Land subsidence related damage to residential real estate and cost-effective adaptation strategies

From sinking to solutions: a methodological approach to assess the cost-effectiveness of adaptation strategies to counteract land subsidence related damage to residential real estate

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Preface

Civil engineers are the embodiment of an interdisciplinary field of practice where, amongst others, engineering, finance, business, policy formation, geography and sociology coalesce in relation to its ever changing environment. The report that lies before you is testimony to this nature. Exploring cost-effective adaptation strategies to counteract damage to residential real estate inflicted by land subsidence consequences is an excellent example of such a multidisciplinary project and as such makes for an ideal Master's thesis graduation project. The different fields are represented by the partners for this project: ABN AMRO bank (financial expertise), the municipalities of Dordrecht and Rotterdam (policy formation) and the TU Delft (engineering). Land subsidence related damage to residential real estate requires a technical understanding of how land subsidence causes damage and what drives it. It requires a financial understanding to estimate the cost figure of the damage, the price of adaptation measures and the impact on the financial situation of the residents, hence the interest of the bank. The financial outlook and engineering perspective on this issue provides an understanding of the situation that municipalities are confronted with. From there, policy formulation can start to prepare for and improve on the future situation. Something they can do by renovating or replacing the affected structures which leads to a negative net result when benefits are weighed against the costs. Adding extra square meters, and in the case of renovation also transitioning to an energy performance A-label can result in a positive net result and prove cost-effective adaptation strategies. For all stakeholders involved, this study has put forward two tools with favourable outcomes than can be applied individually or in combination depending on the physical situation and have the power to attract investment for realization of the adaptation strategy.

Acknowledgements

This endeavour would not have been possible without the considerable commitment of the committee. To the chair, professor Matthijs Kok, who acknowledged and encouraged my unconventional journey from the start and created an extraordinary opportunity for me by bringing all parties together. I thank you for your trust and unceasing enthusiasm. By advocating to take different perspectives on the matter, Dr. Zac Taylor helped grow my understanding and challenge my convictions continuously, a fruitful habit for which I am grateful. Dr. Ton van den Bremer completed this perfectly balanced committee through his ability to share his extensive economic understanding in a most convenient manner while also becoming a father during this period. You are most appreciated. Special thanks to Dr. Sandra Phlippen for the internship position with ABN AMRO Bank at the Economic Bureau but more importantly her open and inclusive character combined with an incredibly thorough scientific dissection of my approach. I would like to extend my gratitude to the whole of the Economic Bureaus, in particular Jeanine van Reeken for practical assistance and Bram Vendel for research input. It has been an absolute pleasure working with all of you. I am also thankful for Paul van Esch and Lisa Lieftink from the municipality of Dordrecht who have welcomed me and provided me with plenty of practical information and access to relevant data. I also had the pleasure of working with Dree Op ‘t Veld, Martijn de Jong-Tennekes and Andre Rodenburgh who were always eager to share whatever it was that could help this project.

In truth, nobody has been more important to me in the pursuit of this milestone than my family, friends and loved ones. This achievement would not have been possible without the unwavering support and sacrifices of my parents, the patience from my girlfriend and necessary distractions by my friends. Lastly, I would like to dedicate this report to my late grandfather Ben Klein-Gebbink, an inspiration to pursue academic development. I thank all of you for your unique contributions.

Abstract

Land subsidence poses significant damage risks to residential real estate, including pile rot, differential settlements, pluvial flood risk, and dewatering risk amounting tens of thousands of euros. In the Netherlands, the number of affected houses has surpassed one million and is estimated to reach two million, accounting for a quarter of all houses in the country. Without an action perspective homeowners are left to their own devices which this research shows can lead to postponing action until risks materialize. To mitigate these risks, multiple adaptation strategies are available. This thesis focuses on determining the cost-effectiveness of two general pathways for residential real estate constructed with either a wooden pile foundation or a shallow foundation: renovating existing houses or replacing them entirely. The study also investigates whether incorporating additional measures aimed at improving overall benefits such as increasing the amount of living space or transitioning towards a more sustainable house with energy label A, is cost-effective by comparing the costs and benefits associated with the adaptation strategies. When the benefits outperform the costs the strategy is labelled favourable. Through a comprehensive analysis, this research provides valuable insights into economically viable approaches for addressing land subsidence-related risks in residential real estate in relation to the location specific characteristics. It proves additional measures are required to make either renovation or replacement a cost-effective adaption strategy. Two options are shown to be cost-effective. Firstly, renovation including additional investments to increase square meters of living space and transitioning to an energy performance A-label. Secondly, replacement including densification by building back more square meters of living space, increasing the amount of houses or a combination of the two. Both require large investments resembling around 75% to 150% of the current housing price respectively. Increasing the amount of square meters even further improves the result however this increasingly affects the character of the neighbourhood and its social composition. With these results, this thesis hence provides an action perspective to homeowners and stakeholders including policy makers and financial institutions by means of a solution space to address land subsidence in an economically favourable way, whilst simultaneously reflecting on the differences in implications for the parties involved.

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1 Introduction

1.1 Context

Land subsidence, defined as ‘the mainly vertical downward displacement of the Earth’s surface’ (Marker, 2015) has great effect on people, property and environment. When superimposed loads, both natural and man-made are combined with insufficient support from the soil land subsides. Mostly relatively slow, this settlement process causes direct damage such as structural damages to infrastructure and buildings both in and on the ground but also indirect damage in the form of increased flood risk as rainwater accumulates in subsided areas as a result of elevation losses (Kok & Costa, 2021) notably extreme weather events in Dordrecht in 2015 and 2020 (DordtCentraal, 2020) resulted in partial flooding of the old inner city, which was constructed on subsided soil.

Other effects include salinization of quays, draining, loss of productivity of peatlands, CO2 emissions due to oxidation, brackish water and flooding due to the diminished storage capacity of the soil. These effects are particularly concerning in urbanized coastal areas in the Netherlands, where flood risks are already relatively high. Moreover, urban areas built on settlement-prone soils like peat or clay face additional challenges. Although no comprehensive global damage reports are available, Deltares (2013) estimates that this worldwide phenomenon costs billions of dollars annually, underscoring the significance of land subsidence as "one of the world's underrated problems."

The Netherlands, with its abundance of urban development on soft soils near rivers and coastal regions, faces substantial risks related to foundation issues due to its unique physical characteristics (Schothorst, 1977). Groundwater extraction for industrial and domestic purposes (Kok & Costa, 2021) and lowering the groundwater table for agricultural needs (Willemse, 2018) constitute the primary drivers of these settlements. One such area affected by land subsidence is the province of Zuid-Holland, where approximately 75% of the region is susceptible to settlements (Provincie Zuid-Holland, 2016). Around 25% of this area consists of peat soil, which is prone to oxidation due to groundwater level reductions. As the ground level experiences downward displacement, water boards are compelled to lower the groundwater level further to prevent building submersion and ensure residents' safety. This self-perpetuating process is irreversible and necessitates a well-founded long-term vision for managing its consequences.

An increasingly evident consequence of land subsidence in the Netherlands is its impact on real estate. Historical buildings constructed between the 16th and 20th centuries were predominantly founded on shallow foundations, which transfer the building's load almost directly to the soil at the earth's surface. This becomes problematic because the top layer of soil is susceptible to subsidence. Unlike artificial materials such as steel or concrete, soil is an organic material with high heterogeneity, leading to uneven settlement across the foundation. Consequently, structures founded on shallow foundations settle with the soil, resulting in walls tilting in various directions. The inability of structures to deform flexibly can lead to brittle cracks in walls, causing damage to the property. To address this issue, buildings constructed until approximately 1970 were founded on deeper, less settlement-prone soil layers using wooden piles (Rijksdienst voor Ondernemend Nederland, 2022). Still we find around 3,8 million houses constructed before 1970 (KCAF, 2018)

In recent years, most buildings have been constructed using concrete piles instead of wooden piles due to the significant drawback of wooden piles. The combination of groundwater table lowering and land subsidence has partially exposed the previously submerged piles. This exposure to oxygen leads to pile rot in wooden piles, reducing their bearing capacity and weakening the foundation. In extreme cases, structural failures can occur but fortunately this is a gradual process with various warning signs such as cracks in masonry, jammed doors and windows, structural skewness, water accumulation, and elevation differences with neighbouring structures. Maintenance becomes necessary for foundations over time, which is a costly, complex, and potentially risky operation as mistakes or unforeseen circumstances can cause (partial) collapse, as observed in Amsterdam in (Tienkamp, 2015) and (Obdeijn, 2021), and (NOS, 2023) this year.

According to researchers from Deltares, without intervention the estimated cost to repair all land subsidence damages on weak soils in the Netherlands from 2013 to 2050 lies between €5 and €39 billion, increasing with €3 to €15 billion because of climate change (Kok & Angelova, 2020), see Figure 1. A decade later, the Kenniscentrum Aanpak funderingsproblematiek (KCAF) estimates that at least 1 million residential homes in the Netherlands currently face or will face foundation issues due to land subsidence, with the number expected to increase (van Capelleveen, 2021). Other studies that include anaerobe bacterial deterioration of wooden piles, earthquakes and tectonic movements estimate the total amount of repairs to cost between €5 and €60 billion ((Born, et al., 2016; Hoogvliet, et al., 2012; Leusink, 2018; Workum & Jong, 2019; KCAF, 2018) This study aims to analyse the costs of several adaptation strategies and compare them to the anticipated cost savings through risk reduction, providing context to the estimates by Deltares and KCAF.

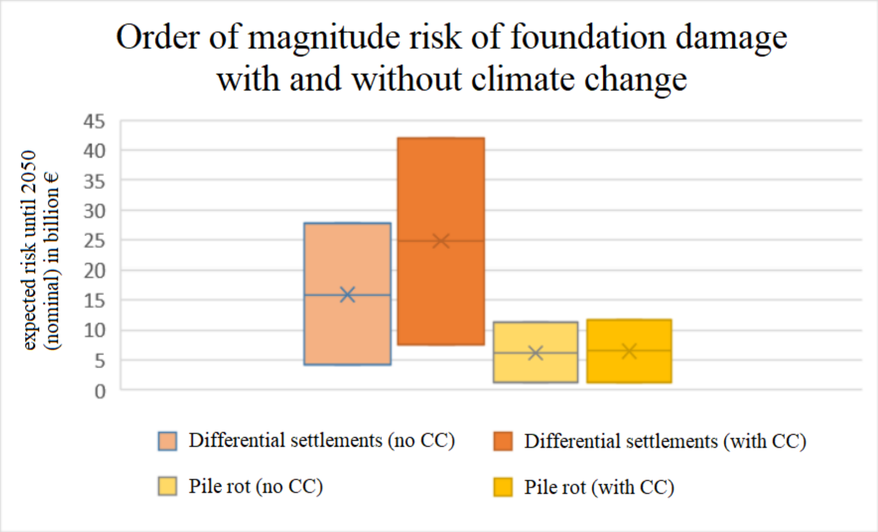

Figure 1: Order of magnitude risk of foundation damage with and without climate change (Deltares)

Climate change plays a significant role in exacerbating this problem. The Intergovernmental Panel on Climate Change (IPCC) warns of increased global warming and associated climate change, resulting in more extreme weather conditions like prolonged droughts and heavy rainfall (IPCC, 2023). These extreme rainfall events have caused floods in Dordrecht in recent years, leading to temporary flooding of numerous properties, as witnessed in 2020 with over 80 reports of flooding in Dordrecht alone (den Toom, 2020), see Figure 2. Although data on damage costs are unavailable, these developments not only increase the potential for damages but also expand the affected areas. The KCAF discovered an alarming trend during a prolonged drought, where notifications of foundation issues significantly increased even outside designated "risk areas," like those with peat soils (2018)

Figure 2: Pluvial flooding of Dordrecht in 2020 (AD)

Many homeowners are unaware of the issues affecting their property until visible damage occurs, which is problematic for foundations since visual inspections are difficult. Homeowners often don't realize that they bear the sole financial burden, which can amount to 30% of the property value (Klaassen, 2015). The Autoriteit Financiele Markten (AFM), the financial services regulator, has warned that since 2021, even the four insurance providers that previously covered housing subsidence risks with an average of €64,000 in damages have discontinued this policy ((AFM, 2021)). Under the assumption of full information and rational decision-making, the housing market would account for this underlying risk, leading to discounted housing prices.

However, related studies on areas prone to flooding (instead of land subsidence) have shown that flood-prone areas exhibit information asymmetry (Votsis & Perrels, 2016)and observed price discounts after a flood to diminish over time (typically a decade) due to evolving risk perceptions ((Atreya, Ferreira, & Kreisel, 2013; Bin & Landry, 2013; Mutlu, Roy, & Filatova, 2023) Mutlu et al., 2023). Similarly, information asymmetry exists regarding foundation conditions. Reports of foundation defects lead to discounts resembling restoration costs, but information on the foundation is only provided for 1 in 40 houses (Phlippen & van Reeken-van Wee, 2023).

Trigger events such as floods immediately impact the housing market by causing price shocks and discounts. These shocks can destabilize both the public and private sectors, as they heavily depend on a strong housing market ((Beltrán, Maddison, & Elliot, 2019; Bishop, et al., 2020). Land subsidence increases the risks of both foundation issues and flooding, but these risks are not efficiently accounted for in the housing market. This allows trigger events to materialize these risks through immediate discounts and manipulate the housing market.

Understanding the risks posed by land subsidence on housing prices is crucial not only for homeowners but also for policymakers and private investors, including mortgage lenders and insurance providers.

becoming increasingly apparent. Financial institutions such as De Nederlandsche Bank (DNB) are implementing new methods to analyse and mitigate financial risks related to climate change (DNB, 2020)Following the guidance of the Taskforce on Climate-related Financial Disclosures (TCFD) established by the Financial Stability Board (FSB), international organizations are collaborating with national-level financial institutions, including banks, to map out and address the effects of climate change on the financial sector. Banks, for example, are impacted by the increased risk of land subsidence due to climate change, as it affects the value of residential housing collateral for outstanding mortgages when foundation quality deteriorates (Feldkamp, 2022). Clients and their mortgage providers can face challenging situations when confronted with the costs. It is crucial for banks to understand the current state of their portfolios and the long-term dynamics. However, many banks have a relatively short investment horizon (Livne & Mironov, 2011), while land subsidence is a slow process that requires a longer-term perspective.

Governmental institutions, including local authorities, indirectly experience the impact of land subsidence through sudden drops in housing prices and the resulting consequences for residents. The socio-economic impact of land subsidence is often overlooked. According to Kok and Costa (2021), property owners are discouraged from disclosing damage information. Policy formation to address land subsidence is complicated due to unclear responsibilities regarding damage recovery from resource extraction, such as groundwater extraction (Galloway, Jones, & Ingebritsen, 1999). Consequently, property owners tend to sell properties without investigating the effects of land subsidence on foundations or flood risk. The lack of policy formation and urgency surrounding land subsidence, exacerbated by climate change, necessitates attention although housing markets do not display the same sense of urgency.

Technical interventions to address underlying causes (mitigation) or prepare for current and future impacts (adaptation) of land subsidence are often readily available but onerous to implement as land subsidence is inseparable from its complex social context consisting of many stakeholders with varying interests (Bucx, et al., 2019). To effectively address land subsidence, awareness of the channels of impact is crucial.

This study focuses on analysing various adaptation measures for land subsidence in urban areas, using the 6M approach developed by Erkens and Stouthamer (2020). A practical case study is conducted in four urban areas with specific land subsidence problems. Following the 6M approach, a cost-benefit analysis (CBA) is employed to evaluate the adaptation strategies in the case study areas.

Since there are no existing guidelines for a land subsidence specific CBA (Kok & Costa, 2021), the Dutch-developed "Maatschappelijke kosten-en batenanalyse" (MKBA) is utilized. This social cost-benefit analysis (SCBA) approach has been extensively tested and implemented in various projects such as the Nieuwe Zeesluisijmuide and the Koning Willem-Alexandertunnel, providing a comprehensive assessment of financial and societal costs and benefits (Romijn & Renes, 2013). According to Mouter (2013)It helps to prioritize strategies, determine the sensibility of realisation and enhance understanding of the issue. This is beneficial for financial institutions and local authorities, aiding in prioritizing strategies, evaluating feasibility, and enhancing understanding of the issue.

The case study areas of interest are located withing the municipalities of Dordrecht & Rotterdam. Research of these areas can reveal environmental hazards like land subsidence and its consequences or even the knowledge that a certain area is investigated for such hazards carries the potential to affect public perception of risks in these areas. Although dependent on the resilience of the housing market and overall economic conditions, revealing the exact locations can lead to devaluation of housing prices in the area. Therefore, only the location-specific characteristics of the four case study areas, two in Dordrecht and two in Rotterdam, are utilized.

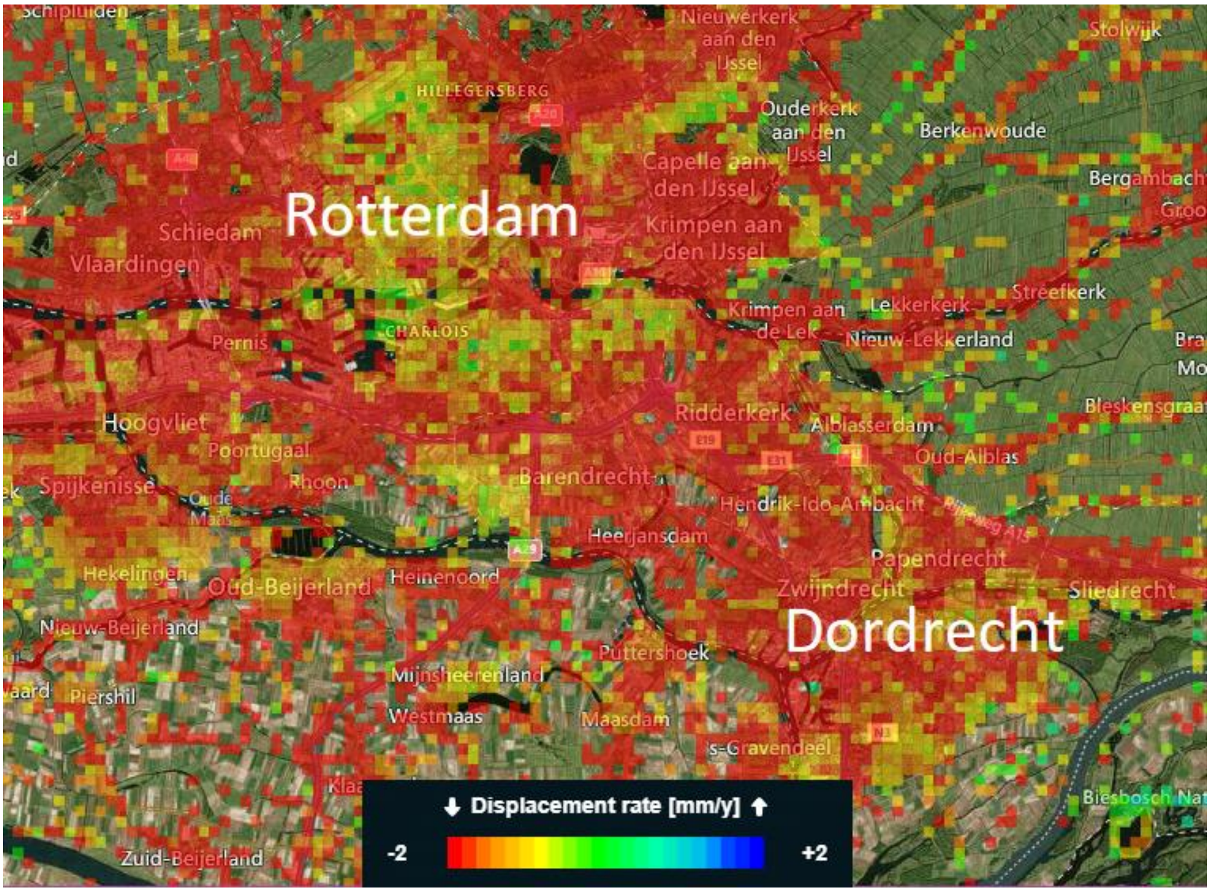

Figure 3: Land subsidence in Rotterdam and Dordrecht (Bodemdalingskaart 2.0)

Consulting the Bodemdalingskaart2.0 with the legend set to a minimum of 2 mm/y displacement (red) the map in Figure 3 shows both Dordrecht and Rotterdam generally satisfying this requirement as the urban areas on the map colour nearly entirely red (NCG, 2023). The case study areas consist of different types of properties with specific characteristics such as foundation or housing type. Also, the choice for the designated case study areas was made for practical reasons as both local authorities (and have shown active interest in addressing land subsidence in their respective municipalities (Hendriks, 2023) and are willing to cooperate in sharing data, insights and findings from previous work on this topic. Furthermore, conversations with officials can substantiate the CBA.

