appendix 11.5 – Investing efficiency

Investing efficiency				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	Radiator foil (Method 1)	102,9%	Window insulation film	45,6%
2	Window insulation film	69,4%	Insulated door panels	40,2%
3	Insulated door panels	59,6%	Radiator foil (Method 2)	23,4%
4	Radiator foil (Method 2)	35,2%	Thermal curtains	15,9%
5	Thermal curtains	23,0%	Secondary glazing DIY	11,4%
6	Secondary glazing DIY	17,5%	Draft stoppers	10,7%
7	Weatherstripping	14,9%	Weatherstripping	9,9%
8	Draft stoppers	13,9%	House air sealing	4,0%
9	House air sealing	6,0%	Glazing replacement	3,6%
10	Glazing replacement	5,6%	Indoor wall insulation	3,0%
11	Indoor wall insulation	4,7%	External wall insulation	0,7%
12	External wall insulation	1,0%	Radiator foil (Method 1)	0,6%
13	Floor rug insulation	0,3%	Ceiling insulation	0,1%
14	Ceiling insulation	0,2%	Floor rug insulation	0,0%
15	Floor insulation	0,2%	Floor insulation	0,0%

Appendix: 12 – Comparison of frameworks R, U, Qv

Appendix 12.1 – Energy efficiency improvements

Energy efficiency improvements			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	4,7%	External wall insulation	5,9%
Indoor wall insulation	4,6%	Indoor wall insulation	5,5%
Floor insulation	0,3%	Floor insulation	-0,1%
Ceiling insulation	0,1%	Ceiling insulation	0,1%
Thermal curtains	5,8%	Thermal curtains	7,7%
Insulated door panels	2,1%	Insulated door panels	2,7%
Floor rug insulation	0,2%	Floor rug insulation	0,1%
U value improvements			
Glazing replacement	10,3%	Glazing replacement	12,4%
Thermal curtains	5,8%	Thermal curtains	7,7%
Secondary glazing DIY	5,7%	Secondary glazing DIY	7,0%
Window insulation film	3,9%	Window insulation film	4,9%
Qv10 value improvements			
House air sealing	2,4%	House air sealing	3,1%
Weatherstripping	1,8%	Weatherstripping	2,3%
Draft stoppers	0,7%	Draft stoppers	1,0%

Appendix 12.2 – Thermal comfort improvements

Thermal comfort improvements			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	2	External wall insulation	1,7
Indoor wall insulation	2	Indoor wall insulation	1,7
Floor insulation	0,1	Floor insulation	0
Ceiling insulation	0	Ceiling insulation	0
Thermal curtains	2,2	Thermal curtains	2,1
Insulated door panels	0,9	Insulated door panels	0,8
Floor rug insulation	0	Floor rug insulation	0
U value improvements			
Glazing replacement	4,6	Glazing replacement	3,5
Thermal curtains	2,2	Thermal curtains	2,1
Secondary glazing DIY	2,0	Secondary glazing DIY	1,9
Window insulation film	1,6	Window insulation film	1,2
Qv10 value improvements			
House air sealing	1	House air sealing	0,9
Weatherstripping	0,7	Weatherstripping	0,7
Draft stoppers	0,3	Draft stoppers	0,3

Appendix 12.3 – Yearly savings

Yearly savings			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	45,9	External wall insulation	30,7
Indoor wall insulation	45,1	Indoor wall insulation	28,7
Floor insulation	2,7	Floor insulation	-0,3
Ceiling insulation	1,4	Ceiling insulation	0,3
Thermal curtains	57,6	Thermal curtains	39,8
Insulated door panels	20,7	Insulated door panels	13,9
Floor rug insulation	2,2	Floor rug insulation	0,4
U value improvements			
Glazing replacement	101,7	Glazing replacement	64,4
Thermal curtains	57,6	Thermal curtains	39,8
Secondary glazing DIY	55,9	Secondary glazing DIY	36,4
Window insulation film	38,9	Window insulation film	25,5
Qv10 value improvements			
House air sealing	23,9	House air sealing	15,9
Weatherstripping	17,8	Weatherstripping	11,9
Draft stoppers	6,7	Draft stoppers	5,1

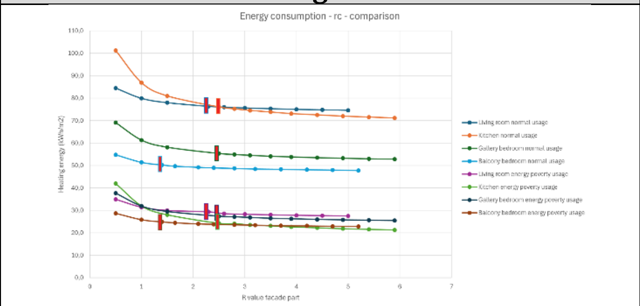
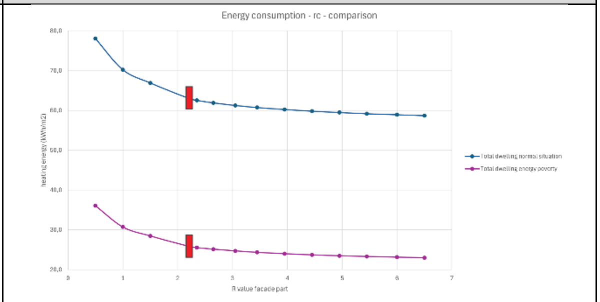
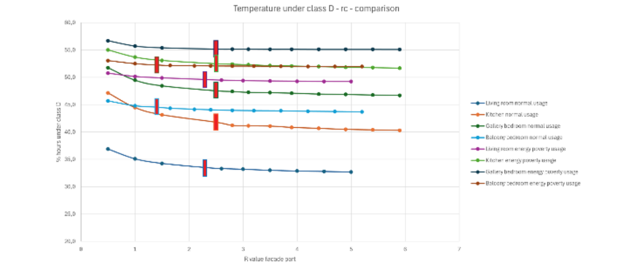
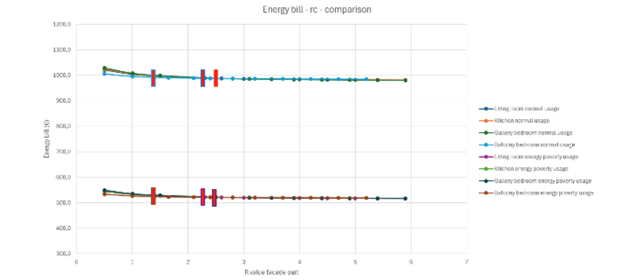
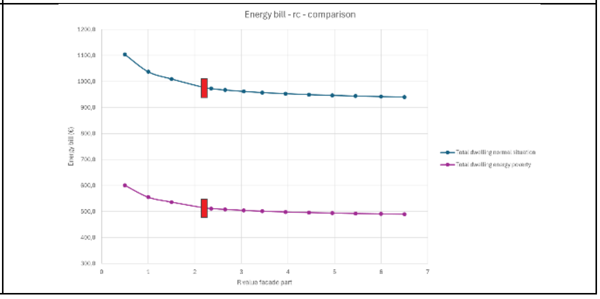
Appendix 12.4 – Payback period

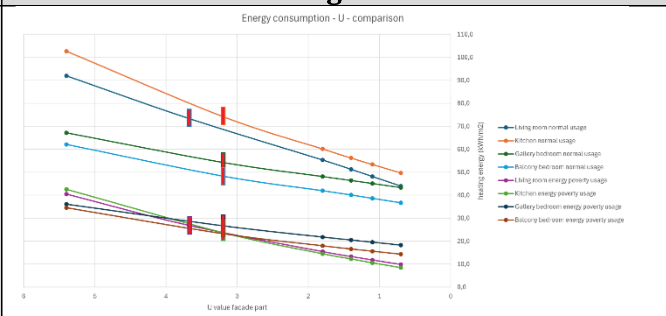
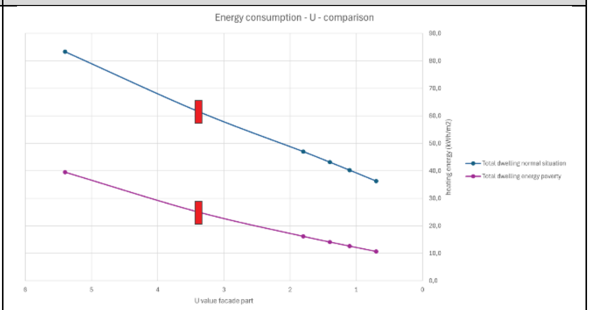
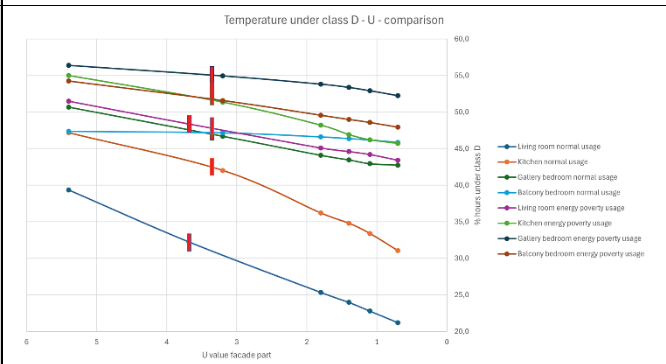
Payback period			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	101,6	External wall insulation	152,3
Indoor wall insulation	21,1	Indoor wall insulation	33,1
Floor insulation	439,9	Floor insulation	-3578,8
Ceiling insulation	414,4	Ceiling insulation	1789,4
Thermal curtains	4,3	Thermal curtains	6,3
Insulated door panels	1,7	Insulated door panels	2,5
Floor rug insulation	357,1	Floor rug insulation	2187,5
U value improvements			
Glazing replacement	17,7	Glazing replacement	27,9
Thermal curtains	4,3	Thermal curtains	6,3
Secondary glazing DIY	5,7	Secondary glazing DIY	8,8
Window insulation film	1,4	Window insulation film	2,2
Qv10 value improvements			
House air sealing	16,7	House air sealing	25,2
Weatherstripping	6,7	Weatherstripping	10,1
Draft stoppers	7,2	Draft stoppers	9,4

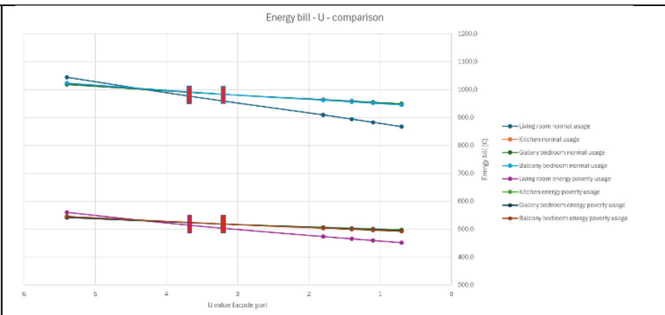
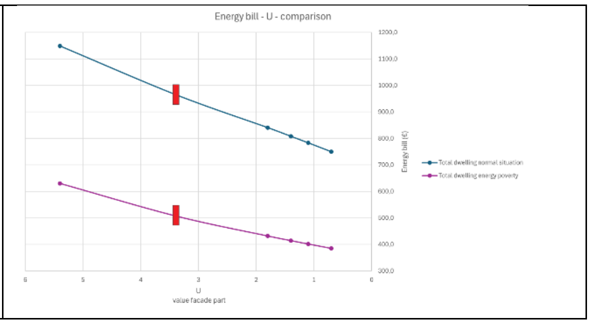
Appendix 12.5 – Investing efficiency

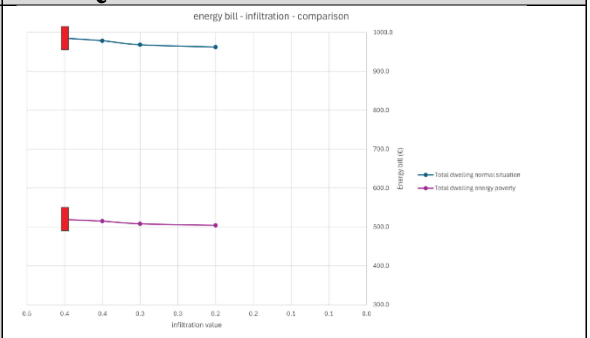
Investing efficiency			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	1,0%	External wall insulation	0,7%
Indoor wall insulation	4,7%	Indoor wall insulation	3,0%
Floor insulation	0,2%	Floor insulation	0,0%
Ceiling insulation	0,2%	Ceiling insulation	0,1%
Thermal curtains	23,0%	Thermal curtains	15,9%
Insulated door panels	59,6%	Insulated door panels	40,2%
Floor rug insulation	0,3%	Floor rug insulation	0,0%
U value improvements			
Glazing replacement	5,6%	Glazing replacement	3,6%
Thermal curtains	23,0%	Thermal curtains	15,9%
Secondary glazing DIY	17,47%	Secondary glazing DIY	11,39%
Window insulation film	69,4%	Window insulation film	45,6%
Qv10 value improvements			
House air sealing	6,0%	House air sealing	4,0%
Weatherstripping	14,9%	Weatherstripping	9,9%
Draft stoppers	13,9%	Draft stoppers	10,7%

Appendix 12.6 – Figures

	R value - singular facades	R value - combined facades
Energy consumption		
% Temp. under class D		
Energy bill		

	U value - singular facades	U value - combined facades
Energy consumption		
% Temp. under class D		

Energy bill		

	Qv10 value - combined facades
Energy bill	

Appendix: 13 – Comparison of intervention scales

Appendix 13.1 – Energy efficiency improvements

Energy efficiency improvements			
Basic interventions			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
Radiator foil (Method 2)	1,2%	Radiator foil (Method 2)	1,6%
Draft stoppers	0,7%	Draft stoppers	1,0%
Thermal curtains	5,8%	Thermal curtains	7,7%
Average	2,6%	Average	3,4%
Intermediate interventions			
Indoor wall insulation	4,6%	Indoor wall insulation	5,5%
Floor insulation	0,3%	Floor insulation	-0,1%
Window insulation film	3,9%	Window insulation film	4,9%
Weatherstripping	1,8%	Weatherstripping	2,3%
Ceiling insulation	0,1%	Ceiling insulation	0,1%
Insulated door panels	2,1%	Insulated door panels	2,7%
Floor rug insulation	0,2%	Floor rug insulation	0,1%
Secondary glazing DIY	5,7%	Secondary glazing DIY	7,0%
Average	2,3%	Average	2,8%
Advanced interventions			
External wall insulation	4,7%	External wall insulation	5,9%
Glazing replacement	10,3%	Glazing replacement	12,4%
House air sealing	2,4%	House air sealing	3,1%
Average	5,8%	Average	7,1%

Appendix 13.2 – Thermal comfort improvements

Thermal comfort improvement			
Basic interventions			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
Radiator foil (Method 2)	0,5	Radiator foil (Method 2)	0,5
Draft stoppers	0,3	Draft stoppers	0,3
Thermal curtains	2,2	Thermal curtains	2,1
Average	1	Average	1,0
Intermediate interventions			
Indoor wall insulation	2,0	Indoor wall insulation	1,7
Floor insulation	0,1	Floor insulation	0,0
Window insulation film	1,6	Window insulation film	1,2
Weatherstripping	0,7	Weatherstripping	0,7
Ceiling insulation	0,0	Ceiling insulation	0,0
Insulated door panels	0,9	Insulated door panels	0,8
Floor rug insulation	0,0	Floor rug insulation	0,0
Secondary glazing DIY	2,0	Secondary glazing DIY	1,9
Average	0,9	Average	0,8
Advanced interventions			
External wall insulation	2,0	External wall insulation	1,7
Glazing replacement	4,6	Glazing replacement	3,5
House air sealing	1,0	House air sealing	0,9
Average	2,5	Average	2,0

Appendix 13.3 – Yearly savings

Yearly savings			
Basic interventions			
Normal usage			
Intervention	Result	Intervention	Result
Radiator foil (Method 2)	12,3	Radiator foil (Method 2)	8,2
Draft stoppers	6,7	Draft stoppers	5,1
Thermal curtains	57,6	Thermal curtains	39,8
Average	25,5	Average	17,7
Intermediate interventions			
Indoor wall insulation	45,1	Indoor wall insulation	28,7
Floor insulation	2,7	Floor insulation	-0,3
Window insulation film	38,9	Window insulation film	25,5
Weatherstripping	17,8	Weatherstripping	11,9
Ceiling insulation	1,4	Ceiling insulation	0,3
Insulated door panels	20,7	Insulated door panels	13,9
Floor rug insulation	2,2	Floor rug insulation	0,4
Secondary glazing DIY	55,9	Secondary glazing DIY	36,4
Average	23,1	Average	14,6
Advanced interventions			
External wall insulation	45,9	External wall insulation	30,7
Glazing replacement	101,7	Glazing replacement	64,4
House air sealing	23,9	House air sealing	15,9
Average	57,2	Average	37,0

Appendix 13.4 – Payback period

Payback period			
Basic interventions			
Normal usage			
Intervention	Result	Intervention	Result
Radiator foil (Method 2)	2,8	Radiator foil (Method 2)	4,3
Draft stoppers	7,2	Draft stoppers	9,4
Thermal curtains	4,3	Thermal curtains	6,3
Average	4,8	Average	6,6
Intermediate interventions			
Indoor wall insulation	21,1	Indoor wall insulation	33,1
Floor insulation	439,9	Floor insulation	-3578,8
Window insulation film	1,4	Window insulation film	2,2
Weatherstripping	6,7	Weatherstripping	10,1
Ceiling insulation	414,4	Ceiling insulation	1789,4
Insulated door panels	1,7	Insulated door panels	2,5
Floor rug insulation	357,1	Floor rug insulation	2187,5
Secondary glazing DIY	5,7	Secondary glazing DIY	8,8
Average	156,0	Average	56,8
Advanced interventions			
External wall insulation	101,6	External wall insulation	152,3
Glazing replacement	17,7	Glazing replacement	27,9
House air sealing	16,7	House air sealing	25,2
Average	45,4	Average	68,5

Appendix 13.5 – Investing efficiency

Investing efficiency			
Basic interventions			
Normal usage			
Intervention	Result	Intervention	Result
Radiator foil (Method 2)	35,2%	Radiator foil (Method 2)	23,4%
Draft stoppers	13,9%	Draft stoppers	10,7%
Thermal curtains	23,0%	Thermal curtains	15,9%
Average	24,0%	Average	16,7%
Intermediate interventions			
Indoor wall insulation	4,7%	Indoor wall insulation	3,0%
Floor insulation	0,2%	Floor insulation	0,0%
Window insulation film	69,4%	Window insulation film	45,6%
Weatherstripping	14,9%	Weatherstripping	9,9%
Ceiling insulation	0,2%	Ceiling insulation	0,1%
Insulated door panels	59,6%	Insulated door panels	40,2%
Floor rug insulation	0,3%	Floor rug insulation	0,0%
Secondary glazing DIY	17,5%	Secondary glazing DIY	11,4%
Average	20,9%	Average	13,8%
Advanced interventions			
External wall insulation	1,0%	External wall insulation	0,7%
Glazing replacement	5,6%	Glazing replacement	3,6%
House air sealing	6,0%	House air sealing	4,0%
Average	4,2%	Average	2,7%

Appendix: 14 – Comparison of structural and non-structural interventions

Appendix 14.1 – Energy efficiency improvements

Energy efficiency improvements				
Structural interventions				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	Glazing replacement	10,3%	Glazing replacement	12,4%
2	External wall insulation	4,7%	External wall insulation	5,9%
3	House air sealing	2,4%	House air sealing	3,1%
4	Floor insulation	0,3%	Ceiling insulation	0,1%
5	Ceiling insulation	0,1%	Floor insulation	-0,1%
Non-Structural interventions				
1	Thermal curtains	5,8%	Thermal curtains	7,7%
2	Secondary glazing DIY	5,7%	Secondary glazing DIY	7,0%
3	Indoor wall insulation	4,6%	Indoor wall insulation	5,5%
4	Window insulation film	3,9%	Window insulation film	4,9%
5	Radiator foil (Method 1)	3,7%	Insulated door panels	2,7%
6	Insulated door panels	2,1%	Weatherstripping	2,3%
7	Weatherstripping	1,8%	Radiator foil (Method 2)	1,6%
8	Radiator foil (Method 2)	1,2%	Draft stoppers	1,0%
9	Draft stoppers	0,7%	Floor rug insulation	0,1%
10	Floor rug insulation	0,2%	Radiator foil (Method 1)	0,0%

Appendix 14.2 – Thermal comfort improvements

Thermal comfort improvements				
Structural interventions				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	Glazing replacement	4,6	Glazing replacement	3,5
2	External wall insulation	2,0	External wall insulation	1,7
3	House air sealing	1,0	House air sealing	0,9
4	Floor insulation	0,1	Ceiling insulation	0,0
5	Ceiling insulation	0,0	Floor insulation	0,0
Non-Structural interventions				
1	Thermal curtains	2,2	Thermal curtains	2,1
2	Radiator foil (Method 1)	2,0	Secondary glazing DIY	1,9
3	Secondary glazing DIY	2,0	Indoor wall insulation	1,7
4	Indoor wall insulation	2,0	Window insulation film	1,2
5	Window insulation film	1,6	Insulated door panels	0,8
6	Insulated door panels	0,9	Weatherstripping	0,7
7	Weatherstripping	0,7	Radiator foil (Method 2)	0,5
8	Radiator foil (Method 2)	0,5	Draft stoppers	0,3
9	Draft stoppers	0,3	Floor rug insulation	0,0
10	Floor rug insulation	0,0	Radiator foil (Method 1)	0,0

Appendix 14.3 – Yearly savings

Yearly savings				
Structural interventions				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	Glazing replacement	101,7	Glazing replacement	64,4
2	External wall insulation	45,9	External wall insulation	30,7
3	House air sealing	23,9	House air sealing	15,9
4	Floor insulation	2,7	Ceiling insulation	0,3
5	Ceiling insulation	1,4	Floor insulation	-0,3
Non-Structural interventions				
1	Thermal curtains	57,6	Thermal curtains	39,8
2	Secondary glazing DIY	55,9	Secondary glazing DIY	36,4
3	Indoor wall insulation	45,1	Indoor wall insulation	28,7
4	Window insulation film	38,9	Window insulation film	25,5
5	Radiator foil (Method 1)	36,0	Insulated door panels	13,9
6	Insulated door panels	20,7	Weatherstripping	11,9
7	Weatherstripping	17,8	Radiator foil (Method 2)	8,2
8	Radiator foil (Method 2)	12,3	Draft stoppers	5,1
9	Draft stoppers	6,7	Floor rug insulation	0,4
10	Floor rug insulation	2,2	Radiator foil (Method 1)	0,2

Appendix 14.4 – Payback period

Payback period				
Structural interventions				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	House air sealing	16,7	House air sealing	25,2
2	Glazing replacement	17,7	Glazing replacement	27,9
3	External wall insulation	101,6	External wall insulation	152,3
4	Floor insulation	439,9	Ceiling insulation	1789,4
5	Ceiling insulation	414,4	Floor insulation	-3578,8
Non-Structural interventions				
1	Radiator foil (Method 1)	1,0	Window insulation film	2,2
2	Window insulation film	1,4	Insulated door panels	2,5
3	Insulated door panels	1,7	Radiator foil (Method 2)	4,3
4	Radiator foil (Method 2)	2,8	Thermal curtains	6,3
5	Thermal curtains	4,3	Secondary glazing DIY	8,8
6	Secondary glazing DIY	5,7	Draft stoppers	9,4
7	Weatherstripping	6,7	Weatherstripping	10,1
8	Draft stoppers	7,2	Indoor wall insulation	33,1
9	Indoor wall insulation	21,1	Radiator foil (Method 1)	179,5
10	Floor rug insulation	357,1	Floor rug insulation	2187,5

Appendix 14.5 – Investing efficiency

Investing efficiency				
Structural interventions				
Ranking	Normal usage		Energy poverty usage	
	Intervention	Result	Intervention	Result
1	House air sealing	6,0%	House air sealing	4,0%
2	Glazing replacement	5,6%	Glazing replacement	3,6%
3	External wall insulation	1,0%	External wall insulation	0,7%
4	Floor insulation	0,2%	Ceiling insulation	0,1%
5	Ceiling insulation	0,2%	Floor insulation	0,0%
Non-Structural interventions				
1	Radiator foil (Method 1)	102,9%	Window insulation film	45,6%
2	Window insulation film	69,4%	Insulated door panels	40,2%
3	Insulated door panels	59,6%	Radiator foil (Method 2)	23,4%
4	Radiator foil (Method 2)	35,2%	Thermal curtains	15,9%
5	Thermal curtains	23,0%	Secondary glazing DIY	11,4%
6	Secondary glazing DIY	17,5%	Draft stoppers	10,7%
7	Weatherstripping	14,9%	Weatherstripping	9,9%
8	Draft stoppers	13,9%	Indoor wall insulation	3,0%
9	Indoor wall insulation	4,7%	Radiator foil (Method 1)	0,6%
10	Floor rug insulation	0,3%	Floor rug insulation	0,0%

Appendix 14.6 – Comparison of frameworks and structural / non-structural / normal usage

Influences	Structural		Non structural		Difference
	Intervention	Energy efficiency	Intervention	Energy efficiency	
U	Glazing replacement	10,3	Secondary glazing DIY	5,7	4,6
R	External wall insulation	4,7	Insulated door panels	2,1	2,6
Qv10	House air sealing	2,4	Weatherstripping	1,8	0,6

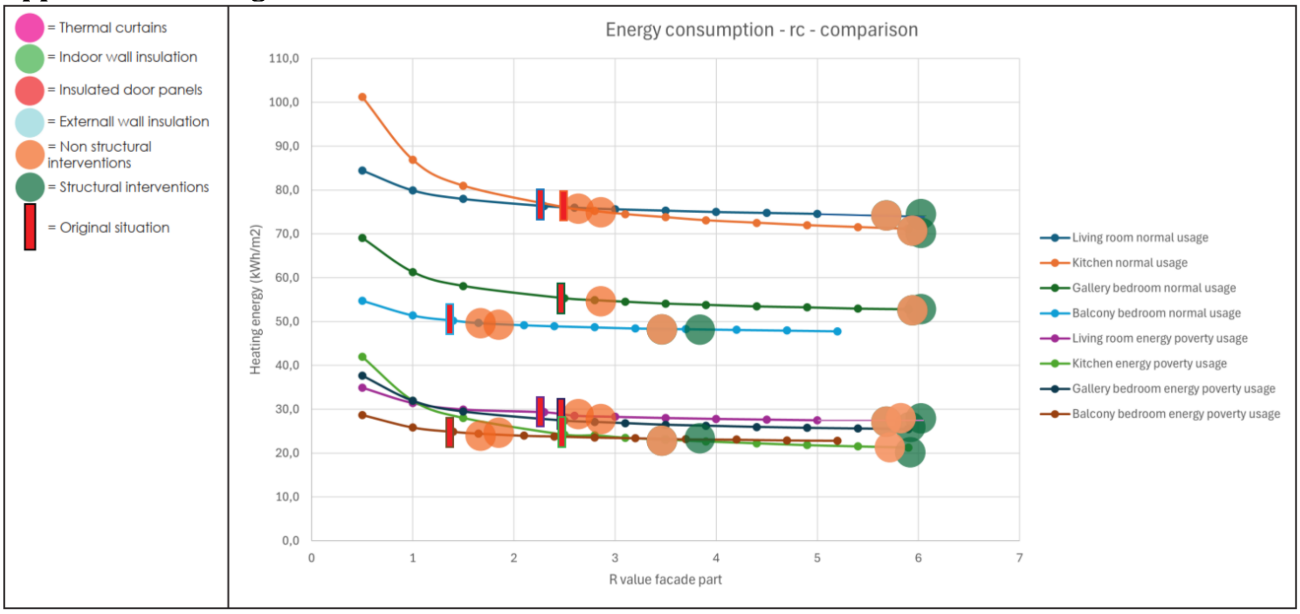
Influences	Structural		Non structural		Difference
	Intervention	Thermal comfort	Intervention	Thermal comfort	
U	Glazing replacement	4,6	Secondary glazing DIY	2,0	2,6
R	External wall insulation	2,0	Insulated door panels	0,9	1,1
Qv10	House air sealing	1,0	Weatherstripping	0,7	0,3

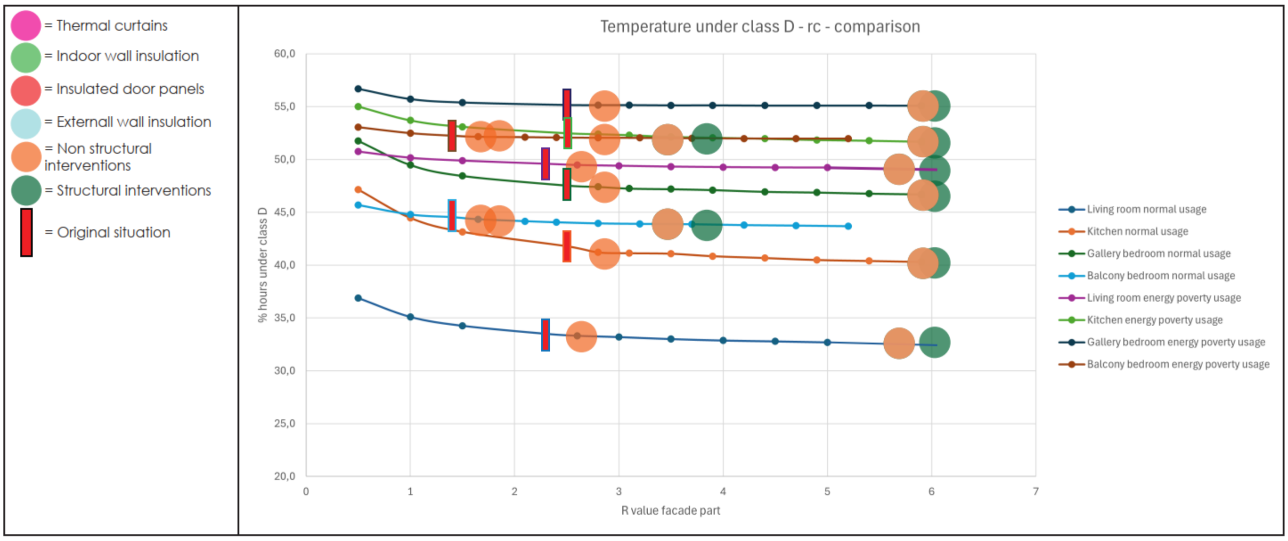
Influences	Structural		Non structural		Difference
	Intervention	Yearly savings	Intervention	Yearly savings	
U	Glazing replacement	101,7	Secondary glazing DIY	55,9	45,8
R	External wall insulation	45,9	Insulated door panels	20,7	25,2
Qv10	House air sealing	23,9	Weatherstripping	17,8	6,1

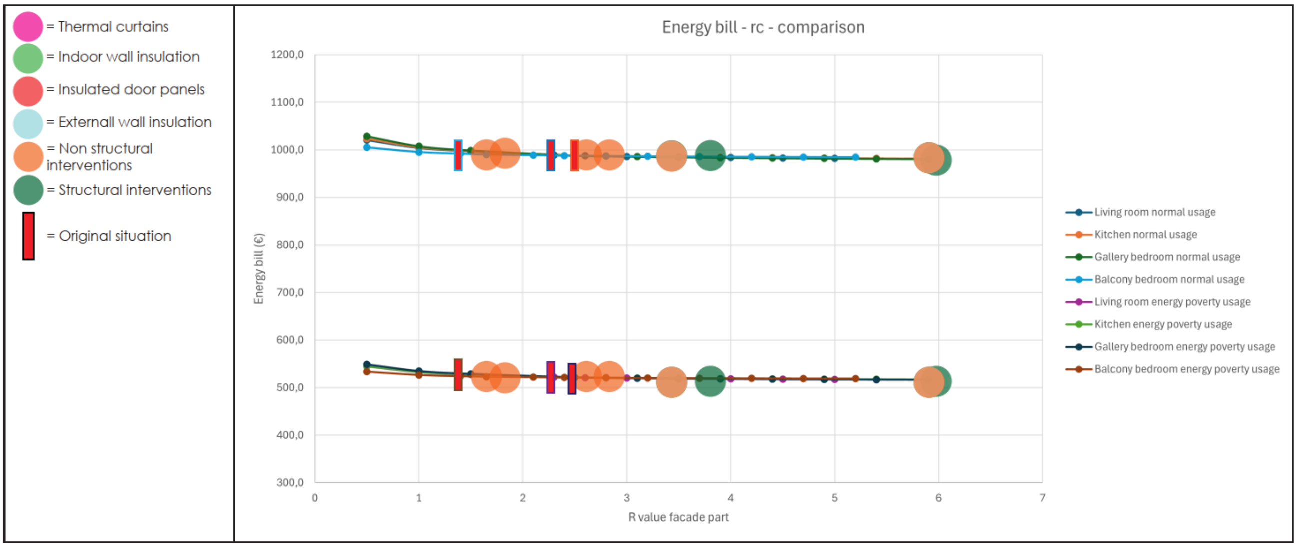
Influences	Structural		Non structural		Difference
	Intervention	Payback period	Intervention	Payback period	
U	Glazing replacement	17,7	Window insulation film	1,4	16,3
R	External wall insulation	101,6	Insulated door panels	1,7	99,9
Qv10	House air sealing	16,7	Weatherstripping	6,7	10

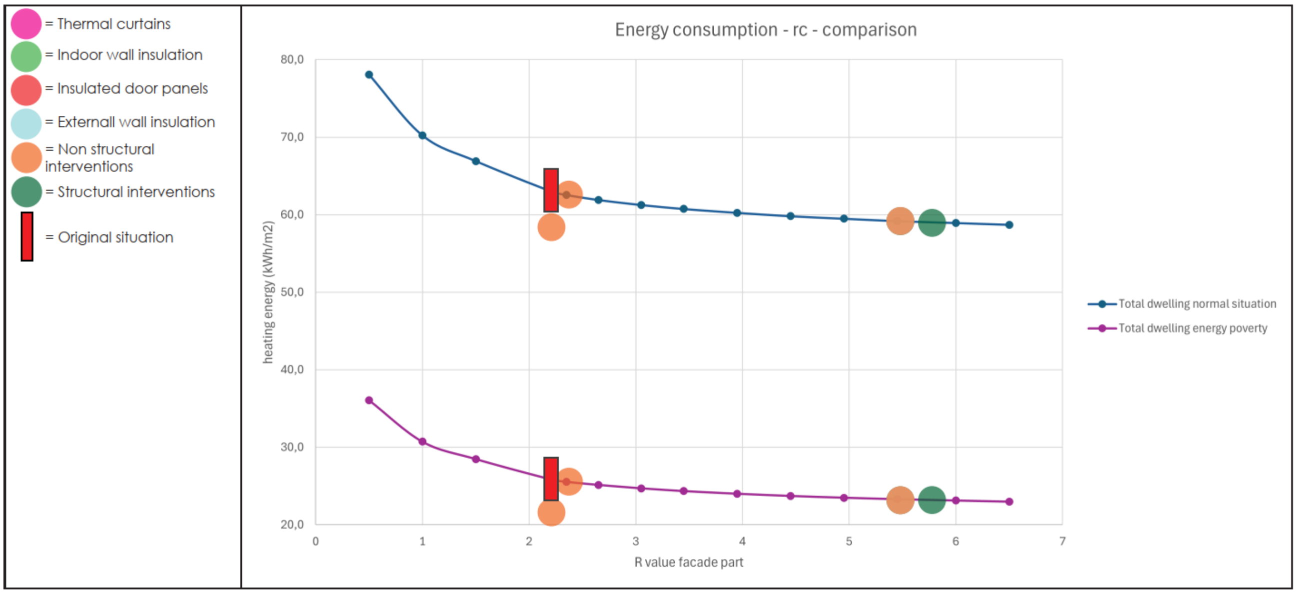
Influences	Structural		Non structural		Difference
	Intervention	Investing efficiency	Intervention	Investing efficiency	
U	Glazing replacement	5,6	Window insulation film	69,4	-63,8
R	External wall insulation	1,0	Insulated door panels	59,6	-58,6
Qv10	House air sealing	6,0	Weatherstripping	14,9	-8,9

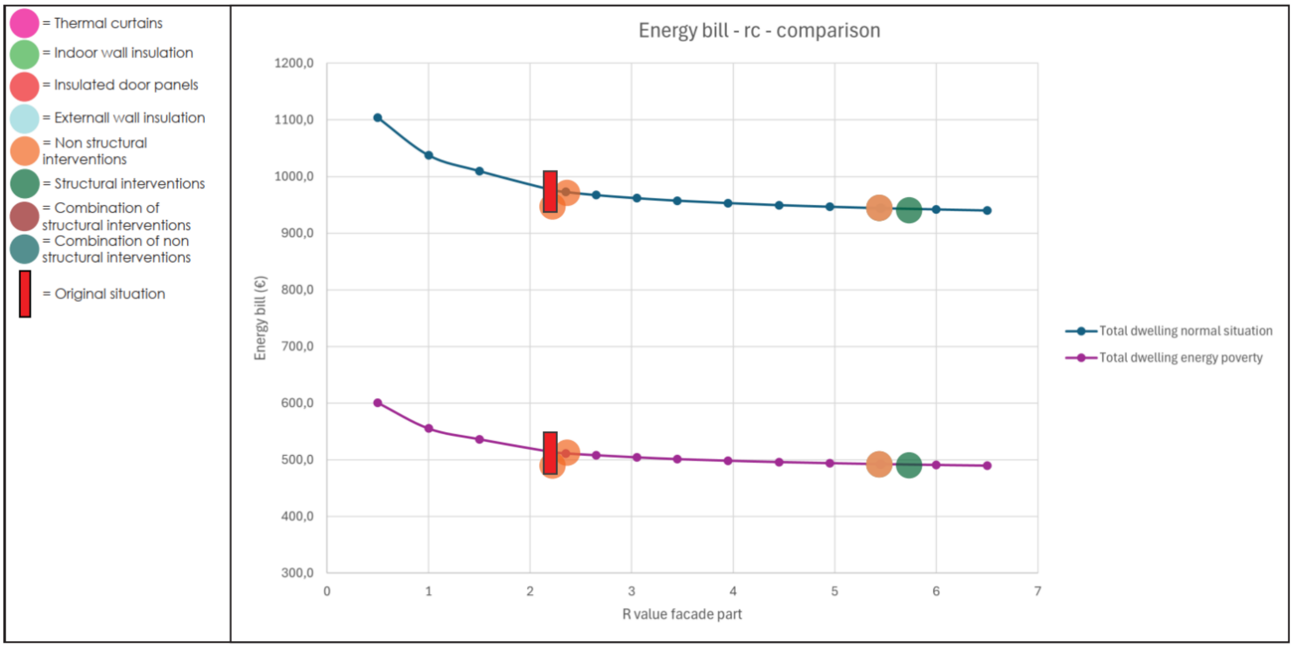
Appendix 14.7 – Figures

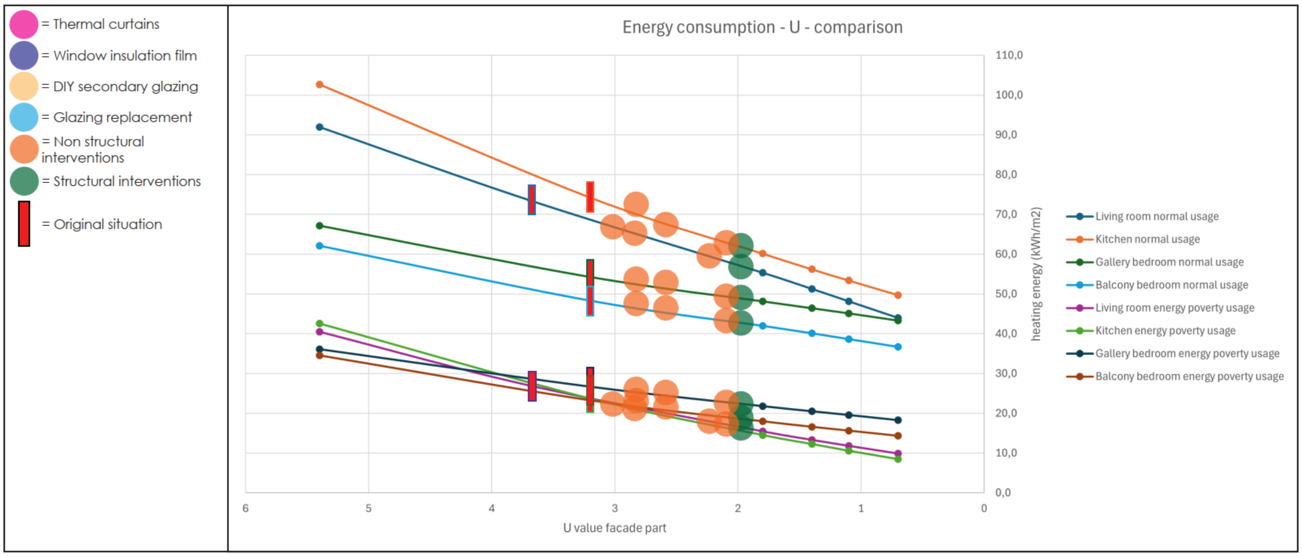


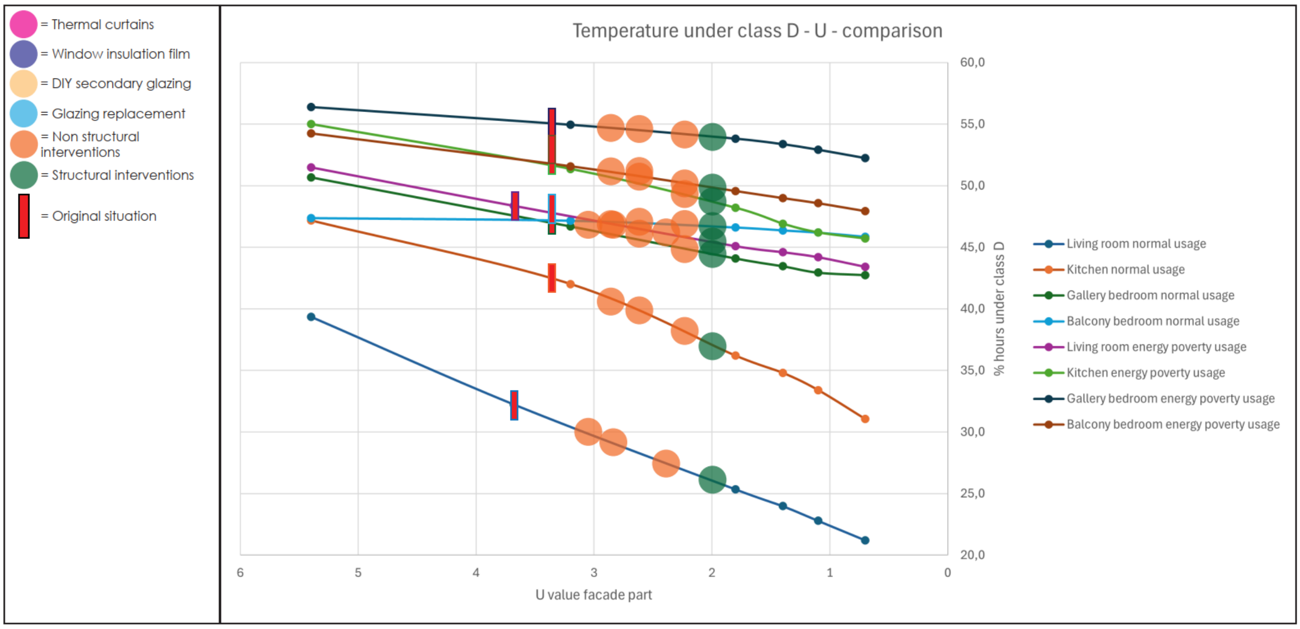


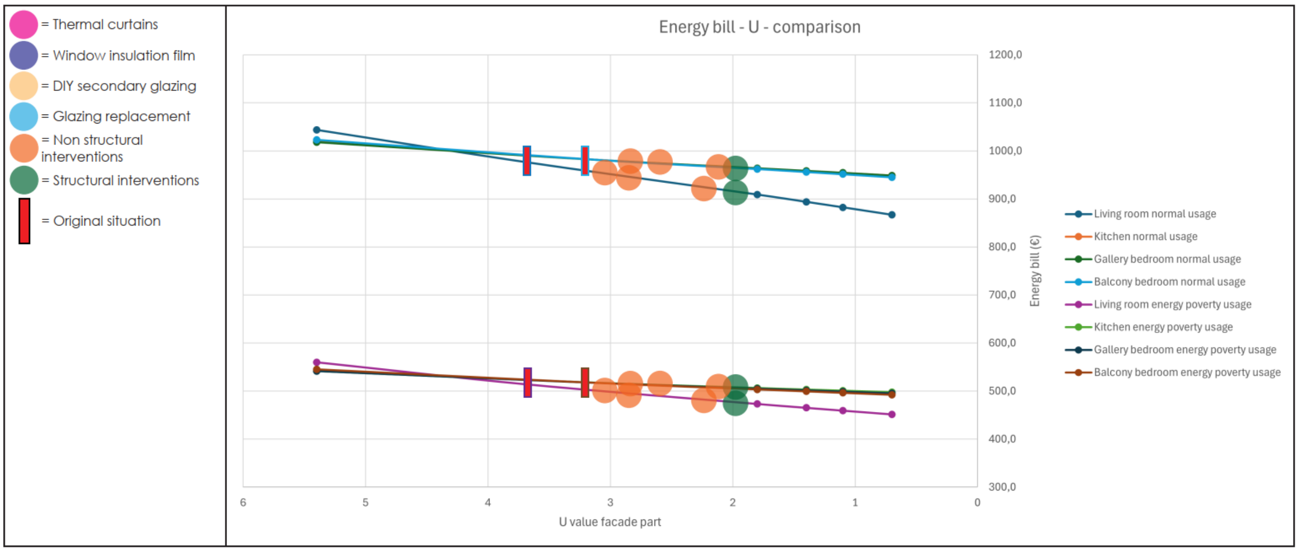


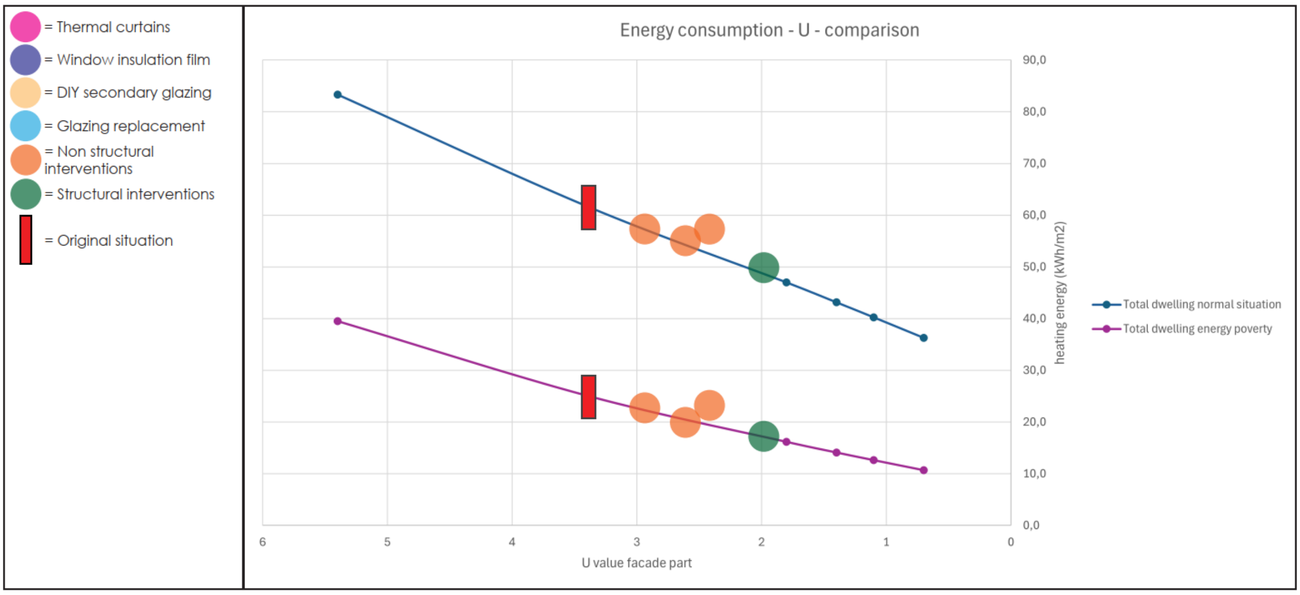

= Thermal curtains
= Indoor wall insulation
= Insulated door panels
= Externall wall insulation
= Non structural interventions
= Structural interventions
= Original situation
Energy consumption - rc - comparison
heating energy (kWh/m2)
80,0
70,0
60,0
50,0
40,0
30,0
20,0
0
1
2
3
4
5
6
7
R value facade part
Total dwelling normal situation
Total dwelling energy poverty

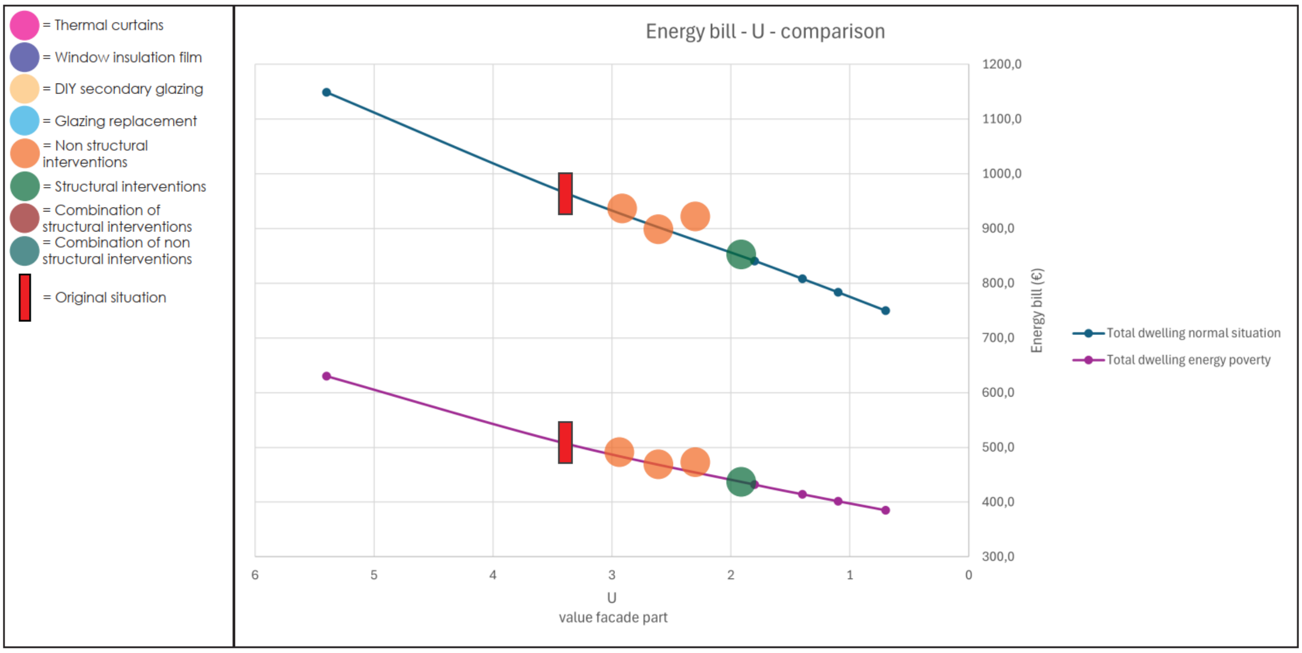

= Thermal curtains
= Indoor wall insulation
= Insulated door panels
= Externall wall insulation
= Non structural interventions
= Structural interventions
= Combination of structural interventions
= Combination of non structural interventions
= Original situation
Energy bill - rc - comparison
Energy bill (€)
1200,0
1100,0
1000,0
900,0
800,0
700,0
600,0
500,0
400,0
300,0
0
1
2
3
4
5
6
7
R value facade part
Total dwelling normal situation
Total dwelling energy poverty

