

Retrofitting for Heat Resilience

A Dutch case study integrating overheating mitigation into cost-benefit analysis

MSc Thesis in Building Technology – P5 report
by Tamara Lalyko | 6075797

Mentors

Dr. Simona Bianchi

Structural Design & Mechanics, TU Delft

Dr. Alessandra Luna Navarro

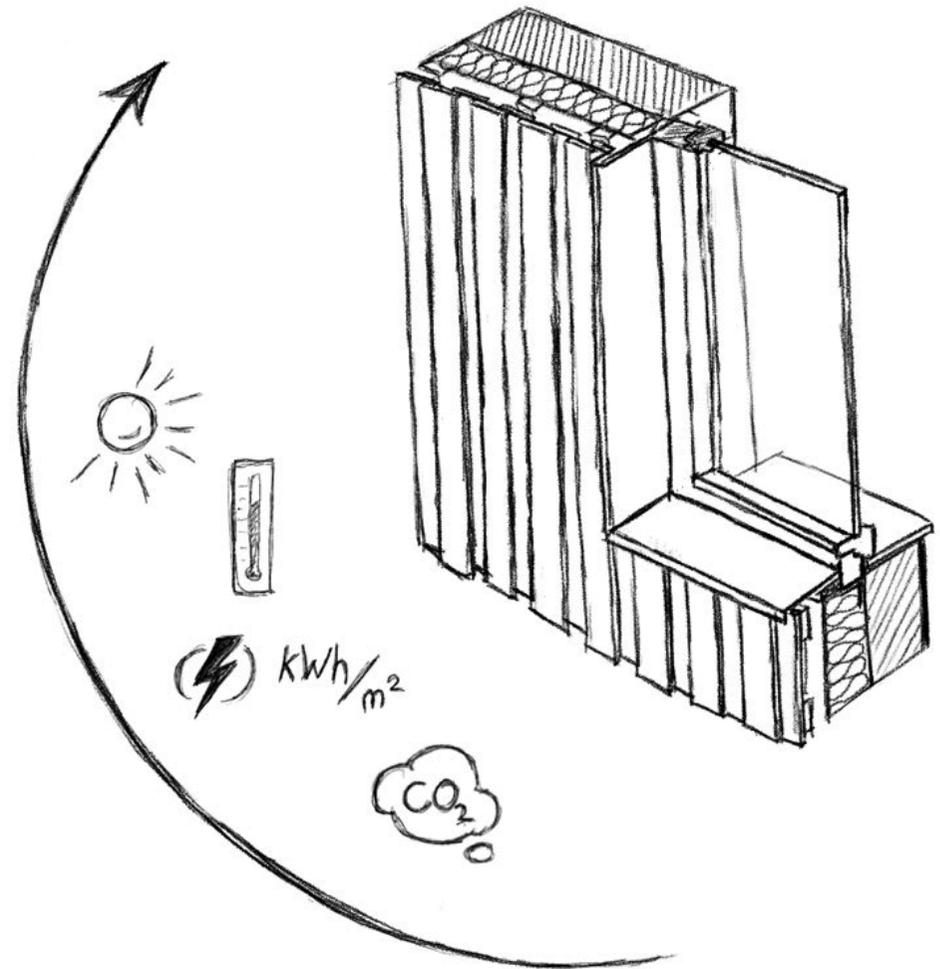
Facade & Product Design, TU Delft

Third Advisor

Ing. Diletta Ricci

PhD candidate, Design & Construction Management, TU Delft

Date 26.06.2025



Acknowledgements

First, I would like to thank my mentors for their trust and belief in me throughout the development of this research. I am especially grateful to Diletta Ricci, who volunteered as my unofficial third thesis coach, for her valuable guidance and collaborative work on the case study. I would also like to thank my mother for her thoughtful revisions and for encouraging deeper reflection in my writing. I am thankful to my friend Anja, from my bachelor studies, for her assistance with the architectural drawings. Finally, I extend my heartfelt thanks to my husband Joshua, as well as to my family and close friends, for their continuous emotional support throughout this journey.

Abstract

With climate change increasing the frequency and severity of heat waves in the Netherlands, the risk of buildings overheating poses a critical challenge to occupant health, energy efficiency, and sustainability goals. Despite regulatory progress on reducing energy-related emissions, current renovation practices often overlook overheating issues.

This study addresses this gap by integrating heat hazard loss as cost into a probabilistic cost-benefit analysis to assess the long-term benefits of improving resilience. The method can assist in decision-making when retrofitting by informing about the financial feasibility of mitigation, including the impact of recurring extreme events.

In a case study, renovation alternatives were tested on a housing unit in Rotterdam. The performance was evaluated considering energy efficiency, heat resilience, and carbon footprint. Using the developed framework, the distribution of costs and cost recovery under climate uncertainty were investigated.

The findings show that while passive cooling measures can significantly reduce overheating, their cost recovery is limited under current climate conditions. Still, the financial analysis shows that resilience improvements prevent operational cost from overshooting in the worst-case scenarios. Finally, integrating heating with cooling in a cost-benefit analysis can disclose counteracting measures that reduce the net benefit.

The study demonstrates that further investigation into cost-effective climate adaptation is crucial to building future-proof environments.

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1 Introduction

1.1 Background

Although the Netherlands is situated in a temperate climate zone, heat waves, a prolonged period of unusually high temperatures, are a rather likely hazard (ANV, 2022a). The impact of heat waves is substantially health-related and rated as 'very serious' by ANV, as they can affect large areas with the significance of impact relating to the number of casualties, lack of basic needs and disruption of day-to-day activities (Ibid). During heat periods when the daily maximum temperature exceeds 30°C, labor productivity decreases, followed by economic loss, and more severe, the general mortality rate going up (Ebi et al., 2021). Especially vulnerable groups, such as people older than 65 or chronically sick, are exposed to a greater risk of dying (Ibid).

Catastrophic		• Flooding from the sea			
Very serious	• Induced earthquake		• River flood	• Hurricane	• Heat/drought
Serious			• Snow storm		• Wildfires
Substantial			• Naturally occurring earthquake		
Limited					
	Very unlikely	Unlikely	Somewhat likely	Likely	Very likely

Figure 1 risk matrix – climate and natural disasters (source: ANV, 2022a)

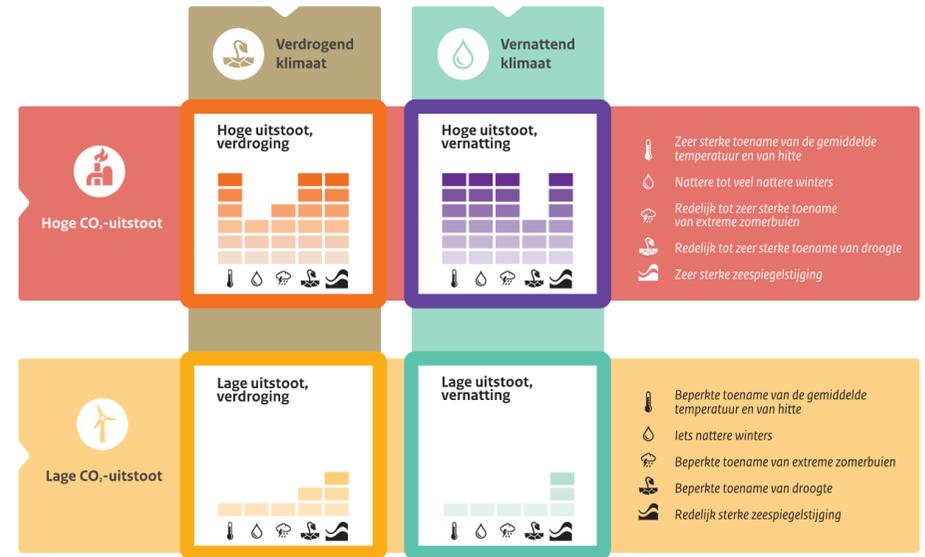


Figure 2. Vier scenario's voor klimaatverandering in Nederland. Het aantal blokjes staat voor de mate van klimaatverandering rond 2100 ten opzichte van 1991-2020. KNMI, 2023

Figure 2 KNMI – climate change scenarios (source: KNMI, 2023)

The KNMI, 'Koninklijk Nederlands Meteorologisch Instituut,' projects an increase likelihood and severity of temperature extremes mainly due to global warming, where the scale of impact will also be influenced by economic growth and demographic development. In 2023, KNMI reported a warming of 2°C since the start of temperature recordings, which has already caused heat waves to become more likely (KNMI, 2023). In 2019, for the first time temperatures above 40°C were reached in large parts of the Netherlands (KNMI - Juli 2019, n.d.). Because of the uncertainties around future climate development, the institute makes predictions for four different scenarios based on either high or limited greenhouse gas emissions development and assuming the climate to either become dryer or wetter (KNMI, 2023).

Considering a low-emission scenario the average of tropical days, $\geq 30^{\circ}\text{C}$, per year goes from 5 up to 9 with an unlikely occurrence of 40°C , but for a high-emission scenario the number rises to 30 with temperatures above 40°C to be expected almost every year (Ibid).

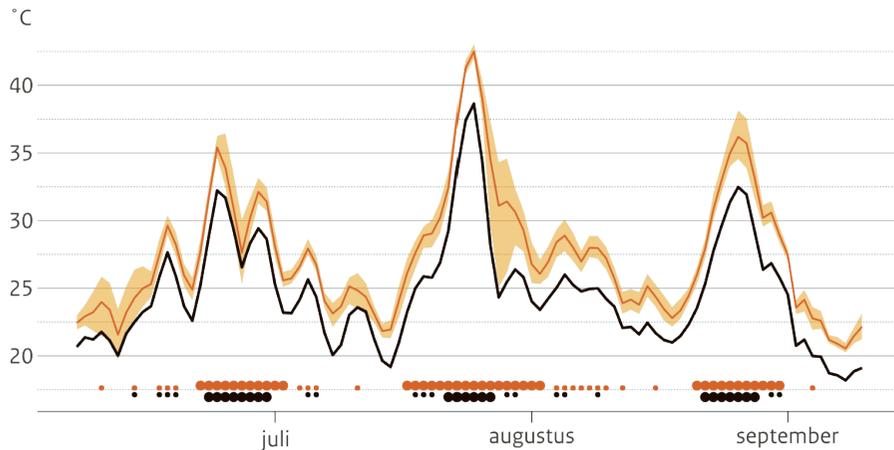


Figure 3 - Heat Wave 2019 projected to 2°C global warming (source: KNMI, 2023)

Based on the KNMI's climate scenarios, the NKWK published a climate damage report estimating property damage and public health costs to range between 77,5 and 173,6 billion euros by the year 2050, depending on the intensity and scenario of global warming (NKWK - KBS, 2020). The report of NKWK expects an increased annual mortality rate by 2050 of, on average, 192 to 657 more heat deaths. Furthermore, the report projects an increased hospital admission rate of 1,079 per 100.000 inhabitants (Ibid).

To mitigate climate change and therefore the impact of future thermal hazards, a reduction in carbon emissions and transition to renewable energy is

needed. According to the European Commission, over one third of the EU's GHG emissions come from buildings (European Commission, n.d.-a).

To achieve a reduction in emissions for energy use in buildings, the EU has set several targets with directives like the renovation wave and the energy performance directive for the building stock. With the renovation wave, the goal is to renovate 35 million buildings by 2030 (European Commission, n.d.-c). While, the energy performance directive aims to increase the average energy performance of the national residential building stock by 16% by 2030 in comparison to 2020, also by incorporating renewable energy sources and therefore reducing fossil energy use (European Commission, n.d.-a). The Dutch building regulation aims to comply with the EU directives by limiting transmission & infiltration values of building envelopes as well as specifying target percentages for renewable energy use (Long-Term Renovation Strategy, 2020; RVO, 2021).

These policies have changed renovation practice to address not only general quality of the buildings and indoor environment but also energy sources and efficiency. Introducing low temperature heating, retrofitting windows, adding insulation to the envelope has become standard practice (Koster, 2024; RVO, 2022).

In the context of heat, the indoor climate of buildings influenced by the main sources of heat, outdoor temperature levels and solar radiation, can warm up to a degree of discomfort or heat stress (NHBC, 2012). A study by Hamdy et al. revealed Dutch dwellings to be prone to overheating, which especially counts for better insulated buildings with large glazed areas (Hamdy et al., 2017). The 'BENG' regulation for new buildings attempts to limit risk of overheating by analyzing thermal comfort in typical summer month but the requirements do not apply for renovation (RVO, 2017, 2019).

Meanwhile, the interest in mechanical cooling systems is growing with 90% of fixed air conditioners installed in the past five years and 15-25% of households considering a purchase for the coming years (Rovers, n.d.).

In conclusion, the growing risk related to heat highlights the urgent need to reduce emissions and adapt buildings to prevent damage. Climate adaptation, also referred to as resilience, has become a recognized field of research. Resilience concerns the retaining of functionality over the duration of disruption.

1.2 Problem Statement

With the increasing frequency and strength of heat hazards in the Netherlands, buildings face a growing risk of overheating, endangering occupant health and comfort while raising energy costs for cooling. Thermally vulnerable buildings are especially affected, and the purpose of energy renovations could be undermined by additional cooling energy implying greenhouse gas emissions.

Integrating passive mitigation strategies in retrofitting presents a crucial strategy to prevent overheating before resorting to active cooling. However, current renovation efforts prioritize energy efficiency for winter conditions, often neglecting overheating. This oversight is further reinforced by the lack of regulatory incentives and by thermal performance assessment considering typical meteorological years without including variability from temperature extremes.

To address this issue, existing studies have developed methods to quantify functional, economic, and ecological losses using simulations of documented heat extremes or future climate scenarios. However, these approaches struggle to estimate expected losses over a specific time period due to uncertainties in climate development and event frequency. As a result,

building stakeholders lack clear understanding of losses to expect from their building's vulnerability over an investment and use case period.

Existing research lacks application of quantitative resilience assessment to analyze cost-benefit and inform the selection of renovation alternatives. In practice, financial feasibility and cost-effectiveness are essential factors in decision-making since the worth of investments can only be determined by relating cost and efforts to expected benefits or downsides. Investigating resilience in cost-benefit analysis could improve renovation practice by revealing mitigation potential and long term cost for measures and further help to identify co-benefits in scenarios like energy retrofitting.

1.3 Scope

1.3.1 Research Objectives

The study will propose a framework for cost-benefit analysis (CBA) of renovation measures at the envelope scale. Adopting a common CBA method, the aim is to integrate the impact of performance variability due to thermal hazard, either in the form of cost or comprehensive specific functional loss.

For the framework design, existing methods for thermal resilience assessment will be reviewed and implemented, taking into account probability, vulnerability, and exposure to thermal hazards. The framework's goal is to inform in-practice decision-making on resilience and financial feasibility. Heat resilience will consequently be assessed in terms of value to the project's stakeholders. Non-expert stakeholders, like owners or occupants, are the ones directly affected by renovation projects. Therefore, the understanding of how stakeholders are impacted by decisions made in renovation planning should be supported.

The focus of the study lies on economic viability and monetary benefits from retrofitting instead of selecting renovation measures purely based on effectiveness. As a result, a main challenge of the study will be estimating hazard losses and probability over the project period and integrating functional loss as cost into the cost-benefit. Furthermore, overheating mitigation needs to be integrated into energy renovation practice to avoid counteracting outcomes.

The cost-benefit analysis will be tested in an exemplary case study of a common residential archetype, that could be subject to retrofitting. The benefits of different envelope renovation packages will be explored, and their impact on the building's thermal resilience will be assessed. The case study aims to prove the method's applicability in a renovation scenario and indicate how thermal hazards impact cost-benefit and review how this could inform non-experts,

The overall goal of this study is to gain insights on heat resilience from a cost-benefit and long-term impact point of view. The research should contribute to the Western European perspective on overheating mitigation in milder climates, where it is not yet standard practice and appropriate adaptation measures needs to be explored. Ultimately, the study seeks to enhance the thermal resilience of buildings by supporting decision-making for cost-effective envelope systems in renovation scenarios.

1.3.2 Research question & sub-questions

Main research question

How can thermal resilience be integrated in cost-benefit analysis to inform decision-making of envelope retrofitting scenarios?

Sub-questions

Literature review

How does heat as a hazard affect buildings and their stakeholders?

How can thermal resilience be measured and indicated considering interest of building stakeholders?

What are mitigation measures and parameters at envelope scale to reduce risk of overheating?

How does heat vulnerability relate to objectives, requirements and processes for renovation in the Netherlands?

Which cost-benefit analysis methods are useful for retrofitting scenarios?

Main research

How can the uncertainty of weather extremes be assessed in cost-benefit?

How can impact from thermal hazard be integrated into cost modelling?

How can risks for long-term hazard loss be outlined in cost-benefit giving insights into resilience?

Use of outcome

How can resilience assessment with cost-benefit inform decision-making for envelope retrofitting?

1.3.3 Limitations

This study faces several limitations that are acknowledged to contextualize its later findings. First, it relies heavily on simulations and literature reviews as a non-experimental study. While simulations provide valuable insights, their validity is constrained by assumptions in the models and the quality of input data. The representation of thermal hazards is simplified, using general metrics and models that may overlook the complexity of interactions between hazards, like wildfires induced by heat and drought.

The framework emphasizes performance domains of interest to the project's stakeholders, like resilience, energy, and comfort, but might exclude domains relevant to the general public on a larger scale. Additionally, the framework won't be validated by stakeholders, limiting insights into its practical usability.

The focus on envelope scale retrofitting excludes broader architectural design parameters like wall-window ratios, room scales, or building typologies, which could significantly influence performance. Furthermore, the study compares a limited number of renovation packages, without investigating the impact of changing detailing parameters within one of them. Finally, the findings are specific to the building archetype and Netherlands and might not apply to other building types.

1.3.4 Methodology

The thesis develops a method for analyzing the cost-benefit of envelope renovations while integrating thermal resilience as a key factor. The research combines qualitative and quantitative methods using a literature review, probabilistic risk assessment, and performance simulation. Part of the research is also design-based, with literature references being used to propose renovation measures. The methodology follows a structured five-phase process, culminating in applying the proposed framework.

Literature Study

A state-of-the-art literature review using Scopus and public information from national institutes establishes foundational knowledge on heat resilience, renovation strategies, and early-stage decision-making. The first chapter outlines heat waves as a hazard, focusing on their impacting properties, the Dutch building stock's vulnerability, and the envelope systems' role in thermal performance. Further, the study identifies resilience metrics, hazard loss assessment methods, and passive mitigation strategies. Another chapter focuses on renovation practices to understand current retrofitting strategies, policies, processes, and benefits for stakeholders. Conclusions are then drawn on how thermal resilience relates to renovation interest. Finally, cost-benefit analysis methods are reviewed to find the most suitable for envelope retrofitting and risk assessment.

Framework Design & Implementation

Building on literature insights and case study requirements, the framework consists of two core components: 1.) Thermal Resilience Assessment, 2.) Cost-Benefit Analysis. The first part includes selecting a method for resilience loss quantification considering decision-maker interest and a metric that serves as a comparison index later in the case study. The second part of the framework

design treats the integration of resilience in cost-benefit decision-making. The method mainly focuses on thermal performance but also considers other criteria in the renovation of value to decision-makers depending on the renovation scenario of the case study. The development addresses the main challenge of assessing the uncertainty of weather extremes over a specific time period in cost-modeling. Retrofit costs are estimated using sources such as RVO's 'kostenkentallen,' and the framework is implemented digitally to analyze trade-offs between different retrofit strategies.

Study Preparation

The case study is developed in parallel with the framework to ensure alignment. The chosen case study is a unit of a residential apartment block in Rotterdam from 1950, representing an older generation of porched houses with low energy performance. Considering regulatory requirements, the decision-maker perspective is defined, and thermal renovation objectives are set. Further, the energy model and other necessary data will be prepared and gathered. Three renovation packages (light to deep intervention) are designed, balancing mitigation potential, cost intensity, and feasibility. If necessary, individual measures are tested beforehand. If necessary, their thermal performance is tested singularly, or their cost-intensity will be reviewed beforehand.

Case Study

The case study will exemplify the proposed framework's application in a specific renovation scenario. The aim is to showcase how heat vulnerability of envelope systems influences cost-effectiveness investigating the previously developed renovation packages. At first, the base case, assuming no renovation, is assessed in terms of running cost, e.g. energy or maintenance, and thermal resilience. Then, the renovation packages will be evaluated by first doing an annual energy and thermal comfort simulations using mild,

typical and extreme weather files. The performance results are then translated into monetary value and thermal resilience is quantified as a qualitative indicator. The variable annual capital costs of the baseline and retrofit are compared to assess savings or losses. Further, lifespan, involved costs, and effort, e.g., construction time, are estimated. Finally, the data is brought together in the cost-benefit analysis.

Evaluation of Results

The final phase evaluates the outcome of the case study. The analysis focuses on identifying the method's strengths and limitations. The quantified resilience index reflects how resilience becomes visible. The feasibility of integrating the framework into real renovation processes can also be questioned. Finally, suggestions for further exploration and for integrating additional resilience metrics and broader application scenarios are provided.

Literature Study		
Heat- Hazard & Resilience	Heat Resilience	Strategic Renovaton
<i>How does heat as a hazard affect buildings and their stakeholders in the Netherlands?</i>	<i>How can thermal resilience be measured and indicated considering interest of building stakeholders?</i>	<i>How does heat vulnerability relate to objectives, requirements and processes for renovation in the Netherlands?</i>
incl. Overheating Buildings Role of the Envelope	<i>What are mitigation measures and parameters at envelope scale to reduce risk of overheating?</i>	<i>Which cost-benefit analysis methods are useful in retrofiting scenarios?</i>

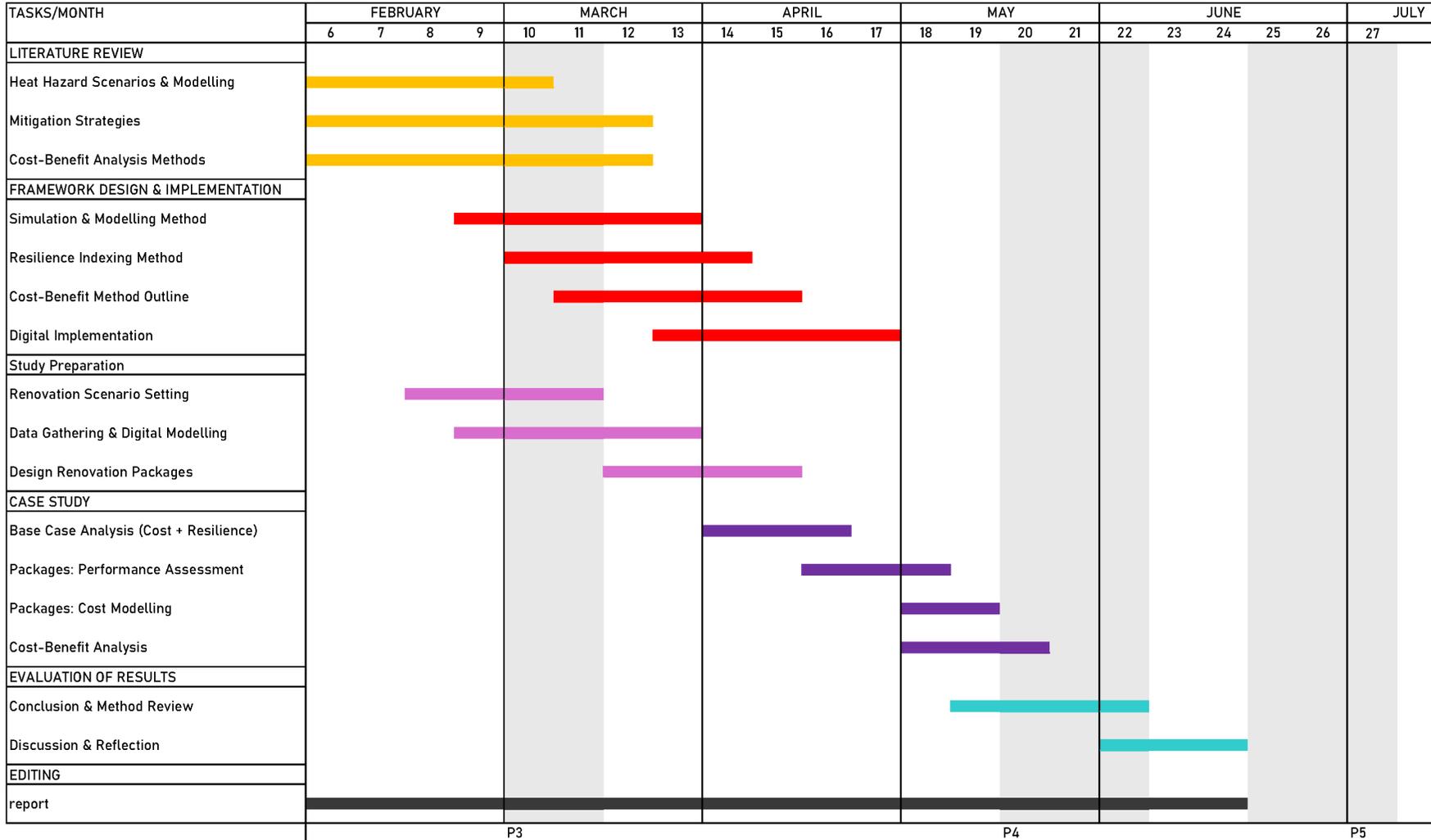
Framework Design & Implementation		Study Preparation
Resilience Assessment	Cost-Benefit	Renovation Scenario & Objective Data Gathering, Digital Modelling Renovation Packages light to deep Intervention mitigation potential, cost intensity, and feasibility
Hazard Modelling Method Hazard Loss Assessment Uncertainty/Performance Variability Resilience Index Metric + Digital Implementation	<i>How can the uncertainty of weather extremes be assessed in cost-benefit?</i> <i>How can impact from thermal hazard be integrated into cost modelling?</i> + Digital Implementation	

Case Study	
Base Case	Light - Medium - Deep Renovation Packages
Current annual capital cost Thermal Performance Simulation Resilience Index	Thermal Performance Simulation annual + thermal hazard Cost-Modelling Resilience Index
Cost-Benefit Analysis	

Evaluation of Results	
Case Study Results	Result Reflection
Conclusion & Method Review	<i>How can resilience assessment inform in practice decision-making for envelope retrofiting?</i>

Figure 4 Research Methodology Outline (source: own)

1.4 Timeline



2 Literature Review

Acronyms

<i>Short</i>		<i>Full Term</i>
AMY	-	Actual Meteorological Year
AWD	-	Ambient Warmness Degree
CBA	-	Cost-Benefit Analysis
CEA	-	Cost-Effectiveness Analysis
CEI	-	Carbon Emission Intensity
COA	-	Cost-Optimal Analysis
EUI	-	Energy Use Intensity
GTO	-	Weighted Limit Temperature

HDD - Heating Degree Days

IOD - Indoor Overheating Degree

NPV - Net Present Value

OEF - Overheating Escalation Factor

PP - Payback Period

TMY - Typical Meteorological Year

2.1 Heat as a Climate Related Hazard

2.1.1 Hazard Definition

Heat waves are a prolonged period of unusually high temperatures (AghaKouchak et al., 2020). Definitions of exact temperature levels that are recognizable for heat vary between climate zones. Therefore, the EU, as an international institution, uses the definition of "a period when maximum apparent temperature (Tappmax) and minimum temperature (Tmin) are over the ninetieth percentile of the monthly distribution for at least two days" (Climate ADAPT, n.d.). For the Netherlands, the Dutch Meteorological Institute framed heat waves more concretely as "a period of at least 5 days, each of which has a maximum temperature of at least 25°C, including at least 3 days with a maximum temperature of at least 30°C (measured at the De Bilt station)" (KNMI, n.d.-a). However, it is noteworthy that meteorological stations do not necessarily measure temperature conditions in dense urban areas, where heat can intensify and last longer (Hamdy et al., 2017).

As previously mentioned, the impact of thermal hazards can be both related to health and economic loss. To assess the most important criterion, 'human perception of temperature levels,' it is essential to consider several influential factors and not only outdoor air temperature (Ebi et al., 2021). The Universal Thermal Climate Index (UTCI) can be used as a metric for the human physiological response to meteorological conditions describing equivalent temperature (°C) (Climate ADAPT, n.d.). The following environmental parameters: air temperature, radiant temperature, wind speed, and humidity influence the metric. The UTCI also considers the clothing adaptation of the population in response to outdoor temperature. To classify heat stress, the UTCI values are divided into 5 levels of heat stress, from no thermal stress to extreme heat stress (See Table 1).

Table 1 - heat stress level (source: Copernicus Europe, 2024)

Stress Category	Temperature range [°C]	Physiological responses	Protection measures
No heat stress	+9 to +26	Averaged sweat rate* of >100 g h ⁻¹ Plateau in rectal temperature time gradient*	Physiological thermoregulation* is enough to ensure thermal comfort. This means that individuals can maintain a thermal equilibrium without excessive strain on the body.
Moderate heat stress	+26 to +32	Change in sweat rate and rectal and skin temperature. Occurrence of sweating at 30 minutes. Mild stress may be experienced, but the body's ability to regulate temperature is generally effective. Individuals may feel some discomfort but can adapt without major physiological strain.	Drinking >0.25 L-1
Strong heat stress	+32 to +38	Averaged sweat rate of >200 g h ⁻¹ ; Rectal temperature increases after 30 minutes' exposure.	Drinking >0.25 L-1; Temporarily reduce physical activity.
Very strong heat stress	+38 to +46	Low core-skin temperature gradient. Increase in rectal temperature after 30 minutes' exposure. Increased strain on the body's thermoregulatory mechanisms. Individuals may experience discomfort, and prolonged exposure could lead to mild thermal strain	Temporary use of air conditioning. Shaded places necessary. Drinking >0.5 L-1. Reduce physical activity.
Extreme heat stress	Above +46	Increase in rectal temperature time gradient. Steep decrease in total net heat loss. Average sweat rate >650 g h ⁻¹ ; Severe strain on the body's thermoregulation. This category is associated with an increased risk of	Temporary body cooling and drinking >0.5 L-1 necessary. No physical activity.

		heat-related health issues, and precautions are necessary to avoid heat-related illnesses.	
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Overheating Buildings

On the other hand, the direct impact of heat on a building is relevant to understanding the losses happening within buildings. Most relevant for overheating are two external sources, the outdoor temperature levels and solar radiation, causing a thermal load on indoor conditions (Hamdy et al., 2017). Solar radiation is absorbed and re-radiated by the external facade layer and when falling through glazed openings also by indoor furniture and surfaces (Lomas & Porritt, 2017). This way heat builds up directly indoors or is conducted from the facade through the envelope, which can also be induced by outdoor temperatures (Ibid). Additionally, there can be internal heat sources contributing to indoor temperatures such as occupants, lighting, appliances and building services (Ibid). Apart from heat sources, ventilation is an important factor contributing or mitigating overheating (NHBC, 2012). Hot outdoor air entering the building can drive up air temperature and further heat the space. At the same time, ventilation creates air flow, which can lower perceived temperatures and if the outdoor air temperature is lower than indoors e.g. nighttime the air flow absorbs the heat back from indoors (Ibid).

Further, there are more influential factors relating to the environment, orientation and construction system of the building. Environmental factors can be surroundings of heat storing sealed surfaces, missing vegetation or heavy traffic in proximity (AghaKouchak et al., 2020; Hamdy et al., 2017). Orientation of a building matters specifically in terms of exposure to the sun. Regarding the construction system, a heavier building will take longer to heat up and cool down due to the heat accumulation in dense materials (NHBC, 2012).

Due to the thermal load, energy use intensity kWh/m² for keeping indoor spaces at thermal comfort level increases (Sun et al., 2016). For material and

component levels, thermal expansion and inertia can affect general performance and durability (Ramakrishnan et al., 2017; Wüest & Luible, 2017).



Figure 5 - Causes for Overheating (source: own)

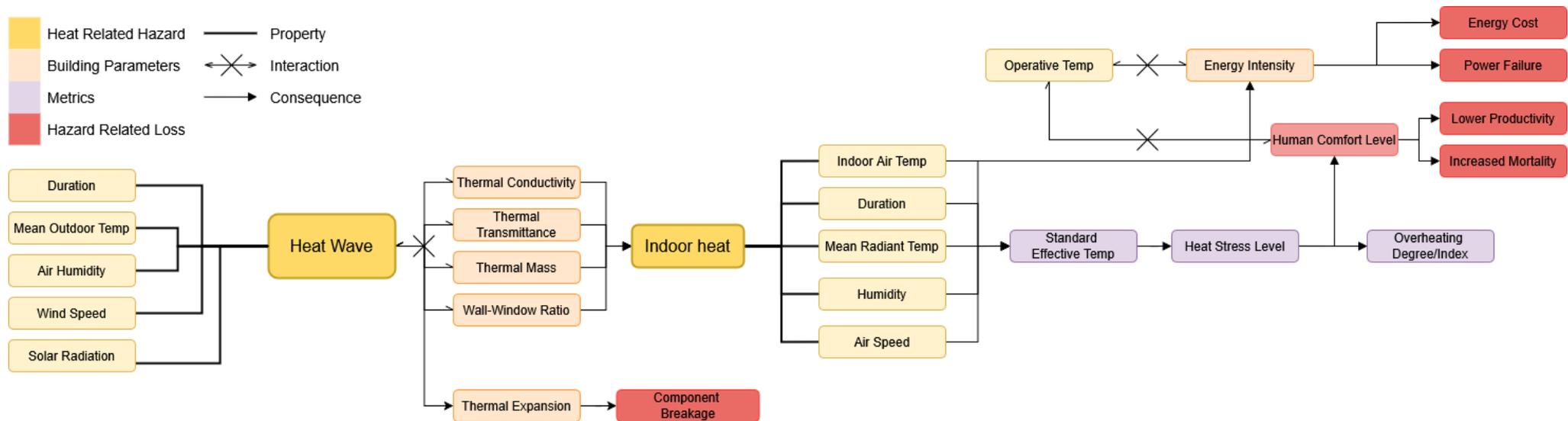


Figure 6 Thermal Hazard Flowchart (source: own)

2.1.2 Regional Context

In the Netherlands, heat waves as thermal hazard are a rather likely event with an annual average of 4.47 days with at least strong heat stress occurring between 1981 and 2010 (Climate ADAPT, n.d.; KNMI, n.d.-a).

A thermal hazard example with severe impact is the heatwave from the 22nd till 27 of July in 2019. The heatwave lasted for 6 days with regionally varying temperature levels. In the east of the Netherlands, the temperature was generally higher and lasted longer. Several weather stations recorded the highest ever measured temperatures in the Netherlands with the most extreme in Gilze-Rijen of 40,7°C on 24th of July (KNMI - Juli 2019, n.d.). The heat was seriously consequential as mortality rose nationwide with in total 400 deaths more than during an average summer week (Reuters, 2019). Mainly

older generations were affected. In total, 1,687 people 80 years or older died, meaning 300 more than during an average summer week (Statistics Netherlands, 2019). The heat also caused incidences of livestock death often due to failing ventilation systems (B.V, 2019).

In a report in 2022, the ANV published projections for hazard risk scenarios also evaluating heat waves. The heat scenario concluded the consequences of combined high intensity heat and drought with a return period of 1/25-30 years. To model the scenario, the heat wave from 2019 and a drought event from 2018 were used as exemplary events occurring simultaneously. The affected area was estimated to be larger than 10.000 km², concerning more than 1 million people for up to 3 months. The total expected loss was rounded up to 2 billion euro with a 13% cut in GDP for more than a month. The event would have consequences for the supply of basic resource needs such as electricity, water and food. The increased mortality was estimated to be around 650 (ANV, 2022b).

In 2017, Hamdy et al. used a self-developed overheating index to test several typologies, giving insights into the heat vulnerability of Dutch dwellings. The risk of overheating was most significant for houses with larger unshaded glazed area e.g. certain detached houses and or lower heat transmission e.g., apartments with a small, well-insulated façade area in the middle of an apartment building. Especially in older dwellings with low insulation and low solar protection flats on upper floors had a higher risk of overheating than ground floors. In comparison, a lower risk was assessed for semidetached houses and ground-corner apartments. The study showed that also more recent better insulated buildings are at risk of overheating (Hamdy et al., 2017).

2.2 Quantitative Resilience Assessment

2.2.1 Definitions

This brief summary aims to better understand the technical terms around the topic of resilience. Exposure, fragility, and vulnerability are two important terms in risk assessment. While exposure refers to 'the condition of being unprotected, especially from severe weather,' fragility refers to the quality of being easily damaged or broken (Merriam Webster, n.d.-a, n.d.-b). Both inform vulnerability as it is defined as 'the system's ability to withstand the impacts of hazards on elements at risk given the intensity of the hazard' (Kim, 2023). Being vulnerable respectively means that in case a hazard of a certain strength occurs, there is a high expected functionality loss or a significant probability of failure.

Resilience, in turn, is related to vulnerability but includes the development of functionality over time from when a disruptive event occurs. It is, therefore, defined as 'the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events' (National Research Council, 2012). This means that response and recovery are the two important interconnected phases of assessing resilience after a disruptive event. The expected losses

over time after disruption then add to a resilience loss. Consequently, increasing resilience can be achieved by lowering the probability of failure to consequences, and speeding up the time of recovery (Bruneau & Reinhorn, 2006).

Bruneau et al. (2003) listed four main dimensions of resilience for physical and social systems: robustness, redundancy, resourcefulness, and rapidity. Robustness means withstanding a given level of stress or demand without any losses. Redundancy means the extent to which parts of a system are substitutable. Resourcefulness is using resources with the right prioritization to achieve goals under limitations. Rapidity refers to recovery and time spent to contain losses (Bruneau et al., 2003).

Besides resilience, Nassim Taleb also defined 'Antifragility' in the context of finance markets. He defined it as a 'state of going beyond robustness,' meaning that 'something does not merely withstand a shock but improves because of it' (Taleb, 2013).

In the context of buildings, exposure to climate hazards is important to the building's structure and the envelope. The envelope is the direct shield from severe weather conditions unwanted in an indoor climate. While vulnerability of the envelope refers to the extent of expected functionality or economic loss, resilience can be measured in terms of loss reduction, including time and ability to recover.

2.2.2 Resilience Assessment Process

In 2024, Kim et al. outlined a process for quantitative resilience assessment based on probabilistic risk assessment. Typically, risk is the product of hazard, exposure, and vulnerability, considering hazard intensity, probability, and system fragility (Kim et al., 2024).

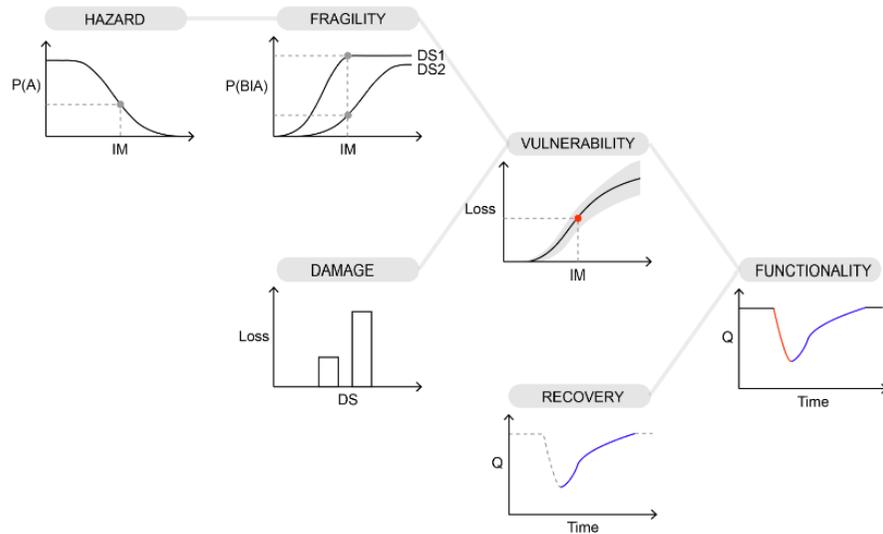


Figure 7 procedure for quantitative resilience assessment (source: Kim et al. 2024)

In quantitative resilience assessments, the parts of risk assessment are used to assess functionality over time, including recovery. First, a hazard probability for a given location is plotted in relation to its intensity as a stressor. Then, the fragility of the system is expressed in several curves determining the probability of exceeding different limit states based on hazard intensity measure (IM). With fragility, the expected loss from exceeding limit states can be assessed. Following, vulnerability can be plotted as the mean of distributed functionality loss in relation to hazard intensity. After determining functional recovery, the functionality development can be plotted over the time span of the disruptive event. The integral loss of functionality over time then expresses resilience loss in turn (Ibid).

2.2.3 Thermal Resilience

2.2.3.1 Performance Assessment

Thermal resilience refers to reducing functionality and economic loss from the effects of heat on a facade and building. As discussed previously, there are three possible subjects, human comfort, energy efficiency and component level thermal performance, which could also include structural stability. Therefore, mitigation can either focus on the indoor thermal environment or the impact of radiation and temperature on facade systems (Hamdy et al., 2017; Ramakrishnan et al., 2017; Sun et al., 2016; Wüest & Luible, 2017). The focus of most studies either lies on human comfort level or energy efficiency, while component performance is seemingly not as relevant.

Energy performance and human comfort are indirectly related, as comfort is dependent on energy performance (Lee et al., 2024). During heat waves, cooling systems demand an excessive amount of energy, which can coincide with power outages (Ibid). So, energy efficiency can also indicate vulnerability to comfort disruption.

There are several performance indicators for both subjects. The most popular for energy efficiency is energy use intensity in kWh/m^2 (See Table 2). For thermal comfort, there are several metrics based on different temperature indicators, such as Heat Index, 'Standard Effective Temperature', or 'Operative Temperature' (Hamdy & Hensen, 2015; Kim, 2023; Lee et al., 2024). Comfort limits indicating overheating can be fixed based on regulatory indications or adaptive, considering different environments or the time and temperature levels at which they occur (Hamdy et al., 2017).

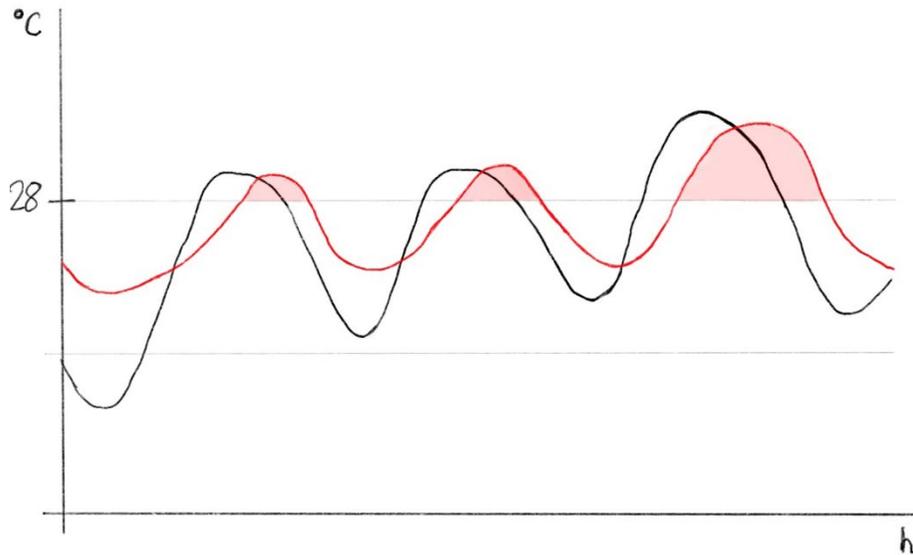


Figure 8 - Heat Resilience Quantification (source: own)

Resilience Metrics

In this section, resilience metrics from the literature are reviewed to further understand existing quantification methods and their applications in research.

Regarding energy, several studies analyze how energy performance develops under thermal hazard or in future climate scenarios (See Table 2). They all quantify energy use intensity [kWh/m^2], also called 'Energy Performance Index', but the application often differs in the period analyzed (Lassandro & Di Turi, 2017; Sun et al., 2016). The results represent the annual expected value or additional expected energy needed due to extremes (Lee et al., 2024). Generally, the metric compares performance across facade systems or effectiveness of retrofitting options (Bianchi, 2023; Lassandro & Di Turi, 2017).

Lee et al. (2024) also looked at the changes in annual cooling energy use and converted it to primary energy demand. Knowing the total energy use, two studies further estimated the utility cost as expected economic loss (Bianchi, 2023; Sun et al., 2016).