1.2 Problem statement

Although land subsidence is a very gradual process and therefore does not pose an immediate threat, it's consequences can be of great concern to health, safety and indirectly to economic stability. A loss of elevation can cause multiple precarious situations. Focussing on effects of land subsidence on residential real estate in urban areas we introduce the four main effects in this subchapter:

1. Pile rot
2. Differential settlements
3. Increased pluvial flood risk
4. Increased dewatering risk

Buildings typically rely on pile foundations to transfer their load to stable soil layers deep underground. Earlier constructions used wooden or shallow foundations, each with their own undesirable outcomes. Since around 1970, concrete piles have been predominantly employed, while remaining structures with wooden piles or shallow foundations are relatively old (50-100 years) and have endured the gradual effects of land subsidence for a considerable period.

Wooden pile foundations do not settle with the soil surface as these piles rest firmly on top of the deeper lying load bearing layer on which they are funded. Unfortunately the wood from which the piles are made is susceptible to fungal decay. White rot and brown rot are considered to be most problematic. Brown rot starts causing it to crack and shrink whereas white rot affects the inside of the pile without any external give-aways (Klaasen, 2013). Fungal deterioration occurs when groundwater levels drop below the tip of the piles and oxygen enters the wood. Groundwater fluctuates in time which means it can temporarily drop below the pile tip. Even worse, the general trend of the groundwater can be downwards sloping causing the groundwater to permanently drop below the pile tip. When the pile is submerged the rotting process is halted only to be continued when the pile tip is oxygenated again. The wood is unable to regenerate so the cumulative dry standing time is linear to the total fungal decay. After enough time, this process can cause collapse of the foundation.

Properties with a shallow foundations are extremely prone to land subsidence effects as the property is constructed directly on top of the soil surface. The property is forced to follow the deformation of the surface as it subsides but is not always able to do so. When land subsides evenly over time, so does the structure and damage can be avoided. However, when uneven settlements occur the inflexible structure cannot reflect the irregularities and cracks appear in the brickwork. In extreme cases a continuation of this process can lead to collapse.

Local discrepancies in elevation and elevation losses over time can lead to the formation of water retaining areas. During peak rainfall the amount of water that is deposited on the surface can become larger than the area is able to discharge (Figure 4). As water flows towards the lowest point under gravity certain low laying areas within a city can become flooded. This type of pluvial flood is called a surface water flood. Water flows out into the streets and when high enough can enter properties. The flood is very slow rising and is very unlikely to exceed 1,0 meter but instead rises a few centimetres to a few decimetres. Still the economic damage to properties can be significant.

Figure 4: Pluvial flooding in urban areas (Wageningen University & Research)

A loss of elevation in combination with too high groundwater levels can instigate wet or damp basements and crawl spaces (Waternet, 2020). Occurrences such as heavy rain or drainage problems can cause the groundwater to rise too high and/or to rapidly. The soil underneath and around the property becomes saturated and moist can infiltrate floors and walls leading to structural damages.

Land subsidence in residential areas has been observed throughout literature and proven to be impactful. The necessity for adaptation seems indisputable. But effective implementation of such measures cannot go without an understanding of governance aspects (who is responsible), financial aspects (who is paying and who is gaining?) and the interaction between physical characteristics of the affected area and optional adaptation measures

To summarize, the scope of this research concerns pile rot, differential settlements, increased pluvial flood risk and dewatering risk as the main unsettling consequences of land subsidence in urban areas. These issues pose significant risk of property damage, impacting multiple stakeholders such as homeowners, residents, housing associations, mortgage providers and local and national governments.

1.3 Knowledge gap

The understanding of the physiological mechanisms of land subsidence and its detrimental impact on property is well-established. Recent literature has also highlighted the role of climate change as a driver of land subsidence, increasing the urgency for adaptation. However, selecting an appropriate adaptation strategy can be challenging, as there is currently no framework that considers the societal context in which the strategy will be implemented.

Effective adaptation strategies aim to mitigate risks associated with land subsidence, such as pile rot, differential settlements, groundwater infiltration, and pluvial flooding. In practice, two approaches can be pursued: extensively modifying existing structures or constructing new ones that meet the desired requirements. These interventions involve significant costs and disruption. Exploring additional measures that may require more resources and time, but yield overall benefits, can be advantageous. The success of adaptation strategies, with or without additional measures, depends on localized characteristics and their associated costs and benefits.

Building upon existing research on the cost of land subsidence risk to real estate this thesis focusses specifically on the interaction between local parameters and the cost-effectiveness of different adaptation strategies for residential housing. An effective measure not only maximizes net gain or minimizes loss but also ensures that the benefits are distributed to stakeholders who bear the costs. Aligning beneficiaries and benefits will be discussed in further detail.

1.4 Research questions and objective

This study aims to narrow the knowledge gap by analysing adaptation measures in three different locations and assessing their interaction with the local environment. The findings from this study can be applied to other areas as well.

By deploying an SCBA of the various land subsidence adaptation strategies this study aims to evaluate the cost effectiveness of the measures in relation to local characteristics of the case study areas in Dordrecht and Rotterdam. By estimating the localised land subsidence related damage to real estate and comparing it with the cost per adaptation strategy the research aims to answer the following **research question:**

What constitutes a cost-effective adaptation strategy to land subsidence related damage to residential real estate?

The objective is to develop a comprehensive understanding of how land subsidence contributes to foundation issues and pluvial flooding in urban areas, while considering the influence of local disparities on the effectiveness of adaptation strategies. The study goes beyond viewing land subsidence as solely a technical or a financial matter and examines its impact and efficacy within the local societal context. To support this objective, the following sub-questions are addressed:

Sub-question 1: How to estimate the risk of land subsidence as a combination of foundation risk and increased pluvial flood risk?

Sub-question 2: What adaptation measures, possibly in combination with additional interventions to increase net-benefit, can be taken to address land subsidence related damage to residential real estate?

Sub-question 3: What is the net-benefit per adaptation strategy for each of the four case study areas?

This interdisciplinary study addresses land subsidence as a complex issue involving engineering, economics, and policy formation. By answering the research question and sub-questions, it offers a valuable tool for understanding, decision-making, and policy development related to the impact of land subsidence on residential real estate. The findings are relevant for various stakeholders, including local and national governments, mortgage providers, real estate developers, urban planners, and investors. The study aims to bridge the gap between these professional fields and foster a shared understanding of land subsidence and potential adaptation strategies, highlighting its multidisciplinary nature.

2 Theoretical Framework

This study draws from the 6M approach to land subsidence (Erkens & Stouthamer, 2020) to evaluate adaptation strategies to land subsidence related damage on residential real estate. This structured approach consists of six distinct steps:

1. **M**easuring
2. Understanding the **M**echanisms
3. Predictive **M**odelling
4. **M**oney (CBA)

~~5. Implementation of **M**easures~~

~~6. **M**onitoring and evaluation.~~

The core focus of this study is developing a well-structured framework for a CBA as a tool for understanding, decision making and policy formation. For such a CBA with regards to land subsidence no guidelines exist (Kok & Costa, 2021). Although implementation and monitoring the evaluation of any measure is outside of the scope of this research, we utilize structured method of the 6M approach to arrive at a logically constructed and scientifically based method for doing the CBA. This is supported by a climate risk model initiated by ABN AMRO called ICEBERG. The theoretical framework is applicable to all four case study areas.

2.1 Measuring

Firstly the physiological phenomena that cause risk of damage to property are to be measured to determine their presence and rate of impact. For the scope of this study these consist of land subsidence, heavy rainfall and fluctuating groundwater levels.

2.1.1 Land subsidence

The initial step is to determine the presence and rate of land subsidence, typically measured in mm/year. Land subsidence can be natural or human-induced, with human-induced rates generally higher (Erkens & Stouthamer, 2020; van Asselen, et al., 2018). Structural damage such as cracks or tilting may indicate subsidence, but a more accurate assessment can be made using Bodemdalingskaart 2.0 (NCG, 2023), a spatially resolved subsidence map of the Netherlands (Heuff, van Leijen, Mulder, Samiei-Esfahany, & Hanssen, 2019) showing deformation rates generated by combining Persistent Scatterer InSAR, GNSS and gravimetry measurements. Figure 3 in the previous chapter already shows Dordrecht and Rotterdam facing a minimum downward displacement of at least 2 mm per year. More granular data on case study area level reveals the land subsidence rate per year for a specific location for an area with a 10 meter radius. Figure 5 below displays the downward displacement graph for one of the Rotterdam areas, representing a model fit based on multiple measurements over a period of at least five years.

Point ID	[redacted]
Linear displacement rate	-4.3 mm/y
Quality	0.65
Point height	-1.3 m
High res DEM height	-0.6 m
No. observations	152

Figure 5: Linear Displacement rate for a case study area 1 in Rotterdam

2.1.1 Pluvial floods

During periods of intense precipitation, if the rate of water inflow surpasses the combined rates of infiltration and engineered drainage, water accumulation occurs in urban areas, leading to flooding. The Klimaateffectenatlas, a website managed by the Climate Adaptation Measures foundation (CAS), provides information on water depth during heavy rainfall in the Netherlands (CAS, 2023). The map utilizes a Rainfall Overlay from Tygron, incorporating elevation data, terrain roughness, and representations of sewer and water systems (Tygron, 2023). The precipitation events are based on a hydrological model and include two extreme showers with average return periods of 100 and 1000 years. The first event has an intensity of 70 mm of rain in 2 hours, while the second has an intensity of 140 mm of rain in 2 hours, corresponding to annual probabilities of 1% and 0.1%, respectively. The map also considers three climate scenarios (current, 2050 low, and 2050 high) to account for the impact of climate change on extreme weather events. However, for the areas of interest (Rotterdam and Dordrecht), the differences in flood depth among these scenarios are negligible, less than 1 cm. Figure 6 illustrates the resulting water depths for a 140 mm in 2 hours rain event.

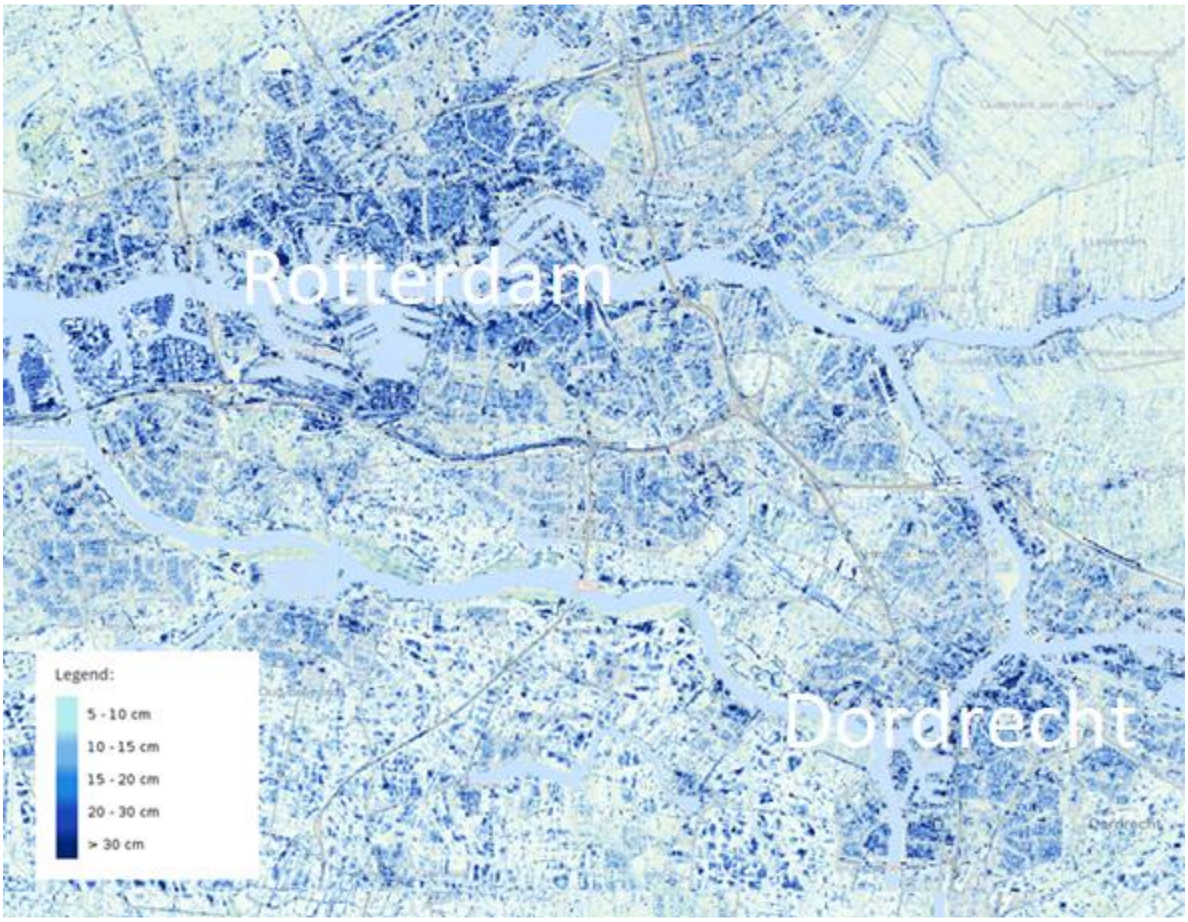

Figure 6: Inundation height after 140 mm of rain in 2 hours for Dordrecht and Rotterdam (Klimaateffectenatlas)

The map simulation time of 2 hours of uniform rain followed by 4 dry hours. Pluvial flooding in urbanized areas is most common during short but intense showers because infiltration is very limited due to unexposed soil. This makes run off and thus accumulation relatively fast. Therefore the short simulation time for high intensity rainfall used in the Klimaateffectenatlas is fitting. Interaction with surface water is neglected due to the short simulation time.

2.1.3 Groundwater levels

Groundwater levels have a significant impact on foundations, with low levels causing pile rot and high levels seeping into the superstructure. Managing groundwater levels is crucial yet complex, influenced by factors such as land subsidence, rainwater discharge, evaporation, and soil permeability. Waterbodies like canals and lakes also affect groundwater levels by infiltrating the soil. Maintaining submerged pile tips while raising groundwater levels to reach the superstructure requires monitoring wells in urban areas. The municipalities of Dordrecht and Rotterdam provide this data. The data from measurements all across the country have been combined in the Nationaal Water Model (NWM) to produce, amongst others, the GLG (Gemiddeld Laagste Grondwaterstand) and GHG (Gemiddeld Hoogste Grondwaterstand) in meters relative to soil surface (Nationaal Georegister, 2010). The GLG and GHG are calculated by averaging the three lowest or highest groundwater level measurements per year over a minimum of eight years. The NWM also predicts GLG and

GHG changes for 2050 under the WH8.5 climate scenario (Informatiepunt Leefomgeving, 2020). Figure 7 displays the current GLG for the Dordrecht-Rotterdam area.

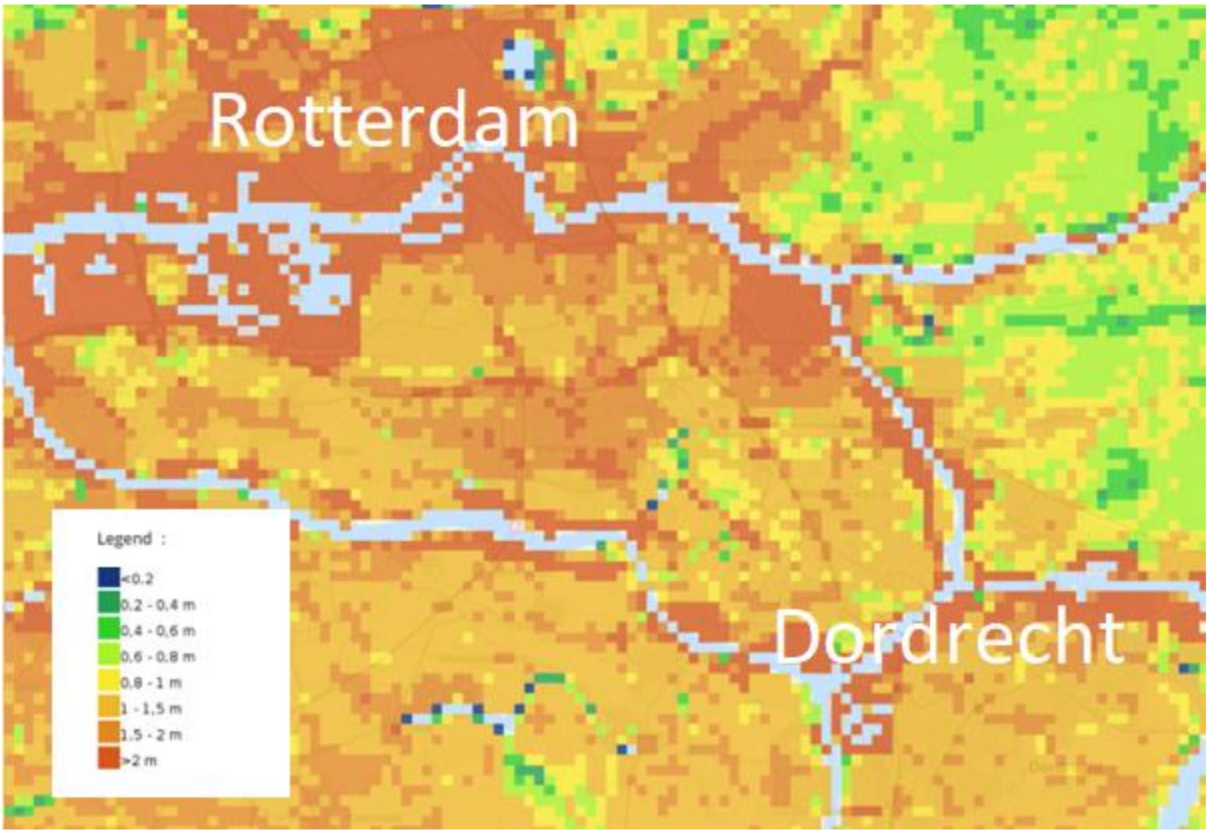

Figure 7: GLG in Dordrecht and Rotterdam relative to ground surface (Nationaal Water Model)

The GLG is used to determine the risk of pile rot whereas the GHG is applicable to estimate dewatering risk. For both parameters the expected change for 2050 under the assumption the WH8.5 scenario is available.

2.2 Understanding Mechanisms

The second step in the 6M approach is describing and illustrating the mechanisms at play. The three drivers (Land subsidence, pluvial flooding and groundwater levels) from the previous paragraph all relate in their own way to residential real estate damages. For each of the four consequences mentioned under 1.2 Problem Statement (pile rot, differential settlements, increased pluvial flood risk and increased dewatering risk) the interaction mechanism between drives and consequences is discussed.

2.2.1 Pile rot

The rotting of piles occurs when oxygen can reach the wooden piles of the foundation. For this reason it is not applicable to shallow foundations. Blue stain, soft rot, white rot and brown rot eat away at the wood leading to fungal decal. The latter two are considered to be most problematic. Brown rot starts feeding on the cellulose and hemicellulose of the wood causing it to crack and shrink visibly. White rot feeds on cellulose and lignin without any external give-aways (Schreurs, 2017) see Figure 8. When the wood cells are destroyed the piles loose baring capacity until they collapse. Fungi require oxygen to be active so fungal deterioration only occurs when groundwater levels drop below the tip of the piles and oxygen enters the wood. If this is the case, the entire pile is at risk of rot as the fungi are able to eat through the core of the pile. With fluctuating groundwater levels the fungal deterioration of the piles becomes a binary process whereby dry standing pile tips decay until the groundwater levels increase beyond the pile tip and the process is halted. However, the pile tip cannot regenerate and so the process of deterioration has a linear relation with the cumulative unsubmerged time. When the pile has been unsubmerged for long enough, the wood has been affected too greatly and cannot hold the weight of the superstructure resulting in a (partial collapse).