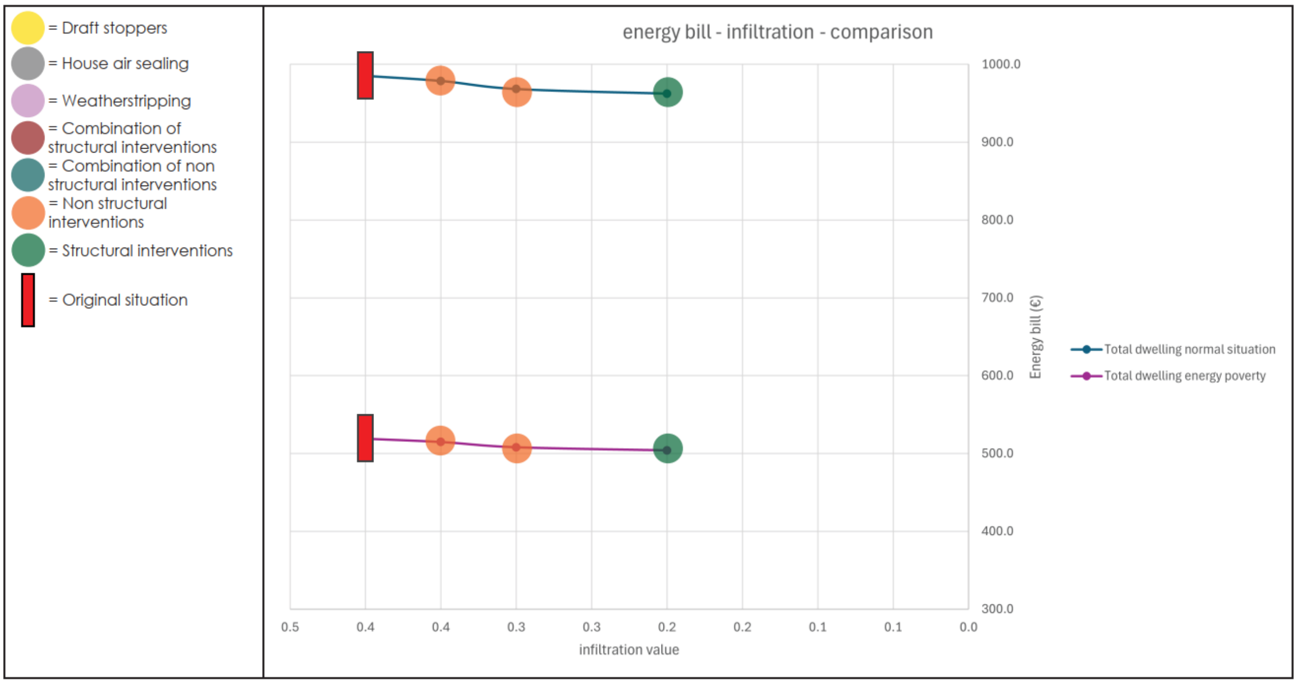

= Thermal curtains
= Window insulation film
= DIY secondary glazing
= Glazing replacement
= Non structural interventions
= Structural interventions
= Original situation
Energy consumption - U - comparison
110,0
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
heating energy (kWh/m2)
6
5
4
3
2
1
0
U value facade part
Living room normal usage
Kitchen normal usage
Gallery bedroom normal usage
Balcony bedroom normal usage
Living room energy poverty usage
Kitchen energy poverty usage
Gallery bedroom energy poverty usage
Balcony bedroom energy poverty usage


= Thermal curtains
= Window insulation film
= DIY secondary glazing
= Glazing replacement
= Non structural interventions
= Structural interventions
= Original situation
Temperature under class D - U - comparison
60,0
55,0
50,0
45,0
40,0
35,0
30,0
25,0
20,0
% hours under class D
6
5
4
3
2
1
0
U value facade part
Living room normal usage
Kitchen normal usage
Gallery bedroom normal usage
Balcony bedroom normal usage
Living room energy poverty usage
Kitchen energy poverty usage
Gallery bedroom energy poverty usage
Balcony bedroom energy poverty usage


= Thermal curtains
= Window insulation film
= DIY secondary glazing
= Glazing replacement
= Non structural interventions
= Structural interventions
= Original situation
Energy bill - U - comparison
1200,0
1100,0
1000,0
900,0
800,0
700,0
600,0
500,0
400,0
300,0
Energy bill (€)
6
5
4
3
2
1
0
U value facade part
Living room normal usage
Kitchen normal usage
Gallery bedroom normal usage
Balcony bedroom normal usage
Living room energy poverty usage
Kitchen energy poverty usage
Gallery bedroom energy poverty usage
Balcony bedroom energy poverty usage


= Thermal curtains
= Window insulation film
= DIY secondary glazing
= Glazing replacement
= Non structural interventions
= Structural interventions
= Original situation
Energy consumption - U - comparison
heating energy (kWh/m2)
U value facade part
Total dwelling normal situation
Total dwelling energy poverty


= Thermal curtains
= Window insulation film
= DIY secondary glazing
= Glazing replacement
= Non structural interventions
= Structural interventions
= Combination of structural interventions
= Combination of non structural interventions
= Original situation
Energy bill - U - comparison
Energy bill (€)
U value facade part
Total dwelling normal situation
Total dwelling energy poverty


= Draft stoppers
= House air sealing
= Weatherstripping
= Combination of structural interventions
= Combination of non structural interventions
= Non structural interventions
= Structural interventions
= Original situation
energy bill - infiltration - comparison
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
Energy bill (€)
0.5
0.4
0.4
0.3
0.3
0.2
0.2
0.1
0.1
0.0
infiltration value
Total dwelling normal situation
Total dwelling energy poverty

Appendix: 15 – Comparison of usage profiles

Appendix 15.1 – Energy efficiency improvements

Comparison of usage profiles – Energy efficiency			
Intervention	**Normal usage**	**Energy poverty**	**Difference**
Glazing replacement	10,3%	12,4%	-2,1%
Thermal curtains	5,8%	7,7%	-1,8%
Secondary glazing DIY	5,7%	7,0%	-1,3%
External wall insulation	4,7%	5,9%	-1,2%
Indoor wall insulation	4,6%	5,5%	-1,0%
Radiator foil (Method 1)	3,7%	0,0%	3,7%
House air sealing	2,4%	3,1%	-0,6%
Weatherstripping	1,8%	2,3%	-0,5%
Insulated door panels	2,1%	2,7%	-0,6%
Window insulation film	3,9%	4,9%	-1,0%
Radiator foil (Method 2)	1,2%	1,6%	-0,3%
Draft stoppers	0,7%	1,0%	-0,3%
Floor insulation	0,3%	-0,1%	0,3%
Floor rug insulation	0,2%	0,1%	0,2%
Ceiling insulation	0,1%	0,1%	0,1%

Appendix 15.2 – Thermal comfort

Comparison of usage profiles – Thermal comfort			
Intervention	**Normal usage**	**Energy poverty**	**Difference**
Glazing replacement	4,6	3,5	1,1
Thermal curtains	2,2	2,1	0,1
Indoor wall insulation	2,0	1,7	0,3
External wall insulation	2,0	1,7	0,3
Radiator foil (Method 1)	2,0	0,0	2
Secondary glazing DIY	2,0	1,9	0,1
House air sealing	1,0	0,9	0,1
Insulated door panels	0,9	0,8	0,1
Weatherstripping	0,7	0,7	0
Window insulation film	1,6	1,2	0,4
Radiator foil (Method 2)	0,5	0,5	0
Draft stoppers	0,3	0,3	0
Floor insulation	0,1	0,0	0,1
Ceiling insulation	0,0	0,0	0
Floor rug insulation	0,0	0,0	0

Appendix 15.3 – Yearly savings

Comparison of usage profiles – Yearly savings			
Intervention	**Normal usage**	**Energy poverty**	**Difference**
Glazing replacement	101,7	64,4	37,25
Thermal curtains	57,6	39,8	17,76
Secondary glazing DIY	55,9	36,4	19,50
External wall insulation	45,9	30,7	15,29
Indoor wall insulation	45,1	28,7	16,32
Radiator foil (Method 1)	36,0	0,2	35,82
House air sealing	23,9	15,9	8,03
Insulated door panels	20,7	13,9	6,74
Weatherstripping	17,8	11,9	5,96
Window insulation film	38,9	25,5	13,35
Radiator foil (Method 2)	12,3	8,2	4,11
Draft stoppers	6,7	5,1	1,55
Floor insulation	2,7	-0,3	3,01
Floor rug insulation	2,2	0,4	1,85
Ceiling insulation	1,4	0,3	1,10

Appendix 15.4 – Payback period

Comparison of usage profiles – Payback period			
Intervention	**Normal usage**	**Energy poverty**	**Difference**
Radiator foil (Method 1)	1,0	179,5	178,5
Insulated door panels	1,7	2,5	0,8
Radiator foil (Method 2)	2,8	4,3	1,4
Window insulation film	1,4	2,2	0,8
Thermal curtains	4,3	6,3	1,9
Secondary glazing DIY	5,7	8,8	3,1
Weatherstripping	6,7	10,1	3,4
Draft stoppers	7,2	9,4	2,2
House air sealing	16,7	25,2	8,5
Glazing replacement	17,7	27,9	10,2
Indoor wall insulation	21,1	33,1	12,0
External wall insulation	101,6	152,3	50,7
Floor rug insulation	357,1	2187,5	1830,4
Ceiling insulation	414,4	1789,4	1375,0
Floor insulation	439,9	-3578,8	-4018,6

Appendix 15.5 – Investing efficiency

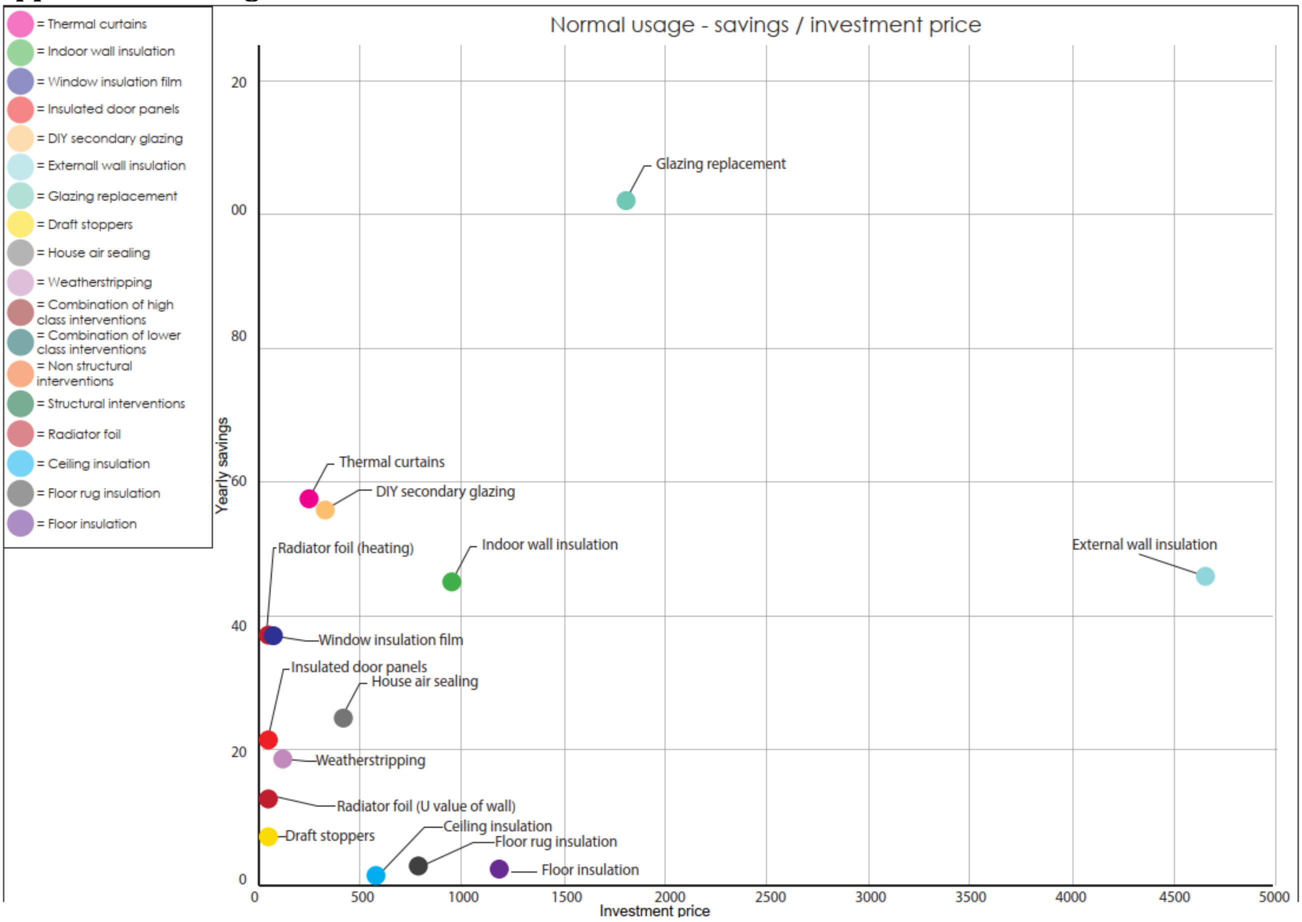
Comparison of usage profiles – Investing efficiency			
Intervention	**Normal usage**	**Energy poverty**	**Difference**
Radiator foil (Method 1)	102,9%	0,6%	102,3%
Insulated door panels	59,6%	40,2%	19,4%
Radiator foil (Method 2)	35,2%	23,4%	11,7%
Window insulation film	69,4%	45,6%	23,8%
Thermal curtains	23,0%	15,9%	7,1%
Secondary glazing DIY	17,5%	11,4%	6,1%
Weatherstripping	14,9%	9,9%	5,0%
Draft stoppers	13,9%	10,7%	3,2%
House air sealing	6,0%	4,0%	2,0%
Glazing replacement	5,6%	3,6%	2,1%
Indoor wall insulation	4,7%	3,0%	1,7%
External wall insulation	1,0%	0,7%	0,3%
Floor rug insulation	0,3%	0,0%	0,2%
Ceiling insulation	0,2%	0,1%	0,2%
Floor insulation	0,2%	0,0%	0,3%

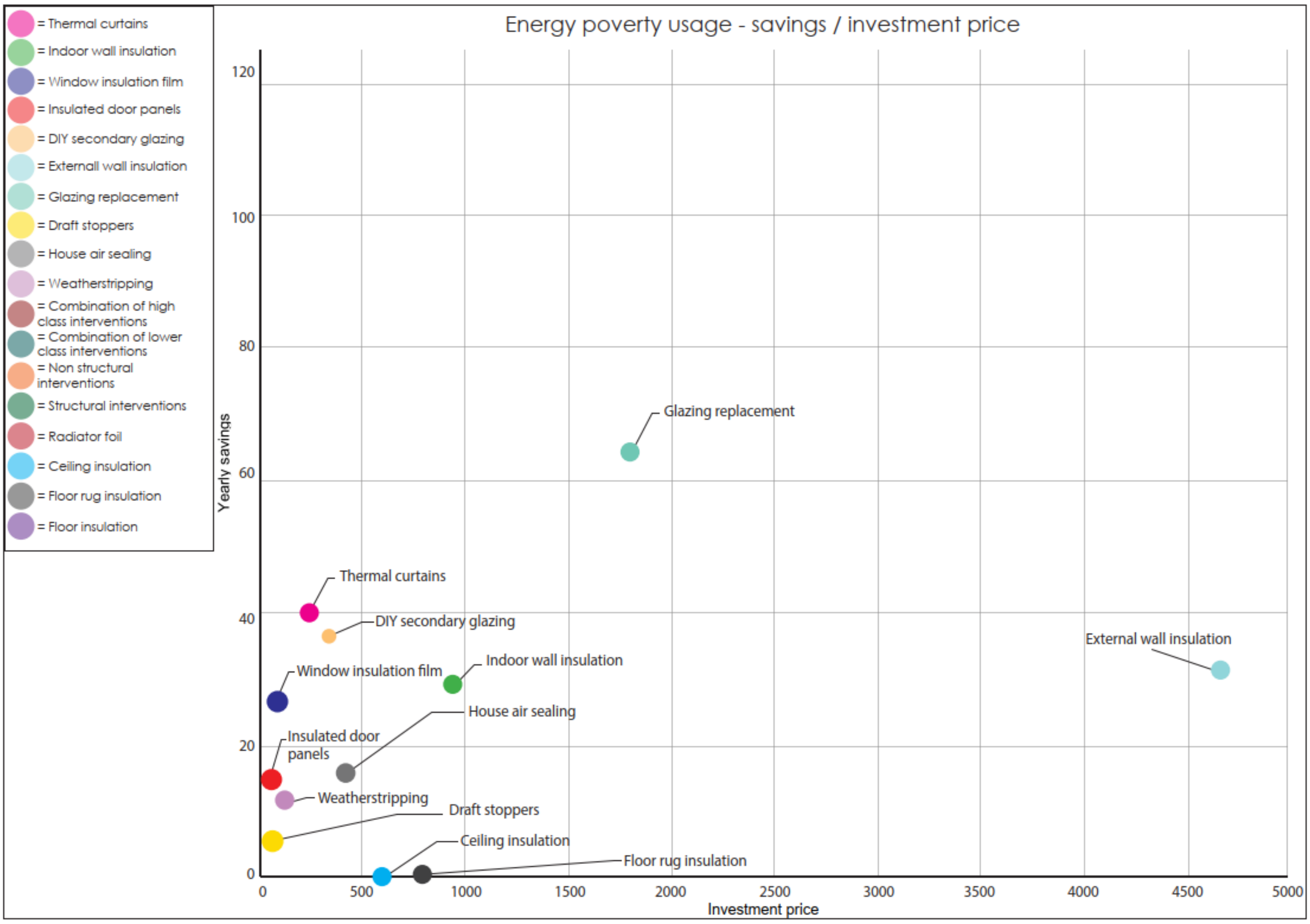
Appendix: 16 – Relation between investment price and savings

Appendix 16.1 – Comparison table

Interventions	Investment price	Yearly savings – normal usage	Yearly savings – energy poverty usage
Glazing replacement	1800	101,7	64,4
Thermal curtains	250	57,6	39,8
External wall insulation	4670	45,9	30,7
Indoor wall insulation	950	45,1	28,7
Radiator foil (Method 1)	35	36,0	0,2
Secondary glazing DIY	320	55,9	36,4
House air sealing	400	23,9	15,9
Insulated door panels	35	20,7	13,9
Weatherstripping	120	17,8	11,9
Window insulation film	56	38,9	25,5
Radiator foil (Method 2)	35	12,3	8,2
Draft stoppers	48	6,7	5,1
Floor insulation	1181	2,7	-0,3
Floor rug insulation	788	2,2	0,4
Ceiling insulation	590	1,4	0,3

Appendix 16.2 – Figures

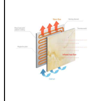
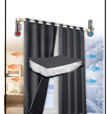
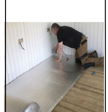
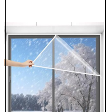
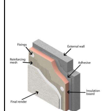
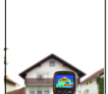




Energy poverty usage - savings / investment price
= Thermal curtains
= Indoor wall insulation
= Window insulation film
= Insulated door panels
= DIY secondary glazing
= Externall wall insulation
= Glazing replacement
= Draft stoppers
= House air sealing
= Weatherstripping
= Combination of high class interventions
= Combination of lower class interventions
= Non structural interventions
= Structural interventions
= Radiator foil
= Ceiling insulation
= Floor rug insulation
= Floor insulation
Yearly savings
Investment price
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Glazing replacement
Thermal curtains
DIY secondary glazing
External wall insulation
Window insulation film
Indoor wall insulation
House air sealing
Insulated door panels
Weatherstripping
Draft stoppers
Ceiling insulation
Floor rug insulation

Appendix: 17 – Summary results of interventions

Summary results of interventions

Intervention scale	Method / appliance	Image	Ddescription	Price	Normal usage results	Energy poverty usage results	Effective in situations:	Pro's	Cons
Basic interventions	Portable space heaters		Compact electric or gas heaters designed to warm small areas quickly.	Individual price: 30,- per unit	-	View CFD results	- Compact spaces - Short timespans of room usage - High heating peak loads - Existing low thermal comfort and indoor room temperatures - Low available budget	Targeted and localized heating, portable and flexible, fast heating time	High energy consumption, dries out air, ineffective in larger spaces and longer usage
	Infrared heating panels		Wall- or ceiling-mounted panels that provide radiant heat.	Individual price: 100,- per panel	-	View CFD results	- High quality building skin - Highly localized room usage - Existing medium thermal comfort and indoor room temperatures - High available budget	Efficient and direct heating, silent operation, low maintenance, aesthetical options	Limited range, requires precise positioning, high investment costs
	Radiator foil		Foil placed behind radiators to reflect heat back into the room.	Individual price: 10,- per 6m roll Case study price: 35,-	Energy efficiency improvement: 1,2% Thermal comfort improvement: 0,5C Yearly savings: 12,- Payback period: 3 years Investing efficiency: 35%	Energy efficiency improvement: 1,6% Thermal comfort improvement: 0,5C Yearly savings: 8,- Payback period: 4 years Investing efficiency: 23%	- Low quality building skin - Low quality existing radiators - Low available budget	Reduces heat losses, cheap and easy to install, effective in older buildings	Limited impact, effectiveness depends on wall type, not suitable on other heat sources
	Draft stoppers		Placed at the base of doors and windows to reduce cold air intrusion and improve thermal comfort.	Individual price: 5,- per stopper Case study price: 48,-	Energy efficiency improvement: 0,7% Thermal comfort improvement: 0,3C Yearly savings: 7,- Payback period: 7 years Investing efficiency: 14%	Energy efficiency improvement: 1,0% Thermal comfort improvement: 0,3C Yearly savings: 5,- Payback period: 9 years Investing efficiency: 11%	- High presence of drafts - Low quality doors - High gaps underneath doors - Low thermal comfort - Low available budget	Immediate effect on thermal comfort, portable and reusable	Requires regular adjustment, not aesthetically pleasing
	Thermal curtains		Heavy, insulated curtains or blinds.	Individual price: 20,- per meter Case study price: 250,-	Energy efficiency improvement: 5,8% Thermal comfort improvement: 2,2C Yearly savings: 58,- Payback period: 4 years Investing efficiency: 23%	Energy efficiency improvement: 7,7% Thermal comfort improvement: 2,1C Yearly savings: 40,- Payback period: 6 years Investing efficiency: 16%	- Effective in rooms which aren't intensely used - Lower quality windows & walls - Low/medium available budget	Blocks cold and drafts, effects on consumption and thermal comfort, easy to install	Only effective near windows, blocks sunlight and daylight when used
Intermediate interventions	Indoor wall insulation		Instalation of foam or fiberboard insulation panels on interior walls to reduce heat loss and improve thermal comfort.	Individual price: 30,- per m2 Case study price: 950,-	Energy efficiency improvement: 4,6% Thermal comfort improvement: 2,0C Yearly savings: 45,- Payback period: 21 years Investing efficiency: 5%	Energy efficiency improvement: 5,5% Thermal comfort improvement: 1,7C Yearly savings: 29,- Payback period: 33 years Investing efficiency: 3%	- Poor building skin quality - Free indoor room space - Large closed facade area - High available budget - DIY installation skills required	Significant reduction in heat losses, improves thermal comfort, doesn't alter exterior, can be installed in older homes	Reduces interior space, can be disruptive to install, risk of moisture buildup
	Floor insulation		Placement of rigid foam or underlayment mats beneath flooring.	Individual price: 20,- per m2 Case study price: 1181,-	Energy efficiency improvement: 0,3% Thermal comfort improvement: 0,1C Yearly savings: 3,- Payback period: 440 years Investing efficiency: 0,2%	Energy efficiency improvement: 0,0% Thermal comfort improvement: 0,0C Yearly savings: Unprofitable Payback period: Unprofitable Investing efficiency: Unprofitable	- Heat loss through floor to crawlspace, ground or neighbours who don't apply heating - High available budget - Generally ineffective in appartment cases - DIY installation skills required	Prevents heat losses through crawling space, long lifespan	Disruptive installation, not always possible in existing buildings, limited to no benefits in certain cases
	Window insulation film		Transparent films that reduce heat loss through windows while allowing sunlight to enter.	Individual price: 10,- per window Case study price: 56,-	Energy efficiency improvement: 3,9% Thermal comfort improvement: 1,6C Yearly savings: 39,- Payback period: 1 years Investing efficiency: 70%	Energy efficiency improvement: 4,9% Thermal comfort improvement: 1,2C Yearly savings: 26,- Payback period: 2 years Investing efficiency: 46%	- Large glazing area of facade - Single / low quality double glazing window panes - Small individual window surfaces - Low available budget - Effective if there is a variation of window panes in facade, single glazing being one of them	Affordable, DIY solution, can help reduce condensation, highly effective	May reduce window clarity, temporary solution, limited impact on drafts
	Door and window weatherstripping		Usage of adhesive foam, silicone strips, or rubber seals to reduce window drafts.	Individual price: 15,- per window Case study price: 120,-	Energy efficiency improvement: 1,8% Thermal comfort improvement: 0,7C Yearly savings: 18,- Payback period: 7 years Investing efficiency: 15%	Energy efficiency improvement: 2,3% Thermal comfort improvement: 0,7C Yearly savings: 12,- Payback period: 10 years Investing efficiency: 10%	- Low quality window frames - Existing draft problems - Low available budget	Reduces drafts, easy and cheap installation, improved heating efficiency	Regular maintenance, not as effective for larger gaps, can be tricky to install correctly
	Ceiling insulation		Installation of insulating materials (foam boards or fiberglass rolls) to the underside of accessible ceilings or attic spaces.	Individual price: 20,- per m2 Case study price: 591,-	Energy efficiency improvement: 0,0% Thermal comfort improvement: 0,0C Yearly savings: Unprofitable Payback period: Unprofitable Investing efficiency: Unprofitable	Energy efficiency improvement: 0,0% Thermal comfort improvement: 0,0C Yearly savings: Unprofitable Payback period: Unprofitable Investing efficiency: Unprofitable	- Underneath attics or other cold spaces - High available budget - DIY installation skills required	Reduces energy costs, long lifespan	Costly, requires professional installation, difficult to place, may cause moisture problems, generally ineffective in appartment cases
	Insulated door panels		Installation of insulating panels to the inside of external doors.	Individual price: 30,- per m2 Case study price: 35,-	Energy efficiency improvement: 2,1% Thermal comfort improvement: 0,9C Yearly savings: 21,- Payback period: 2 years Investing efficiency: 60%	Energy efficiency improvement: 2,7% Thermal comfort improvement: 0,8C Yearly savings: 14,- Payback period: 3 years Investing efficiency: 40%	- Low quality existing doors - Porportionally large exterior door surface of facade - Living space behind exterior door - Low available budget - DIY installation skills required	Improves insulation, can be added to existing doors, cost-effective compared to buying new doors	Limited impact, alters indoor door aesthetics, precise installation
	Rug floor insulation		Insulating underlays beneath rugs.	Individual price: 10,- per m2 Case study price: 788,-	Energy efficiency improvement: 0,0% Thermal comfort improvement: 0,0C Yearly savings: Unprofitable Payback period: Unprofitable Investing efficiency: Unprofitable	Energy efficiency improvement: 0,0% Thermal comfort improvement: 0,0C Yearly savings: Unprofitable Payback period: Unprofitable Investing efficiency: Unprofitable	- Heat loss through floor, crawlspace or neighbours who don't apply heating - High availalbe budget	Heat insulation, hidden, cheap, improved thermal comfort through direct transmission	Limited to no effects
	Secondary glazing		Construction of a DIY window frame to simulate secondary glazing systems.	Individual price: 40,- per frame Case study price: 320,-	Energy efficiency improvement: 5,7% Thermal comfort improvement: 2,0C Yearly savings: 56,- Payback period: 6 years Investing efficiency: 18%	Energy efficiency improvement: 7,0% Thermal comfort improvement: 1,9C Yearly savings: 36,- Payback period: 9 years Investing efficiency: 11%	- Existing low quality windows - Existing medium quality windows - Usefull if no possibilities for glazing replacement are present - Usefull when structural interventions aren't allowed - DIY installation skills required - Medium available budget	Cheap alternative to double glazing, DIY installation, reversible for rental homes, highly effective	Can reduce window visibility, not very durable for long term, condensation risks
Advanced interventions	External wall insulation		Installation of insulating material to the outside of the dwelling on the façade.	Individual price: 250,- per m2 Case study price: 4670,-	Energy efficiency improvement: 4,7% Thermal comfort improvement: 2,0C Yearly savings: 46,- Payback period: 102 years Investing efficiency: 1%	Energy efficiency improvement: 5,9% Thermal comfort improvement: 1,7C Yearly savings: 30,- Payback period: 152 years Investing efficiency: 1%	- Poor building skin quality - Possibilities for facade alteration - Large closed facade area - High available budget - Assessment needed to consider of it outweighs indoor wall insulation	Highly effective for heat losses, long term solution, can improve external aesthetics	Expensive, requires professional installation, disruptive installation, potential planning restrictions
	Glazing replacement		Replacement of existing glazing, to improve energy efficiency while keeping visual aesthetics.	Individual price: 130,- per m2 Case study price: 1800,-	Energy efficiency improvement: 10,3% Thermal comfort improvement: 4,6C Yearly savings: 102,- Payback period: 18 years Investing efficiency: 6%	Energy efficiency improvement: 12,4% Thermal comfort improvement: 3,5C Yearly savings: 64,- Payback period: 28 years Investing efficiency: 4%	- Existing low/medium quality windows - Large glazing area of facade - High available budget	Significantly improves insulation, long life span, property value increases	High cost, may require frame modifications, long payback period
	Whole-house air sealing		Conducting a blower door test to identify existing air leaks and repair them.	Individual price: from 400,- per dwelling Case study price: 400,-	Energy efficiency improvement: 2,4% Thermal comfort improvement: 1,0C Yearly savings: 24,- Payback period: 17 years Investing efficiency: 6%	Energy efficiency improvement: 3,1% Thermal comfort improvement: 0,9C Yearly savings: 16,- Payback period: 25 years Investing efficiency: 4%	- Existing construction damages within dwelling - Existing air and water leaks within dwelling -Existing drafts within dwelling - Old age of dwelling - Medium available budget	Reduces heat losses through cracks, improves air quality, enhances home thermal comfort, works well in combination with insulation	Requires professional help, expensive, risk of poor ventilation, limited effects

Appendix: 18 – Influences on interventions

Appendix 18.1 – Influences of yearly months

The results which have been discussed up to this point focus mostly on the effect of interventions over a period of a year. This is done to give a better indication of the general improvements certain interventions make, as the year-round energy consumption provides a good blank slate and comparison method to other households. At the same time, it is beneficial to discuss the monthly effect of interventions, as the financial situation of energy poverty households can differ between months, as has been discussed in chapter 2.3.2. Discussing interventions in this way provides more clarity in how the effects of interventions change over time and can shed light on the monthly savings for households.

The comparison of the monthly savings shows that most of the energy cost savings are achieved from the months October through May, with most of the energy savings being generated in January and December. This is caused by these months having the coldest average temperatures. The energy savings in the months of April, May and October are significantly less, due to less heating energy being required in these months. Worth noting is that this previously described distribution of monthly savings is characteristic for the normal usage profile. With the simulation of the energy poverty usage profile, the months of October through March generate savings. This means that due to the lower temperature settings, the months of April and May do not require heating energy.

What can be noted from the comparison calculations is that a large part of the differences between energy savings in energy poverty usage profiles and normal usage profiles can be led back to the prolonged energy consumption timeframe. As under normal usage, the months of March, April, October, and November are much more intensively used than under energy poverty usage. The savings interventions do provide in the normal usage profiles is not provided in the energy poverty usage profiles. This difference is further substantiated by comparing the energy savings of the coldest months of January and December, months where savings are generated. This can be seen in the table below. A detailed view of these numbers can be seen in this appendix.

	Energy savings - Low quality interventions (€)		**Energy savings - High quality interventions (€)**	
	Normal usage	**Energy poverty usage**	**Normal usage**	**Energy poverty usage**
January	13,1	13,4	30,9	28,5
December	11,2	12,3	24,4	24,8

Table: *Comparison of simulated months (Own work, 2025)*

It can be seen that the differences between energy savings for the different usages in Januari are minimal. Besides this, the savings in December are actually bigger in energy poverty usage than in normal usage. There are different explanations for this, the first being that due to the extreme cold temperatures of December, the necessary energy consumption of energy poverty households rises more in proportion from November to December than it does for normal households. This can be substantiated by comparing these rises in household energy consumption:

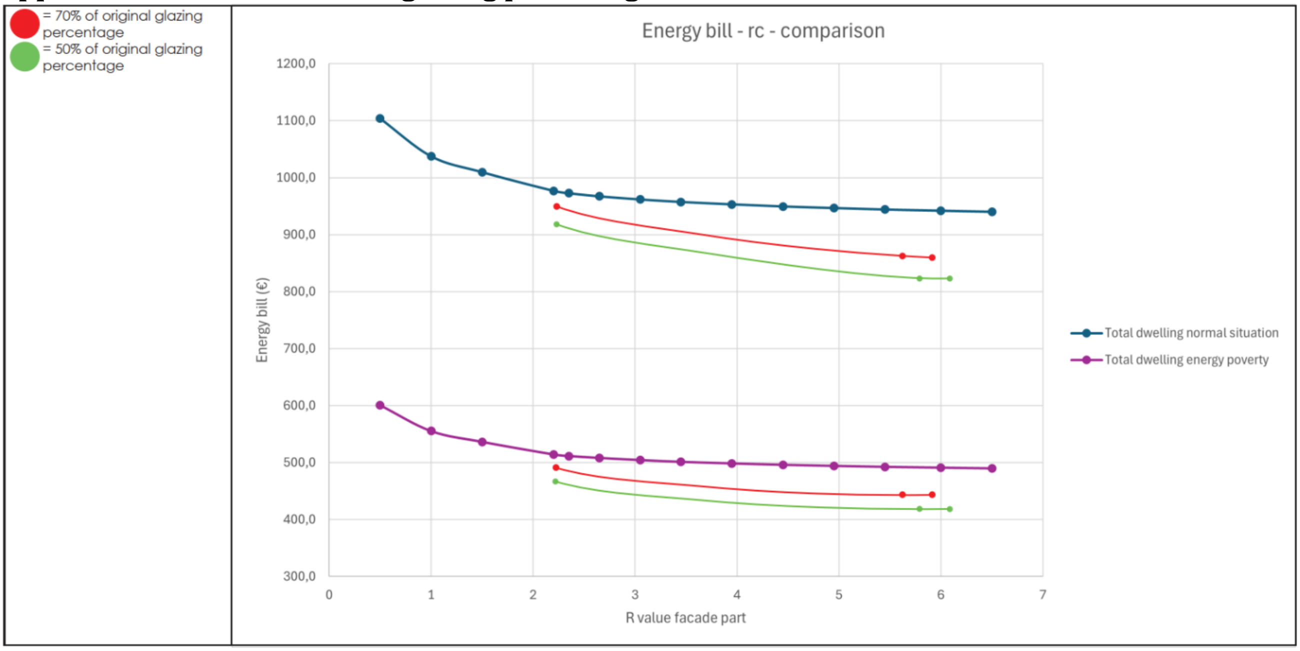
Normal usage: ((154€(dec.) -109€ (nov.))/109€) * 100 = 41%.
Energy poverty: (89€ (dec.) -38€ (nov.))/38€) * 100 = 134%.

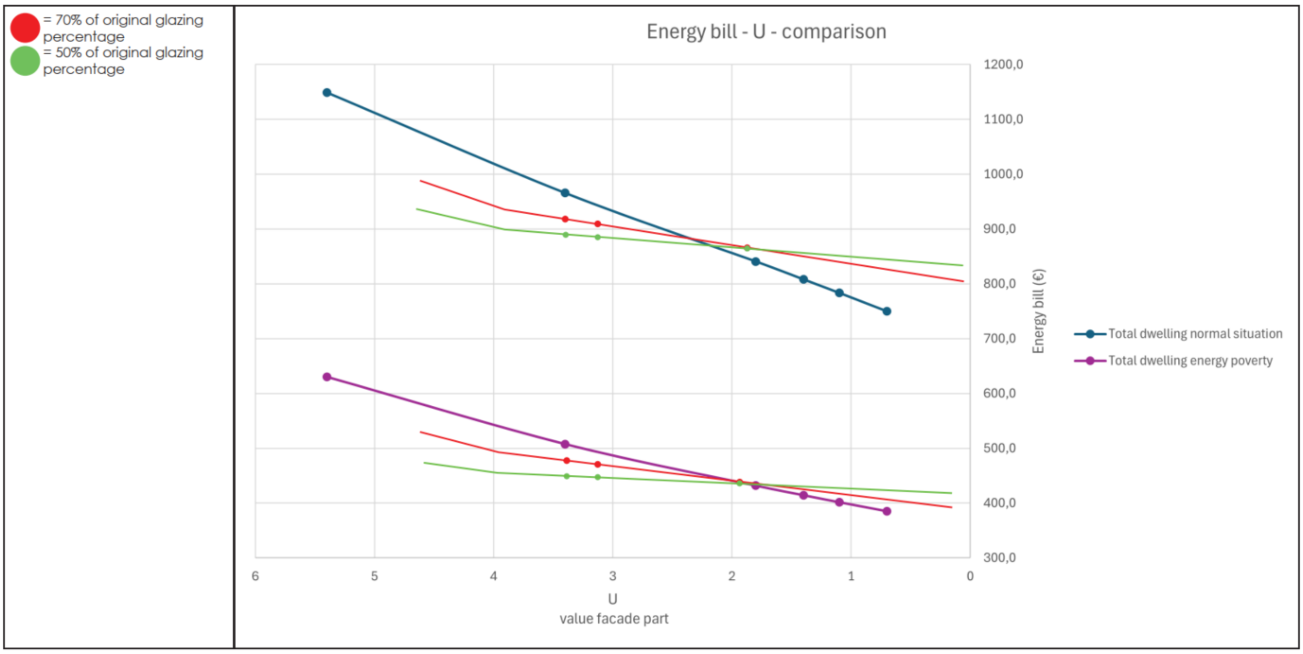
This difference in proportional energy consumption increase could explain the increase of energy savings for this usage. What can be noted from this chapter is the importance of the implementation of approaches in the correct period of the year. On the one hand, this time choice can influence the yearly savings of households and alleviate financial pressure. On the other hand, the indoor thermal quality of households is often worse in these critical months, which increases the effectiveness of interventions in these months.

Monthly gas expenses – Normal usage													
Periods:	Jan	Feb	Mrch	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
No interventions													
Gas (€)	168	126	116	54	39	37	37	37	37	72	109	154	986,1
Low quality interventions													
Gas (€)	155	116	105	47	38	37	37	37	37	64	100	143	916
High quality interventions													
Gas (€)	138	103	92	42	37	37	37	37	37	56	87	129	830
Monthly gas savings – Normal usage													
Low quality interventions													
Gas (€)	13	10	11	7	1	0	0	0	0	8	9	11	70
High quality interventions													
Gas (€)	30	22	24	11	2	0	0	0	0	16	22	24	155

Monthly gas expenses – Energy poverty usage													
Periods:	Jan	Feb	Mrch	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
No interventions													
Gas (€)	105	64	51	25	25	25	25	25	25	26	38	89	519,9
Low quality interventions													
Gas (€)	91	55	45	25	25	25	25	25	25	25	33	77	476
High quality interventions													
Gas (€)	76	46	39	25	25	25	25	25	25	25	29	64	425
Monthly gas savings – Energy poverty usage													
Low quality interventions													
Gas (€)	13	9	6	0	0	0	0	0	0	1	5	12	44
High quality interventions													
Gas (€)	28	17	12	0	0	0	0	0	0	2	9	25	95

Appendix 18.2 – Influences of glazing percentages





Appendix 18.3 – Influences of weather circumstances – intervention effectiveness

Weather file	Year: 2018 energie		Year: 2018 TO5		Year: 2018 TO1 severe	
Usage profile	Normal	Energy	Normal	Energy	Normal	Energy
Indoor wall insulation						
Energy efficiency improvement (%)	4,6	5,7	4,8	6,3	5,1	5,9
Investing efficiency (%)	4,82	3,12	5,43	4,29	6,0	4,5
External wall insulation						
Energy efficiency improvement (%)	4,7	5,9	4,8	6,5	5,1	6,0
Investing efficiency (%)	0,98	0,66	1,12	0,9	1,24	0,94
Window insulation film						
Energy efficiency improvement (%)	3,9	4,9	4,0	5,1	4,1	4,9
Investing efficiency (%)	69,40	45,60	71,18	47,46	72,96	45,70
Glazing replacement						
Energy efficiency improvement (%)	10,3	12,4	10,6	13,8	11,4	13,1
Investing efficiency (%)	5,65	3,57	6,34	4,97	7,14	5,28

Appendix 18.4 – Influences of weather circumstances – base energy consumption

Reference year and situation	Normal usage			Energy poverty usage		
	Energy consumption (kWh)		Total Gas consumption (m³)	Energy consumption (kWh)		Total Gas consumption (m³)
	Heating	Total		Heating	Total	
Average situation 2018/2021 – chapter 3.2	-		627			350
Modelled average situation 2018/2021 – NEN5060 ref:2018 energie	3467	8732	657	1467	5773	2387
Modelled average situation 2018/2021 – NEN5060 ref:2018 TO5 gematigd	4144	9410	719	2322	6627	2387
Modelled average situation 2018/2021 – NEN5060 ref:2018 TO1 zeer streng	4450	9717	750	2803	7109	2387

Appendix 18.6 – Influences of weather circumstances – description
Similar to the previously discussed notion about the gas prices used in the simulations and analysis of interventions, a specific simulation weather file was used to perform the simulations. The weather file which was used was: "NEN5060: 2018 energie". This weather file was set-up by the Dutch Normalization-Institute and specifically allows users to simulate the energy consumption of dwellings. It does so by minimizing the extreme outliers in outdoor temperature throughout the year. Besides this, it has a nearly identical average outdoor temperature and average outdoor temperature range as other weather file (Halfens, 2021). The figure below shows the average temperature, average temperature range and extreme temperature range of other weather files.

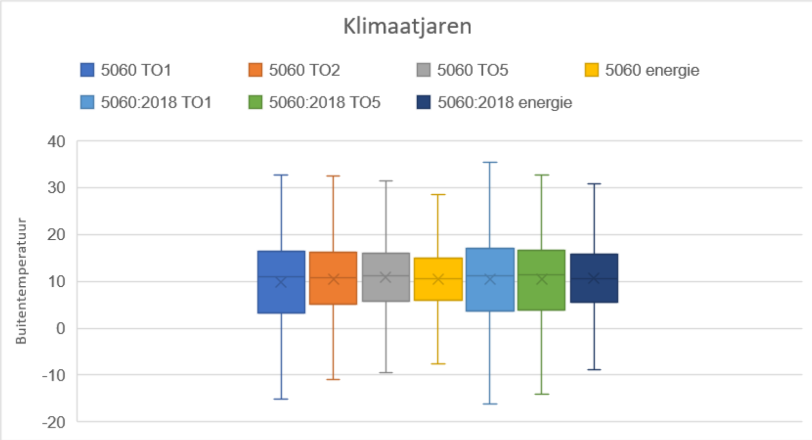


Figure: *Comparison of weather files (Halfens, 2021)*

In order to give an indication into how the effects of simulated interventions will change under different weather circumstances, 4 interventions were tested and compared under the weather files of "NEN5060: 2018 TO5 gematigd (intermediate)", which is represented by the green boxplot in the graph above, and "NEN5060: 2018 TO5 zeer streng (severe)", which is represented by the light blue boxplot in the graph above. Both weather files have a nearly identical average outdoor temperature but differ in their average and extreme outliers.

Appendices 18.3 through 18.5 show the comparison of different interventions under the varying weather circumstances. The first notion which can be made is that there is no clear relation between the weather file year and the improvement in energy efficiency, this can be explained by the base energy usage of the case varying over the different weather files. There is a relationship between the base energy usage and the weather file, with the file with the more extreme colder temperatures and colder average temperature resulting in a higher base energy consumption. Meanwhile, the investing efficiency of interventions does gradually increase the extremer the weather data becomes, giving the notion that interventions become more useful and necessary in time periods with average colder temperatures.

Weather file	**Year: 2018 energie**		**Year: 2018 TO5 intermediate**		**Year: 2018 TO1 severe**	
Usage profile	Normal usage	Energy poverty	Normal usage	Energy poverty	Normal usage	Energy poverty
Indoor wall insulation						
Energy efficiency improvement (%)	4,6	5,7	4,8	6,3	5,1	5,9
Investing efficiency (%)	4,8	3,1	5,4	4,3	6,0	4,5
External wall insulation						
Energy efficiency improvement (%)	4,7	5,9	4,8	6,5	5,1	6,0
Investing efficiency (%)	1,0	0,7	1,1	0,9	1,2	0,9
Window insulation film						
Energy efficiency improvement (%)	3,9	4,9	4,0	5,1	4,1	4,9
Investing efficiency (%)	69,4	45,6	71,2	47,5	73,0	45,7
Glazing replacement						
Energy efficiency improvement (%)	10,3	12,4	10,6	13,8	11,4	13,1
Investing efficiency (%)	5,7	3,6	6,3	5,0	7,1	5,3

Appendix 18.7 – Influences of gas prices

Within the research on the effectiveness of interventions that aim to deal with energy price increases, the effects of these interventions are related to the energy crisis of 2022. This is done by relating the interventions to the energy consumption habits of energy poverty households in 2022 and by relating the financial effectiveness of interventions to the energy prices of the energy crisis of 2022. Constructing the research in this way allows for the results to be closely applied to the reality of energy prices and consumption of the period in which this research is written and to the future, as many outlets state concerns that energy prices will not drop to levels of before 2022/2023. Despite this, it is useful to relate the financial effectiveness of energy poverty interventions to gas prices other than the historic high of 1,5€ of 2023. As predictions of changes in energy prices remain predictions and can be proven either right or wrong. To assess the financial effectiveness of the interventions under other circumstances, calculations which compare the yearly savings and payback period have been made for the gas price scenarios of 1,5€, 1,2€, 1€, 0,85€, and 1,75€.

These calculations show that gas prices heavily influence the effectiveness of interventions. Within the calculations, the comparisons take the yearly savings and payback periods into account, as these can be directly calculated. On the other hand, it can be expected that other aspects of intervention's effectiveness change.

As has been discussed in the research, energy consumption habits change during energy price fluctuations, with higher prices reducing household energy consumption, and lower prices increasing household energy consumption. These energy consumption habits influence the effectiveness of interventions. For example, a lower gas price might lead to a higher base gas consumption, which in turn changes the energy efficiency of an intervention. Besides this, changes in gas prices might result in different base temperature setpoints, which in turn influences the thermal comfort efficiency of interventions. The calculations show how the yearly savings and payback periods of interventions worsen when gas prices reduce, leading to certain interventions to be less interesting investments than they are during energy crises. For example, for DIY secondary glazing used by energy poverty households, the yearly savings of 23,6 and payback period of 14 years during 2023 are much more attractive than the yearly savings of 13,4 and payback period of 24 years it would have meant before 2022. The detailed calculations can be seen in this appendix.