Some studies added environmental impact to the energy performance analysis. Bianchi et al quantified energy-related emissions as expected carbon loss during a hazard event (Bianchi, 2023; Lee et al., 2024).

Studies, such as Lee et al.'s, combine energy performance with comfort metrics to investigate the passive resilience of the construction without technical cooling (Kim et al., 2024; Lee et al., 2024).

Other studies use metrics custom to energy supply disruption, such as 'Passive Survivability', 'Hours of Safety', Thermal autonomy, or 'Temperature-Weighted Thermal Performance' (Nahlik et al., 2017; Sheng et al., 2023). However, some of these metrics have only been applied to cold snaps (Ibid).

Table 2 – energy resilience metrics

<i>Resilience Metrics /Indicators</i>	<i>Description / Quantification Method</i>	<i>Research Purpose</i>	<i>References</i>
Energy Use Intensity /Energy Performance Index	Energy Demand/Use per square meter for a specific period (e.g. average year) [kWh/m ² per a]	Testing various retrofitting strategies and measures for building envelopes case study analysis: assisted living facilities	Baglivo et al., 2023; Lassandro & Di Turi, 2017; Sheng et al., 2023; Sun et al. 2016
Energy Use/ Demand	annual or additional energy needed for e.g. cooling [kWh]	Analysis of retrofit scenarios on vulnerable multi-family buildings in disadvantaged communities	Lee et al., 2024
Primary Energy Demand	annual or additional primary energy depending on energy source & system [kWh]	/	Lee et al., 2024
Utility Cost, Economic Loss	Expected annual loss or [Euro, Dollar]	Multi-criteria comparison of facade systems in mediterranean climate;	Bianchi, 2023; Sun et al. 2016
Expected Carbon Loss	Energy related carbon emissions hazard specific [kg/CO ₂ eq.]	/	Bianchi, 2023

Most of the thermal comfort metrics developed and applied in literature are based on temperature indicators taking several climate condition parameters into account (Kim, 2023; Lee et al., 2024; Ramakrishnan et al., 2017). This is

done to get closer to the real human perception of temperatures, as it depends not only on indoor air (Ibid). While the 'Heat Index', for example, combines dry indoor air bulb and relative humidity, 'Standard Effective Temperature ' also includes mean radiant temperature, air speed, clothing, and metabolic rate (ASHRAE, 2017). To determine overheating in general or with level stages, comfort limits are set as fixed or adaptive using standards and guides like CIBSE or ASHRAE (Hamdy et al., 2017; Kim et al., 2024). Categorical stages of overheating are then classified, ranging from safe to extreme danger (Ibid). In their studies, Ramakrishnan and Lee et al then count the hours where the temperature indicator surpasses the comfort limits as overheated hours.

Another quantification method introduced by Hamdy et al is calculating the hourly temperature difference to the comfort limit and dividing the sum by several values collected, defining the Indoor Overheating Degree (Hamdy & Hensen, 2015). To then relate the indoor overheating to the temperature intensity of the climate scenario, the study proposes to divide the 'Indoor Overheating Degree' by the 'Ambient Warmness Degree' (Ibid).

In 2023, Mirzabeigi et al. extended this method with the 'Weighted Unmet Thermal Performance', where severity of overheating is weighted based on the point in time it is occurring (Mirzabeigi et al., 2023). Using this metric, the study defines resilience class labels to categorize a building's thermal resilience (Ibid).

An exception from most metrics is the building heat performance index (BHPI) because it is not connected to actual weather conditions but describes a building's general thermal fragility (Nahlik et al., 2017). It is quantified by calculating the time elapsed for the indoor temperature to rise from 25°C to a free-running outdoor temperature of 32°C. The study of Nahlik et al. uses this method to classify building archetypes on an urban scale.

Table 3 - Thermal Comfort Metrics

<i>Resilience Metrics /Indicators</i>	<i>Description / Quantification Method</i>	<i>Research Purpose</i>	<i>References</i>
Heat Index (HI)	Combination of dry indoor air bulb temp. & relative humidity to approximate temperature perception; categories safe to extreme danger; distribution of hours with the heat index levels in danger and caution conditions; categorize each hour during an extreme even	Resilience/Vulnerability of Housing to thermal hazard during power outage; Case study analysis housing in disadvantaged communities or assisted living facilities	Sheng et al., 2023; Lee et al., 2024
Hours in Heat Stress	Using Standard Effective Temperature; Calculation of hours where SET >30°C for the period of an extreme event	""	Lee et al., 2024
Indoor Overheating Degree (IOD)	intensity and frequency of overheating with fixed of adaptive comfort limits; temperature difference between indoor free-running temp and temp limit summarized over a period with the time step of an hour, collected for all building zones & averaged over the number of ones and hours (use of CIBSE limits: living areas >28°C, bedrooms>26°C for more than 1% of the annual occupied hours; use of fans	Analysis of average and extreme scenarios for a comparative ranking of the Dutch dwelling stock, Determine and compare resilience indices for present and future scenarios; Comparing resilience retrofit packages in case of power failure	Hamdy et al. 2017; Mirzabeigi et al. 2023

	justifies temp increase up to 3°C depending on air speed) _no use of cooling systems_;		
Overheating Escalation Factor	IOD/Ambient Warmness Degree at 18°C is the Overheating escalation factor (>1 means worse indoors than generally outdoors); Ambient warmness degree is the average of cooling degree hours during summer when outdoor air temp is not lower than 18 (May to Sept)	""	Hamdy et al. 2017; Mirzabeigi et al. 2023
Weighted unmet thermal performance (WUMTP)	multizone indicator with fixed limits; temperature indoors is weighted based on the point in time it is occurring (degradation/recovery); Measured in Degree Hours or degree hours/m²	""	Mirzabeigi et al. 2023
Resilience Class Index	Labeling system A-F based on WUMTP	""	Mirzabeigi et al. 2023
Predicted Thermal Sensation (PTS)	Weighting scale based on SET;0-2 neutral to warm	Comparing facade systems in two cases: 1. cooling system operating also during a heat wave, 2. cooling system power failure during heat wave; used to define limit states for facades	Kim et al., 2024
Building heat performance index (BHPI)	outlines how fast a building overheats; fixed comfort limit 32°C; Calculate the time elapsed for the indoor	Thermal Performance of Building Archetypes under extreme heat to map the urban	Nahlik et al. (2017)

	temperature to increase from 25 to 32°C (or depending on fixed limit)	scale	
Temperature Weighted Thermal Performance	combining BHPI and temperature projections; 'average census tract performance indices are weighted by multiplying by the predicted future 97.5th percentile temperature for that census tract divided by the maximum future predicted temperature for that city'	""	Nahlik et al. 2017
Metrics based on Discomfort Index; Overheated Hours; hours 80% acceptability not met; severe discomfort hours	Discomfort Index (DI) average of wet bulb & dry bulb; this temperature then indexes heat stress mild below 24°C, moderate 24-28°C, severe >28°C; distribution of hours using indoor operative as the weighted mixture of mean radiant and dry bulb temperature; Hours 80% acceptability limits in an adaptive comfort model ASHRAE; (adaptive limits e.g. Australia 20.5–27.5 °C)	Effect of Phase Change Materials on overheating, Analyzing effect of PCM panels, also in combination with night cooling	Ramakrishna n et al., 2017

2.2.4 Dutch Building Regulation

The Dutch building regulations specify two metrics for assessing overheating. The first 'TO July' is included in the norm NTA 8800 and applies to new buildings required to meet the 'BENG' standard without technical cooling. It is a dimensionless metric with a maximum value of 1. To determine the metric, a

building zone's cooling demand is calculated for July, dependent on facade surface per orientation (Rahif et al., 2022).

$$TO_{july;or,zi} = \frac{(Q_{C,nd,july,or,zi} - Q_{C,HP,july,or,zi}) \times 1000}{(H_{C,D,july,or,zi} + H_{gr,an,july,or,zi} + H_{C,ve,july,or,zi}) \times h_{juli}}$$

$Q_{C,nd,july,or,zi}$ cooling demand for orientation or in zone zi;

$Q_{C,HP,july,or,zi}$ cooling units' extracted energy by the booster heat pump for orientation or in zone zi;

$H_{C,D,july,or,zi}$ direct heat transfer coefficient between the heated space and the outdoor air for orientation or in zone zi;

$H_{gr,an,july,or,zi}$ direct heat transfer coefficient or building elements in thermal contact with the ground for orientation or in zone zi;

$H_{C,ve,july,or,zi}$ direct heat transfer coefficient through ventilation for orientation or in zone zi;

h_{juli} total time over July.

The second metric is 'Weighted Limit Temperature' (GTO), which provides a more accurate estimation of overheating in case the TO July slightly exceeds the maximum. The GTO is the sum of weighting factors for hours in July based on the calculated 'Predicted Mean Vote' (PMV) exceeding a threshold of 0.5 and weighted proportional to the 'Predicted Percentage Dissatisfied' (PPD). The GTO also has a limit value of 450 (Rahif et al., 2022).

$$GTO = \sum W f_{i,NTA 88000}$$

$W f_{i,NTA 88000}$ weighting factor using a table for PMV and PPD.

2.2.5 Hazard Scenario Modelling

To quantify thermal resilience, specific outdoor climates conditions are assumed either as static extreme heat as done by Nahlik et al. or actual or typical hourly weather data.

Several studies analyzed the thermal resilience to recent historical hazards or picked a hot summer week (Lassandro & Di Turi, 2017). Although real hazard scenarios are generally known to be exceptionally extreme, probabilistic assessment was not part of these studies.

Another approach in thermal resilience studies is the analysis of annual weather data representing either typical or extreme meteorological conditions (Hamdy et al., 2017). Many studies further include future projections from global climate models, such as CSIRO-Mk3-6-0.5 or HadCM3 (Nahlik et al., 2017; Sun et al., 2016). The models are used to morph climate files to usually three points in time, e.g., 2030, 2050, and 2070, considering also the development of GHG emissions, respectively, RCP2.6 (mild), RCP4.5 (medium), and RCP8.5 (high) (Baglivo et al., 2023). Since the scenario probabilities were unknown, Sun et al. assigned probabilities of 60% for no change, 22.5% for little change, 12.5% for moderate change, and 5% for extreme changes. In another study, Hamdy et al. used projections for 2100 for both an average summer and extreme summer provided by the Dutch norm NEN 5060, where the extreme has a 5% probability of occurring in the present. However, while the average scenario was projected using 2°C global warming, for the extreme scenario, 4°C was used and 1.4 °C added to account for the urban heat island effect (Hamdy et al., 2017).

All of the studies reviewed applied numerical simulation software to estimate indoor climate conditions and energy loads. Numerical models are used to simulate complex physical behaviour using mathematical representations with simplified assumptions (Sirois & Grilli, 2015). The most common tool was EnergyPlus, either on its own or as an engine for CityBes or Honeybee plugin,

the Grasshopper Environment of Rhino 3D (See Table 4). Other software tools were Termolog 13, IDA-ICE, or TRNSYS. For managing a large set of simulations, a study by Sun et al used the jEPlus as a parametric tool for Energy Plus. Furthermore, plugins like Bombyx for Grasshopper were integrated to calculate embodied and operational carbon. After simulation, some studies used Matlab or Python scripts to post-process results (Hamdy et al., 2017; Kim et al., 2024).

Table 4 - Hazard Scenario Modelling in Literature

Reference	Focus	Hazard Scenario	Simulation
Baglivo et al., 2023	Energy	Typical meteorological years morphed to 2030, 2050, 2075 for each RCP2.6, RCP4.5, & RCP 8.5 using <i>Meteonorm</i>	Energy simulation in <i>Termolog 13</i> , using annual hourly data, exported from <i>Meteonorm</i>
Bianchi, 2023	Energy & Emissions	specific example of an intense heat wave scenario (<i>from recent years</i>) + TMY	<i>EnergyPlus</i> , Grasshopper Model, Bombyx Plugin (for life cycle analysis)
Hamdy et al. 2017	Thermal Load (based on comfort)	Summer period: May to September; present average & extreme scenario, future scenario and worst future scenario projected to 2100; extremes based on Dutch standards NEN 5060 probabilities of 5% an actual warmer summer, incl. Urban Heat Island effect	<i>IDA-ICE version 4.6</i> ; accuracy assessed by 'IEA Solar Heating and Cooling program', <i>MATLAB</i> script for statistical analysis
Kim et al., 2024	Economic loss and alternative thermal comfort loss	Comparing actual meteorological data of an extreme to TMY	Honeybee in Grasshopper, <i>EnergyPlus</i>

Lassandro & Di Turi, 2017	<i>Thermal Load</i>	Hottest annual period (week) of July (year unknown)	<i>Design Builder/ EnergyPlus</i>
Lee et al., 2024	<i>Energy, Thermal Comfort</i>	2018 & 2058 annual energy simulation, heat wave (Thermodynamic Global Warming (TGW) dataset v1.0.0)	<i>EnergyPlus, CityBES</i>
Mirzabeigi et al. 2023	<i>Thermal Comfort</i>	hot week from July 31st incl. 4-day power failure (TMY EnergyPlus Weather Repository)	<i>Honeybee in Grasshopper (EnergyPlus)</i>
Nahlik et al. 2017	<i>Thermal Comfort</i>	static extreme outdoor heat of 97.5th percentile exceeding historical data and CSIRO-Mk3-6-0.5 global climate model project future temperatures till 2050	<i>TRNSYS</i>
Ramakrishnan et al. 2017	<i>Thermal Comfort</i>	hourly weather data of the heatwave period of 27–31, January 2009 in Melbourne from Bureau of Meteorology	<i>EnergyPlus, Sketchup</i>
Sheng et al., 2023	<i>Thermal Comfort, Energy</i>	six-day heat wave 2015, three day cold snap 2021	<i>EnergyPlus</i>
Sun et al. 2016	<i>Energy, Cost</i>	3 different weather condition scenarios with HadCM3 (low, medium, high) unknown probabilities were assigned	<i>EnergyPlus, jEPlus as a parametric management tool</i>

2.3 Mitigation Measures & Strategies

2.3.1 Strategies & Role of the Envelope

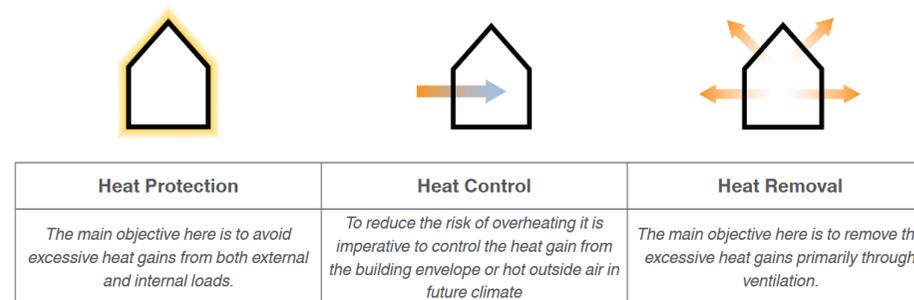


Figure 9- overheating mitigation strategies (source: Wahi, 2020)

Considering that the most relevant causes for overheating are outdoor temperature levels and solar radiation, mitigation measures can be clustered into three main strategies: heat protection, control, and removal (Wahi, 2020). Heat protection refers to avoiding heat gains from external and internal sources by, e.g., reducing or shading glazed areas, using efficient appliances, or coated glazing for solar control (Ibid).

Then controlling heat gains means slowing down temperature absorption by, for example, increasing the insulation of the envelope and windows or having high Albedo light-colored external surfaces (Ibid). Furthermore, nearby outdoor vegetation can help in controlling the surrounding micro-climate (Ibid). Several studies indicate that green roofs or facades can improve indoor thermal comfort and significantly decrease energy costs by lowering peak temperatures (Guo et al., 2024; Lassandro & Di Turi, 2017).

The third category, heat removal, stands for to effective ventilation and strategic placement of thermal mass. In terms of natural ventilation,

convection air flows and wind pressure can be utilized with cross ventilation, low and high apertures, or nighttime ventilation (Wahi, 2020). On the other hand, mechanical ventilation or ceiling fans can assist in lowering perceived temperatures through air flow and remove heat stored in interior surfaces (NHBC, 2012). These ventilation strategies can further be combined with placing high mass elements on the internal side of the envelope (Ibid). The thermal lag effect causes a shift from warmer indoor temperatures to periods, e.g., nighttime, when the outdoor climate has possibly cooled down (Ibid). The stored heat is slowly released back into the indoor air and can be effectively removed by ventilation (Ibid). An alternative application of phase change materials as panels for the internal sides of walls or ceilings (Lassandro & Di Turi, 2017). Phase change materials have a similar effect by absorbing energy, when changing from solid to fluid, which can significantly reduce the hours of severe discomfort (Ramakrishnan et al., 2017).

It can be concluded that the envelope system design impacts all three levels of protection, control, and removal. This proposition is further underlined by findings from sensitivity studies indicating the properties most important for mitigation (Kim, 2023). These properties include thermal conductivity and transmittance in general to a certain degree, heat capacity and material density related to thermal mass, and the wall-window ratio (Ibid).

2.3.2 Applicability for residential buildings

In 2020, Wahi reviewed mitigation strategies applied by literature to adapt residential buildings.

The measures include the following for protection: managing internal gains, solar protection through shading or shutters. Regarding heat control, the review lists both internal, external and cavity wall insulation, but also green facades and high Albedo facade surfaces. Finally heat removal was integrated by increasing exposed thermal mass, enabling cross & night time ventilation and active ventilative or evaporative cooling (Wahi, 2020).

In the following study design chapters, the list of measures will be considered and reviewed for applicability in the case study.

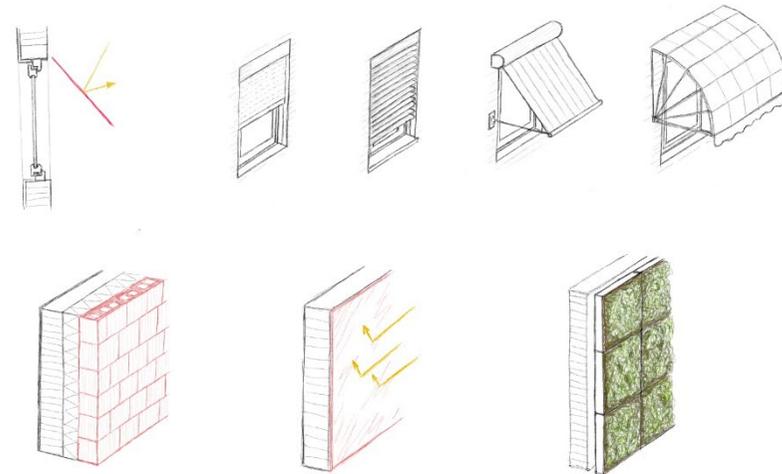


Figure 10 - Mitigation Measures (source: own)

2.4 Renovation Practice

This chapter will explore present renovation practices in the Netherlands. Therefore, several topics will be reviewed including regulatory requirements, renovation process, benefits and bottlenecks.

2.4.1 Energy Renovation Measures

Measures to increase efficiency with renovation mostly concern three domains: transmission, infiltration, and efficient heating systems. Transmission losses can be tackled by increasing insulation rate and avoiding thermal bridges, while airtight sealing of openings and demand-driven and pressure-regulated ventilation decrease infiltration losses. To make the energy supply side more efficient, common measures are introducing heat recovery systems and enabling renewable heat sources, such as heat pumps and low-temperature heating. Low-temperature heating works best when larger heating surfaces enhance the heat transfer coefficient (Koster, 2024).

2.4.2 Dutch Building Stock & Renovation in Numbers

The number of households in the Netherlands is growing. In 2024, there were about 8.4 million, and for the periods of 2022 and 2030, the government projects an increased demand of 900.000 homes, making a yearly average of 100.000 homes respectively (Centraal Bureau voor de Statistiek, n.d.; RVO, 2024).

The government plans to accommodate about 15% of the demand by transforming existing buildings (RVO, 2024). However, the number of residential apartment transformations is decreasing while the number of newly built residential buildings is rising. With 8,755 transformations and 73.638 new-built housing in 2023, the total number is still 20,000 short, and the target quote is missing 5% (Centraal Bureau voor de Statistiek, n.d.).

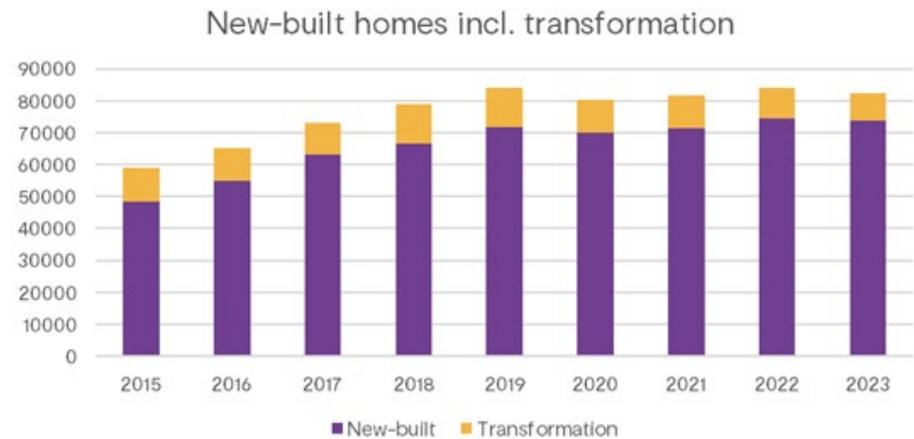


Figure 11 - Development of new homes (source: CBS)

In the Netherlands, most residential buildings are occupied by their owner, respectively 58% in 2019, followed by social rental housing making up 29% and private rental homes accounts for the smallest percentage with 13% (Long-Term Renovation Strategy, 2020). There is a wealth disparity between the occupant groups of owner-occupied and social housing. Naturally, social housing is only available to certain income groups (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2013).

The most common Dutch building archetype is the terraced house, but older detached houses and apartment blocks also make up a significant portion (Pinotti & Perneti, 2021). Concerning the age of the building stock, it is noticeable that about half of Dutch residential buildings were constructed before 1975, and the remaining half is almost equally divided between before and after 1995 (Long-Term Renovation Strategy, 2020).

The Netherlands requires all residential buildings that are being sold, rented out, or delivered to acquire an energy label indexing the energy efficiency of a building. For the label, the fossil energy use intensity (kWh/m² per year) is

evaluated, whereby only consumption for heating, hot tap water, cooling, and ventilation is considered as building-related energy. The collected data is representative of the entire stock, with a clear indication of newer buildings, built after 1995 being more likely to be more energy efficient. Also, owner-occupied homes generally receive more favorable energy labels, while the percentage for unfavorable labels like F or G is more than double for private rental housing (Long-Term Renovation Strategy, 2020).



Figure 12 - Development of new homes (source: CBS)

For the Dutch building stock, insulating roofs and windows are more common than ground-floor slabs and facades. Looking at the accommodation types, again, owner-occupied homes have higher insulation rates for all parts of the envelope, while the ones for private rental homes are significantly lower. The average insulation level for façades and glass is approximately the same in social housing and owner-occupied homes.

In the Netherlands, natural gas is still the biggest source of heating energy, and heating also accounts for the highest energy demand out of all building-

related energy (Long-Term Renovation Strategy, 2020). However, policymaking directly targets a change towards more renewable energy, with e.g., the Gas Act from 2018, which limits new houses from accessing the gas mains (Ibid).

The statistical data contributes to understanding the parties interested in renovation. In the Netherlands, in most cases, the owner and occupant share the same interests, with enough resources available to upgrade their living environment. This also means that the real estate market is focused on investing in selling rather than renting out property. For the other large share of households, social housing associations are responsible for quality management, and their actions are tightly linked to authorities' directives and guidelines. Occupants of social housing belong to lower-income groups at risk of being affected by poverty.

2.4.3 Standards & Requirements

The trend of homes becoming more energy efficient is continuously growing, with policies and directives guiding its way. Part of the EU's energy performance directive is 'nearly energy neutral buildings,' which became a requirement for new buildings in 2020 and the Netherlands (European Commission, n.d.-b). The Dutch name for the directive is BENG, 'bijna energie-neutraal gebouwen,' and the method for determining the energy value of a building is included in the norm NTA 8800. The method uses three indicators: (1.) maximum energy demand in kWh per m² floor area per year, (2.) the maximum primary fossil energy use, also in kWh per m² per year, and (3.) the minimum percentage of renewable energy (RVO, 2017).

Table 5 - Requirements for new-builts and major renovations from Praktijkboek Besluit bouwwerken leefomgeving (source:own)

subject	New-built (BENG)	Major Renovation
Energy	Maximum fossil share 50 kWh/m ² , min. 40% renewables	Min. share renewable $\geq 30 * A_{\text{roof}}/A_{\text{g;tot}}$ [kWh/m ² *a] roof/ floor area (NTA 8800)
Thermal Conductivity [m ² K/W]	Roof: 6.3 m ² K/W Facade: 4.7 m ² K/W Floor: 3.7 m ² K/W (openings 1.65 W/m ² K)	Roof: 6.0 m ² K/W Facade: 4.5 m ² K/W Floor: 3.5 m ² K/W (openings 1.65 W/m ² K)
Infiltration (qv10)	Rooms with outdoor connection $qv_{10} \leq 200$ dm ³ /s if <500m ³	Rooms with outdoor connection $qv_{10} \leq 200$ dm ³ /s if <500m ³
Overheating	TOjuli max. 1 limited overheating in a representative july	none

Also, renovation interventions and refurbishments of thermal energy systems must comply with energy regulations. For major and energy system renovations, a minimum share of renewable energy was introduced in 2022 (RVO, 2021). Major renovation is officially defined as a change of the building envelope larger than 25%. Regarding thermal conductivity, the minimum Rc value for the roof is 6.0 m²K/W, for the façade 4.5 m²K/W and the floor 3.5 m²K/W. The opening requirement is set as a maximum thermal transmittance of 1.65 W/m²K. However, the study 'long-term renovation strategy' found the regulatory values to overshoot the cost-optimal (Long-Term Renovation Strategy, 2020).

2.4.4 Renovation Process

This chapter outlines a general process for renovating building envelopes reviewing three different papers (See Figure 13). In 2024, Prieto et al. summarized phases of a renovation process from three other papers, going from pre-project to pre-construction, construction and then post-construction. Generally, the phases for renovation are similar to the process for a new building, but differ with the extended pre-project phase for analysis and diagnostic and then defining the intervention scope. The pre-construction phase translates to design and planning phase, where a suitable solution is developed and chosen. Then at construction stage this solution is realized and during post-construction its performance is being monitored and maintained (Prieto et al., 2024).

Since, the process for the envelope as part of renovation involves more detailed phases, two more papers outlining a general process, life cycle and decision making stages of facade design were considered (Bianchi et al., 2024; Moghtadernejad et al., 2018). They both include the steps conceptual building design, preliminary and detailed facade design. However, the listed assignments vary especially between preliminary and detailed facade design. Bianchi et al. (2024) included durability considerations already for the preliminary phase and maintenance planning at the detailed stage, while Moghtaderneja et al. (2018) did the opposite. Further, Moghtaderneja et al. (2018) listed several structural performance considerations such as Earthquake, Wind or Blast resistance and deformations for the detailing phase. At the same time, Bianchi et al. did not describe assignments that detailed. For this study, the decision was made to include durability in the conceptual phase in accordance with Bianchi et al. and interpret safety & sustainability which both papers listed in preliminary design as initial considerations of structural stability (Ibid).

From all three studies, a combined chart in Figure 13 was drawn to outline the assignments and decision-making stages throughout a renovation process for

building envelopes. The process includes all four phases from Prieto et al. (2024), but further parts them into sub-stages and more detailed assignments.

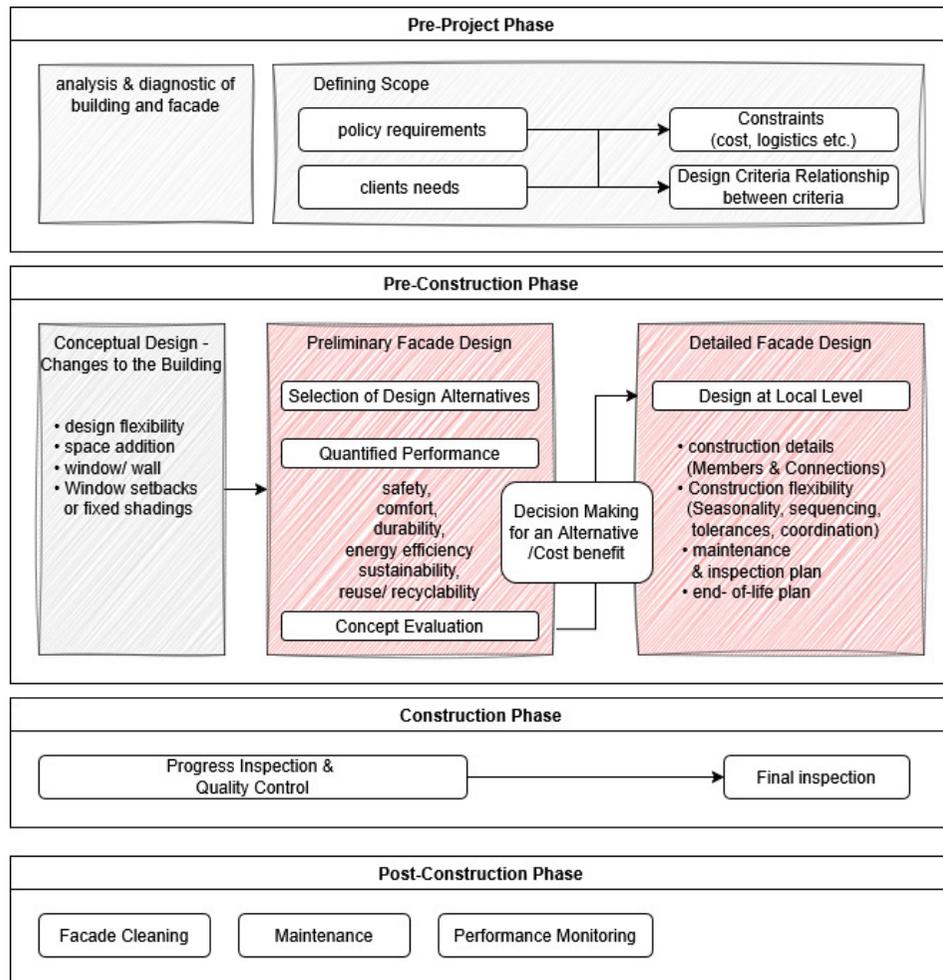


Figure 13 renovation process outline (source: own)

During pre-project phase, the existing building and facade are examined and to define the intervention scope, design criteria and constraints the clients needs are identified and policy requirements considered. Pre-construction includes all three stages from conceptual building design, preliminary facade design to detailed facade design. For renovation, the concept concerning the general building is limited to changes that can be made to the existing building such as design flexibility, space addition or changes to the window-wall ratio. During the preliminary phase, conceptual facade alternatives are developed, and a choice is made between alternatives based on their expected performance in terms of safety, comfort, durability, energy efficiency, sustainability (reuse, recyclability). For the choice, a decision-making method like a cost-benefit assessment can be made use of. Although, in practice the decision is often based on intuition and conversation (Prieto et al., 2024). After selecting a suitable envelope, the detailed design stage examines the design of connections and members as well as execution planning to prepare for construction and post-construction. For the construction phase, a standard procedure for progress inspection and quality control applies, while post-construction focuses on cleaning, maintenance, and monitoring as defined for facades by Moghtaderneja et al. (2018).

From the reviewed renovation processes, it can be concluded that there are several stages to facade design where various aspects are of interest. For multi-objective assessment, the parameters might not be relevant all at the same stage, but the main step for performance-based decision making for envelope systems is from preliminary to detailed design.

2.4.5 Renovation Benefits

Renovating or Retrofitting can have several benefits for multiple parties involved. Not all lie within the interest of the owner, as the funding party, but also the occupants and policymakers taking responsibility for the commonwealth. The owner as an investor can have various goals when renovating, for example, increasing market value with direct monetization

afterward, increasing rentability, or creating a competitive advantage to increase profitability. If the owner is the occupant, there is a direct interest in functional aspects (Den Heijer, 2013; Long-Term Renovation Strategy, 2020).

The term strategic benefits leans on to the category strategic value from Den Heijer. The study outlines what value the facade holds to owners and investors. Strategic value relates to an organization's identity and goals. A strategic benefit can have an expected following economic benefit that can only be estimated, not quantified. For example, this could be an expected long-term property value rise. Strategic benefits from renovation can include, for example, creating a competitive advantage. Strategic value can be expressed as 'opportunity cost,' the implicit cost for an alternative strategy to reach the same goal. Strategic goals that include an occupant target group and building functionality directly translate to functional requirements for facade design (Den Heijer, 2013).

Economic benefits from renovation often either come from improving life cycle cost or property value (Den Heijer, 2013). Practically, qualitative improvement can lead to higher rental premiums or resale values (Bragolusi & D'Alpaos, 2022). Important metrics to assess the economic value of renovation are profitability, such as return on investment, cost-benefit, marginal cost, investment span, and annual capital cost (Den Heijer, 2013). Higher profitability can be achieved by improving space utilization and reducing floor area because of the more efficient material investment (Ibid). Annual capital costs most prominently include energy, maintenance, and cleaning (Ibid). Therefore, reducing annual capital cost benefits owners' return on investment and holds economic benefits for occupants. Especially reducing energy costs by increasing efficiency has proven cost-effective (Sharbaf & Schneider-Marin, 2025). However, energy cost is sensitive to real discount rates and energy price development (Den Heijer, 2013). Renovating also automatically influences maintenance costs. Since maintenance cost usually increases over the functional life span of a component, lifted quality with new installations

reduces costs (Sharbaf & Schneider-Marin, 2025). Also, durability as a somewhat functional benefit is a potential factor expanding service life span, lowering the risk for reinvestment, and justifying higher investment costs (Den Heijer, 2013). Generally, the profitability of an investment is also largely influenced by government subsidies and tax rebates, as they can reduce payback periods or lower interest rates (Sharbaf & Schneider-Marin, 2025).

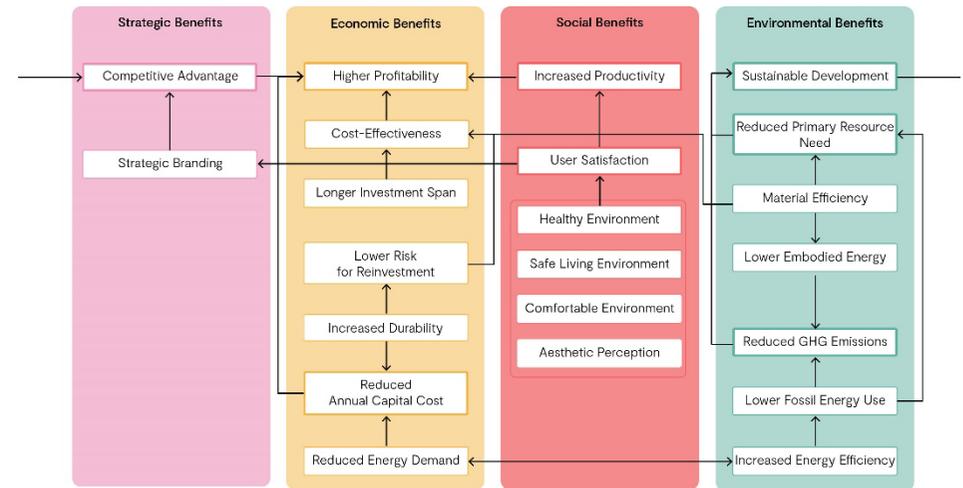


Figure 14 - benefits from renovation (source: own)

Social benefits are most important to occupants but can also have economic benefits in return (See Figure 14). All buildings need to satisfy user-specific needs and according to Maslow's hierarchy of needs there is a clear priority order for the most common, from health, safety, and human comfort to aesthetic perception (Den Heijer, 2013). Retrofitting can contribute to a more comfortable and healthier environment. For example, low-temperature heating and high insulation significantly improve thermal comfort in winter (Bragolusi & D'Alpaos, 2022). Retrofits can also benefit safety conditions, e.g., seismic stability (Bianchi, 2023). Improving user satisfaction affects productivity, leading to economic benefits in terms of rentability (Den Heijer,

2013). Finally, also market value can benefit from renovation as aesthetic perception plays a role in vacancy rates (Ibid).

An owner might not have a direct interest in environmental benefits, but they can be relevant to meeting policy requirements on sustainability (Den Heijer, 2013; Long-Term Renovation Strategy, 2020). For occupants, environmental benefits like improving air quality by, e.g., removing pollutants with greenery, also involve health-related benefits (Sharbaf & Schneider-Marin, 2025). The main environmental benefit from renovation is the reduction of greenhouse gas emissions via reduced fossil energy consumption. Less consumption is influenced by energy efficiency and renewable sources (Ibid). Retrofitting implies the use of new products which inevitably carry embodied carbon. The emissions embodied influence the general building-related emissions. Therefore, material efficiency and using low-carbon materials benefit the overall score. Further, these strategies account for a reduced need for primary resources (Sharbaf & Schneider-Marin, 2025).

One of the most significant findings from the literature is that greater expected benefits allow for a bigger investment budget (Den Heijer, 2013). So, the ratio of cost to advantage is more important than the pure cost. But trying to incorporate multiple aspects into such an assessment also poses challenges, as several benefits of a qualitative nature cannot easily be quantified and, therefore, do not directly translate to monetary value (Sharbaf & Schneider-Marin, 2025). However, research has shown that combining objectives when retrofitting brings greater benefits, making multi-objective cost advantage assessment a necessity (Caruso et al., 2023). To conclude, energy savings are often the primary focus of renovation, but considering a wider range of benefits can maximize the positive impact (See Figure 15).

2.4.6 Renovation Bottlenecks

In a recent study, Prieto et al. (2024) investigated bottlenecks for cost effective renovation measures via field survey and literature review. The research summarized several general subjects for barriers from three studies: institutional barriers, market and economic barriers, financial barriers, technical barriers and behavioral and social barriers (Prieto et al., 2024).

With findings from the field survey, Prieto et al. drew conclusions for main bottlenecks throughout the renovation process. The first is lack of information during pre-project and concept design phase as limited information about the existing building and energy consumption data further impact the process. Second, coordination and communication was listed as a barrier during execution and handover. This can involve coordination issues and clear involvement, but also collaboration between suppliers and lack of central access to information. The third one is unreliable assessments during the concept design. It concerns unreliable assessment and optimization of different design options, uncertainty for building energy performance predictions and the struggle to come up with reliable cost estimations when the planning lacks technical depth (Prieto et al., 2024).

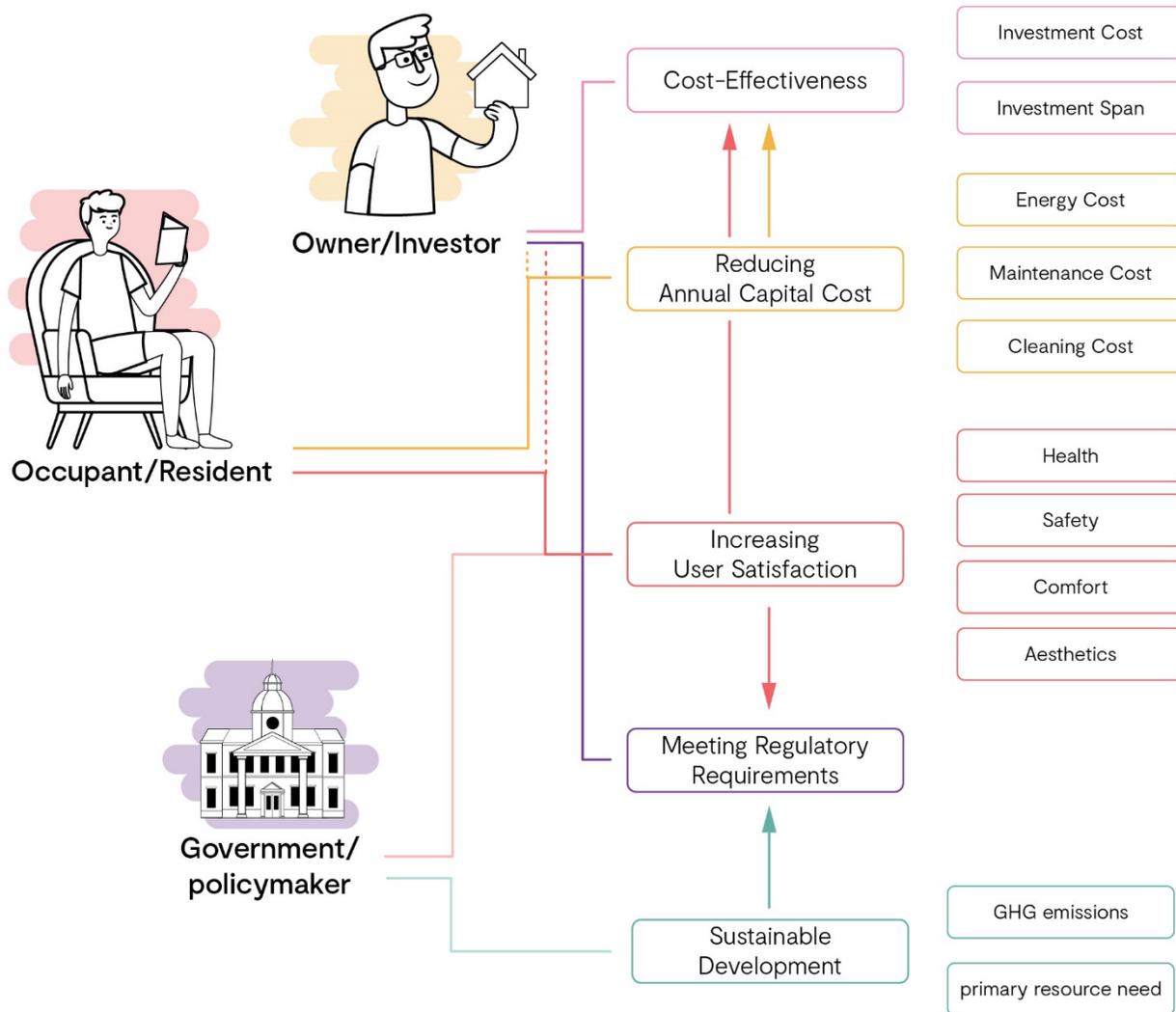


Figure 15 - Stakeholder Interest in Renovation Efforts (source: own)

2.5 Cost-Benefit Analysis

2.5.1 Methods & Definitions

Cost-Benefit Analysis is a part of choosing by advantages methods, including cost-optimal and cost-effectiveness Analysis (Sharbaf & Schneider-Marin, 2025). In cost optimal analysis, alternative scenarios are compared to base case scenarios, e.g., finding the most energy-efficient measures in retrofit alternatives (Ibid). Meanwhile, for cost effectiveness analysis, principal achievements are linked to program cost, such as energy productivity analysis (Ibid). Conversely, cost-benefit analysis compares cost to the monetary value of several direct and indirect benefits or outcomes (Hu, 2019). Here also lies the challenge of estimating the financial value of wider benefits (Sharbaf & Schneider-Marin, 2025). These benefits could include co-benefits, side effects, or externalities (Ibid).

An essential aspect of cost-benefit analysis is to count all related costs for a project over a specific time frame and estimate their theoretical value in the present day (Romijn & Renes, 2013). This is called discounting cost over time and is applied to almost all economic indicators in CBA (Ibid). The reason discounting is that having a certain amount of money today is worth more than receiving the same amount in the future (Ibid). Therefore, future benefits need to be higher than the actual investment cost to break even for any project (Ibid). Essentially, this means the CBA result can easily be compared to the average economic return on investment (Ibid). When comparing a project's economic value to the outcome of similar-risk investments, it is referred to as the opportunity cost of capital (European Commission, 2014).

To discount the cost for each year of the analysis period, the cost or savings are multiplied by a discount factor, which is related to the market interest rate or could be suggested by the government for economic decision-making (NEN-EN 15459-1, 2017; Wahi, 2025). Such suggested discount rates are sometimes called ' Social Rate of Time Preference' (S RTP), indicating the

societal value of present versus future consumption (Sharbaf & Schneider-Marin, 2025). However, it is crucial to distinguish between economic and financial Analysis in CBA, where economic analysis is done from a societal perspective, and the term financial applies to private decisions (European Commission, 2014). Furthermore, the suggested discount rates might also vary for short or longer analysis periods.