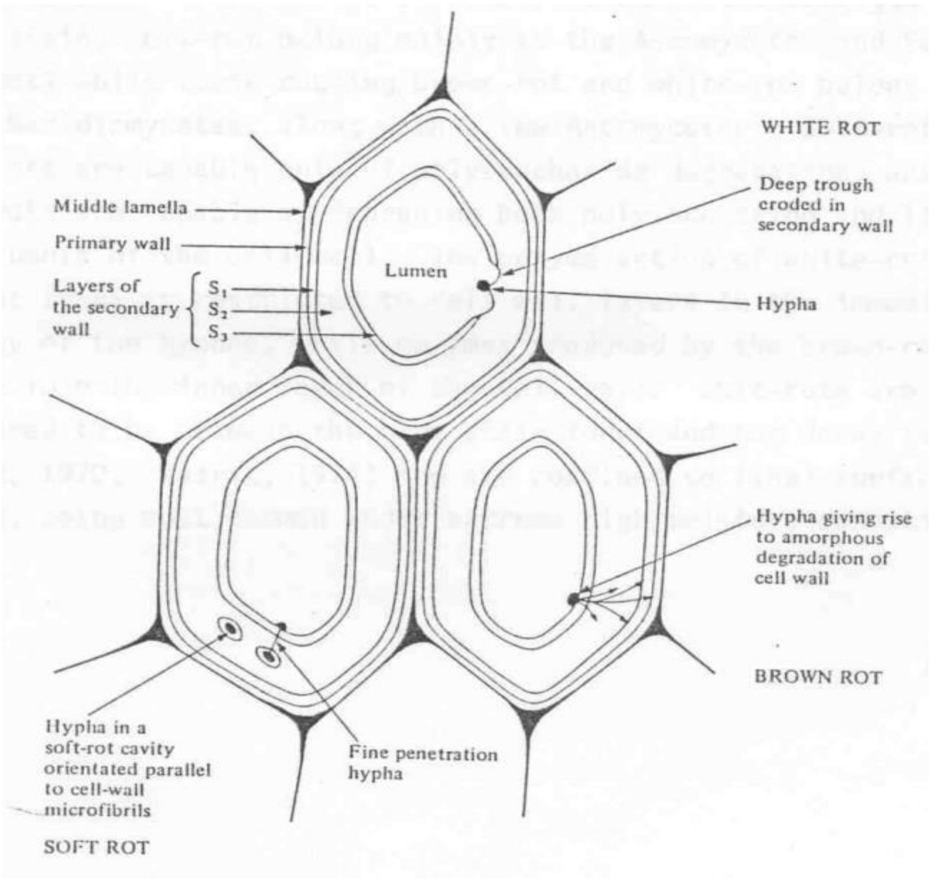

Figure 8: Diagram of wood cells in transverse section showing patterns of degradation produced by three types of wood decay fungi (Montgomery, 1982)

Pluvial flooding indirectly impacts pile rot by influencing groundwater levels, typically rising due to water infiltration in soil. However, in urban areas with extensive pavement, infiltration capacity is reduced. Land subsidence itself does not directly affect pile rot, but lowering groundwater levels in specific areas to mitigate dewatering can result in dry standing pile tips in wooden pile foundations. Consequently, groundwater levels play a pivotal role in determining pile rot. Please refer to Figure 9 for a schematic illustration of the situation.

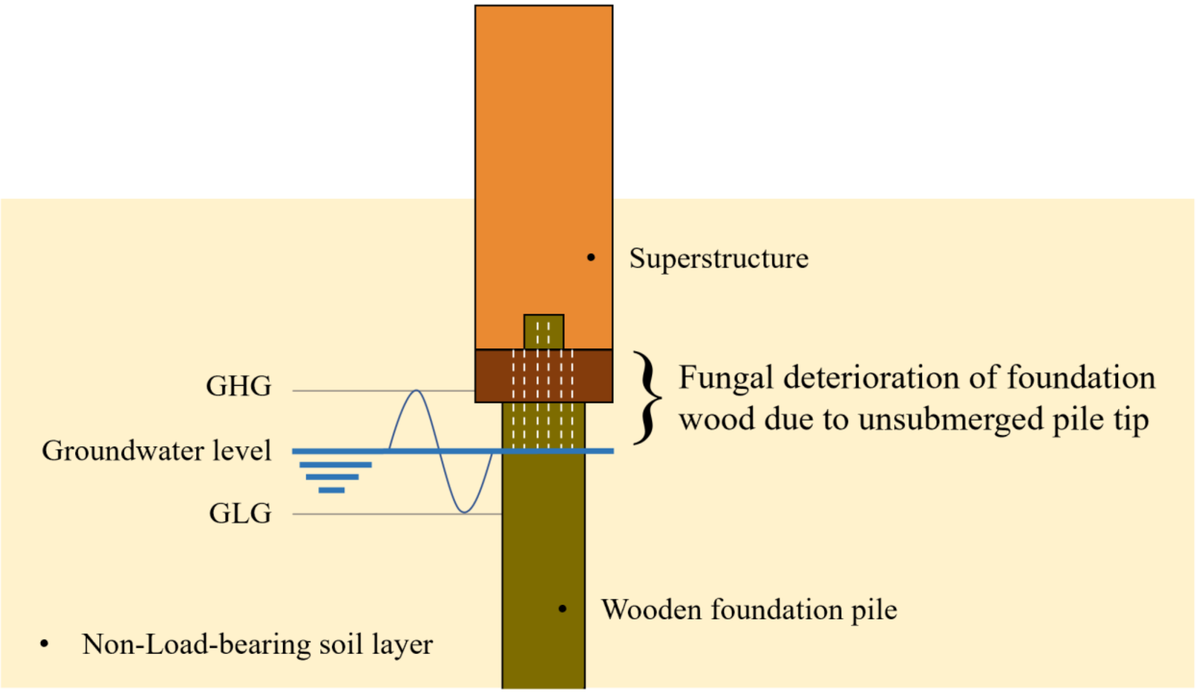

Figure 9: Schematization groundwater level fluctuations in relation to pile rot in wooden pile foundations

2.2.2 Differential settlements

Residential real estate that is not constructed on top of a pile foundation (or any sort foundation for that matter) but instead is built directly on the soil have to deal with settlements. As long as the complete soil surface underneath the structure settles equally fast the structure is simply lowered with little structural consequences. Unfortunately, in practice we find plenty examples of uneven subsidence, referred to as differential settlements.

Human-induced subsidence can mostly be attributed to the withdrawal of hydrocarbons and groundwater, loading of soft soils and shallow groundwater table lowering. Urban areas specifically, are subject to a combination of anthropogenic loading and shallow groundwater table lowering (van Asselen, et al., 2018). See Figure 10 below for an overview of human-induced subsidence.

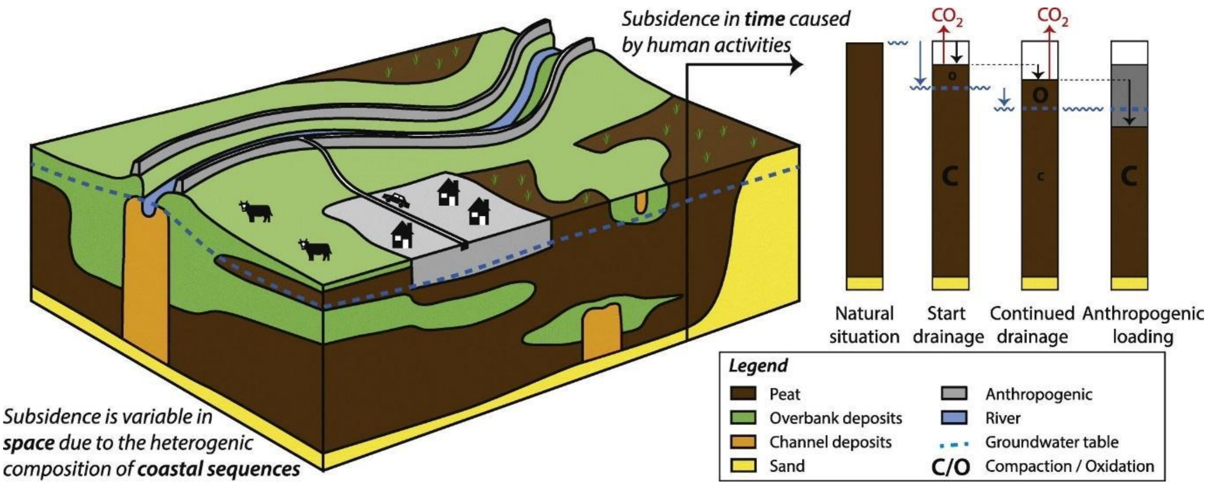

Figure 10: Human-induced subsidence of peat soils

In the Netherlands, land subsidence is significantly influenced by interactions with peat layers in the soil via peat oxidation, compaction, or mining. Peat oxidation occurs when the groundwater level falls below the top of the peat layer, causing the exposed peat to react with oxygen, settle, and release CO2. This subsidence process is often caused by human activities, such as artificial groundwater lowering through drainage systems, and is further intensified by climate change-induced droughts. Additionally, loading of the soil due to construction and transportation activities accelerates subsidence rates.

Differential settlements lead to deformation in structures with shallow foundations, particularly inflexible and rigid structures like brick houses. Damage initiates with minor plaster cracks and slightly sticking doors and windows, progressing to leaning walls, significant cracks in brick walls, and compromised load-bearing capacity of beams (Korff, 2019). Consequently, substantial repairs or even partial rebuilding becomes inevitable.

Land subsidence is the primary driver for differential settlements, although pluvial flood events do affect groundwater levels, which in turn influence soil settlement rates. However, when considering the consequences, it is crucial to focus on land subsidence itself. Please refer to Figure 11 for a schematic representation of this mechanism.

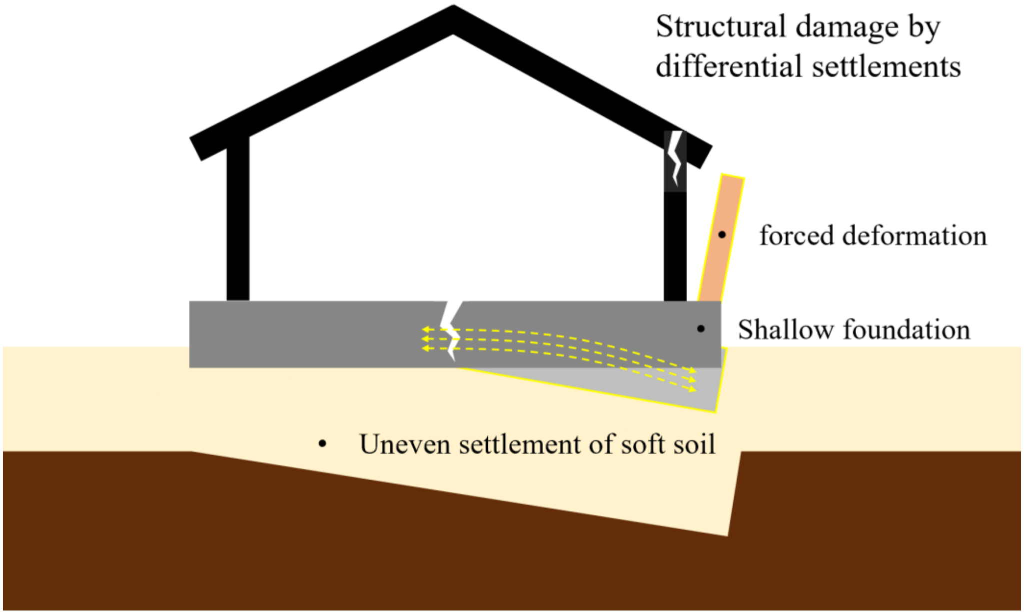

Figure 11: Schematization of differential settlements affecting residential real estate with shallow foundation

2.2.3 Increased pluvial flood risk

The loss of elevation caused by land subsidence can lead to increased risk of flooding. The loss of elevation compared to mean sea level (MSL) increases potential damage during coastal or river floods. The risk of flooding for coastal and river flooding is always apparent and is mitigated by primary flood defences like storm surge barriers, dunes and dikes. Subsidence of urban areas does not increase the probability of this type of flood merely the consequence (see Figure 12). The consequence of such a flood would already be very severe. The addition of land subsidence to this type of flood risk is marginal. For the scope of this thesis increased coastal and river flooding risk is omitted.

Figure 12: Storm surge illustration

Risk of pluvial flooding (flooding during an extreme precipitation event) on the contrary, is included. With inundation heights between between 0 cm and 30 cm for the areas of interest in this study (CAS, 2023), land subsidence can make all the difference in a property to be flooded or not (see Figure 13) and thus its relative contribution is fairly large and cannot be neglected for purposes of this research.

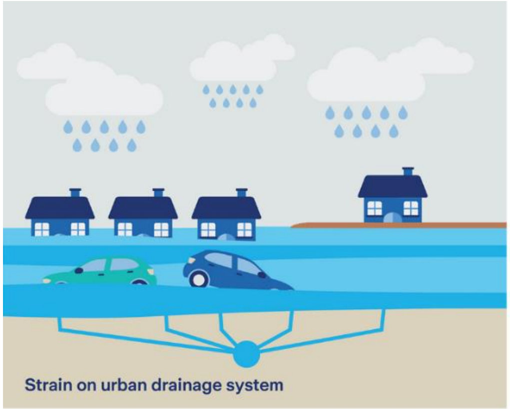

Figure 13:Pluvial flood illustration

In urban areas, pluvial floods occur when rainfall runoff exceeds the capacity of the sewer system (Rosenzweig, et al., 2018; Meng, et al., 2019), posing a significant risk to cities worldwide (Fritsch, Assmann, & Tyrna; Rangari, Gonugunta, Umamahesh, Patel, & Bhatt, 2018). By defining the boundaries of a case study area, the influx and outflux of water can be determined for that specific catchment area. In pluvial flooding, rainfall serves as the influx of water, while the outflux consists of sewerage, infiltration, and evaporation. If the influx exceeds the outflux, the catchment area experiences a net influx of rainwater, which is stored within the boundaries of the case study area.

In urban areas, paved surfaces limit infiltration, causing most of the rainwater to run off as overland flow towards the lowest point under gravity. This runoff is hindered from infiltrating or evaporating due to saturated unpaved soil during storms (Gupta, 2017). The short distance to sewers prevents substantial evaporation. Consequently, most rainwater reaches the gutters, relying on the sewer system for drainage. Inadequate conveyance of the sewer system can result in inundation. When water levels rise above the height of doorsteps, residential structures can be penetrated and damaged. The height of these doorsteps can be estimated using the Algemeneen Hoogte Bestand (AHN) in combination with street view data.

Pluvial flooding is primarily driven by intense rainfall occurring during storms. The intensity (measured in millimetres per hour) of this precipitation varies across time and space and is. High-intensity rainfall is often associated with small rain cells, approximately one kilometre wide, which exhibit significant spatial variability (Bulti & Abebe, 2020). In contrast, extended storms originating from larger rainfall cells tend to have less spatial variance.

The costs associated with pluvial flooding are directly linked to the height of inundation, which results from the accumulation of water. The accumulation process is influenced by the physical layout of the catchment area, including fluctuating surface altitudes. Land subsidence can alter runoff directions and contribute to the formation or exacerbation of local depressions. See Figure 14 for a schematic representation. Pluvial flooding poses a significant challenge for residences built with shallow foundations on soft, subsiding soils, as well as for residences constructed on piles within water-retaining local depressions.

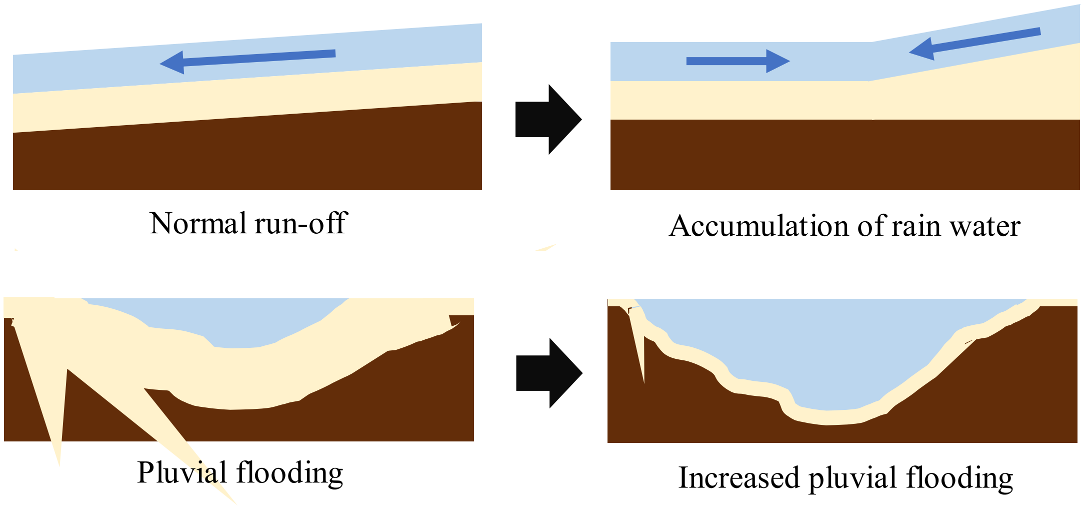

Figure 14: Effect of land subsidence on pluvial flooding

The inundation depth resulting from extreme rainfall events can be predicted through a modelling approach that considers rainfall intensity, altitude maps, and catchment characteristics like sewer conveyance capacity and the percentage of paved areas. The intensity of rainfall serves as the primary input parameter, with higher intensities corresponding to lower event probabilities, expressed as return periods. For example, a return period of 100 years indicates an annual probability of 1%. Maps, such as those produced by Klimaateffectenatlas, are commonly used to visualize these probabilities.

In this study, the modelled inundation heights are based on rainfall events with a return period of 100 involving 70 millimetres rainfall over a two-hour period followed by four dry hours. The modelling also incorporates the effects of land subsidence over time, providing expected inundation depths for the year 2050 under the assumption of the WH8.5 climate scenario.

2.2.4 Increased dewatering risk

Groundwater levels beneath residential properties can potentially reach the underside of the structure, depending on the maximum average groundwater level (GHG) and the amount of land subsidence experienced by properties with shallow foundations. Although less common, buildings supported by wooden piles can also be affected by rising groundwater levels.

When water flows underneath a structure, friction generates a small electric charge. This charge causes negatively charged walls to draw water through permeable masonry via capillary rise. Essentially, the walls absorb water through microscopic tubes in the bricks. The absorbed water can then affect surrounding building materials such as plasterwork or timber floorboards. Rising damp poses health risks, including respiratory conditions, and can lead to structural issues such as Mold, fungus, wood rot, and long-term damage to both the interior and exterior walls of the residence. Inadequate dewatering can result in the consequences depicted in Figure 15.

Figure 15: Small dewatering depth leading to rising damp that causes wet floors and walls (vochtproblemen-vochtbestrijding.nl)

2.2.5 Overview table of mechanisms

Table 1 provides a visual summary of this subchapter relating the four consequences of risk to residential real estate to their most important drivers and relevant foundation type.

Table 1: Combination of consequences with their prominent drivers and foundation types

Consequence	Prominent Driver			Foundation type	
	Land subsidence	Groundwater-levels	Extreme rainfall	Wooden pile	Shallow
Pile rot	**X**	**X**		**X**	
Differential settlements					**X**
Increased pluvial flooding	**X**	**X**	**X**	**X**	**X**
Increased dewatering risk	**X**	**X**		**X**	**X**

2.2.2 Foundation types

This study examines the adaptation mechanisms employed to address land subsidence effects, which are contingent upon the foundation types of structures on and within the soil. Three foundation types are considered: shallow foundations, wooden pile foundations, and concrete pile foundations. Concrete pile foundations, which became the standard post-1970 (Rijksdienst voor Ondernemend Nederland, 2022), do not necessitate notable adaptation measures for land subsidence within the scope of this research. In contrast, prior to this period, wooden pile foundations were prevalent. The subsidence of the soil in which these piles are embedded can result in the pile being dragged down with the soil due to cohesion (known as "negatieve kleef" in Dutch). However, the severity of this problem varies considerably between structures and requires extensive measurements, making it beyond the scope of this research. Pile rot constitutes the other significant issue associated with wooden pile foundations. Both these problems are irrelevant to shallow foundations, as structures with such foundations directly rest on the loadbearing soil layer beneath. Buildings with shallow foundations are particularly susceptible to differential settlement, leading to skewness and cracks. In contrast, the likelihood of differential settlements for structures on wooden piles is considerably lower, and thus excluded from this research.