	Normal usage payback period				
Gas price:	**1,75**	**1,5**	**1,2**	**1**	**0,85**
Glazing replacement	15,2	17,7	22,1	26,6	31,2
Thermal curtains	3,7	4,3	5,4	6,5	7,7
External wall insulation	87,1	101,6	127,1	152,5	179,4
Indoor wall insulation	18,1	21,1	26,4	31,6	37,2
Radiator foil (Method 1)	0,8	1,0	1,2	1,5	1,7
Secondary glazing DIY	7,7	8,9	11,2	13,4	15,8
House air sealing	14,3	16,7	20,9	25,1	29,5
Insulated door panels	1,5	1,7	2,1	2,5	3,0
Weatherstripping	5,8	6,7	8,4	10,1	11,9
Window insulation film	1,2	1,4	1,8	2,2	2,5
Radiator foil (Method 2)	2,4	2,8	3,6	4,3	5,0
Draft stoppers	6,2	7,2	9,0	10,8	12,7
Floor insulation	377,0	439,9	549,8	659,8	776,2
Floor rug insulation	306,3	357,4	446,7	536,1	630,7
	Energy poverty usage payback period				
Gas price:	**1,75**	**1,5**	**1,2**	**1**	**0,85**
Glazing replacement	24,0	27,9	34,9	41,9	49,3
Thermal curtains	5,4	6,3	7,8	9,4	11,1
External wall insulation	130,6	152,3	190,4	228,5	268,8
Indoor wall insulation	28,3	33,1	41,3	49,6	58,3
Radiator foil (Method 1)	153,8	179,5	224,4	269,2	316,7
Secondary glazing DIY	11,6	13,6	17,0	20,4	23,9
House air sealing	21,6	25,2	31,5	37,8	44,5
Insulated door panels	2,2	2,5	3,1	3,8	4,4
Weatherstripping	8,7	10,1	12,6	15,2	17,8
Window insulation film	1,9	2,2	2,7	3,3	3,9
Radiator foil (Method 2)	3,7	4,3	5,3	6,4	7,5
Draft stoppers	8,0	9,4	11,7	14,1	16,6
Floor insulation	X	X	X	X	X
Floor rug insulation	1876,2	2188,9	2736,1	3283,3	3862,7

	Normal usage yearly savings				
Gas price:	**1,75**	**1,5**	**1,2**	**1**	**0,85**
Glazing replacement	118,6	101,7	81,3	67,8	57,6
Thermal curtains	67,2	57,6	46,1	38,4	32,6
External wall insulation	53,6	45,9	36,8	30,6	26,0
Indoor wall insulation	52,6	45,1	36,0	30,0	25,5
Radiator foil (Method 1)	42,0	36,0	28,8	24,0	20,4
Secondary glazing DIY	41,8	35,8	28,7	23,9	20,3
House air sealing	27,9	23,9	19,1	15,9	13,5
Insulated door panels	24,1	20,7	16,5	13,8	11,7
Weatherstripping	20,8	17,8	14,3	11,9	10,1
Window insulation film	45,3	38,9	31,1	25,9	22,0
Radiator foil (Method 2)	14,4	12,3	9,9	8,2	7,0
Draft stoppers	7,8	6,7	5,3	4,4	3,8
Floor insulation	3,1	2,7	2,1	1,8	1,5
Floor rug insulation	2,6	2,2	1,8	1,5	1,2
	Energy poverty usage yearly savings				
Gas price:	**1,75**	**1,5**	**1,2**	**1**	**0,85**
Glazing replacement	75,1	64,4	51,5	42,9	36,5
Thermal curtains	46,5	39,8	31,9	26,6	22,6
External wall insulation	35,8	30,7	24,5	20,4	17,4
Indoor wall insulation	33,5	28,7	23,0	19,2	16,3
Radiator foil (Method 1)	0,2	0,2	0,2	0,1	0,1
Secondary glazing DIY	27,5	23,6	18,9	15,7	13,4
House air sealing	18,5	15,9	12,7	10,6	9,0
Insulated door panels	16,2	13,9	11,1	9,3	7,9
Weatherstripping	13,8	11,9	9,5	7,9	6,7
Window insulation film	29,8	25,5	20,4	17,0	14,5
Radiator foil (Method 2)	9,6	8,2	6,6	5,5	4,6
Draft stoppers	6,0	5,1	4,1	3,4	2,9
Floor insulation	-0,4	-0,3	-0,3	-0,2	-0,2
Floor rug insulation	0,4	0,4	0,3	0,2	0,2

Appendix: 19 – CFD calculations results

Appendix 19.1 – CFD calculations – base situation

Base Situation

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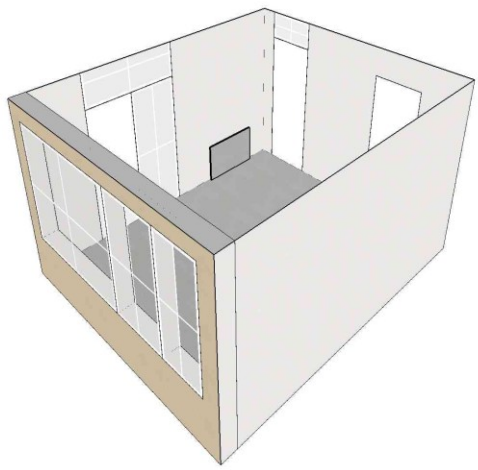
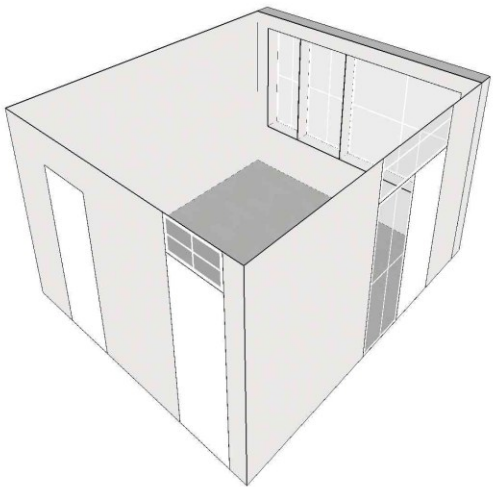
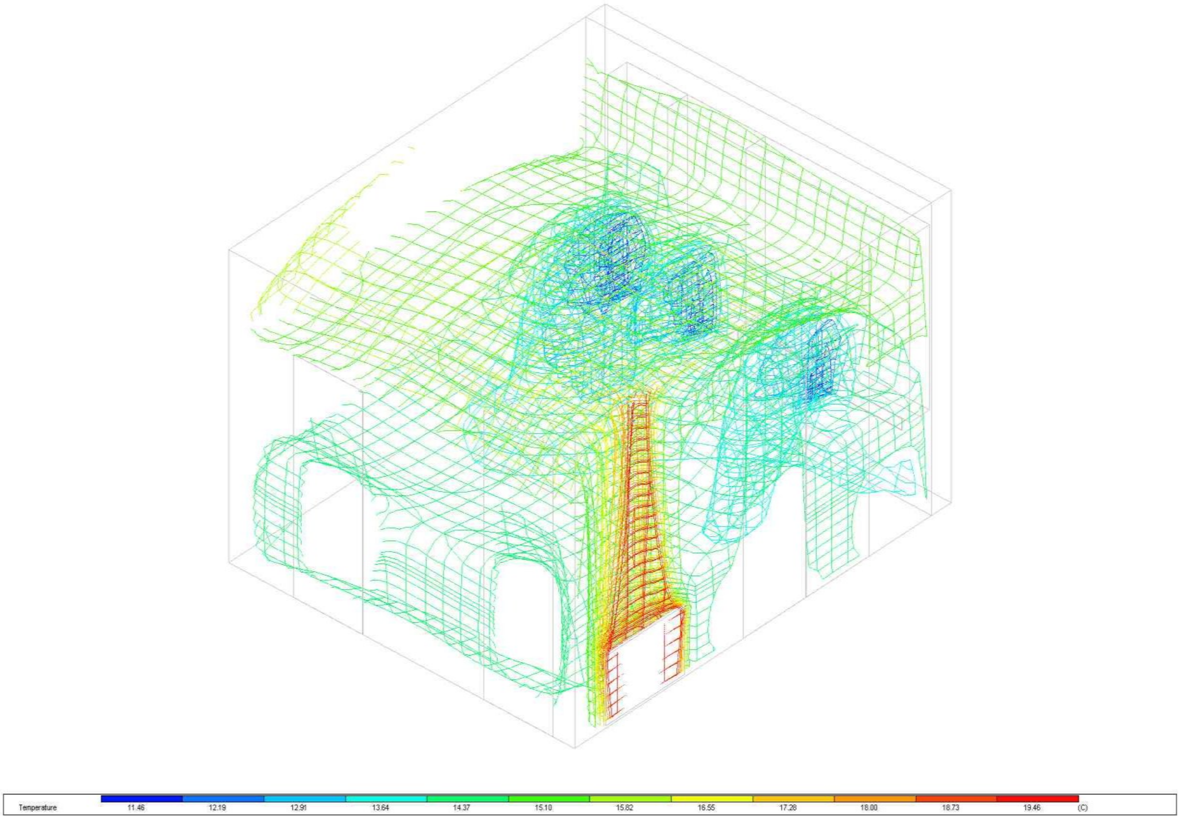
Company:	Student, Delft University of Technology



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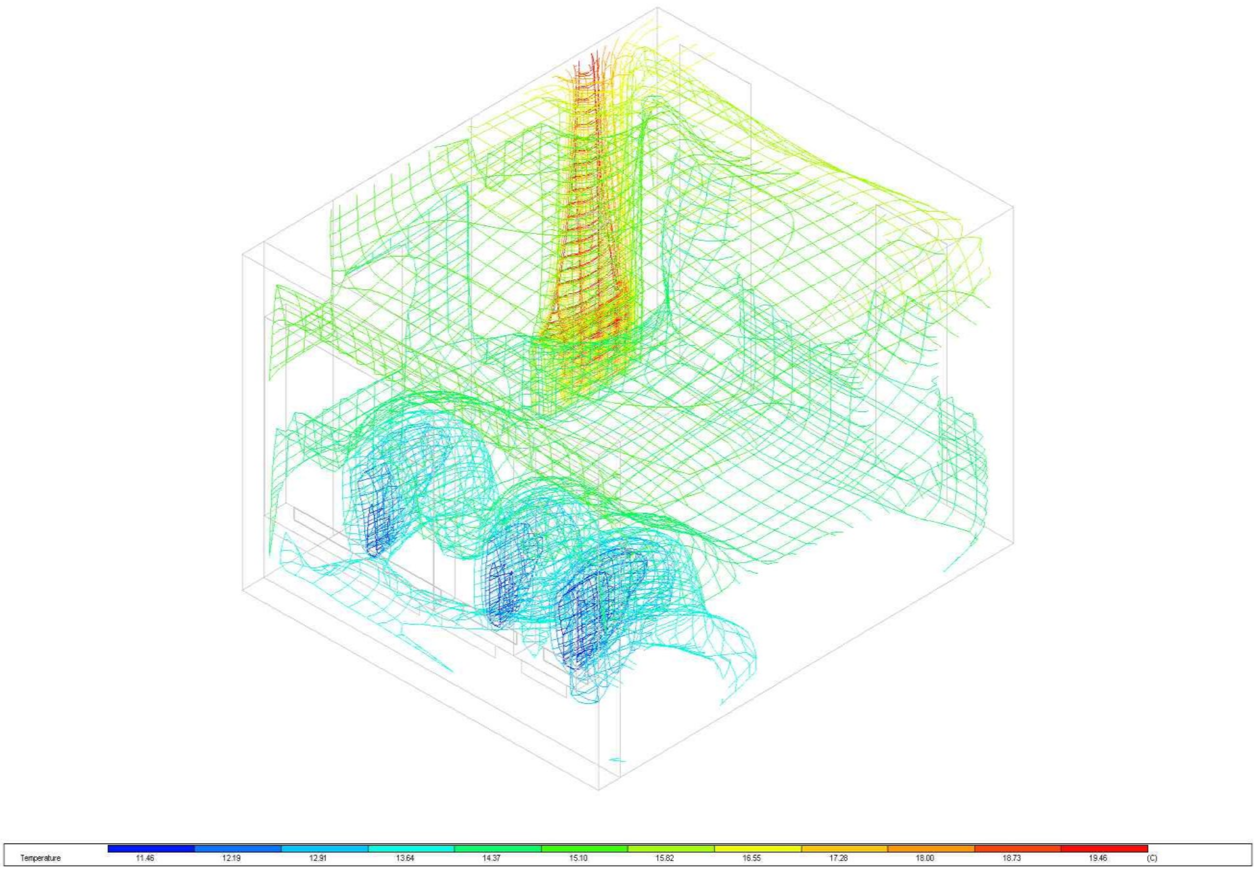
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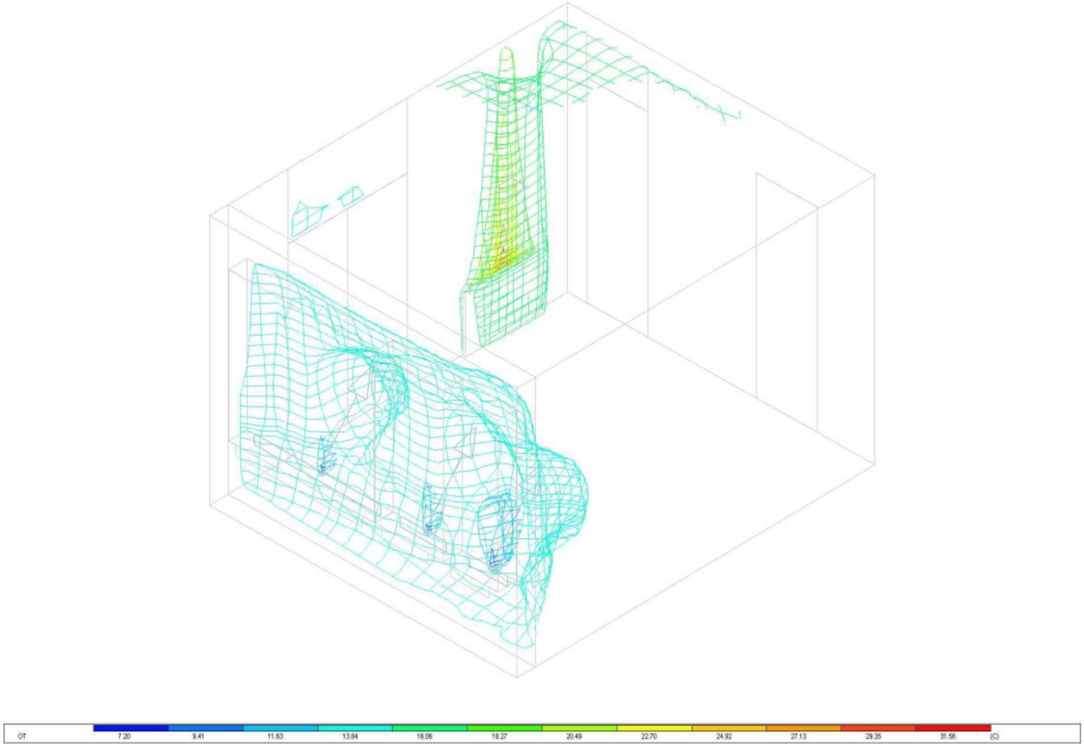
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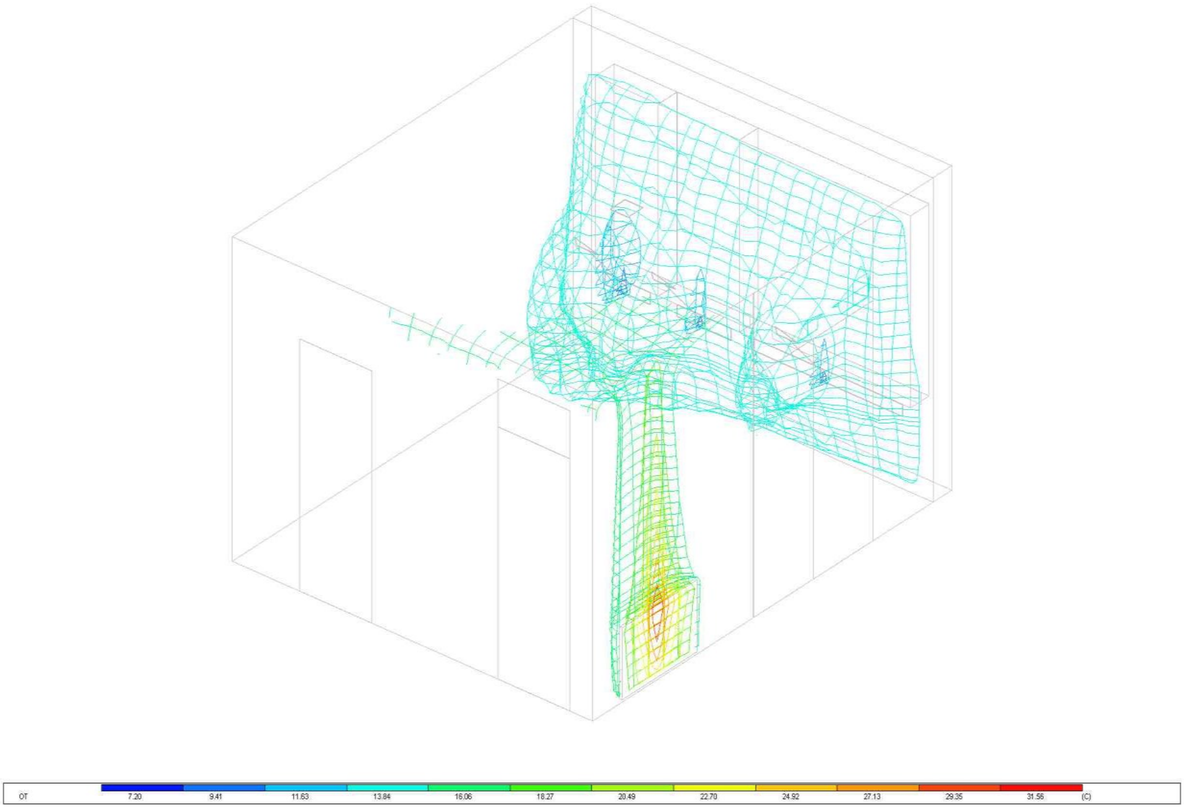
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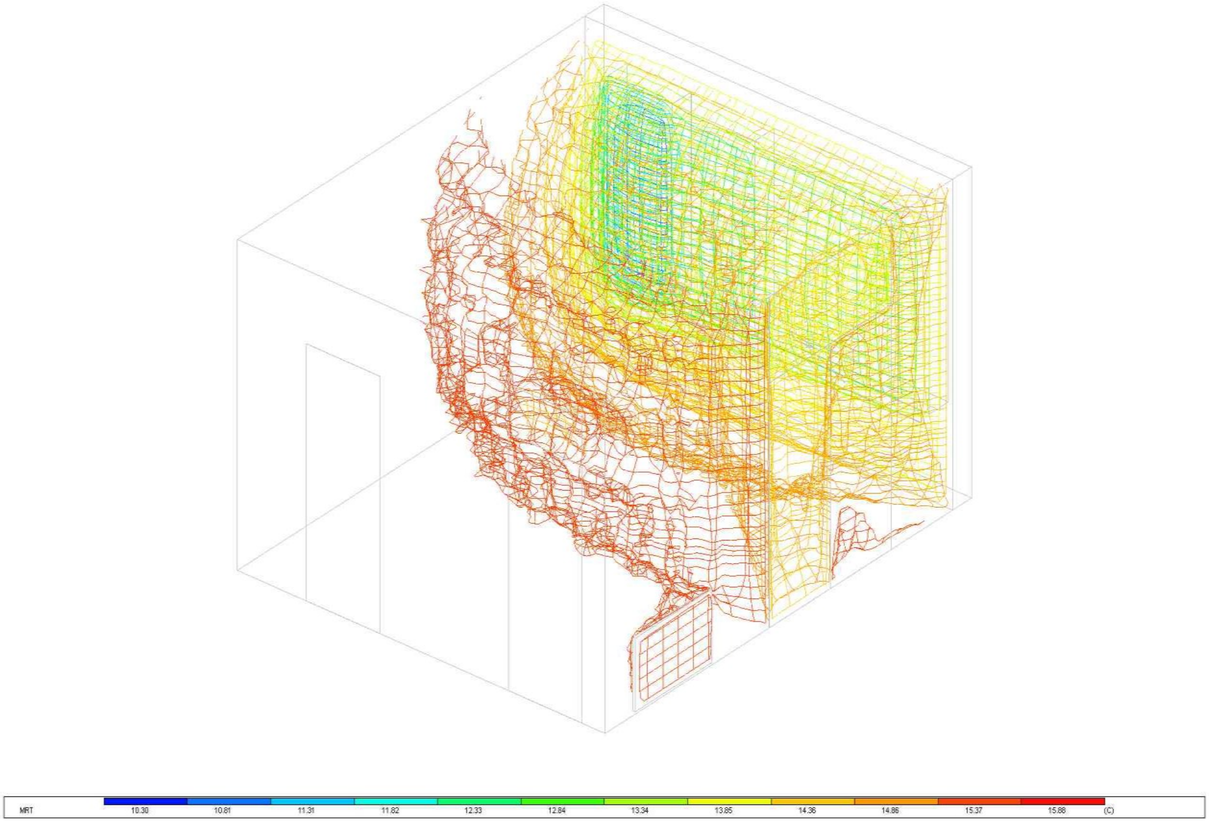
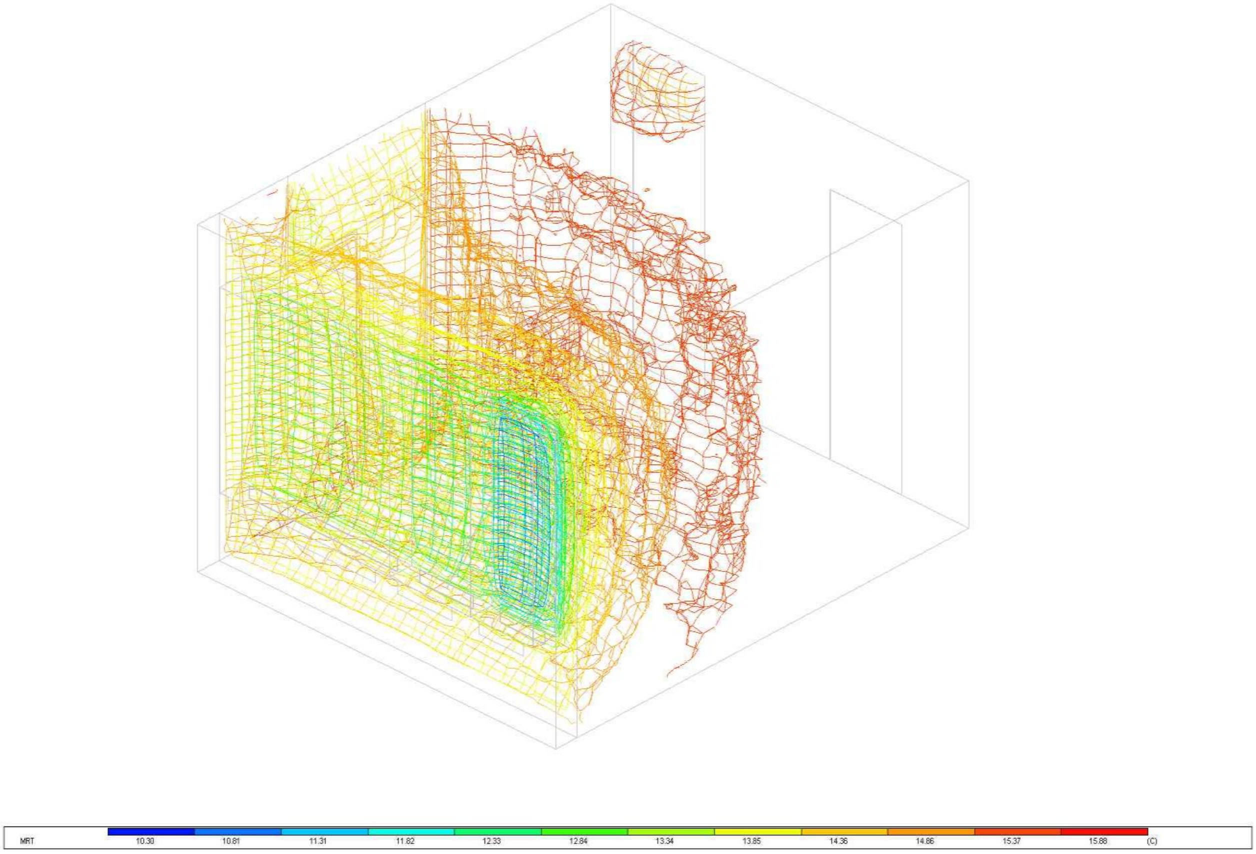
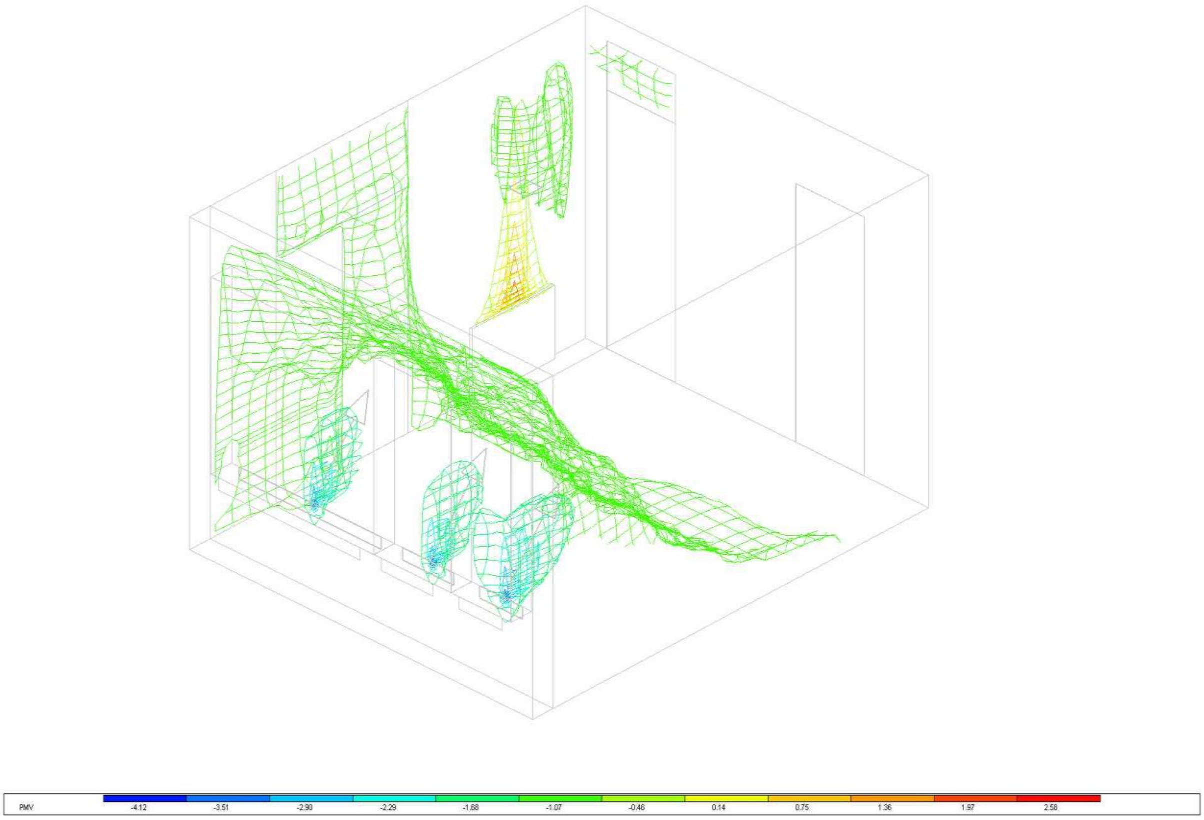
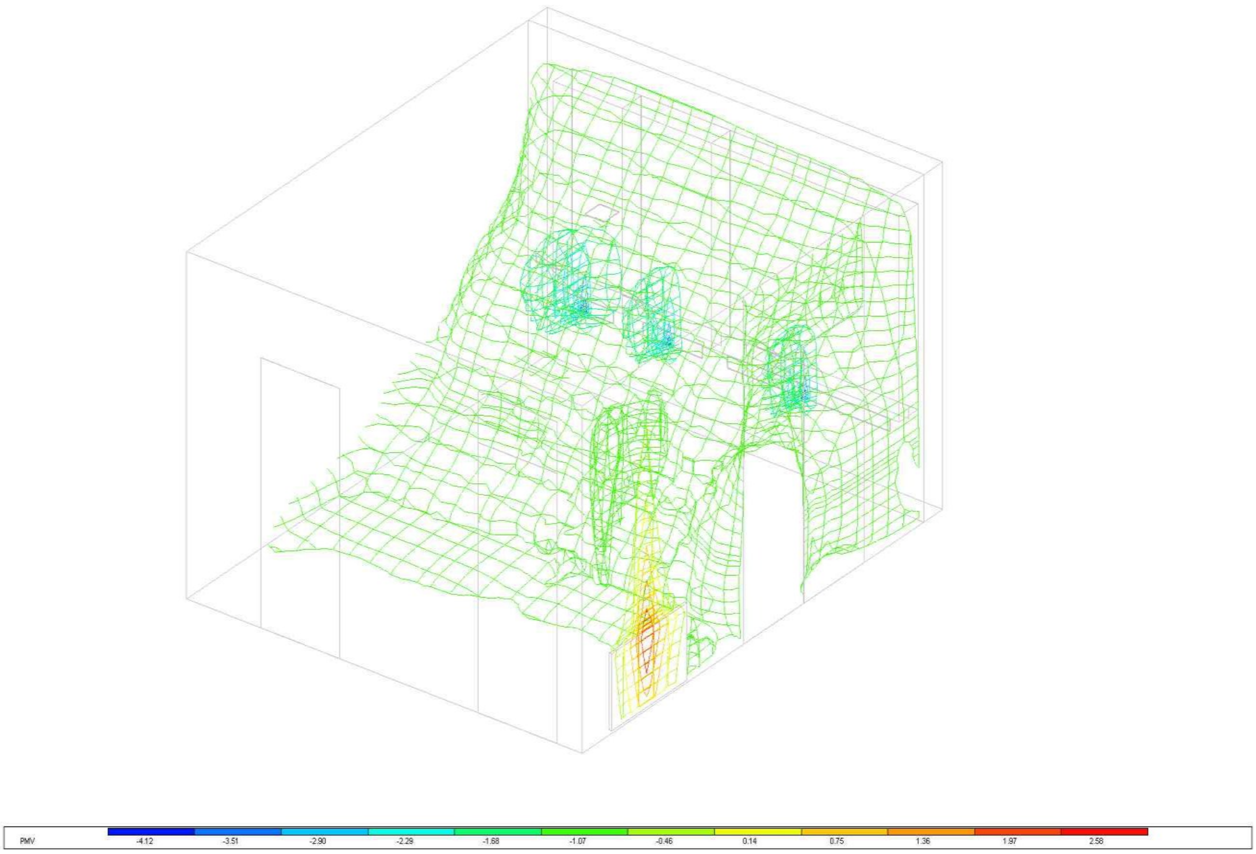
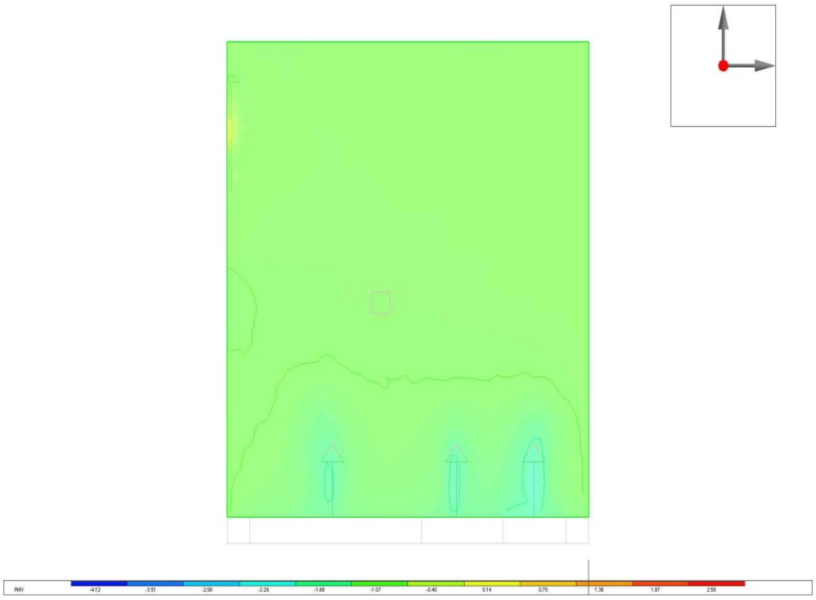
31.56
(C)

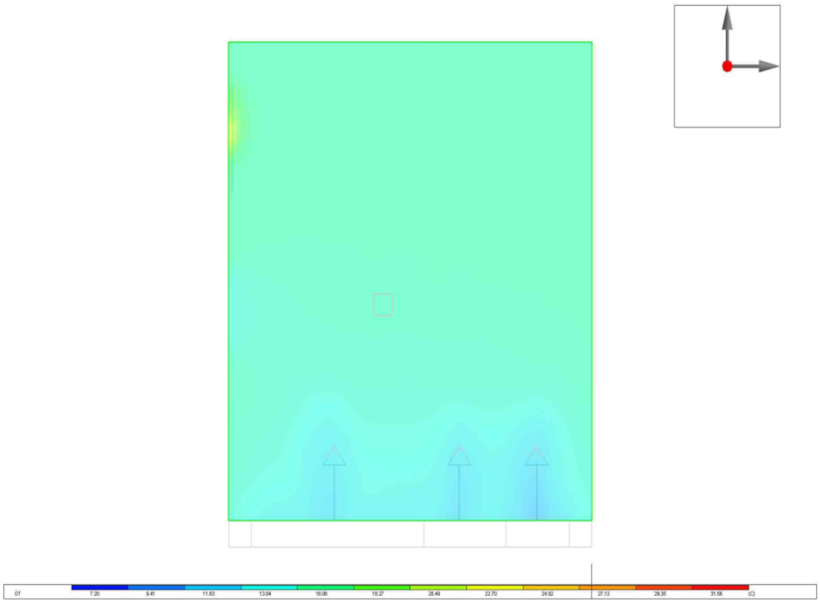

MRT
10.30 10.81 11.31 11.82 12.33 12.84 13.34 13.85 14.36 14.86 15.37 15.88 (C)

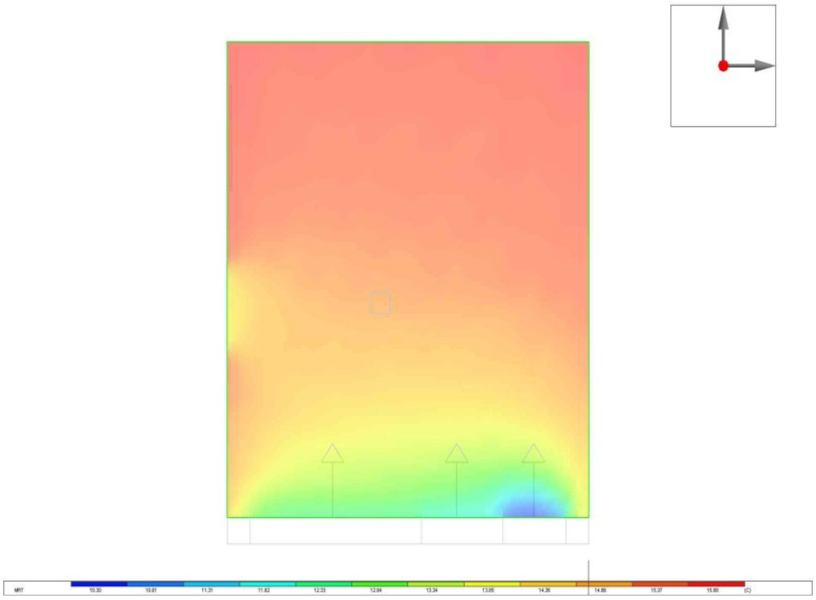

MRT
10.30 10.81 11.31 11.82 12.33 12.84 13.34 13.85 14.36 14.86 15.37 15.88 (C)


PMV
-4.12
-3.51
-2.90
-2.29
-1.68
-1.07
-0.46
0.14
0.75
1.36
1.97
2.58

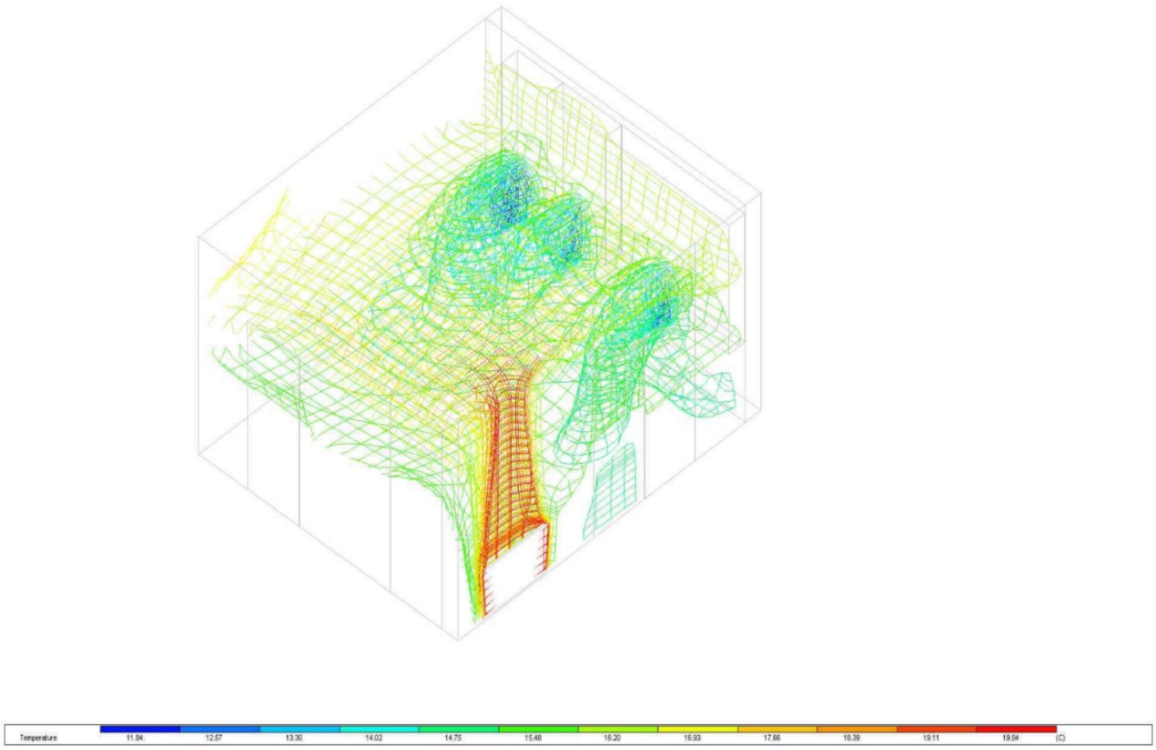

PMV
-4.12
-3.51
-2.90
-2.29
-1.68
-1.07
-0.46
0.14
0.75
1.36
1.97
2.58

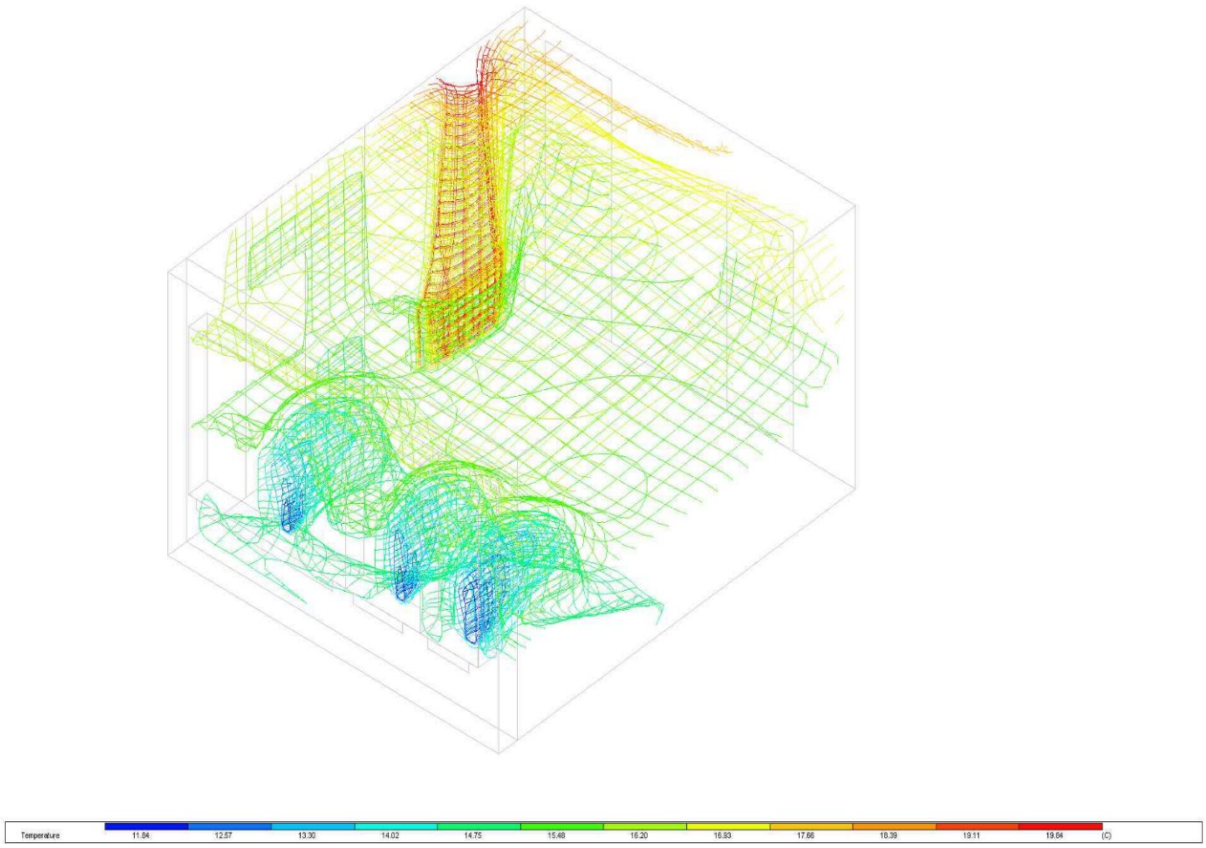


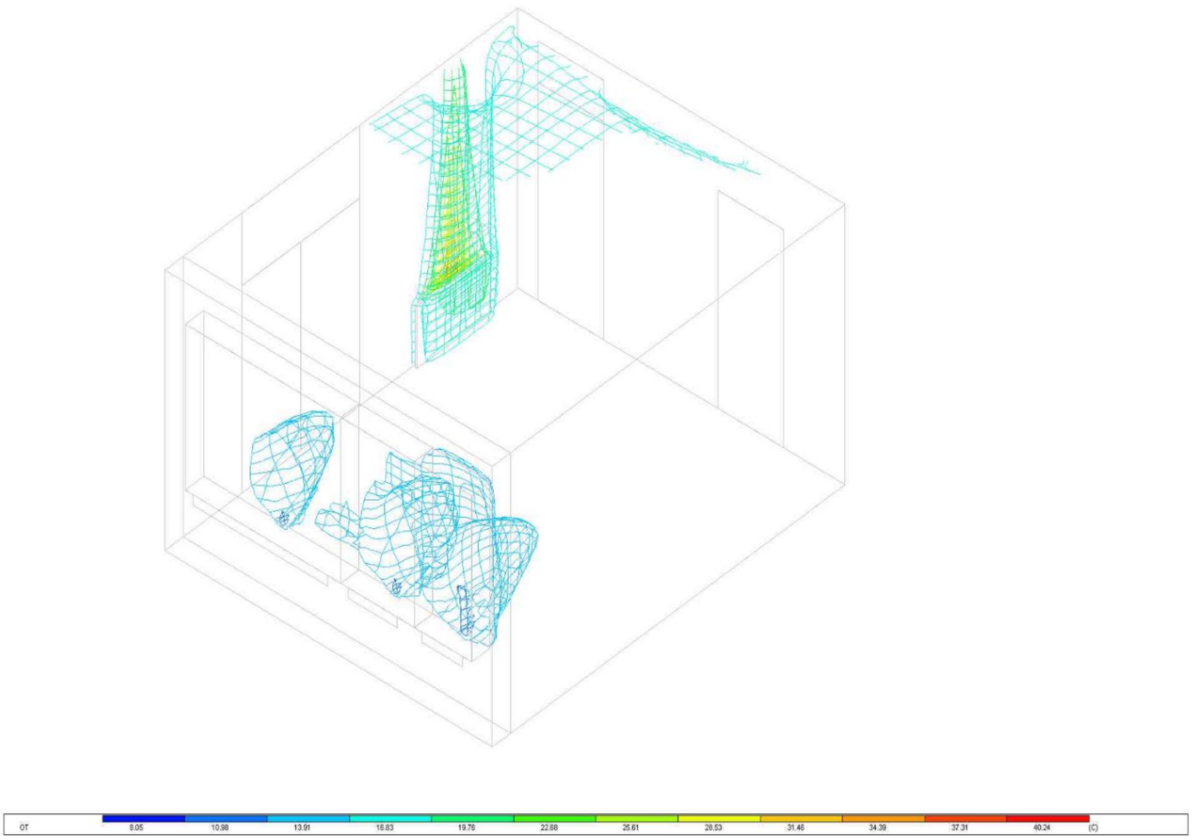


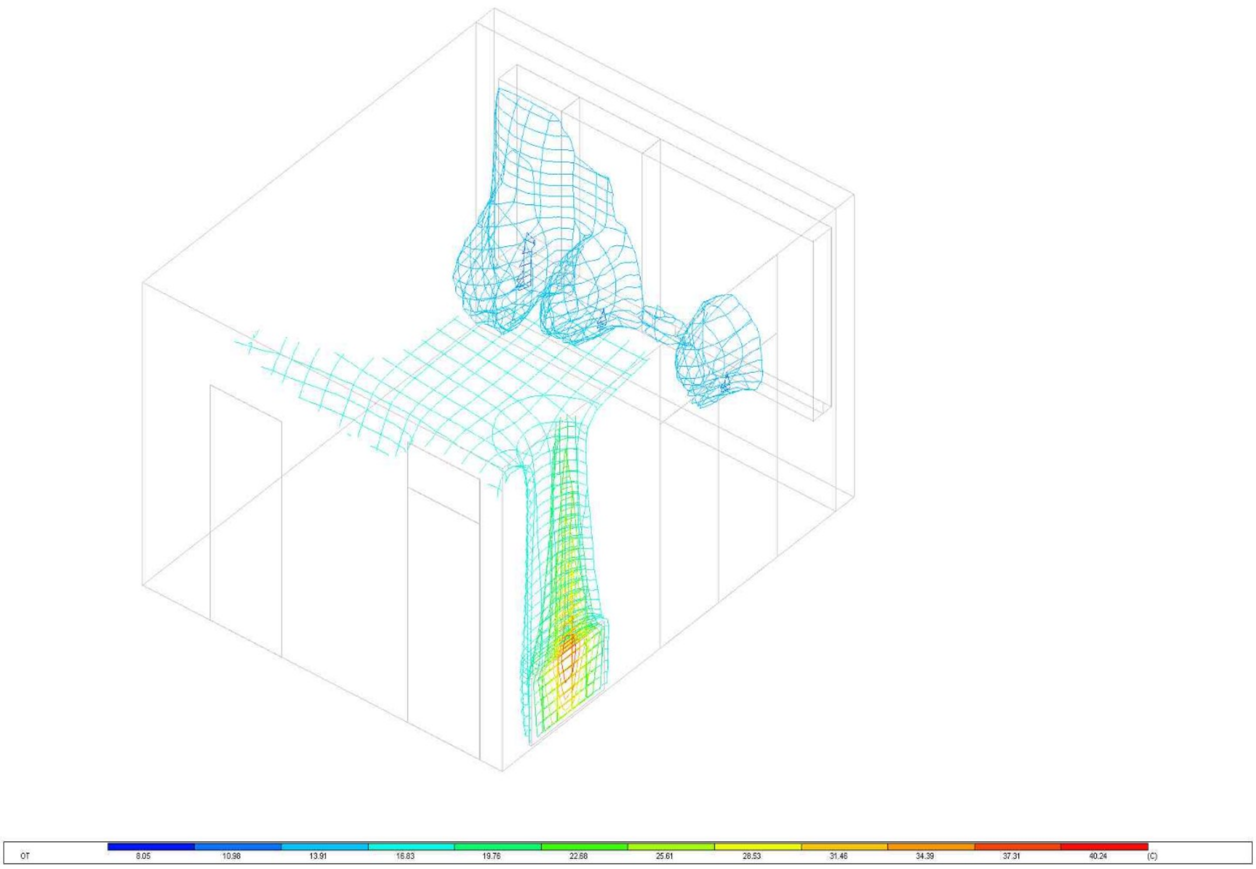


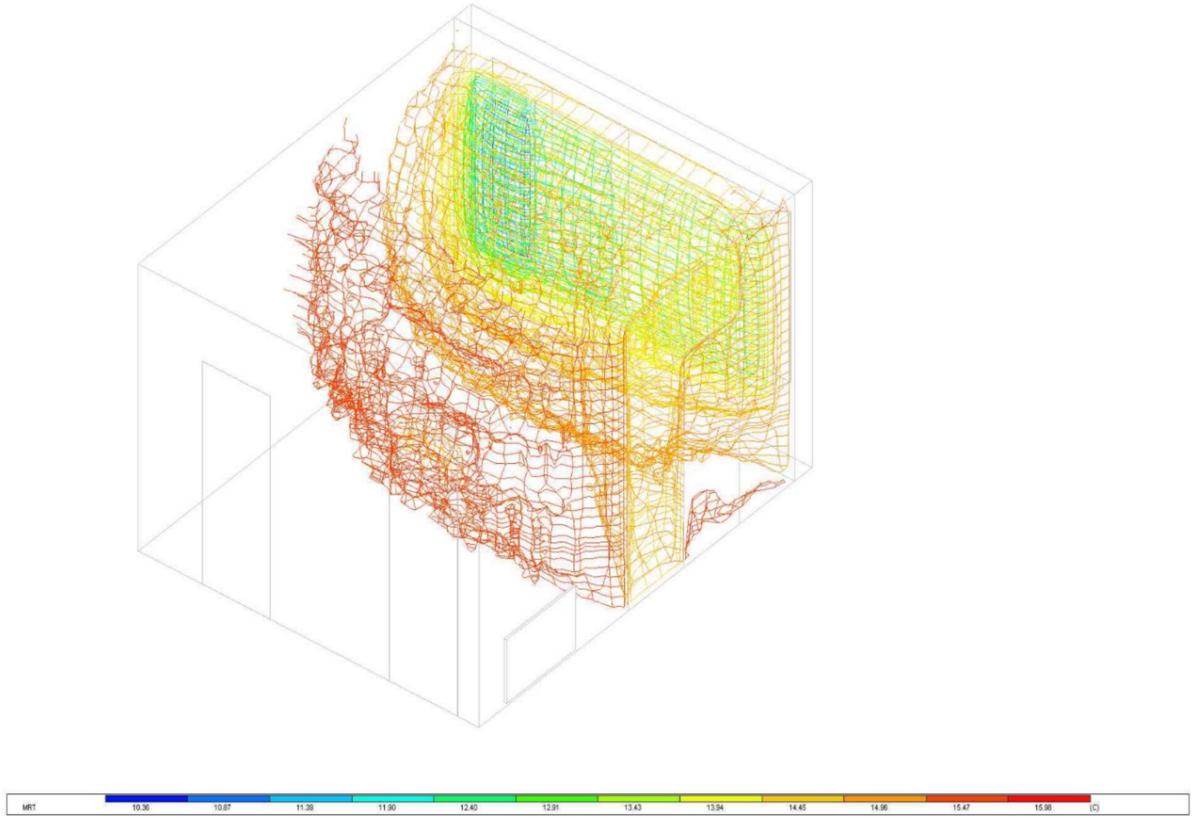
Appendix 19.2 – CFD calculations – Indoor insulation situation

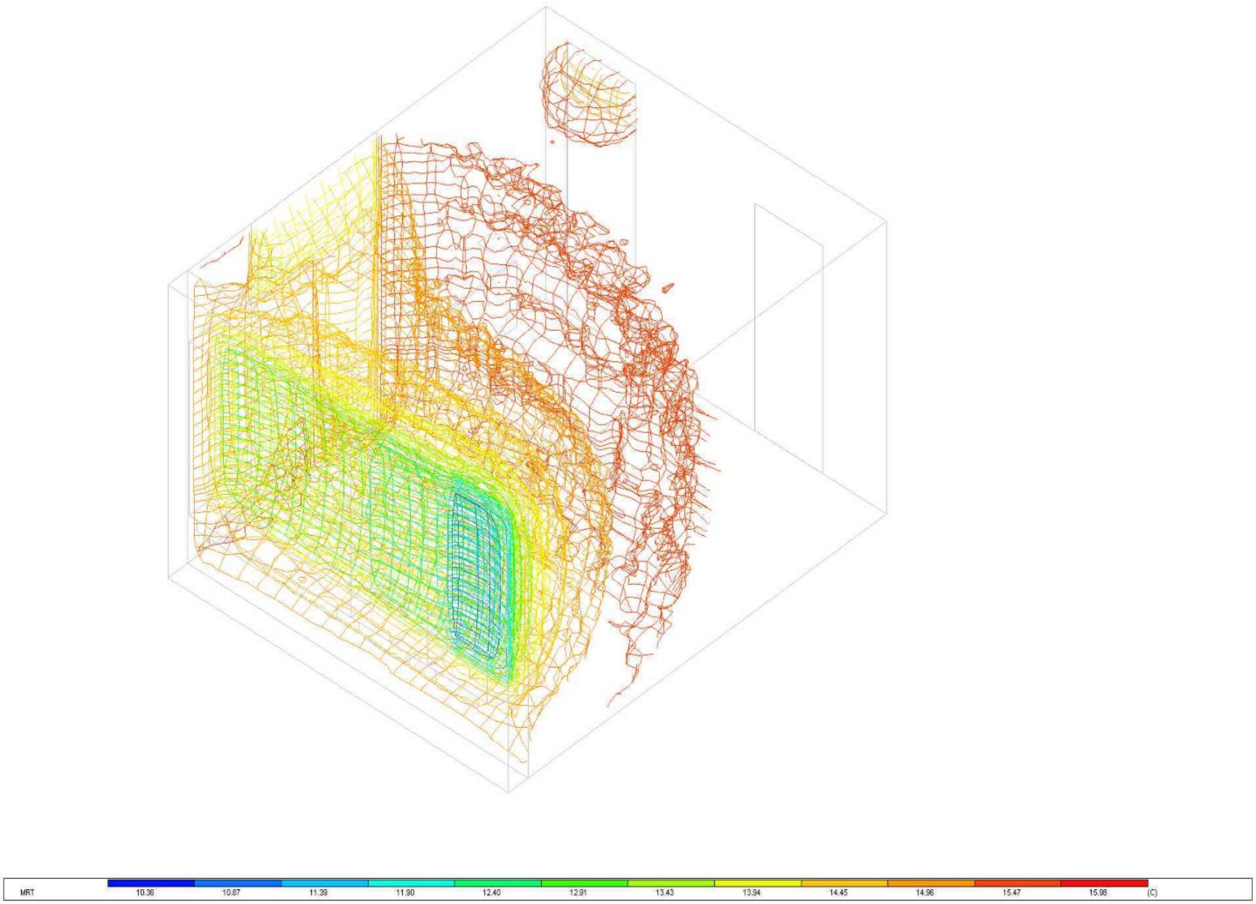


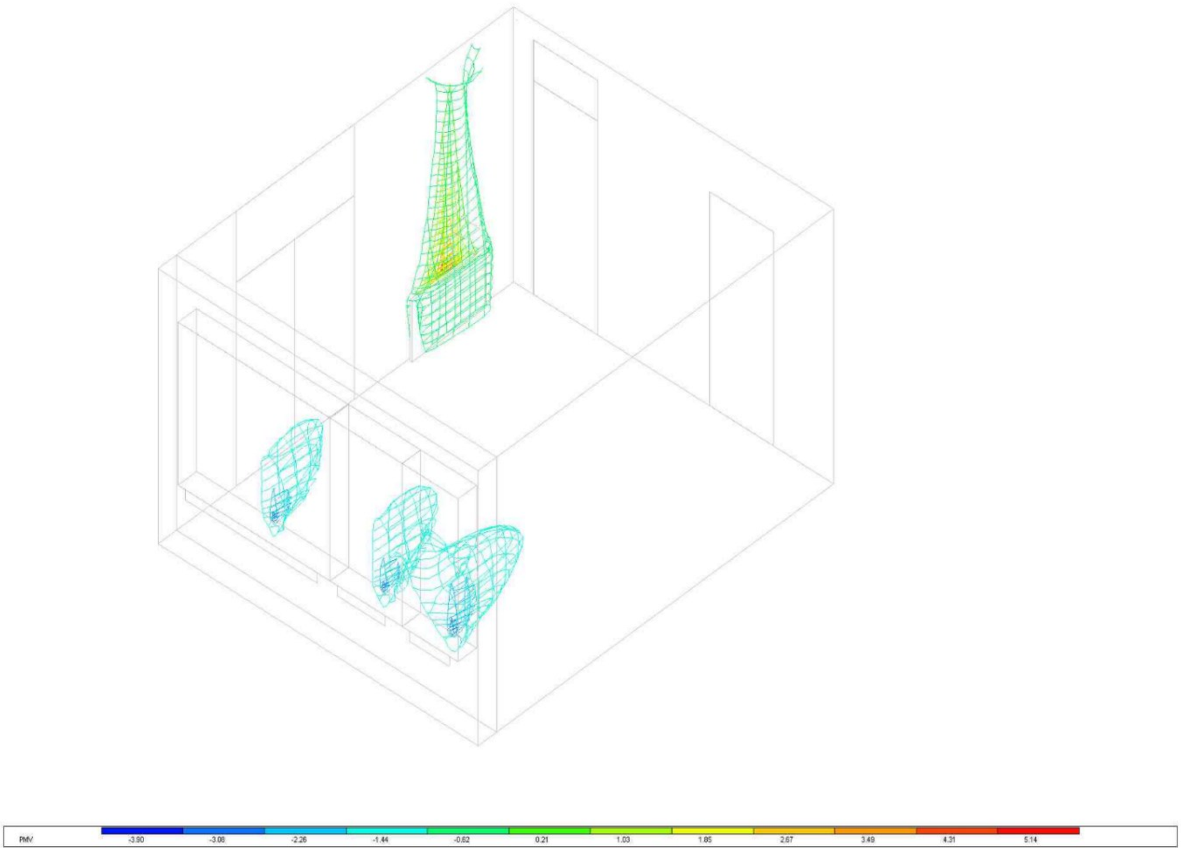


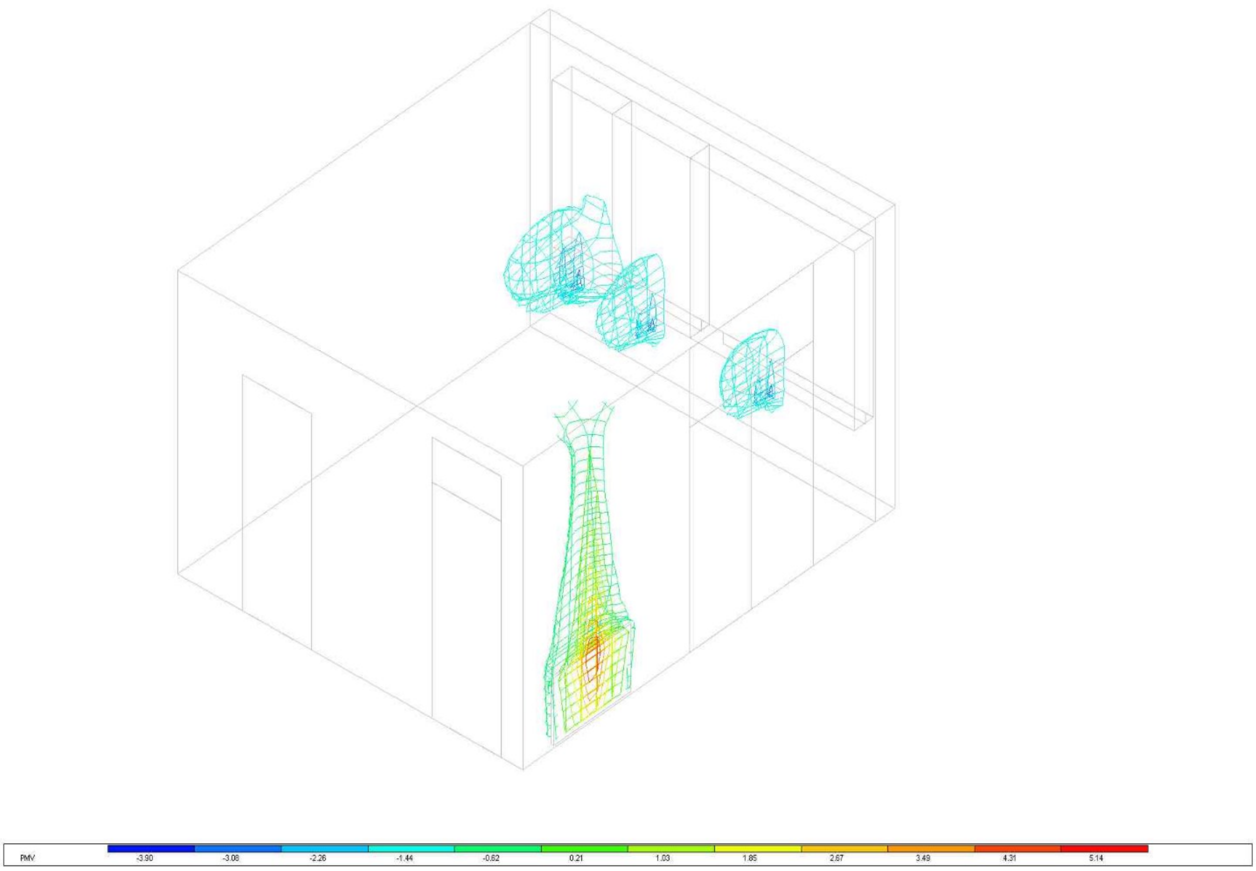

OT
8.05
10.98
13.91
16.83
19.76
22.68
25.61
28.53
31.46
34.39
37.31
40.24
(C)