Since inflation can alter the scale of prices over time, it is recommended to convert the real discount rate to its nominal value (Wahi, 2025). The nominal rate subtracts inflation using the consumer price index from past years, e.g., the last 10 years (Ibid).

There are also types of costs that might be related to the project but are ignored in CBA. The first is anyway costs, referring to any cost that would have occurred across all scenarios and is not altered by any scenario (Sharbaf & Schneider-Marin, 2025). The other irrelevant cost is any cost that occurred before the present decision-making point. They are, therefore, called sunk costs (Ibid). Excluding them is part of the concept 'thinking on the margin', which refers to making considerations only looking forward, for instance, making small changes in the allocation of resources (Mankiw, 2015).

2.5.2 Cost Modelling Methods

Since the relevant costs in CBA depend on a scenario, project, or product purchase, there are different types of cost modelling methods (Sharbaf & Schneider-Marin, 2025).

A standard method for products or elements is life cycle costing, which involves summing up all costs across a product's life span, including investment, operation, maintenance, disposal, or residual value (Ibid). Whole-life cycle costing can be extended to integrate indirect costs or benefits as well as external factors, e.g., financing or potential income (Ibid).

Another product-related method is incremental cost, which is useful for production at scale. It refers to the cost of making one more additional unit of an element (Sharbaf & Schneider-Marín, 2025). Liu et al. have also adopted it in the cost-effectiveness analysis of retrofitting steps to a zero-carbon building (Liu et al., 2023).

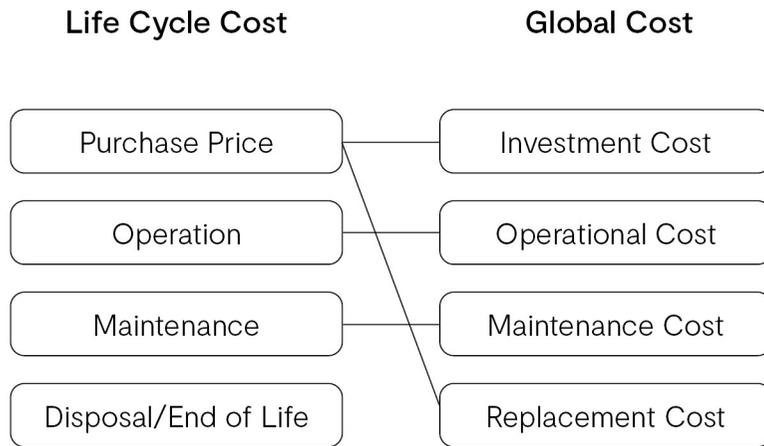


Figure 16 - Cost-modelling relations (source:own)

However, the general project-level modeling method is global costing (Wahi, 2025). For global cost, all life cycle cost aspects of different products or elements are added into broader categories of investment, operation, replacement, and maintenance and then summed up (Ibid). However, the approach also has simplifications, where maintenance cost could be estimated using a ratio of investment cost, while replacement cost is simply the discounted value of investment cost at the end of the component's life span (Ibid).

In decision-making, the total of all life cycle cost purchase or decision related can also be referred to as 'Total Cost of Ownership' (Ellram, 1995).

2.5.3 Economic Indicators

In cost-benefit analysis, several economic indicators give different insights into a case's financial value (Sharbaf & Schneider-Marín, 2025). Common economic indicators that are calculated from discounted cashflows are the 'Net Present Value', the 'Payback Period', the 'Internal Rate of Return', and the 'Benefit Cost Ratio' (Ibid). Some are related to general profitability, defined as 'the extent to which a particular measure's economic outcome is positive or negative' (Ibid).

$$NPV = \sum_{n=0}^N \frac{C_n}{(1+r)^n}$$

Net Present Value (NPV)

The 'Net Present Value' is the sum of all discounted cash flows over the analysis period, counting benefits as positive and costs as negative. The outcome is, therefore, positive or negative, indicating whether the project results in a net benefit. Consequently, a case with a negative NPV should be rejected, and if no budget constraints apply, the scenario with the highest NPV should be adopted (Preciado-Pérez & Fotios, 2017).

$$BCR = \frac{|Present Value[Benefits]|}{|Present Value[Cost]|}$$

Benefit Cost Ratio (BCR)

The 'Benefit Cost Ratio' is the sum of all monetary savings and benefits divided by the sum of the related costs. A ratio larger than one can be considered economically viable. Therefore, if the NPV is equal to 0, the BCR is 1 (Campbell & Brown, 2003).

$$PP = N; 0 = \sum_{n=0}^N \frac{C_n}{(1+r)^n}$$

Payback Period (PP)

The payback period is the estimated time needed to recover the initial investment cost. This estimation can also be simplified to a static calculation without discounting the cost. Depending on the relation between positive and negative cash flows and investment volume, two projects can end up with the same net present value but might differ in payback periods (Layard et al., 1994).

$$0 = NPV \sum_{t=1}^T \frac{C_t}{(1+IRR)^t} - C_0$$

Internal Rate of Return (IRR)

The 'Internal Rate of Return' is a theoretical value for the discount rate that will cause the NPV to result in 0. The indicator mainly informs about how sensitive profitability is to discounting. Hence, the larger the rate, the better and fewer risks affected it (Belaïd et al., 2021; Mayer et al., 2022).

2.5.4 Cost Benefit for Evaluating Retrofitting

In this section, studies evaluating renovation alternatives apply the most common CBA methods. Table 7 lists for all reviewed sources the method, type of cost modelling, analysis period, economic indicator, considered savings or benefits, focus of the study, and any further parameters. In addition, the conclusions drawn in a similar analysis from Sharbat and Schneider-Marín (2025) were considered. For the literature sourcing conducted in this study, the same keywords as in the reference study were applied, but a focus on residential buildings was added (See Table 6).

Table 6 - literature search CBA for retrofitting

<i>Keywords Renovation</i>	renovation, retrofit*, refurbishment, upgrade, modernization
<i>Relation</i>	AND
<i>Keywords Housing</i>	resident*, housing, home
<i>Relation</i>	AND
<i>Keywords CBA</i>	Cost benefit, benefit to cost ratio, net benefit
<i>Relation</i>	AND NOT
<i>Keywords to avoid</i>	Urban, city, policy

Most of the studies reviewed adopted a cost-benefit method, but some also combined it with a cost-optimal analysis, while one applied only COA (See Table 7). On that note, studies using cost-effectiveness analysis seemingly did not show up with the keywords used in the literature search.

Looking at cost modelling methods, global and life-cycle costing were used most frequently and mixed. Regarding economic indicators, the 'NPV',

'Payback Period', and the 'Benefit-Cost Ratio' were most popular. One study by Araújo et al. did not calculate a typical indicator, but compared energy savings (Araújo et al., 2016). Generally, when analyzing benefits, energy cost savings were given priority over related GHG emissions (Sharbaf & Schneider-Marín, 2025).

The European Union suggests a retrofit analysis period of 30 years, which was adopted by most studies, but periods of 10, 20, and 25 years also showed up in the analysis (EED, 2012).

Several studies included a special focus by adding extra parameters. Guazzi et al. estimated the final residual value of components (Guazzi et al., 2017). In contrast, Higney and Gibb used a cost factor for embodied carbon, and Araújo et al. considered the willingness to invest in sustainable solutions (Araújo et al., 2016; Higney & Gibb, 2024).

To avoid idealized assumptions, Galvin's study in 2024 investigated including anyway cost, pre-bound, and rebound effect. These effects refer to the circumstance that households in not yet renovated buildings often use less energy than the estimated demand indicates. In a previous study, Sunikka-Blank and Galvin documented that, on average, German households consume 30% less energy (Galvin & Sunikka-Blank, 2013).

This review can conclude that cost-benefit analysis is a popular method, where common indicators like the NPV give clear guidance on whether one alternative is more beneficial than the other. The costing method depends on the focus and scale of the case analyzed, but the analysis period rather relates to the general observation period.

Table 7 - CBA for Retrofitting Literature Review

Reference	Method	Cost Modelling	Economic Indicator	Analysis Period	Savings / Benefits	Special Focus	Additional Parameters
Araújo et al.	COA & CBA	Life Cycle Cost	Savings	8 (static PP)	primary energy demand	Energy efficiency technologies	Investment willingness for sustainable solutions
Bragolusi and D'Alpaos	CBA	Incremental Cost	NPV	30	energy	/	/
Guardigli et al	CBA & COA	Global Cost	NPV, PP	30	energy	Cost optimal of envelope retrofits	Global cost for 10/20/30 years, annual savings per m ²
Guazzi et al.	COA	Global Cost	PP, Eur/m ² a to kWh/m ² a	30	energy performance	/	Final Value / Residual Value
Galvin	CBA	IC, EC & „Anyway“ Cost	NPV	25	energy	Energy retrofitting	Prebound and Rebound Effects, incl. anyway costs, investment via loan
Higney and Gibb	social CBA	Mix, IC, MC, Administrative Cost, EC	NPV, BCR	30, 20 (EU)	energy, carbon	incl. non-market values & behavioural response	embodied carbon cost factor incl.
Johnstone	CBA	LCC	BCR	component LC	<i>not specified</i>	Population dynamics, housing typologies	/
Liu et al.	CBA	LC incremental cost	TC, NPV, incremental cost-effectiveness ratio	<i>not specified</i>	energy efficiency, carbon & cost	Carbon reduction	/
Mikulić et al.	CBA	<i>unknown</i>	NPV, savings comparison	<i>not specified</i>	energy, economic activity, fiscal impact, carbon emissions	<i>is different to the methods</i>	/

2.5.4.1 Risk Assessment in Cost Benefit

Most parameters in CBA rely on statistical averages, present values, or sometimes even educated guesses (Sun et al., 2016). However, these parameters can change later in reality, which significantly influences the results (Ibid).

Risk assessment for CBA can be a tool for becoming aware of the consequences of changing boundary conditions (European Commission, 2014). The 'Guide to Cost-Benefit Analysis' by the European Commission proposes four methods for risk analysis. The recommended steps include sensitivity analysis, qualitative risk analysis, probabilistic risk analysis, and risk prevention and mitigation.

Sensitivity analysis can be a first step to understand how much each variable influences the results and then further investigate the risks involved for the most controlling ones. All other values are fixed to analyze the sensitivity to one variable, while the calculation is repeated for a series of step values. This way, a switching value can be identified for each parameter, as the point where the economic indicator switches from a positive to a negative outcome. Then, the switching values are compared to the originally estimated ones in order to understand how much the parameter needs to change for a non-profitable outcome (European Commission, 2014).

The step qualitative risk analysis refers to constructing a risk matrix ranking the probability of occurrence and severity of impact for every possible disrupting event. To interpret the matrix, an assessment of acceptable risk levels is required (European Commission, 2014).

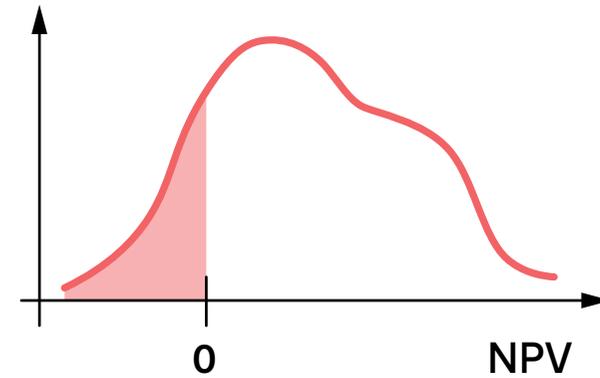


Figure 17 - Economic Risk Sketch

The more in-depth quantitative analysis of probabilistic risk involves calculating or estimating how each parameter is distributed (European Commission, 2014). The probabilistic distribution an indicator can be approximated via a Monte Carlo simulation (Sun et al., 2016). The accuracy of the evaluation depends on how well the parameters' probability was assessed and the number of runs of the Monte-Carlo. However, the common conclusion from this analysis is that there is a general risk of a negative outcome (See Figure 17) (European Commission, 2014).

The last step refers to risk management, where the project parameters are adjusted to avoid, mitigate, or transfer the identified risks. However, the project promoter determines the level of risk acceptance (European Commission, 2014).

3 Framework Design

The framework aims to extend the standard cost-benefit analysis for renovation alternatives by integrating the impact of climate extremes. In case of many exceptional extremes over a use case period of 20-30 years performance could vary potentially influencing the cost-benefit.

Learning from the literature review, a probabilistic approach should be adopted, considering the probability of varying operational costs, such as energy. The influence of climate uncertainty is then reflected in the outcome of the economic indicator. This approach necessitates probabilistic performance and weather data analysis. Resilience studies have found that thermal performance can deviate greatly from the typical weather scenario.

The range of outcomes and how they are distributed can vary across domains, such as severe discomfort and energy intensity. For a cost-benefit analysis, the impact of climate uncertainty needs to be translated into its monetary value (Sharbat & Schneider-Marin, 2025).

The framework should integrate into the renovation planning process, which will be tested in the case study (See Figure 18). The results should answer stakeholders' questions about the value of renovation measures.

This chapter will outline the cost-benefit method for the case study. As a first step, the translation of resilience into cost will be discussed, followed by selecting a comparison metric for heat resilience in the study. Then, the uncertainty of the current climate is analyzed using historical weather data to understand the probability of operational cost later and to select a representative climate extreme for the comparison metric. Also, a suitable economic indicator is based on the accuracy of the outcome with a probabilistic analysis. Lastly, the digital implementation and data use will be explained.

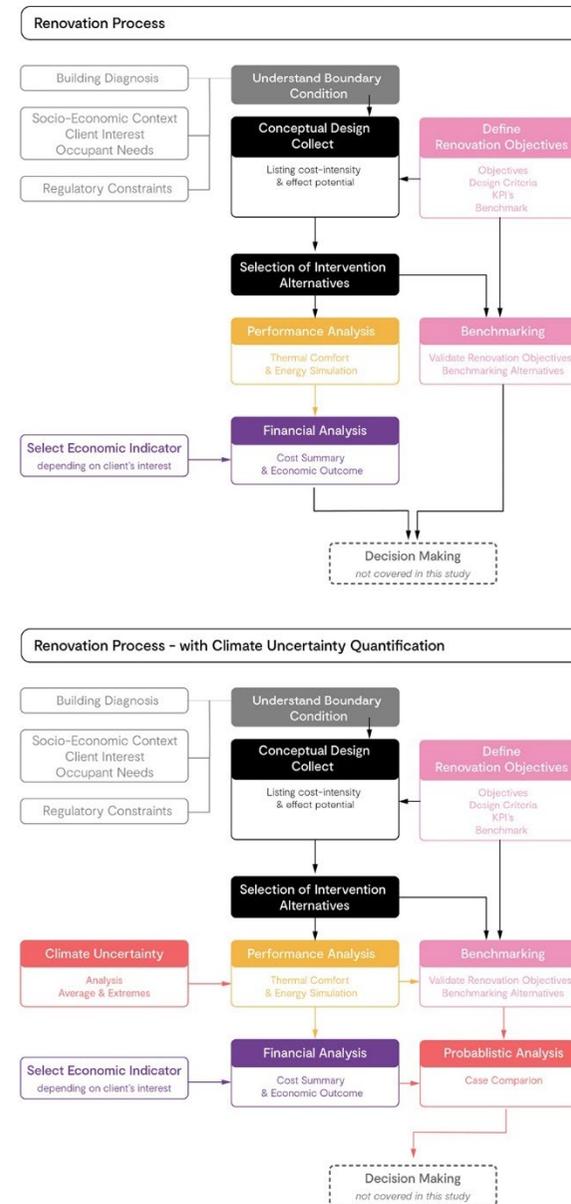


Figure 18 - Integration in Renovation Planning (source: own)

3.1 Resilience as Cost

Learning from resilience studies, the impact of thermal hazard on Indoor climate conditions relates to energy, such as additional cooling loads, carbon emissions, and human comfort.

In cost-benefit analysis, the question arises about how these factors can be translated into cost. For active technical cooling systems, the load can be directly converted to cost, considering the price levels for the energy source and system efficiency. Since greenhouse gas emissions cause future damage to society, various ways exist to estimate the corresponding cost. One is the government's taxation per emitted ton of CO2 equivalent gases (Statistics Netherlands Statistics, 2024). An alternative option is the general economic damage cost, Carbon Steering Levy (CSL), estimated by re-insurance companies, e.g., Swiss Re 145 USD per ton (Swiss Re, 2024). The energy-related emissions can then be calculated using the final energy consumed by the cooling system. However, the cost might not be directly carried by the stakeholders but priced into the energy or material cost (Statistics Netherlands Statistics, 2024).

The discomfort and health-related impact is more challenging to translate into a monetary value. Although economic loss and health-related impacts are visible from a macroeconomic perspective, there is no definite outcome for levels of overheating on the building scale. An alternative approach could be to consider loss of revenue in a private rental scenario, assuming tenants have the right to reduce rent in case of comfort loss. This is the case for insufficient heating in the Netherlands. However, such a rent reduction of 20-40%, depending on the deficiency, is only justified temporarily until the condition is restored (BZK, 2024). Therefore, it cannot take effect regularly but is rather exceptional.

For the cost-benefit analysis, combining energy cost and functional cost would not be reasonable since they do not occur simultaneously. An assumption must be made about whether the indoor climate is cooled down to a comfort level, so either the cooling cost must be borne or functional loss tolerated.

In this study, energy cost were chosen to represent the hazard impact of heat extremes.

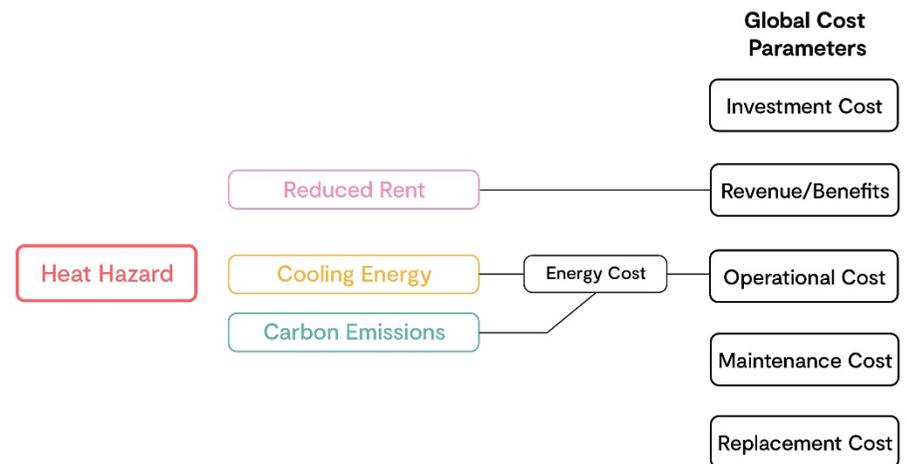


Figure 19 - Hazard Impact as Cost (source: own)

3.2 Comparison Metric

In addition to the cost-benefit analysis, a comparative metric for thermal resilience is quantified to compare how much the impact of climate uncertainty is reflected in the CBA results and also to compare energy savings against comfort improvement. For instance, a measure might improve energy costs significantly but offer little passive protection against overheating. Such circumstances can be identified using the metric.

The metric should be comfort-based since the financial analysis will not consider thermal comfort. For the case study, the metric must be applicable to the building scale and annual analysis, not just singular zones and scenarios. Furthermore, considering the perspective of decision makers, the metric should comprehensively reflect the intensity and duration of comfort loss to expect during extremes. For a renovation objective, such as mitigating overheating, the indicator aims to benchmark how well the objective is met.

The resilience indicators collected during the literature review were reviewed again for their usefulness in this study (See Table 8). Several studies quantify the hours of discomfort using a temperature measure like SET. Indicators like the 'Heat Index' or 'Discomfort Index' give an in-depth understanding of levels of discomfort or heat stress. Purely analyzing hours might not be comprehensive, as there is no acceptability limit.

Regarding analysis periods, some, like 'Weighted Unmet Thermal Performance', were only applied to specific hazards or no period, like the 'Building Heat Performance Index' (Mirzabeigi et al., 2023).

The combination of 'Indoor Overheating Degree' and 'Overheating Escalation Factor' seem the most suitable for an annual analysis, especially because the OEF indicates the relation between indoor overheating and outdoor climate, with $\alpha > 1$ meaning indoors conditions are worse than outdoors. Therefore, these metrics were chosen to be quantified for a qualitative resilience comparison. However, it might take longer to calculate all three metrics, including the 'Ambient Warmness Degree' of the studied year.

Table 8 - Usefulness of Resilience Metrics

Resilience Metrics /Indicators	Description / Quantification Method	Notes	Usefulness in this study
Heat Index (HI)	Combination of dry indoor air bulb temp. & relative humidity to approximate temperature perception; categories safe to extreme danger; distribution of hours with the heat index levels in danger and caution conditions; categorize each hour during an extreme even	active cooling compared to power failure	In depth discomfort understanding
Hours in Heat Stress	Using Standard Effective Temperature; Calculation of hours where SET >30°C for the period of an extreme event	Tested effectiveness of passive measures; past use hazard specific	Easy calculation; result not necessarily comprehensive
Indoor Overheating Degree (IOD)	intensity and frequency of overheating with fixed of adaptive comfort limits; temperature difference between indoor free-running temp and temp limit summarized over a period with the time step of an hour, collected for all building zones & averaged over the number of ones and hours (use of CIBSE limits: living areas >28°C, bedrooms>26°C for more than 1% of the annual occupied hours; use of fans justifies temp increase up to 3°C depending on air speed) no use of cooling systems	/	Comprehensive metric; annual application

Overheating Escalation Factor	IOD/Ambient Warmness Degree at 18°C is the Overheating escalation factor (>1 means worse indoors than generally outdoors); Ambient warmness degree is the average of cooling degree hours during summer when outdoor air temp is not lower than 18 (May to Sept)	Full quantification set up takes time	Comprehensive metric, indoor outdoor relation
Weighted unmet thermal performance (WUMTP); Resilience Class Index	multizone indicator with fixed limits; temperature indoors is weighted based on the point in time it is occurring (degradation/recovery); Measured in Degree Hours or degree hours/m²; Labeling system A-F based on WUMTP	Hazard specific	More complex; in depth analysis
Building heat performance index (BHPI); Temperature Weighted Thermal Performance	outlines how fast a building overheats; fixed comfort limit 32°C; Calculate the time elapsed for the indoor temperature to increase from 25 to 32°C (or depending on fixed limit)	/	Describes the general fragility of the building
Metrics based on Discomfort Index; Overheated Hours; hours 80% acceptability not met; severe	Discomfort Index (DI) average of wet bulb & dry bulb; this temperature then indexes heat stress mild below 24°C, moderate 24-28°C, severe >28°C; distribution of hours using indoor operative as the weighted mixture of mean radiant and dry bulb temperature; Hours 80% acceptability limits in an adaptive comfort model ASHRAE; (adaptive limits e.g. Australia 20.5–27.5 °C)	Used event specific; similar to heat index	In depth discomfort understanding

discomfort hours			
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As demonstrated by Hamdy et al., both fixed and adaptive comfort limits can be used. The fixed limit is taken from the CIBSE Guide A, which defines overheating as an operative temperature exceeding 28°C in living areas and 26°C in bedrooms. Ceiling fans can bend the limit by up to 3°C (Hamdy et al., 2017). For this study, however, the limit was set to 28°C for both living and bedrooms.

$$IOD = \frac{\sum_{z=1}^Z \sum_{i=1}^{N_{occ}(z)} [(T_{fr,i,z} - TL_{comf,i,z}) \times t_{i,z}]}{\sum_{z=1}^Z \sum_{i=1}^{N_{occ}(z)} t_{i,z}}$$

To quantify the 'Indoor Overheating Degree', the values for the occupied hours above the limit are collected, and the limit is subtracted from each temperature level. The delta temp values are added and divided by the number of hours. The quantification of the 'Ambient Warmness Degree' is similar to the IOD, but using outdoor air temperature and a limit of 18°C. Lastly, for the OEF, the IOD is divided by the AWD (Hamdy et al., 2017).

$$AWD_{18^\circ\text{C}} = \frac{\sum_{i=1}^N [(T_{a,i} - T_b) \times t_i]}{\sum_{i=1}^N t_i}$$

$$\alpha_{IOD} = \frac{IOD}{AWD_{18^\circ\text{C}}}$$

Additionally, the indicator overheated hours and degree hours will be quantified for the summer months using a SET limit of 28 degrees, similar to the fixed operative limit (Kim et al., 2024). This will give a more in-depth understanding of the corresponding overheating duration in terms of hours and intensity with degree hours.

3.3 Climate Uncertainty Analysis

3.3.1 Energy Demand Distribution

As recognized earlier, a probabilistic cost-benefit analysis requires knowledge of the probability distribution of annual energy costs. This chapter aims to understand the spectrum and probabilities of energy demand.

Energy intensity can vary greatly due to differences in annual weather. Therefore, this variability is analyzed to first create a demand distribution and later translate it to savings and costs.

This study will exclude the uncertainties of factors like performance. However, as demonstrated by Sun et al., other uncertainties, such as infiltration, system efficiency, and internal gains, can significantly affect the result (Sun et al., 2016).

The analysis is based on historical weather data from the past 30 years (1995-2024) to represent a full climate set (KNMI, n.d.-b). KNMI provides the data for specific regional weather stations. The data can also be downloaded from the platform [ncei.noaa.gov](https://www.ncei.noaa.gov) in English, which is easier to translate into an '.epw' climate file (NCEI, n.d.).

After translating all files, all 30 years were used in a simulation to quantify an ideal air load system's annual cooling and heating demand. The set-point temperatures were set to 18°C for heating and 24°C for cooling as selected in the study preparation chapter 5.2.

Because the values represent continuous real-world variables, a histogram was first plotted, and then a 'Kernel Density Estimation' without bandwidth was constructed instead of an idealized parametric function. The probability density function should account for the condition that the histogram has a longer stretch from the most frequent value to the maximum than to the

minimum (See Figure 20). For cooling, the demand spreads from 1,160.01 to 17,515.24 kWh per year. On the other hand, heating demand is much greater, ranging from 57,970.44 to 78,200.05 kWh per year.

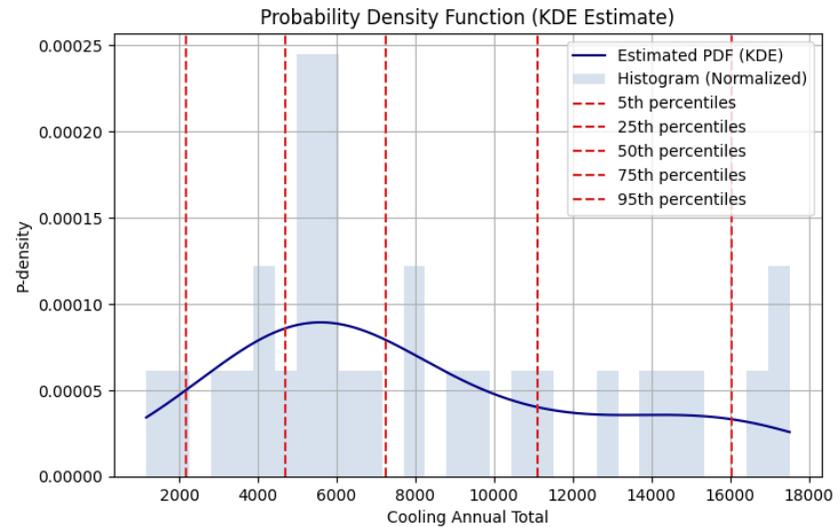


Figure 20 - Probability Density Function of Cooling Demand (source: own)

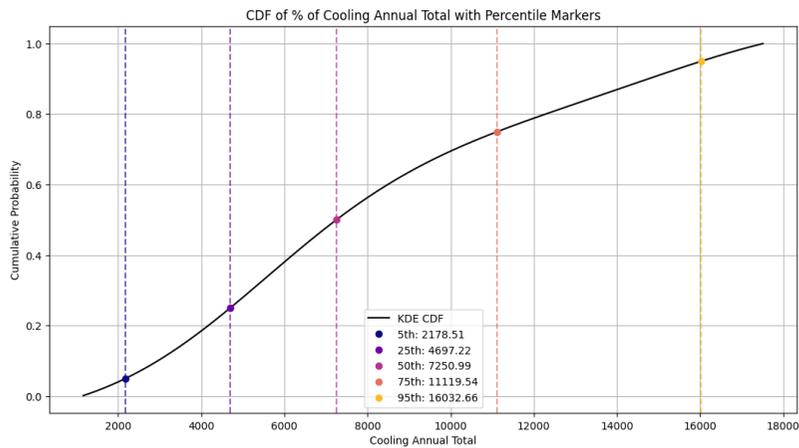


Figure 21 - Cumulative Probability for Cooling Demand with Percentiles (source: own)

A simplification method was adopted to simplify the process of estimating a distribution based on simulations for more scenarios. This method used only certain points of the curve represented by specific years to reconstruct the curve later. Percentiles for continuous variables are not interpreted by using the exact probability of their corresponding value, but as the probability of a value being lower than or equal to their value. For instance, the 5th percentile value of 2,178.51 kWh meets a 0.005% probability on the y-axis, because the probability for an exact value is not quantifiable. Instead, the integral for value ranges gives insight into the probability distribution, meaning there is a 5% chance of a lower demand and a 95% chance of a higher demand for any given year.

At first, the percentile values for the 5th, 25th, 50th, 75th, and 95th percentiles were calculated, and the closest match of the actual annual values was searched for. For this analysis, the probability density function was translated to a cumulative distribution function to visualize percentiles better. Then

again, the actual percentile value on the CDF was estimated for the real years, meaning 5% to 3% (See Table 9). Also, the minimum and maximum years were added, making a total of 7 reference years.

These seven reference points serve as input for a simplified cumulative distribution that can be used to estimate demand in more scenarios, such as the retrofit alternatives. To reconstruct the distribution, the reference points, which mark demand and percentile for each year, are plotted for interpolating a function. Afterward, a set of approximately 5,000 samples will be taken from the function to estimate a new probability density function.

Table 9 - Percentile values for heating and matching years (source: own)

Percentile	Total Annual Demand [kWh]	Closest Matching Year	Total Annual Demand [kWh]	Corresponding Actual Percentile
Minimum (0)	1,160.01	2007	1,160.01	0
5	2,178.51	2021	1,862.97	3
25	4,697.22	2017	4,868.62	27
50	7,250.99	2001	6,832.23	46
75	11,119.54	2003	11,284.98	76
95	16,032.66	1995	16,510.71	97
Maximum (100)	17,515.24	2020	17,515.24	100

Table 10 - Percentile values for heating and matching years (source: own)

Percentile	Total Annual Demand [kWh]	Closest Matching Year	Total Annual Demand [kWh]	Corresponding Actual Percentile
Minimum (0)	57,970.44	2023	57,970.44	0
5	60,206.59	1995	61,731.36	11
25	64,468.82	2018	64,480.99	25
50	68,669.76	2019	6,832.23	51
75	72,675.98	2012	68,769.56	75
95	76,654.87	2011	77,030.71	96
Maximum (100)	78,200.05	2010	78,200.05	100

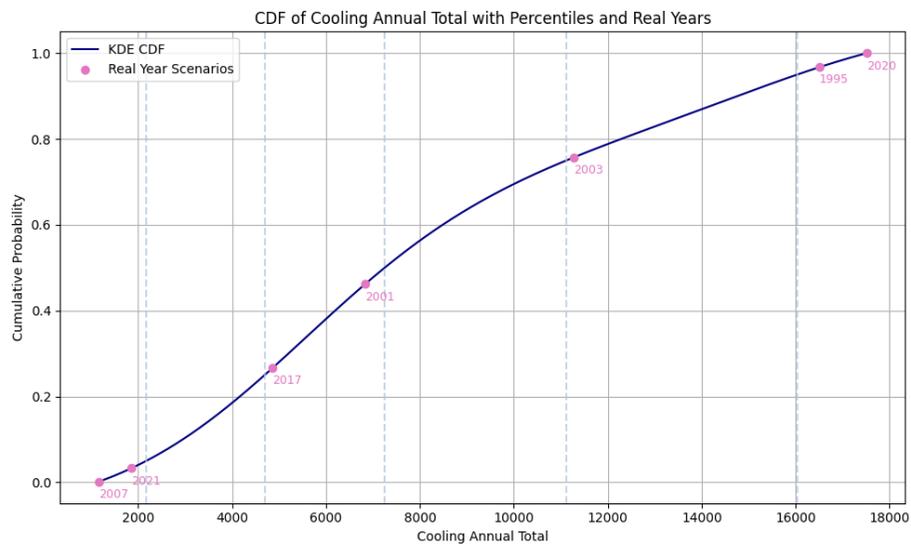


Figure 22 - Cumulative probability for cooling with matching real years (source: own)

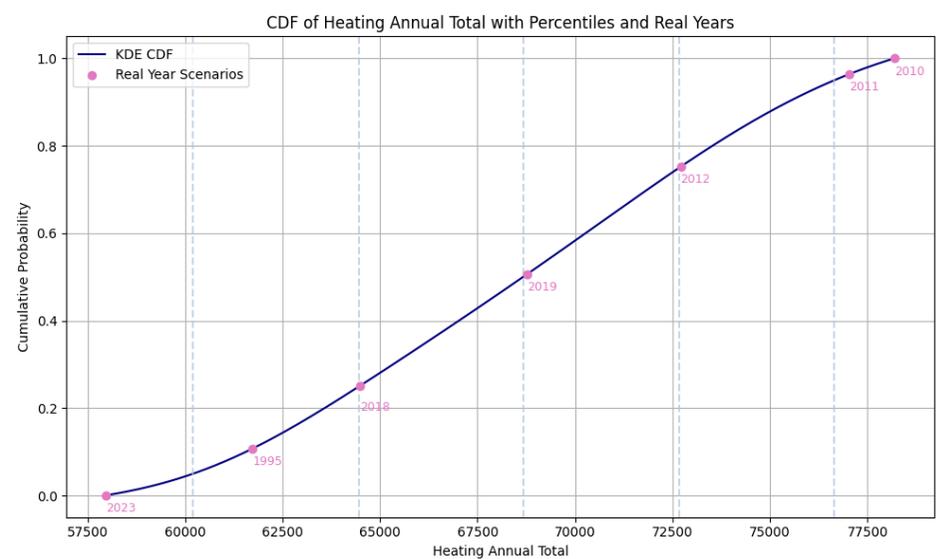


Figure 23 - Cumulative probability for heating with matching real years (source: own)

3.3.1.1 Accuracy Verification

Since the simplification using seven reference years instead of all 30 historical years implies simplifying the cumulative distribution function, the accuracy of both the cumulative distribution function (CDF) and the demand distribution estimation was determined. The absolute and relative errors were calculated for both curves, whereby for the CDF, the deviation between the real and predicted demand of a percentile point was used. For the PDF, the difference in probability estimation for a certain demand was compared.

The relative errors for the percentiles of the cumulative distribution are plotted in Figure 25. With a mean absolute error of 136.84 kWh and a mean relative error of 2.39%, the simplification retains an accuracy of over 97% of the original.

The function comparison and corresponding mean relative errors are shown in Figure 27 & Figure 26. To smooth the estimation and avoid a strong influence on the randomness in the sample set, a bandwidth of 0.6 was used for the kernel density estimation (Weglarczyk, 2018). Under these assumptions, the mean relative errors yielded just under 16% (See Table 11) with a mean absolute error of 7.84e-06 [probability density]. Although a later test showed that a smaller bandwidth would have increased accuracy, the assumptions were maintained for the cost-benefit analysis.

Table 11 - Mean relative error respective to bandwidth of the kernel density estimation (source: own)

bandwidth	Mean Relative Error
None	14.02 - 16.36 %
0.9	19.2 %
0.8	18.29 %
0.7	17.39 %
0.6	15.95 %

0.5	13.94 %
0.3	13.33 %
0.2	13.82 %

Finally, the statistics for exemplary sample sets retrieved from both the real and predicted PDF were compared to see how inaccuracies would produce a difference in results (See Table 12). Therefore, 25,000 samples representative of the distribution were taken using the 'scipy.stats' resample function. The minimum and maximum of the samples came out closest to one another with a difference of just 2-3kWh, which was due to the same bound values from the simulation used to limit the samples. The difference in mean and standard deviation resulted in a much greater overestimation, with approximately 215 kWh for the mean and 127 kWh for the standard deviation.

Table 12 - Sample Set Comparison (source: own)

	Real	Prediction
Min	1,160.64 kWh	1,162.72 kWh
Max	17,514.85 kWh	17,511.46 kWh
Mean	8,096.91 kWh	8,311.28 kWh
Standard Deviation	4,245.99 kWh	4,118.85 kWh

To conclude, reducing the 30 historical years to 7 reference years with probabilistic knowledge gives a representative estimation of the cumulative distribution. However, the method for reconstructing the probability density estimation is subject to notable uncertainty. The results might overestimate the demand by a few hundred kWh, which was considered tolerable for this study.

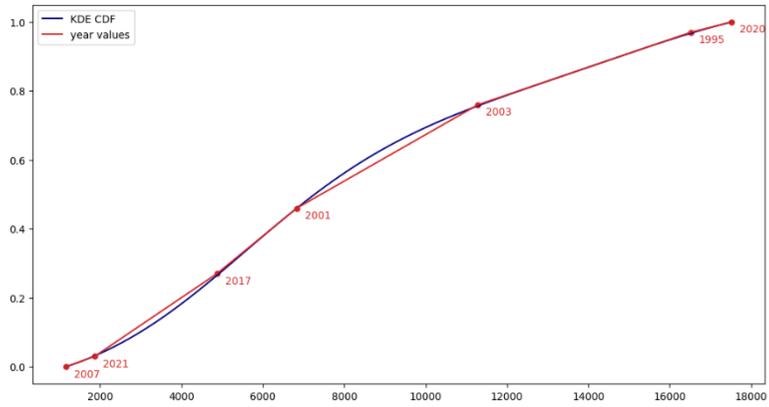


Figure 24 -Simplification with reference years visualized (source: own)

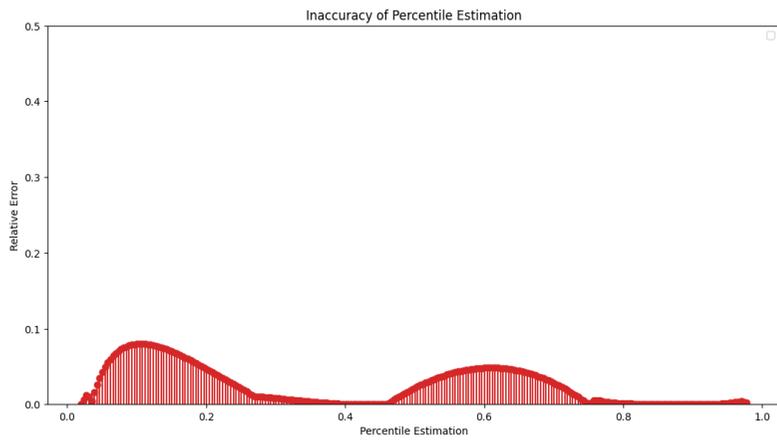


Figure 25 - Accuracy of simplifying the cumulative distribution function with 7 reference years (source: own)

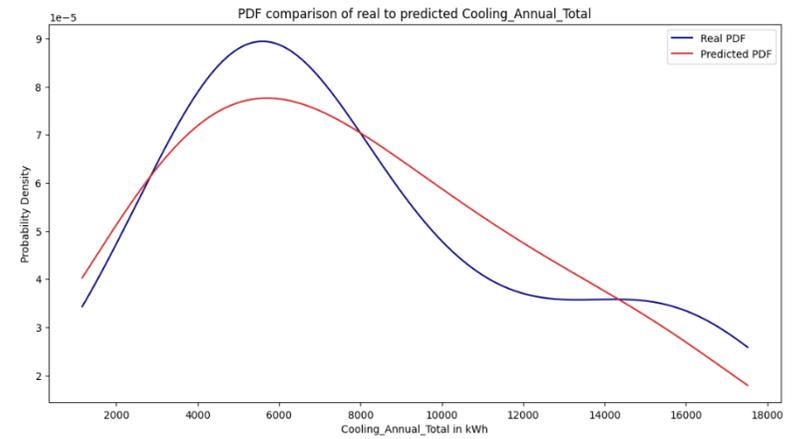


Figure 26 - Real and Predicted Probability Density Function (source: own)

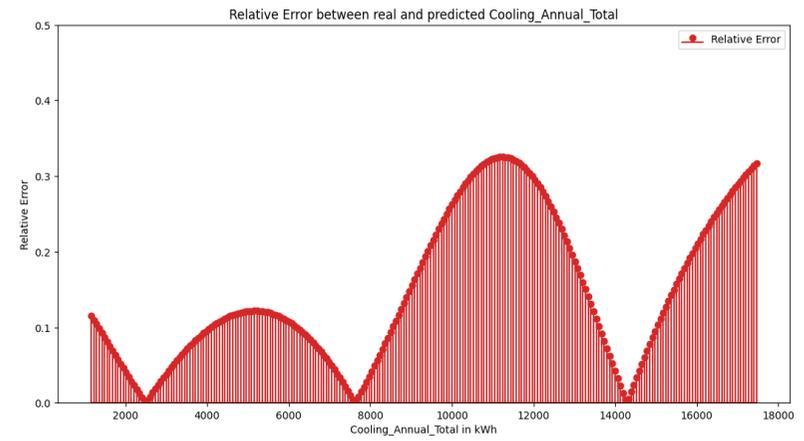


Figure 27 - Accuracy of probability density estimation with seven reference years (source: own)

3.3.2 Thermal Hazard Selection

The goal of the framework is to analyze and understand the impact of potential hazard loss over time. A probabilistic analysis from the preceding chapter serves as the basis for understanding how weather conditions influence the distribution of variables like energy demand; however, the role of heat hazard still needs to be investigated. Accordingly, in this chapter, historical weather data will be analyzed to identify heatwaves and outline annual extremes. Additionally, one specific year representing the extreme, including a heat wave scenario, will be selected. The reference is necessary to quantify the comparison metrics. All selected metrics can be determined for any year; however, the analysis should align with the over-time loss estimation. Therefore, a probabilistic investigation of overheating will inform the selection of a representative extreme with a significant chance of recurrence. The metrics should inform about overheating in realistic extreme weather conditions.

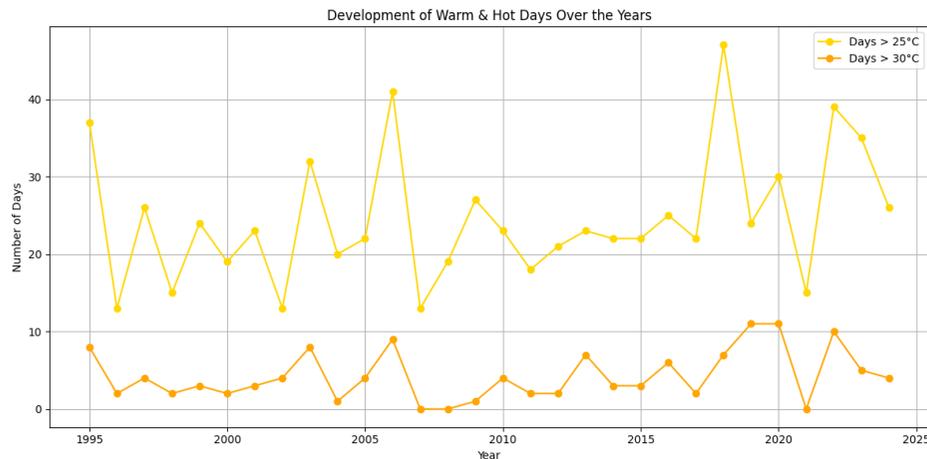


Figure 28 - Warm & Hot Days per Year (source: own)

First, the historical weather data were analyzed, examining the intensity and duration of temperature levels, which are typical benchmarks for extremes (Ouzeau et al., 2016). According to the heatwave definition of KNMI, 25°C and 30°C are interesting benchmarks for daily maximum temperatures. In Figure 28, the number of days exceeding these thresholds was plotted.

3.3.2.1 Heat Waves

To better understand how common heat hazard is in the Netherlands, an analysis based on the KNMI definition investigated all historical years for heat waves.