2.3 Predictive Modelling

All three drivers are continuous dynamic process in time and causally related to climate change. The benefits of the measures imposed to combat the consequences to residential housing relevant in this study are predominantly reliant on the prevented costs of these consequences. Because these costs gradually develop over in time based on the change in climate, a time horizon and a climate scenario describing this development are required.

2.3.1 Time horizon and climate scenario

The study adopts the prevailing approach of using 2050 as the time horizon for climate-related damage consequences maps and models pertaining to residential real estate in the Netherlands, such as the Klimaateffectenatlas. These maps and models rely on global climate scenarios data provided by the Intergovernmental Panel on Climate Change (IPCC). This United Nations body's latest report on projected climate change, the AR6 Synthesis Report, has just now been released (IPCC, 2023). However, as data sources have not yet adjusted to the new information, they still rely on the AR5 Synthesis Report from 2014.

Via a General Circulation Model (GCM), a complex numerical climate model that represents physical processes of the climate system in atmosphere, ocean, cryosphere and land surface, the IPCC constructs climate scenarios that form the scientific evidence base for assessing adaptation planning. The GCM is fed with radiative forcing pathways, a measure of changes in the net transfer of energy in the atmosphere, that in turn is a result of emission scenarios. These emission scenarios are heavily dependent on socioeconomic assumptions such as economic growth, population growth and energy consumption as well as other variables like land use and particulate pollution. All these links in the chain as presented in Figure 16 don't go without adding uncertainty to the end result.

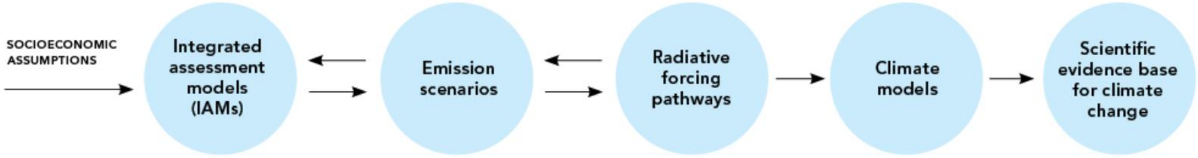

Figure 16: Climate scenario development process (Pielke JR. & Ritchie, 2021)

These assumptions and variables constantly change and often in unexpected directions. The emission scenarios that form the baseline for climate models rely on a representation of the present situation that in practice already no longer holds. Scenarios of the future require continuous updating because the possibilities and probabilities of the future change with unfolding of events in time. Still these projection form a central part of the scientific bases for adaptation policy frameworks whereby climate scenarios are used to identify future climate risks to evaluate the performance of adaptation strategies in risk assessment (Hulme & Dessai, 2008). The performance of the adaptation strategies is directly related to the vulnerability of the asset, in this case residential real estate, to climate and non-climatic stresses such as the availability of financial resources, technologies, skilled people to use the resources and technologies, access to information and legal, social and organisational arrangements. This thesis does not account for the dynamics of non-climatic stresses which are notoriously hard to predict. Instead it takes the most common approach of using the best suited IPCC climate scenario as a scientific base for evaluating the performance of adaptation strategies.

The IPCC has put forward four Representative Concentration Pathways (RCPs) whereby, based on cumulative CO_2 emissions, global mean surface warming is projected (IPCC, 2014). Policy formation and execution will determine the progression or regression of emissions that in turn determine what climate pathway the world is on. All climate scenarios come with a bandwidth to account for the uncertainty interval of the projections. In the best case scenario (RCP2.6) the aim is to keep global warming likely below 2°C the extremes of the bandwidth lie around 0.25 degrees and 1.75 degrees Celsius whereas the worst case scenario (RCP8.5) shows a bandwidth of 1.0 to 2.5 degrees increase until 2050. Graphically the evolution of the global temperature increase until 2100 for both scenarios is represented as a plume graph to incorporate the confidence interval (see Figure 17). The latest iteration of the IPCC report shows similar but slightly higher projections only with smaller bandwidths due to improved climate change knowledge and modelling capabilities.

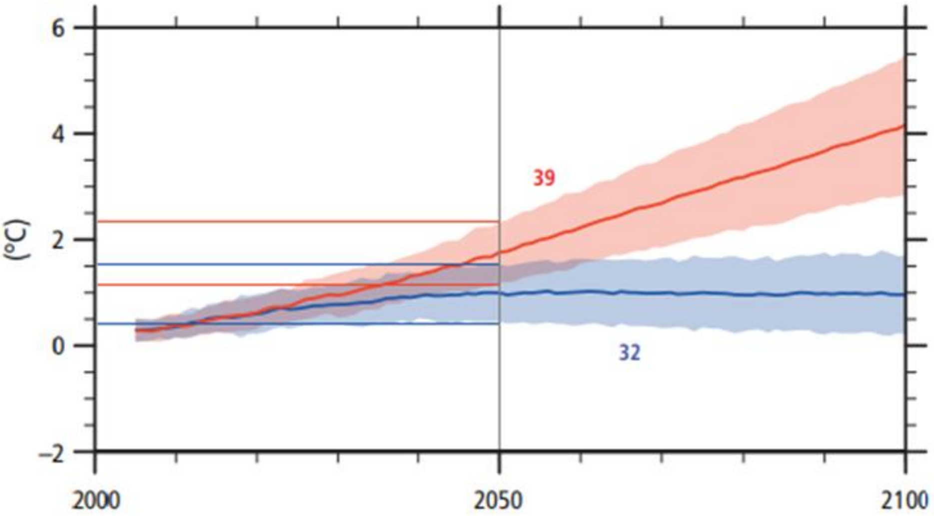

Figure 17: Global average surface temperature change relative to 1986-2005 (IPCC, 2014)

The Dutch Royal Meteorological Institute (KNMI) utilizes the IPCC report as a foundation for developing their own four climate scenarios tailored specifically to the Netherlands. KNMI's scenarios consider two temperature pathways: warm (W) and moderate (G), along with the distinction between high (H) and low (L) volatility in air currents to assess climate change effects. The most extreme scenario for 2050, labelled WH, incorporates a 2-degree Celsius temperature increase and high volatility in air currents, aligning with the RCP8.5 scenario from the AR5 report and the most probable global warming pathway outlined in the latest AR6 report. Consequently, this study adopts the WH scenario for 2050 as the primary scenario for subsequent calculations.

Chapter 4, titled "Results," entails further predictive modelling of the driving factors, utilizing the aforementioned data sources (primarily the Klimaateffectenatlas) as outlined in Table 1: Combination of consequences with their prominent drivers and foundation types. The modelling process remains consistent across all case study areas, but the actual results will vary based on geographical location and specific characteristics.

2.4 Money (Cost Benefit Analysis)

As no guidelines for a CBA approach on land subsidence adaptation exist (Kok & Costa, 2021), this study follows the ‘Algemene leidraad voor maatschappelijke kostenbaten analyse’ published by Central Planning Bureau (CPB) in the previous decade (Romijn & Renes, 2013). Constructed specifically for ex-ante substantiation of decisions in policy formation in the Netherlands. This makes it excellent regarding the research objective of this study. It provides an eight step systematic approach to compare the pros and cons of policy alternatives consisting of:

1. Problem analysis
2. Establish baseline
3. Define adaptation strategies
4. Determine effects and benefits

5. Determine costs
6. Risk analyses
7. Construct cost-benefits overview
8. Present results

This chapter presents a theoretical framework that outlines the qualitative steps involved in determining and calculating each aspect, providing a rationale for their inclusion. Quantitative exercises are conducted to express both the baseline and the four alternative adaptation strategies in monetary terms, while considering the inherent uncertainties. These calculations, along with the corresponding cost-benefit overview, are detailed in chapter 4 Results.

To account for the decades old principle of the time value of money (money in the future holds less value than the same amount today (Jones & Smith, 1982)) this study employs the Net Present Value (NPV) methodology. This approach adjusts Future Cash Flows (FCFs) to their equivalent value in present-day euros. FCFs can encompass both benefits and costs. For each of the 28 years from 2023 to the time horizon of 2050, a discount factor is calculated. All FCFs are then multiplied by the corresponding discount factor for the given year. The discount factor starts at 1.0 for 2023 and gradually decreases each year. The discount factor, present value of a single cash flow and the present value of a calendar year are determined using the following equations:

$$Present\ Value = Future\ Cash\ Flow * Discount\ Factor \tag{1}$$

$$Discount\ factor = \frac{1}{(1 + r_d)^t} \tag{2}$$

$$r_d = discount\ rate \tag{3}$$

$$PV = FCF * \frac{1}{(1 + r_d)^t} \tag{4}$$

$$FCF = \sum Benefits_i - \sum Costs_j \tag{5}$$

The FCFs consist of the benefits and costs within a year. These cost such as construction costs and energy costs are not stagnant but can grow over time. Hence they are indexed yearly in a similar fashion using an index factor (β).

$$FCF = \sum [Benefits_i * \beta_i]_t - \sum [Costs_j * \beta_j]_t \tag{6}$$

$$\beta = (1 + r_p)^t$$

(7)

$$r_p = price\ development\ rate$$

(8)

$$FCF = \sum_{i=1}^{n}\left[Benefits_i * \ (1 + r_{p_i})^t\right] - \sum_{j=1}^{n}\left[Costs_j * \ (1 + r_{p_j})^t\right] \tag{9}$$

$$PV = \frac{\left(\sum_{i=1}^{n}\left[Benefits_i * \ (1 + r_{p_i})^t\right] - \sum_{j=1}^{n}\left[Costs_j * \ (1 + r_{p_j})^t\right]\right)}{(1 + r_d)^t} \tag{10}$$

The Discount Rate (r) represents the expected return on investments with "zero risk" or the Risk-Free Rate (RFR). Although risk-free investments do not exist, treasury bonds are commonly considered safe investments, and their yield sets the minimum expected rate of return. This yield represents the RFR. Based on the 'Rapport Werkgroep Discontovoet 2020' (Ministerie van Financiën, 2020) recommendation, the RFR used in this cost-benefit analysis (CBA) is 2.25%. Inflation has caused an increase in recent years, with the 'Macro Economische Verkenning 2022' (CPB, 2022) suggesting a proposed RFR of 2.5%. While the discount rate depends on economic effects and is expected to rise with inflation rates, this study sets the RFR at 2.5%.

Construction costs are estimated to grow at an annual rate of 4% in the medium to long term (BBN, 2022). Energy prices demonstrate higher volatility compared to other commodities. The European Commission's study on energy prices indicates an estimated annual growth rate of 2.0% for energy costs during the same period until 2050 (European Commission, 2020).

Summing all discounted cash flows (indexed costs and benefits) between 2023 and 2050 results in the Net Present Value (NPV) of an adaptation strategy. For all four adaptation strategies and the baseline an NPV calculation is made so the time value of money is integrated when comparing alternatives. The NPV formula for this study is provided below:

$$NPV = \sum_{t=1}^{28}\left\{\frac{FCF}{(1 + r_d)^t}\right\} \tag{11}$$

$$NPV = \sum_{t=1}^{28}\left\{\frac{\left(\sum_{i=1}^{n}\left[Benefits_i * \ (1 + r_{p_i})^t\right] - \sum_{j=1}^{n}\left[Costs_j * \ (1 + r_{p_j})^t\right]\right)}{(1 + r_d)^t}\right\} \tag{12}$$

The FCF’s consist of the benefits and costs relevant for a specific adaptation strategy. Per case study area five NPV calculations are made relating to the baseline and the four adaptation strategies. The results are than compared between case study areas. For all calculations a minimum, expected and maximum scenario is provided. These scenarios result from incorporating uncertainty ranges of the various parameters. The minimum scenario includes minimized benefits and maximized costs and vice versa for the maximum scenario. These two scenarios provide the upper and lower bounds of the NPV calculation.

2.4.1 Problem analysis

The effectiveness of adaptation strategies varies by location, considering unique risks and potential benefits. Justifying the cost of an adaptation measure depends on the avoided risk and additional benefits generated. Initially, the underlying risks specific to each location, such as pile rot, differential settlement, pluvial flooding, and dewatering risk, are defined to establish a baseline. Subsequently, the NPVs of adaptation strategies are calculated, enabling a discussion and comparison of cost-effectiveness across case study areas in relation to the baseline calculations.

2.4.2 Baseline

The absence of adaptation measures to address local land subsidence until 2050 is known as the baseline. Gradual processes driven by land subsidence, pluvial flooding, and groundwater fluctuations persist and lead to pile rot, differential settlement, increased pluvial flood risk, and heightened dewatering risk. The risk that is unprevented is expected to materialize within the time span and equal to the unavoidable maintenance costs.

The probability and consequences of these processes increase based on KNMI projections under the WH8.5 climate scenario. Land subsidence continues to impact residential real estate as an irreversible process without intervention. The baseline represents the most severe case of land subsidence-related damage, with the four consequences maximized and limited only by climate change. Given the variations in consequences across locations, baseline calculations are conducted for all case study areas assuming no adaptation measures.

2.4.3 Define adaptation strategies

To adapt to land subsidence and relieve its consequences on residential real estate, two main options are available: renovation of existing structures or replacement with new buildings. A combination of these strategies is possible and sometimes even necessary, as was the case in Rotterdam where some residents refused to sell their property (Figure 18). These options can be expanded to include additional measures aimed at maximizing net benefits, resulting in four strategic adaptation alternatives. The primary objective of all adaptation strategies is to eliminate the risks associated with localized land subsidence damage to real estate. While complete elimination of probabilities is not feasible, this research focuses on strategies that provide negligible probabilities for the occurrence of damages.

Figure 18: Combined approach of renovation and replacement, Bloklandstraat Rotterdam (Metro Nieuws, 2018)

To address pile rot in buildings with wooden pile foundations, the foundation can be replaced with concrete piles. Similarly, in buildings with shallow foundations, the risk of uneven settlements can be mitigated by replacing the foundation with concrete piles. Under the renovation pathway, the soil beneath the building is excavated, and concrete piles are installed to provide support. In the case of building replacement, the entire structure, including wooden piles, if present, is removed, and a new house is constructed on a concrete pile foundation.

Preventing pluvial flooding and dewatering risk requires raising the entire building to its original ground level or higher. This process is more straightforward under the replacement pathway, where the structure is removed, the ground level is raised, and new residential real estate is built on the elevated soil. This eliminates groundwater access and local depressions, reducing pluvial flood risk and dewatering risk. Achieving the same benefits through renovation involves raising the existing structure by the same amount. Concrete piers are installed deep in the load-bearing layer of the soil, and hydraulic jacks elevate the structure. Once the desired height is reached, the hydraulic jacks are replaced with concrete blocks and shims, providing support to the structure on the new concrete foundation piers. The space between the old and new floor can be enclosed as crawl space. This technique can also be employed to level or stabilize buildings affected by differential settlements.

To improve the benefits-to-cost ratio of adaptation strategies, additional measures can be implemented. In the case of the replacement pathway, newly constructed houses can adhere to modern standards, incorporating insulation, weatherization techniques, efficient heating, ventilation, and renewable energy sources such as solar panels and heat pumps. Similar energy-efficient improvements can be applied during renovation, taking advantage of the foundation works as an opportunity to enhance energy efficiency without causing significant inconvenience to residents. The objective is to elevate the residence to A-label standards.

Expanding the living space of a residence can also increase net benefits. It has been consistently observed that adding extra square meters to a house enhances its value in the real estate market. This correlation is attributed to increased functionality, flexibility, and the ability to accommodate growing families, create dedicated workspaces, or incorporate desired amenities. Larger living areas provide enhanced comfort, convenience, and a sense of spaciousness, making the property visually appealing. Additional square meters not only address practical needs but also increase the perceived value of the house, making it a valuable investment for potential buyers. Three general approaches can be employed to increase the living space: adding a dormer or an entire floor to the roof, inserting a floor in between existing levels by raising everything above the ground floor ceiling, or constructing a basement beneath the current structure. Collectively, these methods are referred to as adding extra square meters.

In the context of the replacement pathway, an alternative improvement involves densification rather than conforming to the same urban planning (e.g. rebuilding three houses for every two demolished or increasing the size of buildings) achieving more square meters of living space. This approach increases the amount or volume of real estate, thereby potentially improving the benefits-to-cost ratio. However, densification comes with drawbacks, including increased population density leading to reduced personal space, strain on infrastructure and public services, and the conversion of non-residential spaces into residential areas. Horizontal densification can result in the loss of green spaces such as gardens, parks, or playgrounds. Vertical densification can address this issue to some extent but alters the character of the area.

2.4.4 Determine effects and benefits

The effects of the different adaptation strategies are described in the previous paragraph. Benefits consist of prevented risk (PR) and benefits from additional measures and increased property value. The benefits from prevented risk are independent from the chosen adaptation strategy and equal to the risk that is unaddressed in the baseline where no measures are taken. Additional benefits and increased property value are adaptation strategy dependent. The two pathways of renovation and replacement are both split into a conventional adaptation strategy and one with additional measures to increase relative benefit. Table 2 provides an overview of the advantages and disadvantages of the four adaptation strategies and the baseline. The benefit structure for the baseline scenario and the adaptation strategies in formula form is provided below.

$$Benefit_0 = 0 \tag{13}$$

$$Benefit_1 = PR \tag{14}$$

$$Benefit_2 = PR + Extra\ m^2 + Lower\ Energy\ Cost \tag{15}$$

$$Benefit_3 = PR + Increased\ Housing\ price + Lower\ Energy\ Cost \tag{16}$$

$$\begin{aligned} Benefit_4 = PR &+ Increased\ Housing\ price \\ &+ Lower\ Energy\ Cost + Extra\ housing \end{aligned} \tag{17}$$

Table 2: Overview adaptation strategies

	Adaptation strategies	Disadvantages	Advantages
S0	**Baseline** (no interventions)	Land subsidence related risk is not addressed.	No investments are made.
S1	**Renovation** by stabilizing, jacking up the house and constructing concrete pile foundation	• Jacking up houses and constructing new foundation is costly process. • Residents need temporary housing when residence does not allow for them to say during renovation. • No extra value is created. • Energy transition remains unaddressed.	• Land subsidence related risk is minimised. • Preservation of neighbourhood character and property value. • Residents can stay during renovation if residence allows for it spatially.
S2	**Renovation including extra investments** by stabilizing, jacking up the house, constructing concrete pile foundation**,** transition to A-Label and adding extra square meters	• Jacking up houses and constructing new foundation is costly process. • Residents need temporary housing if residence does not allow for them to say during renovation. • Requires additional investment for extra m^2 • Requires additional investment for energy transition	• Land subsidence related risk is minimised. • Character and value are preserved. • Residents can stay during renovation if residence allows for it spatially. • Extra value created by additional square meters of living space • Extra value created by lower energy bill.
S3	**Replacement** of buildings conform prior urban planning	• Alterations of neighbourhood character and property value. • Residents need temporary housing and replacement requires a lot more time than renovation. • New construction is costly process.	• Land subsidence related risk is minimised. • Extra value created by lower energy bill.
S4	**Replacement including densification** by building back more square meters of living space	• Alteration of neighbourhood character and property value. • Residents need temporary housing and replacement requires a lot more time than renovation. • New construction is costly process. • Possible strain on infrastructure and public services	• Land subsidence related risk is minimised. • Extra value created by lower energy bill. • Extra value created by additional properties

2.4.4.1 Benefit of extra square meters

The effect of creating additional living space through renovation or replacement (densification) depends on the specific housing price per square meter in each location. Variations in housing prices exist not only between cities but also within neighbourhoods. These discrepancies can determine the economic viability of adaptation measures in one area while rendering them unfeasible in another.