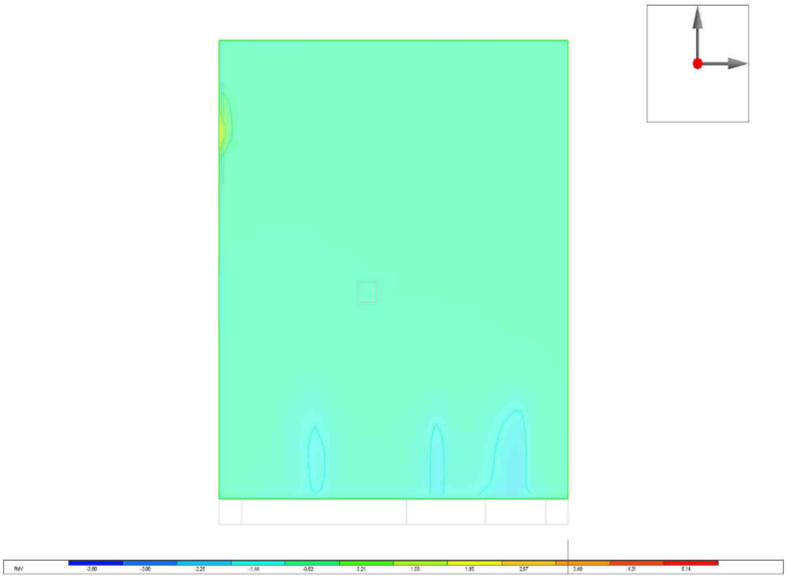

OT
8.05
10.98
13.91
16.83
19.76
22.68
25.61
28.53
31.46
34.39
37.31
40.24
(C)

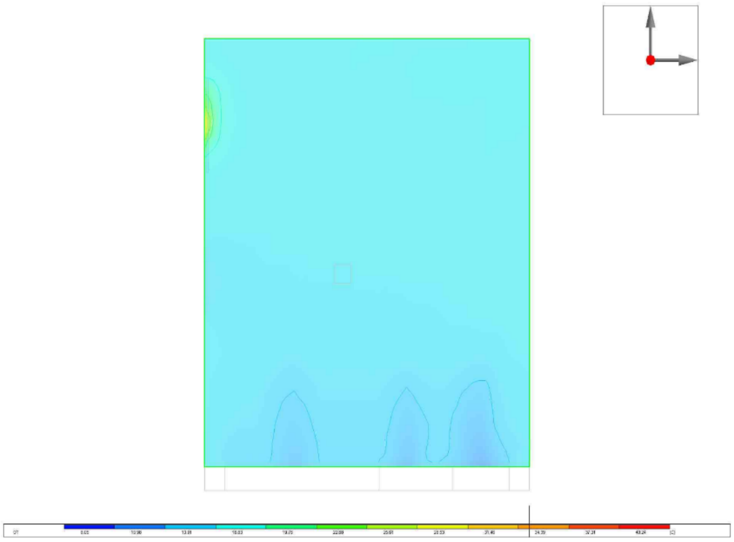

MRT
10.36
10.87
11.39
11.90
12.40
12.91
13.43
13.94
14.45
14.96
15.47
15.98
(C)

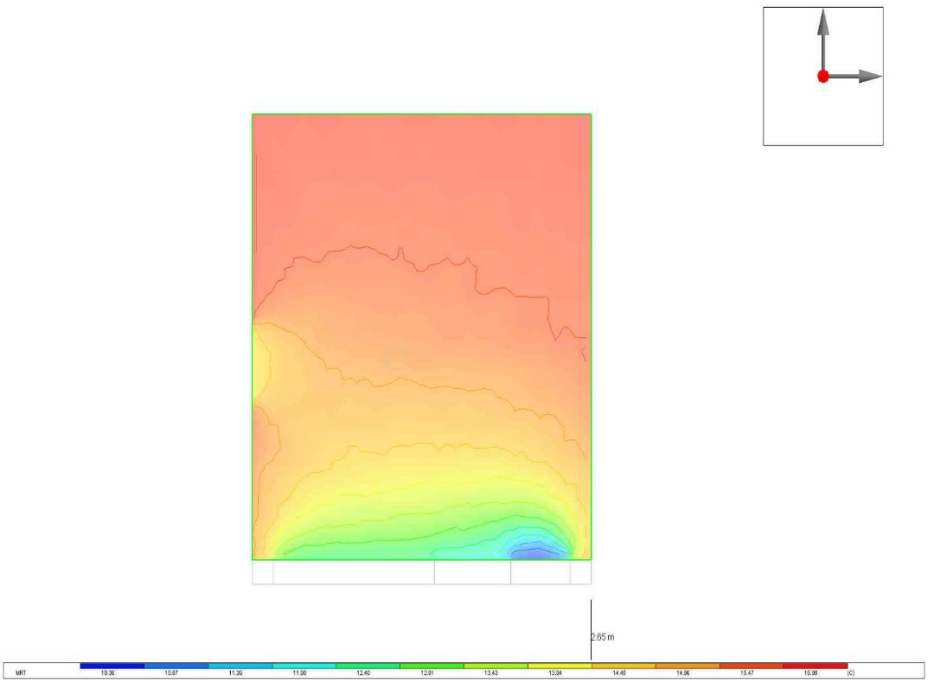

MRT
10.36
10.87
11.39
11.90
12.40
12.91
13.43
13.94
14.45
14.96
15.47
15.98
(C)


PMV
-3.90
-3.08
-2.26
-1.44
-0.62
0.21
1.03
1.85
2.67
3.49
4.31
5.14

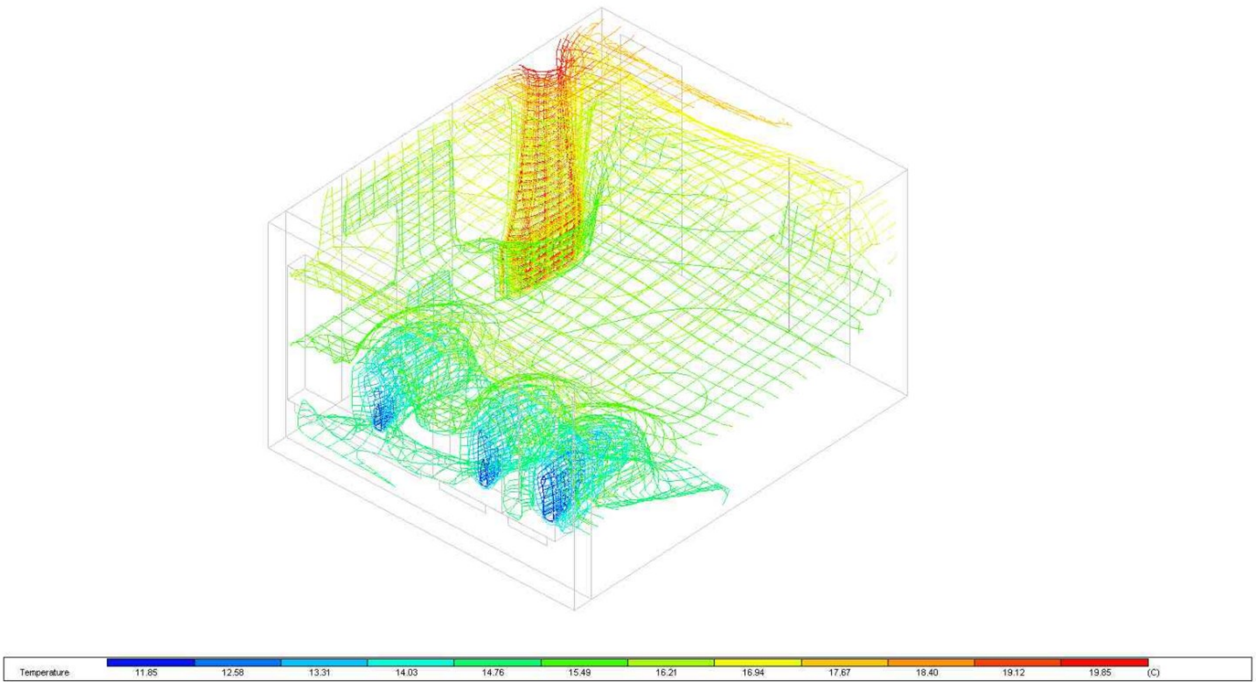

PMV
-3.90
-3.08
-2.26
-1.44
-0.62
0.21
1.03
1.85
2.67
3.49
4.31
5.14

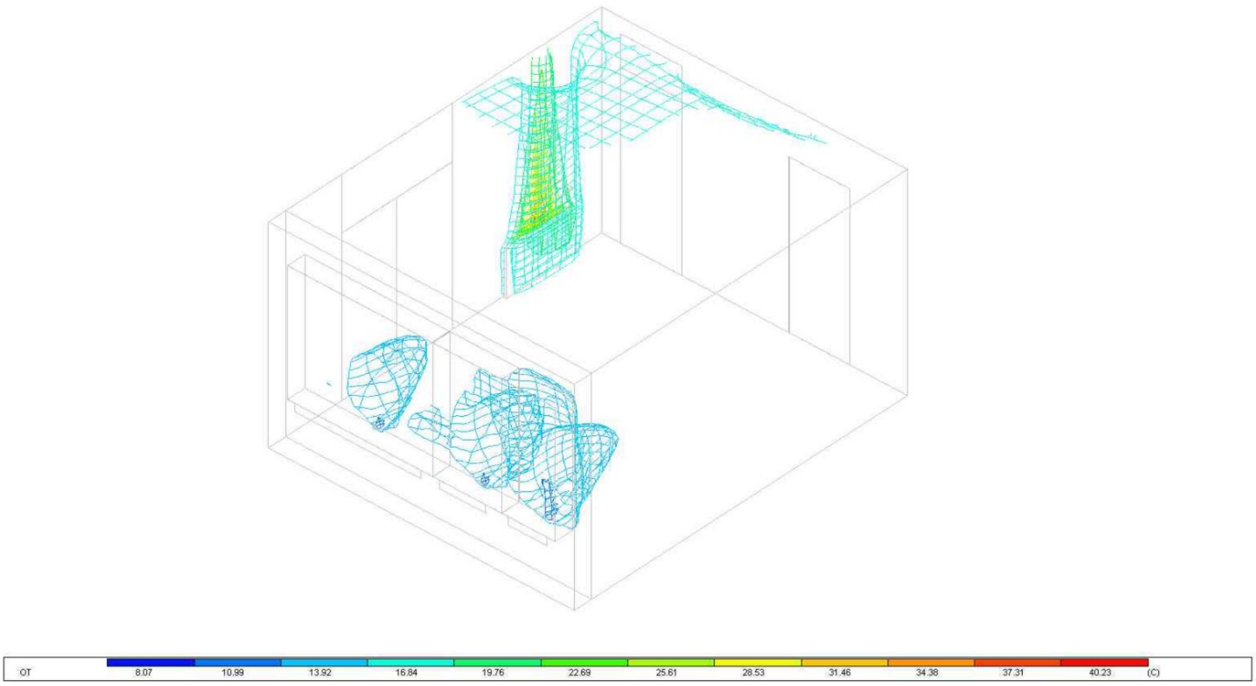


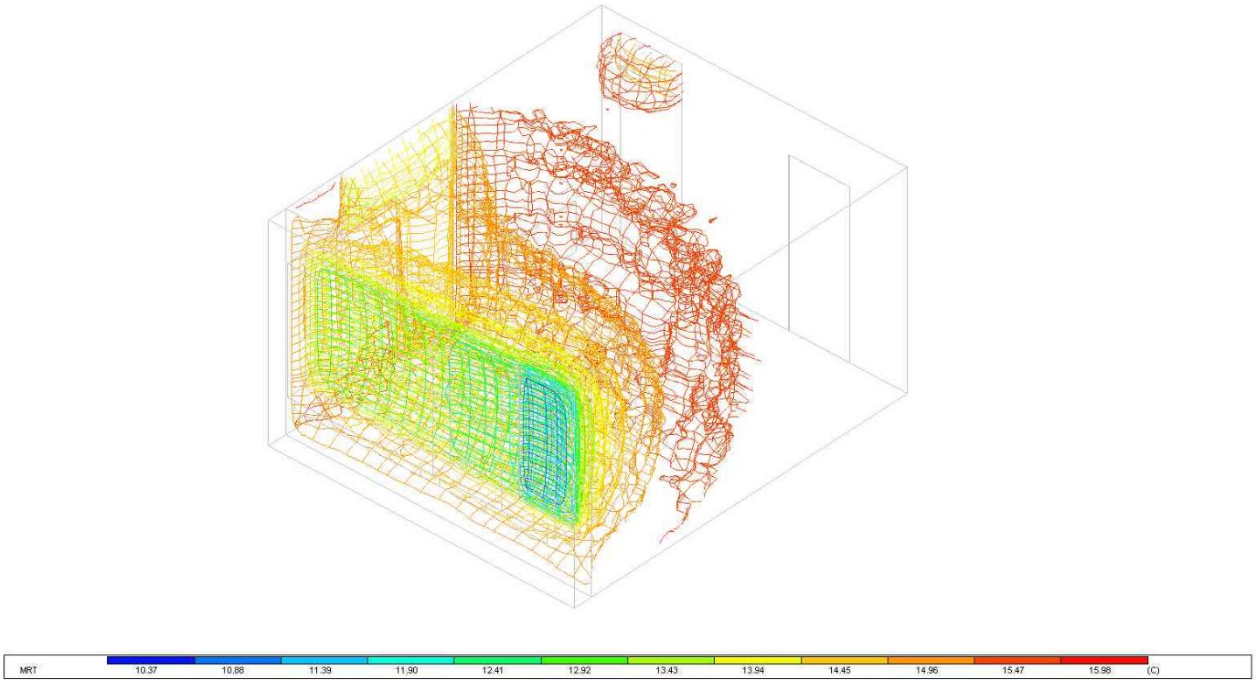


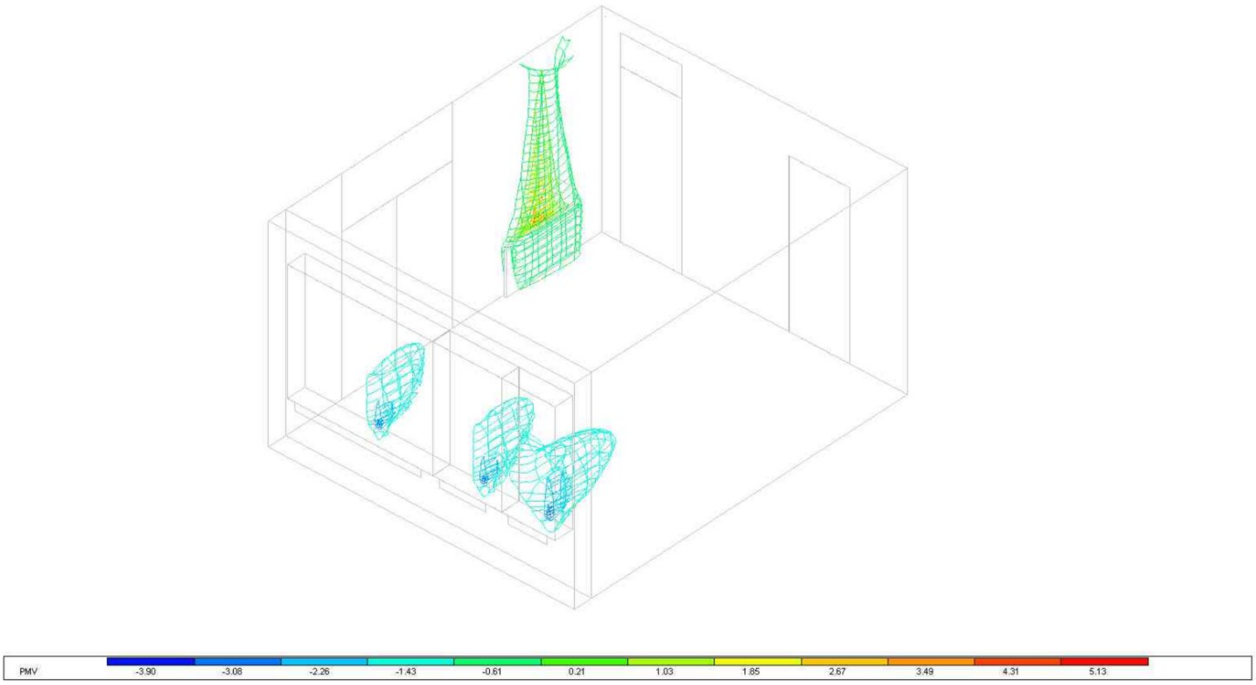

2.65 m

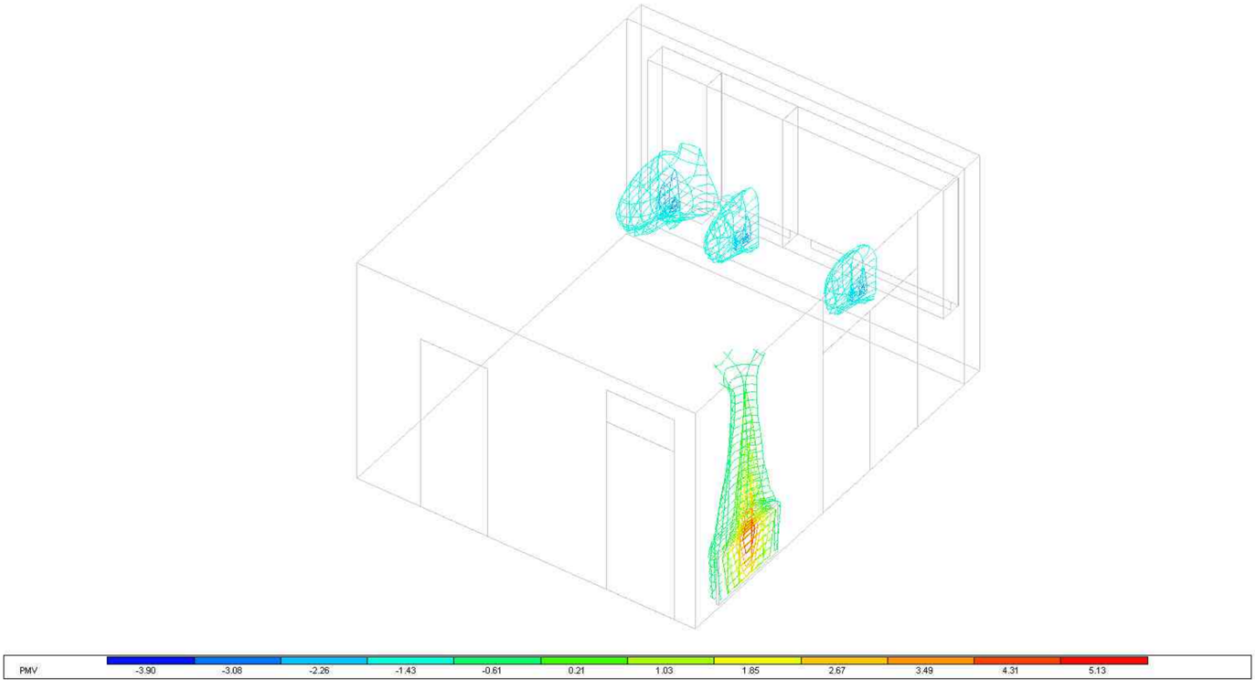
Appendix 19.3 – CFD calculations – External insulation situation

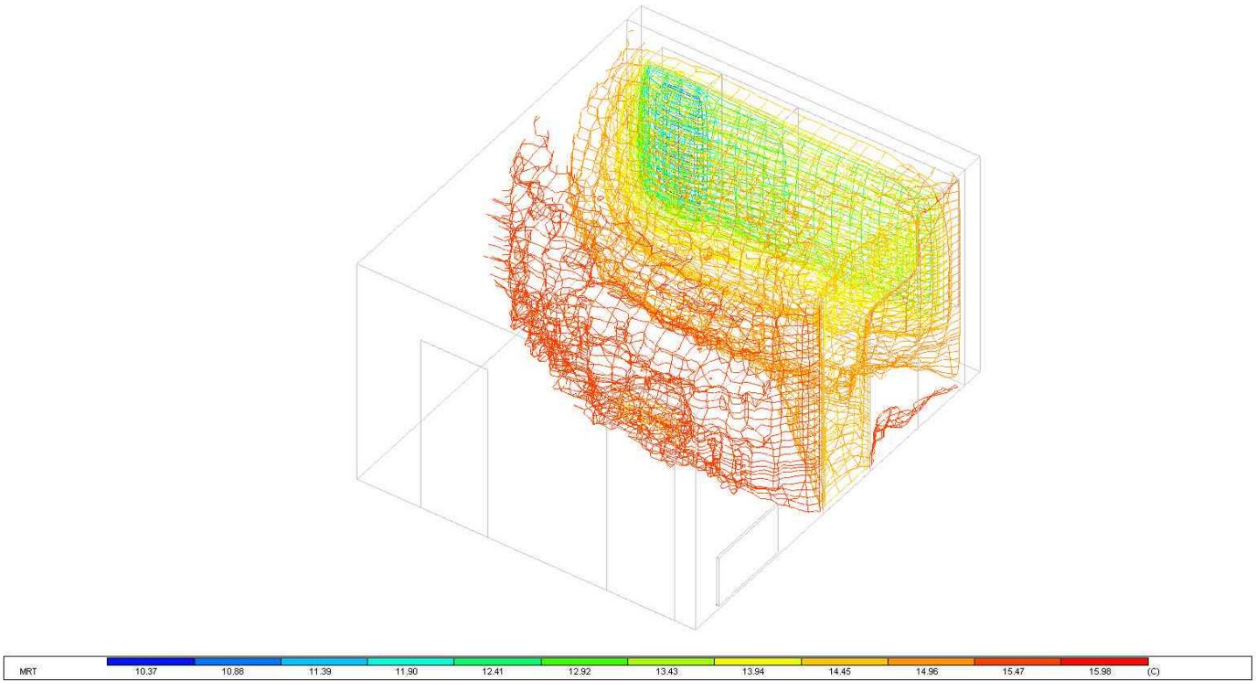


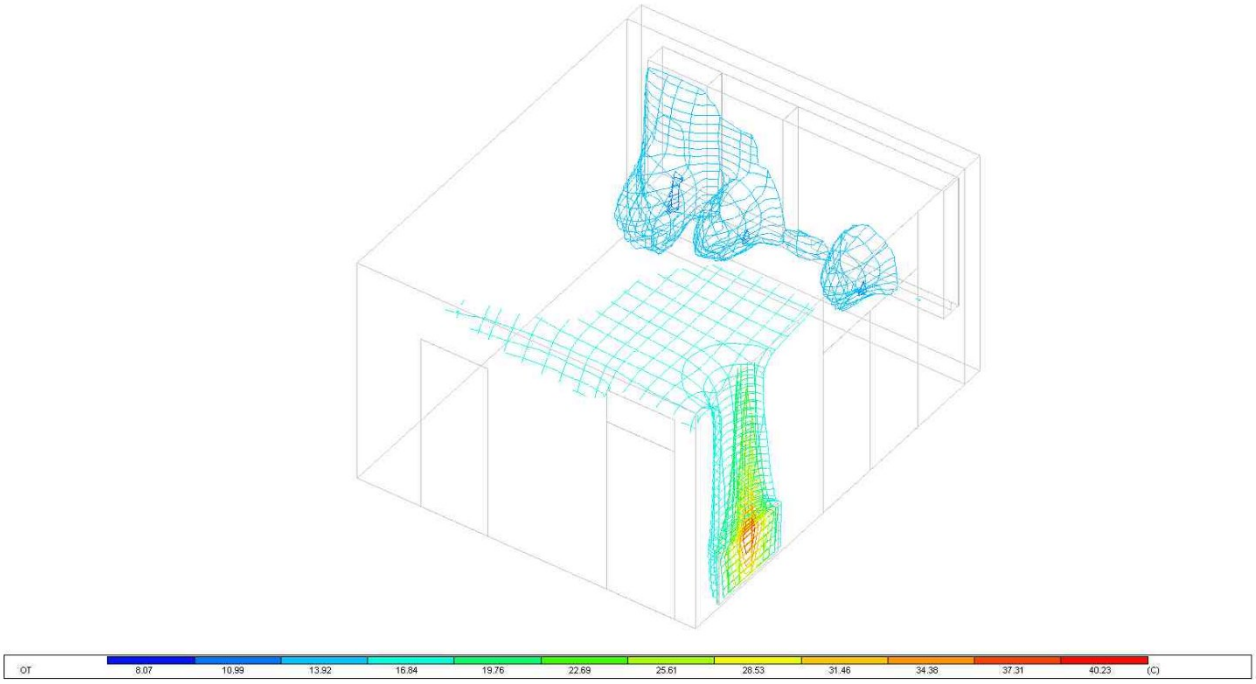


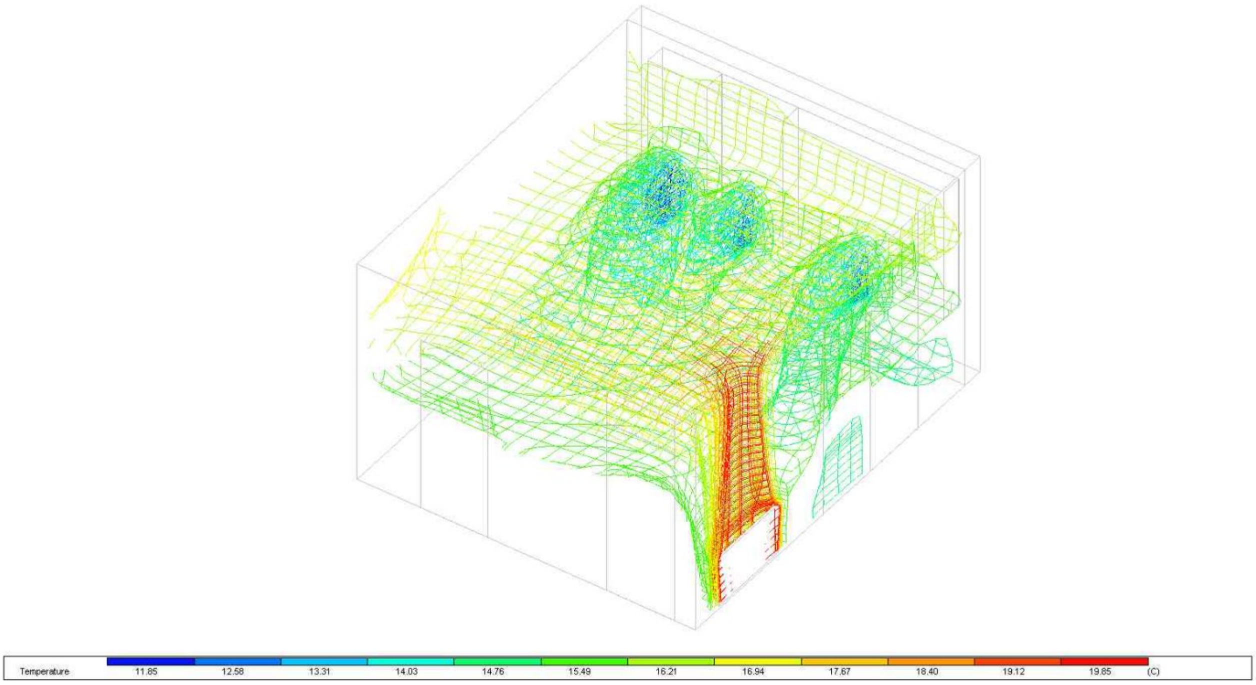

MRT
10.37
10.88
11.39
11.90
12.41
12.92
13.43
13.94
14.45
14.96
15.47
15.98
(C)

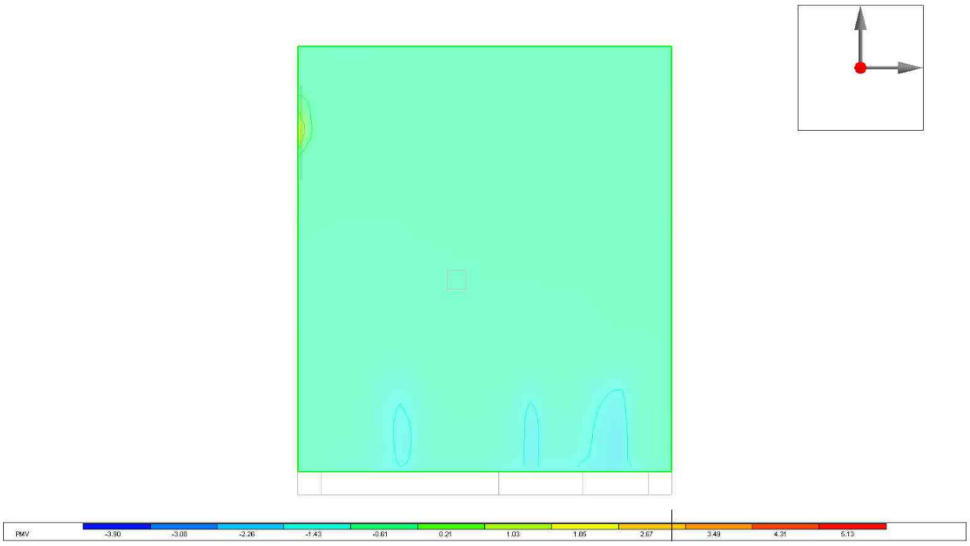

PMV
-3.90
-3.08
-2.26
-1.43
-0.61
0.21
1.03
1.85
2.67
3.49
4.31
5.13

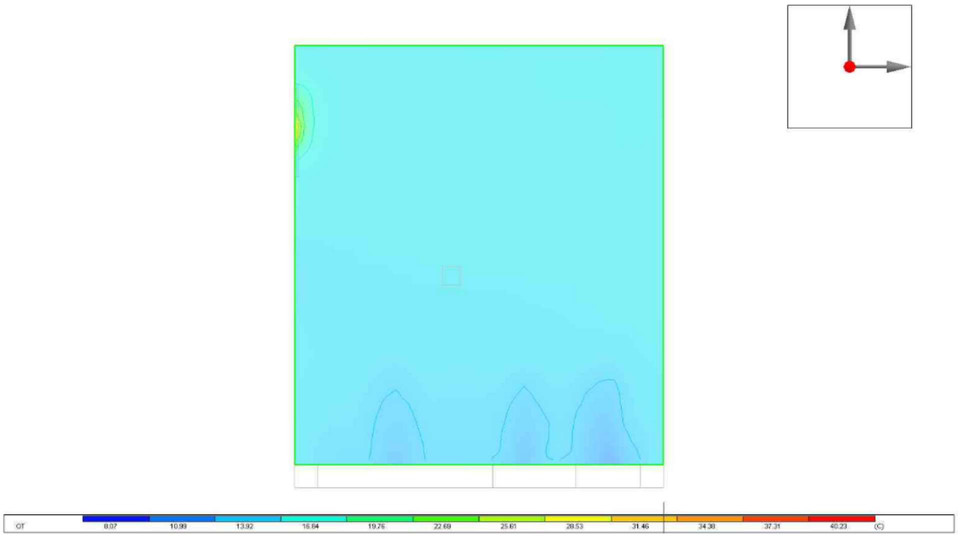

PMV
-3.90
-3.08
-2.26
-1.43
-0.61
0.21
1.03
1.85
2.67
3.49
4.31
5.13

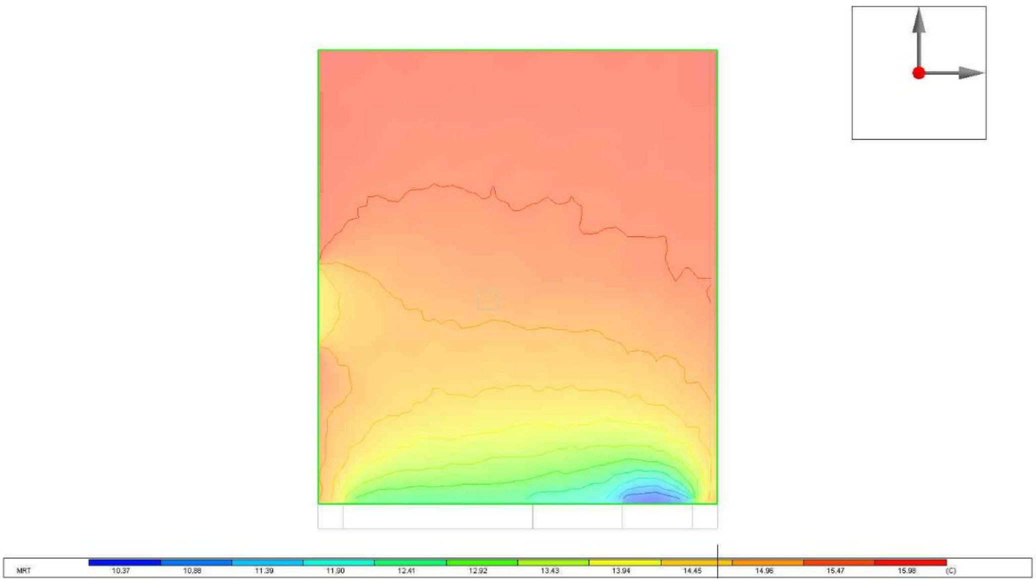

MRT
10.37
10.88
11.39
11.90
12.41
12.92
13.43
13.94
14.45
14.96
15.47
15.98
(C)


OT
8.07
10.99
13.92
16.84
19.76
22.69
25.61
28.53
31.46
34.38
37.31
40.23
(C)

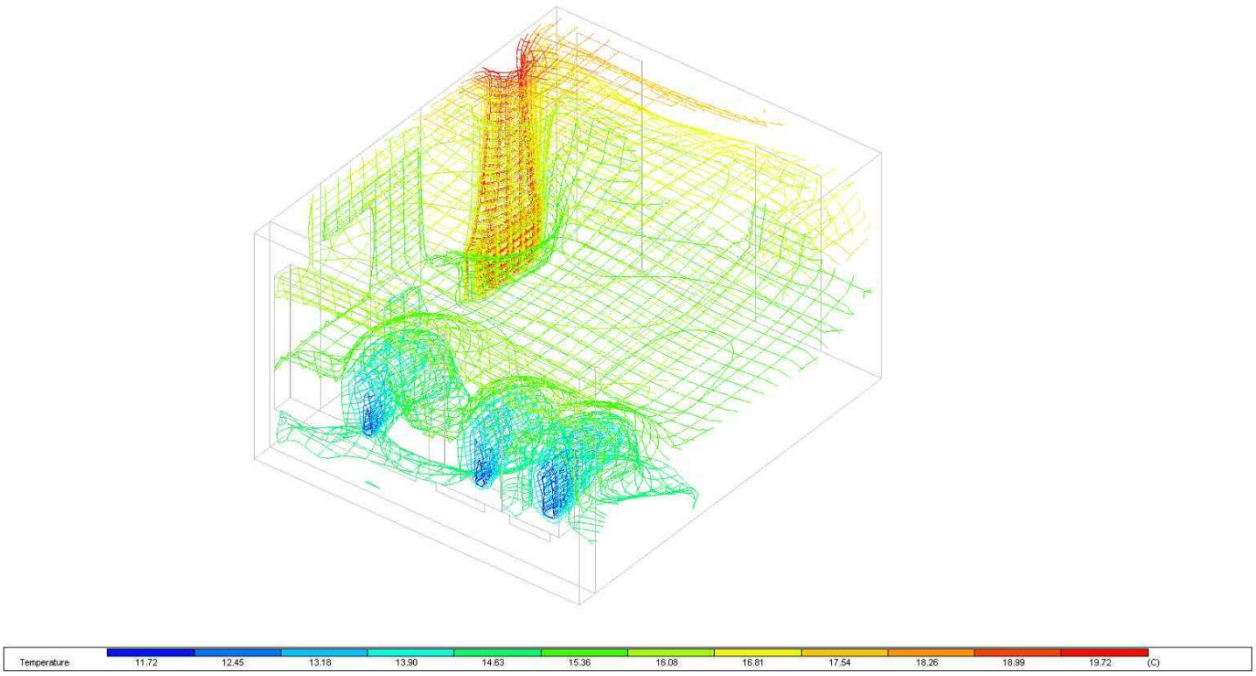

Temperature
11.85
12.58
13.31
14.03
14.76
15.49
16.21
16.94
17.67
18.40
19.12
19.85
(C)

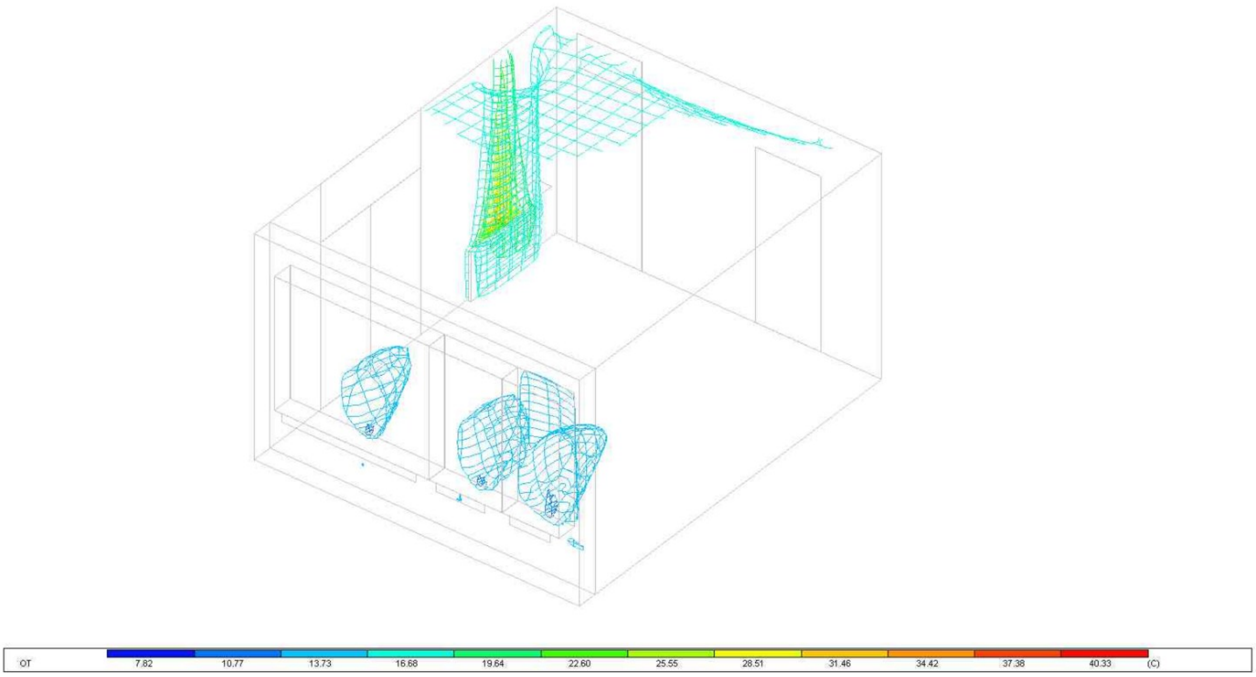

PMV
-3.90
-3.08
-2.26
-1.43
-0.61
0.21
1.03
1.85
2.67
3.49
4.31
5.13

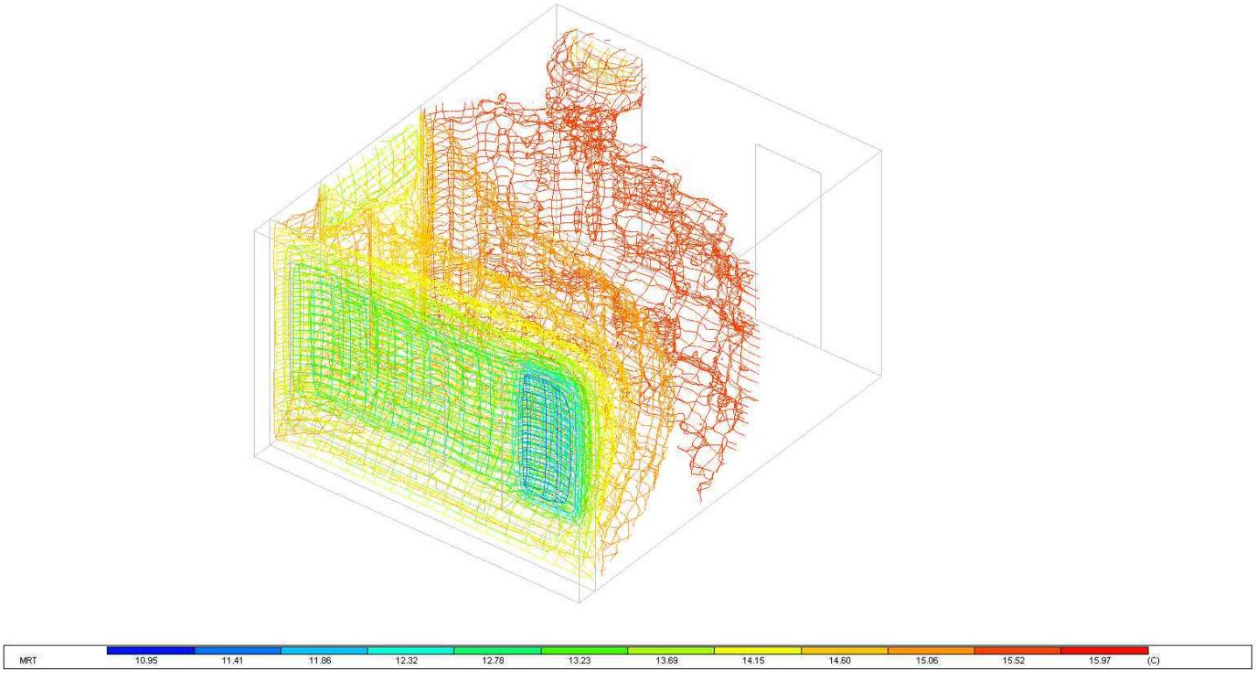

OT
8.07
10.99
13.92
16.84
19.76
22.69
25.61
28.53
31.46
34.38
37.31
40.23
(C)

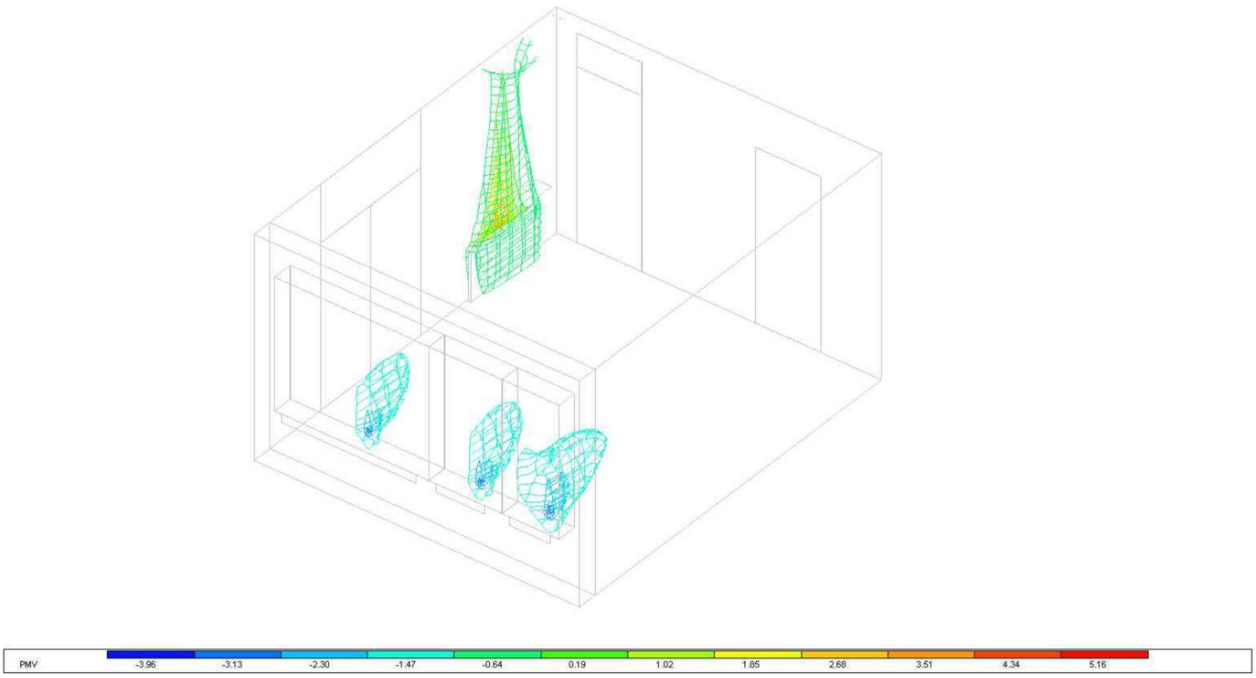

MRT
10.37
10.88
11.39
11.90
12.41
12.92
13.43
13.94
14.45
14.96
15.47
15.98
(C)

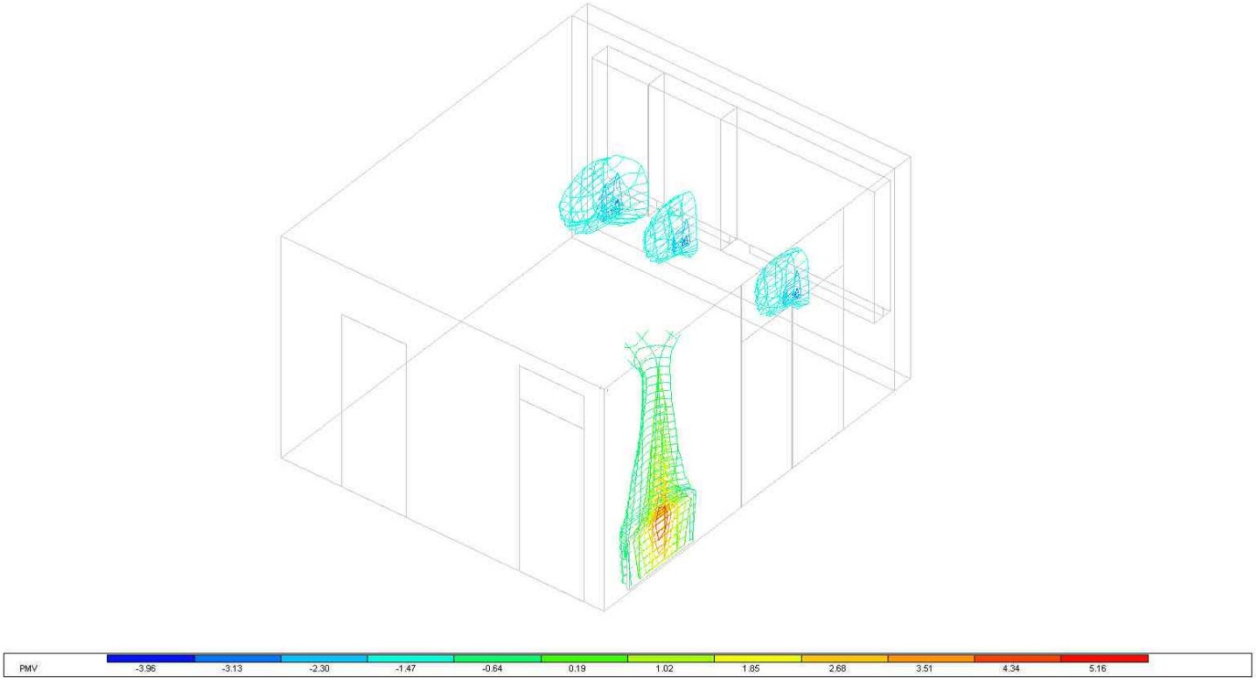
Appendix 19.4 – CFD calculations – Window insulation film situation

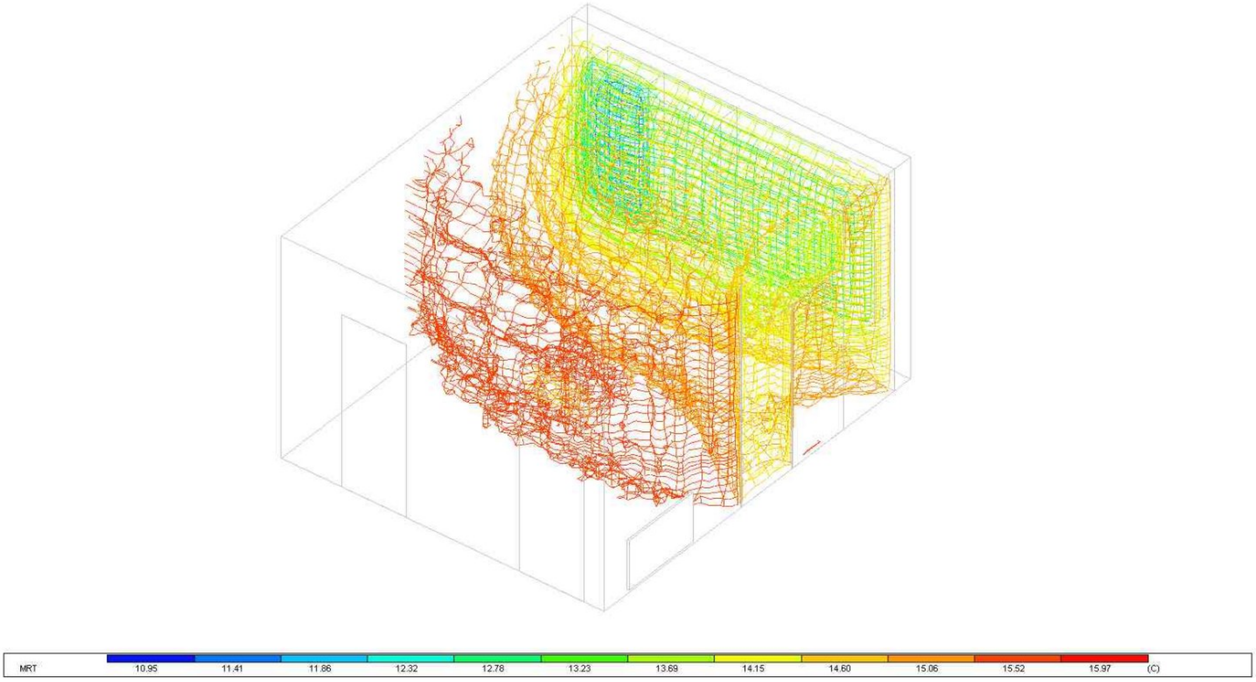


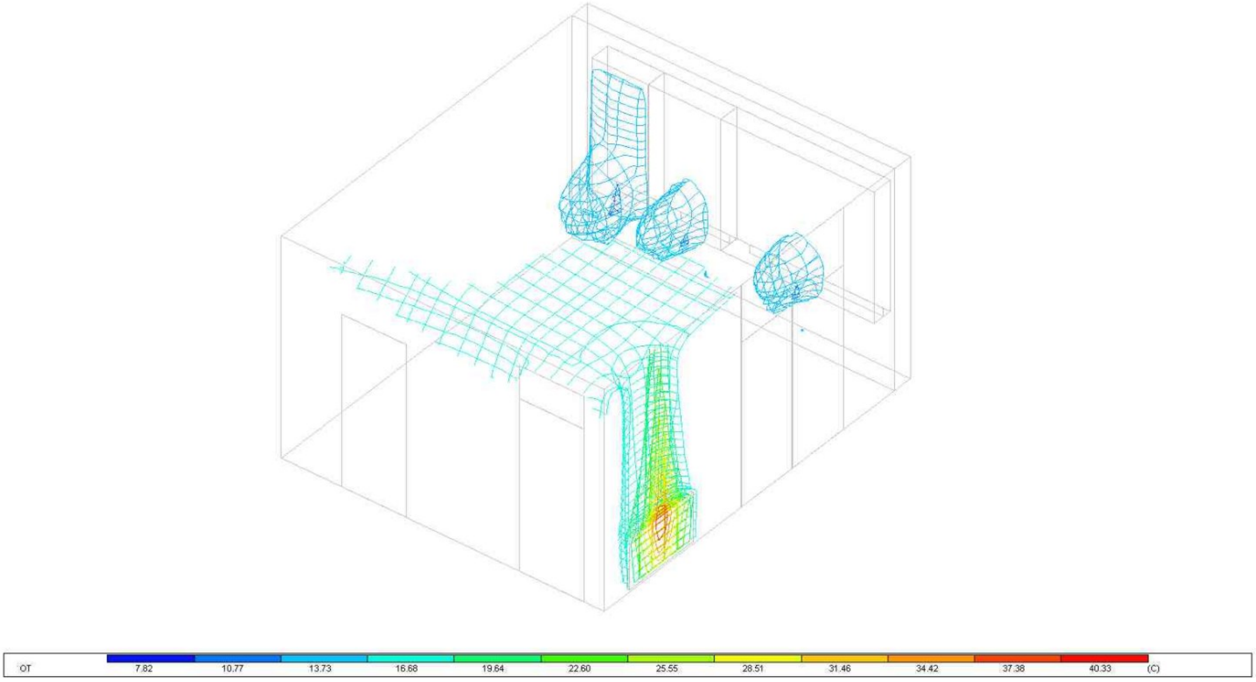


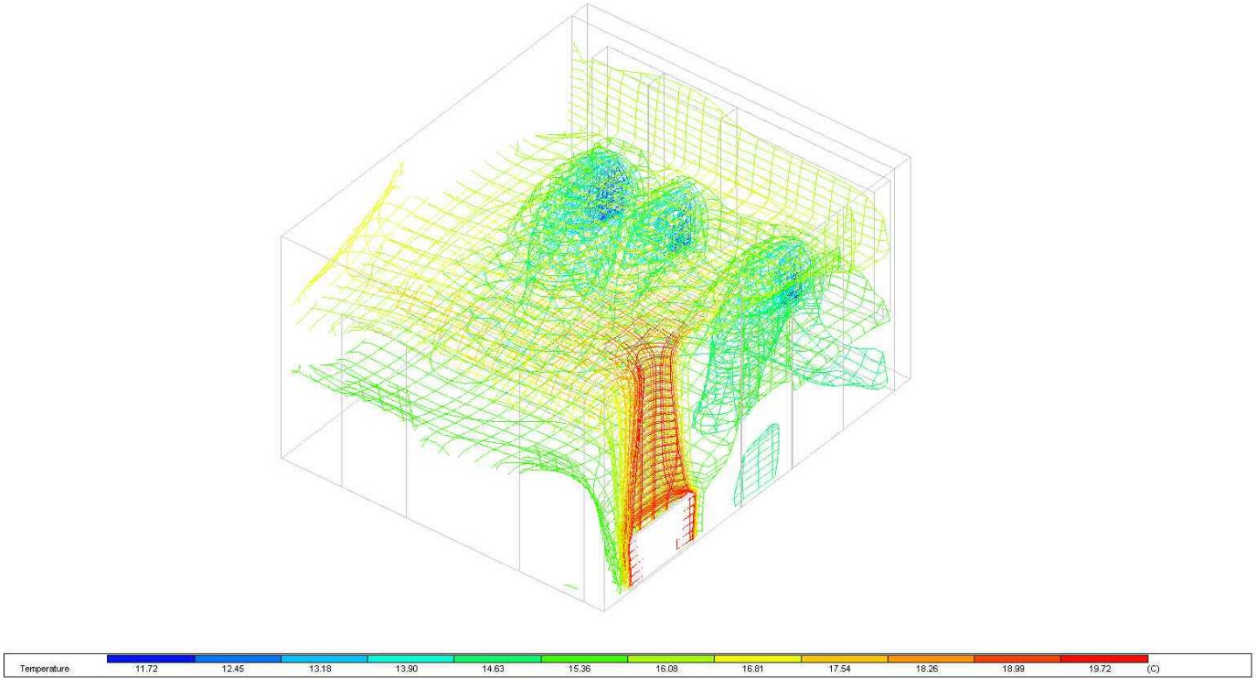

MRT
10.95
11.41
11.86
12.32
12.78
13.23
13.69
14.15
14.60
15.06
15.52
15.97
(C)