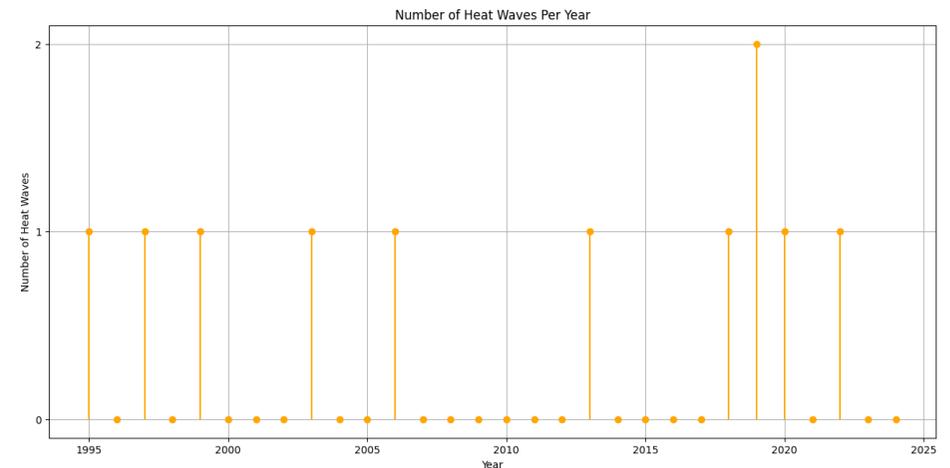


Figure 29 - Plot Number of Heat Waves per Year (source: own)

The results show 11 heat waves occurred in 10 of the 30 years analyzed. 2019 was the only year with two heat waves (See Figure 29). The length varied between 5 days, the first heat wave of 2019, and 20 days in 2018 (See Figure 30). In the Netherlands, heat waves are most common in July and August. From the analysis, it can be concluded that heat as a hazard should be

considered a regular phenomenon and will be experienced several times during a user period of a building of 30 years.

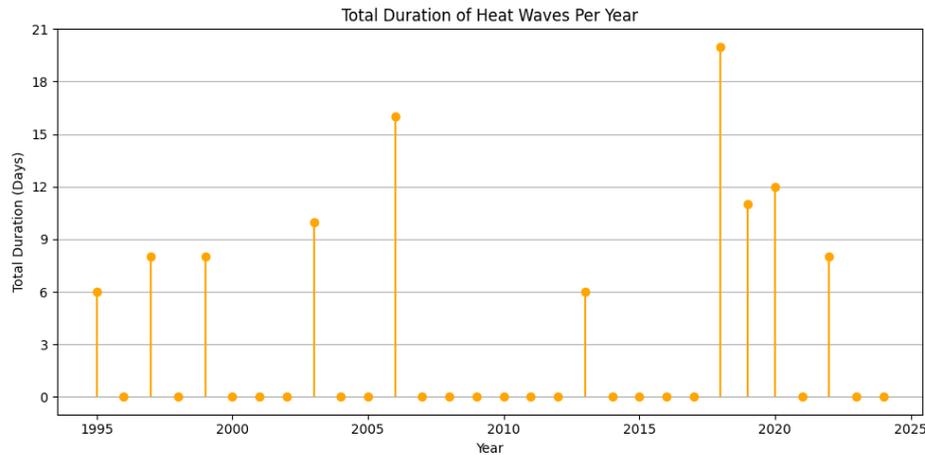


Figure 30 - Plot Total Length of Heat Waves per Year (source: own)

3.3.2.2 Summer Intensity

As discomfort due to overheating can also be experienced outside of the prolonged periods of high temperatures, the general extremity of summer periods, May to September, was analyzed further.

A method similar to the degree days analysis was chosen, where all days exceeding the daily maximum of 25°C were considered. First, the number of days was counted, and the temperature difference to 25°C was taken and summed to a single value. These two scales were plotted on a chart (See Figure 31), and all years, including a heat wave, were labeled for comparison. It is noteworthy that insights from the heat wave analysis can also be found considering the whole summer period. 2018 had the highest number of days above 25°C, with 47, while the intensity of temperatures was rather average. Meanwhile, 2019 had quite a few warm days, though these days were rather

extreme in temperature. In 2019, the highest maximum daily temperature was recorded at 37.2°C in all years.

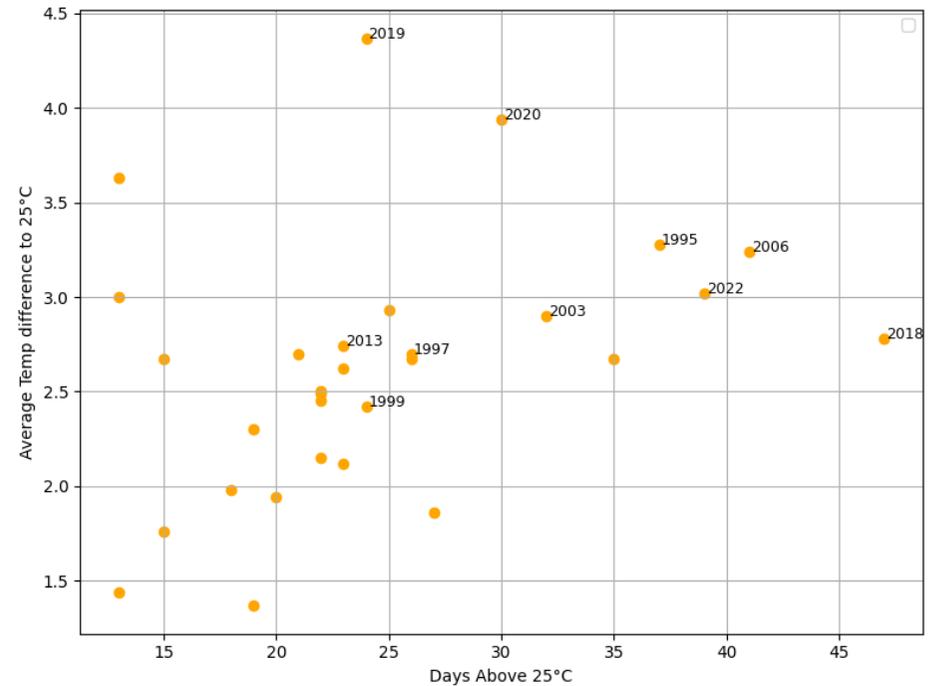


Figure 31 - Intensity and Duration of Daily Maximum Temperatures (source: own)

The two parameters were normalized, and the mean was calculated with equal weights. Then, both development over time and years sorted from lowest to highest value were plotted (See Figure 32 and Figure 33). Especially visible in Figure 32, six years stand out on the summer intensity scale: 2022, 2019, 1995, 2020, 2018, and 2006.

All six years were used in simulation to quantify Overheated Hours and Degree Hours with a limit of 28 SET, for which the results are shown in Table 13. The

level of overheating is not reflected in the same order as the summer intensity measure, with 2022 at the low end, at 0.66 of summer intensity, and the highest value of overheated hours at 174 hours. 2018, on the other hand, scored highest in summer intensity while being relatively low in overheated hours. A possible reason for these results may be that instead of hourly temperature levels, the daily maximum was counted for the summer intensity measure. Also, a temperature threshold of 25°C dry-bulb does not align with the comfort limit of 28 SET. Considering the annual energy demand with a set-point temperature of 24°C, the years again line up differently. Here, 2020 ranks highest, with one of the highest values of overheated hours, although it sits rather in the middle in terms of summer intensity.

It was concluded that a measure of summer intensity does neither accurately represent demand nor overheating. It could only be used to generally describe the intensity of outdoor temperatures respective to the Dutch heat wave threshold values. The indicator would need adjustments to correspond to the threshold for indoor overheating and does not work as an indicator for a probabilistic selection of an annual extreme. However, the analysis of summer season temperatures was insightful for learning about the yearly duration and intensity of heat.

Table 13 - Overheating during the Warmest Summers (source: own)

Year	Summer Intensity	Overheated Hours >28 SET	Degree Hours >28 SET	Energy Demand kWh
2022	0.66	174	588	14,071.11
2019	0.66	101	191	14,697.04
1995	0.67	151	365	16,510.48
2020	0.68	162	309	17,515.24
2006	0.72	117	117	17,077.96
2018	0.74	113	553	15,263.55

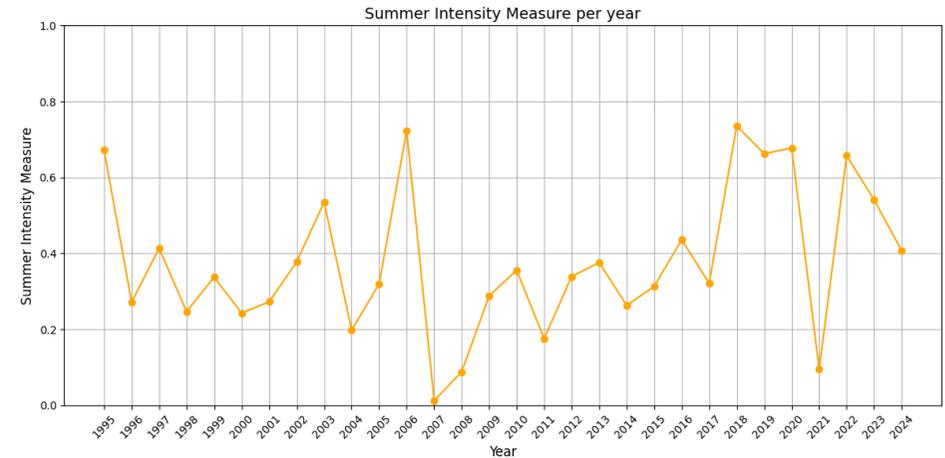


Figure 32 – Summer Intensity of the Years (source: own)

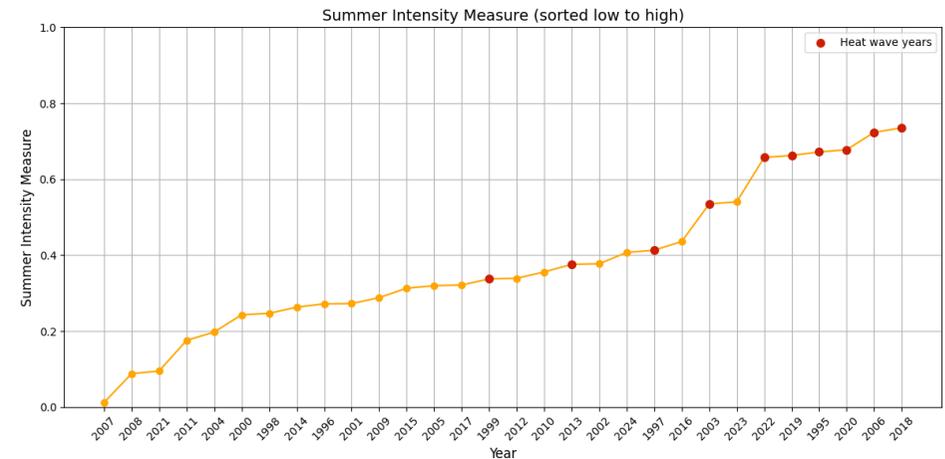


Figure 33 – Summer Intensity low to high (source: own)

3.3.2.3 Probabilistic Overheating Analysis

For the final probabilistic selection of the reference year, the overheated hours 28 SET in the summer of all 30 historical years were quantified through simulations. This approach was chosen to more accurately assess the relation between comfort and annual weather.

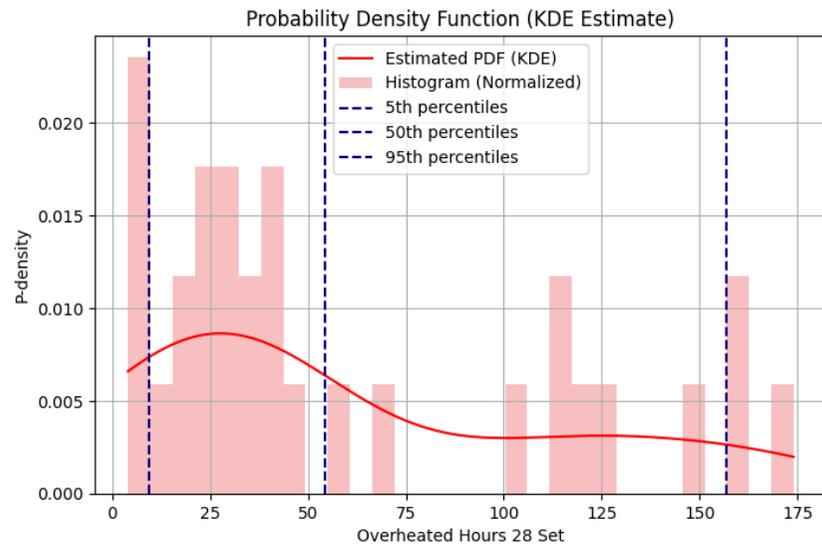


Figure 34 - Probability Density of Overheated Hours (source: own)

First, the probability density function was plotted with the marked 5th, 50th, and 95th percentiles. The closest matching years were estimated on the cumulative graph (See Figure 35). With just 4 hours, 2021 came out lowest, while 2007 matched the 5th percentile, closest representing 2% of the data with six hours. 2016 met the 50th percentile closest with 60 overheated hours. As mentioned, the 2022 summer resulted in the highest number of overheated hours, followed by 2020 for the 95th percentile.

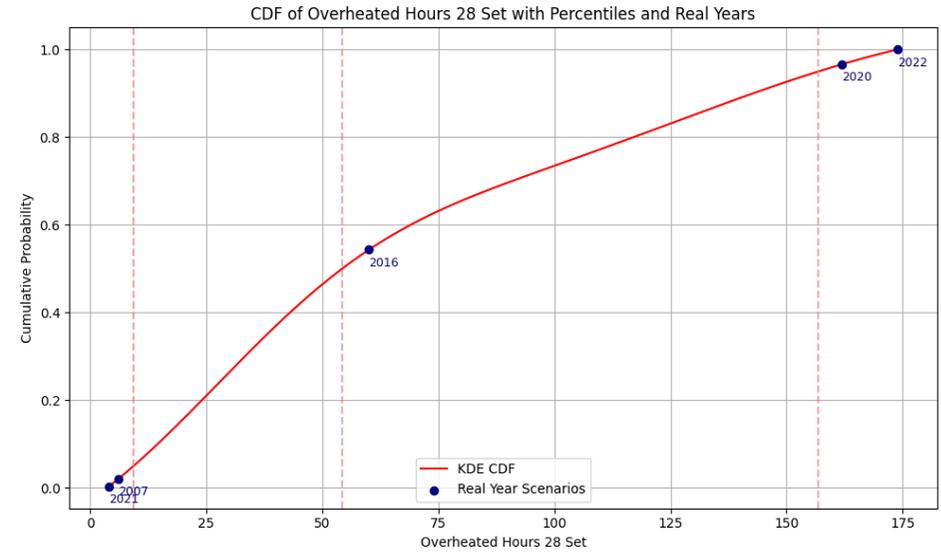


Figure 35 - Cumulative probability of Overheated Hours marking Years closest to percentiles (source: own)

In the end, the 95th percentile was chosen as the reference scenario for the case study. The selection relates to the 5% exceeding scenario of the NEN 5060:2018+A1:2021 norm for energy performance analysis (NEN 5060+A1, 2021). The reason for not using the norm scenario was to stay in the same context as the energy demand analysis.

2020 was chosen as the representative year for a 5% chance of exceeding, though it represents 97% of the data with 162 overheated hours. The year also reappears on the annual demand distribution as the year producing the highest energy demand. The year will reference the hypothetical case of discomfort in case of no technical cooling, while the energy cost associated represent the highest cost for actively mitigating the extreme. Furthermore, the year was chosen because of a 3-5% chance of exceeding the already extreme case of 2020, which has a realistic chance of occurring again within

the analyzed future period. The 2020 summer period will be used for all comparative resilience metrics in the case study.

3.3.2.4 Heat Wave Contribution to Annual Values

To better understand the contribution of heat hazards to overheating and cooling, the heat wave years were identified in the probabilistic analysis. The heat wave years are labeled on the cumulative distribution functions in Figure 36 and Figure 37, with the remaining years also visible as smaller points. Most of the heat wave years sit above the 50th percentile but also mix with other years in the middle of the distribution.

The six hottest years from the summer intensity analysis stand out as the top six in terms of cooling demand. However, neither scores highest in overheating collectively nor ranks in a similar order, as noted before. Only 2020 and 1995 are found in a similar position in both distributions, sitting closest to the top 95th percentile.

Out of all heat wave years, 1999 has the lowest annual value in both cases, sitting even below the 50th percentile. This suggests that a heat hazard does not necessarily push the annual value above the average; however, for the cases of 1999 and 2013, a more in-depth investigation of summer temperatures and heatwave intensity would be required. Although, generally, heat waves seem to relate to annual overheated hours and energy demand.

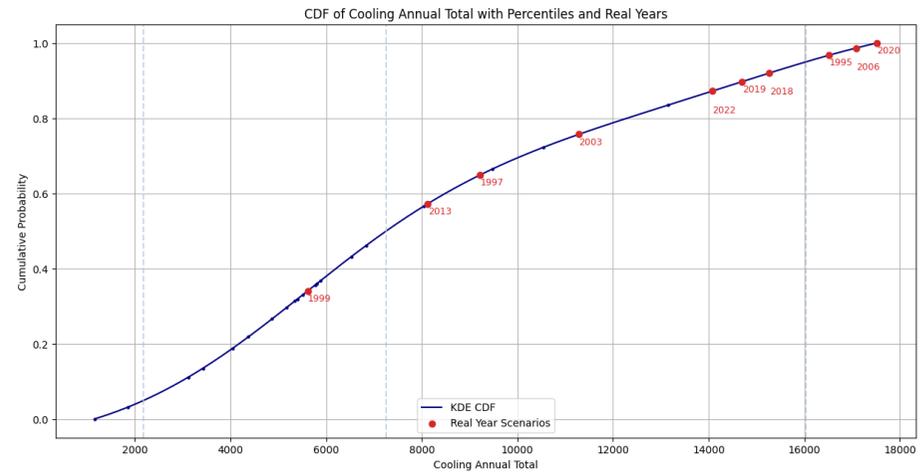


Figure 36 - Cumulative Distribution of Annual Cooling Energy Demand (source: own)

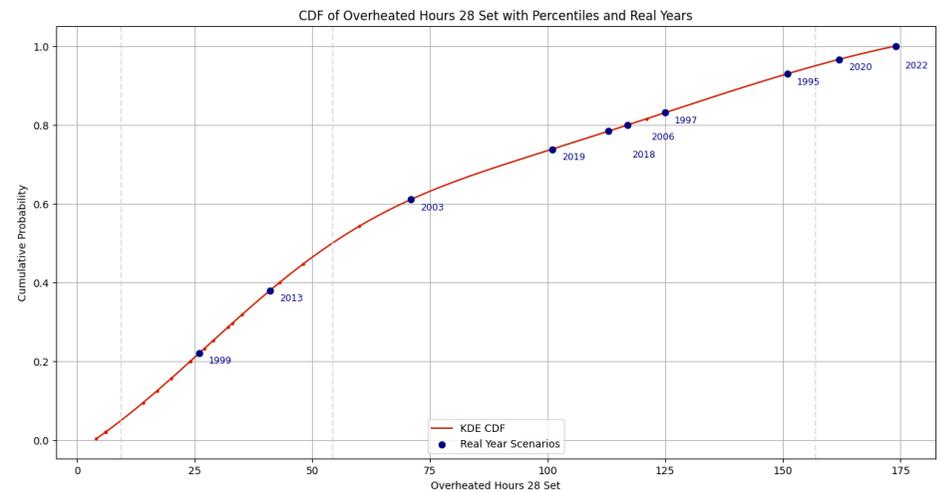


Figure 37 - Cumulative Distribution of Annual Overheated Hours (source: own)

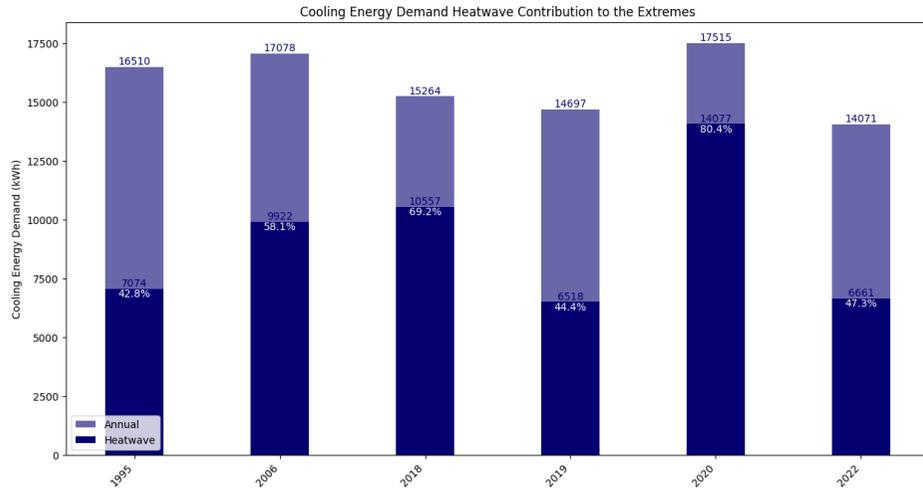


Figure 38 - Heat Wave Contribution to Annual Cooling Energy Demand in kWh (source: own)

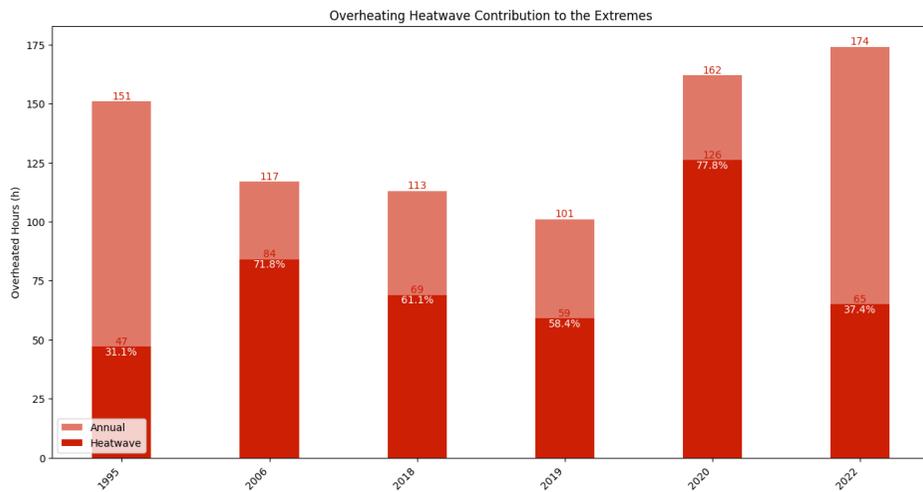


Figure 39 - Heat Wave Contribution to Annual Overheated Hours ≥ 28 SET (source: own)

Therefore, the contribution of heat waves to the annual value was further investigated. The heat wave and full summer periods were simulated considering the top six years of summer intensity and cooling demand. For the heat wave period 8 days were added as surcharge before and after. The results are shown in bar charts (Figure 38 and Figure 39), marking the percentage of heat wave contribution. Regarding energy demand, for all six years, heat waves make up at least 40% of the annual. In three of the years, 2022, 1995, and 2019, the percentage is below 50%. In terms of overheating, heatwaves sometimes make up a certain percentage of the annual total, ranging between 30% and 78%. For the three years identified, the heat waves again contributed the least, although in 2019, overheating made up more than 50%. In 2020, the heat wave contribution resulted in the highest, percentages of 80.4% for energy and 77.8% for overheating. Notably the 12-day heat wave was the third longest of all. The year, in general, scored rather high in temperature intensity than duration (See Figure 31).

In all cases, heat waves contributed significantly to the annual value. The correlation between high annual energy values and overheating, as well as heat as a hazard, is evident in both analyses.

3.3.2.5 Definition of Annual Extremes

For the later probabilistic long-term impact study on the cost-benefit analysis, it is necessary to outline an annual threshold for heat extremes. Since energy cost was chosen to represent hazard loss, the limit would be a demand value, where, if exceeded, it indicates an extreme. The six years with the hottest summers scored the highest in terms of energy demand. Therefore, the range of their annual values was chosen to outline the extremes. 2022 sits at the low end of the six, matching the 87th percentile with a demand of 14,071.36 kWh. The threshold was then lowered to the 85th percentile, resulting in a slight surcharge, which now includes all values above 13,520 kWh in the baseline scenario. This means that any annual value surpassing the 85th percentile value for cooling will be classified as extreme, corresponding to an extreme

event. The extreme range now includes 15% of all possible values. In the following section, the expected and exceptional frequency of such extremes will be explored.

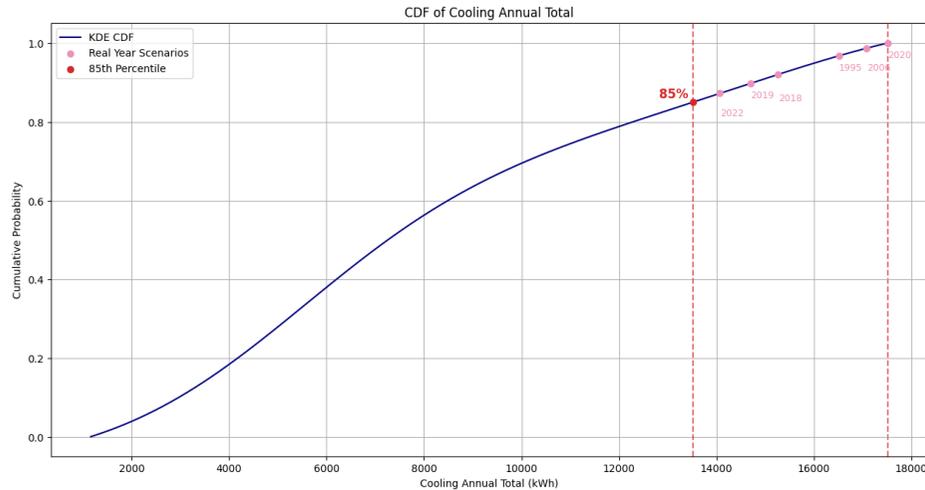


Figure 40 – Percentile Area of Extremes on the CDF for Cooling (source: own)

3.3.3 Exceptional Frequency of Occurrence

The probabilistic analysis for cooling and the 85th percentile definition outlined a scenario with a 15% change of occurring again for any given year. The most probable expected frequency of occurrence given a period of 30 years would consequently be 4.5 years. Thus, it is reasonable to expect approximately 4 to 5 years with cooling demand above this threshold.

A frequency of six as documented over the past 30 years is outside of this range and whether this was a statistically significant can be answered with a binominal test (“Binomial Test,” 2008). To later review, whether a frequency of extreme values was significantly exceptional. The test assessed both the probability of observing exactly a given number of years with extreme

demand, and the cumulative probability of observing that number or more. These probabilities were calculated using the binomial probability mass function and its corresponding cumulative distribution.

To determine whether the observed frequency qualifies as statistically exceptional, the analysis identified the smallest number of high-demand years for which the cumulative probability falls below or near the commonly used five percent significance level (Ibid). In this case, the threshold was found to be eight or more years, which corresponds to a cumulative probability of approximately 6.98 percent. Although this is slightly above the five percent threshold, it was considered a reasonable approximation for the purpose of setting a conservative benchmark. For six or more years above the threshold, the cumulative probability falls just below 30 percent. This indicates that such a deviation would not be considered statistically significant and lies well within the expected range of variability.

Additionally, the z-score was determined indicating how far the number k lies from the expected in terms of standard deviations (Ibid). Table 14 presents a summary for the number of years ranging from zero to ten high-demand years.

In conclusion, the occurrence of eight or more years with cooling demand above the 85th percentile threshold within a 30-year period can be considered significantly exceptional. As such, it serves as a suitable worst-case scenario for cost-benefit analysis and risk management.

Table 14 - Binominal Test for Number of Extremes (source: own)

k (number of extreme years)	$P(X=k)$	$P(X \geq k)$	Z-Score
0	0.007631	1.000000	-2.30
1	0.040398	0.992369	-1.79
2	0.103372	0.951971	-1.28

3	0.170259	0.848599	-0.77
4	0.202809	0.678340	-0.26
5	0.186107	0.475531	0.26
6	0.136843	0.289424	0.77
7	0.136843	0.152581	1.28
8	0.042007	0.069785	1.79
9	0.018121	0.027778	2.30
10	0.006715	0.009658	2.81

3.4 Cost-Benefit Method

3.4.1 Cost Modelling at Project Scale

Global cost modelling was chosen for the case study because the CBA analysis focuses on the project scale and does not require the in-depth life cycle cost of all components. Some cost parameters can be simplified with this approach, such as maintenance or replacement costs. If possible, maintenance cost can be estimated as an annual ratio of investment cost; Annex E of EN15459-1:2017 offers references for such rates for components, etc. (NEN-EN 15459-1, 2017). Otherwise, specific maintenance efforts can be estimated for specific points in time when they are needed. Replacement cost can be reduced to the discounted investment cost at the end of a component's life span. Also, the norm offers an overview of the component's life span.

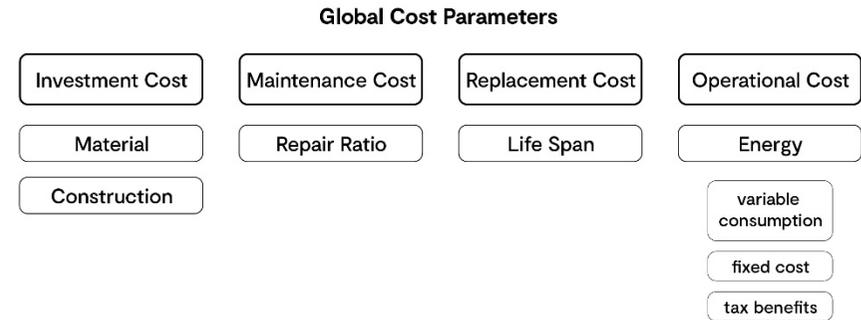


Figure 41 - Global Cost Modelling (source: own)

Using universal national data, investment cost can be estimated using the 'RVO' or 'Archidat' databases. Generally, operational costs include all variable and fixed costs for each year that support the building's daily function, such as electricity, domestic hot water, heating, cooling, and ventilation. However, the cost is irrelevant for decision-making in the retrofitting scenario, which can be neglected. For this study, operational cost is reduced to energy cost for heating or cooling. It can be estimated by dividing the total annual energy demand by the performance coefficient and multiplying by the cost per unit, e.g., kWh or m³. Then, the fixed cost, e.g., grid connection, can be added and tax reductions subtracted (Wahi, 2025). Energy price development is another optional factor for price development over time.

3.4.2 Economic Indicator Selection

In general, the cost-benefit analysis could inform about the probability of a net negative or non-beneficial outcome, as well as the worst case to the best outcome. The economic indicator for the CBA should therefore support these insights on uncertainty. For the selection, all prevalent indicators from the literature study were compared (See Table 15).

The measure 'Total Cost of Ownership' can generally be used to compare how cost changes by making choices and comparing cost against qualitative benefit. An uncertainty analysis would indicate a risk of a higher resulting cost than expected.

Analyzing the Net Present Value, Benefit Cost Ratio, or Payback Period is more reasonable for monetary benefits. While the Net Present Value also gives insights into expected profits, the BCR indicates whether the outcome is a net positive or negative. With an uncertainty analysis, the risk for a negative outcome is quantified with both indicators, because of the clear flipping point of 0 for the NPV and 1 for the BCR. However, as both calculations use the same discounted cash flow basis, the NPV is more informative. Regarding the 'Payback Period', the central insight gained from the quantification is only how fast an investment pays off, meaning an uncertainty analysis would offer to see the risk of payback time increasing.

Concluding on the reflection on gained insights with uncertainty analysis, the NPV stands out as the most informative indicator for a project's net benefits and losses compared to the status quo. An analysis without revenue but only savings as benefits also indicates the difference in total cost of ownership compared to the baseline scenario. Therefore, the NPV is the most important indicator to adopt. However, when payoff is not a stakeholder priority, the total cost of ownership is the more suitable indicator for a cost-effectiveness

analysis, considering only non-monetary benefits. For this study, the relevance of the total cost of ownership will be decided on later in the case study.

Table 15 - Insightfulness of Economic Indicators in Uncertainty Analysis (source: own)

<i>Economic Indicators</i>	Total Cost of Ownership	Net Present Value	Benefit-Cost Ratio	Payback Period
<i>Description</i>	sum of all costs from investment to operation	present value of all future cashflows	net benefits divided by upfront cost	time required to recover the capital sh inflows
<i>Method</i>	life cycle costing summarized (deduct resale value) compare to revenue stream qualitative indices to see	sum of discounted benefits & costs over project time span	sum of all net benefits divided by sum of all upfront cost, if >1 beneficial	NPV=0 solve for time variable
<i>Heat Hazard Effect</i>	Energy Cost, Ecological Cost	Energy Savings, Revenue Loss	Energy or Ecological Savings, Revenue loss	Energy or Ecological Savings, Revenue loss
<i>Risk Analysis</i>	Energy or Ecological Cost Uncertainty	Energy or Ecological Cost, Revenue Uncertainty	Energy or Ecological Cost, Revenue Uncertainty	Energy or Ecological Cost, Revenue Uncertainty
<i>Gained Insights</i>	Comparing changes to the cost of keeping status quo, cost can be compared to qualitative benefits or revenue	Net positive outcome; expected Profit	Is the project beneficiary or not	How fast does an investment become profitable? Does the PP match desired time frame, Cost-Optimal Solution Comparison
<i>Gained Resilience Insight</i>	Risk for total cost to going up	Risk for no profits/benefits	Risk for no net benefit	Risk affecting time for pay back
<i>Advantages</i>	valuable for private decision-making	suitable for analysing profits, clear cutting point	clear cutting point	suitable for finding turning points
<i>Disadvantages</i>	no clear cutting point, savings or profits not directly visible, decision making with risk analysis not easier	not knowing when which costs occur	not showing direct profitability, could neglect specific life cycle costs?	no clear cutting point, as long as pp < analysis period ok.
ADOPT OR NOT	ADOPT cost summaries	ADOPT	NOT	NOT

3.4.3 Overall Framework

This section summarizes the overall cost-benefit method for application and the steps involved in the analysis.

Going back to the integration into renovation planning, cost-benefit analysis is helpful to validate the overall worth of renovation measures, while comparison metrics help to benchmark the qualitative benefits of mitigating overheating.

The central aspect of the framework is quantifying the financial risk for the economic indicator deviating in a worst-case scenario of exceptionally frequent extremes. The risk analysis is focused on the variability of energy costs and savings due to climate uncertainty with a threshold for heat extremes. The uncertainty can be estimated using historical weather data of the past 30 years and annual simulations for specific years, representing percentiles to construct probability distributions. The estimated distribution of annual energy demand for heating or cooling can then be translated into cost or savings. The cost further depends on the technical system, e.g., air conditioning, and the prices depending on the energy source, such as electricity. Carbon cost related to energy use and the development of energy prices, is a potential extension to the approach.

The probabilistic performance analysis also allows for determining the average energy efficiency, the maximum value corresponding to the year 2020 and the efficiency at the 85th percentile threshold for extreme. The heat resilience for comfort, on the other hand, is quantified for a specific weather extreme with a realistic chance of recurrence.

The financial risk analysis will be done using a Monte Carlo simulation, meaning the NPV calculation is done a sufficient number of times, e.g., 5,000, sampling a different energy savings value based on its probability for every run. Other global cost parameters, such as the investment cost, will stay fixed

during the simulation. Before, a desired analysis period and discount rate are set. In addition to the distribution of energy cost, the effect of a changed discount rate can also be tested. Finally, a new distribution for the NPV or TCOO can be estimated based on all collected results. For the NPV distribution, the overlap with negative values can be calculated, indicating the risk for a non-profitable outcome. Furthermore, a statistical analysis on the influence of the samples above threshold per calculation on the economic indicator can be done to identify the financial outcome and risk of the worst case.

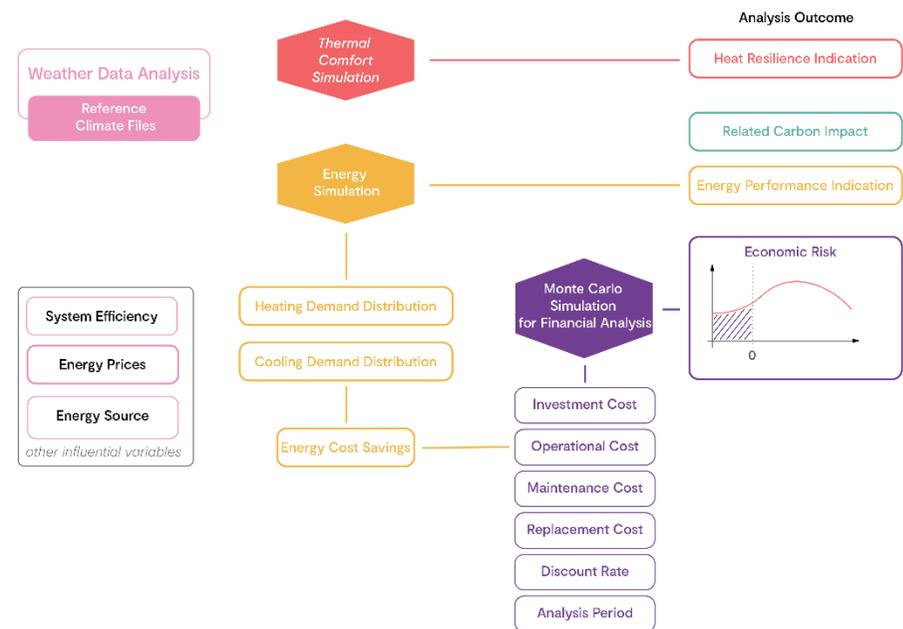


Figure 42 -Theoretical Background (source: own)

3.5 Digital Implementation

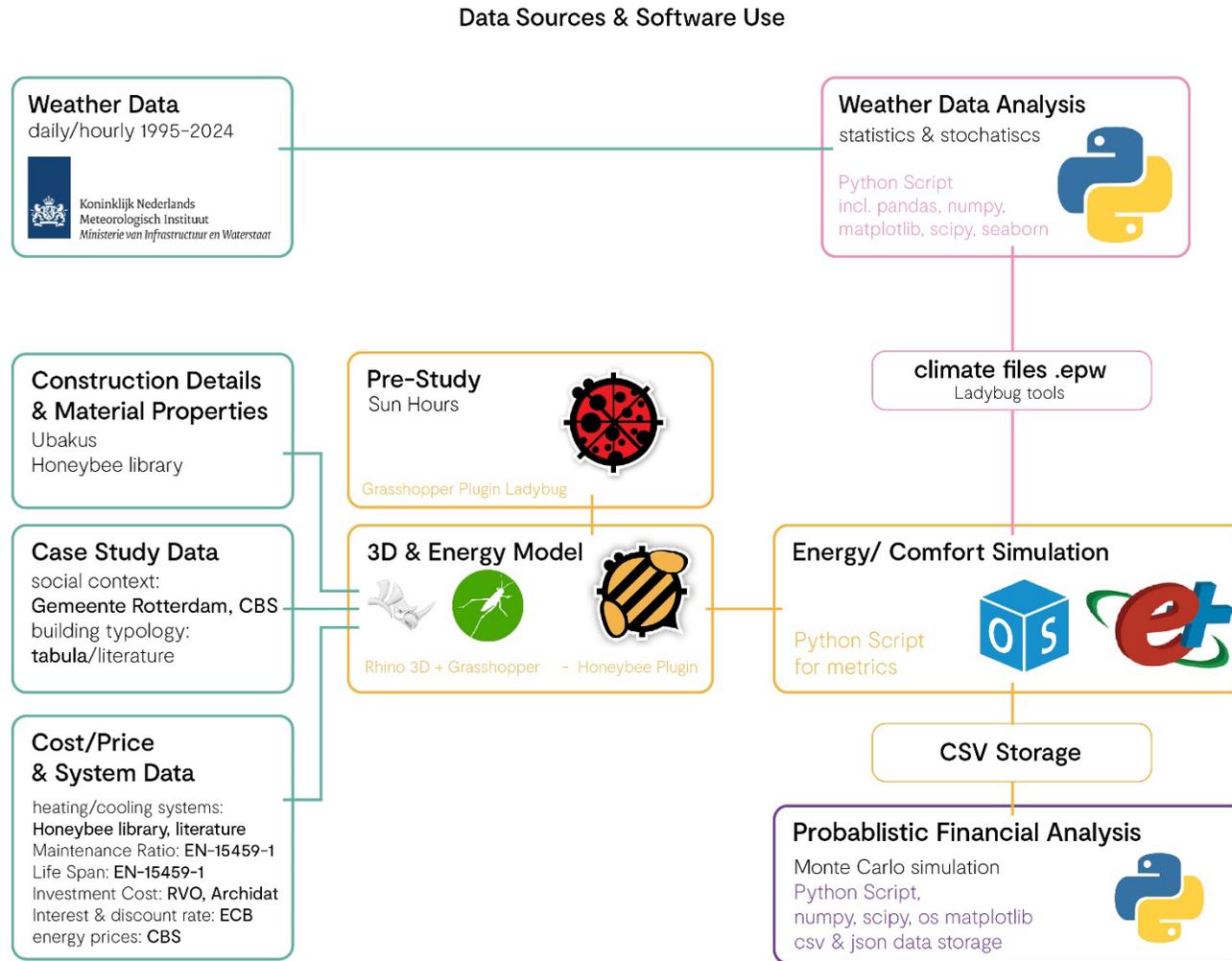


Figure 43 - Data Sources and Software Use (source: own)

3.5.1 Data Sources

Several public platforms and libraries were used to collect all necessary data for the analysis. The historical weather data was sourced from the noaa.gov and KNMI platforms, both of which provide daily and hourly data for the station closest to the case study site (KNMI, n.d.-b; NCEI, n.d.).

For the construction details and material properties, the building physics tool 'Ubakus' and the 'tabula' data platform were used (*TABULA WebTool*, n.d.; *U-Value Calculator*, n.d.). The tabula web tool offers data on renovation projects for similar building archetypes in the Netherlands. Construction set data from the library of the energy simulation tool was filled in the remaining information gaps.

The municipality and city archive of Rotterdam provided information regarding the case study building specifically. The energy provider Eneco publishes specifications of the local district heating system and cost, while general energy costs were sourced from the public national platform CBS Statline.

For the cost-benefit settings and product data, norm data, e.g., NEN-EN 15459-1, and product data sheets were considered. The main source for the investment cost came from RVO's 'Kostenkentallen' and Archidat's 'bouwkosten' database (*Archidat Bouwkosten, Actuele Richtprijzen Voor de Bouw.*, n.d.; *Kostenkentallen*, n.d.).

Lastly, the platform Ubakus and the Bombyx plugin provided sufficient information for embodied carbon calculations.

3.5.2 Probabilistic Weather Data Analysis

All uncertainty analysis for weather data was conducted in a Python script using various libraries. At first, the historical daily weather data was downloaded from the KNMI portal as one file and adjusted slightly to be read

as a CSV. The data from the CSV was translated to a 'pandas' data frame in the script. Then, with the Gaussian KDE function from Scipy and other numpy functions, the probabilities were estimated. Matplotlib was used to visualize the data in a graph. The data was again stored in CSV files when calculating annual indicators like the 'Ambient Warmness Degree'.

Hourly data was downloaded from 'ncei.noaa.gov' and translated using the 'ladybug tools' in the 'Grasshopper' environment to create the actual meteorological epw files for the energy simulations.

3.5.3 Energy & Thermal Comfort Simulation

The energy and thermal comfort simulations were all done using the Honeybee plugin from the Ladybug tools in the visual coding environment 'Grasshopper' for Rhino 3D.

This way, the 3D geometries like rooms, doors, and windows for the energy model could be drawn as Rhino geometries and then loaded into Grasshopper to construct a honeybee energy model. The 'OpenStudio' component uses the 'Honeybee' model in the energy simulation, which runs on an 'EnergyPlus' engine. The simulation results are stored in a SQL file, from which the relevant values like demand, operative temperature, and standard effective temperature are extracted. The comfort metrics are also calculated in Grasshopper using a Python script. Here, living and bedrooms are filtered from the data, and the average overheated hours and IOD are calculated for the building. Also, the AWD is sourced from the previous analysis CSV to determine the OEF.

Lastly, all results for comfort and energy are stored in a CSV file for the cost-benefit analysis.