Extra living space can be added within the existing property, either as a basement or by inserting a floor between the first floor and the roof. Property price encompasses factors beyond living space, including location, environmental and social aspects, and the value of the land. Consequently, smaller houses generally have a higher property value per square meter. Doubling the living space does not equate to doubling the property value. Therefore, it is assumed that the value of an additional square meter of living space is equal to the current square meter price of the property multiplied by a reduction factor of 75%. This calculation is as follows:

$$P_{housing}\ [€/m^2] = \frac{(75\%\ Property\ value)}{surface\ area\ living\ space} \tag{18}$$

The property value is deduced from the average WOZ value of the neighbourhood (Atlasleefomgeving, 2023). The maximum amount of extra square meters to be realized is equal to the surface area of the ground floor. The maximum extra value created that can be attributed to the realization of extra square meters can be calculated using the following formula:

$$Benefit_{extra\ square\ meters} = P_{housing} * A_{ground\ floor} \tag{18}$$

2.4.4.2 Benefit of transitioning to A-Label

Improving on the sustainability of the residence by investing in energy saving measures or replacing it with a more sustainable alternative decreases the energy bill compared to the baseline. This has two effects. Namely, the a reduced energy bill saves money each month which is a benefit on its own. But also, the perceived value of the property increases as people are willing to offer more money to buy it since it has a better energy label. Both effects can be monetarily expressed. The energy cost reduction can be calculated using the table provided by the Dutch Economic Institute for the Build environment (EIB) in corporation with the Energy research Centre Netherlands (ECN) provided under Appendix A (van Hoek & Koning, 2018). Table 3 on the energy savings for transitions towards an A-Label provides an overview specified per type of residence: social rent, private rent or private owned, corrected with a general price increase until 2022 of 17,4% according to CBS (CBS, 2023). The table includes the observed housing price increase published by Brainbay (Brainbay, 2022), the data processing organisation of the NVM which is a Dutch cooperative association of brokers and valuers in real estate.

Table 3: Energy savings and housing price increase due to transition to an A-Label

Energy savings per year for transition to A-Label *(corrected for price increase to 2023)*				**Housing price**
Label	Social rent	Private rent	Private owned	Increase [%]
A	€ 0,-	€ 0,-	€ 0,-	0,0%
B	€ 175	€ 90	€ 175,-	2,8%
C	€ 325	€ 235	€ 350,-	5,4%
D	€ 500	€ 380	€ 760,-	8,0%
E	€ 700	€ 705	€ 1.050,-	10,40%
F	€ 970	€ 940	€ 1.410,-	12,8%
G	€ 1.260	€ 1.410	€ 1.940,-	14,3%

The table quickly shows that the effects of transitioning to an A-Label are dependent on the type of residence, prior energy label and the prior housing price. The benefit of a transition to A-Label is twofold. The yearly cost of energy decreases and the value of the property increases. In formula form we find:

$$Benefit_{transition\ to\ A-Label} = S_{transition} + \Delta P_{transition} \tag{19}$$

$$S_{transition} = Savings\ on\ energy\ consumption \tag{20}$$

$$\Delta P_{transition} = Housing\ price\ increase \tag{21}$$

The total cost savings resulting from decreased energy consumption is the summation of the yearly cost savings multiplied by the corresponding discount factor for that year until the time horizon (2050).

2.4.4.1 Benefit of replacement

New construction holds a higher value compared to existing housing due to several factors. Firstly, new construction offers modern amenities and tailored features that cater to the evolving needs and preferences of homebuyers. These include energy-efficient systems, smart home technology, updated designs, and functional floor plans, enhancing comfort and convenience. Secondly, new constructions typically have lower maintenance costs, as they are built with the latest materials and techniques, ensuring structural integrity and compliance with regulations. This provides peace of mind to homeowners. Lastly, owning a brand-new property with no prior occupancy allows for personalization and customization.

On average, new construction is more expensive than existing housing but the price development between new construction and existing housing is not always in step. During the period of 2017-2019 price increases for new construction of more than 10% very common. New-builds increasingly outperformed the market but in 2021 the opposite trend was observed. The enormous shortage on the housing market resulted in price increases for existing housing to be just higher than that of new construction. On average new construction between 2013 and 2022 is worth between €35.000 euro (minimum) and €65.000 (maximum) more than existing housing. The expected price premium for replacement of the current building fluctuates around €50.000 (expected) (NVM, 2021). To validate this assumption, this range reflects the expected return on housing construction of €425 per/m2 for houses of around 100 square meters (CPB, 2019).

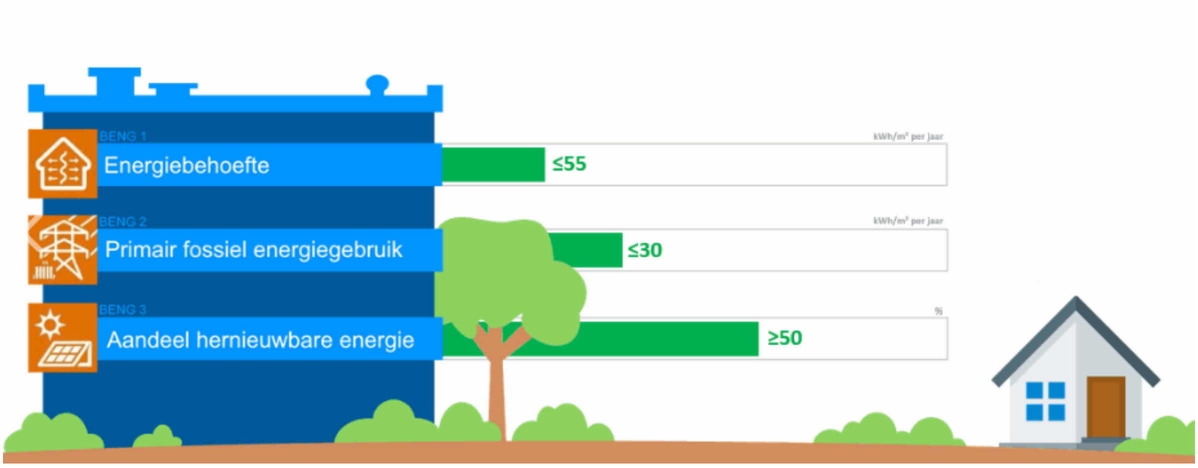

Figure 19: BENG pillars for residential real estate

Apart from the increased housing price, residents can also benefit from lower energy bills in new construction. In the Netherlands, the BENG (Bijna Energie Neutraal Gebouw) or near energy-neutral building label is positioned above an energy A-Label. Founded on three pillars: Energy demand, Primary fossil energy use and Share of renewable energy (Figure 19) has become the standard for new residential construction projects (RVO, 2022).

Energy savings under the replacement pathway depend on the current energy label of the house. Table 4 below provides an overview of the energy savings for the replacement pathway when new construction complies with the BENG standards. The price increase mentioned in the last column is irrelevant, as it is already accounted for in the previously mentioned markup.

Table 4: Energy savings and housing price increase due to replacement and built back conform BENG standards

Energy savings per year for replacement conform BENG standards ***(corrected for price increase to 2023)***				**Housing price**
Label	Social rent	Private rent	Private owned	Increase [%]
BENG	€ 0,-	€ 0,-	€ 0,-	0%
A	€ 350,-	€ 375,-	€ 530,-	2,20%
B	€ 530,-	€ 465,-	€ 705,-	5,10%
C	€ 675,-	€ 610,-	€ 880,-	7,70%
D	€ 850,-	€ 760,-	€ 1.290,-	10,40%
E	€ 1.055,-	€ 1.080,-	€ 1.585,-	12,70%
F	€ 1.320,-	€ 1.315,-	€ 1.940,-	15,30%
G	€ 1.615,-	€ 1.785,-	€ 2.465,-	16,80%

The additional value of the replacement strategy thus can be written as:

$$Benefit_{replacement} = S_{transition} + \Delta P_{transition} \tag{22}$$

$$S_{replacement} = Savings\ on\ energy\ consumption \tag{23}$$

$$\Delta P_{replacement} = Housing\ price\ increase \tag{24}$$

Strategy four includes densification of the area by building back more living space than before. This can be done by increasing the sizes of the houses, putting more houses back or a combination of the two. This minimum densification factor is calculated back from the gap in net-benefit for strategy three.

2.4.5 Determine the cost

Each adaptation strategy incurs specific costs and benefits. The total cost of a chosen strategy is the sum of its relevant individual cost items. Assuming that all strategies effectively reduce the probability of damage to residential real estate to near zero, the cost of residual risk is negligible. The baseline, which lacks intervention measures, does not involve specific cost items but leaves the risk of damage unaddressed. Therefore, the costs of the baseline consist of the combined risks associated with pile rot, differential settlements, pluvial flooding, and dewatering. The cost structure for both the baseline and the adaptation strategies is outlined below.

$$Cost_0 = Land\ subsidence\ related\ Risk \tag{25}$$

$$Cost_1 = Temporal\ housing + Renovation \tag{26}$$

$$\begin{aligned} Cost_2 = {} & Temporal\ housing + Renovation + Investement\ extra\ m^2 \\ & + Investements\ transtion\ to\ A_{Label} \end{aligned} \tag{27}$$

$$Cost_3 = Temporal\ housing + Destruction + Construction \tag{28}$$

$$\begin{aligned} Cost_4 = {} & Temporal\ housing + Destruction + (Construction \\ & * Densification) \end{aligned} \tag{29}$$

2.4.5.1 Temporary Housing

Residents may need to temporarily vacate their homes depending on the type of construction work being conducted. This requirement can be due to safety regulations or practical considerations, as access to the ground floor is necessary for the construction process. For renovation strategies, temporary housing may only be needed for a few days during the lifting of the structure, allowing residents limited access to the first floor. However, this solution may not be feasible for smaller houses that cannot accommodate its residents without utilization of the ground floor, and residents must find alternative housing for the remaining renovation period.

In the case of replacing existing structures with new construction, temporary housing is the only option. The current residences are demolished to make room for new ones, leaving no house for residents to remain in. Throughout the entire project, from demolition to construction, residents must be housed in temporary accommodation (Figure 20).

Figure 20: Temporary housing Groningen (NCG)

The cost of temporary housing is determined by multiplying the cost per time period by the duration of the required temporary housing. Monthly costs can be estimated using guidelines provided by insurance companies. Comparable situations, such as the reinforcement operation in Groningen overseen by the Nationaal Coordinator Groning (NCG), can also be used to estimate costs. During this operation, residents were compensated approximately €1750 per month when their houses were uninhabitable during renovation work or while awaiting the completion of a newly constructed house (NCG, 2023). This study adopts this monthly cost of temporary housing for further calculations. In formulaic representation, we have:

$$Cost_{temporary\ housing} = Price_{temporary\ housing} * t \tag{30}$$

$$Cost_{temporary\ housing} = € 1750 * t \tag{31}$$

The duration of the temporary housing situation is directly related to the choice of adaptation strategy. For the renovation pathway the duration of the renovation work is estimated in consultation with a construction firm specialized in these types of renovations. The estimated durations are provided in Table 5.

Durations for the replacement pathways can be estimated from comparable construction projects. Although new technologies such as industrialised housing and robotic production are expected to reduce construction times of complete neighbourhoods to around 1,5 years (Fijn Wonen, 2022) current lead times are roughly 2 years for houses and apartment buildings and around 3 years for residential towers (CPB, 2019). This corresponds to the average construction time for a single house of 1,5 years (Vereniging Eigen Huis, 2023). The duration of the replacement strategies are also included in Table 5.

Table 5: Construction duration per adaptation strategy

Overview		Foundation	Duration	
		Type	Min	Max
0	Baseline (no interventions)	Shallow	0	0
		Wooden Pile	0	0
1	**Renovation** by stabilizing, jacking up the house and constructing concrete pile foundation	Shallow	4	6
		Wooden Pile	6	8
2	**Renovation** by stabilizing, jacking up the house, constructing concrete pile foundation**, transition to A-Label** and adding **extra square meters**	Shallow	9 (basement)	11 (extra floor)
		Wooden Pile	6	8
3	**Replace** buildings conform prior urban planning	Shallow	24	36
		Wooden Pile	24	36
4	**Replace** buildings and apply **densification**	Shallow	24	36
		Wooden Pile	24	36

2.4.5.2 Renovation

For both renovation strategies the main cost items obviously derives from renovation work. Several construction methods for foundation repair exist. Table 6 provides an overview of the construction methods and their ability to address land subsidence related damage consequences for wooden pile foundations and shallow foundations. To deal with all the consequences of land subsidence the property needs to be raised. This is required to deal with pluvial flooding and dewatering risk. Graphical illustration of the various construction methods are provided under Appendix B.

Table 6: Ability of foundation renovation methods to address consequences of land subsidence

Renovation	Prominent Driver			Foundation type		
Construction method	Pile rot	Pluvial flooding	Dewatering	Differential settlement	Pluvial flooding	Dewatering
Adding piles (pressed/screwed)	☐	☐	☐	☐	☐	☐
Pile head lowering	☐	☐	☐	n.a.	n.a.	n.a.
Cantilever pile and (ring)beam	☐	☐	☐	☐	☐	☐
Prestressed concrete beams	☐	☐	☐	☐	☐	☐
Floor slab piling	☐	☐	☐	☐	☐	☐

For cost estimations, this study focuses solely on foundation renovation options that involve raising the property using hydraulic jacks to address pluvial flooding and dewatering. Among the options presented in Table 6, the floor slab piling method (tafelconstructie) is the most commonly used and least complex, making it the decisive factor for cost estimation.

The refoundation process begins with an assessment of the foundation and the development of a renovation plan by engineers based on the extent of damage. Actual renovation work involves site preparation, excavation of the house perimeter, and removal of the floor to access the foundation. The building is then disconnected from gas, water, and electricity supplies and structurally stabilized before it can be lifted. This may involve reinforcing walls with beams, installing a ring beam or prestressed beams underneath the structure, or pouring a new concrete floor. Once the structure is ready, it is lifted from its original foundation, stabilized, and raised to the desired height before a new concrete pile foundation is installed. The space between the current soil surface and the new floor height can be filled or closed off as a crawl space.

Following the connection of the structure to the new foundation, additional repairs to masonry, pipes, supports, and frames may be necessary and plantation and pavements need to be restored. The cost of this process includes labour, materials, machinery, permits, and inspections. During this period, the ground floor of the house is uninhabitable, but with temporary structures, the first floor can remain accessible. However, this option is only applicable to houses with ample living space from the first floor upwards. Otherwise, residents require temporary housing or need to be bought out before construction work begins. The total renovation time spans several months, with actual lifting activities lasting less than three days. Several research studies have reported foundation renovation costs for terraced houses ranging from €50,000 to €80,000 (Patel, Pnachal, & Siddharth, 2016) and some even go as high as €80,000 (Deltares, 2013). Table 7, created in collaboration with an construction company with expertise in foundation renovation, presents a more specific cost figure for the renovation pathway in collaboration with a construction company. The cost is presented in euros per square meter, with a range of +/- 15% providing minimum and maximum values. These numbers are rounded for convenience. The cost of renovation depends on the foundation type and the inclusion of additional living space, such as a basement or an extra floor between the ground floor and the first floor/attic.

Table 7: Cost estimation of foundation renovation methods

Overview		**Foundation**	**Cost [/m^2]**		
		Type	Min (-15%)	Expected (incl. 21% tax rate)	Max (+15%)
1	**Renovation** by stabilizing, jacking up the house and constructing concrete pile foundation	Shallow	€ 2060,-	€ 2420,-	€ 2785,-
		Wooden Pile	€ 2060,-	€ 2420,-	€ 2785,-
2	**Renovation** by stabilizing, jacking up the house, constructing concrete pile foundation**,** transition to A-Label and adding extra square meters as a **basement**	Shallow	€ 4735,-	€ 5445,-	€ 6260,-
		Wooden Pile	€ 3445,-	€ 3965,-	€ 4560,-
	Renovation by stabilizing, jacking up the house, constructing concrete pile foundation**,** transition to A-Label and adding extra square meters as an **extra floor**	Shallow	€ 2725,-	€ 3135,-	€ 3605,-
		Wooden Pile	-	-	-

The table immediately shows that constructing a basement underneath a building with a shallow foundation is far more expensive than for a structure with a wooden pile foundation. This is because the soil underneath the structure needs to be excavated without it subsiding. Realizing extra living space by inserting an extra floor after lifting the first floor and/or attic by about 2,50 meters is cheaper than constructing a basement. The cost of inserting an extra floor for structures with wooden pile foundations has not been estimated yet. The normative prices per square meter that are not used for further calculations are darkened. For the total cost of renovation the price per square meter is to be multiplied by the area of the building:

$$Cost_{Renovation} = P_{Renovation} * A_{building} \tag{32}$$

$$P_{Renovation} = price\ of\ renovation\ per\ m^2 \tag{33}$$

$$A_{building} = Surface\ are\ of\ the\ structure \tag{34}$$

2.4.5.3 Investments transition to A-Label

Cost associated with transitioning to A-Label are dependent on the current label of the property. It takes a larger investment to go from a G-Label to an A-Label than from a B-Label. The EIB in collaboration with ECN published a comparison of the investment cost and the projected savings regarding energy consumption for improving the energy label (van Hoek & Koning, 2018). It found that the marginal investment cost from a G-Label upwards are relatively stable with the exception of the transition from A-Label to BENG. This transition is, with current technologies and prices, far from economically viable. For graphs and illustrations consult appendix A. This study aims to find cost-effective measures and so the transition step to BENG standards is omitted. The investment cost provided by the EIB does not include the cost of finishing or a discount for subsidies. The latter accounts for around 30% of investment cost if more than one energy saving measure is implemented. Assumed is that this is enough to cover the extra cost of finishing so they cancel out. A markup for large houses (larger than 100m2) is assumed to raise cost of investment by 20%. The cost of can be calculated using Table 8 below. It combines the cost of investment published by the EIB in 2018 with a rounded general price increase until 2022 of 17,4% (CBS, 2023).

Table 8: Cost of investment for transition to A-label

	2018 (EIB)	**2022 (CBS)**	**> 100 m^2**
Label	Cost of investment		Markup (+20%)
A	€ 0,-	€ 0,-	€ 0,-
B	€ 6.060,-	€ 7.115,-	€ 7.272,-
C	€ 10.860,-	€ 12.750,-	€ 13.032,-
D	€ 13.860,-	€ 16.270,-	€ 16.632,-
E	€ 16.860,-	€ 19.795,-	€ 20.232,-
F	€ 21.060,-	€ 24.725,-	€ 25.272,-
G	€ 27.060,-	€ 31.770,-	€ 32.472,-

The values in the table are national averages. Per region these values can change, as illustrated in Figure 21 below. A step van C-Label to A-Label has a smaller impact on the price of a house in the province of Utrecht compared to the province of Groningen. Likely due to differences in local supply and demand and physical differences in impact on energy label transitioning between houses in the city and in the country side. Where in the city heat stress is more prevalent whereas in the countryside residences cool faster. The percentages from Dordrecht and Rotterdam match with the national average.

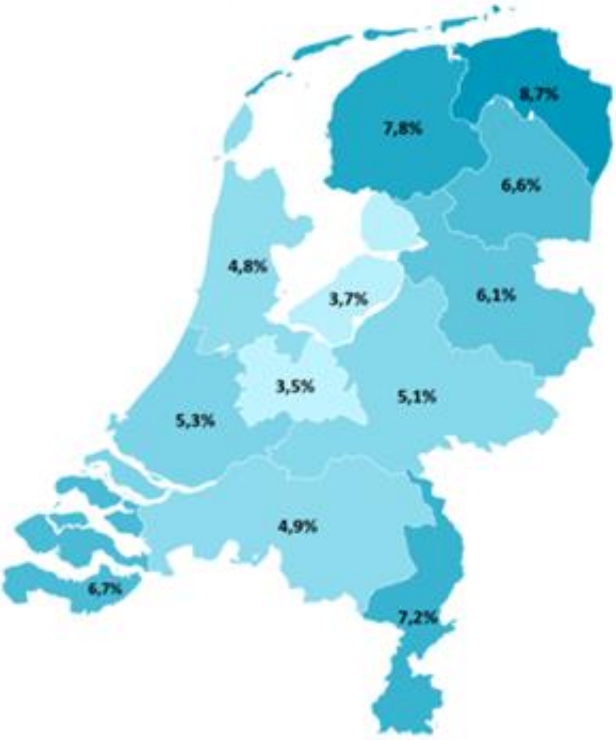

Figure 21: Added value of transition from C to A label (Brainbay)

2.4.5.4 Demolition of value

To facilitate new construction, the existing building, including its foundation, is removed, resulting in a significant loss of property value. The vacant land that remains holds less value compared to a property with a functional building. Following demolition, a new building is erected on the same land. For the sake of simplicity, this study assumes that the entire housing price of the property is eliminated during demolition, just as it assumes that the new housing price is established upon completion of the new construction. Prior to commencing demolition work, the property must be purchased from the owner at the current housing price. Once the new construction is finished, the house can be sold back to the previous owner or placed on the market at the new price. The actual costs of demolition are included in the construction expenses.