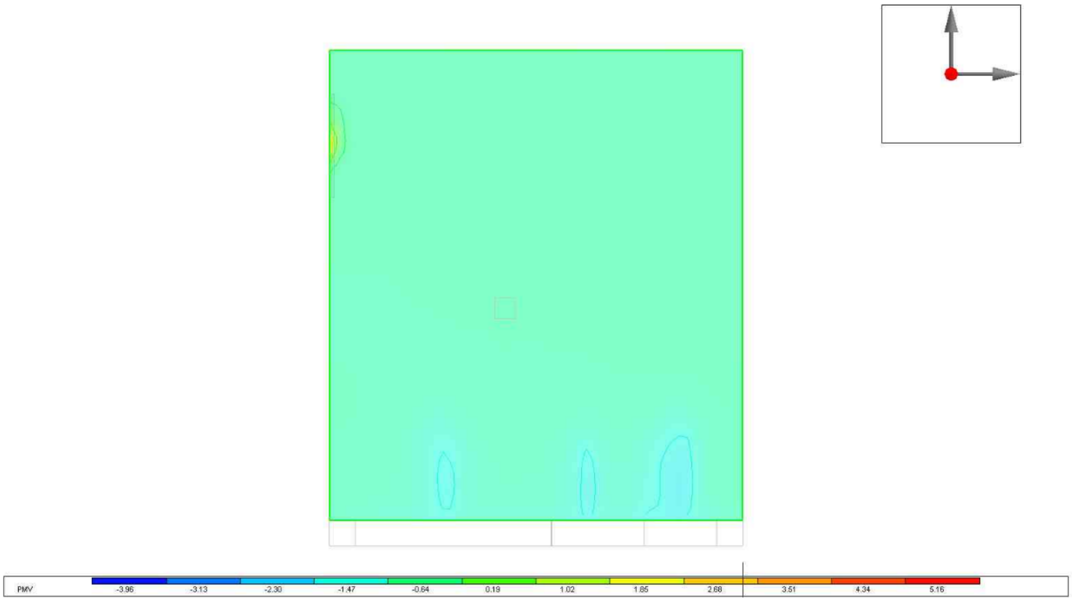

PMV
-3.96
-3.13
-2.30
-1.47
-0.64
0.19
1.02
1.85
2.68
3.51
4.34
5.16

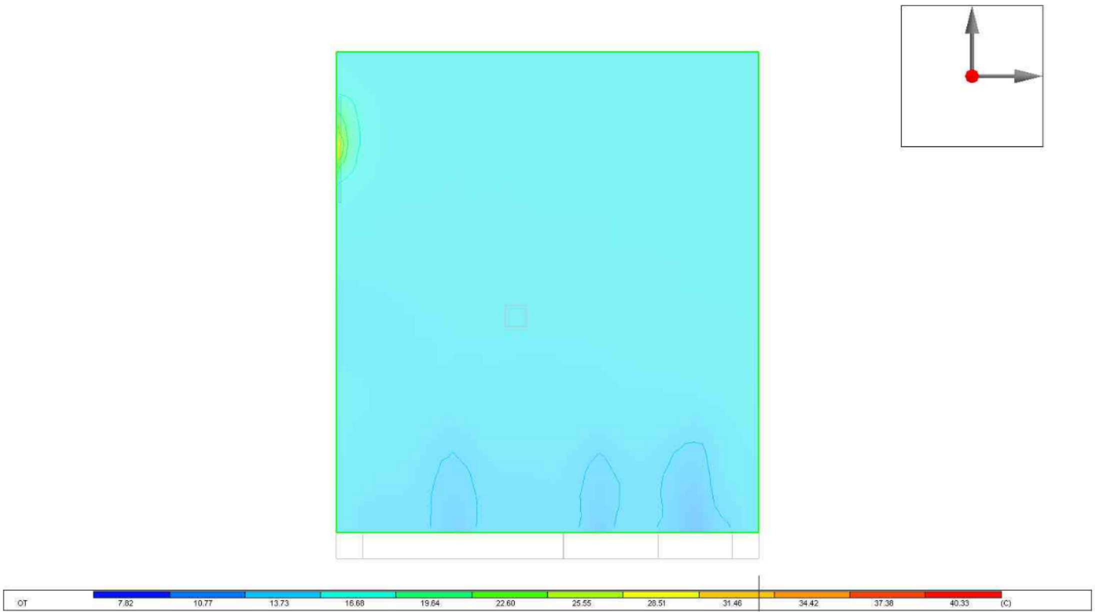

PMV
-3.96
-3.13
-2.30
-1.47
-0.64
0.19
1.02
1.85
2.68
3.51
4.34
5.16

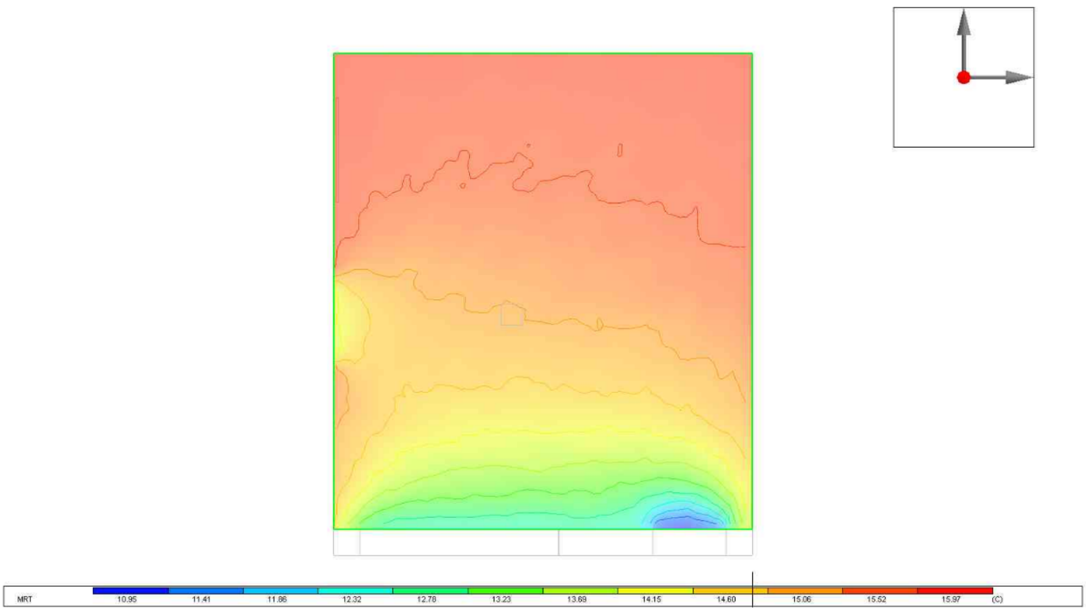

MRT
10.95
11.41
11.86
12.32
12.78
13.23
13.69
14.15
14.60
15.06
15.52
15.97
(C)


OT
7.82
10.77
13.73
16.68
19.64
22.60
25.55
28.51
31.46
34.42
37.38
40.33
(C)

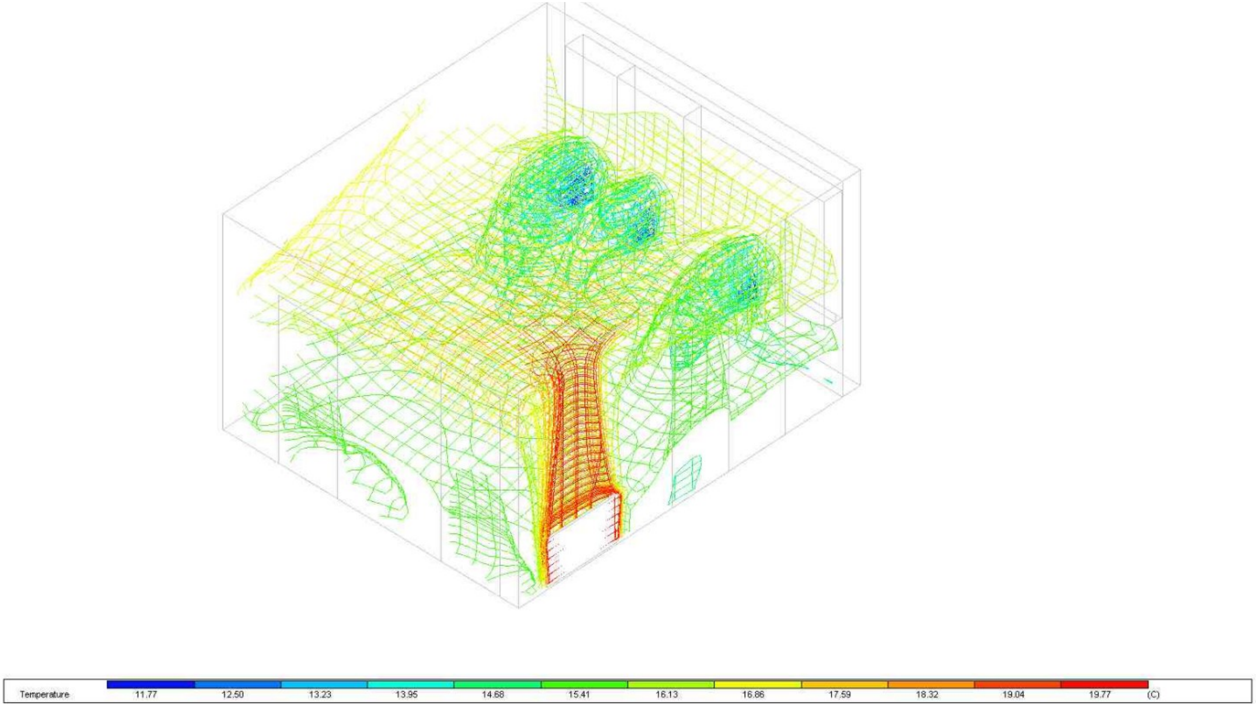

Temperature
11.72
12.45
13.18
13.90
14.63
15.36
16.08
16.81
17.54
18.26
18.99
19.72
(C)

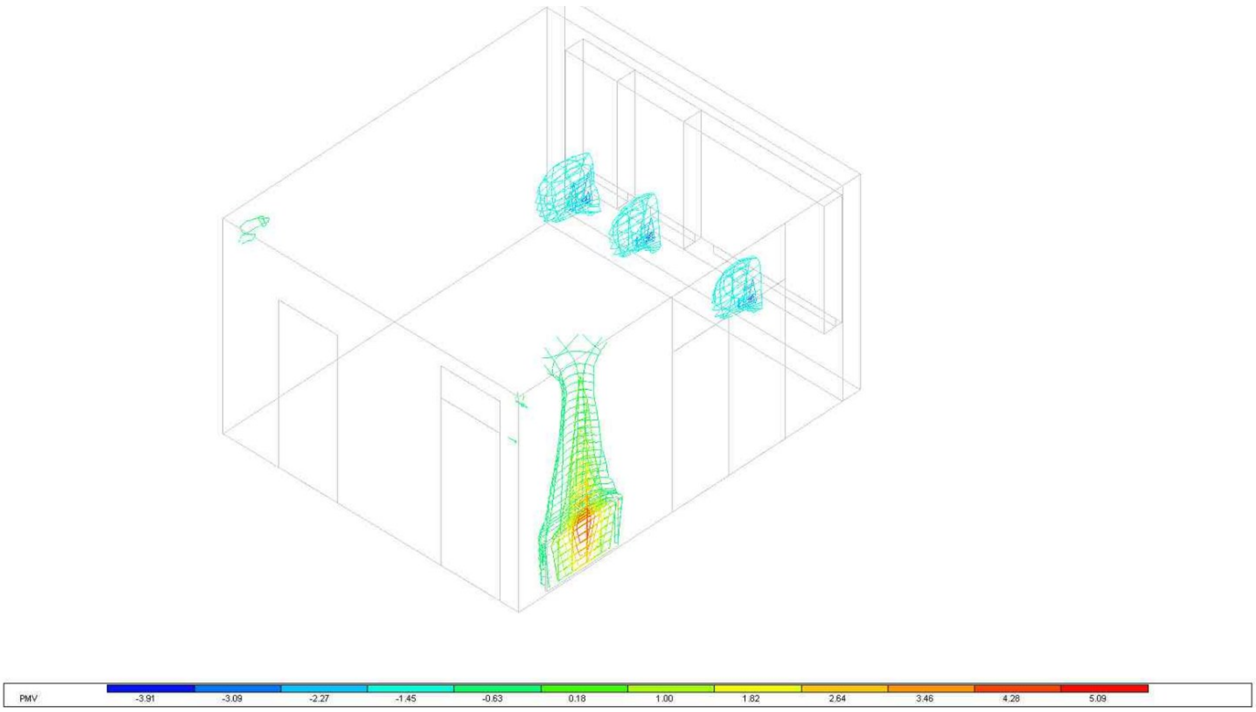

PMV
-3.96
-3.13
-2.30
-1.47
-0.64
0.19
1.02
1.85
2.68
3.51
4.34
5.16

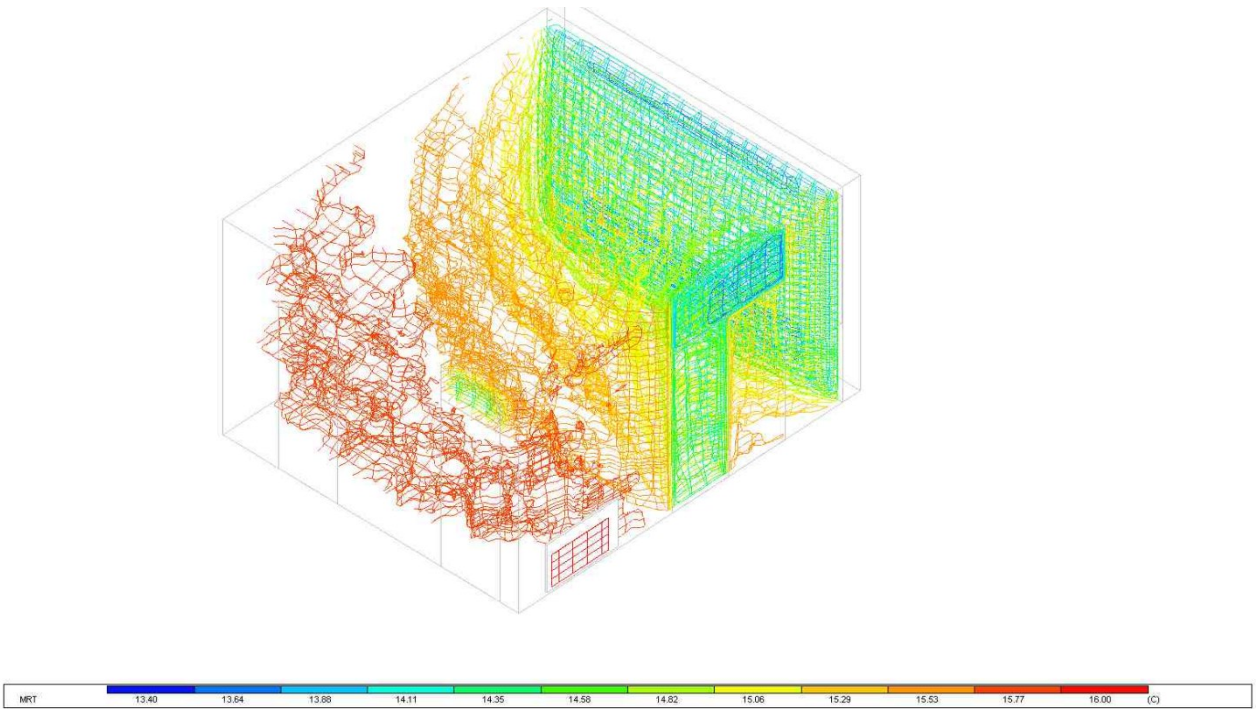

OT
7.82
10.77
13.73
16.68
19.64
22.60
25.55
28.51
31.46
34.42
37.38
40.33
(C)

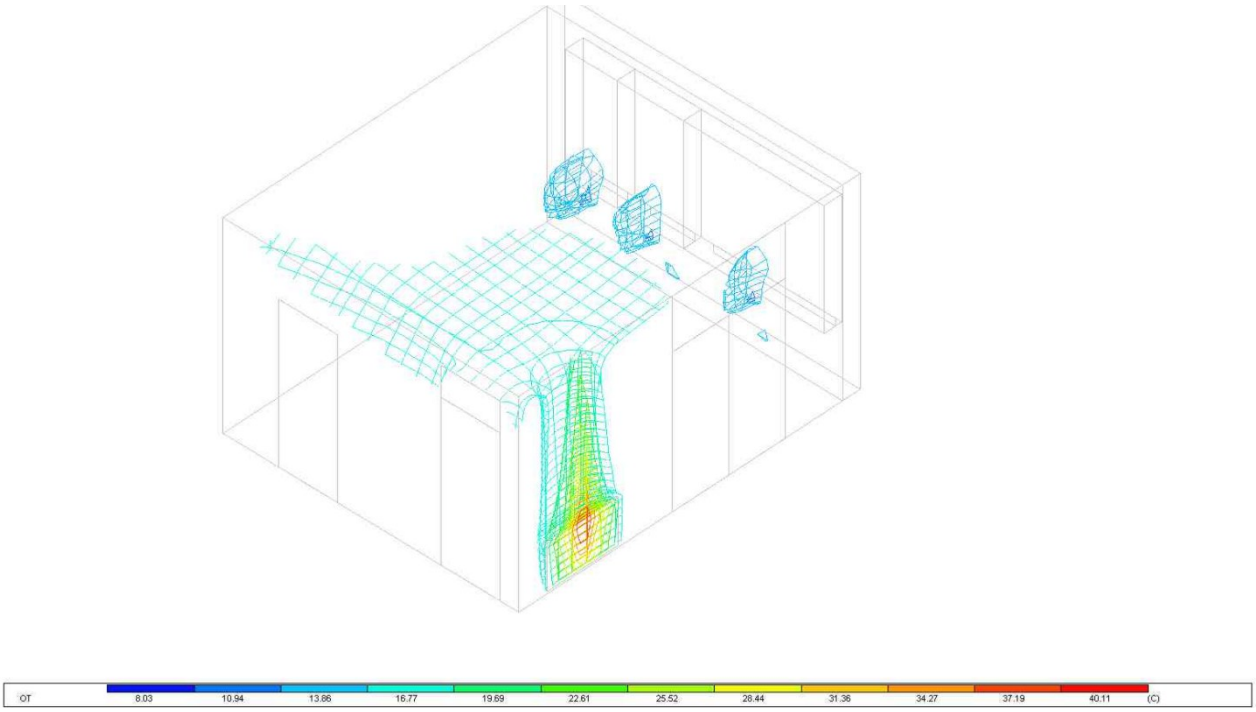

MRT
10.95
11.41
11.86
12.32
12.78
13.23
13.69
14.15
14.60
15.06
15.52
15.97
(C)

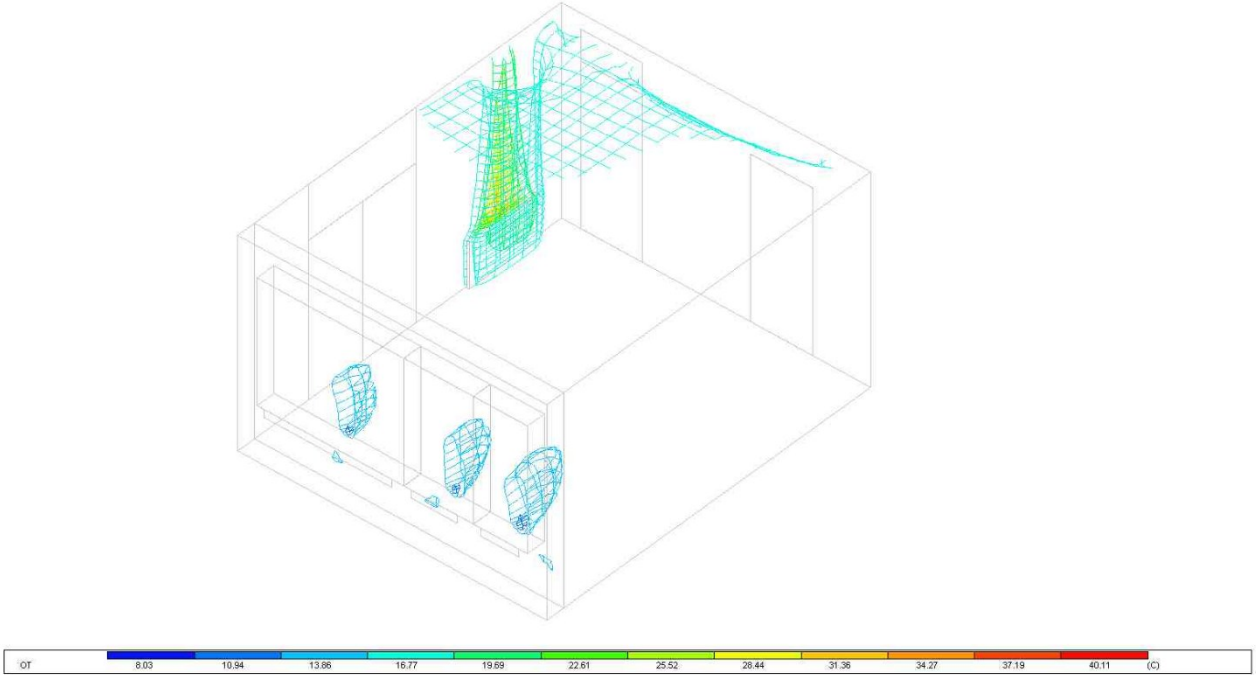
Appendix 19.5 – CFD calculations – Glazing replacement situation

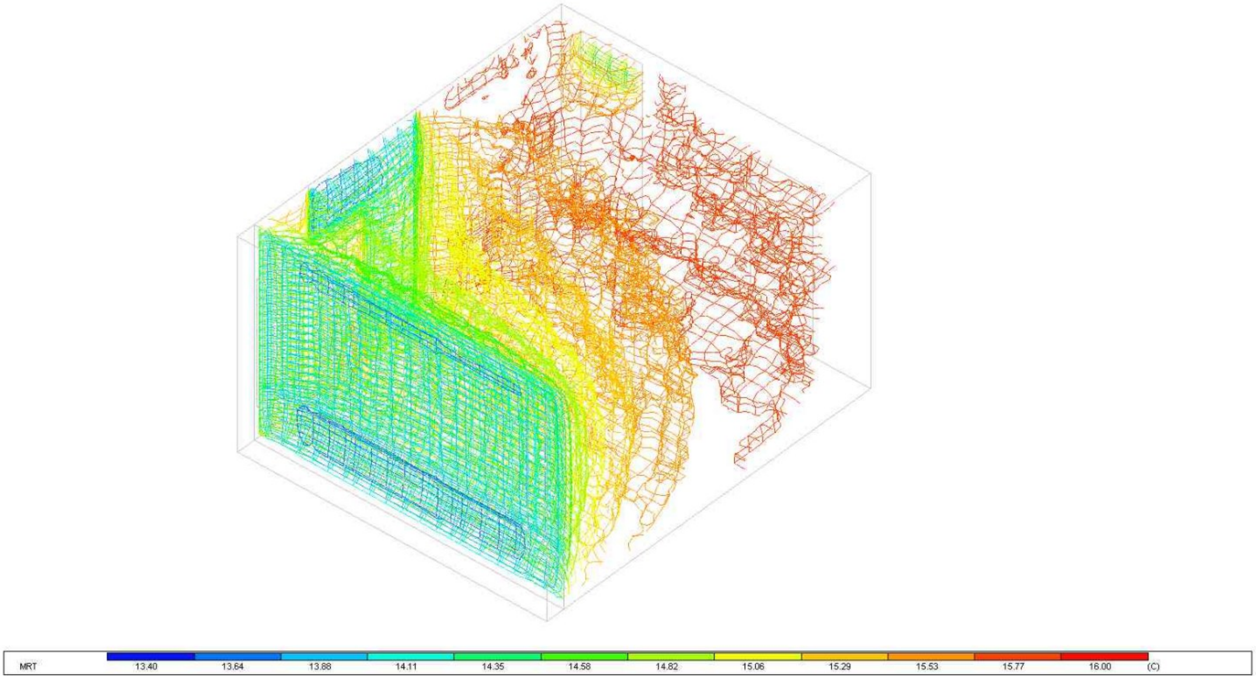


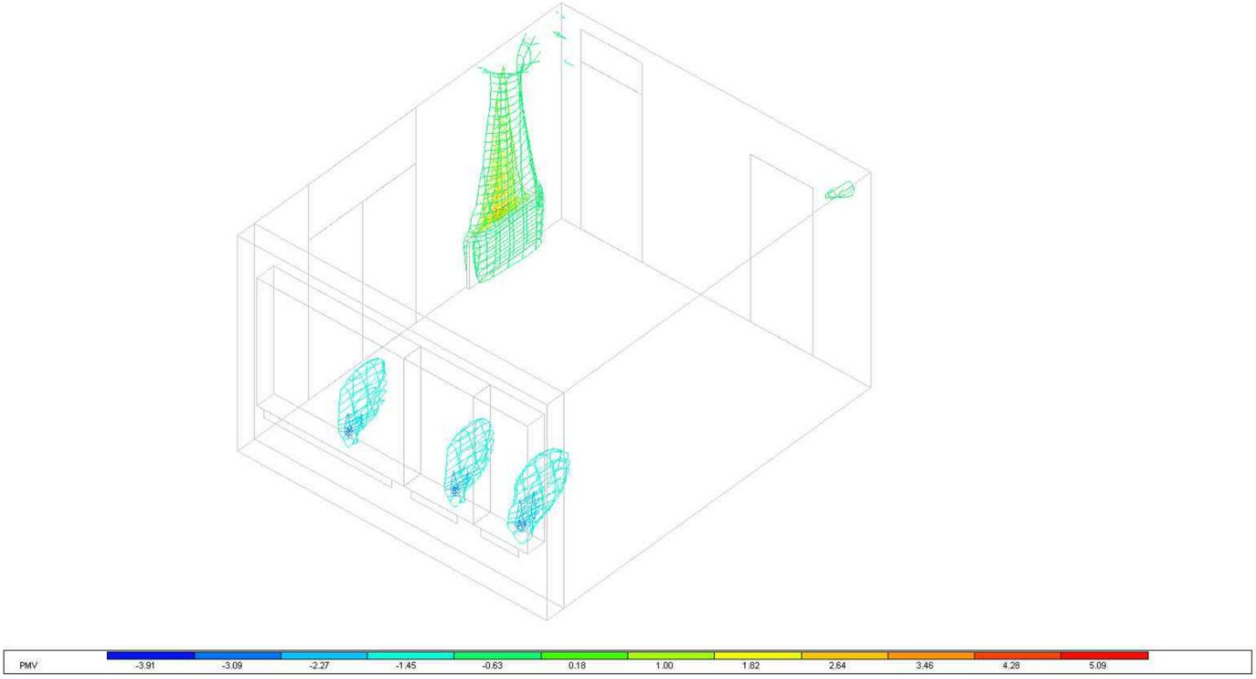


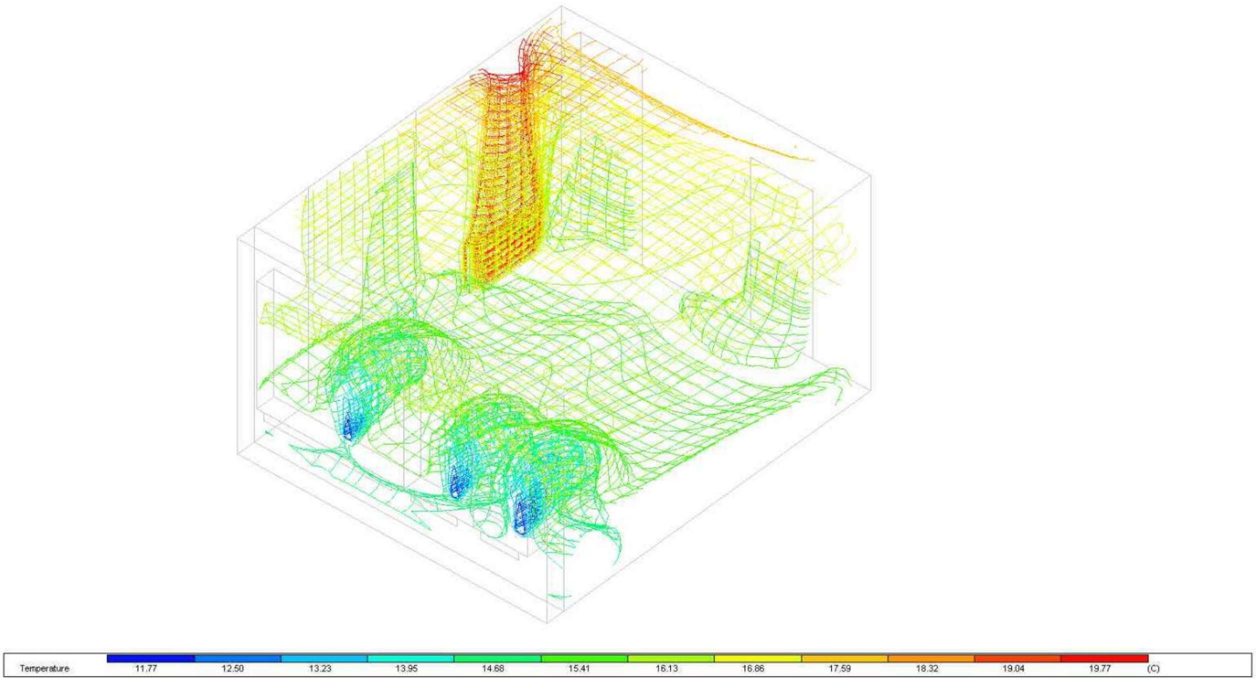

MRT
13.40
13.64
13.88
14.11
14.35
14.58
14.82
15.06
15.29
15.53
15.77
16.00
(C)

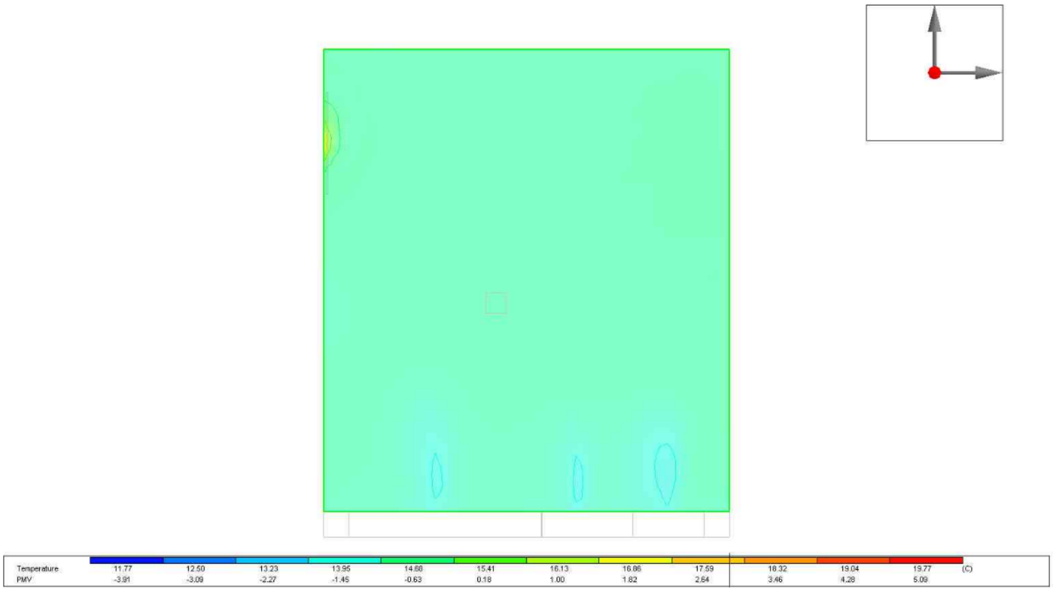

OT
8.03
10.94
13.86
16.77
19.69
22.61
25.52
28.44
31.36
34.27
37.19
40.11
(C)

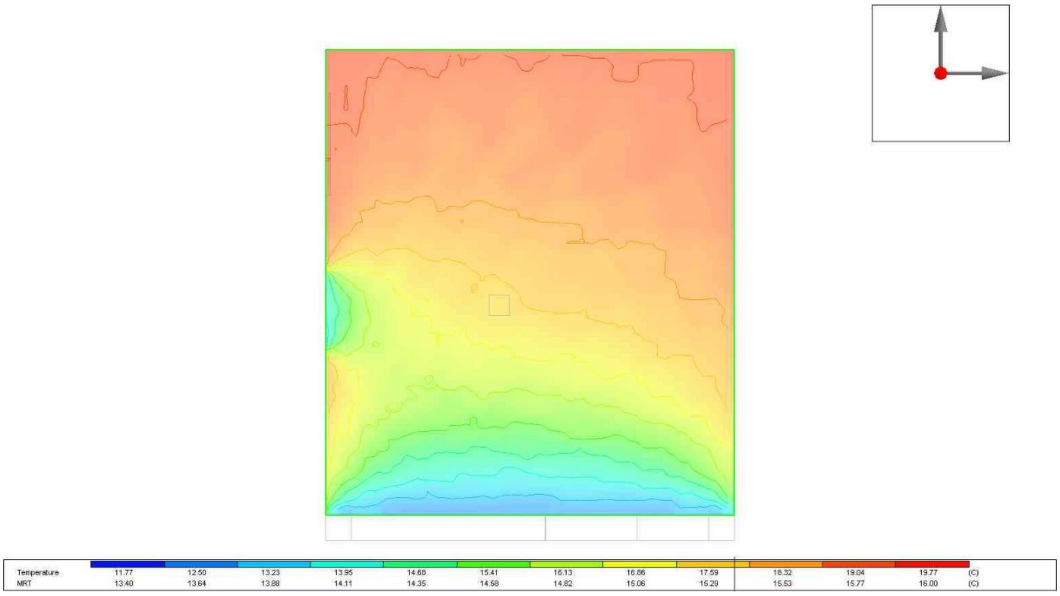

OT
8.03
10.94
13.86
16.77
19.69
22.61
25.52
28.44
31.36
34.27
37.19
40.11
(C)

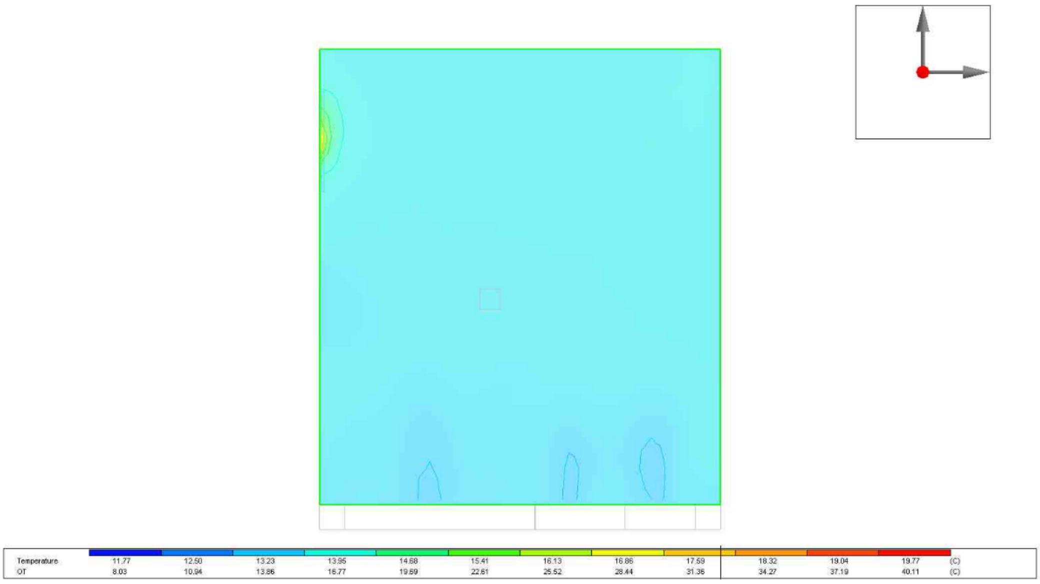

MRT
13.40
13.64
13.88
14.11
14.35
14.58
14.82
15.06
15.29
15.53
15.77
16.00
(C)


PMV
-3.91 -3.09 -2.27 -1.45 -0.63 0.18 1.00 1.82 2.64 3.46 4.28 5.09

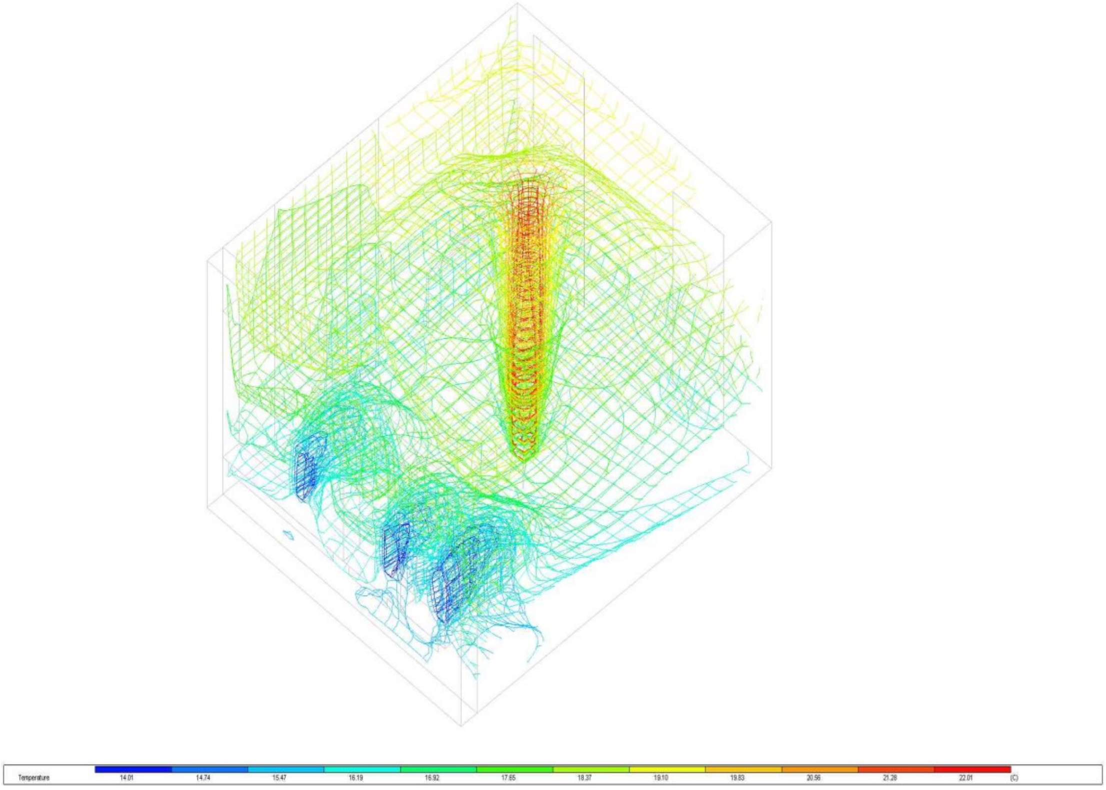

Temperature
11.77 12.50 13.23 13.95 14.68 15.41 16.13 16.86 17.59 18.32 19.04 19.77 (C)

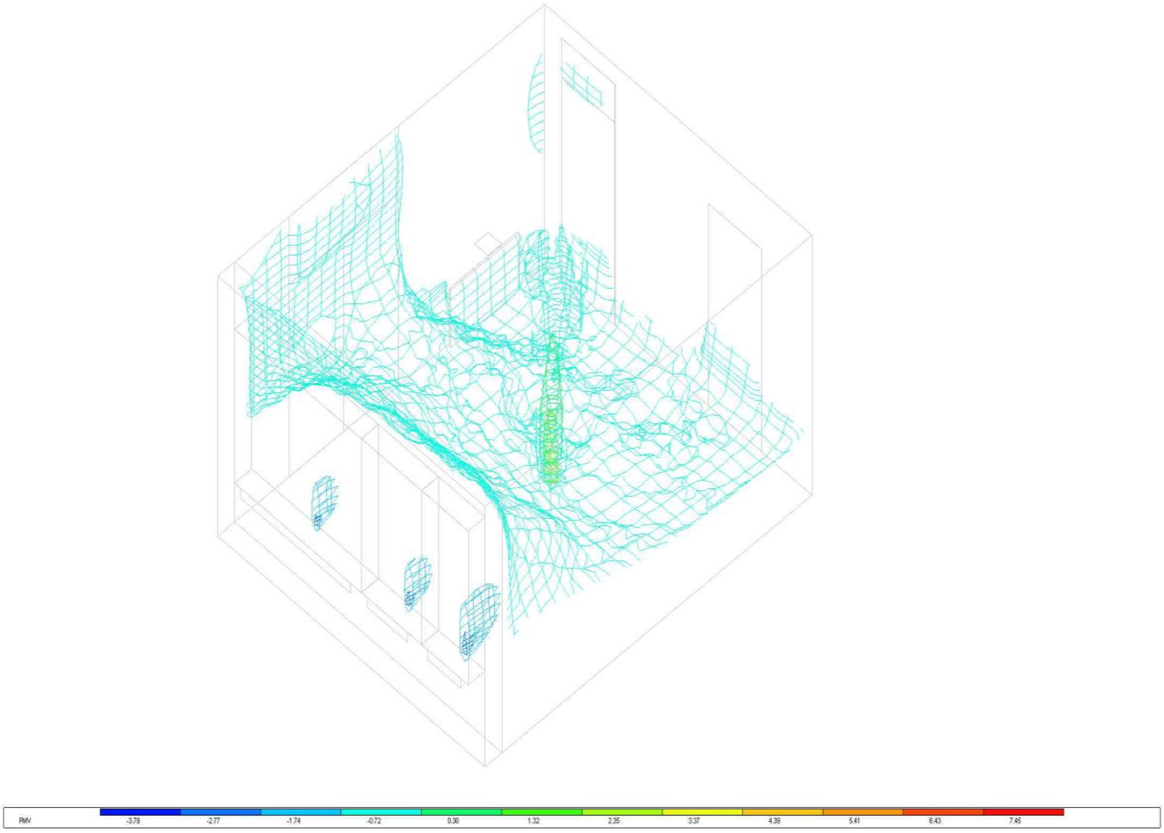

Temperature
11.77 12.50 13.23 13.95 14.68 15.41 16.13 16.86 17.59 18.32 19.04 19.77 (C)
PMV
-3.91 -3.09 -2.27 -1.45 -0.63 0.18 1.00 1.82 2.64 3.46 4.28 5.09

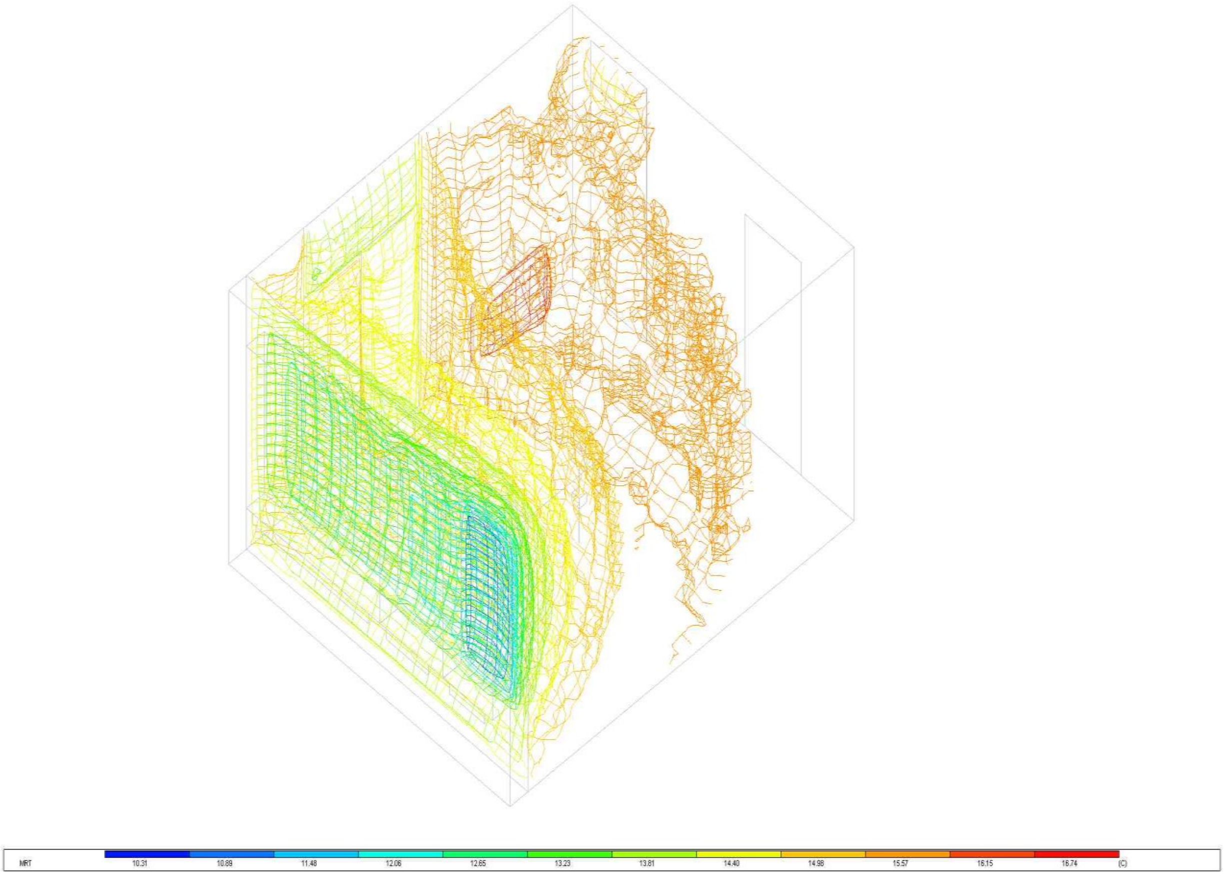

Temperature
11.77 12.50 13.23 13.95 14.68 15.41 16.13 16.86 17.59 18.32 19.04 19.77 (C)
MRT
13.40 13.64 13.88 14.11 14.35 14.58 14.82 15.06 15.29 15.53 15.77 16.00 (C)

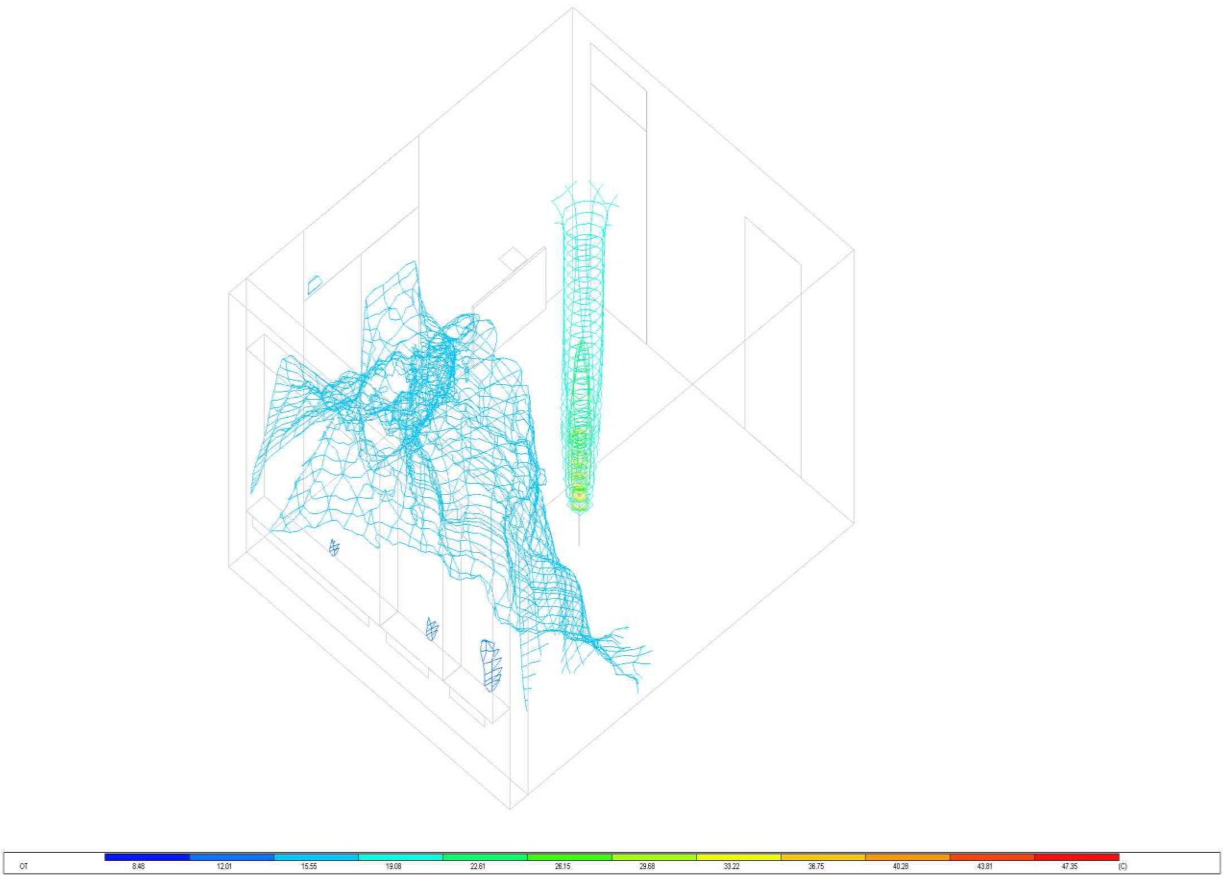

Temperature
11.77 12.50 13.23 13.95 14.68 15.41 16.13 16.86 17.59 18.32 19.04 19.77 (C)
OT
8.03 10.94 13.86 16.77 19.69 22.61 25.52 28.44 31.36 34.27 37.19 40.11 (C)