3.5.4 Cost-Benefit Analysis Set up

The cost-benefit analysis was again set up as a Python script. The full workflow is shown in Figure 49. The script consists of a fixed, non-variable part and a repetitive part for the Monte-Carlo simulation that loops through numerous times.

```
"S01_simple_shading ": {  
  "household_size": 8,  
  "file": "AC_Simple-01_extra_TMY.csv",  
  "cooling_file": "AC_Simple-01_extra_CDD.csv",  
  "heating_file": "AC_Baseline_HDD.csv",  
  "overheating_file": "Scenario_Comfort.csv",  
  "cooling_energy_source": "electricity",  
  "heating_energy_source": "districtheating",  
  "cooling_system_type": "air_conditioning_split",  
  "heating_system_type": "district_heating",  
  "cooling_cop_or_eer": 2.9,  
  "heating_cop_or_eer": 1.0,  
  "investment_cost_cooling": 8300,  
  "investment_cost_heating": 12150,  
  "maintenance_cost_item1": 470,  
  "maintenance_cycle_item1": 5,  
  "replacement_cost_item1": 0,  
  "replacement_cycle_item1": null  
}
```

Figure 44 - JSON Data Storage (source: own)

All input information for the computation is stored in JSON files. In the JSON, every scenario has its dictionary with data on the energy sources, system,

investment, maintenance, and replacement cost, as well as references to the CSV with the simulation output. The cost estimation was conducted in an Excel file and then transferred to JSON. There are four JSON files, one for the baseline scenario, another for the retrofit options, one to store universal data, e.g., prices, and another to store the analysis settings like run period, start year, and discount rate.

The fixed script stands before the Monte-Carlo loop, where all data is loaded into variables from the JSON files first. An empty cost data frame is set with the length of the analysis period and an index for all years from 0 to (n-1).

The global cost parameters are added as columns to the frame. Since the NPV is calculated by comparing the renovation scenario to the baseline, all renovation costs are assumed to be real negative costs and the baseline cost as positive avoided benefits. Therefore, for each parameter, the difference is taken, and then the values are placed in the data frame for the point in time the cost is occurring.

The global cost parameters are added as columns to the frame. For the total cost of ownership, the cost for each scenario is considered separately. The NPV is calculated by comparing the renovation scenario to the baseline; all renovation costs are assumed to be real negative costs and the baseline cost as positive avoided benefits. Therefore, for each parameter, the difference is taken, and then the values are placed in the data frame for the point in time the cost is occurring.

Only operational costs or savings as the variable parameter are treated differently from the fixed investment, maintenance, and replacement costs. At first, the simulation results for the scenarios are loaded from the CSV. Since the values represent energy demand, system efficiency is applied to the demand values to account for improved efficiencies, e.g., switching from a gas boiler to district heating. Then, considering the price differences for energy

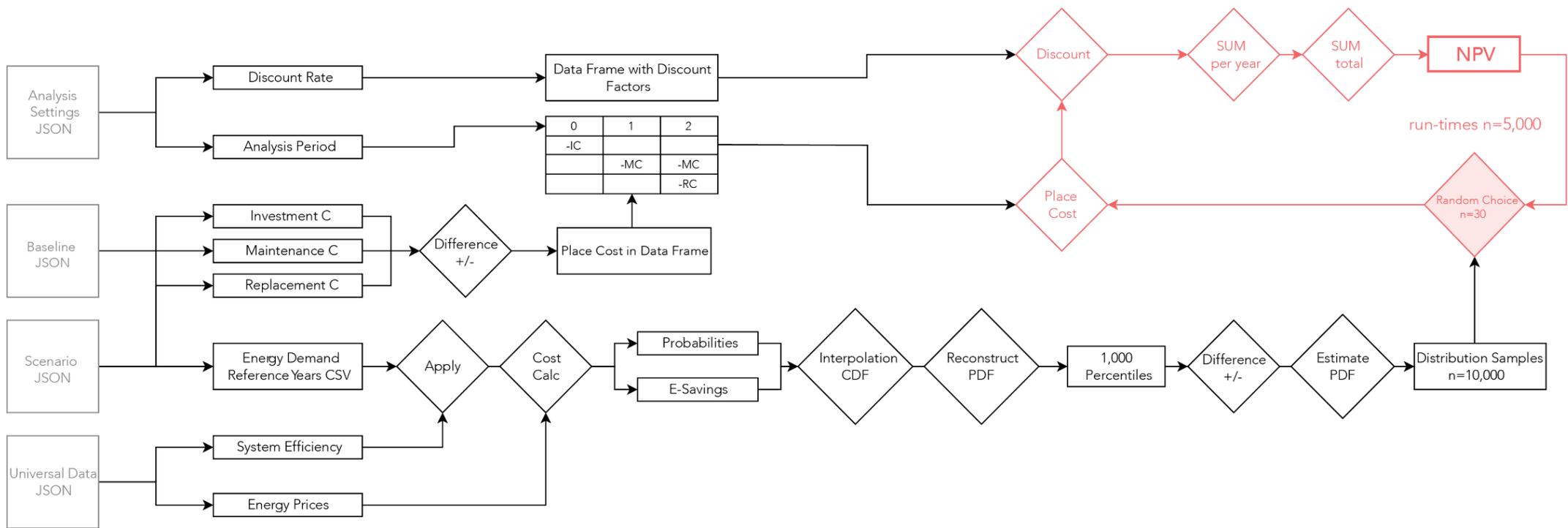


Figure 45 - Flowchart CBA Script (source: own)

sources, the energy use value is multiplied by the price per kWh, and, optionally, fixed costs are added. These seven values of energy cost for the reference years form the base for the probability distribution. Using estimated percentiles, a cumulative distribution function is interpolated, and new samples are calculated to construct a probability distribution function for energy cost. To estimate savings, a considerable (1,000) number of percentile values are taken for both the baseline and renovation scenarios. Then, the baseline value is subtracted from the scenario value. The set of savings serves as input for estimating the probability density. Finally, a sufficient number of samples, e.g., 10,000, are taken from the PDF to accurately represent the distribution. The probability estimation is done separately for heating and cooling to enable separate analyses of one or the other.

The following script section is repetitive and focused on randomly sampling the energy cost or savings. In every run, 30 samples are randomly chosen from the distribution samples and placed into the cost data frame. All costs in the data frame are then discounted using the discount factor for each year.

For the NPV calculation, first, the cost categories for each year are added and then summed for all years. Here, the loop is closed. For an accurate estimation, the NPV must be computed a sufficient number of times, e.g., 5,000.

Finally, the list with all NPVs is stored in a CSV file and can be analyzed statistically, for instance, to calculate the mean or the overlap with negative values. To store the results for each scenario, a new JSON file was set up, where the statistical values for the NPV, but also energy efficiency, carbon emissions and resilience metrics would be saved.

For total cost of ownership or just summing discounted global costs, the process remains the same except the savings estimation and cost difference operations are left out.

4 Study Preparation



Figure 46 – Gijssingstraat, Tussendijken, Rotterdam West (source: own)

4.1 Case Study Description

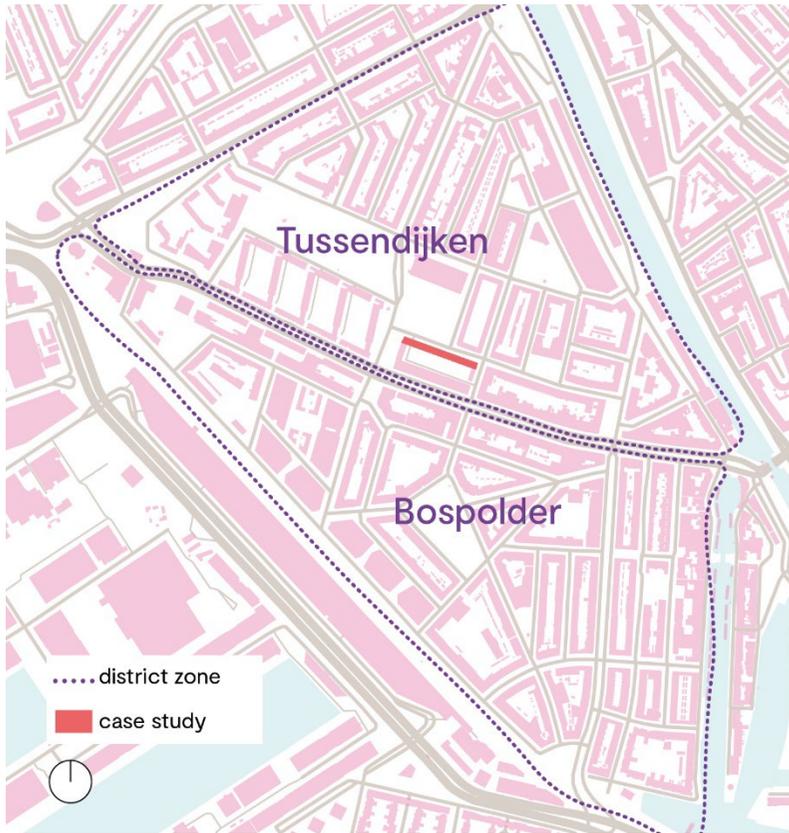


Figure 47 - district map (source: own, open street map)

For the case study, one unit of an existing row of porch houses was selected and used as an example case for applying the framework. The building row, 'Gijsingstraat 76-112', is located in the residential district 'Tussendijken' in Rotterdam West. The street goes one block apart parallel to a main street with shops and a tramline separating the district Tussendijken and Bospolder. The districts are part of a denser urban area approximately 3 km from the city

center. The buildings are four stories high with an unconditioned attic under a gable roof. Most of the buildings in the neighborhood have a similar height and typology, apart from a series of 8-storey gallery flats next to the north-western side of the block.

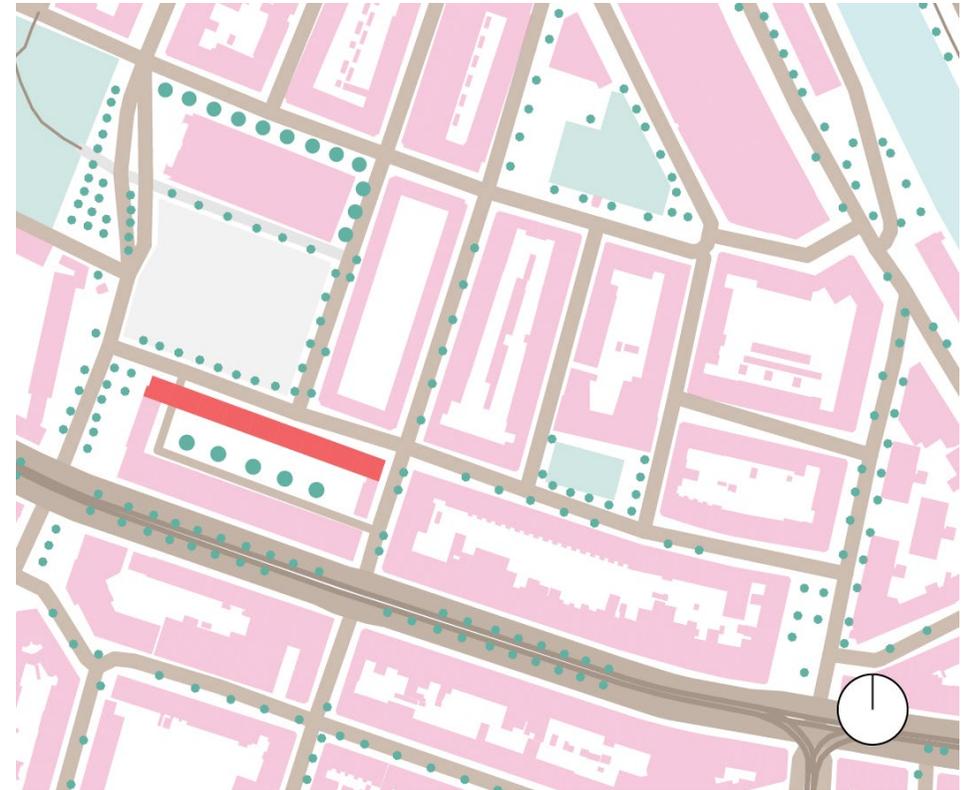


Figure 48 - neighborhood map (source: own, open street map)

Across the street is a public marketplace, 'Visserijplein', and a residential apartment block of the same typology (See Figure 48). The trees along the street are rather small and never surpass the building's height. The street side

with the entrances is oriented to the north-east, while the courtyard side faces south-west. Every unit has access to a 20m deep garden in the courtyard with some trees. Behind the gardens passes a back alley used by the main street shops, which can also be accessed from 'Gijsingstraat' via an under-passage through one of the last units of the row.

The block's apartments are privately owned and managed by the owner association VVE (IABR-ATELIER ROTTERDAM & POSAD MAXWAN, 2019). Therefore, they are either owner-occupied or private rental. The houses were built in 1952 and have not received a major envelope renovation since. To analyze the interior layout and construction of the building, the permit plans were sourced from the city archive of Rotterdam (Stadsarchief Rotterdam, n.d.). Every unit has 4 apartments on a floor with a central staircase access and two apartments per floor. While the right-side apartments are slightly bigger, with 3-bedroom and an approximate area of 62,3 m², the left-side apartments have 2-bedrooms and about 54,8m².

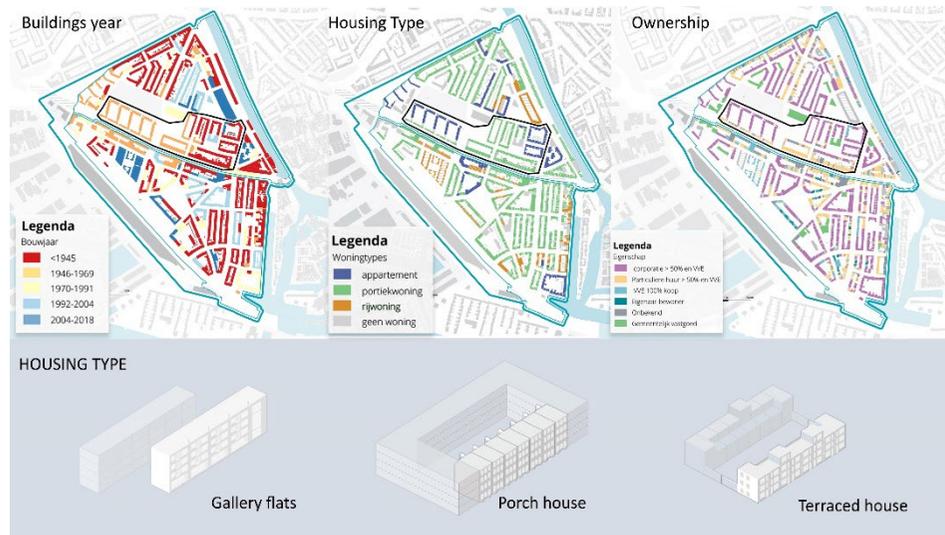


Figure 49 - district buildings age, typologies, ownership (source: IABR-ATELIER ROTTERDAM & POSAD MAXWAN, 2019)



Figure 50 - Context pictures (source: own)

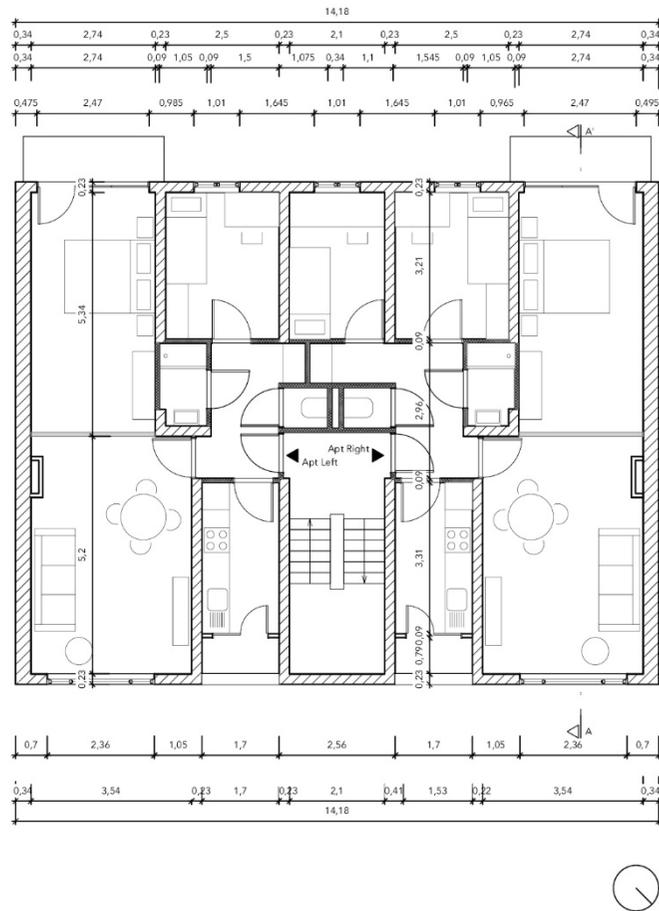


Figure 51 - standard floor plan 1. & 2. Floor (source: own)

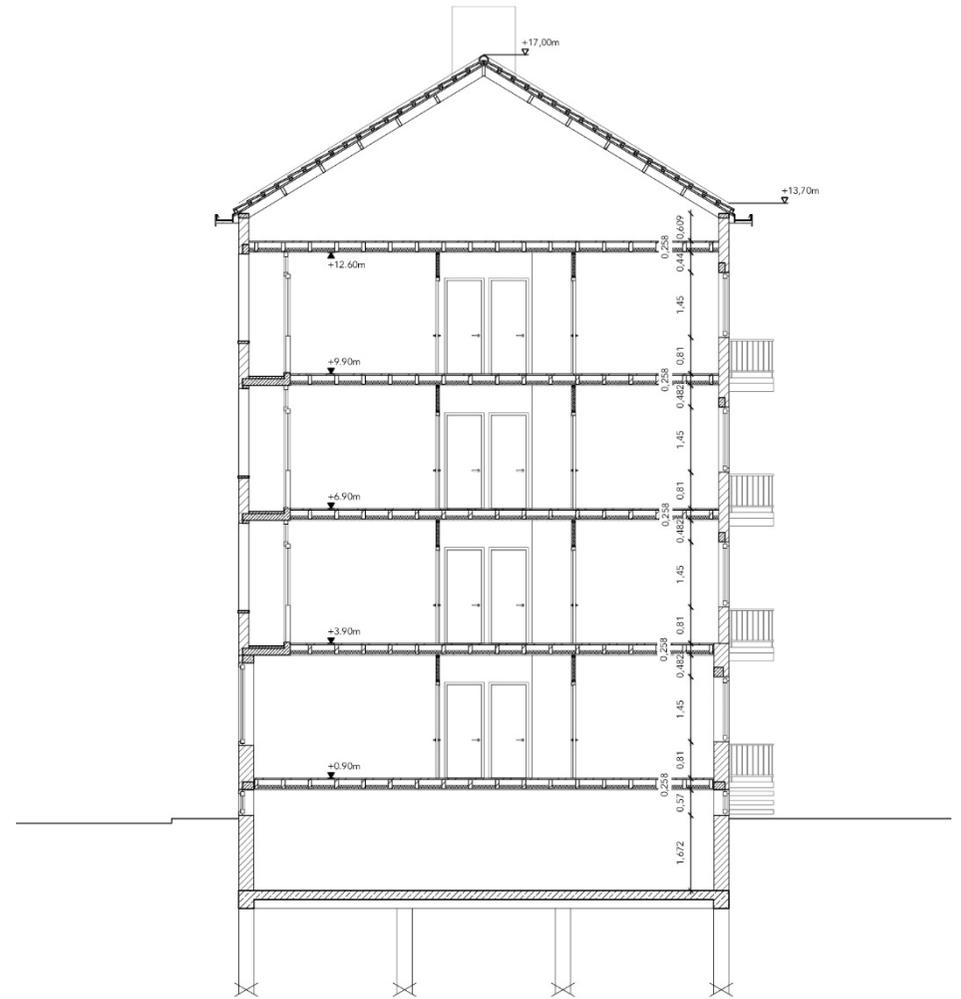


Figure 52 - Unit Cross section (source: own)

The kitchen is always the first room, right next to the staircase facing the street. Apart from the ground floor, all apartments have a small loggia balcony. The bathrooms are located centrally next to the hallway and have no windows. The separate bedrooms all have views of the courtyard. On the apartment's outward end, two larger rooms stretch from one facade to the other. It is interpreted from the plans that they can be connected to become one big living room or separated into a north-side living room and a south-side bedroom. The larger bed/living room has access to a balcony.

Energy Efficiency

To understand the energy efficiency of the status quo, all existing energy labels for the building row were collected. In total, labels for 15 apartments were found, with some only displaying the label and others also specifying primary energy use and heating demand (Rijksoverheid, n.d.). Table 16 labels are assigned to the apartment's floor and a clear correlation becomes visible. While the ground to 2. floors' labels range from C (7x) to one time E (1x), the third floor apartments received much worse classifications, ranging from D to G. An average heating demand per square meter of 205,33 kWh/m² was calculated.

The case study building was chosen because it represents a common typology in urban areas with low energy efficiency (RVO, 2022). Moreover, it is subject to the municipality's ongoing energy transition project that intends to connect both districts Bospolder & Tussendijken to the district heating system (source). Before, the main source for heating was natural gas, where apartment units had individual or central gas condensing boilers (Gemeente Rotterdam, n.d.-b). The project promoters expect to improve carbon emissions by 39% compared to gas heating (Eneco, 2023). In addition to the transition project, the municipality grants a subsidy of a basis amount of 5,000 and 2,100 per apartment benefited up to a sum of 50,000 Euro for renovations connected to measures to increase energy efficiency (Gemeente Rotterdam, n.d.-a).

Table 16 - Existing energy-labeling for the row of houses (source: (Rijksoverheid, n.d.))

Apartment Floor	Energy Label	Primary Fossil Energy Use [kWh/m ²]	Heating Demand [kWh/m ²]
00 Ground floor	C (4x)	249.75	173.17
01 First Floor	C	204.47	141.65
	D	-	-
	E		
02 Second Floor	C	228,8	149,75
	D (3x)	268.45	192.42
03 Third Floor	D	-	-
	E	-	-
	F	378.82	265.26
	G	621.71	312

Construction Details

The building was constructed with solid masonry walls of Dutch standard brick (measured on site). The walls on the ground floor and basement level are 34cm thick, whereas the walls on the upper storey floors on the north side are 23cm and the south side is 30cm. Based on the brick size, the assumption is made that the 34cm is a triple-layer brick wall of 32cm with a 2cm interior plaster layer, and the 23cm consists of a double-leaf wall with plaster, as well as the 30cm wall, which might have some extra drywall construction internally.

In the plan's sections, the interior floors are detailed as a timber-joist lightweight construction approximately 25cm tall. Currently, some of the windows are timber-framed single glazing and in bad condition, while others have already been replaced by double-glazing with operable ventilation slits (See Figure 59). Most of the balcony windows and doors are only half glazed, and some north-side loggias were closed with windows. Several kitchens have

mechanical exhaust ventilation penetrating through the facade. Meanwhile, there are hints on the south side for ventilation gaps above the bedroom windows. Currently, there is no exterior shading on either side of the building.

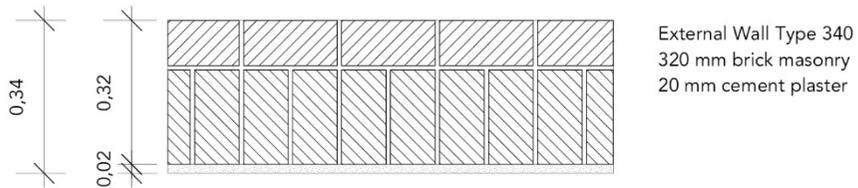
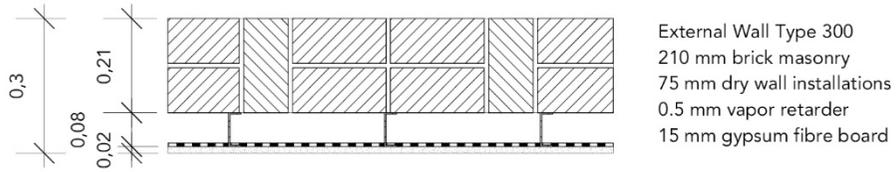
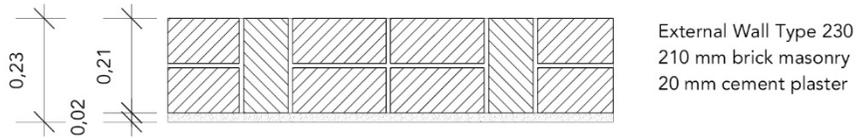
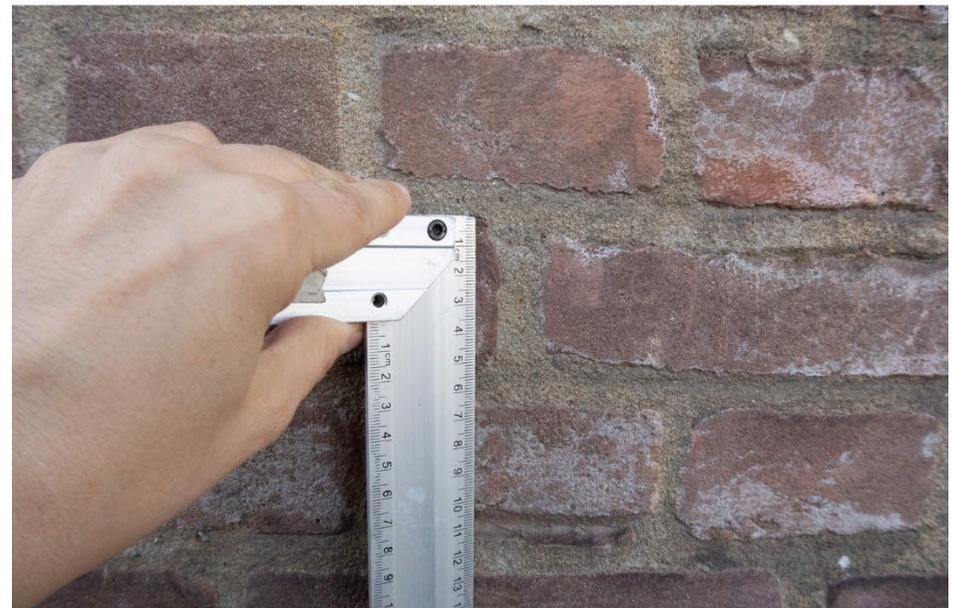


Figure 55 - Wall Types Baseline (source: own)

Figure 56 - Pictures of Brick Measurement (source: own)



4.2 Case Study Scenario

For the baseline scenario of the case study, a unit in the middle of the row was selected. This was to make the results more universally applicable for the entire row by excluding factors like heat exchange through side walls or extra shading from corner buildings.



Figure 58 - Building unit selection (source: own)

For the case study, an owner-occupied scenario is assumed, where the client and resident share the same interests. Considering the building has not yet been renovated, monetary resources might be limited. This combination means there is an interest in thermal comfort, while budget constraints apply, and investment recovery is preferable.

The maximum number of residents is estimated to be 3 for the left-side apartment and 5 for the right-side apartment, making an average of 0.05 ppl/m². The building, in its current state, has no airtight sealing and is therefore considered leaky, with 0.0006 m³/s per m². Also, natural ventilation losses can not be neglected.



Figure 59 - Close-up pictures windows (source: own)

Individual gas condensing boilers are the baseline heating system with an efficiency rate of 0.85 (Wahi, 2025). In reality, there is no technical cooling system in place, but it will be assumed in some of the renovation scenarios for comparability. The setpoint temperatures are set to 18°C for heating and 24°C for cooling, though cooling is only set from May to September. Surveys conducted by TNO found that most people will start active mechanical cooling as soon as the indoor temperature reaches 25°C to then set the temperature to 20-21°C (Rovers, n.d.). For this study, these findings were simplified to the conservative estimate of 24°C as a cooling setpoint, which is further supported by the RAAK research project, stating Dutch residents to feel discomfort from 25°C onwards (RAAK-project, n.d.). For heating, before calibration the lowest considerable value was chosen, as found by a report of the ENERGISE research group in 2019 (Vasseur et al., 2019).

To simplify the construction set, wall type 230 is applied to all exterior walls (see Table 17). The interior walls are assumed to be 90mm lightweight drywall construction. Single-glazed windows with a transmission of 5.2 W/(m²K) and non-insulated doors of 3.5 W/(m²K) are set as the baseline scenario (TABULA WebTool, n.d.). This assumption is made because a significant number of the apartments in the buildings still have single-glazing. A standard concrete slab is applied instead of timber joist flooring for the energy modeling to avoid model fragility due to lightweight construction under extreme temperatures.

Table 17 - Baseline Assumptions (source: own)

Scenario	Baseline
Infiltration	leaky: 0.0006 [m ³ /s per m ²]
Ventilation	natural (setpoints interior: 18-25°C, exterior: 15°C)
Wall - Transmission	Brick masonry: 1.83 W/(m ² K)
Façade Solar Absorption	Brick: 0.65 [UNIT]

Window - Transmission	Single glazing: 5.2 W/(m ² K)
Interior Floor - Transmission	Concrete 100mm: 1.16 W/(m ² K)
Interior Walls	Dry-wall gypsum: 0.62 W/(m ² K) (See Figure 60)
Shading	NONE
Heating System	Individual gas condensing boiler
Cooling System	Case dependent

The energy model will be calibrated using the average label value of 205,33 kWh/m² for heating demand.

4.3 Renovation Objectives

Since this study focuses on the role of heat hazard in thermal performance analysis for renovations, selecting renovation objectives builds on the common targets of energy retrofitting. As discussed in the literature review, energy retrofits aim to increase efficiency, reduce heating cost and primary energy use, and reduce carbon emissions. Additionally, health and thermal comfort are compulsory constraints. Yet, the integration of the impact from heat hazard is lacking. Therefore, the aspects are extended by cooling cost, efficiency, and mitigating overheating.

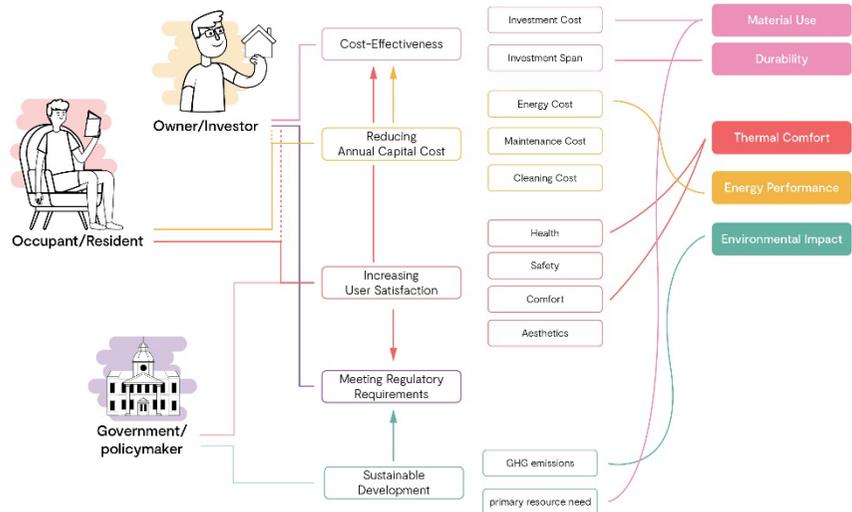


Figure 61 - Renovation Interest related to thermal performance (source: own)

Generally, all objectives belong to either one of the three levels of sustainable development: economic, social, and ecological impact. Using these categories but also considering the direct interest of stakeholders, the objectives are simplified into two primary ones: 'energy cost reduction' and 'thermal comfort increase', with the secondary goal of 'decreasing the energy-related footprint'.

Criteria and KPIs are assigned for the larger objectives to specify how improvements should be measured. To reduce energy costs, it is most sensible to use energy efficiency for both heating and cooling as a more universal criterion than cost. Efficiency is then measured as 'Energy Use Intensity,' representing the average outcome to expect. The indicator includes both demand and system/source efficiency.

Table 18 - Renovation Objectives

Objective	Criteria	KPI	Climate Reference Scenario
Energy cost reduction	Heating Efficiency	EUI [kWh/m ² per a]	Average/Expected
	Cooling Efficiency	EUI [kWh/m ² per a]	Average/Expected 85 th percentile Extreme 2020
Thermal comfort increase	Mitigate Overheating	IOD, OEF	Extreme 2020
Reduce energy related footprint	Direct & Indirect Emissions	CEI [CO ₂ eq. / kg]	Average/Expected

Regarding thermal comfort, the main focus is mitigating overheating, which is measured using the metrics 'Overheated Hours', 'Indoor Overheating Degree', and 'Overheating Escalation Factor', as selected in the chapter '4.2 Comparison Metric'. Theoretically, comfort during the cool season also needs to be included, but this is out of the scope of this research. This study assumes that the heating system supplies heat as desired, neglecting qualitative differences between low and high temperature heating.

The secondary objective is narrowed down to the general criteria of direct and indirect emissions. It is assessed by 'Carbon Emission Intensity' to make it comparable to energy efficiency. The calculation includes operational emissions for both heating and cooling. Embodied emissions are excluded but accounted for in the cost-benefit analysis.

4.4 Baseline Analysis

4.4.1 Energy Model Setup

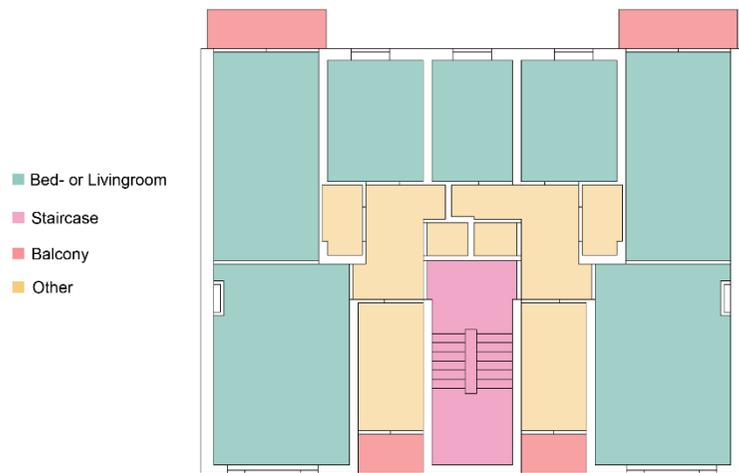


Figure 62 - Floor plan - Room functions (source: own)

For the case study simulations, an energy model with Honeybee is set up in the Rhino Grasshopper environment. The structure of the model setup is visualized in Figure 63.

The scenario settings are translated to a construction set and building program, where some parameters, such as the occupancy schedule, are sourced from a base program for mid-rise apartments.

For the model, at first, the geometries for rooms, windows, and doors are clustered at floor level. This is done to ease future simulation tests of single floors. When creating the floor model, all apartment-specific constraints are

also assigned. This includes naming rooms, assigning programs, and setting windows to operable. Afterwards, the floor objects are intersected, and other adjacent unconditioned rooms, such as a staircase, are added. The side walls touching the next building unit are set to adiabatic, and the customized construction set is applied

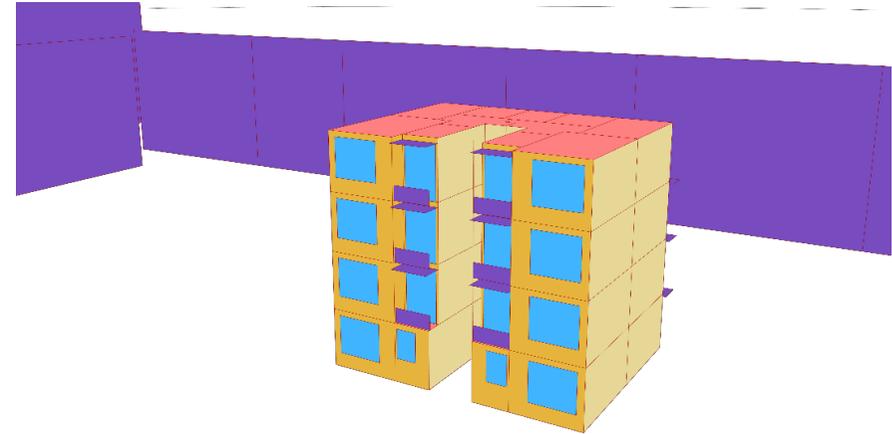


Figure 63 - Energy Model Screenshot (source: own)

For the energy simulation, an ideal air load system is assumed under the constraint of natural ventilation. For the comfort simulation, the rooms are set to not-conditioned. Finally, the building model is created from the room model and all relevant shading (See Figure 63). For calculating the 'Standard Effective Temperature', to the simulation outputting air temperature, radiant temperature and humidity the assumptions for a clothing rate of 0.5, metabolic rate of 1 and an air speed of 0.1m/s were made.

However, after this setup was tested in simulations several times, the model was simplified, taking out the unconditioned rooms and setting all adjacencies to adiabatic to reduce computational power.

4.4.2 Calibration & Solar Gain Analysis

Before starting on simulations of for actual case study, the energy model was calibrated with the E+ annual load component. For the simulations, a climate file of the typical meteorological year for 2020 was used, which is based on weather data from the 'De Bilt' station (Heiranipour et al., 2024).

As previously mentioned, the target value for heating demand was 205,33 kWh/m². The first value of 168.89 kWh/m² was too low, the minimum indoor degrees for ventilation were adjusted from 20°C to 18°C to allow for more losses. Then, the final value coming closest was 209.6 kWh/m² with a respective cooling load of 24.99 kWh/m².

Table 19 - Model calibration (source: own)

model type	changes	heating load	cooling load
only conditioned rooms	min 20°C indoor for ventilation	168.89 kWh/m ²	24.99 kWh/m ²
	min 18°C indoor for ventilation	209.6 kWh/m ²	24.99 kWh/m ²

Also, peak loads were estimated with the E+ component the entire building. The highest peak load found considering all rooms of the entire building was 10.08 kWp. Adding the peak loads for only the third floor sums to the value 62.52 kWp.

To better understand the environment and possible heat gains from solar radiation, the sun angles and direct sun hours were analyzed for the summer months. The gained insights served as background information for later selecting and placing sun shading.

The analysis shows that the north-eastern facade receives very little direct sun, while the south-western facade get a lot of the direct sun hours. Especially, the third floor is affected, since it is not shaded from any balcony above. Consequently, it is assumed that the south-west is much more affected by solar gains, which means mitigation measures should directly target this condition. To reference the window to wall ratio of the southern façade, the apartments full exterior wall surface is 170.2m² with windows holding a space of 55.1m². The WWR is therefore about 32%.

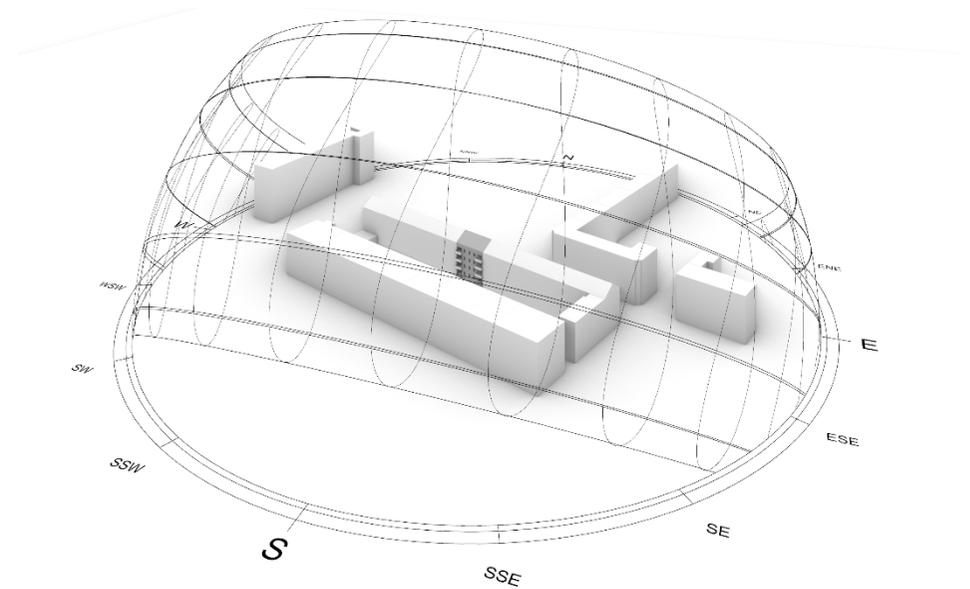


Figure 64 - Sun angles - whole year (source: own)

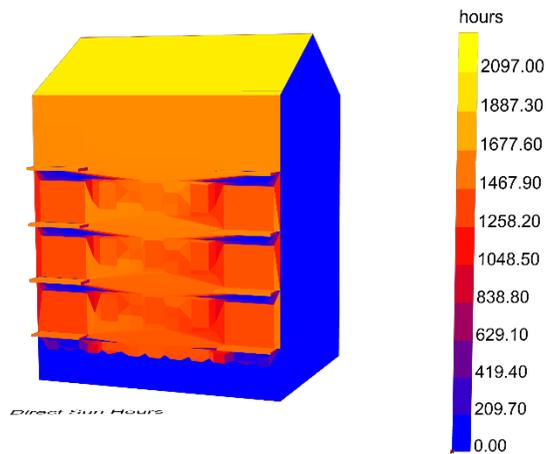


Figure 65 - Direct Sun Hours – South-west - Summer period (source: own)

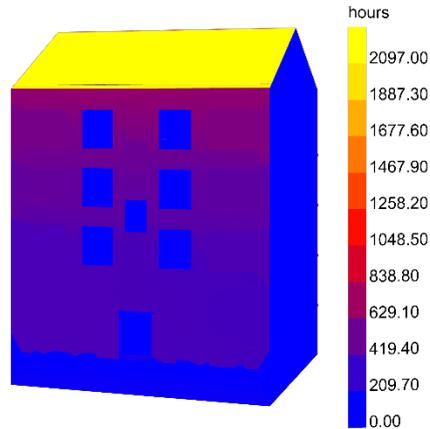


Figure 66 - Direct Sun Hours – North-east - Summer period (source: own)

4.5 Renovation Packages

Based on the prior analysis of the case study building, it is evident that there is considerable potential for improving both energy efficiency and resilience to overheating. Comprehensive renovation could involve the construction principles of heating/cooling systems, energy supply sources, external wall systems, openings, and floors and roofs.

Regarding systems and supply, gas condensing boilers generally have a lower efficiency and higher emission factor than sources like district heating or heat pumps.

The building's envelope is not yet insulated, meaning the transmission needs to be decreased from 1,83 to 0.22 W/(m²K) to bring the walls up to standard. The solid brick wall already provides some thermal mass with a phase shift of 8.3 h. Given that it is also exposed to the indoor space, exterior insulation seems more logical.

For the single-glazed windows and doors, insulation would mean going from 5.2 W/(m²K) to 1.65 W/(m²K), which requires at least double-glazing. Moreover, the building can be considered leaky. Air-tight sealing could be improved by retrofitting the openings and adding even more exterior insulation to close up any former ventilation gaps.

There is currently no solar shading, apart from some balconies on the southwestern side. Furthermore, the brick facade is not very reflective, with an absorption value of 65%.

Table 20 - List of renovation measures (source: own)

Construction Principle	Measure	Meets Objective	Label
Heating system	District heating	heating cost, emission reduction	simple
Cooling system	Air-conditioning	mitigate overheating	medium
	Ceiling fans	mitigate overheating	simple
	Evaporative coolers	mitigate overheating	simple-medium
Energy supply	PV panels	energy cost, emission reduction	simple-medium
Ventilation	HVAC with heat recovery	heating cost	deep +
Wall-System	Exterior insulation	heating cost, emission reduction	deep
	Interior insulation	heating cost, emission reduction	deep
	Green facade	cooling & heating cost, emission reduction, mitigate overheating	deep +
	White paint	cooling cost, emission reduction, mitigate overheating	deep +
	Balcony extensions/canopies	mitigate overheating	deep +
Openings	Double-glazing	heating cost, emission reduction	medium
	Triple-glazing	heating cost, emission reduction	medium
	Awnings	cooling cost, emission reduction,	simple

		mitigate overheating	
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4.5.1 Possible measures

Following the identification of improvement potentials in the case study building, a selection of renovation measures was compiled. These were assessed based on their cost intensity, depth of intervention, and the specific objectives they address.