Demolishing a property may also entail the loss of potential income or benefits that could have been derived from it, known as opportunity cost. However, since residents are temporarily housed elsewhere during this period, the calculation omits the potential rental income. Therefore, we have the following relationship:

$$Cost_{Demolition} = Current\ housing\ price \tag{35}$$

2.4.5.4 Construction cost

When the previous buildings have been removed the construction of the new houses can start. The cost of this process depends on the type of house that is constructed, construction method and type of finishing. For structural elements (foundation, concrete skeleton, roof, ceilings, stairs and façade, interior wall and roof finishing) and installations (liquid and gas installation, climate systems and electricity) alone the costs exceed €1200 per square meter (Kok, Meuwese, Saitua Nistal, Semenov, & Smit, 2020). By consulting various constructors and construction consultants, verified by open sources (ITX Bouwconsult, 2023) the full cost of construction per square meter is estimated anywhere between €1400 and €2000. The expected value is assumed to be average of the two. This assumption agrees with the earlier notion that construction cost inherit a 15% variance both up and down from the average. Table 9 below provides an overview of the construction costs per square meter.

Table 9: Construction cost for new construction per square meter

Construction cost **[/m^2]**		
Min	Expected	Max
€1400,-	€1750,-	€2000,-

2.4.5 Determine the risk

Over the years the definition of risk has been known to undergo development (Aven, 2012). References in a professional or scientific context of more than three centuries ago mention risk as an expected value loss but nowadays it can refer to the probability of an event, (objective) uncertainty, possibility of a loss, probability and severity of consequences or according to the ISO Guide 'the effect of uncertainty on objectives' (ISO, 2009). This study regards risk as a quantitative measure based on probability, a measure for representing or expressing uncertainties. Thus following the rules of probabilistic calculus. Henceforth risk is defined as the probability of occurrence (p) or likelihood of an event multiplied by the consequences (C) or impact of such event. In formula form this writes as:

$$R = p * C \tag{36}$$

$$Risk = probability * Consequence \tag{37}$$

The total risk is the sum of the individual risk items. As explained under 1.2 Problem statement the four relevant risk items for this study consist of: Pile rot or Differential settlement, Pluvial flooding and dewatering risk. Rewriting formula (37) gives:

$$R_{total} = \sum_{i=1}^{n} R_i = (p_i * C_i) \tag{38}$$

Pile rot and differential settlements do not occur simultaneously. Depending on the type of foundation (wooden pile or shallow) one or the other is of importance. Introducing the foundation parameter α to represent the type of foundation, formula (38) is now written as:

$$R_1 = \alpha_{foundation\ type} * (p_{pile\ rot} * C_{pile\ rot}) \tag{39}$$

$$R_2 = (1 - \alpha) * (p_{diff.\ settlement} * C_{diff.\ settlement}) \tag{40}$$

$$\alpha_{foundation\ type} = 1\ for\ wooden\ pile\ foundation \tag{41}$$

$$\alpha_{foundation\ type} = 0\ for\ shallow\ foundation \tag{42}$$

$$R_3 = (p_{pluvial\ flood} * C_{pluvial\ flood}) \tag{43}$$

$$R_4 = (p_{dewatering} * C_{dewatering}) \tag{44}$$

Three of four risks are always present, but their consequences or probabilities can become extremely small depending on location-specific parameters. The specific probabilities and consequences for each case study area are determined using consequence maps from Klimaateffectenatlas (CAS, 2023), as well as calculation methods proposed by the Nationaal Kennis- en Innovatieprogramma Water en Klimaat and adopted by the KCAF, along with calculation methods from the Klimaatschadeschatter (NKWK, 2019). These methods follow a three-step principle to determine damage costs: threat, exposure, and damage relationship. The numerical values for probabilities and consequences inherently contain uncertainty, and therefore, the confidence interval of the parameters is included. Further discussion on these methods can be found here.

2.4.5.1 Pile rot risk

The threat of pile rot is associated with low groundwater levels. Exposure to rotting piles is limited to properties with wooden pile foundations. The probability of a property having a wooden pile foundation can be estimated based on the property's age and known foundation types in the neighbourhood or determined from prior foundation surveys. Similarly, the height of the pile head, which determines the exposure to groundwater fluctuations (see 2.2.1 Pile rot), can be estimated (with relatively large uncertainty) or determined (high certainty) using the same approach (NKWK, 2019).

Groundwater levels may not be directly available for the specific location of interest, so GLG maps constructed from the NWM are used. However, these maps deviate from the actual situation, especially in urban areas where factors like construction work, leaking pipes, subsurface infrastructure, and trees can cause local variations in groundwater levels. The GLG map for the warm scenario of 2050 is utilized to determine the dry stand time of the pile heads. A triangular distribution with lower (a) and upper (b) bounds, along with an educated guess (c), is employed to determine the probability of the random variable representing the dry stand time of the pile head.

In formulaic representation:

$$X \sim T(a, b, c) \tag{45}$$

Which looks like this (TU Delft, 2023):

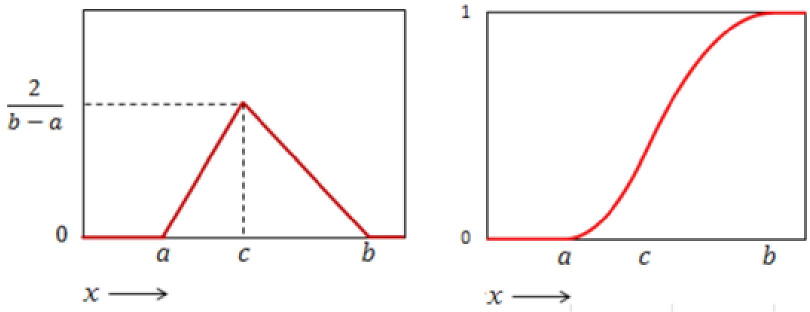

Figure 22: Probability density function and Cumulative distribution (TU Delft)

The combination of pile head height and GLG levels determines the annual cumulative dry stand time for the wooden pile heads according to the following table:

Table 10: Dry stand time per year for various differences between GLG and pile head depth

GLG relative to pile head depth	Cumulative dry stand time in days per year
GLG ≥ 20 cm above pile head	1,5 days/year
5 cm < GLG < 20 cm above pile head	22 days/year
GLG ≤ 5 cm above pile head	29 days/year

The consequence is constructed from damage estimations classified under five labels ranging from D0 to D5. Renovation of the foundation is necessary when damage level D5 is reached. When the pile is submerged the rotting process stops but it continues where it left of when the pile head falls dry. The cumulative dry stand time before D5 is related to the type of soil where the pile head is located. With GeoTOP the soil layer at the pile head is estimated (Rijksoverheid, 2023). Table 11 below shows the dry stand time per soil type that is required before D5 is reached. It is constructed from KCAF expertise (NKWK, 2019).

Table 11: Dry stand time to reach damage class D5 per soil type

Soil type	Cumulative dry stand time to reach D5
Sand	After 10 years
Peat	After 15 years
Clay	After 20 years

KCAF has produced a table with the minimum and maximum expected repair cost per property for each of the damage classes (NKWK, 2019) . These cost have been corrected using the calculation tool by CBS to produce the graph in Figure 23. Immediately the large difference between minimum and maximum repair cost of damage level D4 and D5 stands out. The estimation by KCAF provides a range of more than €100.000,- for the highest damage class (D5). The table and a graphical depiction the corrected numbers for 2023 are provided below.

Table 12: Renovation cost per damage class (KCAF)

Damage class	Renovation work	Cost of repairs per property		
		Min	Expected	Max
D1	• Interior painting	€ 572	€ 1.430	€ 2.288
D2	• Interior painting • Filling/repairing cracks • Rent scaffolding	€ 572	€ 3.146	€ 5.720
D3	• Interior painting • Filling/repairing cracks • Rent scaffolding • Repair plasterwork	€ 2.288	€ 6.864	€ 11.440

D4	• Interior painting • Filling/repairing cracks • Rent scaffolding • Repair plasterwork • Repair window frames, floors	€ 11.440	€ 40.040	€ 68.640
D5	• Interior painting • Filling/repairing cracks • Rent scaffolding • Repair plasterwork • Repair window frames, floors • Repair foundation	€ 34.320	€ 85.800	€ 137.280

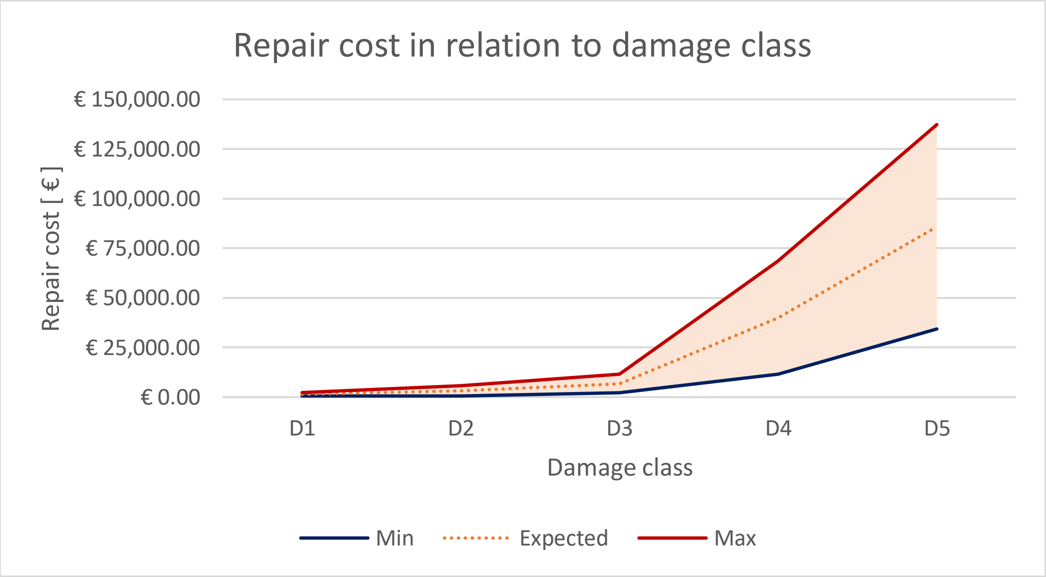

Figure 23: Repair cost in relation to damage class

2.4.5.2 Differential settlement risk

Properties with shallow foundations are prone to uneven settling. Similar to estimating the probability of a wooden pile foundation, the probability of having shallow foundations can be determined based on the property's age and surrounding foundation data or prior foundation surveys.

Exposure to uneven settling is influenced by land subsidence rates. An assessment of soil sensitivity to differential settlement, based on physical characteristics, is necessary to evaluate damage consequences. The subsidence rate is obtained from Bodemdalingskaart 2.0 (NCG, 2023) and adjusted to account for soil and property characteristics. Six characteristics, linked to correction factors, are considered, including the thickness of the anthropogenic fill layer, variance in settlement sensitivity across the neighbourhood, and the presence of clay.

Regarding soil characteristics, a thicker anthropogenic fill layer increases soil preload, reducing the probability of differential settlement. Higher variance in settlement rates indicates heterogeneous soil conditions, increasing the likelihood of differential settlements.

Clay, known to shrink and swell during dry and wet periods, respectively, increases the probability of differential settlement.

Property characteristics impacting sensitivity to differential settlement are also considered. These include the property's age (reflecting foundation quality), the presence of a basement or souterrain (less than half the height below street level), and whether only part of the property has a substructure like a basement or souterrain. Older properties have a higher likelihood of experiencing differential settlements as the foundation deteriorates. Basements or souterrains stabilize properties horizontally, reducing sensitivity to differential settlements. In contrast, properties with partial basements or other substructures are asymmetrical, increasing sensitivity to differential settlements

Table 13: Correction factors for land subsidence rates

Characteristic	Symbol	Value	Factor
Correction factors for soil characteristic			
Thickness of fill layer	γ_{S1}	0 – 1 m	1
		1 – 2 m	0,95
		> 2 m	0,85
Constructed on clay	γ_{S2}	Yes	1,5
		No	1
Local variance in settlement rates	γ_{S3}	Low	1
		Average	1,15
		High	1,25
Correction factors for property characteristics			
Quality of foundation (based on property age)	γ_{P1}	High	0,8
		Average	1
		Low	1,2
Presence of basement/souterrain	γ_{P2}	Yes	0,8
		No	1
Presence of partial substructure	γ_{P3}	Yes	1,2
		No	1

The measured land subsidence rate (r_{LS}) from Bodemdalingskaart2.0 is multiplied by the correction factors to find the corrected land subsidence rate ($r_{LS_{corrected}}$) as follows:

$$r_{LS_{corrected}} = \gamma_{S1} * \gamma_{S2} * \gamma_{S3} * \gamma_{P1} * \gamma_{P2} * \gamma_{P3} * r_{LS} \tag{46}$$

Table 14 below is constructed in line with the guidelines compiled by the Organisation for Independent Foundation Research (F3O, 2012). It provides the relation between the corrected land subsidence rate and the expected damage class for 2050. The consequence is calculated from the corresponding damage class. For the repair costs in relation to the damage class consult Figure 23.

Table 14: Corrected land subsidence and corresponding damage class in 2050 (F3O)

Corrected land subsidence rate per year	Damage class in 2050
< 2 mm	D2
2 – 3 mm	D3
3 – 4 mm	D4
> 4 mm	D5

2.4.5.3 Pluvial flood risk

Intense rainfall leading to land and building inundation causes both direct and indirect damages, including property damage, loss of productivity, business interruption, emergency response and recovery costs, health concerns, and environmental impacts. This research focuses specifically on the direct damage to residential housing, which includes structural damage and damage to electrical systems, appliances, furniture, and personal belongings. The total cost of these damages depends on the characteristics of the structure, household effects, and the level of inundation inside the residence.

Current urban flood models, such as the 3Di Model (3Di Watermanagement, 2023) used by Stichting Toegepast Onderzoek Waterbeheer (STOWA, 2022), simulate the inundation height of open surfaces by integrating ground level maps, land use maps, and sewerage data. However, these models do not calculate the inundation height inside properties. Instead, they assume that the water level inside properties is the same as the surrounding inundation height, which is a valid assumption when water can enter the residence. For water to enter a residence, the inundation height must exceed the height of the doorstep, which typically sits 15 centimetres above ground level but may vary for each residence. Therefore, when the surrounding surface's inundation height exceeds the doorstep height, the residence is considered flooded with the same inundation height.

Two assumptions are made regarding the cost of repairs. Firstly, the maximum repair cost corresponds to an inundation height of 30 centimetres. Any inundation height beyond this does not incur additional repair costs. Secondly, repair costs are assumed to increase linearly. The consequence of pluvial flood risk (Q) is calculated using the following formula:

$$Q_{inundation} = \alpha_{doorstep} * h_{inundation} * P_{inundation} \tag{47}$$

$$\alpha_{doorstep} = 0 \; when \; h_{inundation} < \alpha_{doorstep} * h_{doorstep} \tag{48}$$

$$\alpha_{doorstep} = 1 \; when \; h_{inundation} > \alpha_{doorstep} * h_{doorstep} \tag{49}$$

$$h_{inundation} = inundation \; height \tag{50}$$

$$P_{inundation} = price \; of \; inundation \; per \; square \; meter \tag{51}$$

This research builds on two sources to estimate damage by pluvial flooding. Firstly the report on water damage estimation for standard buildings by STOWA (Hoes, Heijkers, Bloemberg, Nieuwenhuis, & Klopstra, 2013). Secondly, insurance provider Achmea provides a direct damage estimation per square meter based on 107 submitted insurance claims (Pleumeekers, et al., 2019). This discrepancy can be attributed to the fact that not all direct damages are claimed. This study uses the damage estimation per square meter from Achmea as the lower limit and the standardized numbers from STOWA as the upper limit. The averaged of both numbers serves as the expected cost of pluvial flooding per square meter. Table 15 provides an overview of these numbers corrected for 2023 and Figure 24 shows the upper and lower boundaries for a residence with a 15cm high doorstep.

Table 15: Damage cost of inundation by pluvial flooding

Damage	Achmea	Expected	STOWA
	Min	Average	Max
Direct damage ≥ 30cm inundation	€ 80,08	€ 194,29	€ 308,5
Direct damage per cm inundation	€ 2,67	€ 6,48	€ 10,28

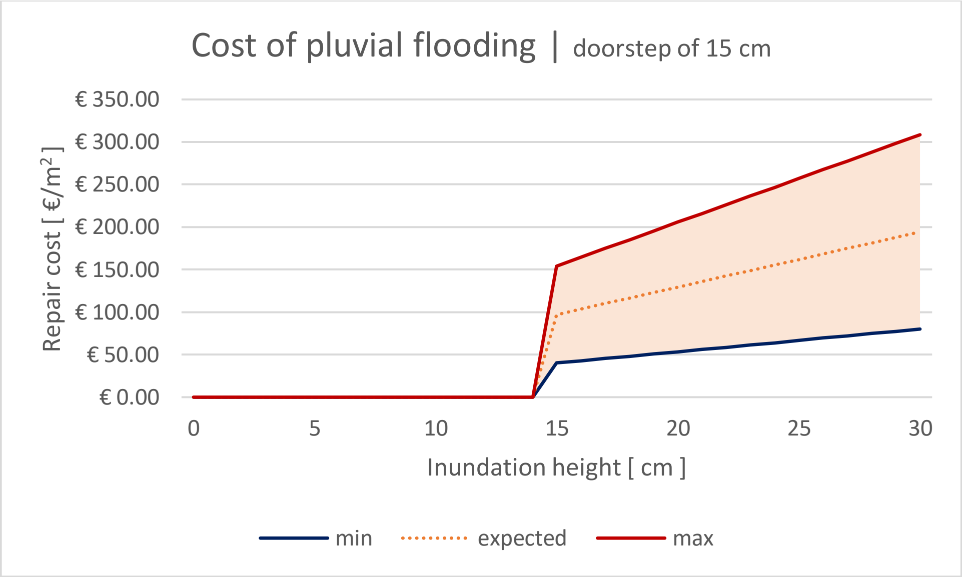

Figure 24: Damage cost of inundation by pluvial flooding for a doorstep of 15 cm

Precipitation data from the National Rain Radar serves as input for the simulation, varying in space and time. The combination of rainfall intensity and duration leads to inundation when the amount of rainwater exceeds the sewer system's capacity to discharge it. Calculating the return period for localized inundation can be complex due to multiple combinations of rainfall intensity and duration (Beersma, Hakvoort, Overeem, & Versteeg, 2019). In this study, the 2050 WH scenario inundation map from the Klimaateffectenatlas is used for a 2-hour rainfall event with a return period of 100 years, equivalent to 70 mm of rain in 2 hours. The annual exceedance probability is the inverse of the return period, which is 1% per year over a 28-year period (2023 to 2050). Combining this with the previous formula yields the following result:

$$R_{inundation} = \sum_{t=1}^{28} \left(Q_{inundation} * \frac{1}{T} \right) \tag{52}$$

$$T = return\ period \tag{53}$$

$$R_{inundation} = \sum_{t=1}^{28} \left(\frac{\alpha_{doorstep} * h_{inundation} * P_{inundation}}{T} \right) \tag{54}$$

2.4.5.4 Dewatering risk

Dewatering risk occurs when a property's functions are affected by a structurally low drainage depth, leading to issues such as rotting floor joists, moisture in walls, plaster damage, and mould growth. If the height difference between the groundwater level and the underside of the structure is less than 80 centimetres, dewatering risk takes effect (van de Winckel, 2005).

The highest average groundwater level (GHG) typically occurs at the end of winter, especially in lower-lying areas of the Netherlands. Climate change is expected to further increase the GHG in many locations, thereby increasing dewatering risk. Drainage systems, including ditches and underground drainage, have been implemented on a large scale to mitigate groundwater flooding (Figure 25).