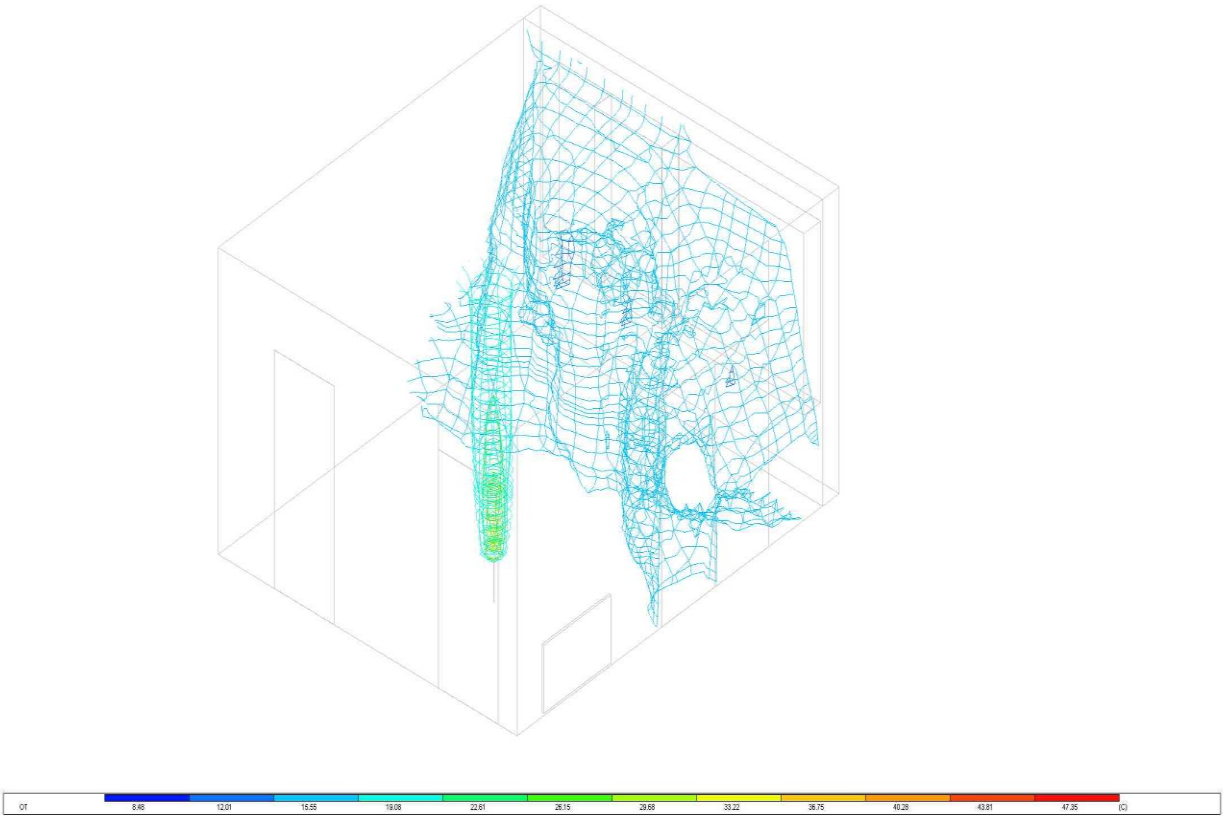
Appendix 19.6 – CFD calculations – Warm air circulator situation 1000W

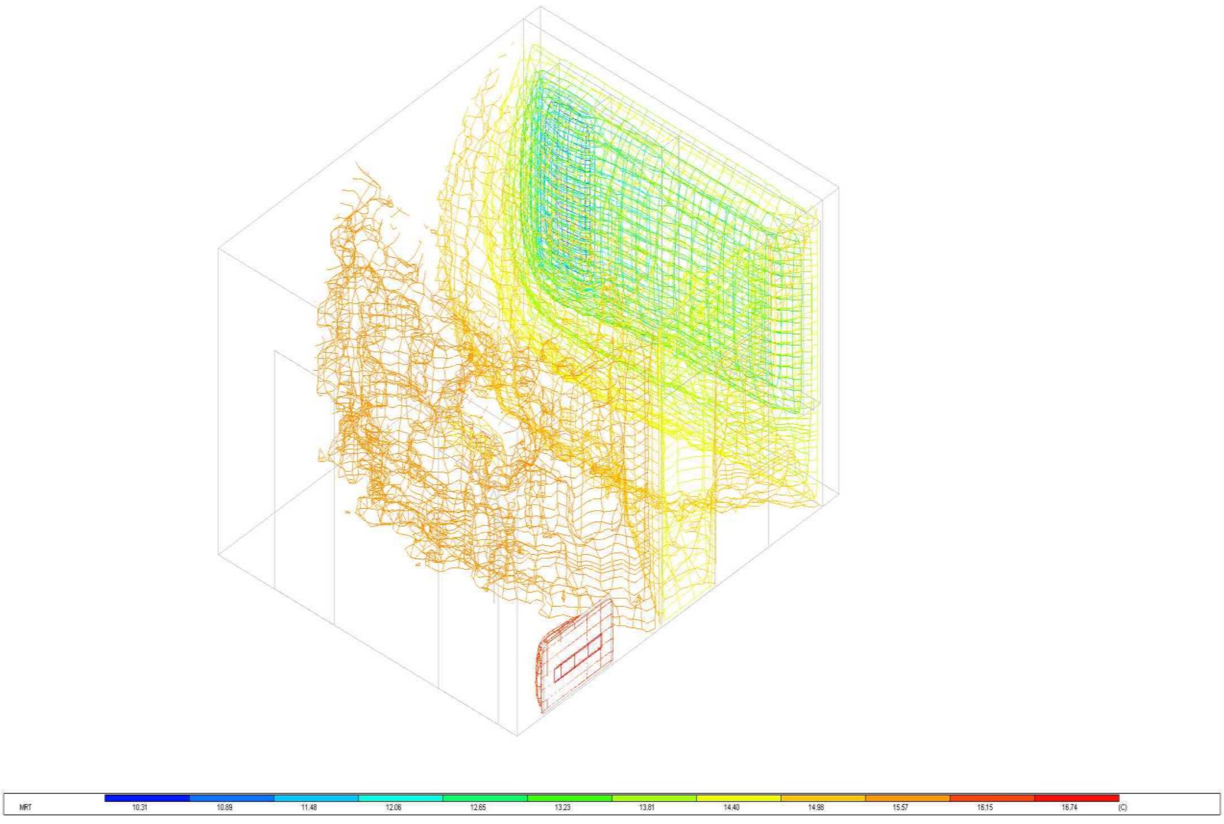


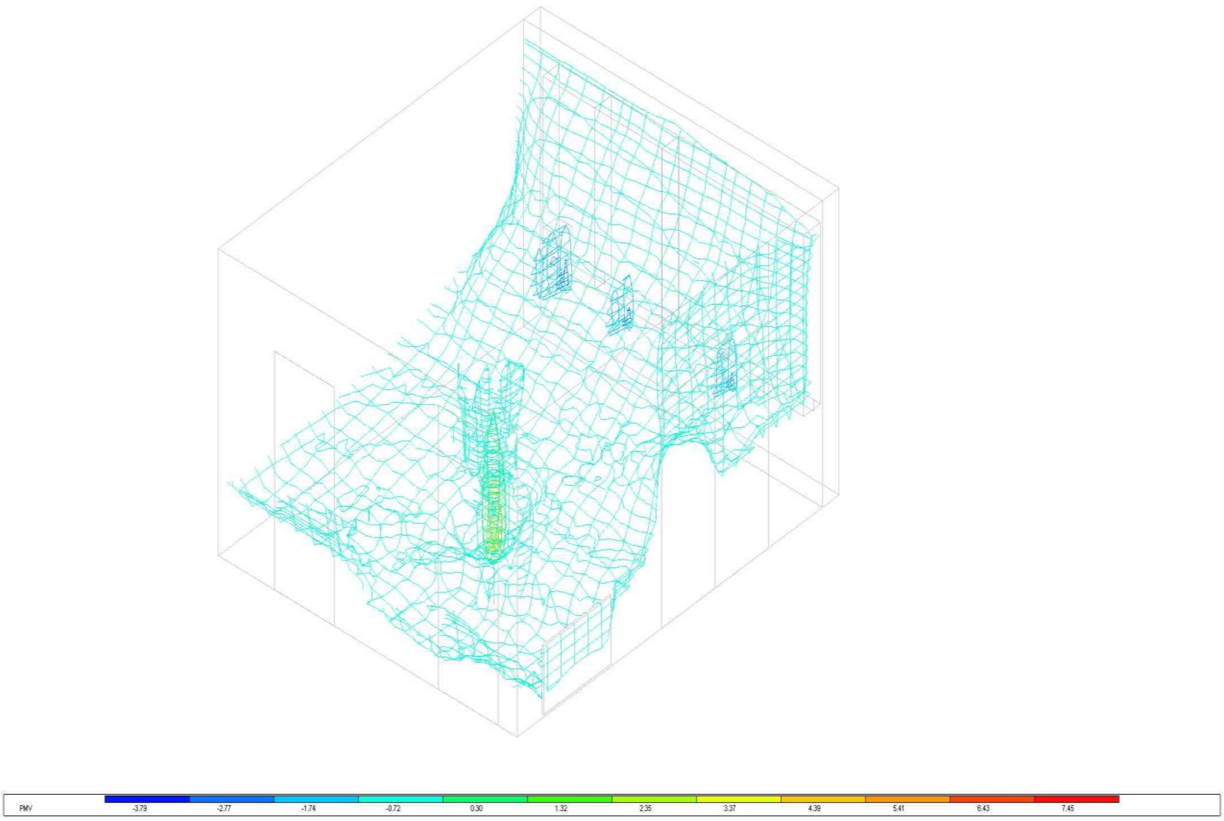


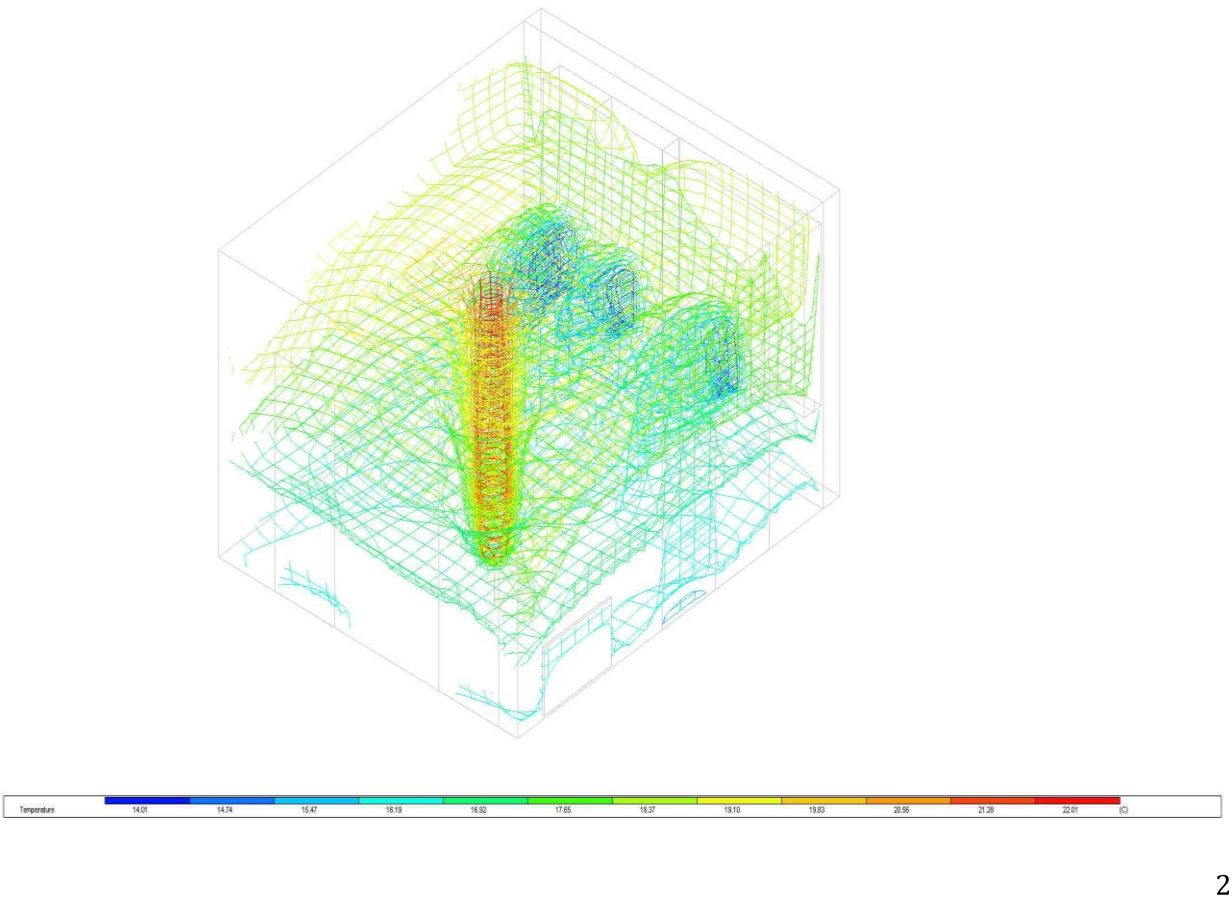

MRT
10.31
10.89
11.48
12.06
12.65
13.23
13.81
14.40
14.98
15.57
16.15
16.74
(C)

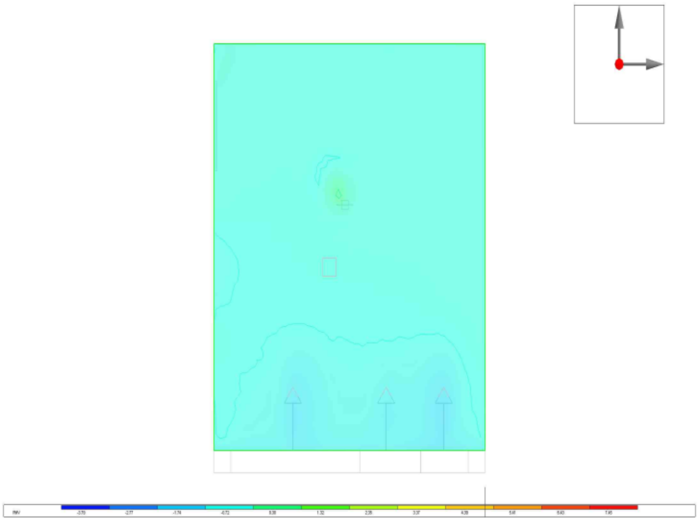

OT
8.48
12.01
15.55
19.08
22.61
26.15
29.68
33.22
36.75
40.28
43.81
47.35
(C)

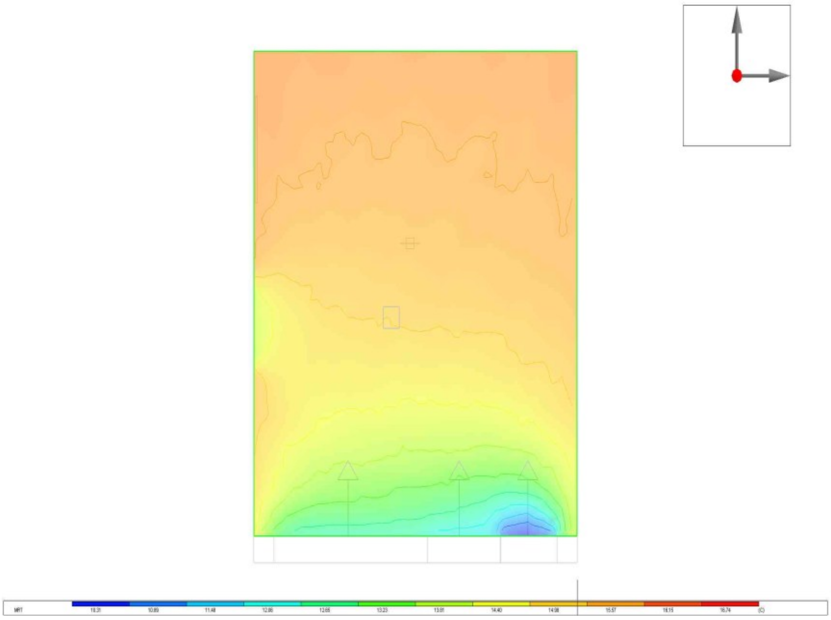

OT
8.48
12.01
15.55
19.08
22.61
26.15
29.68
33.22
36.75
40.28
43.81
47.35
(C)

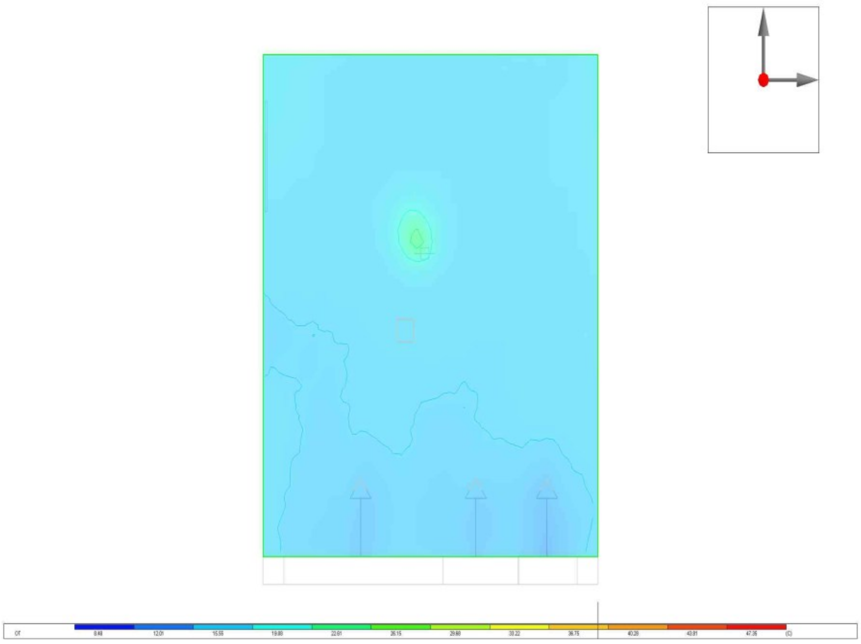

MRT
10.31
10.89
11.48
12.06
12.65
13.23
13.81
14.40
14.98
15.57
16.15
16.74
(C)


PMV
-3.79
-2.77
-1.74
-0.72
0.30
1.32
2.35
3.37
4.39
5.41
6.43
7.45

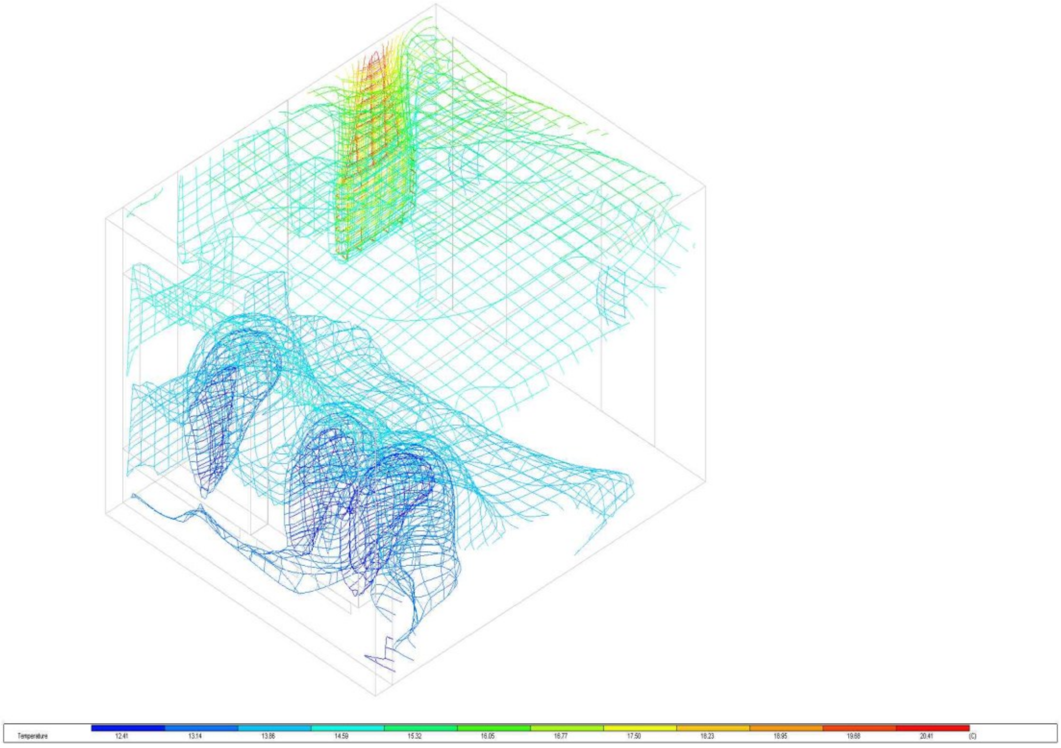

Temperature
14.01
14.74
15.47
16.19
16.92
17.65
18.37
19.10
19.83
20.56
21.28
22.01
(C)



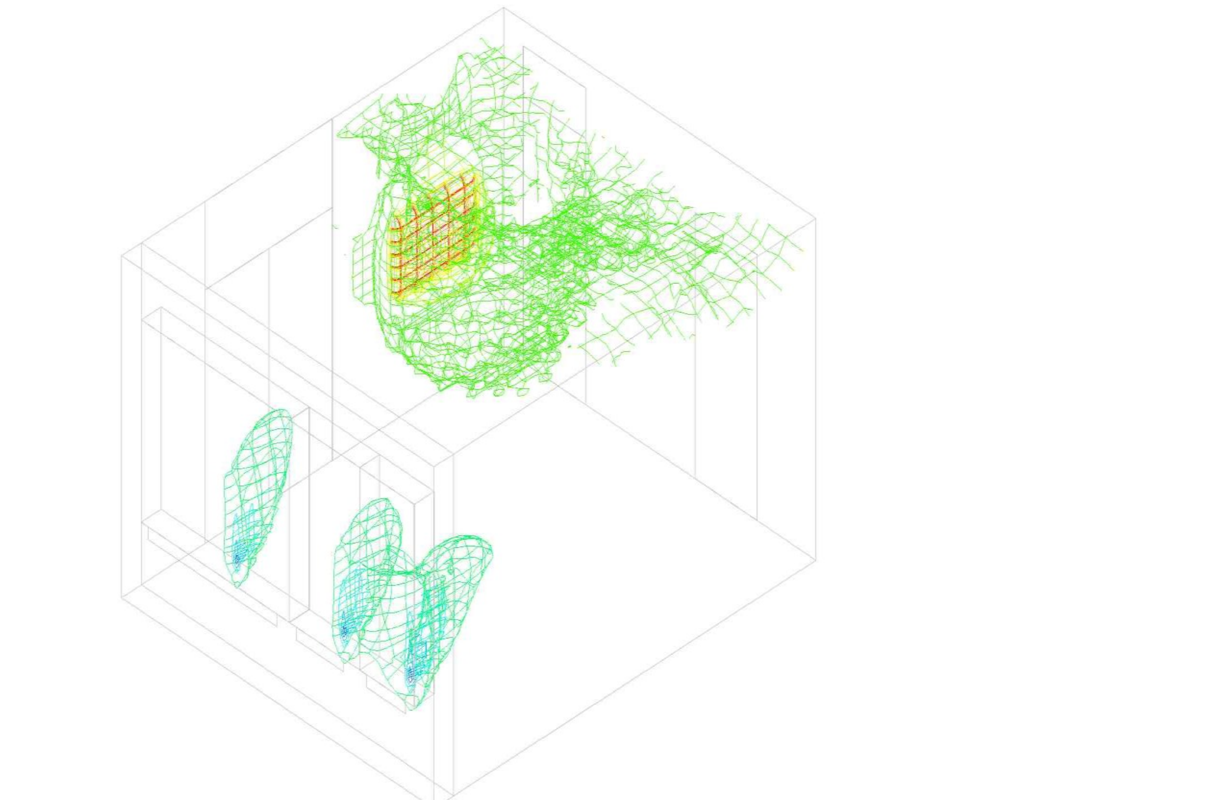


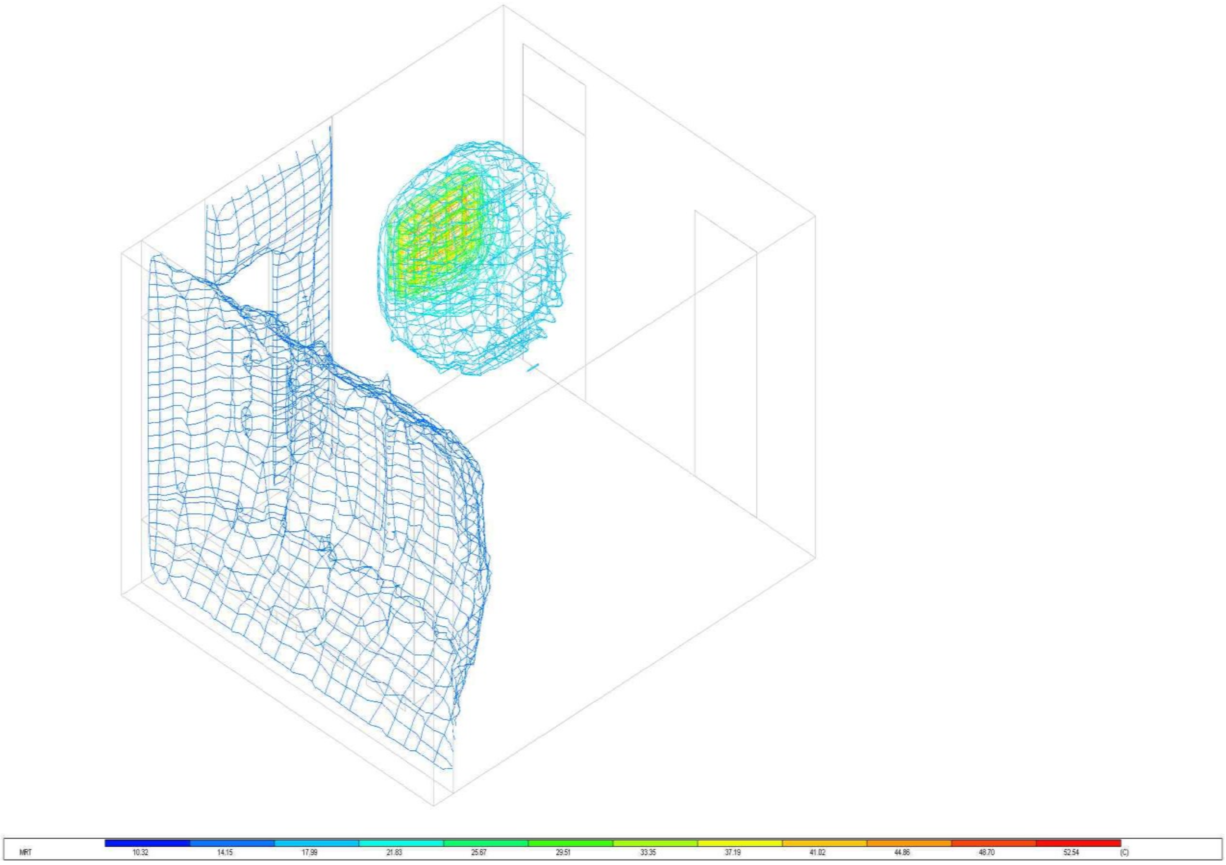


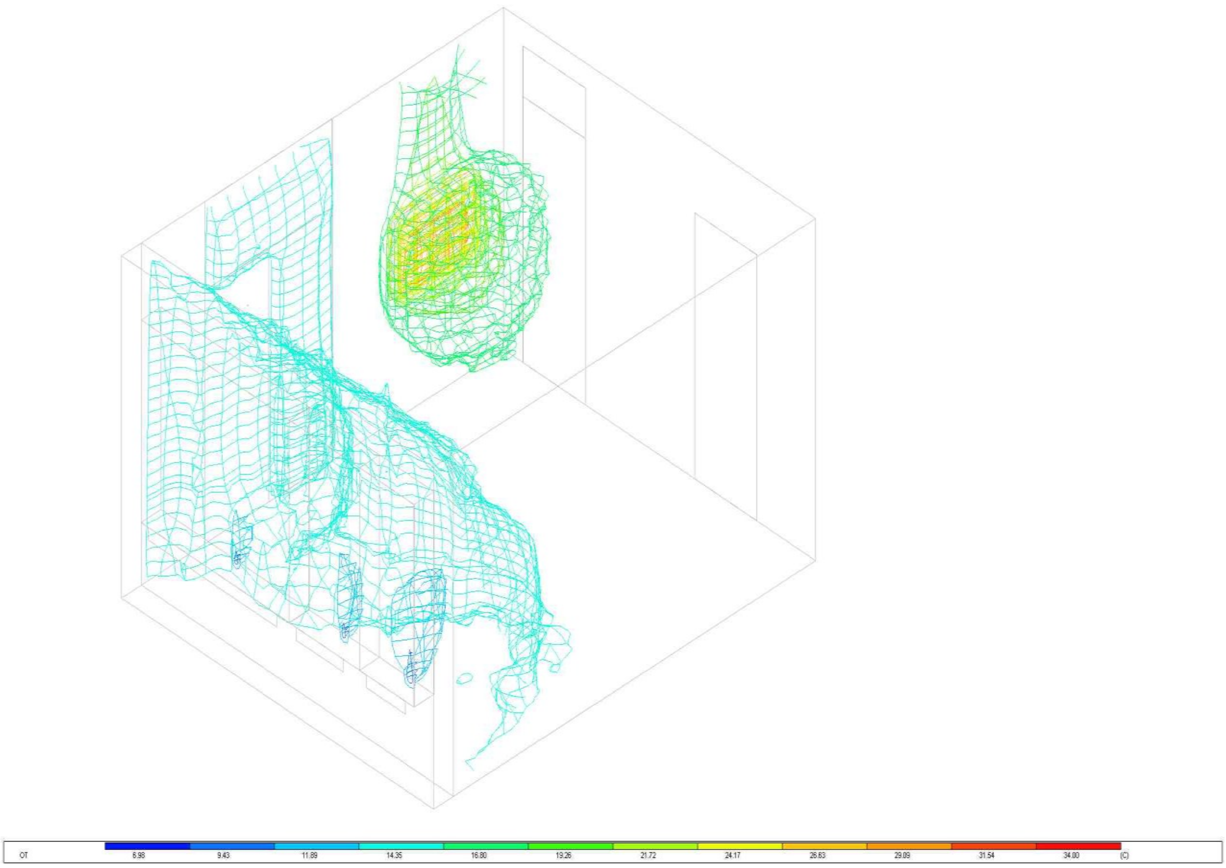
Appendix 19.7 – CFD calculations – Infrared heating panels situation

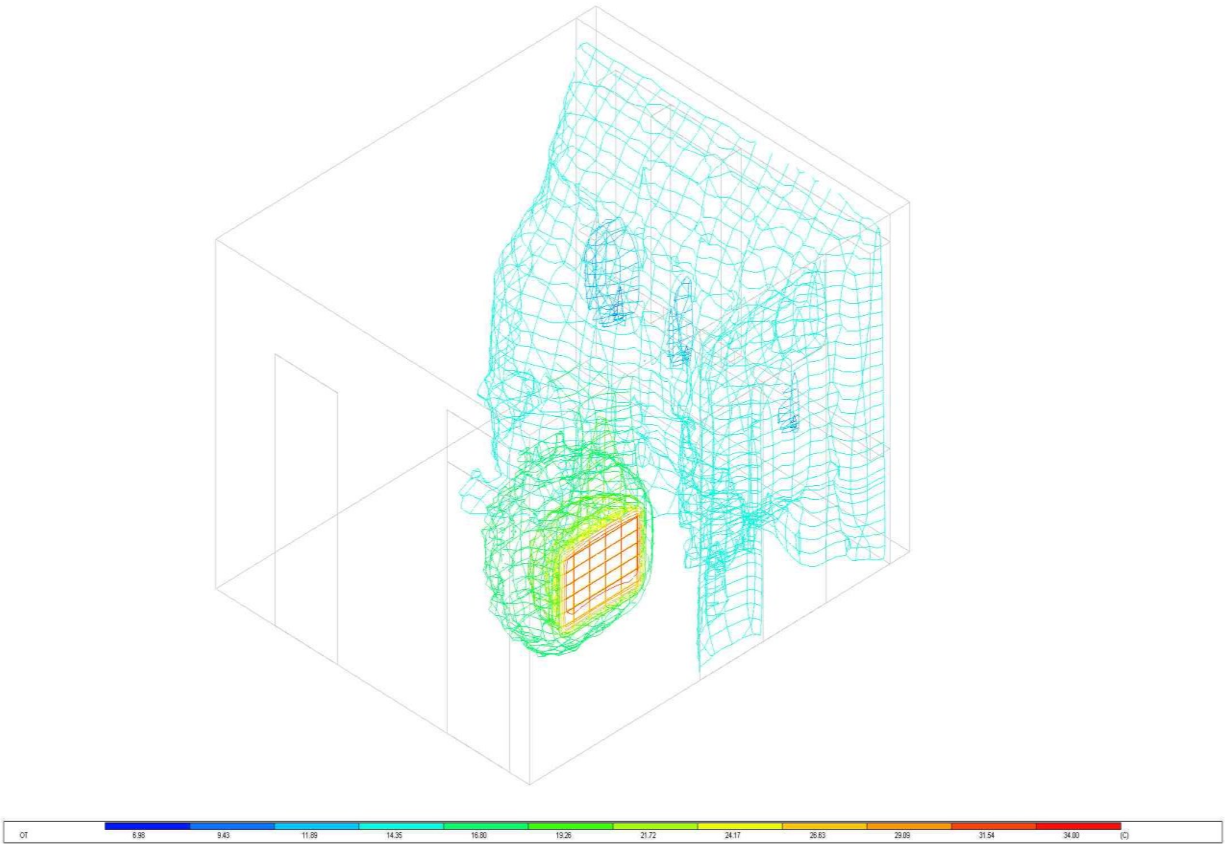


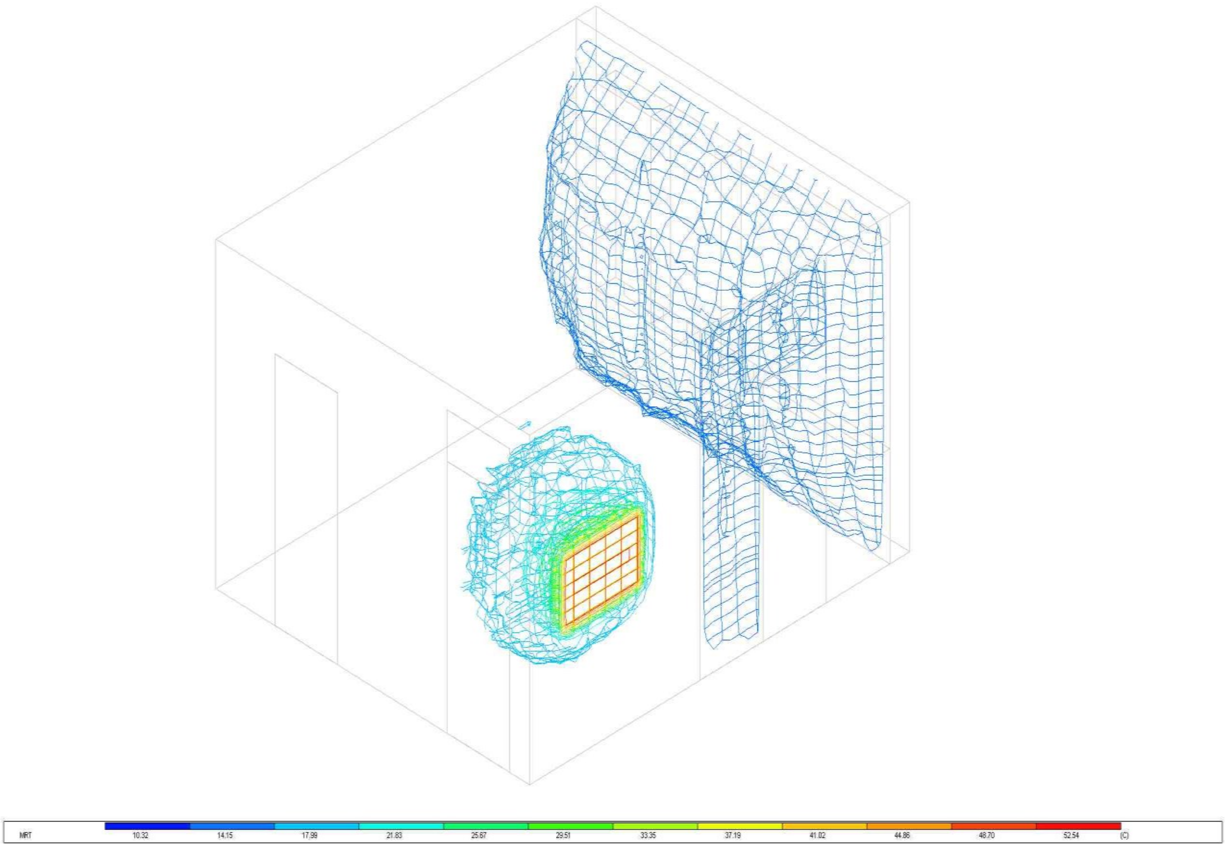
1

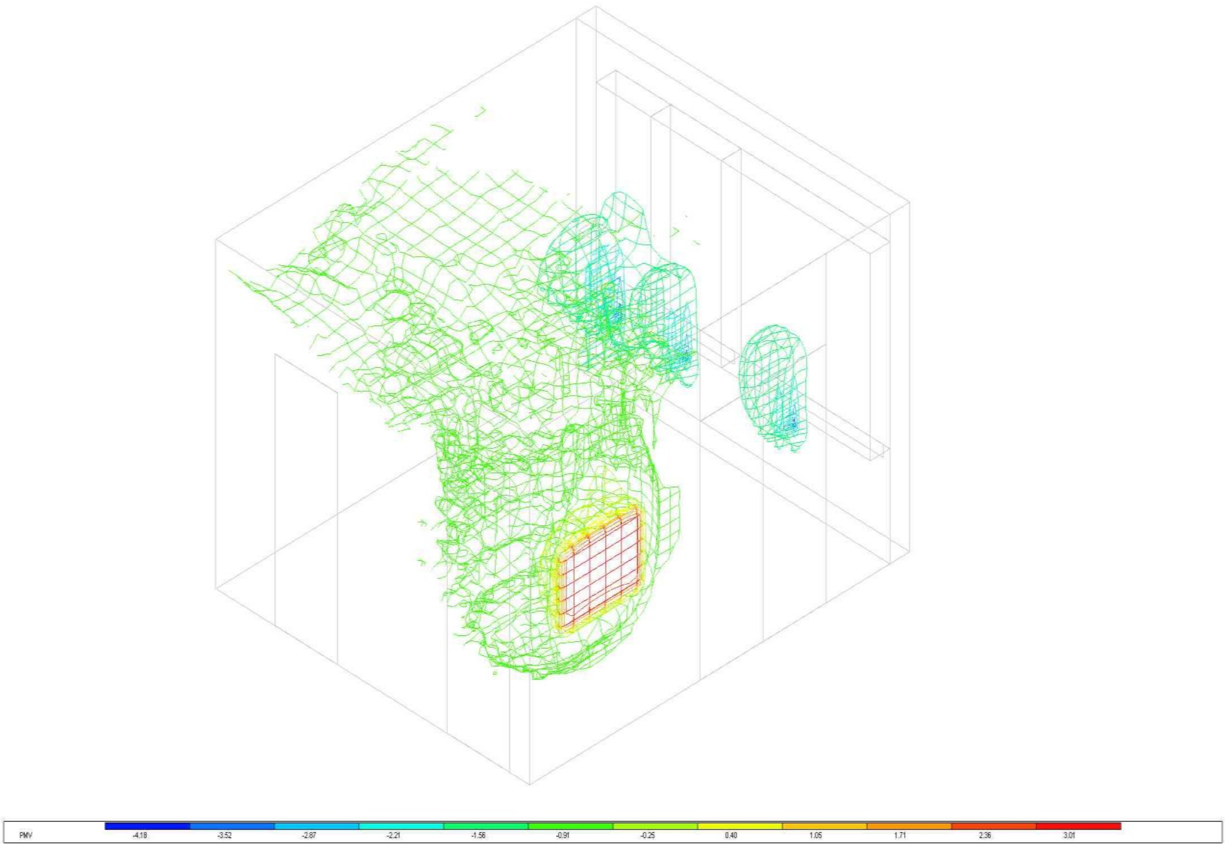


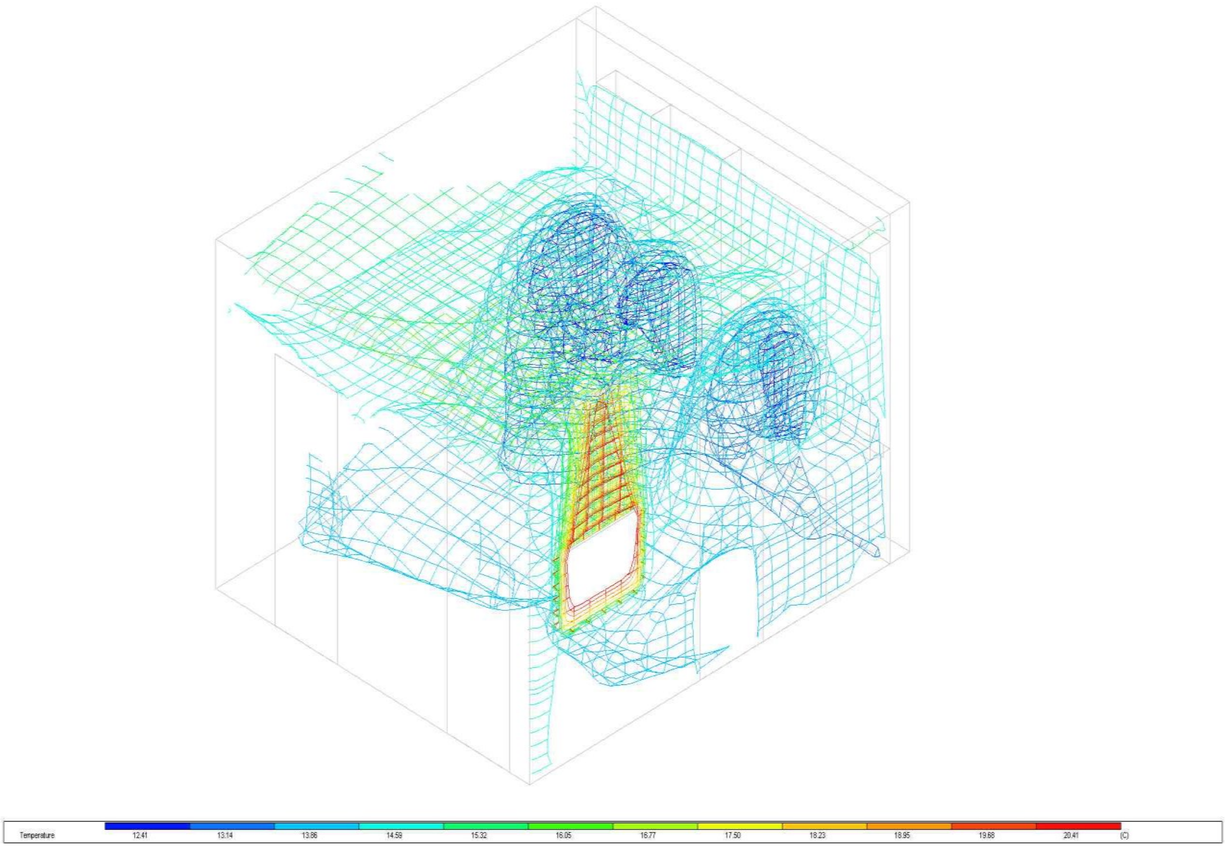

MRT
10.32 14.15 17.99 21.83 25.67 29.51 33.35 37.19 41.02 44.86 48.70 52.54 (C)

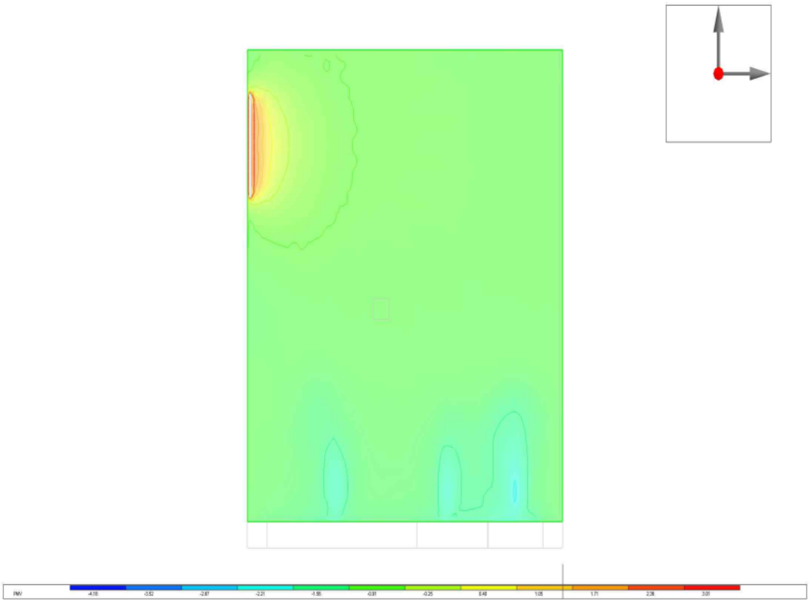

OT
6.98 9.43 11.89 14.35 16.80 19.26 21.72 24.17 26.63 29.09 31.54 34.00 (C)

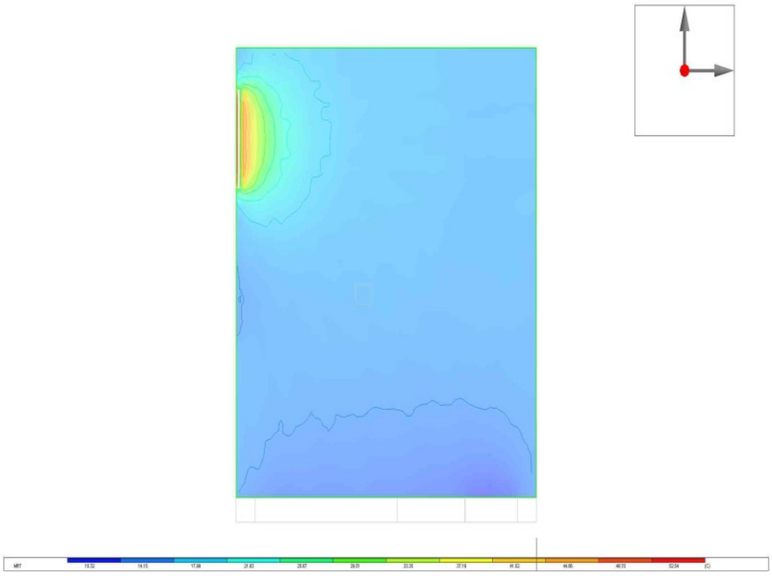

OT
6.98
9.43
11.89
14.35
16.80
19.26
21.72
24.17
26.63
29.09
31.54
34.00
(C)

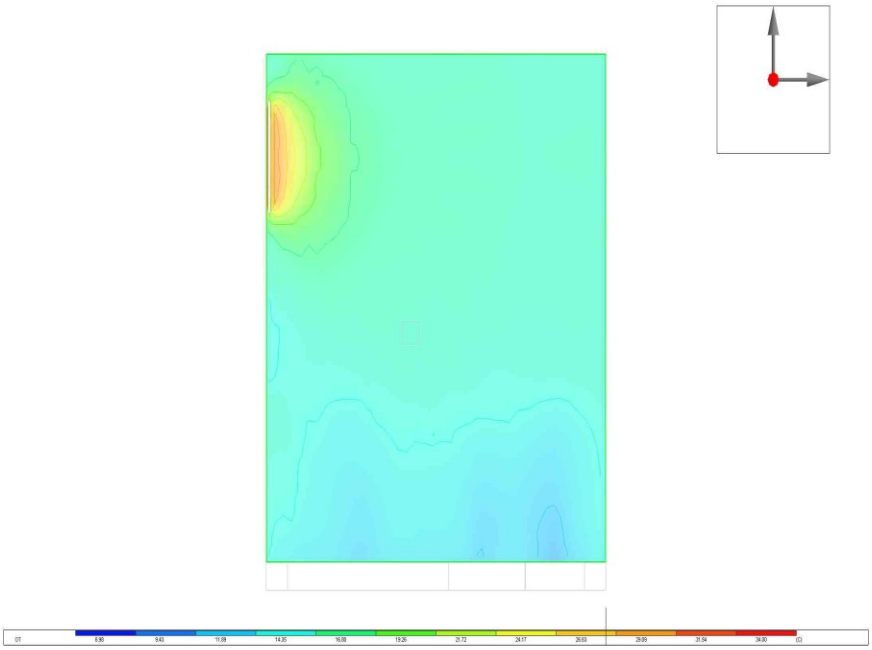

MRT
10.32
14.15
17.99
21.83
25.67
29.51
33.35
37.19
41.02
44.86
48.70
52.54
(C)


PMV
-4.18
-3.52
-2.87
-2.21
-1.56
-0.91
-0.25
0.40
1.05
1.71
2.36
3.01

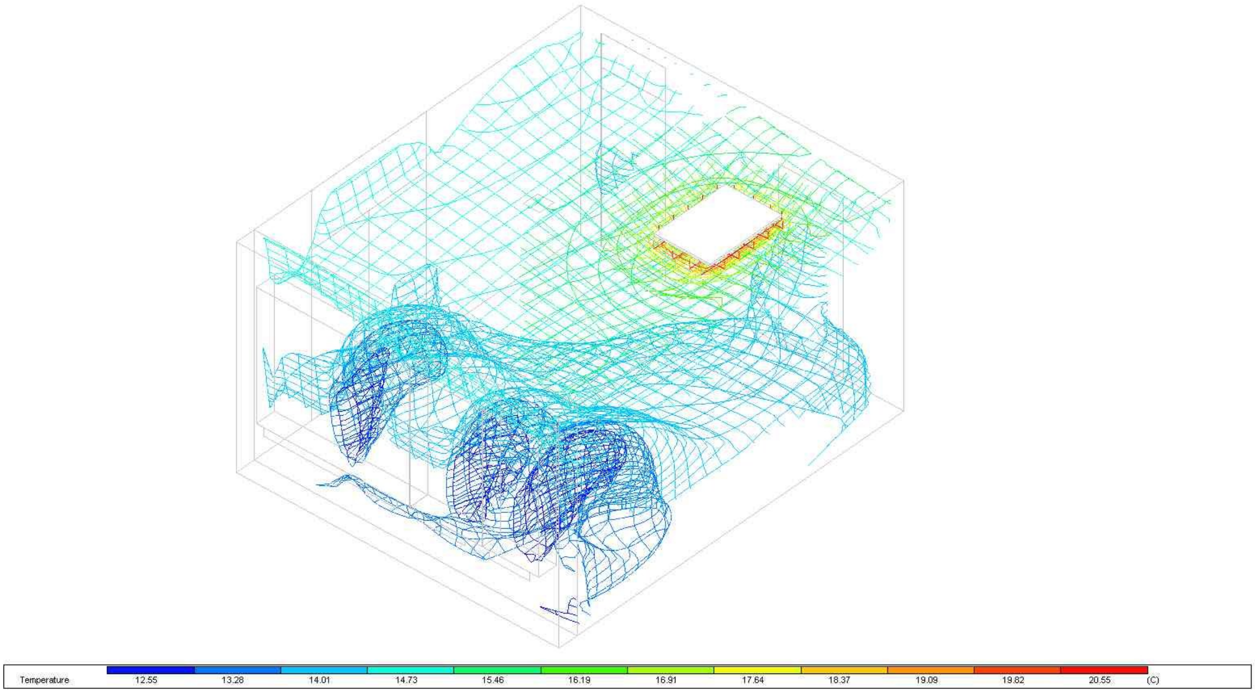

Temperature
12.41
13.14
13.86
14.59
15.32
16.05
16.77
17.50
18.23
18.95
19.68
20.41
(C)