In the context of the ongoing district heating project, switching the heating source from gas to district heating seems most sensible. Also, because this study does not focus on heating in detail, other sources like heat pumps were excluded from the scenarios.

For technical cooling three possible options were selected for residential buildings: air-conditioning, evaporation coolers and ceiling fans. While fans mainly alter the perception of heating and help heat removal through effective ventilation, evaporative systems integrated into external walls cool down dry air from the outside by adding humidity (Stein, 1997). Air-conditioning on the other hand, works by cooling indoor air and exhausting the excess temperature through a compression, evaporation cycle to the outdoor environment (Ibid). ACs therefore consist of two connected units inside and outdoors (Ibid). Evaporation coolers exist in different forms attached to external walls, windows or ventilation systems, taking up opening space in facades (Ibid). All of these cooling technologies rely on electricity. In this context, photovoltaic (PV) panels may serve as a suitable energy source, especially considering the correlation between high solar radiation and cooling demand.

Based on insights from the literature, several passive strategies can mitigate indoor overheating while concurrently reducing cooling energy demand.

These include solar shading, high-albedo surfaces, the addition of thermal mass, and green infrastructure.

For exterior shading, there is a wide range of options also in terms of cost. Shutters, screens or horizontal louvres shades are fixed close and parallel to window openings, while awnings or canopies do not cover the window as much Figure 67. In comparison to shutters, awnings are more occupant friendly as they leave more view of the outdoors and less expensive though the shading might be less effective (Table 23). Painting walls exposed to the sun white is another simple option increasing solar reflectivity from 65% to 95% (Pal et al., 2020).

Then, the alternative deeper interventions are green facades or roof, and adding more thermal mass to the wall when insulating. For example, 'Poroton' bricks, which have vertical holes filled with perlites, provides extra thermal mass when insulating the external walls (*U-Value Calculator*, n.d.). Apart from mass, Green facades might be cost intensive and maintenance intensity is unclear.

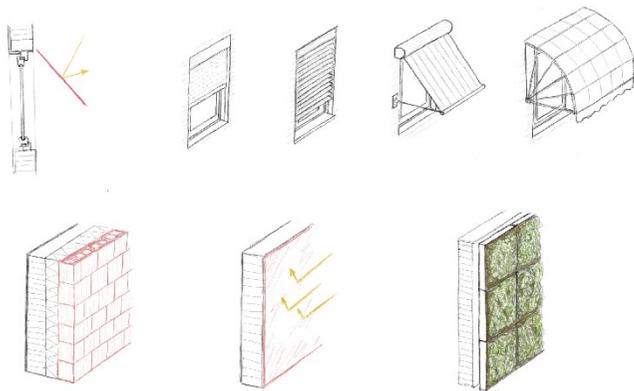


Figure 67 - Passive Mitigation Measures (source: own)

Ventilation strategies were deliberately excluded from this analysis. Passive ventilation approaches seem impractical due to the variability and unpredictability of occupant behavior in this multi-tenant scenario. Mechanical ventilation systems, in turn, require deeper indoor interventions, for which feasibility needs to be verified in detail.

Two primary building envelope measures were evaluated in relation to heating efficiency: retrofitting glazed openings and insulating external walls. It is noteworthy that these measures will also influence the cooling loads and overheating. Though, double-glazing has less impact than triple glazing, the effect is still significant and already fulfills the regulatory standard, while also being less cost-intensive (*Kostenkatalogen*, n.d.; *TABULA WebTool*, n.d.). Changing just the windows would cost about 43.000 Eur, whereas the investment cost for 140mm mineral with stucco finish is estimated around 42.000 Eur including scaffolding (*Archidat Bouwkosten, Actuele Richtprijzen Voor de Bouw.*, n.d.). While similar in cost to window replacement, wall insulation often necessitates concurrent window upgrades. This is due to large discrepancies in transmission values creating thermal bridges, which can increase the risk of surface condensation (Schöck Ltd & Oxford Bookes University, 2018).

Measures addressing the roof and floor insulation were not considered in detail due to uncertainties regarding existing construction details and intervention feasibility. Nevertheless, their thermal impact could be substantial.

4.5.2 Study Design

The renovation alternatives were curated with reference to the overarching analytical objectives. These scenarios aimed to provide insights into the long-term financial viability of building envelope retrofits, especially passive measures, and assess the implications of neglecting overheating risks.

The case study building currently has no technical cooling control, which poses a challenge for a cost-benefit analysis. Introducing active cooling from a zero baseline implies a qualitative improvement but initially results in financial losses. As noted in chapter 4.1 Resilience as Cost, quantifying social costs related to thermal discomfort or heat stress remains methodologically uncertain.

The baseline scenario was defined to include a cooling system by default to address this issue. This supports the approach of analyzing how a heat hazard bears financial loss. Across all scenarios, the same cooling system will be assumed, and investment, replacement, and maintenance of the systems are considered fixed costs. Thus, the comparison cases represent the cost of the opportunity of omitting passive mitigation measures. The goal is to identify the most effective alternatives, looking at intervention depth and mitigation strategy.

Also, considering the stakeholder perspective, this study focuses on operational cost savings to recover the investments over time. For this reason, rental income effects were excluded from the financial evaluation.

The most feasible for both heating and cooling measures were sorted from low to high according to their respective intervention depths and investment costs. For this arrangement three levels of intervention depth and cost intensity were defined as 'Simple', 'Medium' and 'Deep'. Measures going beyond the scope of Deep were added to '+'. The heating measures span from connecting to district heating to exchanging windows and finally insulating the wall system. However, cooling measures are rather simple and do not depend on each other (See Table 21).

Table 21 - Measure ranking (source: own)

Intervention level	Heating	Cooling	
Simple	District heating	Awning shadings	White paint
Medium	+ double-glazing	""	
Deep	+ exterior insulation	""	""
+	/	+ Balcony extensions	+ Thermal mass + PV panels

In the following case study, at first, the switch to district heating will be combined with the cooling interventions in isolation as 'Simple' cases (See Table 21). A separate analysis is going to assess the outcome of considering only cooling-related investments and benefits. Subsequently, a combined case will be introduced. Window replacements are anticipated to be paired with solar shading elements for the 'Medium' retrofit scenario. In the 'Deep' scenario, high-albedo façade painting will be added, as such measures would naturally coincide with external insulation work. However, passive strategies proposed for the medium and deep scenarios may be adapted based on the effectiveness observed in the simpler scenario analyses.

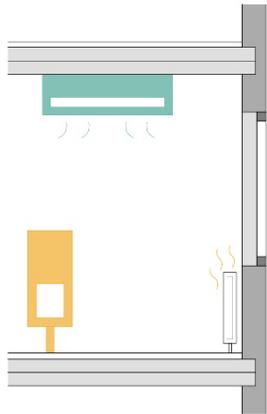
Table 22 - Scenario Specifications (source: own)

Scenario	Baseline	S01- Shading	S02- Paint	S03- Combi	Medium	Deep
Cooling System	Air-condition	Air-condition	Air-condition	Air-condition	Air-condition	Air-condition
Heating System	Gas-boiler	District heating	District heating	District heating	District heating	District heating
Wall Transmission	1,83 W/(m ² K)	0,22 W/(m²K)				
Albedo/Absorption	0.65	0.65	0.2	0.2	0.65	0.2
Window Transmission	5.2 W/m ² K	1.65 W/m²K	1.65 W/m ² K			
Sol. & Vis. Reflectance of Shading	/	0.1	/	0.1	0.1	0.1
Infiltration	0.0006 [m ³ /s per m ²]	0.0006 [m ³ /s per m ²]	0.0006 [m ³ /s per m ²]	0.0006 [m ³ /s per m ²]	0.0003 [m³/s per m²]	0.0001 [m³/s per m²]
Ventilation	natural	natural	natural	natural	natural	natural



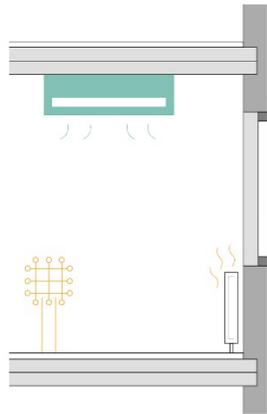
Figure 68 - Placement of shading and white paint on the southern facade (source: own)

BASELINE



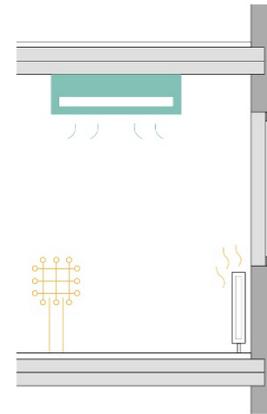
- Air-condition
- Gas Boiler
- No insulation
- No shading
- Single glazing

SIMPLE 01 - SHADING



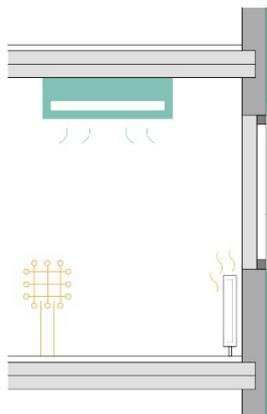
- Air-condition
- District-Heating
- No insulation
- Exterior shading

SIMPLE 02 - PAINT



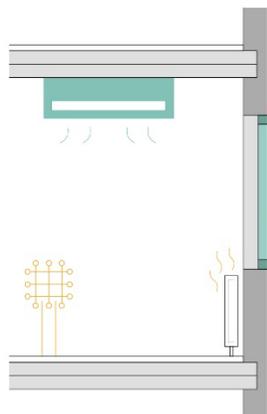
- Air-condition
- District-Heating
- No insulation
- No shading
- White paint

SIMPLE 04 COMBINATION



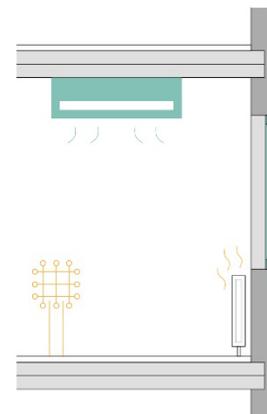
- Air-condition
- District-Heating
- No insulation
- Exterior shading
- White paint

MEDIUM + SHADING



- Air-condition
- District-Heating
- No insulation
- Exterior shading
- Double glazing

DEEP + SHADING & PAINT



- Air-condition
- District-Heating
- Insulation-stucco wall
- Exterior shading
- Double glazing
- White paint

Figure 69 - Renovation Scenarios Explained (source: own)

5 Case Study

5.1 Data Input

The first step to the case study was fixing the general analysis settings starting in 2025 and running an analysis period of 30 years, as commonly found in the literature. For the discount rate, several studies on cost-benefit analysis for retrofitting were reviewed using varying rates between 1 and 10% (Araújo et al., 2016; Liu et al., 2023). Most European studies, however, employed discount rates ranging from 3 to 4% (Belaïd et al., 2021; Bragolusi & D'Alpaos, 2022; Guardigli et al., 2018; Higney & Gibb, 2024). Finally, since discounted also relates to the regional economic context, a rate of 3% was chosen from a German study (Groh et al., 2022).

Due to prices fluctuating and rising annually, all energy prices were collected for the year 2024 to have a complete reference set (CBS, 2025). Any cost related to technical cooling and heating system maintenance was assumed to be a cost in the renovation scenarios. Fixed electricity cost and tax reduction were neglected since there is no switch between energy sources for technical cooling, and electricity is not relevant in heating.

The value for the gas-boiler efficiency, 0.85, was taken from a reference study on a similar building archetype in the Netherlands (Wahi, 2025). For district heating, an efficiency of 1.0 was assumed since the price refers to the kWh heat supplied to the building. Deficiencies due to lower-temperature district heating are neglected in this study.

For Air-conditioning, the Dutch regulations state, "air conditioners or other cooling systems must have at least an energy label A+ to count towards the points score. For this purpose, their power must be at least 100 W/m² at a working temperature of up to 35 °C." The COP of an air-conditioning system can vary greatly according to the manufacturer. Considering a product

selection of split units with a cooling capacity between 2.5 and 9.5 kW, the COP could range from 2.0 to 3.1. In the end, a COP of 2.9 was declared plausible and considered a conservative estimate, since a lower COP results in higher savings.

Table 23 - CBA Input Data Summary (source: own)

Analysis Settings	
Start Year	2025
Analysis Period	30 years
Discount Rate	3%
Number of simulation runs	5,000
Number of samples	10,000
Universal Data	
Variable Electricity Price	0.243 Euro/kWh
Variable Gas Price	0.1604 Euro/kWh
Fixed Gas Price	247.16 Euro
Variable District Heating Price	0.168 Euro/kWh
Fixed District Heating Price	291.42 Euro
Efficiency Air-conditioning	2.9
Efficiency Gas-boiler	0.85
Efficiency District Heating	1.0
Carbon Rate Electricity	0.37 kg CO ₂ eq./kWh
Carbon Rate Gas	0.22 kg CO ₂ eq./kWh
Carbon Rate District Heating	0.12744 kg CO ₂ eq./kWh

The CO₂ emission rates and the district heating fact sheet were taken from statistical sources. In 2022, the district heating system of Rotterdam produced 5.2 kg CO₂ per GJ of heat. The emissions are related to the energy sources used in heat production. The fact sheet states that 37% is residual heat from the gas power plant, 22% comes from the gas-boiler backup, 18% residual heat from the waste treatment plant, 17% from biomass, and many smaller

contributors (Eneco, 2023). The General Electricity grid of the Netherlands in 2024 produced 370 kg CO₂ eq. Per kWh, on average.

Table 24 shows the cost estimations for investment, maintenance, and replacement. Considering the maintenance and replacement involved, the cost for each simple measure is quite comparable, at around 12,000 per retrofit step.

For the first scenario 'S01', the shading was applied to all south-west facing windows, although some are already shaded from balconies above. However, when comparing the overheated hours of either awning only on unshaded windows with awnings on all windows, the difference shows in the thermal comfort. Overheated hours are reduced from 138h to 128h, while the cost is also raised from 5,040 to 8,300. A low-cost price for textile screens was assumed. For the simulations, the shadings were set to 'always on'. The maintenance was assumed to happen every 5 years, since such products usually have a similar length warranty (Byzon Zonwering, n.d.; Zonnerij, n.d.).

For exterior white wall paint, as in S02 & S04, since the south-west side receives the most sun, only painting this side of the building was calculated, whereas the distinction was not possible in the simulation. The cost for painting was sourced online ("Kosten schilderwerk 2025," n.d.). The paint's life span was estimated to be 15 years, which is a relatively high value considering in official recommendations for repainting vary between 5 and 15 years (Keim Specialist, n.d.; Verfcompleteet, 2024). Still, 15 was chosen because the protective function of the paint is unnecessary in this case. However, only the Albedo effect is relevant, and a replacement at least once in 30 years seemed reasonable.

In the 'Deep' retrofit scenario, the insulation retrofit includes mineral wool with a stucco finish and PVC window sills, which are required as the windows sit further back in the facade. Furthermore, some rather uncertain parameters

exist, such as the estimated construction time of 4 weeks for the scaffolding, though the price contribution is not significant.

Table 24 - Cost Estimation for All Scenarios (source: own)

District Heating IC	Connection Cost	8	households	1,518.62	per unit	12,188,96	12,190.00	Euro
Shading IC	<i>All southern openings</i>					8,303.40	8,300.00	Euro
	Awning w:1000mm	12	pcs	329.05	Per piece	3,948.60		
	Awning w:3000mm	8	pcs	544.35	Per piece	4,354.80		
Shading MC	Repair cost	36	m	13.10	Per m	471.60	470	Euro
	Cycle (warranty)						5	Years
Shading RC	Life span						30	Years
Paint	<i>Full southern facade</i>					5,953.11	6,000.00	Euro
	Painting	136.5	m ²	40	Per m ²	5,460.00		
	Scaffolding for 1 week	34	m ²	14.45	Per m ²	493.11		
Paint RC	Life span						15	Years
Windows IC	<i>Retrofit all windows to double-glazed</i>					42,714.18	42,700.00	Euro
	PVC; 2-division; 1000x1450	14	pcs	711.02	Per piece	9,954.28		
	PVC; 3-division; 1800mm	16	pcs	646.15	Per piece	10,338.40		
	PVC; double doors; 1800mm	6	pcs	2268.33	Per piece	13,609.98		
	PVC; one door; 900mm	8	pcs	1101.44	Per piece	8,811.52		
Façade IC	<i>Exterior insulation</i>					41,488.56	41,500.00	Euro
	140mm mineral wool incl. stucco	256.6	m ²	130.7	Per m ²	33,537.62		
	Scaffolding for 4 weeks	388.5	m ²	15.35	Per m ²	5,963.48		
	Street Protection Net	194.25	m ²	0.5	Per m ²	97.13		
	Windowsills PVC 1000mm	14	m	34.08	Per m	477.12		
	Windowsills PVC 2000mm	33.6	m	42.06	Per m	1.413,22		

District Heating IC	Connection Cost	8	house holds	1,518.62	per unit	12,188.96	€12,190.00
Shading IC	<i>All southern openings</i>					8,303.40	€8,300.00
	Awning w:1000mm	12	pcs	329.05	Per piece	3,948.60	
	Awning w:3000mm	8	pcs	544.35	Per piece	4,354.80	
Shading MC	Repair cost	36	m	13.10	Per m	471.60	€470
	Cycle (warranty)						5 Years
Shading RC	Life span						30 Years
Paint	<i>Full southern facade</i>					5,953.11	€6,000.00
	Painting	136.5	m ²	40	Per m ²	5,460.00	
	Scaffolding for 1 week	34	m ²	14.45	Per m ²	493.11	
Paint RC	Life span						15 Years
Windows IC	<i>Retrofit all windows to double-glazed</i>					42,714.18	€42,700.00
	PVC; 2-division; 1000x1450	14	pcs	711.02	Per piece	9,954.28	
	PVC; 3-division; 1800mm	16	pcs	646.15	Per piece	10,338.40	
	PVC; double doors; 1800mm	6	pcs	2268.33	Per piece	13,609.98	
	PVC; one door; 900mm	8	pcs	1101.44	Per piece	8,811.52	
Façade IC	<i>Exterior insulation</i>					41,488.56	€41,500.00
	140mm mineral wool incl. stucco	256.6	m ²	130.7	Per m ²	33,537.62	
	Scaffolding for 4 weeks	388.5	m ²	15.35	Per m ²	5,963.48	

	Street Protection Net	194.25	m ²	0.5	Per m ²	97.13	
	Windowsills PVC 1000mm	14	m	34.08	Per m	477.12	
	Windowsills PVC 2000mm	33.6	m	42.06	Per m	1.413,22	

5.2 Performance Results

5.2.1 Energy Efficiency & Cost

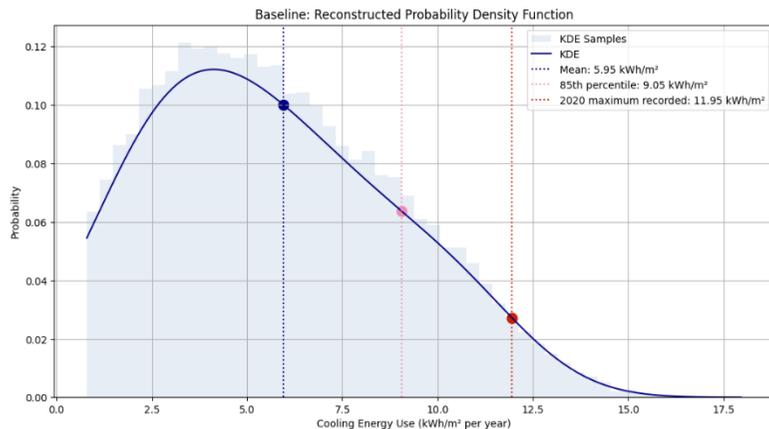
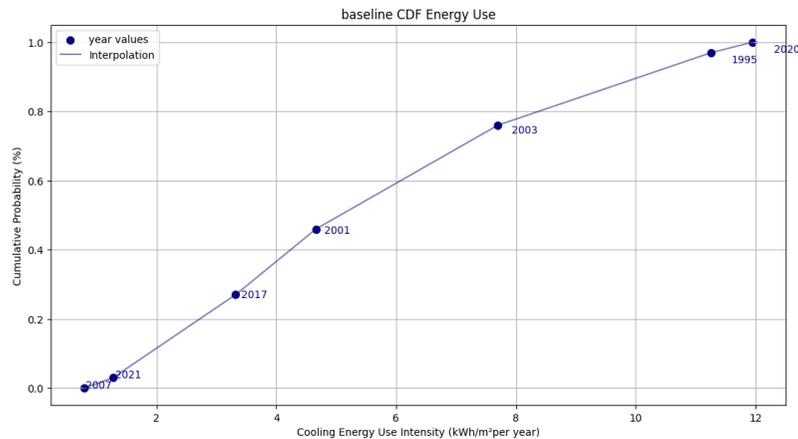


Figure 70 - Probabilistic Estimation for Cooling Energy Use Intensity (source: own)

Energy simulation results for the seven reference years were used to reconstruct the distribution of energy use and to assess efficiency and costs across the baseline and scenarios (See Figure 70 - Probabilistic Estimation for Cooling Energy Use Intensity (source: own)). For cooling and heating, the value of the lowest reference year was used to bound the values at the bottom to avoid negative underestimations. The conditioned space in the model covered 505.33 m² making it the reference area for the efficiency. The results count as a total for all eight apartments and are displayed in Table 25 and Table 26.

Table 25 – Energy Efficiency Results & Cost Estimation for Heating (source: own)

Scenario	Heating EUI mean	Heating Cost mean	Heating Savings mean
Baseline	160.7 kWh/m ²	€13,279.5	//
Simple 01 shading	136.5 kWh/m ²	€11,896.8	€1,382.7
Simple 02 paint	142.3 kWh/m ²	€12,384.2	€ 895.3
Simple 04 combi	142.3 kWh/m ²	€12,384.2	€ 895.3
Medium 01 shading	119.0 kWh/m ²	€10,397.7	€2,881.8
Deep 01 shading-paint	74.8 kWh/m ²	€ 6,645.5	€6,634.0

For heating, switching to district heating led to the average energy use intensity dropping from 160.7 kWh/m² to 136.5 kWh/m². However, when applying high-albedo white paint in S02 and S04, a different 142.3 kWh/m² result was obtained. For the window retrofit scenario, the efficiency increased to 119.0 kWh/m² and for the full façade renovation to 74.8 kWh/m². The baseline annual energy use was 81,250 kWh, corresponding to €13,279.5 heating cost for all households including fixed costs. In scenario S01-shading, the use decreased to 69,080 kWh (€11,896.8). Scenarios S02 and S04 (white paint) resulted in 71,980 kWh (€12,384.2). For the Medium and Deep scenario, the energy use dropped to 37,820 kWh (€10,397.7) in M01 and 60,160 kWh (€6,645.5) in D01. The difference in energy use from the baseline scenario

implies cost savings of about €1,382.7 for switching to district heating, which is reduced to €895.3 for the case with a high Albedo facade. Combining district heating with the window retrofit increased the savings to 2,881.8 € and even 6,634.0 for insulating the façade.

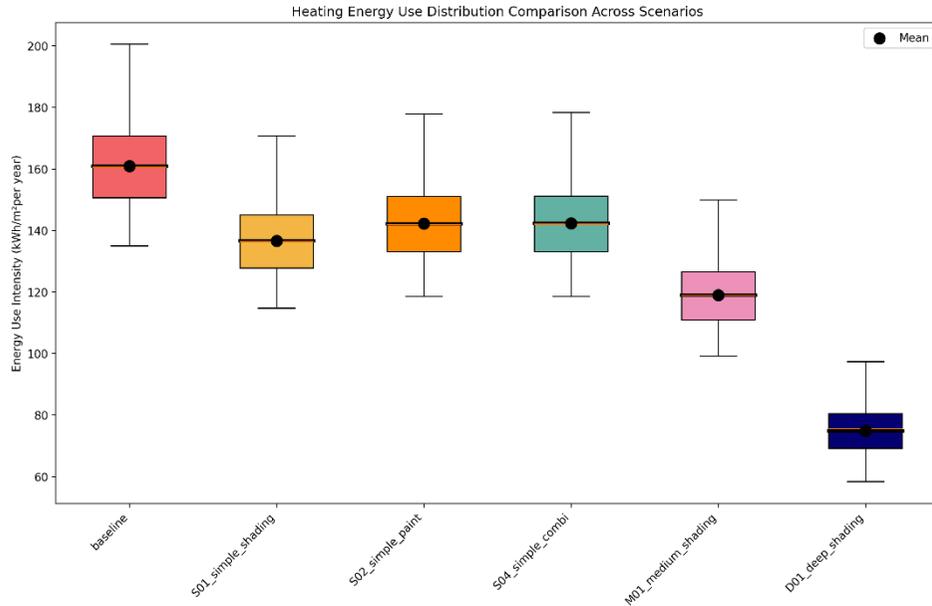


Figure 71 - Energy Use Intensity Heating (source: own)

Cooling efficiency also increased across the renovation alternatives. The mean EUI of 5.99 kWh/m² (Baseline) fell to 5.62 kWh/m² with shading (S01), 5.76 kWh/m² with paint (S02), and 5.42 kWh/m² with combined measures (S04). The mean energy use intensity of the Medium reduced to a similar level of S01 with 5.57 kWh/m², while for the Deep scenario came closest to S04 with 5.45 kWh/m². Looking also at EUI of the 85th percentile and the maximum value of 2020, the energy intensity for the baseline rose to 9.05 and even 11.95 kWh/m² at max. The intensity dropped again across the scenarios with the

lowest value of all in the Deep case of 8.40 and 11.23 kWh/m². Here, the S04 combi scenario scored second lowest with 8.45 and 11.36 kWh/m². The average cooling cost for the baseline is €738.2 (3,037.9 kWh), but it can rise to €1,114.1 or even €1,467.7 in extreme years. The general cooling cost is reduced as efficiency increases across the scenarios. Scenario S04 had the lowest average value at €665.2 (€2,737.62 kWh). But for the 85th percentile and the maximum again D01 scored lowest with €1,030.2 - €1,379.6. The decrease in energy and cost has respective savings, that are lower at the mean, ranging from €28.3 to €73, compared to the 85th percentile, €29 to €84.

Table 26 - Energy Efficiency Results & Cost Estimation for Cooling (source: own)

Scenario	Cooling EUI mean	Cooling Cost mean	Cooling EUI 85 th percentile	Cooling Cost 85 th percentile	Cooling EUI 2020 max	Cooling Cost 2020 max
Baseline	5.99 kWh/m ²	€738.2	9.05 kWh/m ²	€1,114.14	11.95 kWh/m ²	€1,467.7
S01 shading	5.62 kWh/m ²	€688.5	8.62 kWh/m ²	€1,059.43	11.57 kWh/m ²	€1,420.1
S02 paint	5.76 kWh/m ²	€709.9	8.79 kWh/m ²	€1,085.84	11.71 kWh/m ²	€1,437.3
S04 combi	5.42 kWh/m ²	€665.2	8.45 kWh/m ²	€1,032.60	11.36 kWh/m ²	€1,394.9
M01 shading	5.57 kWh/m ²	€686.9	8.57 kWh/m ²	€1,053.55	11.49 kWh/m ²	€1,410.4
D01 shading-paint	5.45 kWh/m ²	€670.0	8.40 kWh/m ²	€1,030.24	11.23 kWh/m ²	€1,379.6

In the boxplot graph (Figure 71 & Figure 72), the mean is indicated by a black line, and the median by an orange line. For cooling, the threshold of the 85th percentile and the maximum recorded value for 2020 were additionally marked on the plot.

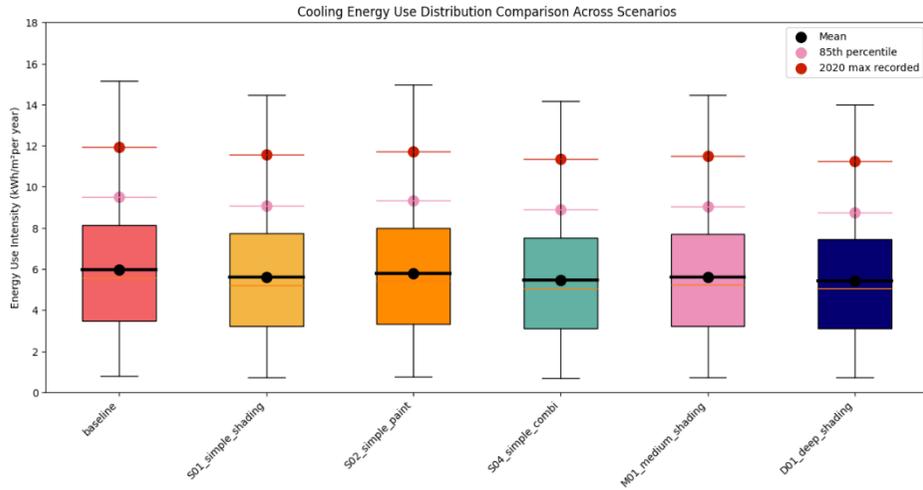


Figure 72 - Energy Use Intensity Cooling (source: own)

5.2.2 Energy Cost Savings

To illustrate how savings are distributed in comparison to all renovation alternatives, the probability density functions and generated samples are plotted in Figure 74 for heating and Figure 75 for cooling. The sample sets represent the ones that were later used for calculating the 'Net-Present Value' in the cost-benefit analysis.

The savings were estimated by reconstructing the probability density functions for energy use and then calculating the savings for a large number of percentiles (See Figure 73). The initial savings set was then used as a base for

another probability density estimation, from which 10,000 samples were generated.

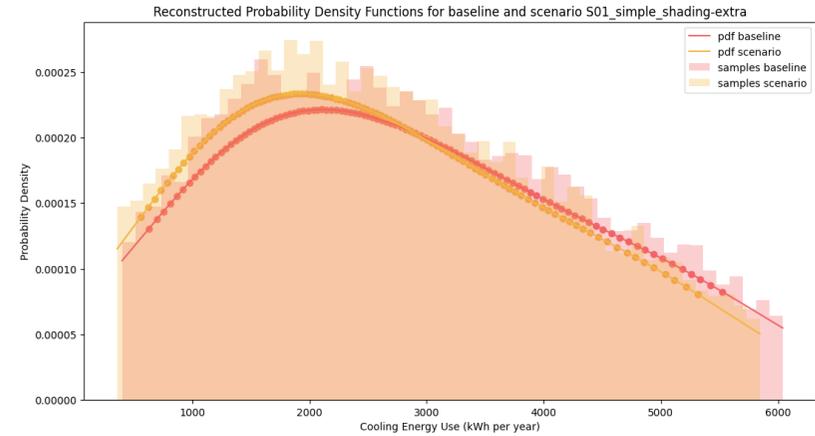


Figure 73 - PDF Overlay Baseline & S01 shading (source: own)

Considering the distributions for heating savings in Figure 74, the dispersions seem to increase with the savings from a few hundred to more than a thousand. In any case, the sample sets and distributions don't overlap with one another. In simple cases, savings are side by side, while the Medium and Deep sit at greater distances.

Also, for cooling savings, the widening of dispersion with increasing savings is visible throughout the scenarios. However, the cooling cost savings are much smaller compared to heating. Here, the distributions largely overlap (See Figure 75).

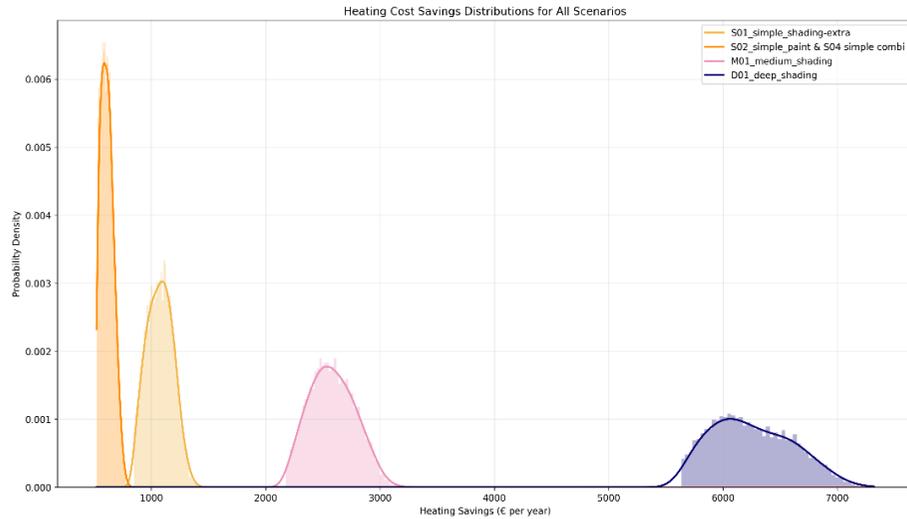


Figure 74 - Energy Heating Savings Distributions for all Scenarios (source: own)

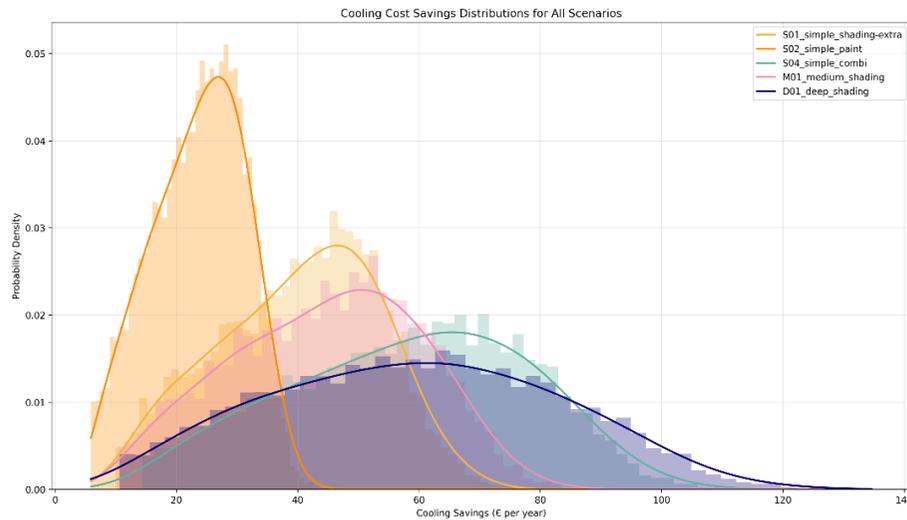


Figure 75 - Energy Cooling Savings Distributions for all Scenarios (source: own)

5.2.3 Overheating Mitigation

The comparison of heat resilience metrics was evaluated for all scenarios, including the five retrofit options and the baseline, for the summer period of 2020.

Table 27 - Results for Heat Resilience Indicators (source: own)

Scenario	Overheated Hours >28 SET	% Delta	Degree Hours >28 SET	% Delta	IOD	OEF	% Delta
Baseline	162 h	/	309 dh	/	2.39	1.76	/
S01 shading	128 h	-21%	193 dh	-37%	1.87	1.38	-22%
S02 paint	136 h	-16%	237 dh	-23%	2.26	1.66	-6%
S04 combi	105 h	-35%	145 dh	-53%	1.75	1.29	-27%
M01 shading	137 h	-15%	235 dh	-24%	1.96	1.44	-18%
D01 shading	107 h	-34%	128 dh	-59%	1.19	0.87	-51%

The indicator overheated hours above 28°C SET represents only the duration of overheating, while Degree Hours also account for the intensity of overheating (See Table 27). The baseline scenario recorded 162 overheated hours and 237 degree hours. Scenario S01-shading reduced this to 128 hours and 193 degree-hours, a 21% and 37% improvement. For Scenario S02-paint, 136 hours and 237 degree-hours, reflecting a 16% and 23% reduction. Scenario S04-combi performed best regarding overheated hours, with a value of 105 h, corresponding to a 35% improvement. Additionally, the degree

hours were reduced notably to 145 hours. Meanwhile, the Medium scenario resulted more similar to the S02 scenario with 137 h and 235 dh. Finally, the Deep retrofit yielded results similar to S04 in overheated hours with 107h but improved by 59% for degree-hours with 128 dh.

In Figure 77 - Heat Wave Contribution to the Annual Value in 2020 for All Scenarios (source: own), the contribution of the heatwave with a margin of plus minus eight days was plotted, to illustrate how many hours would be endured during the hazard period. The comparison shows the percentage of hours increasing for the total annual value decreasing.

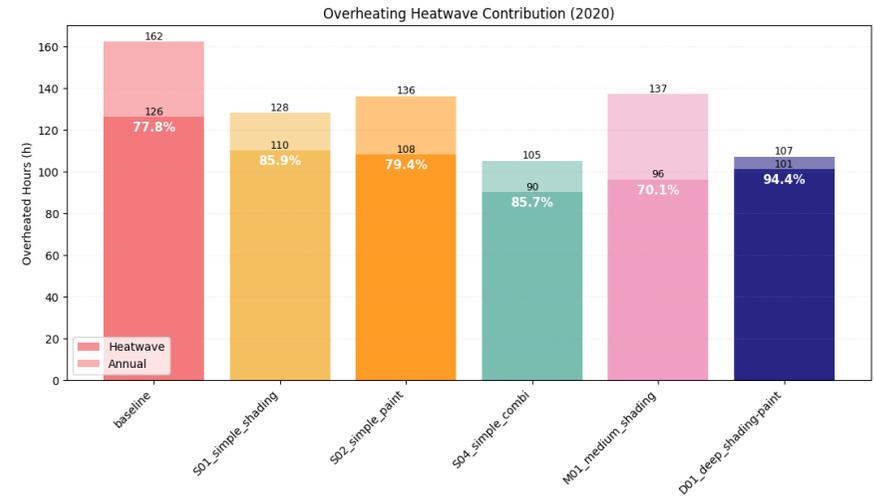


Figure 77 - Heat Wave Contribution to the Annual Value in 2020 for All Scenarios (source: own)

The third metric, the Overheating Escalation Factor (OEF), was calculated by dividing the IOD by the Ambient Warmness Degree (AWD), which was 1.36 for the reference summer (See Figure 78). The OEF in the baseline scenario was 1.76. It decreased to 1.38 in S01, 1.66 in S02, 1.29 in S04, 1.44 in M01 and 0.87. For all simple cases and the Medium, the OEF remained above 1.0, while only the Deep retrofit yielded under 1.0, indicating indoor conditions were better on average than the outdoors.

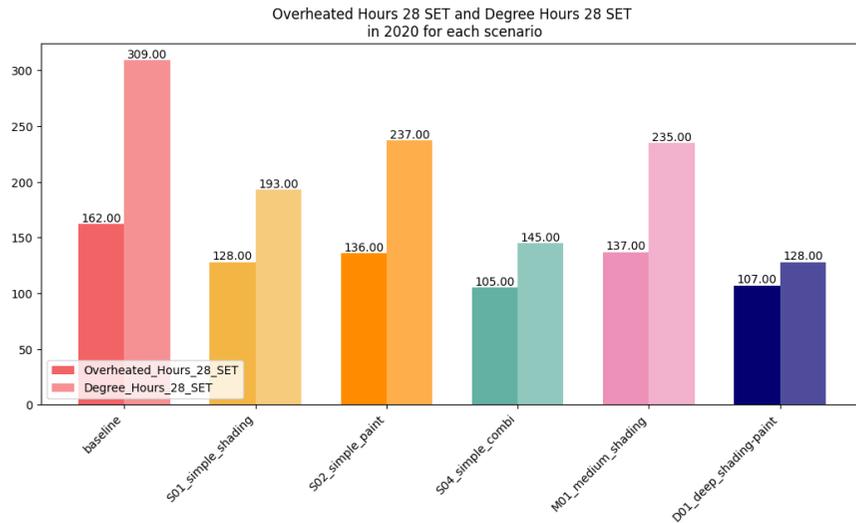


Figure 76 - Results for Overheated Hours (source: own)

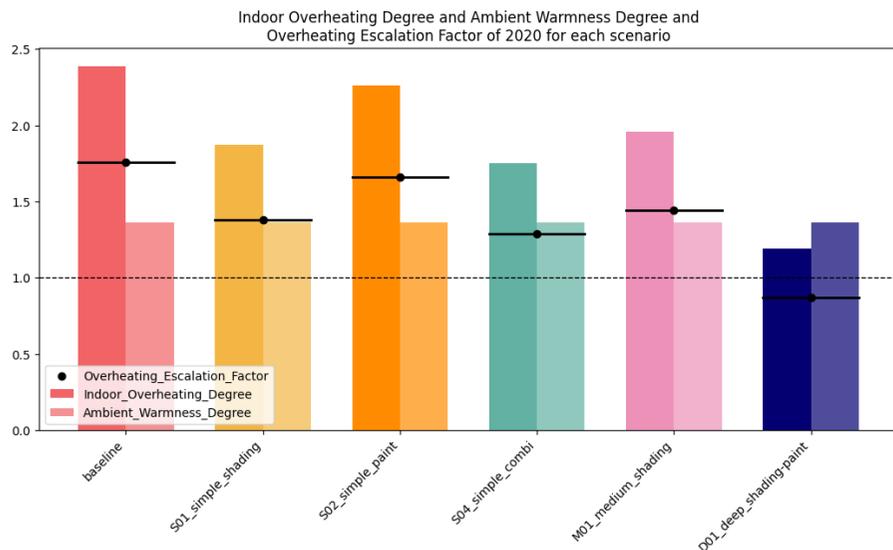


Figure 78 - Results for IOD and OEF (source: own)

5.2.4 Carbon Footprint Reduction

The carbon intensity analysis of operational savings revealed a significant reduction in emissions for all retrofit scenarios compared to the baseline (See Table 28). For heating, the baseline exhibited the highest mean carbon intensity at 35.10 kg CO₂ eq./m²·a. In contrast, the Deep 01 scenario achieved the greatest reduction, with an average of 9.45 kg CO₂ eq./m²·a, followed by the Medium case at 14.99 kg CO₂ eq./m²·a. With 17.30, Scenario S01 (shading) resulted lower than Scenarios S02 (paint) and S04 (combined measures) with values of 18.02 and 18.01 kg CO₂ eq./m²·a.

Cooling-related emissions were considerably lower overall (See Figure 80). The baseline mean was 2.06 kg CO₂ eq./m²·a, while retrofitted scenarios ranged from 1.86 in S04 combi and D01 to 1.98 in S02 paint. Despite the narrower absolute differences in cooling emissions, all retrofit options showed

consistent minor reductions. In Figure 80, the 85th percentile threshold and maximum recorded in 2020 were also labeled, illustrating a similar dispersion development as cooling energy use.

When combining heating and cooling, the total average carbon intensity dropped from 37.15 kg CO₂ eq./m²·a in the baseline to 11.31 in D01. The Medium performed second best with 16.85, while the differences between the Simple scenarios were rather slight, yielding between 19.17 and 20.01 (See Table 28). In general, the asymmetry of heating and cooling energy use largely influences the result.