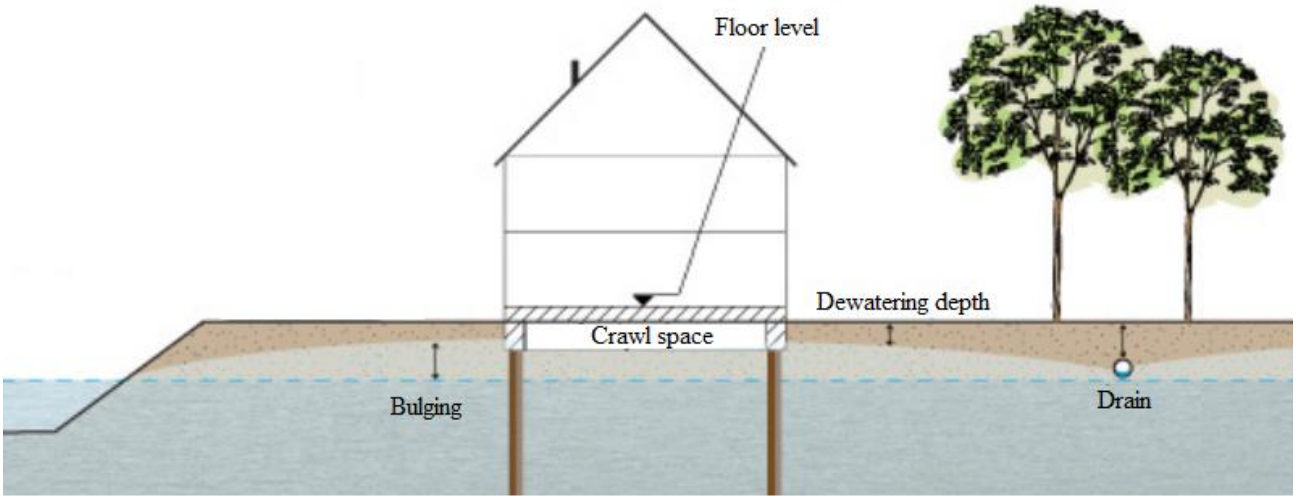

Figure 25: Schematization of groundwater level and dewatering depth (3BW, 2012)

Unfortunately, a detailed map of the current groundwater flooding situation is not available for the Netherlands. The NWM model used has limited predictive capabilities for groundwater flooding due to its low resolution and dependence on local conditions. However, changes in groundwater levels until 2050 can be relatively accurately modelled. Klimaateffectenatlas.nl has published a map showing the projected GHG increase for the 2050 WH scenario in cities (CAS, 2023). Table 16 presents the projected GHG increase for 2050 derived from this map.

Table 16: Change in dewatering risk (Klimaateffectenatlas)

Change in dewatering risk	**Change in GHG [m]**
Strong decrease	> -1.0
Decrease	-0.25 / -1.0
Light decrease	-0.1 / -0.25
Hardly any change	0.0
Light increase	+0.1 / +0.25
Increase	+0.25 / +1.0
Strong increase	> +1.0

Estimating the damage caused by dewatering risk is, with the current body of knowledge and research, cannot be done very accurately. To the best of my knowledge no methods for calculating this risk are developed. For this reason the study assumes a linear relation between damage and dewatering height. When the distance between GHG and the bottom of the property is larger than 80 centimetres the damage is assumed to be non-existent and maximised when equal to 0 centimetres. The cost of repairs are derived from Table 12 by taking damage class D4 as it includes repair cost for floors and walls. Table 17 provides an overview of the cost followed by an illustration (Figure 26) of the repair cost for dewatering risk in relation to GHG levels.

Table 17: Renovation costs for damage class D4

Damage class	**Cost or repairs per property**		
	Min	Expected	Max
D4	€ 1.440	€ 5.040	€ 8.640

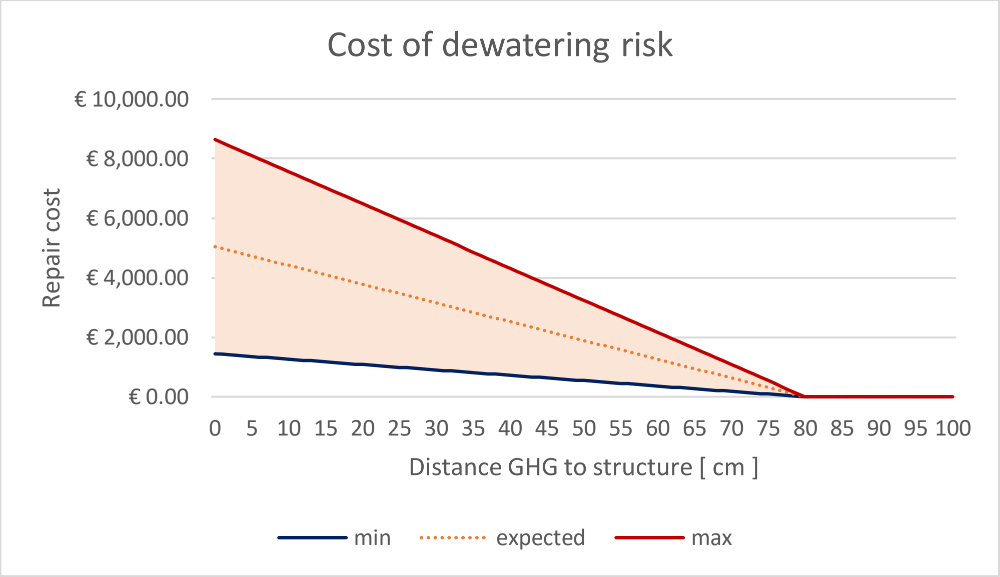

Figure 26: Cost of dewatering risk in relation to dewatering height

In formula form we find:

$$Total\ R_{dewatering} = \left(0.8 - h_{dewatering}\right) * P_{dewatering} \tag{55}$$

$$R_{dewatering} = Risk\ of\ dewatering\ damage \tag{56}$$

$$h_{dewatering} = dewatering\ depth \tag{57}$$

$$P_{dewatering} = price\ of\ repairs\ for\ dewatering\ damage \tag{58}$$

3 Research Methods and Design

This chapter elaborates on the research approach, research context, sampling and analysis.

3.1 Design

This study aims to understand the cost-effectiveness of adaptation strategies to land subsidence-related damage in residential real estate regarding its surrounding environment. It combines climate risk maps (e.g., Klimaateffectenatlas, Bodemdalingskaart) with the ICEBERG v2.0 climate risk model from ABN AMRO to analyse four adaptation strategies in four specific case study areas. The climate risk maps provide risk estimates, while the ICEBERG model provides asset-specific information such as building age, surface area, and foundation type. The risk is monetized using the Klimaatschadeschatter approach and methods proposed by KCAF (NKWK, 2019). The monetized risk is compared to the cost of the adaptation strategies until 2050, aligning with the time horizon of most climate risk maps. Discounting future cash flows to 2023 using a net present value calculation accounts for the time value of money. The cost-effectiveness of each adaptation strategy is evaluated by comparing it to the baseline scenario. This cost-benefit analysis is repeated for all four case study areas, allowing for a comparison of the cost-effectiveness of the adaptation strategies across different local characteristics.

3.2 Research Context

This research project is a collaboration with ABN AMRO and the municipalities of Dordrecht and Rotterdam. These partners have expressed interest in analysing climate risk, particularly land subsidence-related foundation issues and their impact on the financial situation of real estate. The municipalities provide data on assets in the case study areas. A joint team from Dordrecht and Rotterdam, along with a research agency specializing in the housing market and asset valuation, has been formed to assess future prospects for neighbourhoods facing subsidence challenges. The study focuses on exemplary cases in Dordrecht and Rotterdam, contributing to ongoing efforts and benefiting from access to relevant data in these areas.

3.3 Research Procedures

6M approach, CBA, gather data, fill in formulas, NPV per strategy, compare strategy results per case study. Compare case study results per strategy. Sensitivity analysis. Discuss, recommendations.

3.3.1 Wealth distribution

For analysing the effectiveness of adaptation strategies, it is crucial to consider the distribution of costs and benefits among stakeholders. Aligning benefits with the beneficiaries facilitates the implementation of adaptation strategies. This wealth distribution, which is discussed in chapter 5, plays a significant role.

In this study, the following stakeholders are recognized in relation to the research objective: residents, homeowners, mortgage providers, local governments, housing corporations, and investors. Residents refer to the occupants of at-risk properties, while homeowners are the property owners. In some cases, homeowners and residents are one and the same. Homeowners are responsible for maintenance and repair costs arising from foundation issues, pluvial flooding, or dewatering risk. Mortgage providers become stakeholders when homeowners have mortgages with financial institutions. Local governments are responsible for tasks such as creating zoning plans, negotiating with housing corporations for housing construction, monitoring the process, maintaining public spaces, and implementing the Environmental Management Act (Rijksoverheid.nl, accessed on 24 March 2023). Local governments are significantly affected by land subsidence, making them important stakeholders. Housing corporations are stakeholders in places where they own one or multiple houses. Lastly, adaptation measures involving private sector investment attract investors as stakeholders.

3.4 Data collection

The data for calculation of the costs, benefits and risk comes from various sources. Table 18 below showcases a comprehensive overview of the various data sources and their respective purposes. In today's data-driven world, organizations rely on diverse sources to gather valuable insights and make informed decisions. This compilation provides a holistic view of the data landscape.

Table 18: Overview of data sources, owners and purpose

Data source	Owner	Purpose
ICEBERG v2.0	ABN AMRO	Asset specific characteristics
BAG Viewer	Kadaster	Asset specific characteristics
Klimaateffectenatlas.nl	CAS	Inundation height for pluvial flooding, GHG levels, foundation risk maps
Atlasleefomgeving.nl	Rijksoverheid	Average WOZ value
Drechtsteden.nl	Drechtsteden	Groundwater levels (GHG, average, GLG)
Duikinjefundering.nl	Gemeente Rotterdam	Foundation risk maps, Foundation reports (validation)
Gisweb 2.0	Gemeente Rotterdam	Groundwater levels (GHG, average, GLG)
Bodemdalingskaart 2.0	Open source	Lans subsidence rates
Schade aan funderingen door droogte	KCAF / NKWK	Methods for damage estimation of wooden pile and shallow foundations
BROloket (GeoTOP)	Rijksoverheid	Soil type underneath asset
Prijzen toen en nu	CBS	Price corrections
RCP8.5 scenario/ WH8.5 scenario	IPCC/ KNMI	Climate scenario
Google Streetview	Google	Doorstep height estimation, validation of characteristics

3.5 Sampling

The municipalities of Dordrecht and Rotterdam provide two case study areas each: Dordrecht 1, Dordrecht 2, Rotterdam 1, and Rotterdam 2. These case studies are representative for a larger population of neighbourhoods with similar land subsidence-related damages across the Netherlands. In Rotterdam alone, there are over 120,000 properties with wooden pile foundations and over 25,000 with shallow foundations. The exact number is not known but municipalities are working towards integrating historical archive data and available foundation surveys to map out the size and location of the issues (Figure 27, green means available foundation survey). Similarly, in Dordrecht, there are thousands of residences with shallow foundations. While the sample size is relatively small, it can be expanded when the study yields valuable insights for further research.

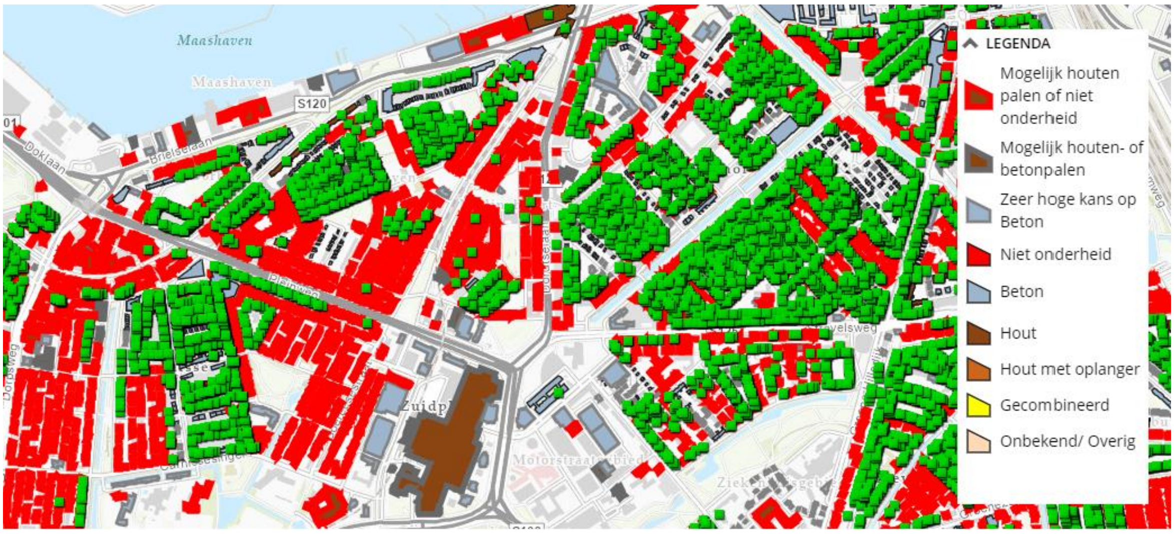

Figure 27: Digital map of foundation types and available survey data in Rotterdam (duikinjefundering.nl)

The sample encompasses different land subsidence problems based on foundation type (wooden pile or shallow foundations), property type, and ownership. It represents four distinct combinations of local characteristics to assess the cost-effectiveness of the four adaptation strategies under varying conditions. To facilitate effective comparison and discussion, the number of varying characteristics has been limited.

All residences in the sample will be over well 100 years old in 2050 to ensure that land subsidence poses a significant enough risk to warrant the implementation of adaptation strategies. Additionally, for the purpose of this research all residences in the sample are relatively small. Under the assumption that part of the the cost scale with the size of the house while some of the costs are fixed and that these properties have limited options for action, it is anticipated that the outcomes for these relatively small residences are conservative when applied to larger residences. Furthermore, these types of houses are very common and can be found throughout cities across the country.

Within the confines of the case study area the sample is analysed based on land subsidence related parameters including: size of the residence, size of the ground floor, energy performance label, average WOZ-value, building age, land subsidence rates, GLG and GHG, pile head height and inundation height. The combination of factors represent the heterogenous character of residential real estate. The normative values of these parameters are used for calculations, not a normative residence. The combination of factors can therefor not be found in one house. This fictional normative residence that incorporates the normative values of each of the parameters instead represents the normative situation for the entire sample. This approach is better suited to generalization of the outcomes to the case study area as a whole.

To maintain confidentiality and prevent potential social unrest among residents in the area of interest, the exact locations of the residences in the sample are not disclosed. The report's remarks could affect housing prices, so anonymization is necessary. The following sections introduce each case study area individually, including a data table with the most relevant parameters. A full table with asset specific characteristics is provided under Appendix C Data tables for the case study areas.

3.5.1 Dordrecht 1 | Shallow foundation, privately owned

The residence from this case study that is investigated is the largest out of the four case study areas and hence has the largest ground level surface area too. The average age of the asset is 135 years in 2050 but the sample displays a large range in building age. The shallow foundation ensures pile rot is not of any concern. It concerns a privately owned terraced house with one floor and an attic, often referred to as an 'arbeiderswoning'.

Table 19: Overview essential parameters for case study area Dordrecht 1

Parameter	Value	Unit	Range
Foundation type	Shallow		
Age building (in 2050)	120 to 150	years	30 years
Living space (total m^2)	79	m^2	
Surface area (ground floor)	50	m^2	
Property value	250.000	€	+/- 10%
Energy Label	E		D,E,F
Ownership	Private		

3.5.2 Dordrecht 2 | Shallow foundation, housing corporation

The residence from this case study that is investigated is the smallest out of the four case study areas and hence has the smallest ground level surface area too. Not unexpectedly, it is the only one with its price tag, making it the cheapest of the four. The average age of the asset is 165 years in 2050 making it the oldest of the four and consequentially has been exposed to land subsidence for the longest period of time. The shallow foundation ensures pile rot is not of any concern. It concerns terraced house with one floor and an attic, often referred to as an 'arbeiderswoning', owned by a housing corporation.

Table 20: Overview of essential parameters for case study area Dordrecht 2

Parameter	Value	Unit	Range
Foundation type	Shallow		
Age building (in 2050)	160 to 170	years	10 years
Living space (total m^2)	56	m^2	
Surface area (ground floor)	32	m^2	
Property value	200.000	€	+/- 10%
Energy Label	F		D,E,F
Ownership	Corporation		

3.5.3 Rotterdam 1 | Shallow foundation, private ownership

The residence from this case study that is investigated is the youngest of the four. The average age of the asset is 132 years in 2050. The shallow foundation ensures pile rot is not of any concern. It concerns a privately owned terraced house with two floors.

Table 21: Overview of essential parameters for case study area Rotterdam 1

Parameter	Value	Unit	Range
Foundation type	Shallow		
Age building (in 2050)	123 to 141	years	18 years
Living space (total m^2)	78	m^2	
Surface area (ground floor)	45	m^2	
Property value	250.000	€	+/- 10%
Energy Label	F		D,E,F
Ownership	Private		

3.5.4 Rotterdam 2 | Wooden pile foundation, private ownership

The residence from this case study that is investigated is the only one with a wooden pile foundation so differential settlements are of no influence to this property. The average age of the asset is 143,5 years in 2050 making, It concerns a privately owned terraced house with two floors.

Table 22: Overview parameters for case study area Rotterdam 2

Parameter	Value	Unit	Range
Foundation type	Wooden pile		
Age building (in 2050)	138 to 149	years	11 years
Living space (total m^2)	77	m^2	
Surface area (ground floor)	45	m^2	
Property value	250.000	€	+/- 10%
Energy Label	E		D,E,F
Ownership	Private		

3.6 Research integrity

The research integrity relies on four pillars: Reliability, Generalizability, Validity and Ethics

3.6.1 Reliability

The method applied is objective by nature as it relies heavily on data gathered from objective measurements provided by unbiased suppliers. Data gathering is reliable through transparency. The use of open sources helps increase transparency. It is important however to acknowledge the motivations of the different parties involved: ABN AMRO as a bank and the municipalities of Dordrecht and Rotterdam as a local governments. Their interests might be reflected in the data they provide.

3.6.2 Generalizability

The outcome that the framework provides will be specific to the area of interest but the framework itself is generalizable. The applicability of the framework can be reviewed and applied elsewhere as it is already used on four different locations with a unique combination of characterise variables. This improves generalizability outside the case study areas. This study relies on method developed in and for use inside the Netherlands. Although lessons can be learned and applied outside the Netherlands, care must be taken to alter the framework to fit foreign construction, measuring and calculation methods as well as include rules and regulations for that specific area.

3.6.3 Validity

The validity of this research is a measure of the accuracy of the study to deliver on its goals (Saunders et al., 2009) by applying clear substantiated academically accepted methods for exploration, extraction and delivery of results. The study draws directly from the latest sources in corporation with organisations active on the topic of land subsidence related damage to residential real estate. The aim is not to be perfectly precise on the exact numbers used but to paint a strongly founded picture of the interaction between local characteristics of an urban area where residential real estate is effected by land subsidence and the cost-effectiveness of different adaptation strategies. Outcomes and assumptions are compared to prior research on this topic for validation.

3.6.4 Ethics

All parties involved are made aware of the objective and autonomous position of the researcher prior to the start of the study.

4 Findings

This chapter presents a comprehensive evaluation of the cost-effectiveness of the four adaptation strategies (Renovation, Renovation including extra investments, Replacement and Replacement including densification), along with the baseline, in addressing land subsidence affecting the four case study areas (Dordrecht 1, Dordrecht 2, Rotterdam 1, Rotterdam 2). The baseline represents the conventional practices or non-adaptive actions undertaken in response to the four land subsidence consequences (Pile rot, Differential settlements, Pluvial flood risk, Dewatering risk) put forward in this thesis.

By inserting the values from chapter 3 into the equations of chapter 2 the cost, benefit and risk is calculated for each year. By means of a discount factor the results are discounted from their respective year to 2023 so their cost-effectiveness can be compared. An energy index is used to account for general price dynamics in the energy market and similarly a construction index accounts of the price dynamics of construction cost (2.4 Money (Cost Benefit Analysis). Appendix D provides an overview table per adaptation strategy for all case study areas. The tables provide all expected discounted future cash flows for all costs, benefits and prevented risk. The last column sums these items into a discounted Net Benefit per year until 2050. Summation of this column represents the Net Present Value of the adaptation strategy.

The primary objective is to assess the net present value (NPV) of each adaptation strategy, providing a quantitative measure of its financial performance up to and including 2050. By considering the temporal aspect of costs and benefits, the NPV allows us to capture the overall value generated by a particular strategy in terms of net monetary gain or loss which is the result of subtracting the sum of the benefits by the sum of the costs. Depending on the strategy, benefits include prevented risk, value of extra living space, increased housing price and energy savings whereas the costs, again depending on the strategy, include risk, cost of renovation, cost of temporary housing, costs for transition to A-label and construction costs.

In the paragraphs hereafter, the adaptation strategies are discussed one by one. Each of the adaptation strategies is accompanied by an overview table reflecting the cost structure (Cost), benefit structure (Benefit) and the net result (Net) preceded by short reminder of what the adaptation strategy entails. For closer inspection of the discounted cash flows per year, see Appendix D.