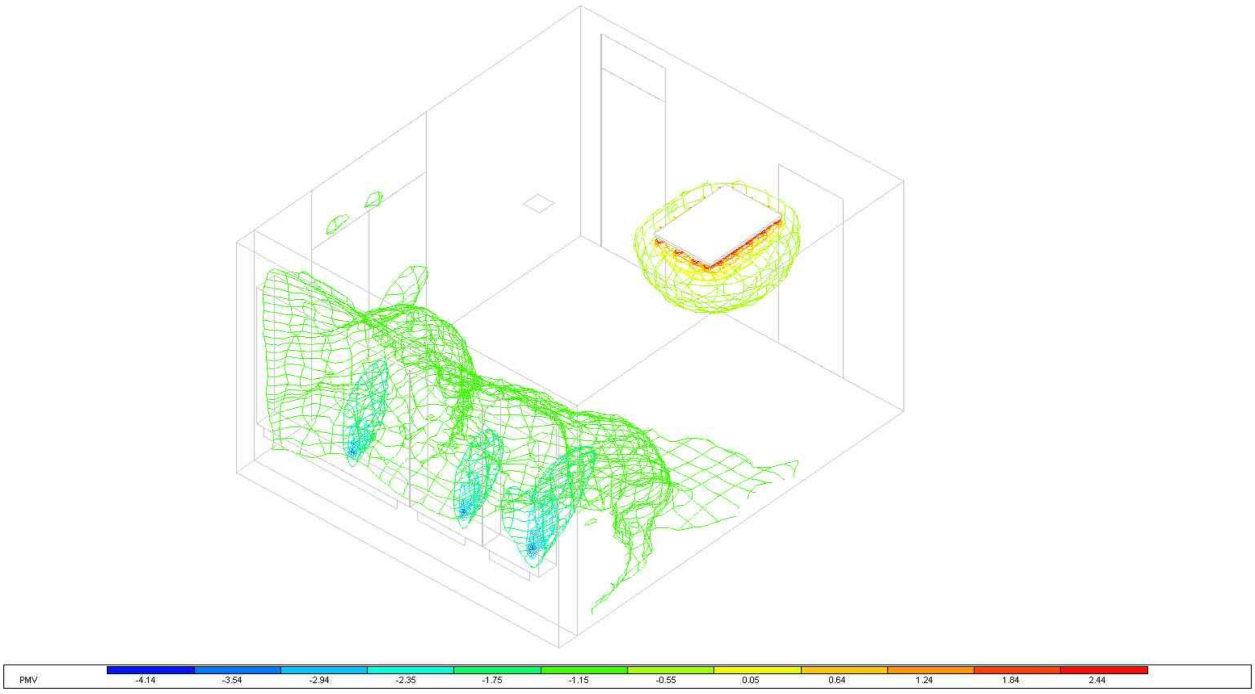


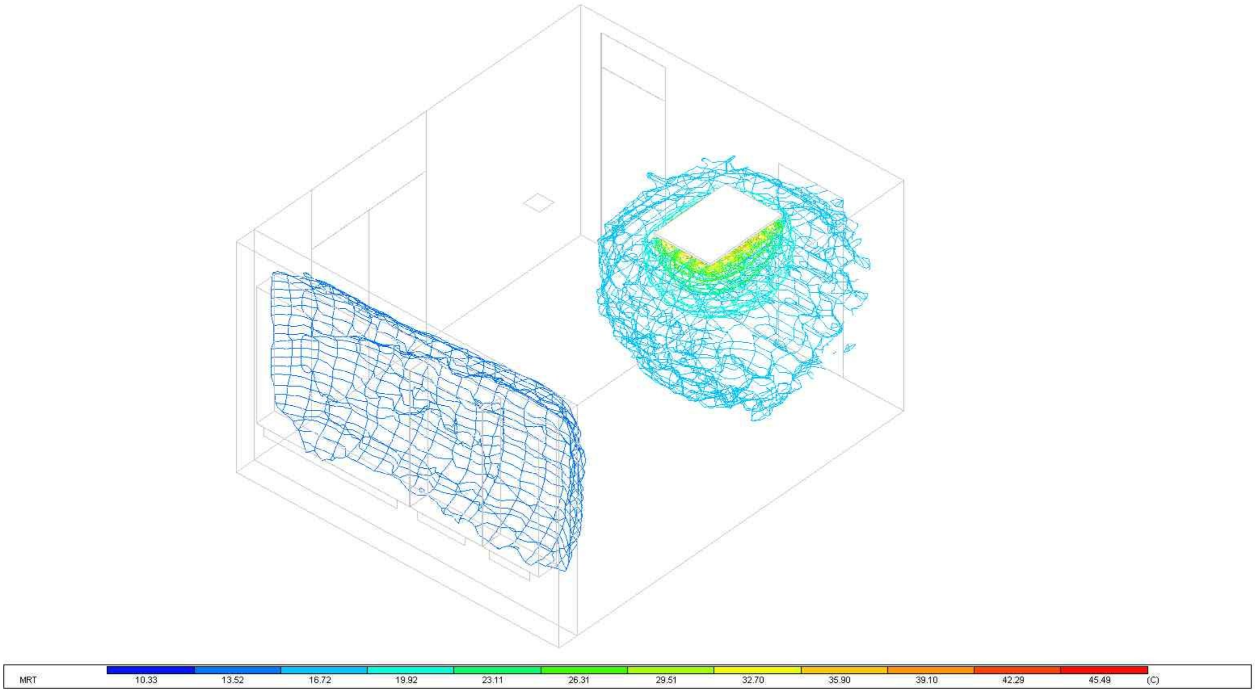


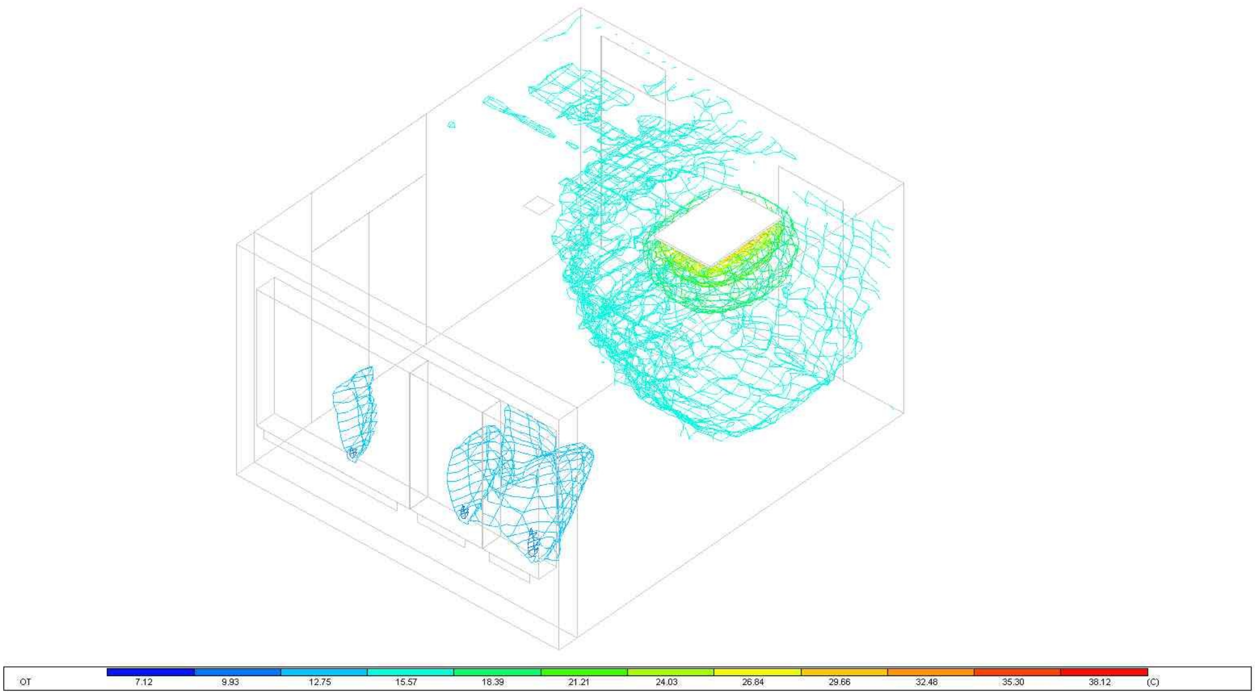


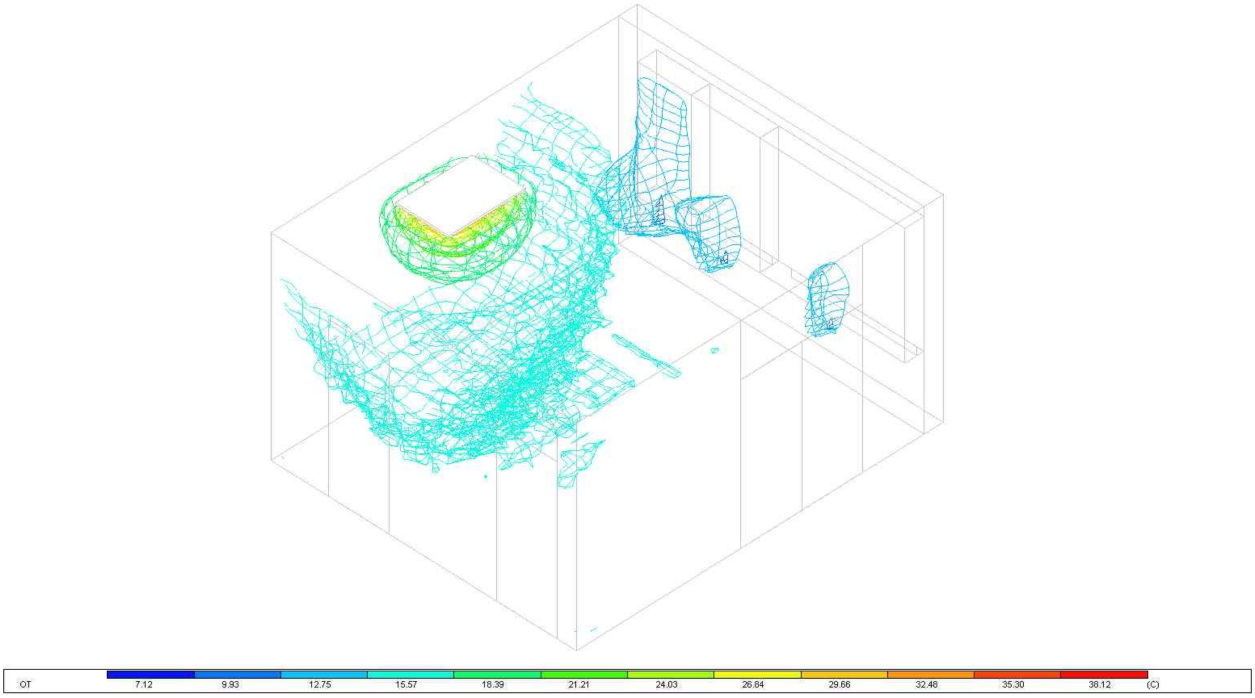
Appendix 19.8 – CFD calculations – Infrared heating panels ceiling situation

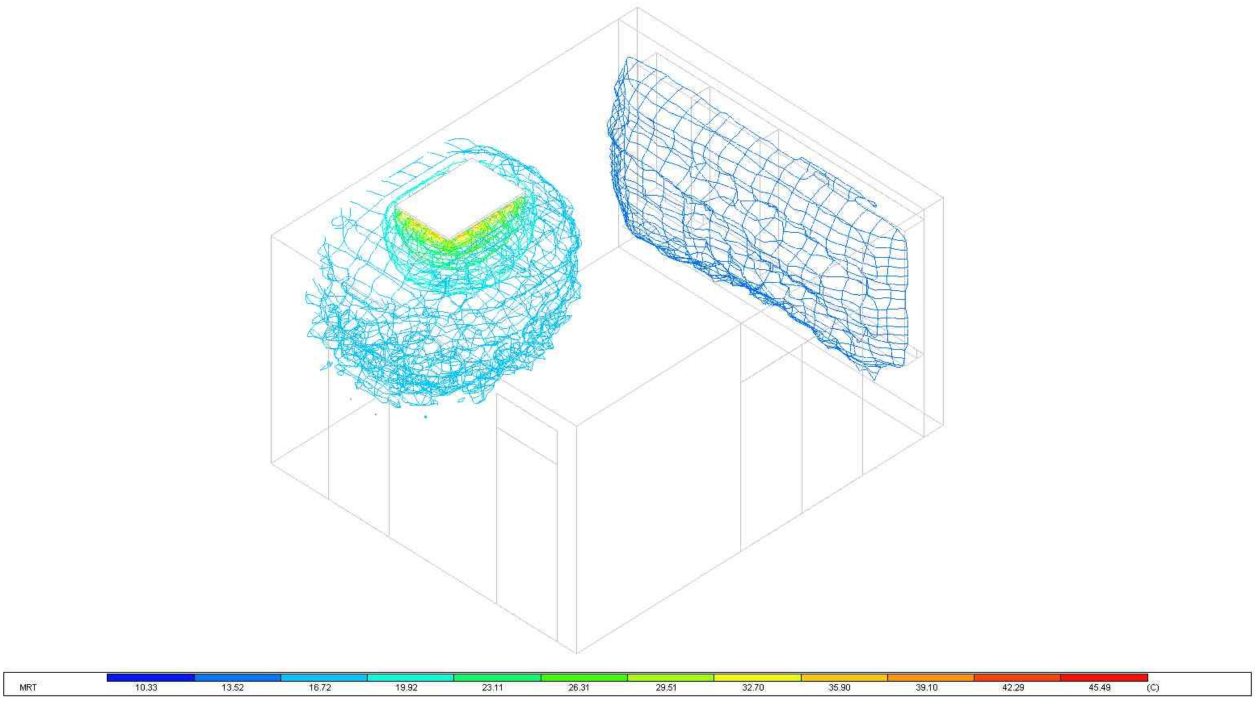


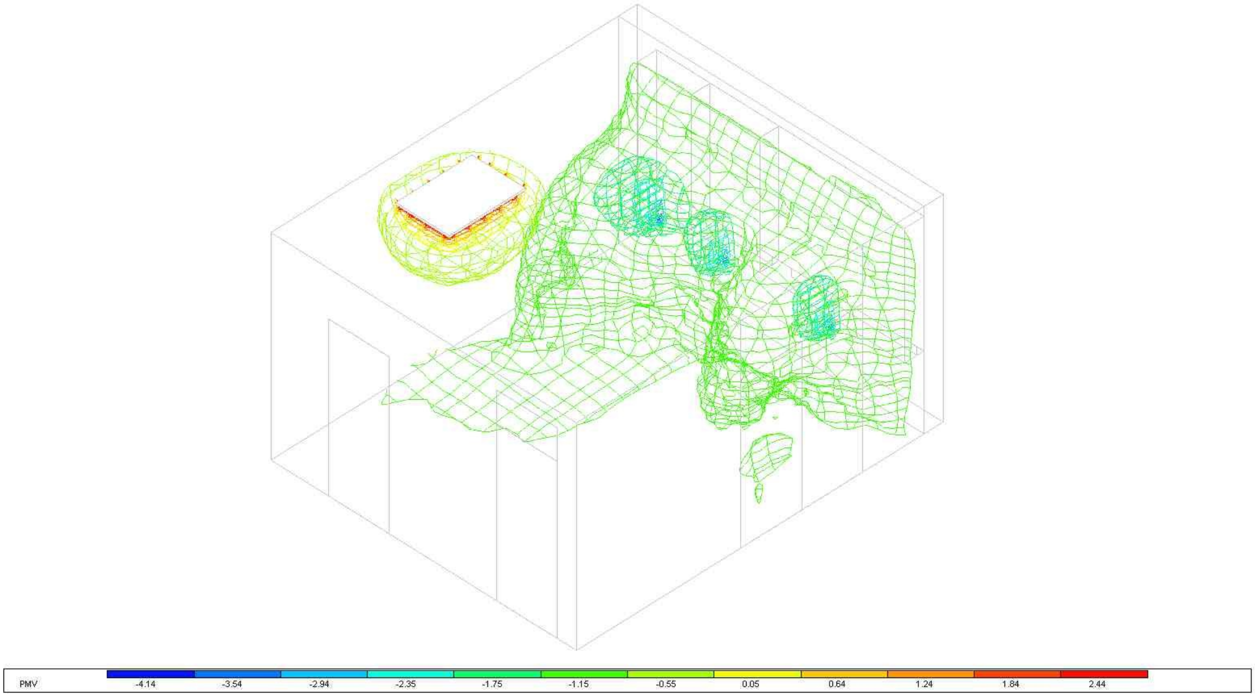


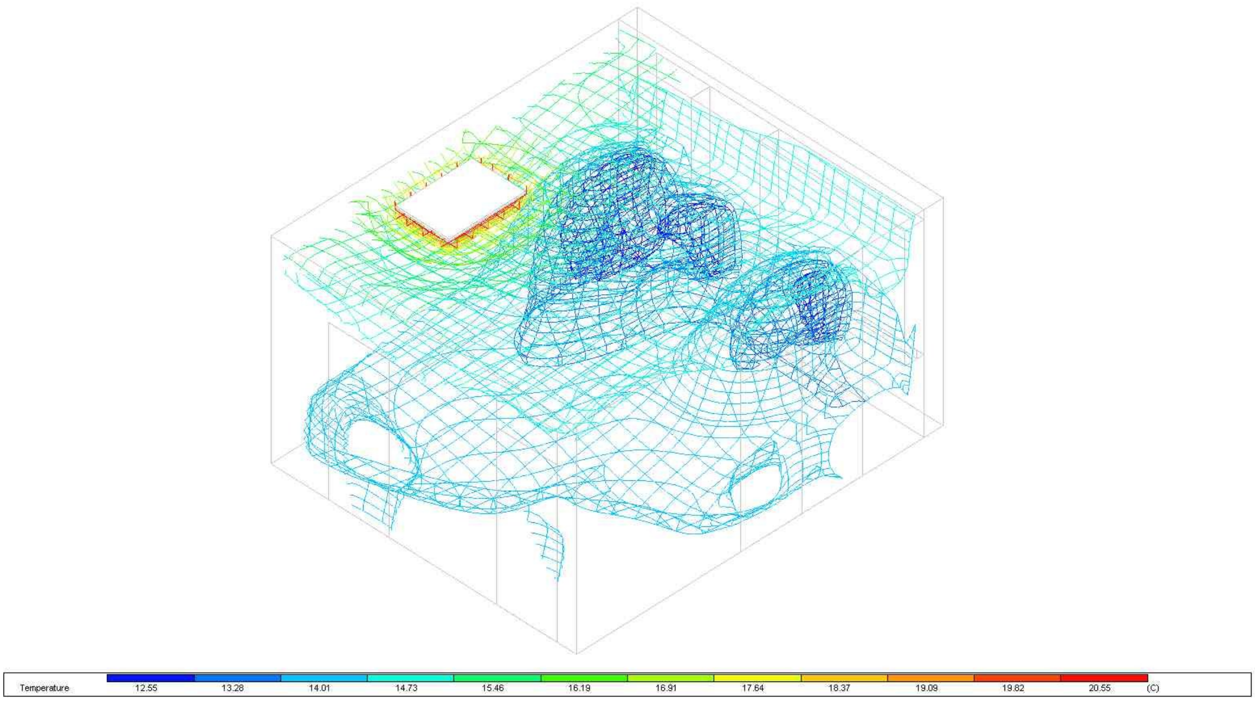

MRT
10.33
13.52
16.72
19.92
23.11
26.31
29.51
32.70
35.90
39.10
42.29
45.49
(C)

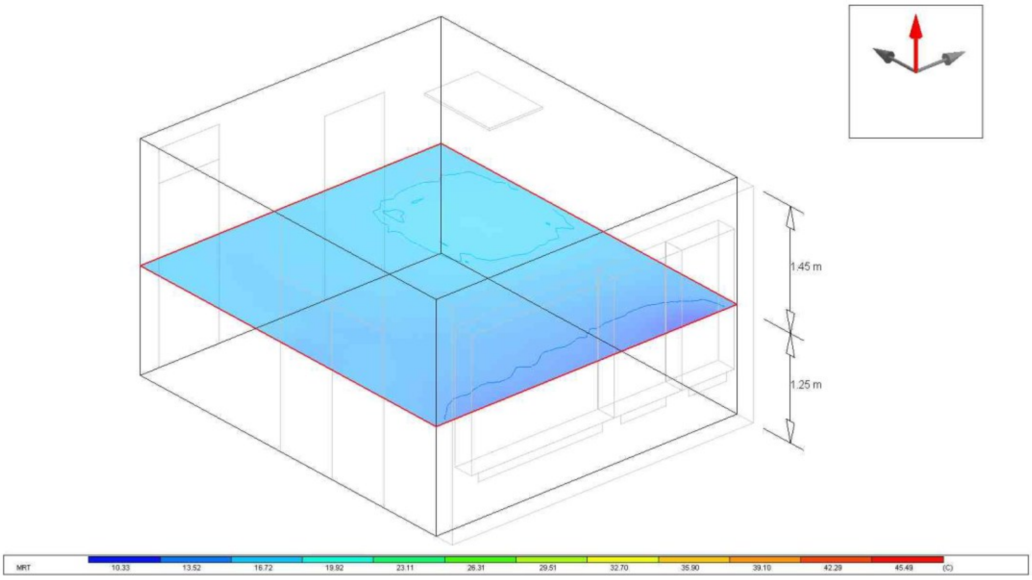

OT
7.12
9.93
12.75
15.57
18.39
21.21
24.03
26.84
29.66
32.48
35.30
38.12
(C)

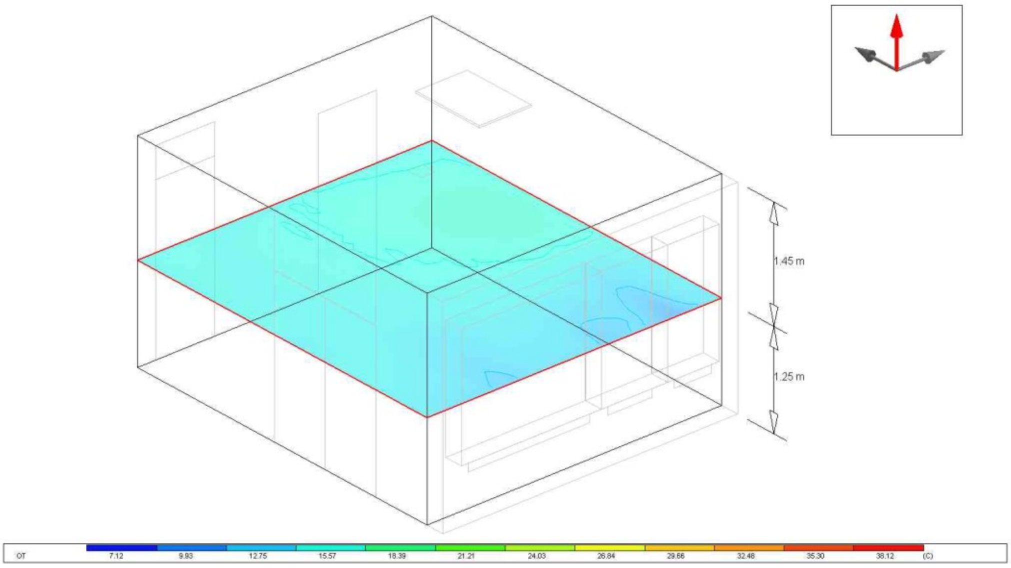

OT
7.12
9.93
12.75
15.57
18.39
21.21
24.03
26.84
29.66
32.48
35.30
38.12
(C)

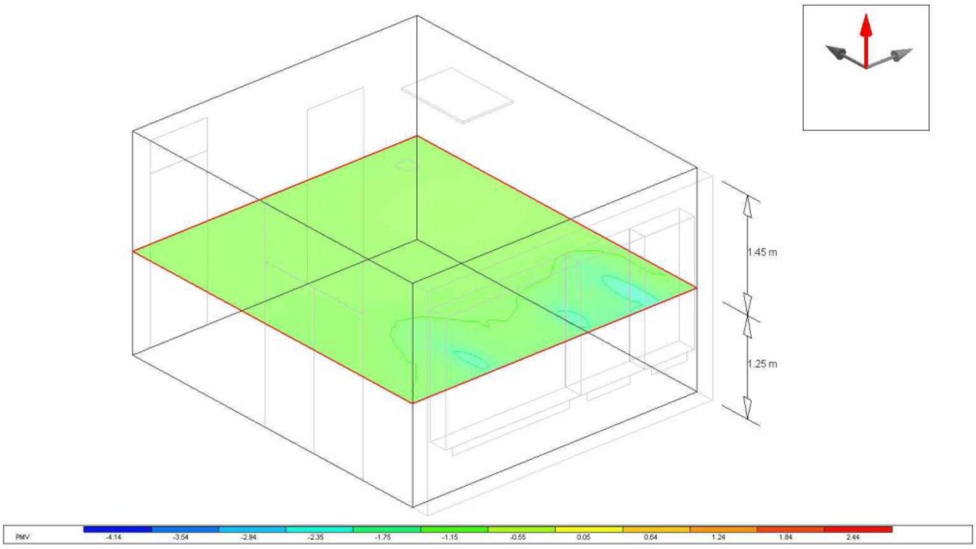

MRT
10.33
13.52
16.72
19.92
23.11
26.31
29.51
32.70
35.90
39.10
42.29
45.49
(C)


PMV
-4.14
-3.54
-2.94
-2.35
-1.75
-1.15
-0.55
0.05
0.64
1.24
1.84
2.44

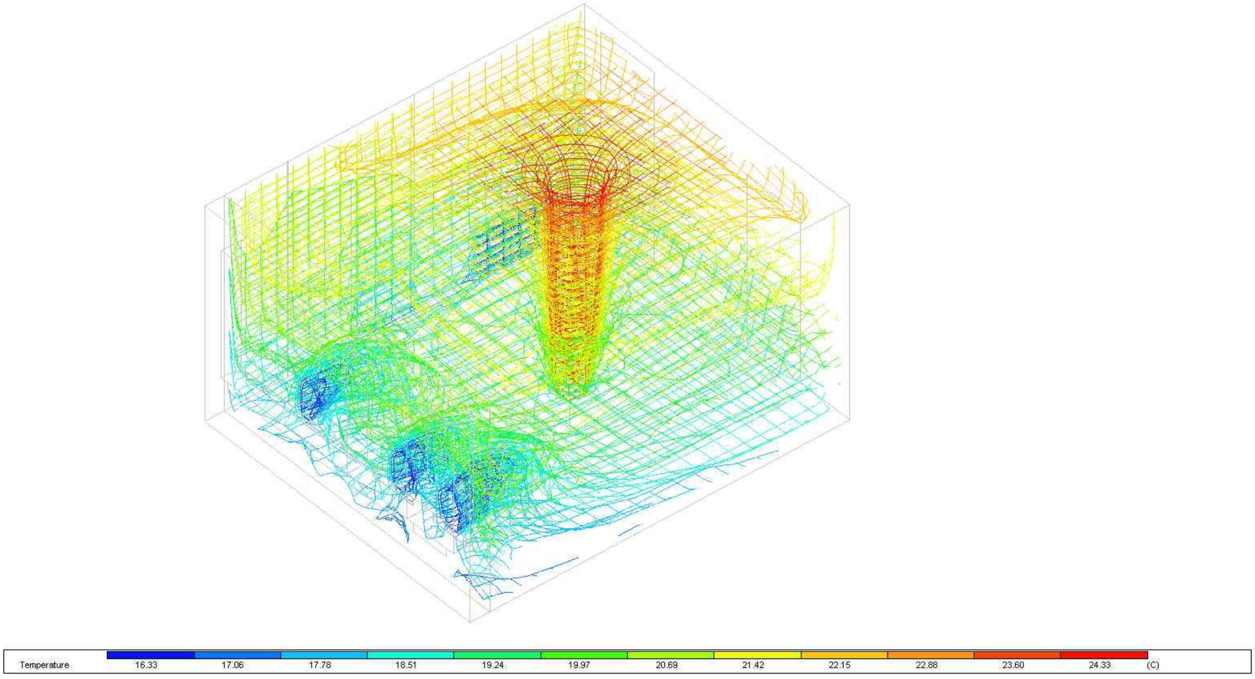

Temperature
12.55
13.28
14.01
14.73
15.46
16.19
16.91
17.64
18.37
19.09
19.82
20.55
(C)

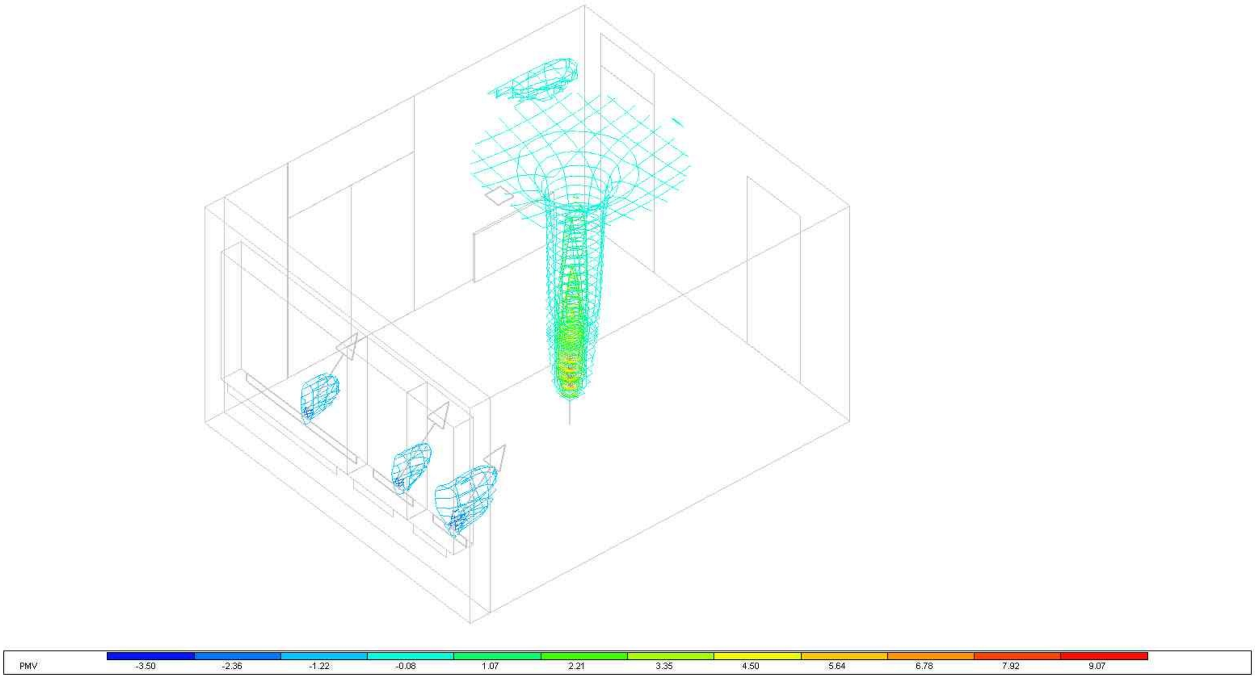

1.45 m
1.25 m
MRT
10.33 13.52 16.72 19.92 23.11 26.31 29.51 32.70 35.90 39.10 42.29 45.49 (C)

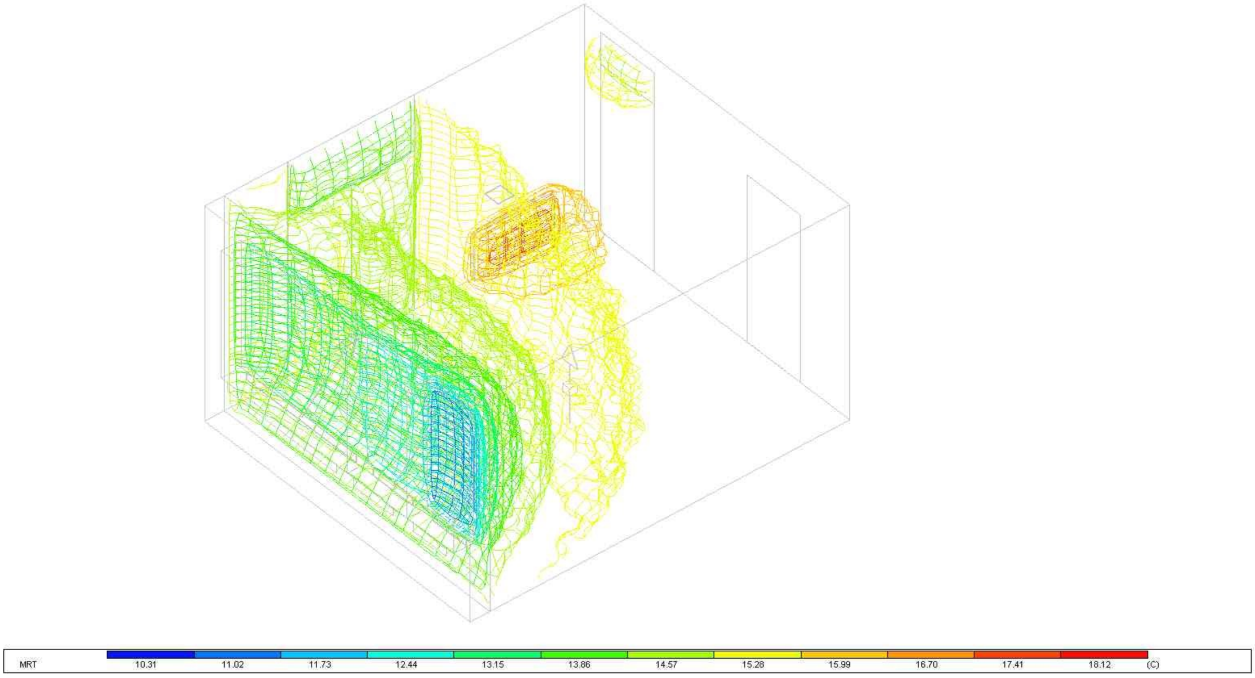

1.45 m
1.25 m
OT
7.12 9.93 12.75 15.57 18.39 21.21 24.03 26.84 29.66 32.48 35.30 38.12 (C)

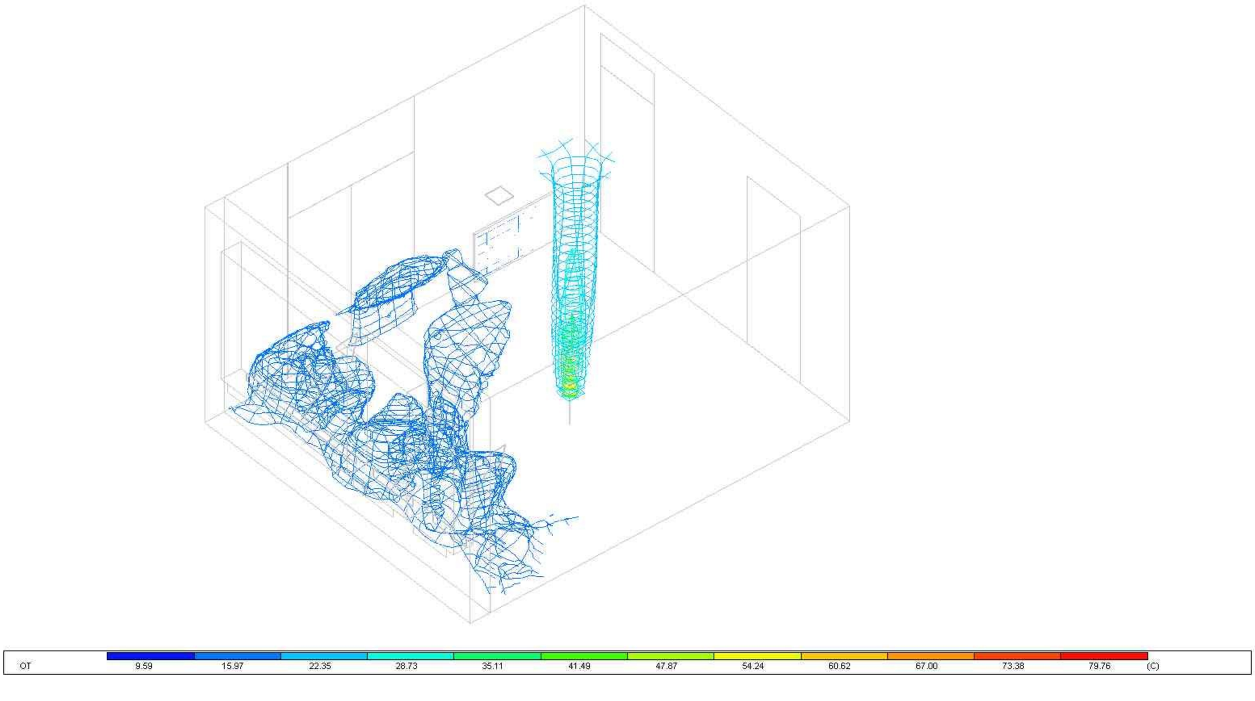

1.45 m
1.25 m
PMV
-4.14 -3.54 -2.94 -2.35 -1.75 -1.15 -0.55 0.05 0.64 1.24 1.84 2.44

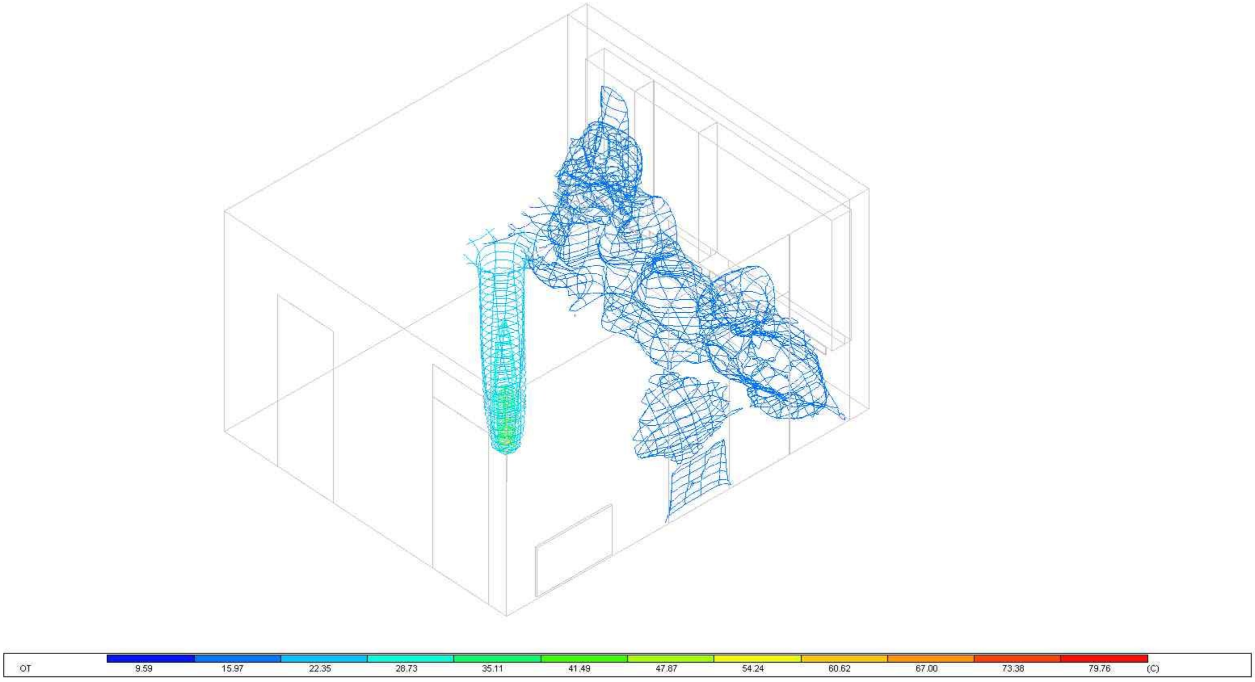
Appendix 19.9 – CFD calculations – Warm air circulator situation 2000W

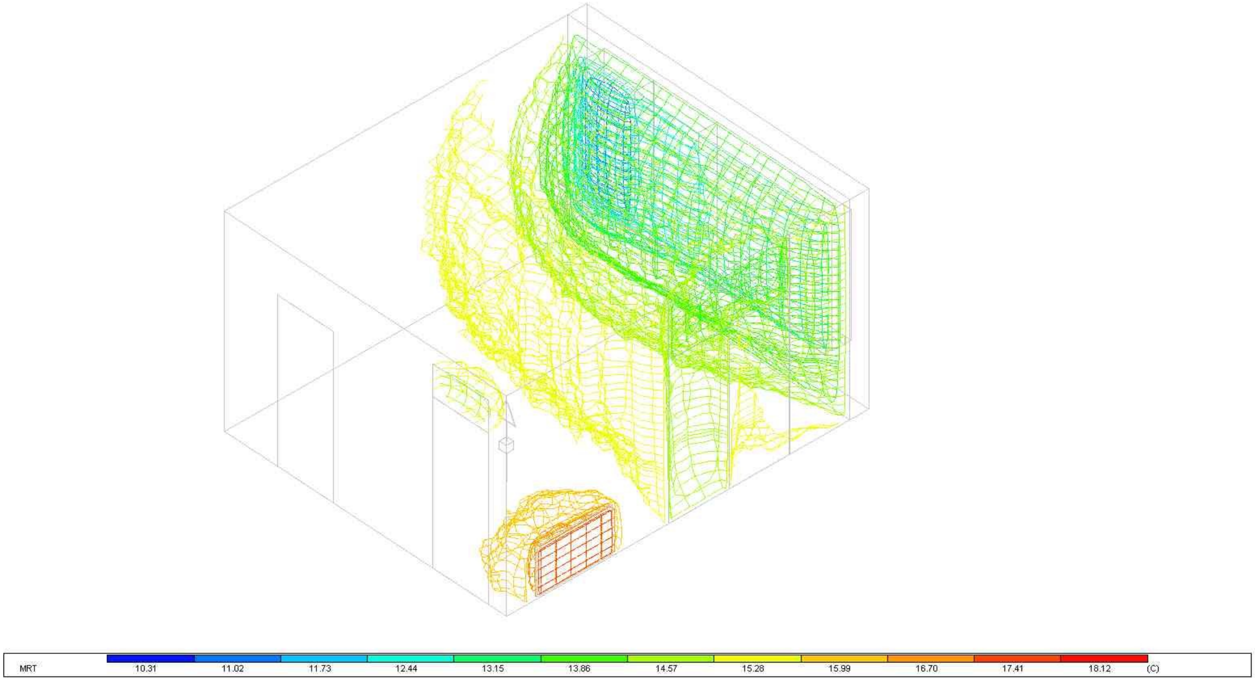


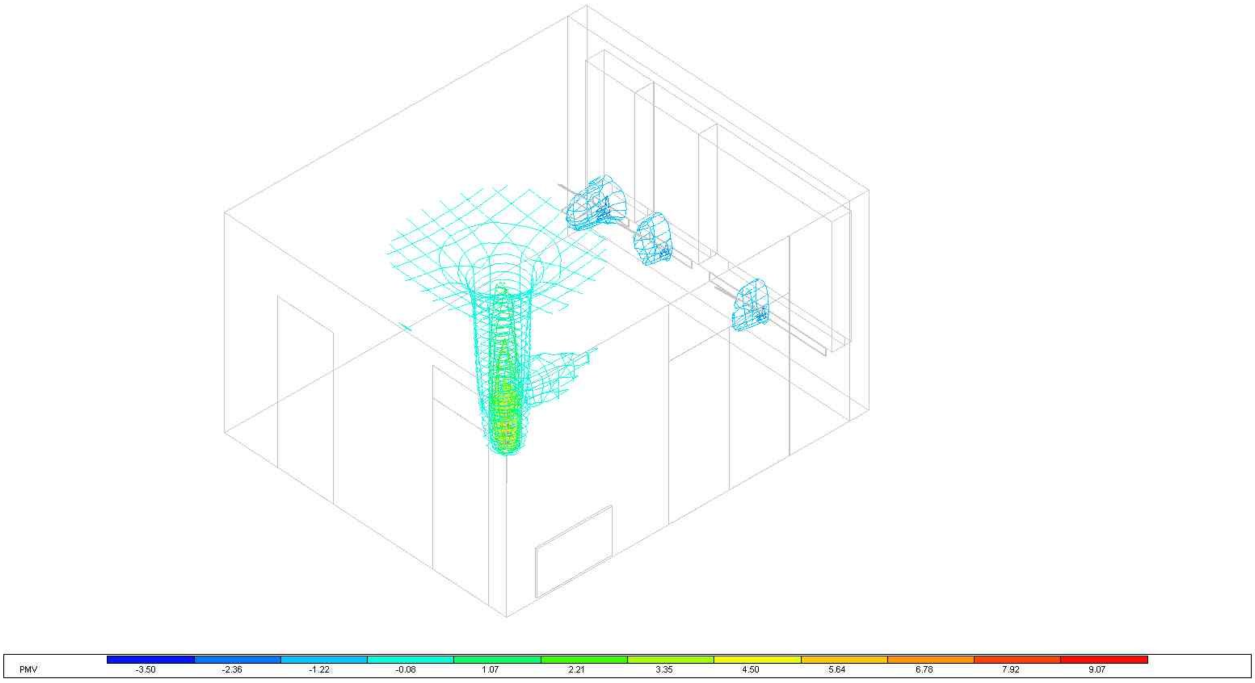


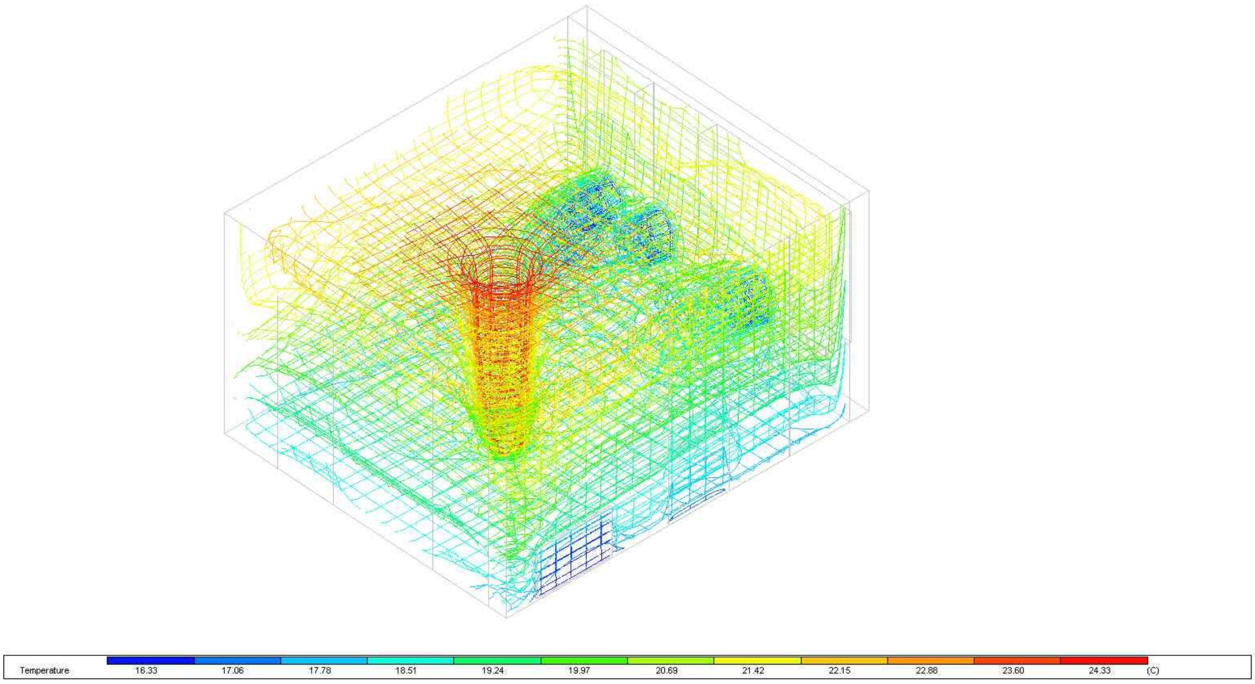

MRT
10.31
11.02
11.73
12.44
13.15
13.86
14.57
15.28
15.99
16.70
17.41
18.12
(C)

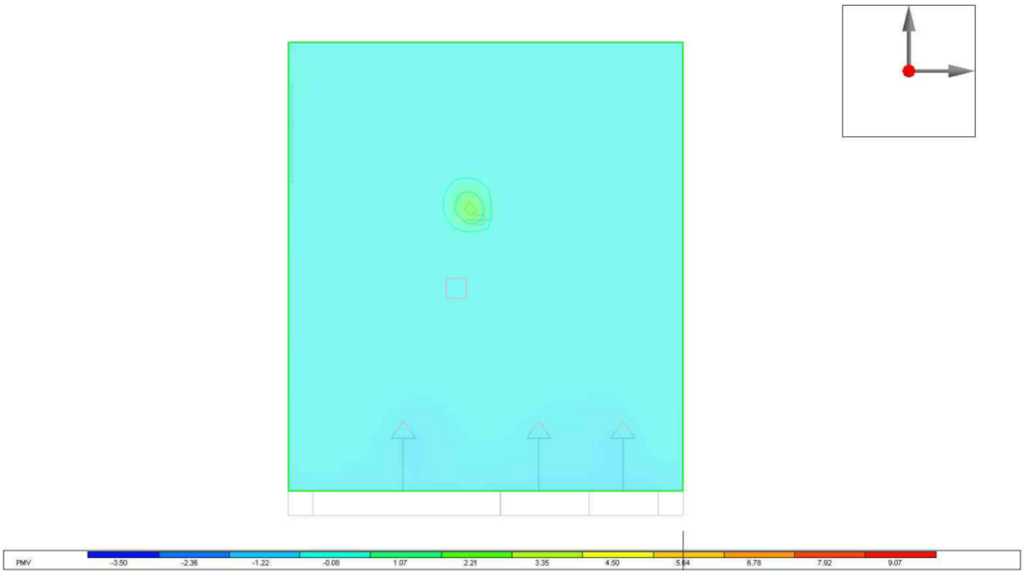

OT
9.59
15.97
22.35
28.73
35.11
41.49
47.87
54.24
60.62
67.00
73.38
79.76
(C)

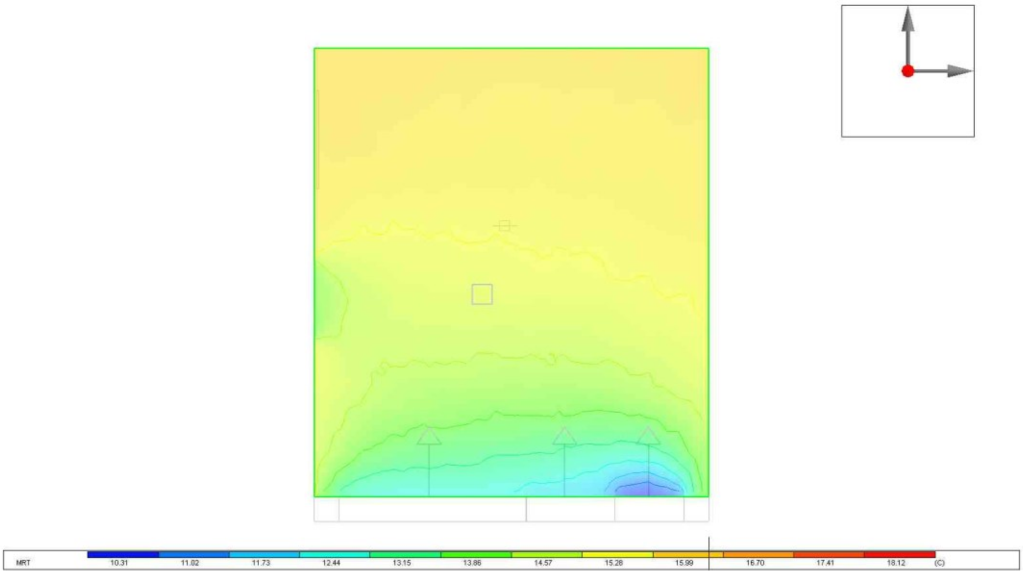

OT
9.59 15.97 22.35 28.73 35.11 41.49 47.87 54.24 60.62 67.00 73.38 79.76 (C)

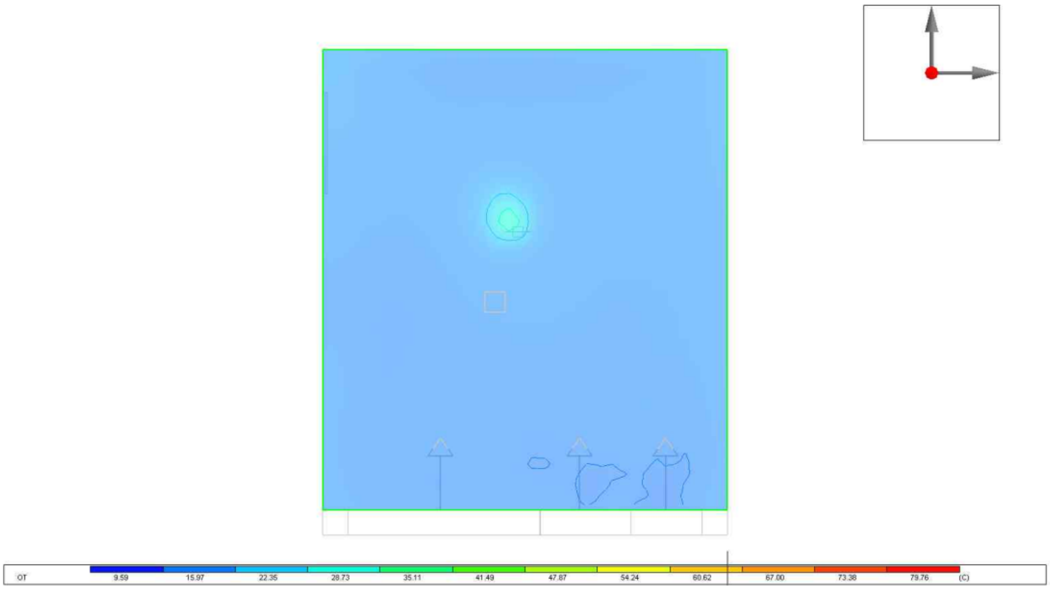

MRT
10.31 11.02 11.73 12.44 13.15 13.86 14.57 15.28 15.99 16.70 17.41 18.12 (C)