Table 28 - Carbon Intensity Results for all Scenarios (source: own)

Scenario	Heating related Mean [kg CO ₂ e/m ² ·a]	Cooling related Mean [kg CO ₂ e/m ² ·a]	Combined Mean [kg CO ₂ e/m ² ·a]
Baseline	35.09	2.06	37.15
S01 shading	17.25	1.92	19.17
S02 paint	18.03	1.98	20.01
S04 combi	18.03	1.86	19.89
M01 shading	14.99	1.92	16.85
D01 shading-paint	9.45	1.86	11.31

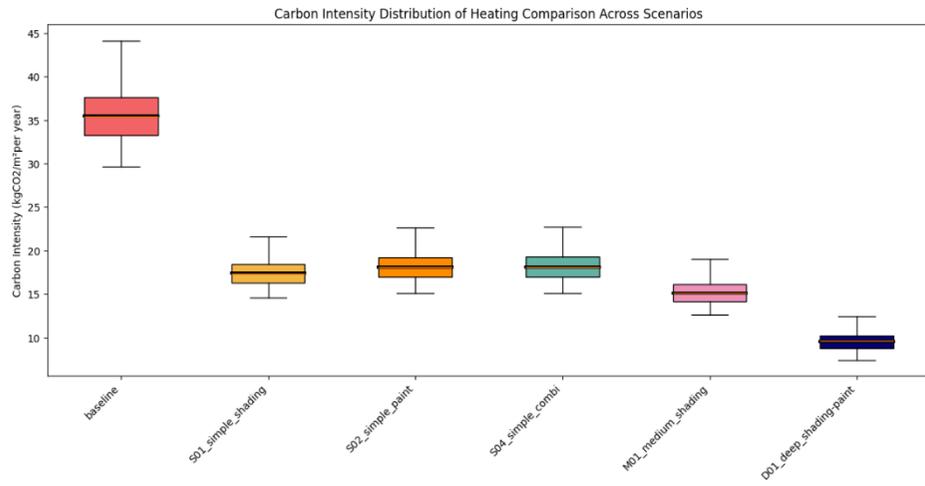


Figure 79 - Heating Related Emission Intensity (source: own)

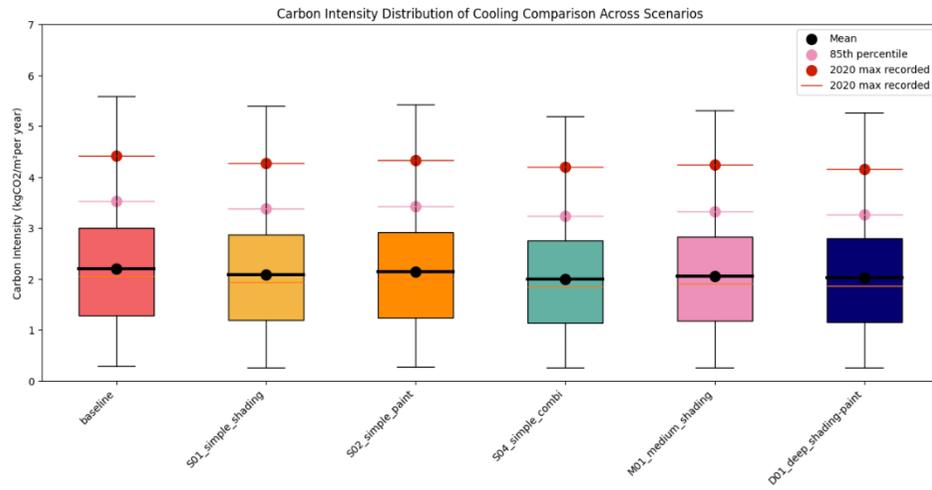


Figure 80 - Cooling Related Emission Intensity (source: own)

5.3 Cost-benefit Results

5.3.1 Total Cost of Ownership Results

Before analyzing cost-recovery, the Total Cost of Ownership for cooling measures was calculated to investigate how costs develop when extremes occur exceptionally often. The TCOO now represents all global costs associated with cooling per scenario discounted for the analysis period.

It should be noted that, similarly, the cost of ownership for the air-conditioning system was also neglected, as it is assumed to be the same across all scenarios. The baseline, therefore, only includes the distribution of variable operational costs for cooling (See Figure 82). The added cost, e.g., investment or maintenance in the other scenarios, was not variable; therefore, it only influenced the level of cost, not the distribution.

This analysis was conducted to examine the passive measures of shading and white paint specifically. In the previous analysis, measures such as insulation, which also involve heating, improved cooling energy use, making it difficult to distinguish which costs should be considered a cooling investment. The focus of the analysis is on observing the influence of extremes on operational costs. For the Medium and Deep scenarios, the decision was made to exclude only the cost of the district heating switch while retaining the envelope retrofitting cost.

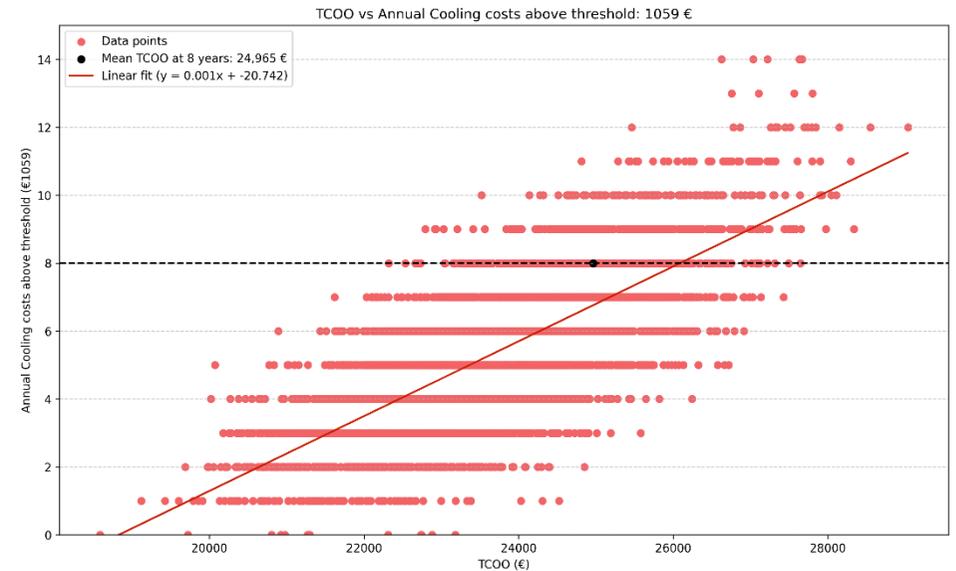


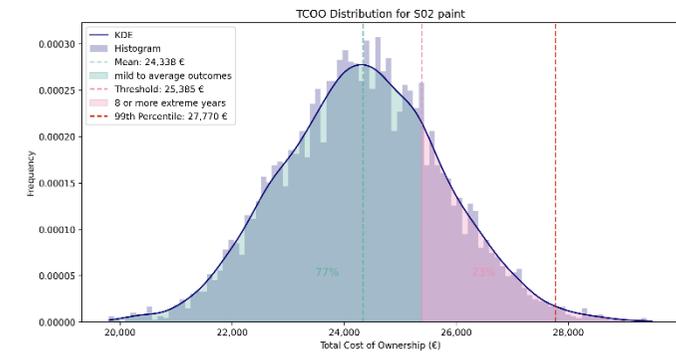
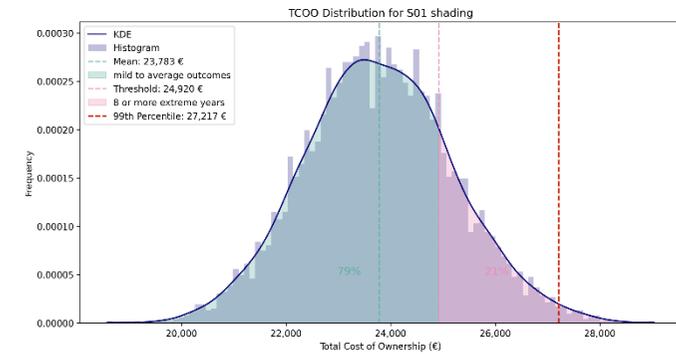
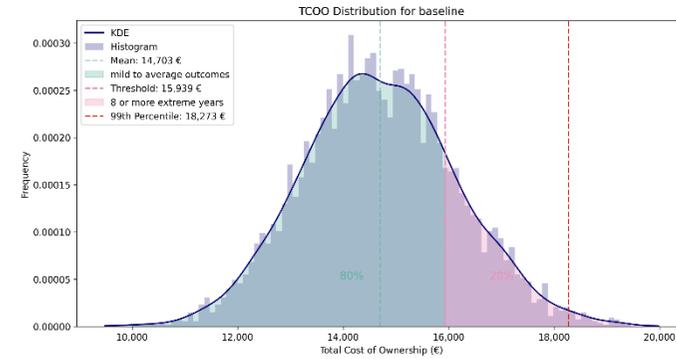
Figure 81 - Correlation between TCOO and number of annual values above 85th percentile (source: own)

Table 29 summarizes the results for the TCOO distributions that are illustrated in Figure 82 as graphs. Also marked and labeled in the graphs is the threshold for eight or more years breaching the 85th percentile of energy use. The value was calculated as the average of all TCOO values with exactly 8 years above the 85th percentile as cost (See Figure 81). The limit values of the 85th percentile are included in the table. Additionally, the 99th percentile was determined, representing the upper edge of the distribution. The estimated probability for 8 or more extreme scenarios occurring varies between 18 to 23%. The notable changes in the TCOO appear to be primarily due to the added ownership costs for shading and paint. This becomes clear when calculating this fixed share of cost. For shading, the measures' investment, maintenance, and replacement costs, discounted, add up to €10,035.16. The total cost for painting is similar at € 9,851.17. It is noteworthy that the

operational cost sum in the baseline is only a few 1,000 Euros greater than the cost of ownership.

Table 29 - Probabilistic TCOO Results (source: own)

Focus	TCOO Mean [Euro]	Standard Deviation [Euro]	Minimum value with min. 8 years above threshold 85 th [Euro]	Probability for the worst-case [%]	Maximum value 99 th percentile [Euro]
Baseline - 85th percentile limit €1,114					
Cooling	14,703.22	1,463.94	15,939.0	20%	18,272.97
Simple 01 shading - 85th percentile limit €1,059					
Cooling	23783.19	1,421.18	24,920.0	21%	27,217.10
Simple 02 paint - 85th percentile limit €1,086					
Cooling	24,338.37	1,441.40	25,385.0	23%	27,769.72
Simple 04 combi - 85th percentile limit €1,033					
Cooling	33,147.93	1,389.88	34,357.0	20%	36,312.48
Medium 01 shading - 85th percentile limit €1,054					
Cooling	66,320.75	1,373.76	67,572.0	18%	69,615.45
Deep 01 shading-paint - 85th percentile limit €1,030					
Cooling	111,474.33	1,353.93	112,643.0	20%	114,604.62



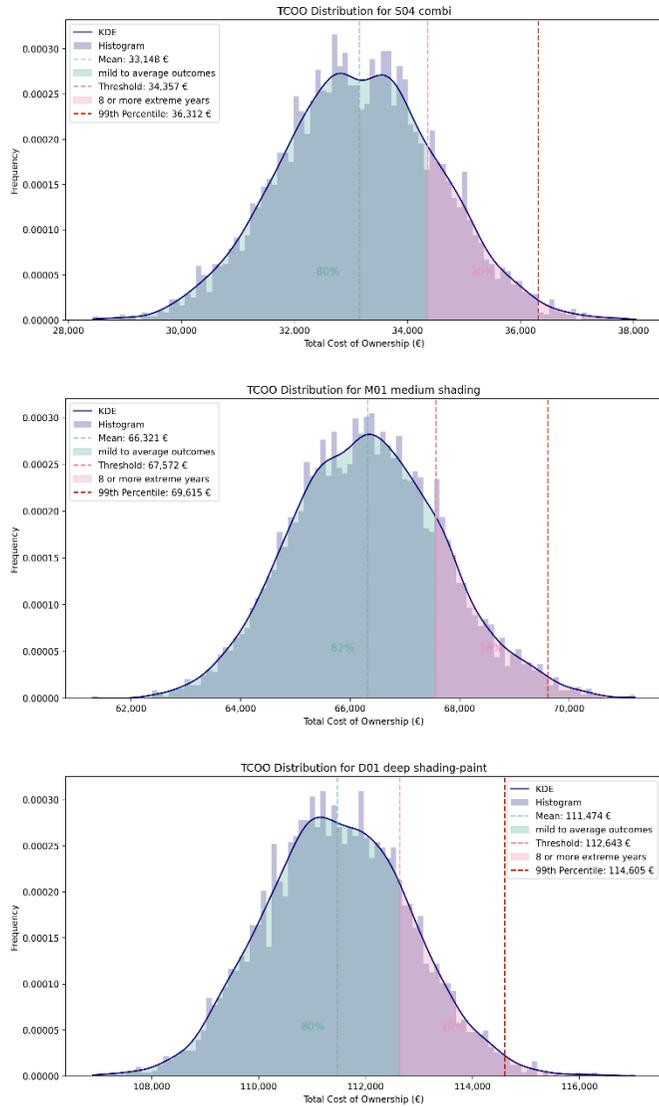


Figure 82 - NPV Distributions for Simple S01, S02, S04 incl. only Cooling (source: own)

To understand the dispersion of cost changes, the differences between the mean and the threshold as well as the 99th percentile were mapped (See Figure 83). The values represent the added cost for a scenario with 8 or more years with an extraordinary high demand as minimum and maximum. These numbers, however, must be interpreted with caution, as the precise accuracy of the Monte Carlo results is not certain. The distance of the mean to the threshold of the baseline yields around 1,236 Euro and, for the 99th percentile, around 3,570 Euro. Throughout most scenarios, this distance decreases with a range of 27 to 190 for the threshold and 135 to 439 for the 99th percentile. Only, for the threshold in the Medium, the value increases by 15 Euro.

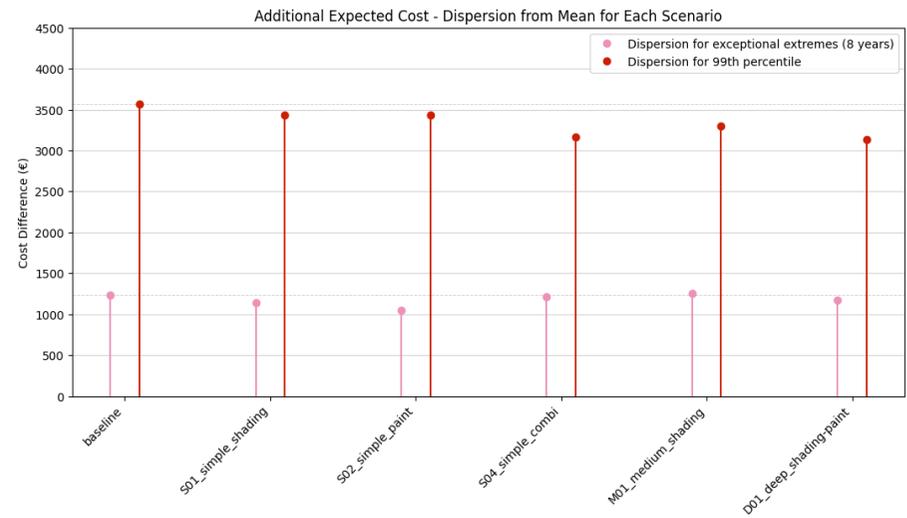


Figure 83 - Stemplot of Dispersion all scenarios (source: own)

5.3.2 Net Present Value Results

In this section, the analysis results for the NPV from the Monte Carlo Simulation are presented for each scenario.

Initially, the cost recovery for cooling measures only was reviewed by examining three simple scenarios. As noted previously, distinguishing the investment for heating and cooling is difficult in the Medium and Deep retrofit. Therefore, they were omitted in this section. The results were processed by estimating the probability density and calculating the mean, standard deviation, and overlap to negative values. Furthermore, to understand how the extreme annual values influenced the result, the relation between demand and savings was analyzed. Then, a threshold marker for savings was defined, and the area for exceptional recurring frequency was outlined as the worst-case scenario. The full operation is explained in more detail in the following section.

After the cost recovery of overheating mitigation, the NPV for heating efficiency measures was determined. For this analysis, the mean, standard deviation, and negative overlap were calculated.

Finally, cooling and heating measures were both integrated into a combined analysis to see counteracting or strengthening effects. Additionally, the influence of the savings threshold was examined here.

Energy Savings Threshold

In chapter 4.3.2.5, a threshold for cooling demand was determined that marks the point for a high annual demand to be associated with an exceptional extreme. In the NPV calculation, however, the demands are translated to savings. Therefore, first, the correlation between demand and savings needed to be reviewed to verify whether high demand also corresponds to high savings.

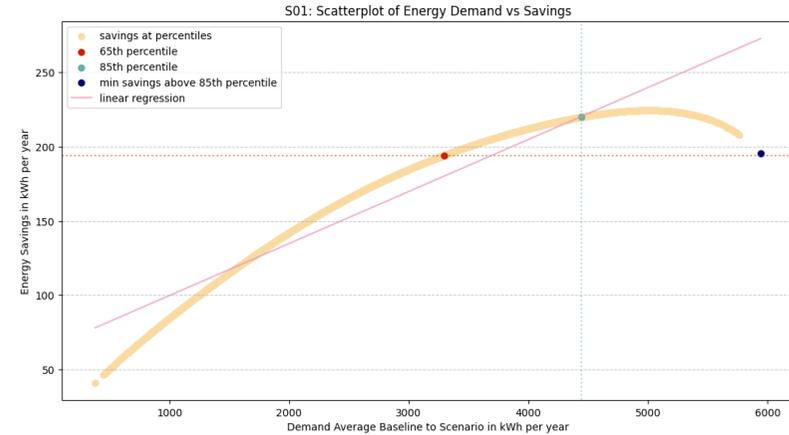


Figure 84 - Demand and Savings Correlation for S01 shading (source: own)

In Figure 84, the average of the baseline and scenario demand is plotted against the corresponding savings of S01 shading. A linear regression was added to better illustrate the development of savings. The plots show that savings do increase with demand; however, at the upper end, the savings yield a specific value and then decrease again at the maximum. The 85th percentile of demand, which serves as the threshold, is also marked on the plot. The savings at this marker point are higher than at the maximum point of 2020. This condition suggests that savings larger than those at the 85th percentile cannot be simply taken as a threshold. Thus, the lowest savings after the 85th percentile demand were determined as the threshold value. The now larger interval, therefore, also includes savings from lower-range demand scenarios, and the percentile first matching the value of the savings, marked by the red point in the graph, was estimated. The savings for all scenarios were analyzed in this manner, yielding varying results.

For S01, the minimal savings of the interval were 195.55 kWh (€47.52), corresponding to 65.7% (See blue point in Figure 84). 124.62 kWh (€30.28) are the minimal savings in S02 at 79% and 299.04 kWh (€72.67) in S04 at 73%. In the Medium scenario, the 78.8th percentile meets the minimum savings at 235.61 kWh (€57.25). Lastly, at 84.99%, the minimal savings for the Deep scenario are met with 342.58 (83.25 €).

Table 30 - Savings Threshold in each scenario (source: own)

Scenario	Demand at 65 th percentile	Savings at 65 th percentile [kWh]	Savings at 65 th percentile [Euro]
Simple shading	3,221.86 kWh	193.89 kWh	€ 47.12
Simple paint	3,273.87 kWh	113.95 kWh	€ 27.69
Simple combi	3,139.61 kWh	282.53 kWh	€ 68.65
Medium shading	3,171.44 kWh	212.04 kWh	€ 51.53
Deep shading-paint	3,131.83 kWh	278.93 kWh	€ 67.78

However, in the end, the 65th percentile was chosen to ensure coherence across the scenarios. The threshold values, along with their corresponding demands, are listed in Table 30. This way, the extreme interval expands from 15% probability to 35%, meaning the demand value can be considered high but not necessarily correspond to hazard. Considering a 35% interval, the expected frequency of events that meet the probability is 10.5 years. Using a significance interval of 5%, the frequency that would be considered exceptional rises to 15 years.

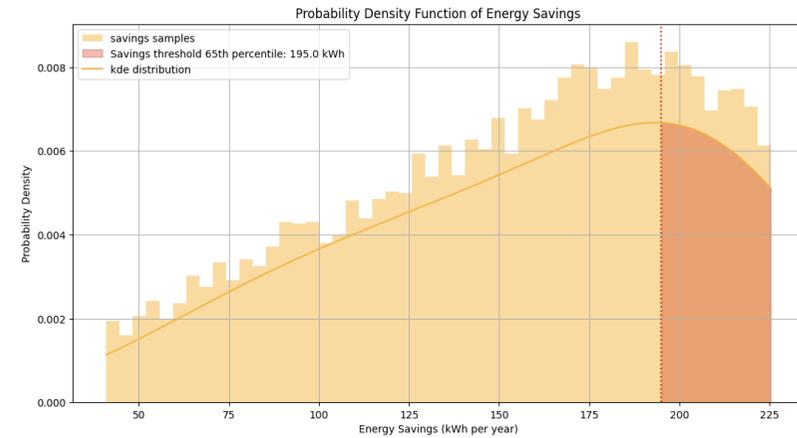


Figure 85 - Savings distribution with threshold (source: own)

5.3.2.1 Cooling NPV Results

In the first analysis, the cost recovery of the simple overheating mitigation measures was reviewed for all Simple scenarios. Table 31 lists the results and important indicators. The NPV resulted in a negative in all cases, with a number not too far from the initial investment volume. For S01 and S02, the results yielded around € -9,000, while the combination in S04 resulted in a spread of around € -18,500. When examining the standard deviation, the increase in dispersion for the scenarios with higher savings is notable, although the deviation is less than a hundred euros.

Using the savings threshold at the 65th percentile and the 15-year frequency rate, the NPV was calculated, outlining scenarios in which high-demand years occur exceptionally frequently. The interval sums between 6 to 7% of the values and raises the NPV of about 72 to 114 Euro in the Simple shading scenario. In S02, the NPV is raised by 45 to 67 Euros, and in S04, by 108 to 168 Euros.

Table 31 - Probabilistic NPV Results for Cooling Measures (source: own)

Scenario	NPV Mean [Eur]	Standard Deviation [Eur]	Threshold for ≥ 15 years	99% Inteval [Eur]	Negative Overlap total
S01 shading	-9031.41	50.22	-8,959	-8917.86	100.00%
S02 paint	-9376.06	28.84	-9,331	-9309.54	100.00%
S04 combi	-18512.92	74.71	-18,404	-18344.36	100.00%

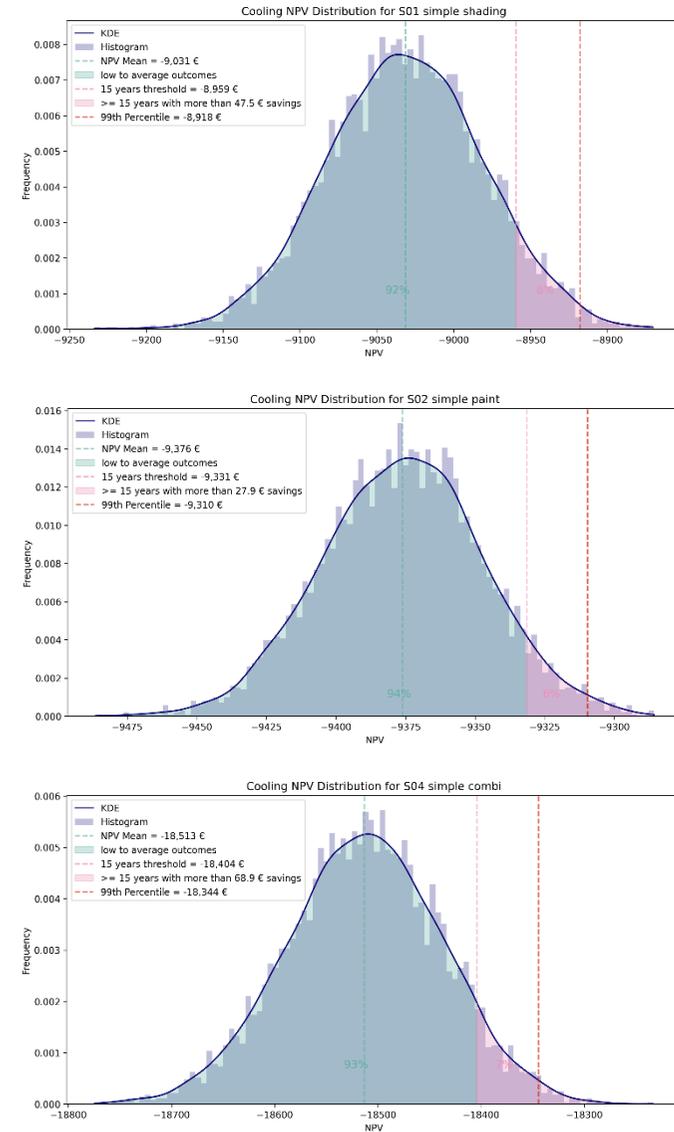


Figure 86 - NPV Distributions for Simple S01, S02, S04 incl. Cooling (source: own)

***Only Cooling**

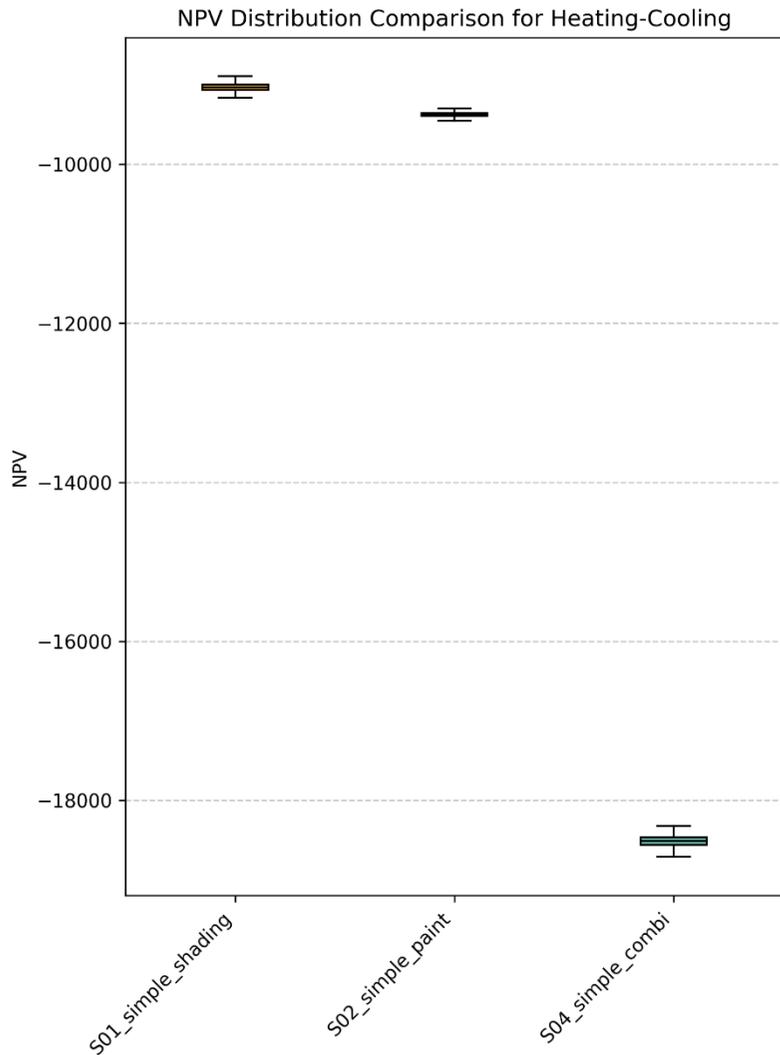


Figure 87 - NPV Boxplot Comparison for S01, S02, S04 incl. Cooling (source: own)

5.3.2.2 Heating Cost-benefit Results

In the second part of the Net Present Value simulations, only heating benefits were analyzed for all 5 scenarios, though S02 and S04 were assumed to perform the same.

To outline the distributions, a confidence interval of 95% as well as the 1st and 99th percentile were determined. For S01 shading, the mean NPV resulted as €9,523 with a standard deviation of €425.4 and zero overlap with losses. In S02 & S04, heating alone yielded a mean NPV of €205 and a std of €215, with a total negative overlap of 16.70%.

In the Medium scenarios, the results deviated about €761.4 from the mean of €-2,712.76 with almost a 100% of the results being negative. The results for the Deep scenario, however, came out largely positive with a mean of €29,933.4 and a standard deviation of €1,329.9. Again, the dispersion clearly increases together with the savings.

Table 32 - Probabilistic NPV Results for Heating Measures (source: own)

Scenario	NPV Mean [Eur]	Standard Deviation [Eur]	Confidence Interval 95% [Eur]	99 th percentile [Eur]	Negative Overlap total
S01 shading	9,522.72	425.36	8,725.00 to 10,376.70	10,539.88	0.00%
S02 & S04 paint	205.03	214.98	-213.46 to 633.70	707.73	16.70%
M01 shading	-2,712.76	761.39	-4,190.55 to -1,236.16	-944.19	99.96%
D01 shading-paint	29,933.44	1,329.93	27,384.08 to 32,559.34	33,000.9	0.00%

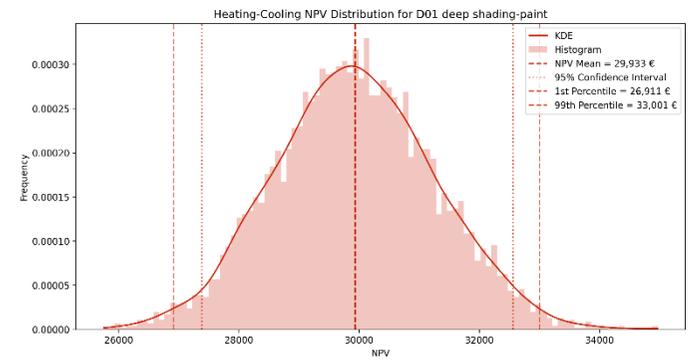
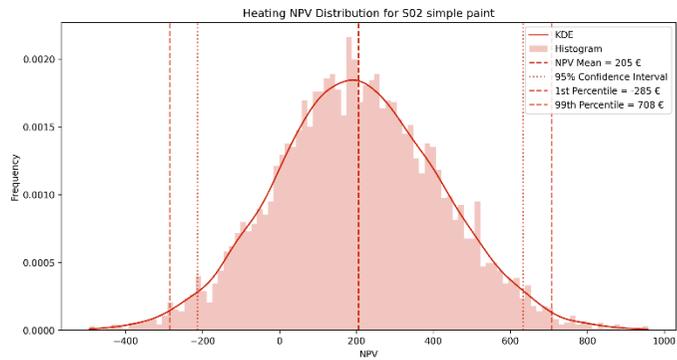
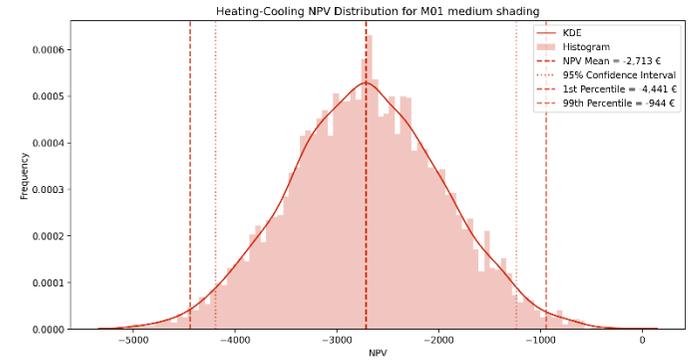
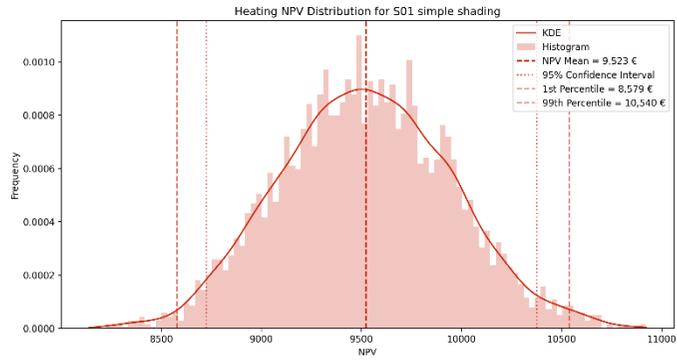


Figure 88 - NPV Distributions for Simple S01, S02, S04 incl. Heating (source: own)

***Only Heating**

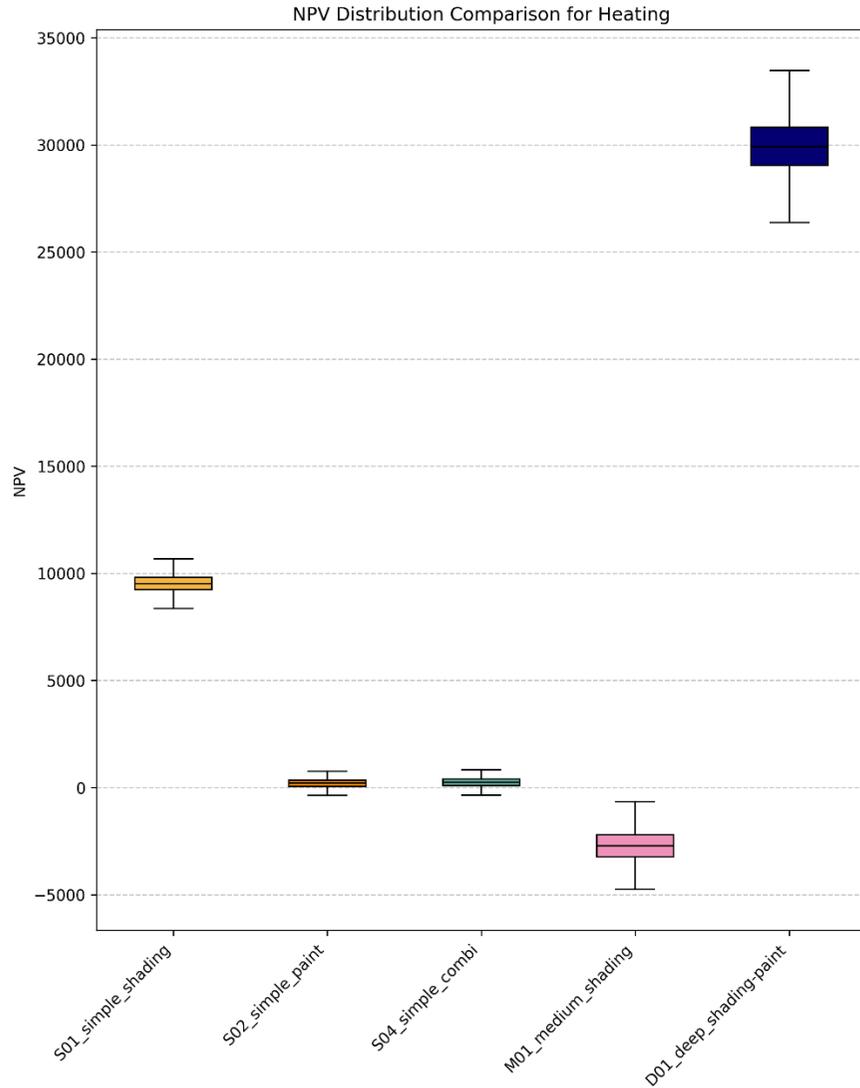


Figure 89 - NPV Boxplot Comparison for S01, S02, S04 incl. Heating (source: own)

5.3.2.3 Combined Heating Cooling Results

As the final step in the cost-recovery analysis, the heating and cooling costs were combined into a single NPV simulation (See Figure 90).

For the outcome, only the NPV results for Simple Shading and the Deep combination resulted in positive values, although S01 yielded a much lower NPV, approximately €490, with a 12% chance of no cost recovery. The Deep scenario yielded a 100% positive result, with a range of €14,900 to €20,050. The other scenarios, however, yielded 100% negative values. The lowest is S04 combi with €-18,270, followed by M01 shading with €-11,650, and then S02 paint with -9,160. The standard deviation here increased with the depth of the scenario from 210 in S02 to 1,340 in D01.

Table 33 - Probabilistic NPV Results for Heating & Cooling Measures (source: own)

Scenario	NPV Mean [Eur]	Standard Deviation [Eur]	Confidence Interval 95% [Eur]	99% Inteval [Eur]	Negative Overlap total
S01 shading	490.20	423.61	-332.35 to 1,340.75	1,481.36	12.12%
S02 paint	-9,163.11	210.30	-9,555.51 to -8,735.34	-8655.72	100.00%
S04 combi	-18,274.74	232.76	-18,721.41 to -17,802.89	-	100.00%
M01 shading	-11,652.29	749.69	-13,105.84 to -10,155.79	-9,931.61	100.00%
D01 shading-paint	17,461.66	1,335.65	14,884.07 to 20,048.46	20,573.86	0.00%

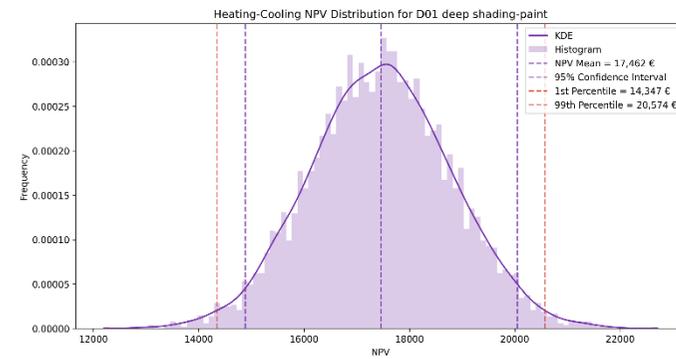
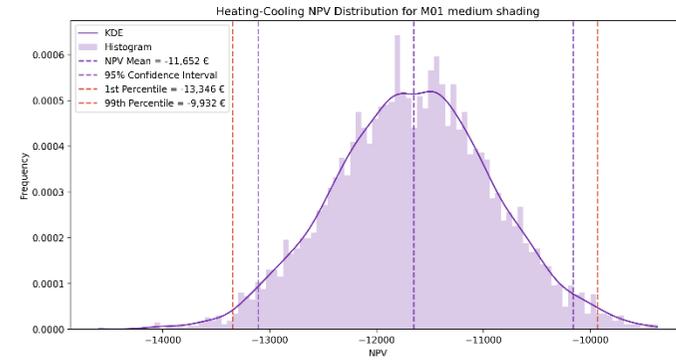
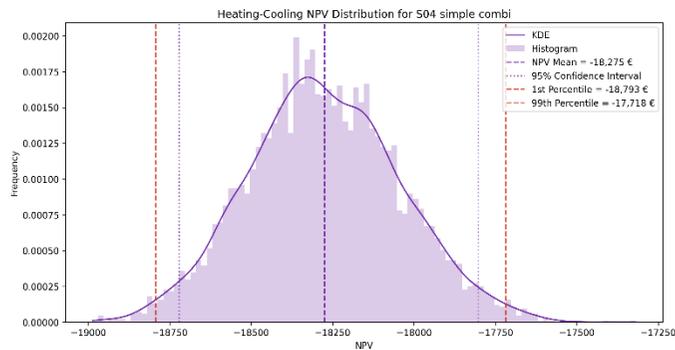
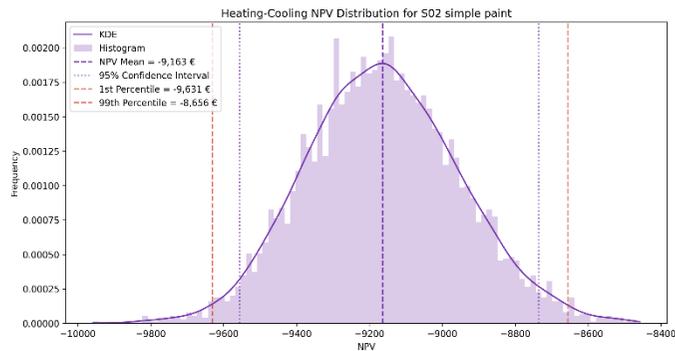
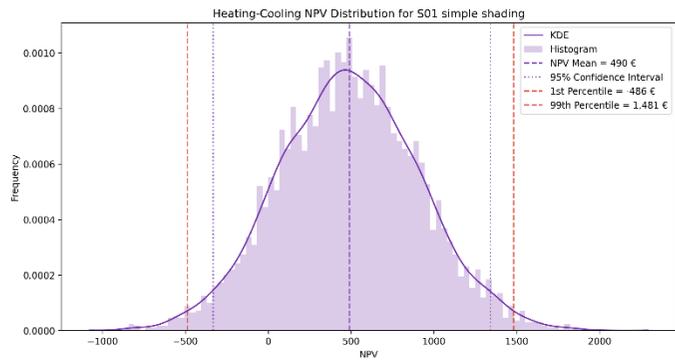


Figure 90 - NPV Distributions for Simple S01, S02, S04 incl. Heating & Cooling (source: own)

To review again the influence of cooling savings, especially in worst-case scenarios, on the outcome, first, all NPV values, including those with 15 or more savings values above the threshold, were marked in the graphs (See Figure 91). In the plots, these scenarios occur throughout the distribution but appear to concentrate in the center. To affirm any interpretations, the correlation of cooling or heating savings was plotted in Figure 92. The graphs show a steeper regression for heating than cooling savings, indicating the asymmetry in influence.

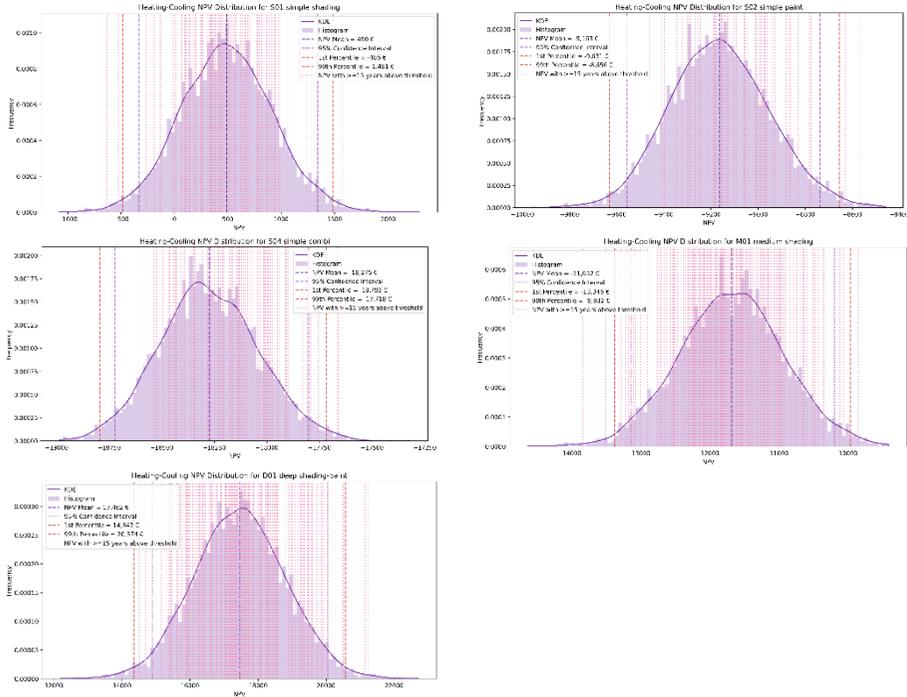


Figure 91 - probabilistic NPV Results for Heating & Cooling - worst-case marked (source: own)

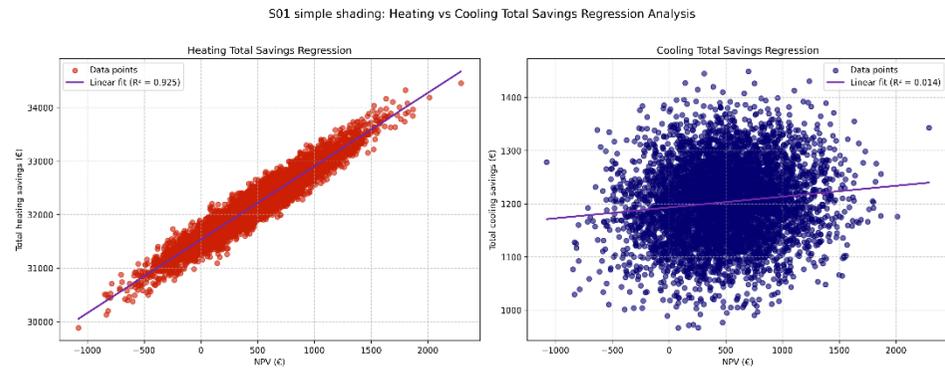


Figure 92 - Regression Analysis for Total Savings and NPV Result (source: own)

*Heating & Cooling

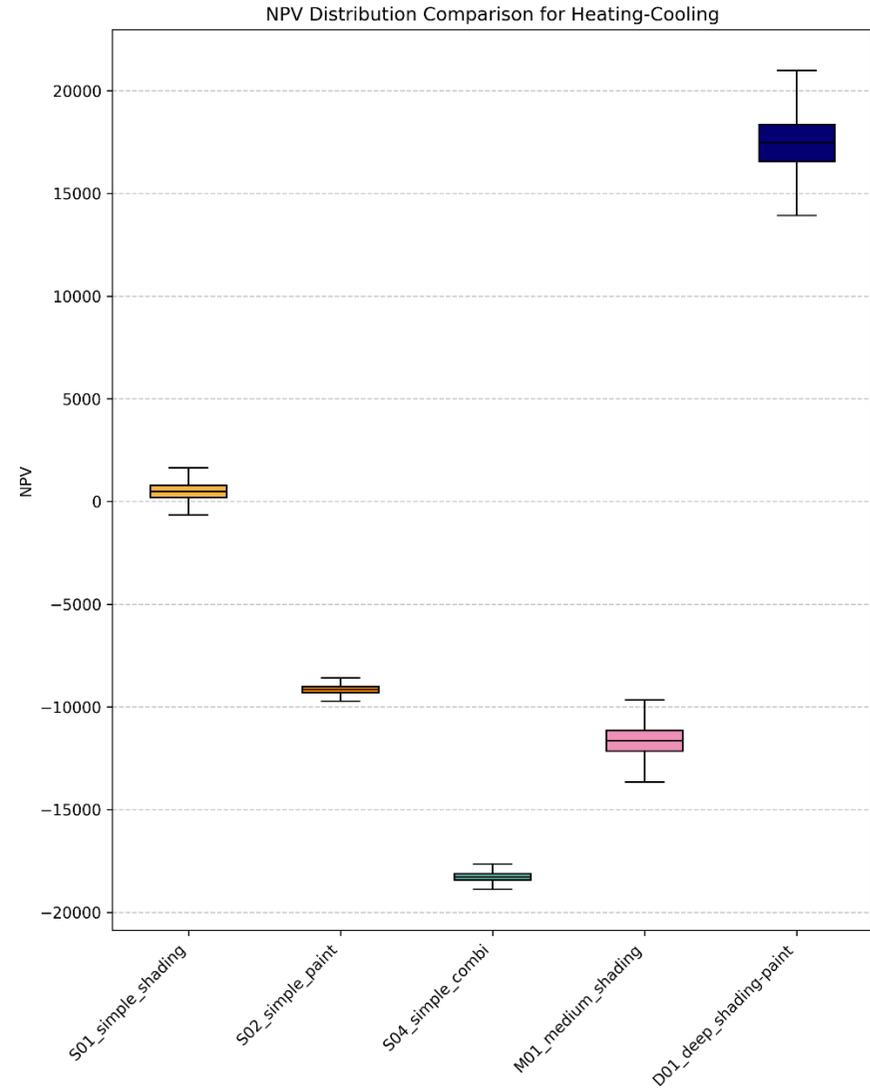


Figure 93 - NPV Boxplot Comparison for S01, S02, S04 incl. Heating & Cooling (source: own)

6 Evaluation of Results

6.1 Discussion

The discussion is structured in five parts. First, it revisits the renovation objectives to contextualize the scope and focus of the evaluation. Second, the financial value of the retrofitting alternatives is analyzed considering the probabilistic 'Total Cost of Ownership' and Net Present Value (NPV) estimations. Third, the overall performance is compared by comparing effectiveness across domains and cost recovery. The fourth section reflects on the limitations of the findings and uncertainties inherent in the analysis. Finally, the discussion considers the broader implications of the findings, including how they align with or diverge from related studies.

6.1.1 Case Study Results

The following will evaluate the results for each indicator in relation to the predefined renovation objectives: reducing energy costs through improved efficiency, enhancing thermal comfort by mitigating overheating, and minimizing the building's carbon footprint. The results of each retrofit measure are assessed in terms of their effectiveness in these domains (see Table 32).

Energy Efficiency

Regarding energy efficiency, the switch to district heating significantly improved the heating demand, although the high-albedo facade surface of S02 and S04 counteracted the improvement noticeably. Combining both paint and shading (S04) proved to be the most effective considering cooling intensity. Among the two measures, shading (S01) demonstrated a stronger influence on reducing cooling loads than reflective surfaces (S02). Nevertheless, the effect on cooling savings is rather insignificant compared to heating, primarily due to the already low cooling demand and associated costs in the baseline scenario. When factoring in the negative effect of white paint

on heating, Scenario S01 emerges as the most effective strategy for improving overall energy efficiency.

Thermal Resilience

All passive cooling measures significantly improved mitigating overheating. This was evident across all comparison metrics, including 'Overheated Hours', 'Indoor Overheating Degree', and 'Overheating Escalation Factor'. Like cooling intensity, shading has more mitigation impact than a high-albedo surface, while the biggest increase in resilience comes from combining the two measures. However, even this combined strategy did not equalize indoor and outdoor thermal conditions without mechanical cooling.

Ecological Impact

The effectiveness of minimizing the ecological footprint is similar across all scenarios, though S01 brought the biggest improvement, with 48%. This was primarily driven by the switch to district heating, which had a substantially greater effect on operational carbon emissions than any cooling-related measure. The emissions intensity related to heating was the biggest contributing factor to the overall footprint.

Cost-benefit Analysis

In the first part of the cost-benefit analysis, the volumes of the global cost categories were estimated, also simulating the effects of climate uncertainty. The volume of operational cooling costs for the next 30 years is generally relatively low compared to the investment volume for passive measures. Nevertheless, the increase in cost for extreme scenarios is notable, and the 20% probability outlines a realistic chance. When comparing the cost dispersion of the scenarios to the baseline, additional costs for extreme scenarios can be reduced by the passive measures. This indicates a long-term mitigation that can be quantified, yielding a few hundred euros in this case, though the uncertainty of the simulation needs to be considered.

Table 34- Benchmarking for Renovation Objectives (source: own)

Renovation Objective	Criteria	Baseline	S01 - shading	- %	S02 - paint	- %	S04 - combi	- %	M01 - shading	- %	D01 - shading-paint	- %
Energy Cost Reduction	Heating Efficiency - EUI [kWh/m ² per a]	160.7 kWh/m ²	136.5 kWh/m ²	15.1%	142.3 kWh/m ²	11.4%	142.3 kWh/m ²	11.4%	119.0 kWh/m ²	25.9%	74.8 kWh/m ²	53.5%
	Cooling Efficiency - EUI mean [kWh/m ² per a]	5.99 kWh/m ²	5.62 kWh/m ²	6.2%	5.76 kWh/m ²	3.8%	5.42 kWh/m ²	9.5%	5.57 kWh/m ²	7.0%	5.45 kWh/m ²	7.5%
	EUI - extreme min 85th percentile [kWh/m ² per a]	9.05 kWh/m ²	8.62 kWh/m ²	4.8%	8.79 kWh/m ²	2.9%	8.45 kWh/m ²	6.6%	8.57 kWh/m ²	5.3%	8.40 kWh/m ²	7.2%
	EUI - extreme max 2020 scenario [kWh/m ² per a]	11.95 kWh/m ²	11.57 kWh/m ²	3.2%	11.71 kWh/m ²	2.0%	11.36 kWh/m ²	4.9%	11.49 kWh/m ²	3.8%	11.23 kWh/m ²	6.0%
Thermal Comfort Increase	Mitigate Overheating - 2020 scenario Overheated Hours 28 SET	162 h	128 h	21%	136 h	16%	106 h	34%	137 h	15%	107 h	34%
	Degree Hours 28 SET	309 dh	193 dh	37%	237 dh	23%	145 dh	53%	235 dh	24%	128 dh	59%
	Overheating Escalation Factor	1.76	1.38	21.6%	1.66	5.7%	1.29	26.7%	1.44	18%	0.87	51%
Reduce Energy Related Footprint	Direct & Indirect Emissions - Carbon Emission Intensity [kg CO ₂ eq/m ²]	37.15 kg CO ₂ eq/m ²	19.17 kg CO ₂ eq/m ²	48.4%	20.01 kg CO ₂ eq/m ²	46.1%	19.89 kg CO ₂ eq/m ²	46.5%	16.85 kg CO ₂ eq/m ²	54.6%	11.31 kg CO ₂ eq/m ²	69.6%

For the second part of the analysis, the probabilistic NPV estimation gave clear insights into the cost-recovery potential of the retrofitting strategies. Across all simple scenarios, cooling-related investments alone failed to recover costs. Additionally, the positive effects of mitigating unlikely exceptional events were slight, amounting to around 100 Euros. A reason for this circumstance was the generally low savings range, which was insufficient to demonstrate a scenario for mitigation. Still, when considering just cooling cost-benefit, such positive effects can be quantified for worst-case scenarios.

For the heating-only analysis, the comparable alternatives included the district heating switch, also featuring a high-albedo facade, additional window retrofitting, or a major facade renovation. While district heating is safely profitable, the investment in S02 & S04 NPV turned out to be more risky, with a considerable chance of no cost recovery. The analysis shows that cost recovery will take longer for not-insulated buildings with high-Albedo facades. However, it must be emphasized that this scenario is just theoretical, as the building is not painted in its current state, and painting costs were not included in the estimation. Although heating efficiency was further improved in the Medium scenario, the outcome indicates no possibility for cost recovery. In contrast, the financial return for the Deep retrofit scenario scored the highest of all alternatives, with a net benefit of 20,000 euros higher than S01.

When integrating cooling with heating, only in Scenario Simple 01 and Deep 01 did the heating savings outweigh the cooling losses, resulting in a positive overall NPV. While the outcome of D01 is largely beneficial, the chance of a no-return in S01 is considerable. In contrast, for scenarios S02 and S04, the NPV improved negligible compared to cooling-only results. For the Medium scenario, the results worsened compared to the just-heating analysis.

Overall, there is potential for heating savings to compensate for cooling losses, provided they are not severely affected by passive cooling measures. For the deep retrofit, the high-Albedo facade did not seriously negatively

affect the outcome. A future comparison case for passive measures in the deep retrofit would give insights into how passive cooling measures affected the outcome.

To conclude the NPV analysis, the just-heating analysis indicated a greater financial return that compensates for cooling losses in the combined analysis. However, the effect of neglecting passive measures while including cooling costs in the case of just heating measures needs to be explored. This is particularly necessary to uncover the adverse effects of heat vulnerability and changes in heat resilience compared to the current status quo.

Throughout all scenario analyses, the effect of climate uncertainty on the outcome depended on the level of cost or savings. A larger spread of costs was also represented in the distribution of total costs, meaning the distributions narrowed by retrofitting. While higher savings also lead to a larger dispersion of results. Generally, the temperate coastal climate of the Netherlands results in a pronounced asymmetry between heating and cooling demands, which amplifies the influence of heating-related measures on both cost and emissions.

Finally, when considering both the performance analysis for energy and heat resilience as well as the financial analysis, Deep renovation emerges as the most profitable and best-performing choice, especially in terms of heat resilience. Although the combination of passive measures can achieve similar resilience improvements through a simple retrofit, cost recovery is not feasible. Still, the simple heating measure of switching to district heating, on its own or combined with shading, holds both financial feasibility and significant performance improvement. In contrast, the Medium scenario would have necessitated higher savings to recover the much larger investment volume. From a stakeholder perspective, budget plays a role in final decision-making. Simple scenarios could still be the preferable choice despite the riskier investment.

6.1.2 Implications and Limitations

The findings presented in this study are inherently limited to the specific conditions of the case study. Therefore, the results can only give an indication and are not directly generally applicable to similar residential typologies in the Netherlands. Variations in building orientation, window-to-wall ratios, or shading geometry could significantly alter the outcome.

Several uncertainties also remain within the cost-benefit analysis. These include the real future economic development, as represented by the discount rate, and the development of investment or energy costs. Additionally, carbon cost was not included in energy and investment costs, which could alter the monetary impact of choices over time. The ongoing decarbonization of the energy supply, particularly through the expansion of renewable energy sources, could reduce the carbon intensity of both district heating and electricity (Eneco, 2023). As a result, the expenses for gas heating would increase, while district heating would become more affordable. Furthermore, uncertainties arise from the variable lifespans of parts, particularly when external damage or degradation is taken into account. Moreover, the efficiency of heating and cooling systems is an important uncertainty that affects energy loads (Sun et al., 2016).

Regarding the overall cost-benefit, accuracy and sensitivity testing would be needed for the NPV and TCOO simulation to confirm the stability of the analysis. During the case study, the TCOO simulation was observed to be more sensitive because of greater sample variability compared to the NPV. Another aspect is the choice of analysis period, where the depth of renovation and investment budget could also relate to a preferred use case period.

Additionally, occupant behavior can significantly impact thermal performance. For instance, in this case, the external shading is a measure entirely dependent on user behavior. Consequently, its effectiveness might vary in practice. The energy savings may be lower than assumed if users do not fully utilize the

system. In a study summary of the RAAK project on overheating housing in the Netherlands, it was found that an essential factor in mitigation is ventilation scheduling. Specifically, night ventilation, in combination with shading, was able to reduce overheating levels below threshold (RAAK-project, n.d.). This aligns with the study's finding that protective measures, such as shading, may not be sufficient on their own to prevent overheating from escalating. Furthermore, the prebound or rebound effect, as described by Galvin in 2023, can contribute to the overestimation of savings (Galvin, 2023). This would be the case if the simulation had not been well-calibrated for real-world performance. However, the numerical model could still have assumed unrealistic parameters (Sun et al., 2016).

Moreover, future climate scenarios were not considered in the analysis approach. Based on the projection by KNMI, cooling demand may increase over time, while heating demand could decrease. This shift could alter the balance of benefits among retrofit measures.

After testing the framework in a case study, the question arises whether the value of heat resilience is accurately represented in the cost-benefit analysis. Notably, the significant improvement in cooling efficiency compared to overheating indicators is particularly noteworthy, as also observed in a 2023 study by Sheng et al. Given that the cooling cost for air conditioning is generally low in the current Dutch climate, cost recovery proved to be difficult. This finding has yet to be supported by literature. In a recent study, Hyyrynen et al. analyzed the cost-benefit of mechanical cooling compared to the societal cost of overheating. When quantifying the value of statistical life in comparison to the cooling cost associated with mitigation, active cooling proved to be 1.8 to 18 times more beneficial (Hyyrynen et al., 2025). A similar analysis on the project scale for private decision-making has yet to be explored. It would enable the comparison of benefits between passive and active cooling scenarios.

Regarding the probabilistic approach to CBA, for this case study, assessing risk became a secondary factor, as the simulations did not result in a wide dispersion of costs.

Finally, outlining the results for worst-case scenarios proved easier and more comprehensive in terms of the total cost of ownership. Since the correlation between savings and demand is not always linear, the interval for extreme demand value becomes fuzzy and needs to be widened.

6.2 Conclusions

In this section answers to the initial research question and sub-questions will be reflected on.

Framework Design

Three sub-questions were set for the development of the framework: 'How can impact from thermal hazard be integrated into cost modeling?', 'How can the uncertainty of weather extremes be assessed in cost-benefit?' and 'How can risks for long-term hazard loss be outlined in cost-benefit giving insights into resilience?'

For the first option, insights from the literature on heat hazard impact helped outline two possible approaches: either monetizing functional loss or including added energy and carbon costs. For this study, energy cost was chosen because it integrates well into the standard analysis for heating retrofits. In contrast, the real cost of discomfort cannot be determined with certainty. In any case, loss of revenue due to a lack of comfort would make an interesting comparison case for evaluating how only heating retrofits could negatively affect cooling.

Generally, considering any type of thermal hazard necessitates a probabilistic approach to cost-benefit and energy performance analysis. The reason being

that extremes are not typically represented in the standard weather scenario, leading to the second question.

To address this question, the approach primarily relied on existing guidelines for cost-benefit analysis. Obtaining a comprehensive perspective on how energy performance is distributed requires testing a full 30-year climate cycle. Only afterward could reference years be determined to reconstruct the distribution with sufficient accuracy and speed up the simulation process. With knowledge of the probability of energy demand, a Monte Carlo simulation for cost-benefit analysis can be conducted to estimate how the financial outcome is distributed.

The third question required a definition of extremes based on the probabilistic analysis. The annual demand of hazard years was analyzed in the context of the general demand distribution, leading to the conclusion that hazards significantly contribute to annual cooling, even though overheating and intensive cooling can also happen in shorter periods throughout the year. A high demand does not necessarily relate to a heat wave by definition. Additionally, when comparing thermal comfort indicators and energy intensity, the years might be distributed differently, posing a challenge to identifying extremes later in the analysis. In any case, a threshold for overall extreme years, including hazards, can be defined.

Additionally, for a worst-case scenario, an exceptional frequency of extremes needed to be defined. Knowing the frequency and intensity of hazards, the financial analysis results for worst cases can be outlined, and the long-term mitigation impact can be understood. Unlikely weather extremes are found at the lower or upper end of the distribution. This turned out to be easily applicable to calculating the discounted cost total rather than the net benefits. However, the specific results for long-term mitigation of the case study impact did not yield beneficial outcomes. Additionally, for integrating heating with cooling retrofits, the impact of extremes was not significant due to the much higher impact of heating costs on the analysis. Additionally, further analysis of

the accuracy of each Monte-Carlo simulation is necessary to strengthen the approach.

Overall, the process for probability estimation remains labor-intensive, with opportunities for improvement, while being generally feasible and insightful.

Use of Outcome

The last sub-question relates to the research outcome, 'How can resilience assessment inform decision-making for envelope retrofitting?'

The applied cost-benefit analysis results provided insights into the impact of climate uncertainty on cost recovery, while the comparison metrics indicated qualitative improvements in resilience.

Using the analysis method, stakeholders, like owners or occupants, can understand the long-term financial implications of retrofitting alternatives and compare them to the qualitative benefits. Specifically, learning about added costs in worst-case scenarios and whether those can be mitigated. Metrics quantifying overheating in terms of duration and intensity could assist in classifying the qualitative state of buildings. Additionally, learning about overheating scenarios to expect during the set analysis period puts a scale on the building's vulnerability.

In their study on probability estimations for energy efficiency, Sun et al. stated that uncertainty analysis can support 'targeting energy savings more reliably' (Sun et al., 2016). This study's approach was extended to cost-benefit, but the insights are similar. Knowledge of the likelihood of cost recovery through energy savings can support investment decision-making for more cost-effective alternatives. It is essential for combining heating and cooling savings. However, as probabilistic analysis was required, the outlined CBA approach became more complex and burdensome in terms of workload compared to a standard CBA.

Examining the case study application, the probabilistic approach appears most useful in scenarios where the average NPV outcome is closer to 0. Otherwise, the improvement through mitigating worst-case scenarios is not as relevant. Using typical climate data in a static CBA might be helpful for faster analysis of in which direction the outcome will lean.

The case study also demonstrated the value of integrating heating and cooling, giving insights into the combinatoric effect. These findings are supported by Sheng et al.'s conclusion on the necessity of approaching heating and cooling in combination to avoid negative influences on one or the other (Sheng et al., 2023).

Overall, the feasibility and practical usefulness of the application have yet to be validated.

6.3 Future Development

Ultimately, when considering the overall approach to integrating heat resilience into cost-benefit analysis to inform decision-making, it becomes clear that further development is necessary to complete and extend the analysis.

First of all, carbon cost provides an easily applicable extension to the approach, especially for integrating considerations of taxation and decarbonization plans. In addition, future climate scenarios could reveal how overheating losses and probability develop over time.

As an alternative approach, a cost-effectiveness analysis might be more appealing to fewer decision-makers in owner-occupied cases. In such cases, qualitative benefits might be more relevant to the decision-maker than cost recovery. Cost-effectiveness studies on passive mitigation could also provide more insights into the strategies that should be adopted in mild coastal climates, considering different building typologies. Furthermore, alternative

strategies such as PV panels, green facades, or phase change material applications could be tested.

Lastly, the decision-making process between active cooling and passive protection should be explored further to provide a perspective on renovation planning for alternative pathways. The affordability of additional cooling costs may also influence this decision-making scenario. eating losses and probability develop over time.

7 Reflection

7.1 Graduation Process

How is your graduation topic positioned in the studio?

The Building Technology graduation studio offers various research topics: Façade and Products, Energy and Climate, Transparent structures / Glass Design, Computational Design, Resource-Efficient Building Design, Nature-Inclusive Design, and Sustainable Structures.

This thesis research on 'cost-benefit analysis for heat resilient retrofits' is closely related to the focus on overheating and renovating of the facades and products group. Despite this connection, the topic was initially developed from suggested topics within the sustainable structures theme. The suggested topics were 'design tools for multi-hazard resilience' and 'low-carbon resilient envelopes'. The research conducted in this study links the two topics but also extends into building economics, a field that has not previously been studied and is not integrated into the department's field of expertise.

How did the research approach work out (and why or why not)? And did it lead to the results you aimed for? (SWOT of the method)

The developed framework was designed to understand the influence of climate extremes on pay-off through renovation benefits and compare to qualitative resilience benefits. Therefore, the aim was to gain insights on worthwhile mitigation measures.

The approach proved effective in highlighting asymmetries between financial and wider benefits and gaining certainty on cost recovery. Its weaknesses are the workload involved and the high complexity, which might limit its direct application in practice.

An opportunity would be integrating the method into user-friendly digital tools for clients and designers. The tool would assist in investment decision-making and is based on gathered performance data by designers. The method could be further used in research on a larger scale to find the universally best-performing renovation measures that help to achieve sustainability and resilience goals for the building sector while offering monetary benefits.

However, the approach lacks stakeholder validation to determine real-world benefits for certain. Also, remaining uncertainties concerning occupant behavior or price development could make the predicted outcome deviate from the real one. Lastly, decision-making that is only guided by monetary profits might neglect many of the qualitative benefits essential to building design.

What is the relationship between the methodical line of approach of the graduation studio (related research program of the department) and your chosen method?

The department's research methods involve experimental testing, a wide range of computational tools, and numerical modelling to investigate the performance and limitations to building construction. The methodological approach often involves design-based research to develop construction technologies to improve building practices. This thesis's approach aligns with the department's methodologies by using several computational modelling methods and tools to evolve performance-based design and planning.

How are research and design related?

The developed framework and renovation design measures were firmly based on literature findings from related studies and reviewed for applicability in the regional context. Additionally, prior analysis and simulations supported the

sensible application of measures. In general, data-driven design enforces a strong connection between research and design.

Did you encounter moral/ethical issues or dilemmas during the process? How did you deal with these?

The topic of heat resilience relates to society's interest in ensuring safe and healthy living conditions that are not vulnerable to hazardous extremes. Overheating poses a threat to humans' health and safety in buildings.

Despite this knowledge, quantifying the qualitative functional loss due to summer extremes remains difficult. Further, embedding functional loss in a cost-benefit analysis could not be resolved. Instead, the cost of creating habitable living conditions with energy was accounted for, and comfort metrics were introduced for comparison. Using these two implementations helped to relate qualitative improvements for health and safety to monetary value.

7.2 Societal Impact

To what extent are the results applicable in practice?

The developed framework assists in decision-making during pre-construction renovation planning, particularly for owners and housing associations. It offers a method for evaluating not just energy savings but also thermal resilience, an increasingly important performance criterion under changing climate conditions. While its complexity might limit direct adoption, simplified approaches or user-interface software could support practical use.

To what extent has the projected innovation been achieved?

The project contributes a novel methodology that integrates thermal resilience into cost-benefit analysis, something not yet addressed in standard renovation assessments. In this study, cost-benefit analysis was successfully combined with

quantitative resilience assessment by combining energy efficiency, thermal comfort, emissions, and financial return in a framework. Nonetheless, the approach could stretch further to cost-optimal and cost-effectiveness analysis for decision-making in owner-occupant scenarios.

Does the project contribute to sustainable development?

What is the impact of your project on sustainability (people, planet, profit/prosperity)?

What is the socio-cultural and ethical impact?

The thesis projects support national efforts to improve the ecological footprint of the built environment and adapt buildings to the changing climate. These aims are also part of the international 'Sustainable Development Goals'.

The proposed assessment method makes performance estimation in those domains more reliable. By focusing on resilience in terms of thermal comfort, carbon emissions and energy use in vulnerable buildings, the project highlights the importance of creating awareness of the impact of climate hazards. The project enables conscious decision-making for both owner and occupant. It also questions the blind application of energy retrofitting measures without considering the overheating risk. Additionally, promoting passive mitigation strategies to balance the need for active cooling aligns with the goals.

What is the relation between the project and the wider social context?

The research responds to national and EU-level directives and programs for energy renovations and promoting renovation to accommodate for housing demand. Furthermore, it contributes to the growing discourse on adapting the existing building stock to future climate conditions, a challenge for both architecture and urban planning.

How does the project affect architecture / the built environment?

By quantifying the thermal performance and economic risk of renovation measures, the project encourages a more performance-based architectural practice. It emphasizes that design decisions must be informed by lifecycle impacts and climatic stressors, particularly as passive solutions become more critical in a warming world.

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9 Appendix

9.1 Weather Data Analysis csv

This is a link to the developed code used in this thesis:

https://github.com/tamilaly/Heat_Resilience_Cost-Benefit

Year	Number_of_Heat_Waves	Dates_for_Each_Heat_Wave	Span_of_Each_Heat_Wave
1995	1	1995-07-29 00:00:00 to 1995-08-03 00:00:00	6
1996	0		
1997	1	1997-08-06 00:00:00 to 1997-08-13 00:00:00	8
1998	0		
1999	1	1999-07-28 00:00:00 to 1999-08-04 00:00:00	8
2000	0		
2001	0		
2002	0		
2003	1	2003-08-03 00:00:00 to 2003-08-12 00:00:00	10
2004	0		
2005	0		
2006	1	2006-07-15 00:00:00 to 2006-07-30 00:00:00	16
2007	0		
2008	0		
2009	0		
2010	0		
2011	0		
2012	0		
2013	1	2013-07-21 00:00:00 to 2013-07-26 00:00:00	6
2014	0		
2015	0		
2016	0		
2017	0		
2018	1	2018-07-19 00:00:00 to 2018-08-07 00:00:00	20
2019	2	2019-07-22 00:00:00 to 2019-07-26 00:00:00; 2019-08-23 00:00:00 to 2019-08-28 00:00:00	5; 6
2020	1	2020-08-05 00:00:00 to 2020-08-16 00:00:00	12
2021	0		
2022	1	2022-08-09 00:00:00 to 2022-08-16 00:00:00	8
2023	0		
2024	0		

Figure 94 - Heat Wave Analysis based on KNMI Weather Data (source: own)

Year	all_days	days_above_25	days_above_30	%_days_above_25	TX_diff_to_25	norm_%_days_above_25	norm_TX_diff_to_25	summer_intensity_measure
1995	365	37	8	10.14	3.28	0.71	0.64	0.67
1996	366	13	2	3.55	3.0	0.0	0.54	0.27
1997	365	26	4	7.12	2.7	0.38	0.44	0.41
1998	365	15	2	4.11	2.67	0.06	0.43	0.25
1999	365	24	3	6.58	2.42	0.32	0.35	0.34
2000	366	19	2	5.19	2.3	0.18	0.31	0.24
2001	365	23	3	6.3	2.12	0.29	0.25	0.27
2002	365	13	4	3.56	3.63	0.0	0.75	0.38
2003	365	32	8	8.77	2.9	0.56	0.51	0.53
2004	366	20	1	5.46	1.94	0.2	0.19	0.2
2005	365	22	4	6.03	2.49	0.27	0.37	0.32
2006	365	41	9	11.23	3.24	0.82	0.62	0.72
2007	365	13	0	3.56	1.44	0.0	0.02	0.01
2008	366	19	0	5.19	1.37	0.18	0.0	0.09
2009	365	27	1	7.4	1.86	0.41	0.16	0.29
2010	365	23	4	6.3	2.62	0.29	0.42	0.36
2011	365	18	2	4.93	1.98	0.15	0.2	0.18
2012	366	21	2	5.74	2.7	0.23	0.44	0.34
2013	365	23	7	6.3	2.74	0.29	0.46	0.38
2014	365	22	3	6.03	2.15	0.27	0.26	0.26
2015	365	22	3	6.03	2.45	0.27	0.36	0.31
2016	366	25	6	6.83	2.93	0.35	0.52	0.44
2017	365	22	2	6.03	2.5	0.27	0.38	0.32
2018	365	47	7	12.88	2.78	1.0	0.47	0.74
2019	365	24	11	6.58	4.37	0.32	1.0	0.66
2020	366	30	11	8.2	3.94	0.5	0.86	0.68
2021	365	15	0	4.11	1.76	0.06	0.13	0.1
2022	365	39	10	10.68	3.02	0.76	0.55	0.66
2023	365	35	5	9.59	2.67	0.65	0.43	0.54
2024	366	26	4	7.1	2.67	0.38	0.43	0.41

Figure 95 - Weather Data Analysis csv (source: own)

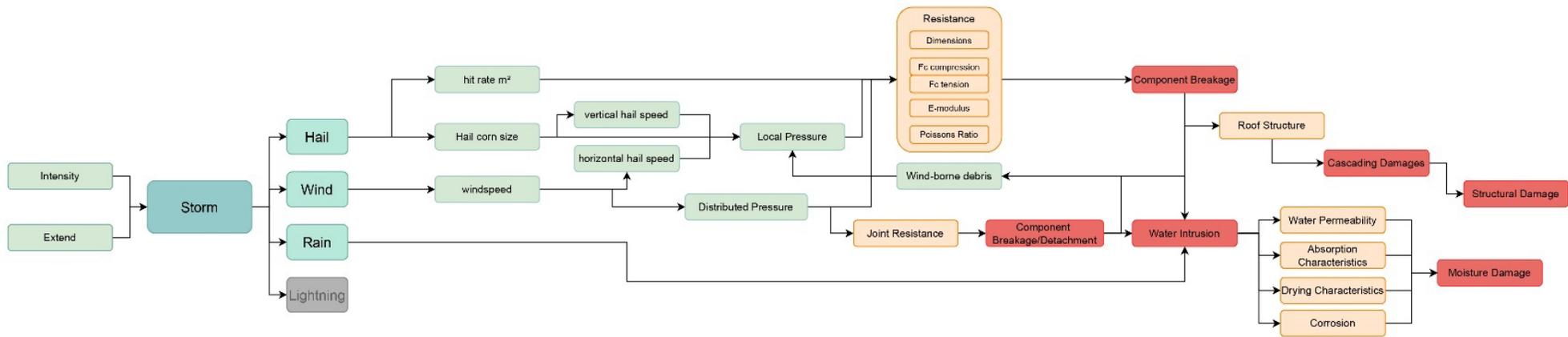


Figure 96 - Storm Hazard Flowchart (source: own)

9.2 Storm – Wind and Heavy Rainfall

Globally, storms account for the most deaths directly related to weather with 39% (Ebi et al., 2021).

In this sub-chapter, the impact of storms in terms of wind and heavy precipitation will be discussed in separate paragraphs, while the impact of flooding as a result of heavy rain and storms is part of the next sub-chapter. Lightning as a hazard is completely excluded.

Wind

Storms can carry wind gusts and downwinds. According to KNMI, the intense wind starts at 75km/h, respectively, a nine on the Beaufort scale (KNMI - *Windstoten En Storm*, n.d.). 9 Beaufort is defined as relatively causing small damages to buildings and roofs including breakage of chimneys (KNMI - *Windschaal van Beaufort*, n.d.). The most important indication for storminess is

wind speed, which is typically measured at every meteorologic data station (Cusack, 2013). A larger cascading effect of windstorms is flooding from the sea, for which the probability increases with the ocean level rise (Amini & Memari, 2020).

Wind-induced damage either results from wind pressure or wind-borne debris. In theory, damage is proportionally but not linearly related to wind speed. Further, the landscape significantly affects the development of wind speed (Cusack, 2013).

In a building, roof failure is typically the first damage to initiate a progressive sequence of damage (Amini & Memari, 2020). The detachment of components such as tiles, aerals, and facade elements create wind-borne debris, resulting in more damage. The flying debris moves at very high speeds, posing a serious threat to people and property (Milardi et al., 2024). The envelope is usually most affected in a building, e.g., roof covering or sheathing, wall siding, soffits, windows, and doors. Windows and doors are most vulnerable to wind-borne debris. The risk of being damaged by wind is generally higher for taller buildings (Amini & Memari, 2020).

Rain

On the other hand, storms can also carry heavy rainfall, which can have several cascading damage effects. KNMI defines heavy rain as daily precipitation of more than 50 millimeters. For the Dutch climate, more than 50 millimeters in an hour and more than 100 millimeters in a day would make an extreme (KNMI - *Extreme Neerslag*, n.d.). Cascading hazards from extreme precipitation are pluvial and fluvial flooding. Other cascading effects include waterborne disease outbreaks, landslides, property damage, and disruption of agricultural production, sewage networks, and traffic (AghaKouchak et al., 2020). On a building scale, direct consequences from moisture accumulation can be rain penetration, frost damage, moisture-induced salt migration, discoloration by efflorescence, biological degradation or structural cracking (Blocken et al., 2013).

9.2.1 Dutch Context - Storm

In the Netherlands, wind and rainstorms are a common weather phenomenon.

Winds

Strong winds typically develop offshore on the North Sea and then blow onto the coast (KNMI - *Windstoten En Storm*, n.d.). Downwinds, in turn, are caused by the rapid air cooling by heavy rain and are sudden and local events (ANV, 2022b).

An example of severe windstorm loss in the Netherlands is the triple storm in February 2022. In a period of four days, three storms hit the coastal regions most intensively. The middle storm, Eunice, turned out to be the strongest storm of the last 50 years, with wind speeds of up to 145 km/h. The storms caused five fatalities and severe property damage, with insured losses of at least 500 million euros (ANV, 2022b).

Another example of damages from downwind occurred in Leersum on June 18th, 2021. The event injured 9 people and damaged about 100 residential houses, with 10 to 20 of them uninhabitable. Further damages included several gas leakages and about 1,600 fallen trees. Though downwind affected a community of less than 10,000 inhabitants, the total damages accounted for about 13.3 million euro (ANV, 2022b).

According to KNMI, the impact of climate change on thunderstorms and wind-gust development remains uncertain. By the year 2100, strong northwest winds, exceeding 14 m/s, may become less frequent, while southwest winds are expected to occur more often, with an increase of roughly double the decrease (KNMI, 2023). However, windstorm-related losses are influenced by changing weather patterns and factors such as population density, wealth, insurance coverage, and the complexity and vulnerability of production and living systems (DORLAND et al., 1999).

Rain

Extreme rain, as indicated by KNMI, has a return period of once in 100 years for impacting a large area, while local events are a bit more likely (KNMI - *Extreme Neerslag*, n.d.). Most insured losses from precipitation occur in summer. Summer storms may become more extreme under climate change, which means more rainfall could occur in the same amount of time (KNMI, 2023).

An example of a heavy rainfall event happened in Limburg in mid-July 2021. It primarily affected the community of Valkenburg, which was close to the German and Belgian borders. In four days, Limburg experienced 48 hours of rainfall, accounting for nearly a quarter of the annual precipitation. In some parts of Germany, rainfall rates exceeded the expected 1-in-100-year return periods, with certain areas reaching 1-in-1,000-year levels. This event was caused by a small low-pressure area of cool air drawing in warm air from

Eastern Europe, resulting in prolonged heavy rain over Western Germany and the Netherlands (ANV, 2022b).

The excessive rainfall triggered fluvial flooding due to excess drainage through rivers, with the Roer River reaching a maximum flow of 270 m³ per second, compared to its usual 12 m³ per second. The flooding caused estimated damages of 600 million euros, with 2,360 to 3,000 homes affected. Among these, the residents of 700 homes were displaced due to their severely damaged states (Nu.nl, 2021b; ENW, 2021) (ANV, 2022b).

9.2.2 Storm – Hail

Hail is a frozen form of precipitation. Hail occurs often in the context of thunderstorms, which are included in the term hailstorm. Hailstorms are generally hard to predict in advance (AghaKouchak et al., 2020). Usually, hail corn size correlates with the extent of the storm, but large hail corn can also appear in small streaks. A size larger or equal to 2cm can be considered severe hail (Wouters et al., 2019).

Consequences of severe hailstorms include extensive property damage to buildings, vehicles, and agriculture, but can also result in the loss of human life and livestock (AghaKouchak et al., 2020). The damage depends mostly on two impacting parameters: hail corn diameter and hit rate on m² per second (Li et al., 2024). But for a thorough assessment, hail speed is another relevant parameter consisting of vertical gravity force and horizontal wind-induced force (Paterson & Sankaran, 1994). From damage to a building's facade layer also, cascading damages from water entering the building emerge.

9.2.3 Dutch Context – Hail

In the Netherlands, hail belongs to the hazard with the highest insured damages (*Klimaatschademonitor*, 2024). Hailstorm events typically affect a size of a couple thousand km² with large variations depending on the storm

(Wouters et al., 2019). Larger hail sizes mainly occur over the summer between May and August (Wouters et al., 2019). In the south of the Netherlands, larger hail diameters are more likely, with a return period of 10 years for a diameter of 6cm, compared to the north, with a return period of 35 years (Wouters et al., 2019).

An exemplary event is a heavy hailstorm in Brabant in July of 2016, where the hail developed in a super-cell thunderstorm. The hail corn diameter varied between four and ten centimeters. The storm heavily affected a small number of communities. The total damages to houses, cars, agricultural greenhouses, and gardening centers were estimated between 500 million and one billion euros. However, insured losses accounted for 671 million euros, making it the most impactful single-day event since 2007 (ANV, 2022b).

Predictions for the future development of hail under climate change are highly uncertain. However, the KNMI suspects hailstones will grow bigger should humidity levels increase, as this is part of one of the scenarios (KNMI, 2023).

In a 2019 study, Wouters et al. calculated return periods for hail sizes in the Netherlands from reports on hail events. On a national level, a diameter equal to or larger than 7 cm is estimated to return once every 10 years, a diameter equal to or larger than 9 cm once every 50 years, and equal to or larger than 11 cm for every hundred years (Wouters et al., 2019).

9.3 Flooding

Globally, flooding accounts for about half of all weather-related extremes, though in terms of direct weather-related deaths, floods only account for about 16% (AghaKouchak et al., 2020; Ebi et al., 2021).

There are several types of flooding, including pluvial, fluvial, and storm surges. Pluvial flooding is also known as flash flood or surface water flood. It is purely

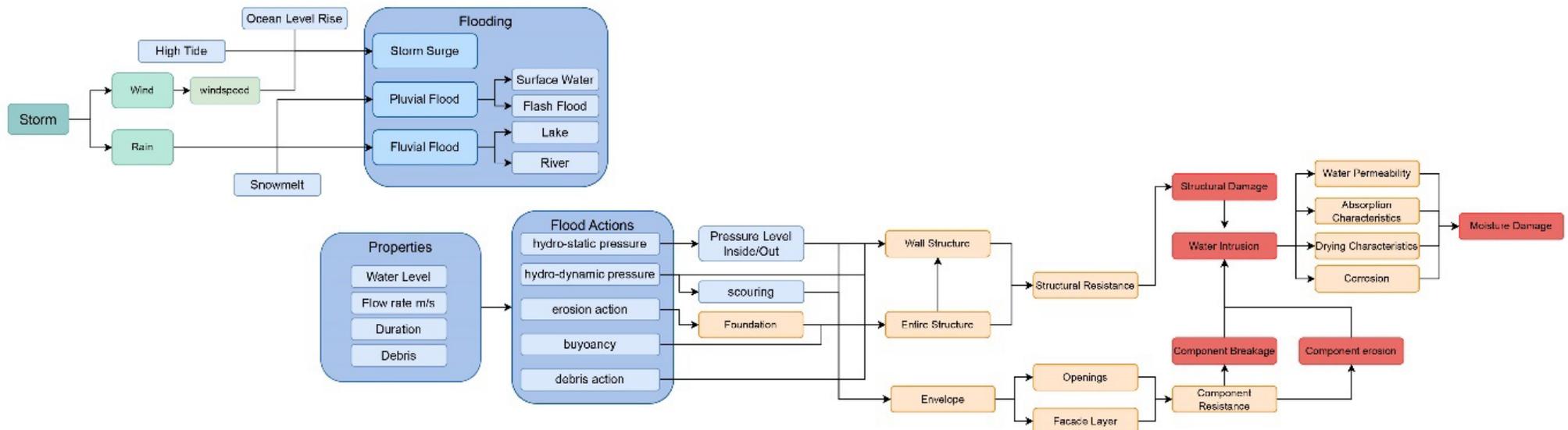


Figure 97 - Storm Hazard Flowchart (source: own)

induced by extreme rainfall independent from any water body. Surface water flooding results from drainage exceeding capacity, while flash flooding refers to an intense, high-velocity torrent of water potentially created by excessive rainfall or snowmelt. Fluvial flooding, in turn, relates to an overflowing body of water such as a river or lake. The rise of water levels can also potentially be due to rainfall or snowmelt (Zurich, 2024). Lastly, coastal flooding, also known as storm surge, is induced by windstorms, as the name indicates. Intense winds force water ashore, often coinciding with high tide (Amini & Memari, 2020).

Flooding can be natural, such as high drainage of excess water, or caused by human failure to intentionally manipulate flood protective infrastructure (ANV, 2022b).

On an urban scale, flooding can cause disruption and damage to critical infrastructure such as road networks, drinking water, and electricity, as well as

property damage and health-related impacts (AghaKouchak et al., 2020). The most common cause of death by flooding is drowning. However, other serious health threats include wounding, infectious and parasitic diseases, respiratory infections, skin or soft tissue infections, and exacerbation of non-communicable diseases. Health-related impacts are similar to or result from flooding coinciding with storms. After extreme flooding, morbidity will continue for at least 10 more days (Ebi et al., 2021).

Parameters that determine the severity of a flood are maximum water level, flow rate or speed, duration, and the creation of waterborne debris. There are several more relevant physical flood actions on a building. First, hydro-static pressure is a lateral pressure from the pure presence of water due to a flood depth differential between in and outside and capillary rise. Hydrodynamic pressure, however, refers to pressure from moving water. Water velocities change when water flows around objects and creates turbulence at corners.

Waves breaking on a building produce changing pressure levels. Water flow can also cause vortices on the upstream side of a building. Vortices then erode the soil close to the building, potentially down to the foundation level. Another action is buoyancy, a vertical force that uplifts and even flips the building. Lastly, waterborne debris driven by dynamic water flow impacts the building in terms of static, dynamic, and erosion actions. Effects like damming can even increase the water pressure further (Kelman & Spence, 2004; Wüthrich et al., 2025).

Flood-induced damages are almost inevitable once water levels reach the first floor. Damages mostly concern exterior walls and the foundation systems (Amini & Memari, 2020). Hydrodynamic pressure and vortices can scour the facade at corners and the foundation. Collisions from floating debris below water level can damage and break facade elements and openings. Like windstorm damages, initial damages to the facade or foundation can propagate cascading damages as water and debris enter the building. The water damages contents, interior finishes, or the screed (Wüthrich et al., 2025). However, hydrostatic pressure release also takes away lateral load on the structure (Kelman & Spence, 2004). Depending on the severity of a flood, partial or complete structural failure is not necessarily only due to lateral loads but also buoyancy or erosion (Wüthrich et al., 2025).

9.3.1 Dutch Context Flooding

Flood protection is a national responsibility in the Netherlands, with about 60% of the land considered flood-prone. As 26% of the land is below sea level and 29% of the land area is prone to river flooding, only 4% of the Dutch land area is not protected from flooding by dykes, dunes, and dams (ANV, 2022b).

Destructive flooding events in the past have given incentives for rigorous flood protection, such as the coastal flooding of 1953 in the province of Zeeland. The flooding affected about 600.000 people and led to 1.835 fatalities. The total damages would be 680 million euros today (ANV, 2022b).

In the Netherlands, fluvial flooding mostly concerns the three big rivers, Rijn, Maas, and Waal, or other bigger lakes like the IJsselmer. The flooding from the heavy rainfall in 2021 in Limburg and Western Germany is an exemplary event demonstrating the potential impact of the hazard (ANV, 2022b).

In 2022, the ANV modeled a 1-in-1000-year coastal flooding event and a scenario for 1-in-a-100-year fluvial flooding. Both include a dike breach along a big river or the coastline. While the consequences of extreme flooding are more severe in terms of affected area, fatalities, and cost, the causes of the impact are similar, hitting critical infrastructure and disrupting the distribution of basic needs. The predictability and ability to evacuate for both events are estimated to be low. Considering the extent and severity of expected loss, flooding events are more impactful than other hazards (ANV, 2022b). The likelihood of flooding from the sea is tightly linked to the rise in ocean levels. The KNMI predicts a rising sea level at the Dutch coastline of 16-34cm in a low global emission scenario and 19-38cm in a high emission scenario until 2050 (KNMI, 2023).

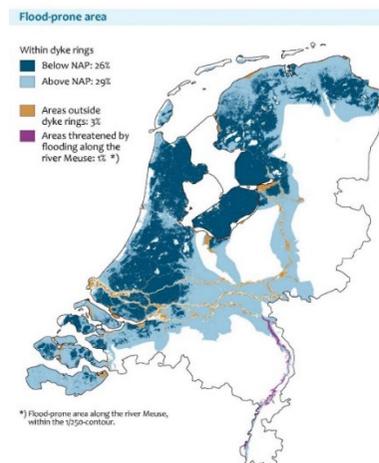


Figure 98 -flood prone area inside the Netherlands (source: (PBL, n.d.))