PMV
-3.50 -2.36 -1.22 -0.08 1.07 2.21 3.35 4.50 5.64 6.78 7.92 9.07


Temperature
16.33 17.06 17.78 18.51 19.24 19.97 20.69 21.42 22.15 22.88 23.60 24.33 (C)


PMV
-3.50
-2.36
-1.22
-0.08
1.07
2.21
3.35
4.50
5.64
6.78
7.92
9.07


MRT
10.31
11.02
11.73
12.44
13.15
13.86
14.57
15.28
15.99
16.70
17.41
18.12
(C)


OT
9.59
15.97
22.35
28.73
35.11
41.49
47.87
54.24
60.62
67.00
73.38
79.76
(C)

Appendix: 20 – CFD calculations comparisons – retrofits

Appendix 20.1 – CFD calculations comparisons – Normal situation

Normal Situation	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	13,8
Improvement (%)	**0,0%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	13,5
Improvement (%)	**0,0%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-2,0
Improvement (%)	**0,0%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	14,5
Improvement (%)	**0,0%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	14,0
Improvement (%)	**0,0%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-1,4
Improvement (%)	**0,0%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	15,5
Improvement (%)	**0,0%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	15,0
Improvement (%)	**0,0%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-1,1
Improvement (%)	**0,0%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	15,5
Improvement (%)	**0,0%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	15,8
Improvement (%)	**0,0%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-1,1
Improvement (%)	**0,0%**

Appendix 20.2 – CFD calculations comparisons – Indoor wall insulation

Indoor wall insulation	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	14,2
Improvement (%)	**2,8%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	14,5
Improvement (%)	**6,6%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-1,4
Improvement (%)	**30,0%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	16,4
Improvement (%)	**11,6%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	15,2
Improvement (%)	**7,9%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-0,7
Improvement (%)	**50,0%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	16,8
Improvement (%)	**7,7%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	15,8
Improvement (%)	**5,1%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-0,6
Improvement (%)	**43,9%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	16,8
Improvement (%)	**7,7%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	15,8
Improvement (%)	**0,0%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-0,6
Improvement (%)	**43,9%**

Appendix 20.3 – CFD calculations comparisons – External wall insulation

External wall insulation	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	14,4
Improvement (%)	**4,2%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	14,6
Improvement (%)	**7,5%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-1,0
Improvement (%)	**50,0%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	16,6
Improvement (%)	**12,7%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	15,3
Improvement (%)	**8,5%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-0,6
Improvement (%)	**57,1%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	16,9
Improvement (%)	**8,0%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	16,0
Improvement (%)	**6,3%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-0,6
Improvement (%)	**43,9%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	16,9
Improvement (%)	**8,0%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	16,0
Improvement (%)	**1,3%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-0,6
Improvement (%)	**43,9%**

Appendix 20.4 – CFD calculations comparisons – Window insulation film

Window insulation film	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	14,0
Improvement (%)	**1,4%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	14,3
Improvement (%)	**5,6%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-0,7
Improvement (%)	**65,0%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	16,0
Improvement (%)	**9,4%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	15,1
Improvement (%)	**7,3%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-0,6
Improvement (%)	**57,1%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	16,8
Improvement (%)	**7,7%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	16,0
Improvement (%)	**6,3%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-0,5
Improvement (%)	**53,3%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	16,8
Improvement (%)	**7,7%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	16,0
Improvement (%)	**1,3%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-0,5
Improvement (%)	**53,3%**

Appendix 20.5 – CFD calculations comparisons – Glazing replacement

Glazing replacement	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	14,2
Improvement (%)	**2,8%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	16,8
Improvement (%)	**19,6%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-0,6
Improvement (%)	**70,0%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	16,2
Improvement (%)	**10,5%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	17,6
Improvement (%)	**20,5%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-0,5
Improvement (%)	**64,3%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	17,0
Improvement (%)	**8,8%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	19,0
Improvement (%)	**21,1%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-0,4
Improvement (%)	**62,6%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	17,0
Improvement (%)	**8,8%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	18,5
Improvement (%)	**14,6%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-0,4
Improvement (%)	**62,6%**

Appendix 20.6 – Average effectiveness per intervention

Average effectiveness per intervention			
Intervention	Operative Temperature	Mean radiant temperature	PMV
Indoor wall insulation	7,45	4,9	41,95
External insulation	8,23	5,9	48,98
Window insulation film	6,65	5,13	57,18
Glazing replacement	7,73	19	64,88

Appendix 20.7 – Comparison of combined comfort scores

Combined comfort score (PMV=50%, OT = 30%, MRT = 20%)	
Glazing replacement	38,56%
Window insulation film	31,58%
External insulation	28,14%
Indoor wall insulation	24,19%

Appendix 20.8 – Ranking per parameter: Operative temperature

Ranking per parameter: Operative temperature		
Ranking	Intervention	Improvement
1	External insulation	8,23%
2	Glazing replacement	7,73%
3	Indoor wall insulation	7,45%
4	Window insulation film	6,55%

Appendix 20.9 – Ranking per parameter: Mean Radiant Temperature

Ranking per parameter: Mean Radiant Temperature		
Ranking	Intervention	Improvement
1	Glazing replacement	18,98%
2	External insulation	5,9%
3	Indoor wall insulation	4,9%
4	Window insulation film	5,13%

Appendix 20.10 – Ranking per parameter: PMV

Ranking per parameter: PMV		
Ranking	Intervention	Improvement
1	Glazing replacement	64,88%
2	Window insulation film	57,18%
3	External insulation	48,98%
4	Indoor wall insulation	41,95%

Appendix 20.11 – Intervention improvements per location: Point 1

Intervention improvements per location: Point 1			
Intervention	Operative Temperature (%)	Mean radiant temperature (%)	PMV (%)
Indoor wall insulation	2,8	6,6	30,0
External wall insulation	**4,2**	7,5	50,0
Window insulation film	1,4	5,6	65,0
Glazing replacement	2,8	**19,6**	**70,0**

Appendix 20.12 – Intervention improvements per location: Point 2

Intervention improvements per location: Point 2			
Intervention	Operative Temperature (%)	Mean radiant temperature (%)	PMV (%)
Indoor wall insulation	11,6	7,9	50,0
External wall insulation	**12,7**	8,5	57,1
Window insulation film	9,4	7,3	57,1
Glazing replacement	10,5	**20,5**	**64,3**

Appendix 20.13 – Intervention improvements per location: Point 3

Intervention improvements per location: Point 3			
Intervention	Operative Temperature (%)	Mean radiant temperature (%)	PMV (%)
Indoor wall insulation	7,7	5,1	43,9
External wall insulation	8,0	6,3	43,9
Window insulation film	7,7	6,3	53,3
Glazing replacement	**8,8**	**21,1**	**62,6**

Appendix 20.14 – Intervention improvements per location: Point 4

Intervention improvements per location: Point 4			
Intervention	Operative Temperature (%)	Mean radiant temperature (%)	PMV (%)
Indoor wall insulation	7,7	0,0	43,9
External wall insulation	8,0	1,3	43,9
Window insulation film	7,7	1,3	53,3
Glazing replacement	**8,8**	**14,6**	**62,6**

Appendix: 21 – CFD calculations comparisons – heating

Appendix 21.1 – CFD calculations comparisons – Normal situation

Normal Situation	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	13,8
Improvement (%)	**0,0%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	13,5
Improvement (%)	**0,0%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-2,0
Improvement (%)	**0,0%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	14,5
Improvement (%)	**0,0%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	14,0
Improvement (%)	**0,0%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-1,4
Improvement (%)	**0,0%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	15,5
Improvement (%)	**0,0%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	15,0
Improvement (%)	**0,0%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-1,1
Improvement (%)	**0,0%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	15,5
Improvement (%)	**0,0%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	15,8
Improvement (%)	**0,0%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-1,1
Improvement (%)	**0,0%**

Appendix 21.2 – CFD calculations comparisons – Warm air circulator 1000W

Warm air circulators (1000W)	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	15,5
Improvement (%)	**11,0%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	14,0
Improvement (%)	**3,6%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-1,5
Improvement (%)	**25,0%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	16,5
Improvement (%)	**12,1%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	15,0
Improvement (%)	**6,7%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-0,7
Improvement (%)	**48,6%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	16,0
Improvement (%)	**3,1%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	15,7
Improvement (%)	**4,5%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-0,7
Improvement (%)	**32,7%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	16,5
Improvement (%)	**6,1%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	15,9
Improvement (%)	**0,6%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-0,7
Improvement (%)	**32,7%**

Appendix 21.3 – CFD calculations comparisons – Warm air circulator 2000W

Warm air circulators (2000W)	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	16,0
Improvement (%)	**13,8%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	14,5
Improvement (%)	**6,9%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-0,1
Improvement (%)	**96,0%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	20,0
Improvement (%)	**27,5%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	15,4
Improvement (%)	**9,1%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-0,1
Improvement (%)	**94,3%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	16,0
Improvement (%)	**3,1%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	16,0
Improvement (%)	**6,3%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-0,1
Improvement (%)	**92,5%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	16,0
Improvement (%)	**3,1%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	16,0
Improvement (%)	**1,3%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-0,1
Improvement (%)	**92,5%**

Appendix 21.4 – CFD calculations comparisons – Infrared heating panels wall placement

Infrared heating panels wall	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	14,0
Improvement (%)	**1,4%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	14,3
Improvement (%)	**5,6%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-1,6
Improvement (%)	**22,0%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	15,5
Improvement (%)	**6,5%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	16,2
Improvement (%)	**13,6%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-0,9
Improvement (%)	**35,7%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	15,5
Improvement (%)	**0,0%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	17,0
Improvement (%)	**11,8%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-0,9
Improvement (%)	**15,9%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	18,0
Improvement (%)	**13,9%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	21,8
Improvement (%)	**27,6%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-0,7
Improvement (%)	**34,6%**

Appendix 21.5 – CFD calculations comparisons – Infrared heating panels ceiling placement

Infrared heating panels ceiling	
Point 1	
Operative temperature	
Operative temperature point 1 without intervention	13,8
Operative temperature point 1 with intervention	13,2
Improvement (%)	**-4,5%**
Mean radiant temperature	
Mean radiant temperature point 1 without intervention	13,5
Mean radiant temperature point 1 with intervention	13,8
Improvement (%)	**2,2%**
PMV	
PMV point 1 without intervention	-2,0
PMV point 1 with intervention	-1,2
Improvement (%)	**42,5%**
Point 2	
Operative temperature	
Operative temperature point 2 without intervention	14,5
Operative temperature point 2 with intervention	15,4
Improvement (%)	**5,8%**
Mean radiant temperature	
Mean radiant temperature point 2 without intervention	14,0
Mean radiant temperature point 2 with intervention	16,0
Improvement (%)	**12,5%**
PMV	
PMV point 2 without intervention	-1,4
PMV point 2 with intervention	-1,0
Improvement (%)	**28,6%**
Point 3	
Operative temperature	
Operative temperature point 3 without intervention	15,5
Operative temperature point 3 with intervention	17,0
Improvement (%)	**8,8%**
Mean radiant temperature	
Mean radiant temperature point 3 without intervention	15,0
Mean radiant temperature point 3 with intervention	18,0
Improvement (%)	**16,7%**
PMV	
PMV point 3 without intervention	-1,1
PMV point 3 with intervention	-1,0
Improvement (%)	**6,5%**
Point 4	
Operative temperature	
Operative temperature point 4 without intervention	15,5
Operative temperature point 4 with intervention	15,0
Improvement (%)	**-3,3%**
Mean radiant temperature	
Mean radiant temperature point 4 without intervention	15,8
Mean radiant temperature point 4 with intervention	14,7
Improvement (%)	**-7,5%**
PMV	
PMV point 4 without intervention	-1,1
PMV point 4 with intervention	-1,0
Improvement (%)	**6,5%**

Appendix 21.6 – Average effectiveness per intervention

Average effectiveness per intervention			
Intervention	Operative Temperature	Mean radiant temperature	PMV
Warm air circulators 1000w	8%	4%	35%
Warm air circulators 2000w	12%	6%	94%
Infrared heating panels	5%	15%	27%
Infrared heating panels ceiling	2%	6%	21%

Appendix 21.7 – Comparison of combined comfort scores

Combined comfort score (PMV=50%, OT = 30%, MRT = 20%)	
Warm air circulators 2kw	51,66
Warm air circulators 1kw	20,57
Infrared heating panels	18,09
Infrared heating panels ceiling	12,22

Appendix 21.8 – Ranking per parameter: Operative temperature

Ranking per parameter: Operative temperature		
Ranking	Intervention	Improvement
1	Warm air circulators 2000w	11,88%
2	Warm air circulators 1000w	8,08%
3	Infrared heating panels	5,45%
4	Infrared heating panels ceiling	1,70%

Appendix 21.9 – Ranking per parameter: Mean Radiant Temperature

Ranking per parameter: Mean Radiant Temperature		
Ranking	Intervention	Improvement
1	Infrared heating panels	14,65%
2	Infrared heating panels ceiling	5,98%
3	Warm air circulators 2000w	5,90%
4	Warm air circulators 1000w	3,85%

Appendix 21.10 – Ranking per parameter: PMV

Ranking per parameter: PMV		
Ranking	Intervention	Improvement
1	Warm air circulators 2000w	93,83%
2	Warm air circulators 1000w	34,75%
3	Infrared heating panels	27,05%
4	Infrared heating panels ceiling	21,03%

Appendix 21.11 – Intervention improvements per location: Point 1

Intervention improvements per location: Point 1			
Intervention	Operative Temperature (%)	Mean radiant temperature (%)	PMV (%)
Warm air circulators 1000w	11	3,6	25
Warm air circulators 2000w	**13,8**	**6,9**	**96**
Infrared heating panels	1,4	5,6	22
Infrared heating panels ceiling	-4,5	2,2	42,5

Appendix 21.12 – Intervention improvements per location: Point 2

Intervention improvements per location: Point 2			
Intervention	Operative Temperature (%)	Mean radiant temperature (%)	PMV (%)
Warm air circulators 1000w	12,1	6,7	48,6
Warm air circulators 2000w	**27,5**	9,1	**94,3**
Infrared heating panels	6,5	**13,6**	35,7
Infrared heating panels ceiling	5,8	12,5	28,6

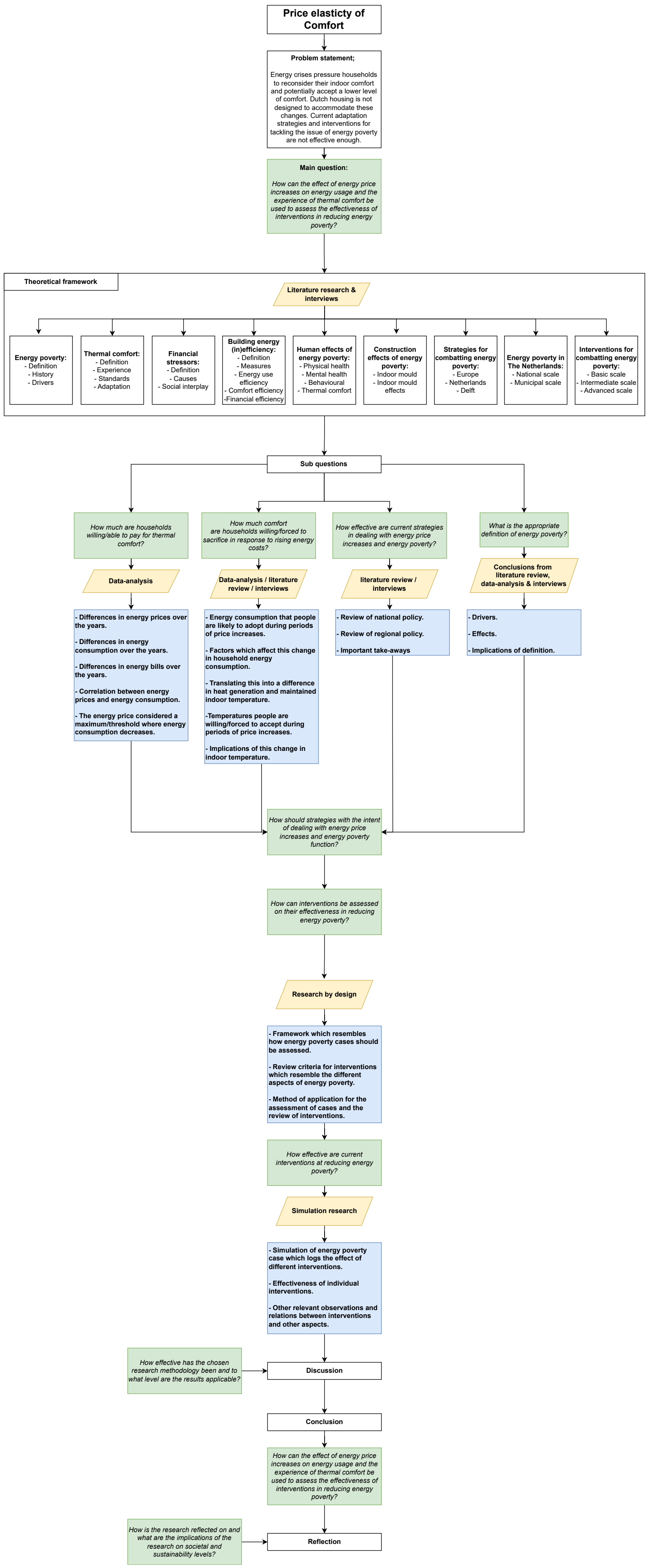
Appendix 21.13 – Intervention improvements per location: Point 3

Intervention improvements per location: Point 3			
Intervention	Operative Temperature (%)	Mean radiant temperature (%)	PMV (%)
Warm air circulators 1000w	3,1	4,5	32,7
Warm air circulators 2000w	3,1	6,3	**92,5**
Infrared heating panels	0	11,8	15,9
Infrared heating panels ceiling	**8,8**	**16,7**	6,5

Appendix 21.14 – Intervention improvements per location: Point 4

Intervention improvements per location: Point 4			
Intervention	Operative Temperature (%)	Mean radiant temperature (%)	PMV (%)
Warm air circulators 1000w	6,1	0,6	32,7
Warm air circulators 2000w	3,1	1,3	**92,5**
Infrared heating panels	**13,9**	**27,6**	34,6
Infrared heating panels ceiling	-3,3	-7,5	6,5

Appendix: 22 – Research framework



Price elasticty of Comfort
Problem statement;
Energy crises pressure households to reconsider their indoor comfort and potentially accept a lower level of comfort. Dutch housing is not designed to accommodate these changes. Current adaptation strategies and interventions for tackling the issue of energy poverty are not effective enough.
Main question:
How can the effect of energy price increases on energy usage and the experience of thermal comfort be used to assess the effectiveness of interventions in reducing energy poverty?
Theoretical framework
Literature research & interviews
Energy poverty: - Definition - History - Drivers
Thermal comfort: - Definition - Experience - Standards - Adaptation
Financial stressors: - Definition - Causes - Social interplay
Building energy (in)efficiency: - Definition - Measures - Energy use efficiency - Comfort efficiency -Financial efficiency
Human effects of energy poverty: - Physical health - Mental health - Behavioural - Thermal comfort
Construction effects of energy poverty: - Indoor mould - Indoor mould effects
Strategies for combatting energy poverty: - Europe - Netherlands - Delft
Energy poverty in The Netherlands: - National scale - Municipal scale
Interventions for combatting energy poverty: - Basic scale - Intermediate scale - Advanced scale
Sub questions
How much are households willing/able to pay for thermal comfort?
Data-analysis
- Differences in energy prices over the years.
- Differences in energy consumption over the years.
- Differences in energy bills over the years.
- Correlation between energy prices and energy consumption.
- The energy price considered a maximum/threshold where energy consumption decreases.
How much comfort are households willing/forced to sacrifice in response to rising energy costs?
Data-analysis / literature review / interviews
- Energy consumption that people are likely to adopt during periods of price increases.
- Factors which affect this change in household energy consumption.
- Translating this into a difference in heat generation and maintained indoor temperature.
-Temperatures people are willing/forced to accept during periods of price increases.
- Implications of this change in indoor temperature.
How effective are current strategies in dealing with energy price increases and energy poverty?
literature review / interviews
- Review of national policy.
- Review of regional policy.
- Important take-aways
What is the appropriate definition of energy poverty?
Conclusions from literature review, data-analysis & interviews
- Drivers.
- Effects.
- Implications of definition.
How should strategies with the intent of dealing with energy price increases and energy poverty function?
How can interventions be assessed on their effectiveness in reducing energy poverty?
Research by design
- Framework which resembles how energy poverty cases should be assessed.
- Review criteria for interventions which resemble the different aspects of energy poverty.
- Method of application for the assessment of cases and the review of interventions.
How effective are current interventions at reducing energy poverty?
Simulation research
- Simulation of energy poverty case which logs the effect of different interventions.
- Effectiveness of individual interventions.
- Other relevant observations and relations between interventions and other aspects.
How effective has the chosen research methodology been and to what level are the results applicable?
Discussion
Conclusion
How can the effect of energy price increases on energy usage and the experience of thermal comfort be used to assess the effectiveness of interventions in reducing energy poverty?
How is the research reflected on and what are the implications of the research on societal and sustainability levels?
Reflection

Appendix: 23 – Comparison of frameworks R, U, Qv on façade interventions

Appendix 23.1 – Energy efficiency improvements

Energy efficiency improvements			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	4,7%	External wall insulation	5,9%
Indoor wall insulation	4,6%	Indoor wall insulation	5,5%
Thermal curtains	5,8%	Thermal curtains	7,7%
Insulated door panels	2,1%	Insulated door panels	2,7%
Average	**4,3%**	**Average**	**5,4%**
U value improvements			
Glazing replacement	10,3%	Glazing replacement	12,4%
Thermal curtains	5,8%	Thermal curtains	7,7%
Secondary glazing DIY	5,7%	Secondary glazing DIY	7,0%
Window insulation film	3,9%	Window insulation film	4,9%
Average	**6,4%**	**Average**	**8,0%**
Qv10 value improvements			
House air sealing	2,4%	House air sealing	3,1%
Weatherstripping	1,8%	Weatherstripping	2,3%
Draft stoppers	0,7%	Draft stoppers	1,0%
Average	**1,6%**	**Average**	**2,1%**

Appendix 23.2 – Thermal comfort improvements

Thermal comfort improvements			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	2	External wall insulation	1,7
Indoor wall insulation	2	Indoor wall insulation	1,7
Thermal curtains	2,2	Thermal curtains	2,1
Insulated door panels	0,9	Insulated door panels	0,8
Average	**1,8**	**Average**	**1,6**
U value improvements			
Glazing replacement	4,6	Glazing replacement	3,5
Thermal curtains	2,2	Thermal curtains	2,1
Secondary glazing DIY	2	Secondary glazing DIY	1,9
Window insulation film	1,6	Window insulation film	1,2
Average	**2,6**	**Average**	**2,2**
Qv10 value improvements			
House air sealing	1	House air sealing	0,9
Weatherstripping	0,7	Weatherstripping	0,7
Draft stoppers	0,3	Draft stoppers	0,3
Average	**0,7**	**Average**	**0,6**

Appendix 23.3 – Yearly savings

Yearly savings			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	45,9	External wall insulation	30,7
Indoor wall insulation	45,1	Indoor wall insulation	28,7
Thermal curtains	57,6	Thermal curtains	39,8
Insulated door panels	20,7	Insulated door panels	13,9
Average	**42,3**	**Average**	**28,3**
U value improvements			
Glazing replacement	101,7	Glazing replacement	64,4
Thermal curtains	57,6	Thermal curtains	39,8
Secondary glazing DIY	55,9	Secondary glazing DIY	36,4
Window insulation film	38,9	Window insulation film	25,5
Average	**63,5**	**Average**	**41,6**
Qv10 value improvements			
House air sealing	23,9	House air sealing	15,9
Weatherstripping	17,8	Weatherstripping	11,9
Draft stoppers	6,7	Draft stoppers	5,1
Average	**16,1**	**Average**	**11,0**

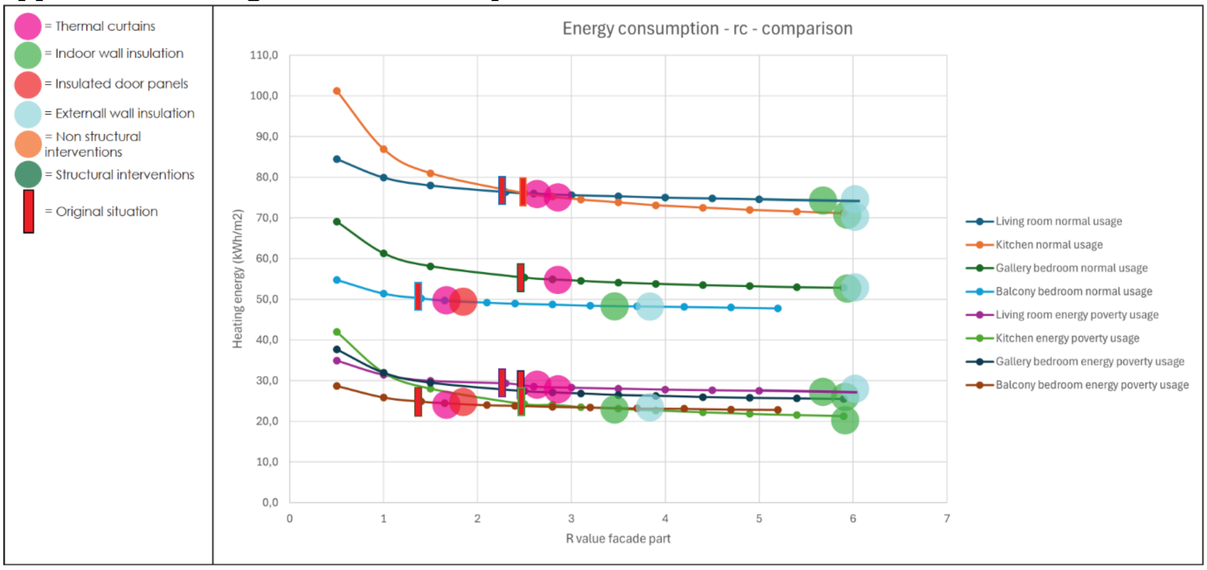
Appendix 23.4 – Payback period

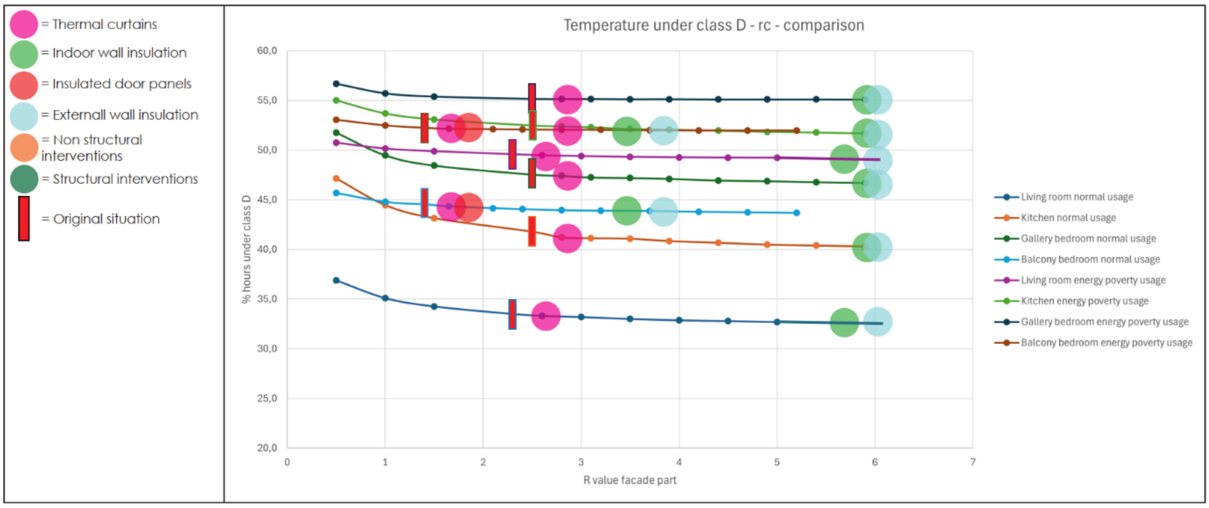
Payback period			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	101,6	External wall insulation	152,3
Indoor wall insulation	21,1	Indoor wall insulation	33,1
Thermal curtains	4,3	Thermal curtains	6,3
Insulated door panels	1,7	Insulated door panels	2,5
Average	**32,2**	**Average**	**48,5**
U value improvements			
Glazing replacement	17,7	Glazing replacement	27,9
Thermal curtains	4,3	Thermal curtains	6,3
Secondary glazing DIY	5,7	Secondary glazing DIY	8,8
Window insulation film	1,4	Window insulation film	2,2
Average	**7,3**	**Average**	**11,3**
Qv10 value improvements			
House air sealing	16,7	House air sealing	25,2
Weatherstripping	6,7	Weatherstripping	10,1
Draft stoppers	7,2	Draft stoppers	9,4
Average	**10,2**	**Average**	**14,9**

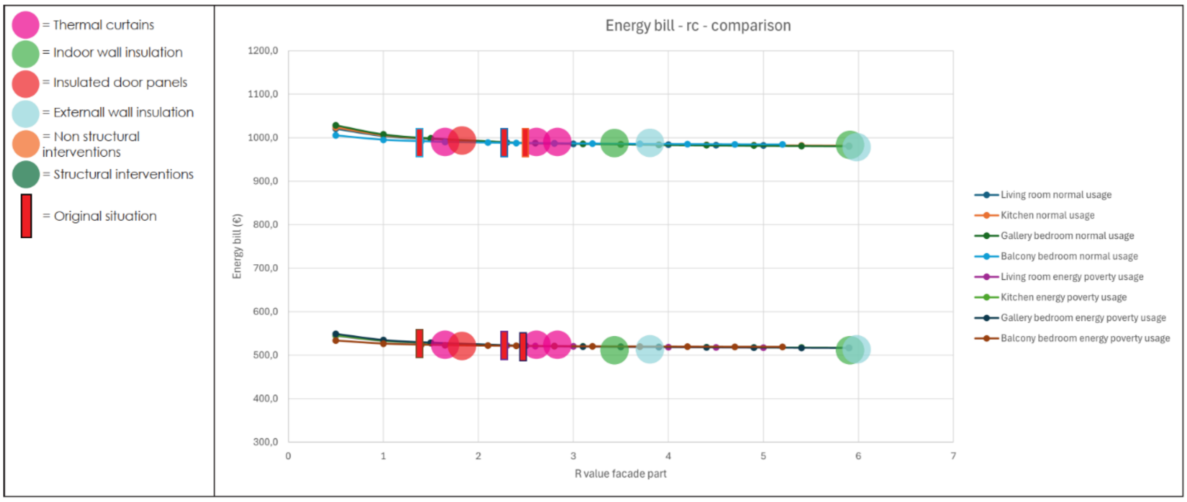
Appendix 23.5 – Investing efficiency

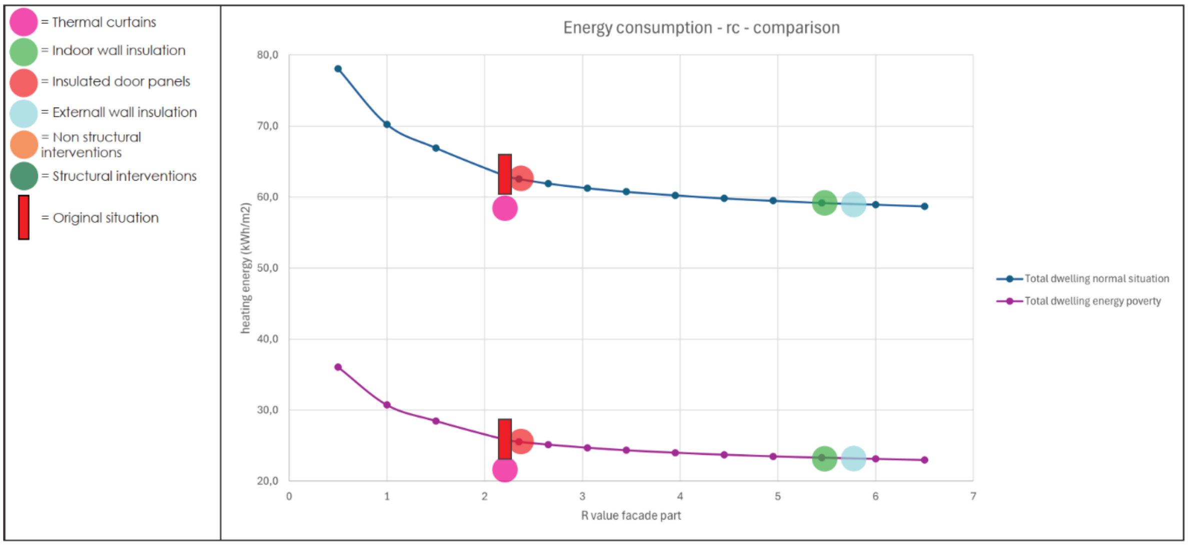
Investing efficiency			
R value improvements			
Normal usage		Energy poverty usage	
Intervention	Result	Intervention	Result
External wall insulation	1,0%	External wall insulation	0,7%
Indoor wall insulation	4,7%	Indoor wall insulation	3,0%
Thermal curtains	23,0%	Thermal curtains	15,9%
Insulated door panels	59,6%	Insulated door panels	40,2%
Average	**22,1%**	**Average**	**15,0%**
U value improvements			
Glazing replacement	5,6%	Glazing replacement	3,6%
Thermal curtains	23,0%	Thermal curtains	15,9%
Secondary glazing DIY	17,5%	Secondary glazing DIY	11,4%
Window insulation film	69,4%	Window insulation film	45,6%
Average	**28,9%**	**Average**	**19,1%**
Qv10 value improvements			
House air sealing	6,0%	House air sealing	4,0%
Weatherstripping	14,9%	Weatherstripping	9,9%
Draft stoppers	13,9%	Draft stoppers	10,7%
Average	**11,6%**	**Average**	**8,2%**

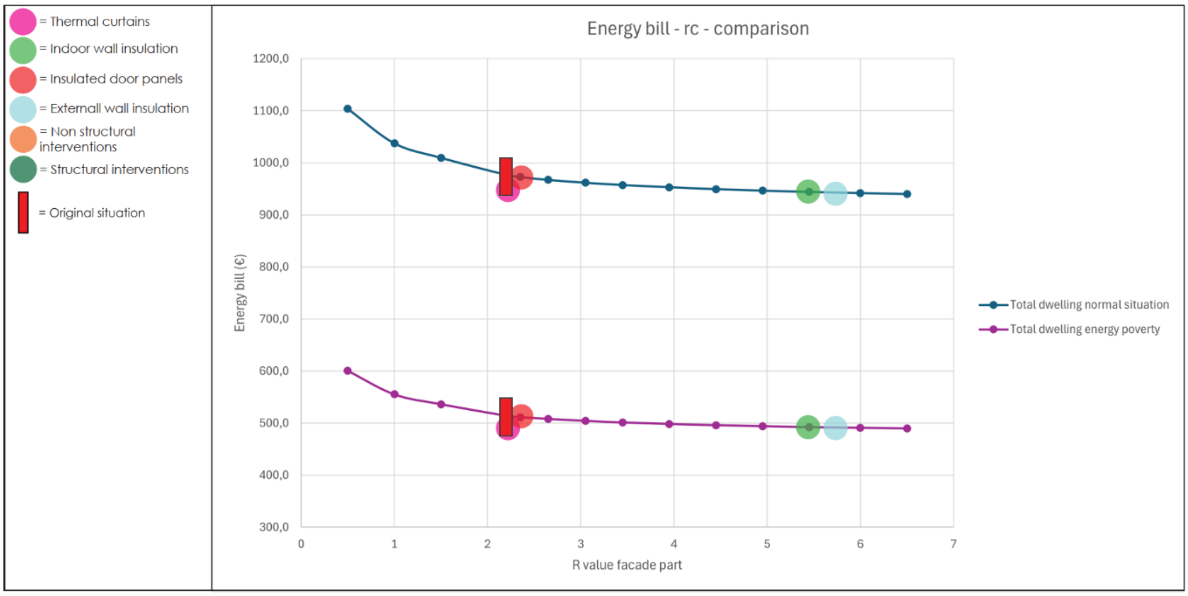
Appendix 23.7 – Figures – R value improvements



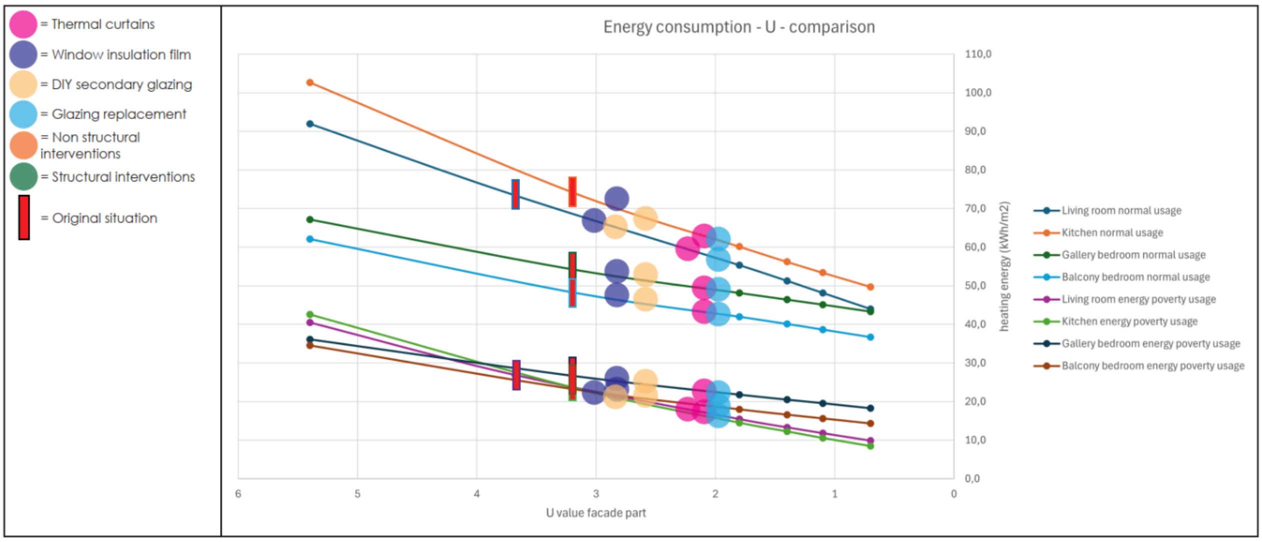

= Thermal curtains
= Indoor wall insulation
= Insulated door panels
= Externall wall insulation
= Non structural interventions
= Structural interventions
= Original situation
Temperature under class D - rc - comparison
% hours under class D
R value facade part
Living room normal usage
Kitchen normal usage
Gallery bedroom normal usage
Balcony bedroom normal usage
Living room energy poverty usage
Kitchen energy poverty usage
Gallery bedroom energy poverty usage
Balcony bedroom energy poverty usage

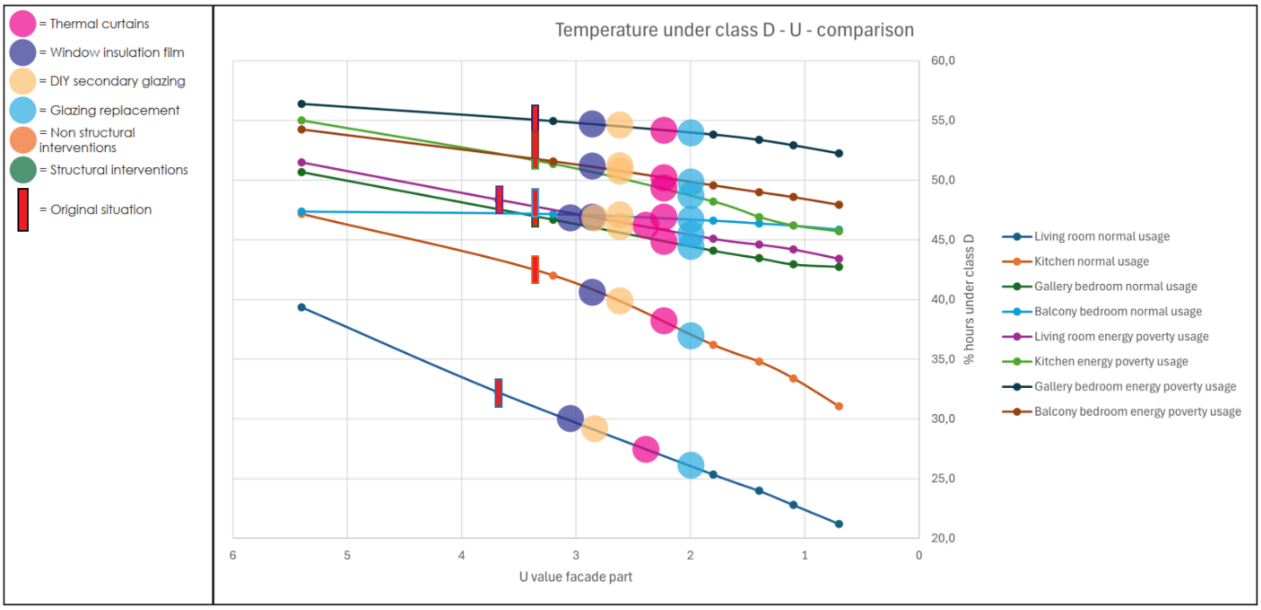

= Thermal curtains
= Indoor wall insulation
= Insulated door panels
= Externall wall insulation
= Non structural interventions
= Structural interventions
= Original situation
Energy bill - rc - comparison
Energy bill (€)
R value facade part
Living room normal usage
Kitchen normal usage
Gallery bedroom normal usage
Balcony bedroom normal usage
Living room energy poverty usage
Kitchen energy poverty usage
Gallery bedroom energy poverty usage
Balcony bedroom energy poverty usage

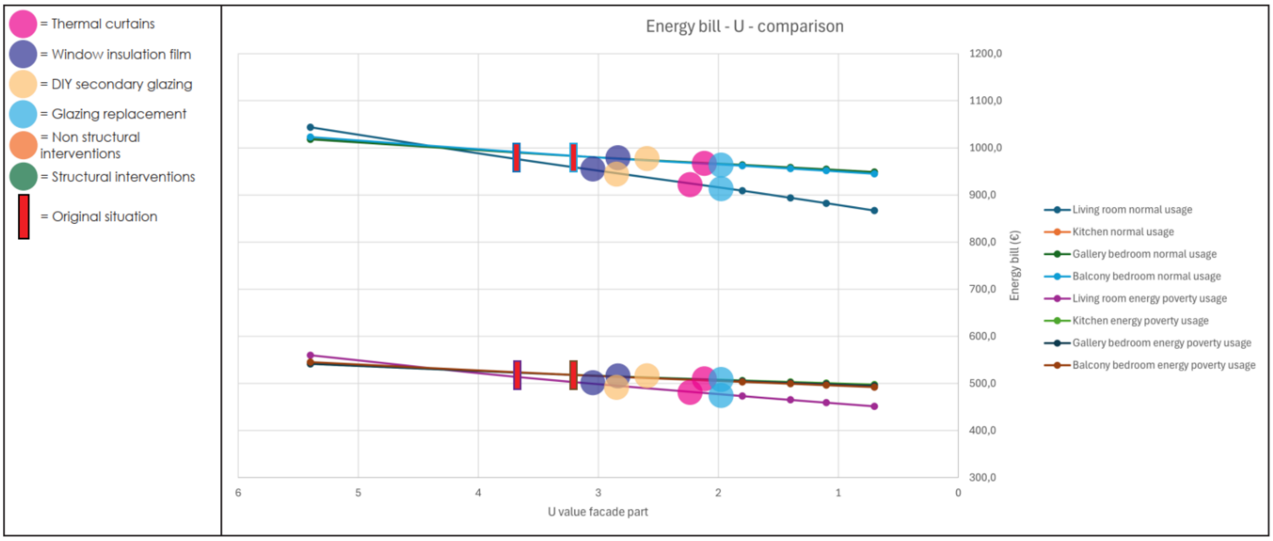

= Thermal curtains
= Indoor wall insulation
= Insulated door panels
= Externall wall insulation
= Non structural interventions
= Structural interventions
= Original situation
Energy consumption - rc - comparison
heating energy (kWh/m2)
R value facade part
Total dwelling normal situation
Total dwelling energy poverty

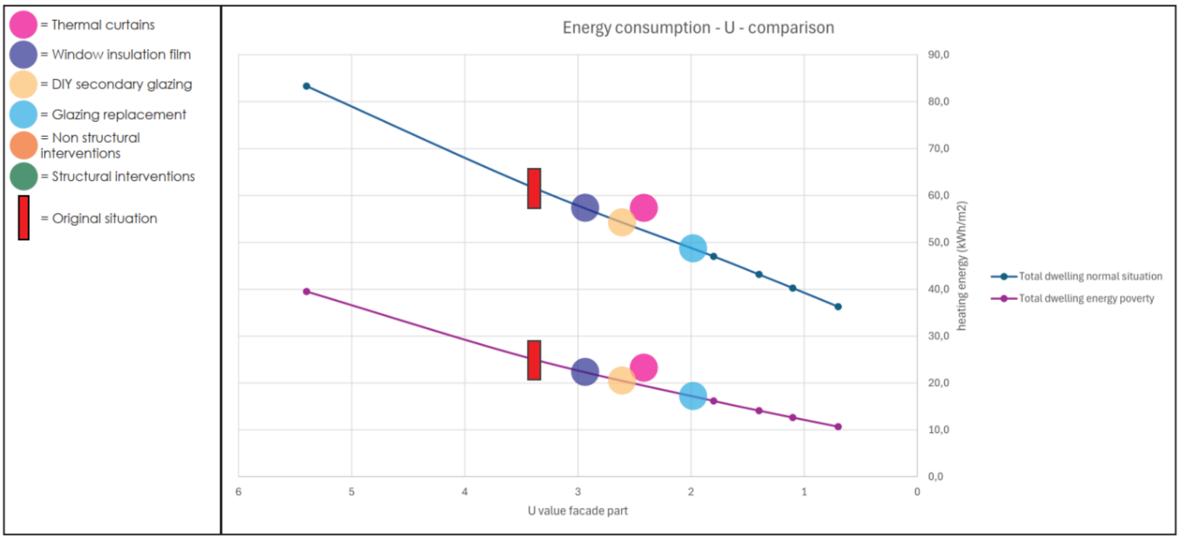

= Thermal curtains
= Indoor wall insulation
= Insulated door panels
= Externall wall insulation
= Non structural interventions
= Structural interventions
= Original situation
Energy bill - rc - comparison
Energy bill (€)
1200,0
1100,0
1000,0
900,0
800,0
700,0
600,0
500,0
400,0
300,0
0
1
2
3
4
5
6
7
R value facade part
Total dwelling normal situation
Total dwelling energy poverty

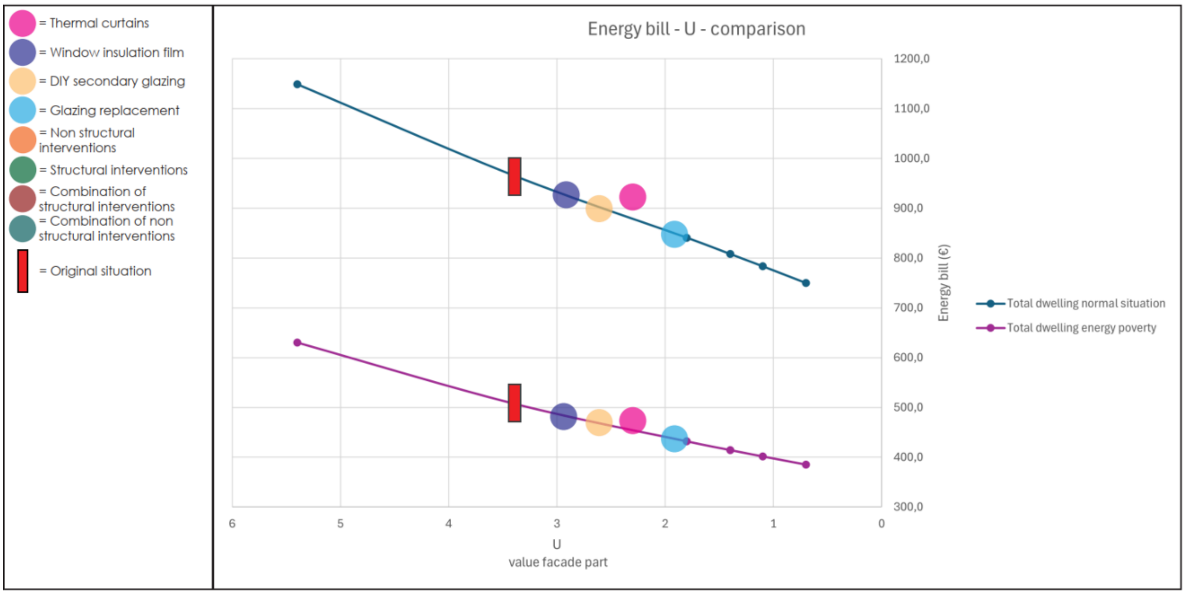
Appendix 23.8 – Figures – U value improvements



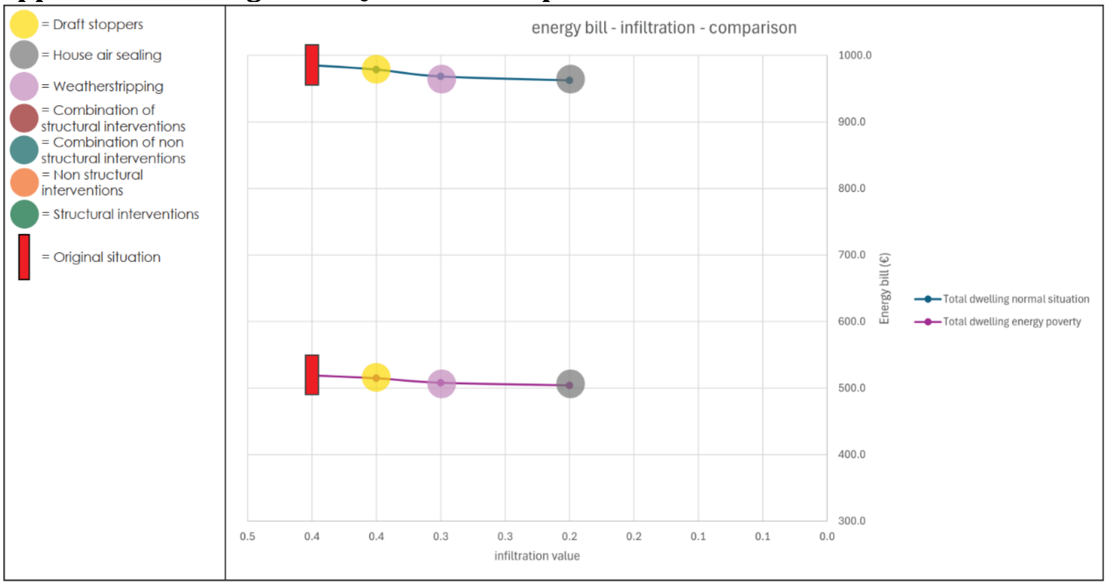





= Thermal curtains
= Window insulation film
= DIY secondary glazing
= Glazing replacement
= Non structural interventions
= Structural interventions
= Original situation
Energy consumption - U - comparison
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
heating energy (kWh/m2)
6
5
4
3
2
1
0
U value facade part
Total dwelling normal situation
Total dwelling energy poverty


= Thermal curtains
= Window insulation film
= DIY secondary glazing
= Glazing replacement
= Non structural interventions
= Structural interventions
= Combination of structural interventions
= Combination of non structural interventions
= Original situation
Energy bill - U - comparison
1200,0
1100,0
1000,0
900,0
800,0
700,0
600,0
500,0
400,0
300,0
Energy bill (€)
6
5
4
3
2
1
0
U
value facade part
Total dwelling normal situation
Total dwelling energy poverty

Appendix 23.9 – Figures – Qv10 value improvements



Appendix: 24 – Energy poverty assessment outline


Concern
1
There is concern to believe that energy poverty is a substantial problem in a certain building.
Review
2
To get an image on the energy poverty situation in the building, different aspects are reviewed.
Energy usage
2.1
Regular energy (gas) usage
Energy usage during high energy prices
Initial remperature indication
Building characteristics
2.2
Building construction year
Building quality
Building characteristics
Possible building bottlenecks
Target group
2.3
Occupant age
Occupant background
Incomes
Personal factors
2.4
Personal complaints
Specific questions
Personal insights and experiences
Review conclusions
3
The review of the building will lead to different conclusion into the problems and possibilities at play in the building.
Suggested approaches
4
The conclusions lead to the suggestion of approaches for combatting energy poverty. These approaches implement interventions on different scales.
Implementation
5
The assessment will conclude by providing notions on the most effective ways for implementing the approaches.
Basic interventions
4.1
Low budget & no/little installation
For example:
Localized air heaters
Draft stoppers
Thermal curtains
Intermediate interventions
4.2
Medium budget & DIY installation
For example:
Indoor wall insulation
DIY secondary glazing
Door and window weatherstripping
Advanced interventions
4.3
High budget & professional installation
For example:
Exterior wall insulation
Glazing replacements
House air sealing