4.1 Baseline (S0)

No interventional measures are taken and all land subsidence consequences combined result in unavoidable maintenance cost and thus form the cost structure. Without any benefits the cost structure equals the net result.

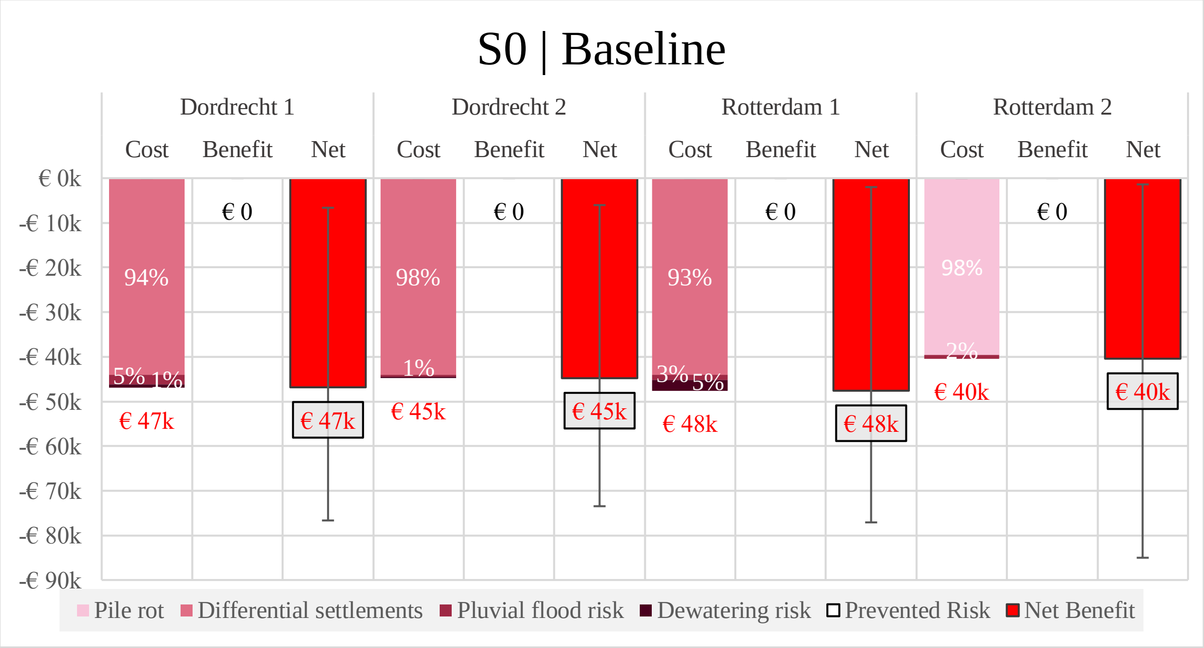

Figure 28: Net Present Value of the Baseline (S0)

The baseline, which entails maintaining the status quo without implementing any risk prevention measures, proves to be an unfavourable approach. It offers no benefits in terms of risk prevention and therefore fails to mitigate any potential hazards. Consequently, the costs associated with the baseline are equal to the net result, rendering it an unwise decision. Across the four case study areas examined, the costs remain relatively stable, ranging from approximately € 40k to € 50 euros. Notably, the largest portion of these costs is attributed to land subsidence-related consequences concerning maintenance cost of foundation repairs. Regardless of whether the properties have shallow foundations or wooden pile foundations, the expenses incurred for such repairs dominate the overall cost.

The cost of dewatering risk and pluvial flood risk does not surpass 5% of the total costs. Damage to the floor is costly but when compared to the cost of renovating the foundation it is but a minor consequence. Nevertheless this still amounts to a few thousand euros and in terms of cost-effectiveness these two consequences cannot be neglected.

The spread of the net results is consequent for the properties with a shallow foundation while for the wooden pile foundation this margin is even larger. The worst case scenarios amount to € 75k and € 90k respectively whereas the best case scenario projects damages of less than € 5k. This reflects why homeowners are in doubt about what to do and more importantly *when* to take action.

Over a longer period of time it is likely that the costs as portrayed in Figure 28 materialize but it is difficult pinpoint when exactly. In a situation where residents who are also the owners of the house (or people looking to buy a house) do not plan to stay in the house for a longer period of time, they might behave opportunistically and choose for a strategy resembling the baseline situation to deal with (or disregard) land subsidence related consequences to residential real estate. They expect to be faced with only minor consequences during their period of ownership and eventually transferring the risk to the new owners. This forms an explanation, besides a housing shortage, as to why land subsidence risk is not reflected in current housing prices all too well.

4.2 Renovation (S1)

Land subsidence issues are mitigated by renovating the foundation an stabilizing the house before jacking it up to a secure elevation height.

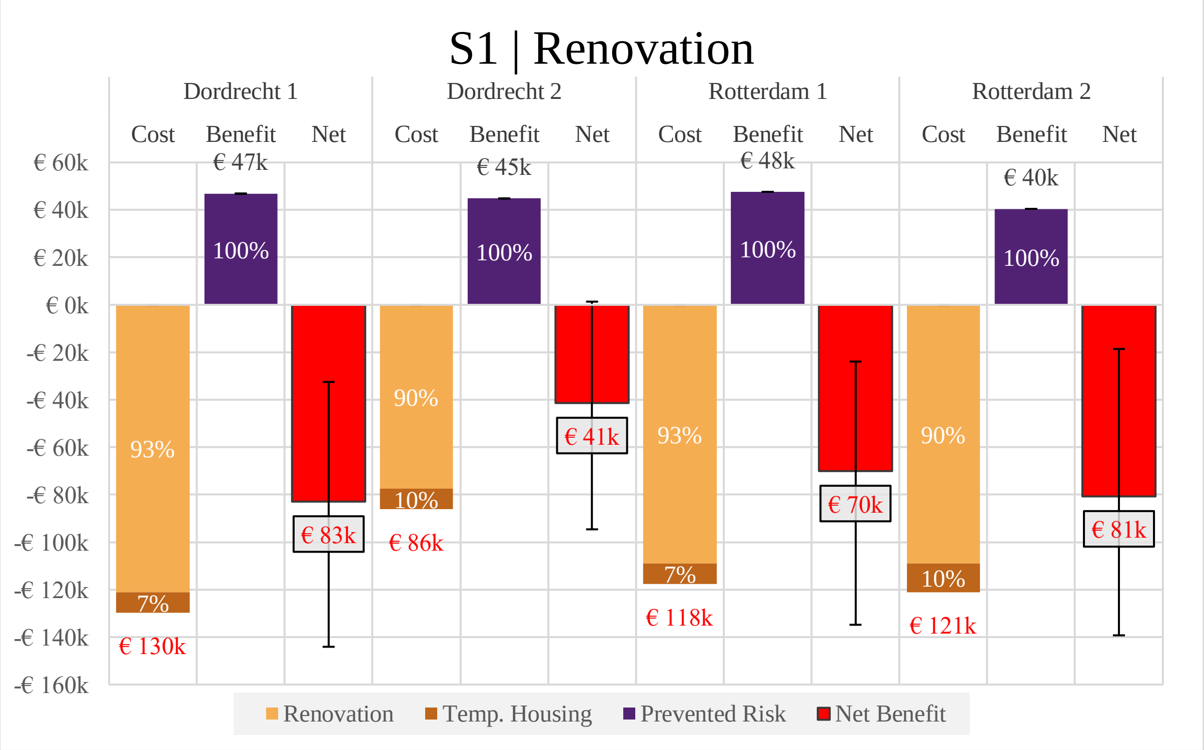

Figure 29: Net Present Value of the Renovation Strategy (S1)

In examining the four case study areas, it becomes evident that the adaptation strategy of renovating the residence yields a negative net result across the board. The prevented risk resulting from this strategy constitutes a portion ranging from one third to half of the total cost incurred. This adaptation strategy performs unfavourably.

It is important to note that both the prevented risk and the cost of renovation are closely linked to the size of the house, respectively 54, 32, 45 and 45 square meters for the case study areas. As the size of the house decreases, the prevented risk decreases correspondingly, as does the cost of renovation. However, the cost of renovation per square meter significantly surpasses the benefit of prevented risk per square meter. As a result, for smaller houses, the gap between costs and benefits narrows, leading to a less negative net result. For this reason, the renovation strategy, however inefficient, is preferable for case study area Dordrecht 2. For small houses it can therefore be reasoned that renovation of the property can be more cost-efficient than taking no measures.

Remarkably, the total cost of this renovation strategy amounts to approximately one fourth to one third of the housing price (respectively € 250k, € 200k, € 250k and € 250k) emphasizing the substantial financial implications associated with such an approach. Referring back to previous statements on the cost-effectiveness of this strategy for smaller residences, a less negative net result of only a few thousand euros needs to be weighted up against the large investments that need to be made. It is unlikely that homeowners are able and/or willing to put up their money for this so it require outside investments or a loan. Regarding the unfavourable net result of this adaptation strategy, it is near impossible to build a business case to find outside investments or organisations that are willing to provide such a big loan.

The spread of the net result has become a little larger compared to the baseline as this strategy encompasses the same and additional elements. Only in the case of Dordrecht 2 can a scenario where the costs are minimized and the benefits maximized lead to a marginally positive net result. In all other cases even the best case scenario will leave a net negative result.

4.3 Renovation including extra investments (S2)

Land subsidence issues are mitigated by renovating the foundation, stabilizing the house before jacking it up to a secure elevation and extra investments are made to increase the amount of living space and transitioning to an energy A-Label.

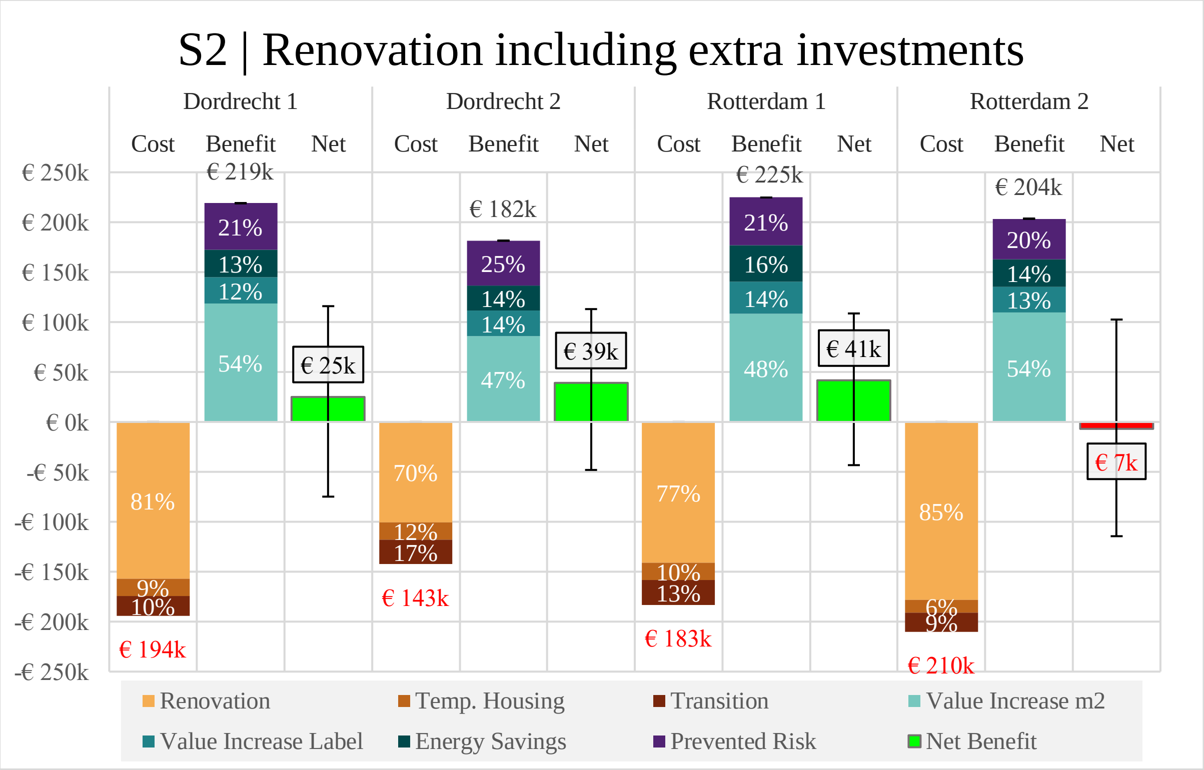

Figure 30: Net Present Value of the Renovation including extra investments Strategy (S1)

In all case study areas characterized by a shallow foundation, adaptation strategy S2 that involves renovation and additional investments proves to yield an anticipated positive net result. Making this a favourable adaptation measure when concerning shallow foundations.

The primary contributor to the overall cost remains the expense associated with the renovation, which is increased to accommodate the construction of extra square meters. Specifically, for case study areas with shallow foundations, this entails inserting an additional floor between the ground floor and the roof as this is cheaper than constructing a basement. However, for the Rotterdam 2 case study area which features a wooden pile foundation, only the cost of constructing extra square meters by means of a basement is known. As a result, the cost of renovation becomes higher leading to a negative net result.

Across all case study areas, the composition of costs and benefits exhibits similarity. The expenses associated with transitioning to an energy performance A-label are of comparable magnitude to the costs incurred for temporary housing, comprising approximately 10 to 15% of the total expenditure. Also no significant difference is perceived between the benefits of transitioning to an A-label for a privately owned house (Dordrecht 1, Rotterdam 1 and Rotterdam 2) or a house owned by a housing corporation (Dordrecht 2).

The primary driver of benefits is the added value of extra square meters of living space. This single benefit component alone is comparable in significance to the cumulative contribution of energy savings, increased housing value, and risk prevention. It is worth noting that for Dordrecht 2 the benefit of extra square meters combined with the prevented risk already balances out the cost of renovation and temporary housing. This means that renovation strategies that include investments for extra square meters but exclude a transition to A-Label *can* result in a positive net result. This is not necessarily the case as for Dordrecht 1 this would be insufficient.

Notably, the increase in renovation costs resulting from the inclusion of extra investments proves to be highly favourable. Take the smallest house (Dordrecht 2) for example, the renovation costs are increased by € 25k (compared to strategy S1) which generates € 80k in benefits for extra square meters of living space. This closes the gap of renovation cost from € 75k under strategy S1 to only € 20k under S2. Confirming that additional investments for increasing the amount of living space is a cost-effective endeavour.

The same can be said for transitioning to an A-label which too requires additional investments (cost of transition) but provide a larger benefit in the form of a lower energy bill and increased housing price. Using the same example (Dordrecht 2) the cost of transitioning is found to be around € 25k whereas the combined benefit of this measure (saving plus increased value) comes down to € 45k, hence confirming this measure to be cost-effective.

Taken together, the additional measures of transitioning to an A-label and constructing extra square meters outperforms the associated cost increase for houses where a new floor can inserted instead of having to construct a basement underneath the structure (for this study shallow foundations instead of wooden pile foundations).

For similar reasons the spread between worst and best case scenarios is larger for case study Rotterdam 2 than for a similar sized house with a shallow foundation (Rotterdam 1). This range of about 200k is similar to Dordrecht 1 because this residence is larger. Strategy S2 stacks additional measures compared to S1, hence the range increases.

In all cases the findings suggest that the investment in renovating with additional investments is a more favourable approach to land subsidence related damages to residential real estate than solely renovating or implementing no measures at all. This strategy requires large investments that resemble roughly 75% of the original housing price to realize the proposed adaptations.

With a positive net result it is possible to attract investors or persuade mortgage provides to lend (more) money. However, it must be noted that although the value increase from extra square meters and a house with a better energy performance label is of similar importance to an owner-resident as a housing corporation or outside investor, the prevented risk and lower energy bill is not. For an owner-resident planning to live in the house only for a short period of time, the prevented risk and lower energy bill don't influence their decision for taking action as much as it does an outside investor or housing corporation that plan to own the house for a longer period of time. Hence, for the latter two this adaptation strategy is favourable whereas for the owner-resident with a shorter time horizon it might not be.

4.4 Replacement (S3)

Land subsidence issues are mitigated by replacing the entire structure by a new one conform prior urban planning but by todays construction standards. This increases the value of the property and lowers the energy bill.

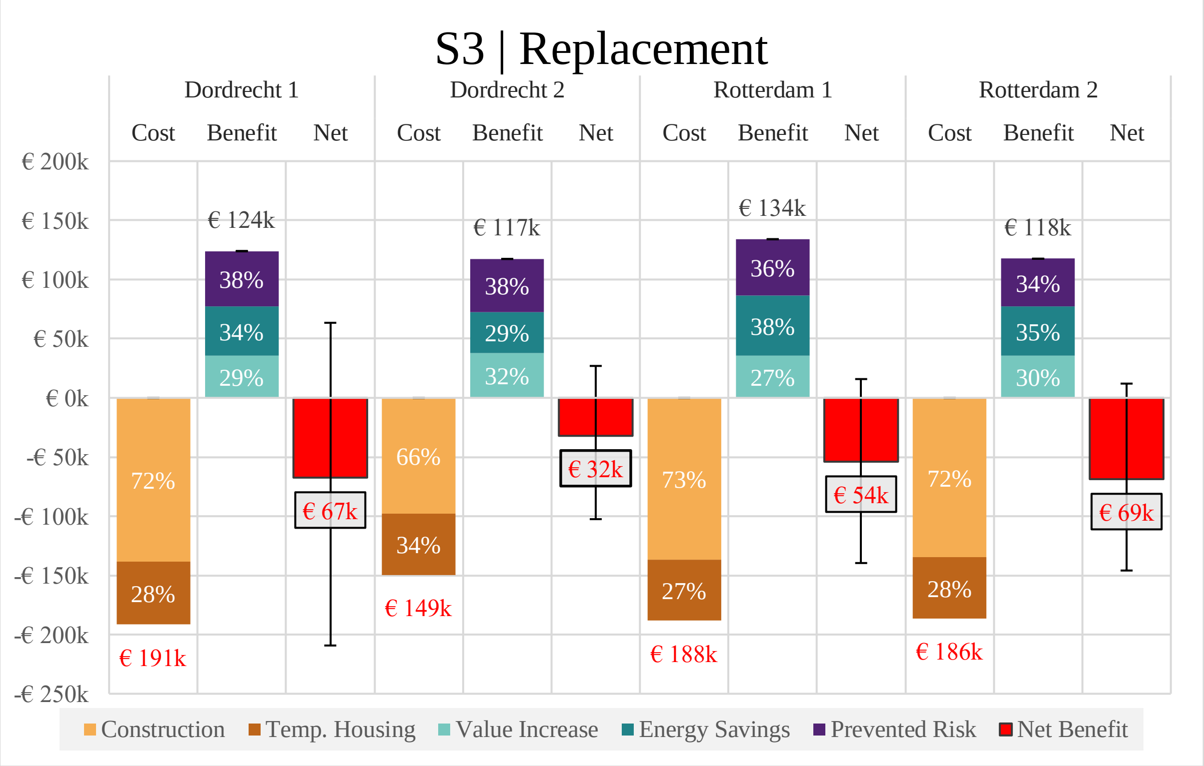

Figure 31: Net Present Value of the Replacement Strategy (S3)

The analysis of adaptation strategy S3 reveals a net negative result across all four case study areas. In comparison to strategy 2, this strategy omits the most valuable measure of constructing extra square meters of living space.

While transitioning to BENG (Nearly Energy Neutral Building) standards proves to be cost-effective (providing more benefits than costs), it alone does not generate sufficient benefits to outweigh the construction cost offset, let alone combined with the cost of temporary housing that, since the renovation process takes longer, increases the total cost even further.

Although the benefits of this strategy related to the transition in energy efficiency rating surpass those of adaptation strategy 2 (due to the additional benefits offered by the BENG standards compared to A-label standards) they are still not enough to balance the cost of construction and generate a net benefit.

The cost and benefit structure remains relatively stable across case study areas. The variation in net results primarily reflects the size of the property, with larger houses exhibiting a wider spread of outcomes. In the best-case scenarios positive net present values are observed but it is important to note that this adaptation strategy is not expected to be favourable. On the contrary, the findings suggest that this strategy will yield adverse financial implications. Hereby destroying any change on outsider investment. Also the chances that banks or other institutions are willing to provide financial means to execute this adaptation strategy are slim.

4.5 Replacement including densification (S4)

Land subsidence issues are mitigated by replacing the entire structure by a new one conform todays construction standards and a densification factor is applied to increases the amount of living space. This increases the value of the property and lowers the energy bill.

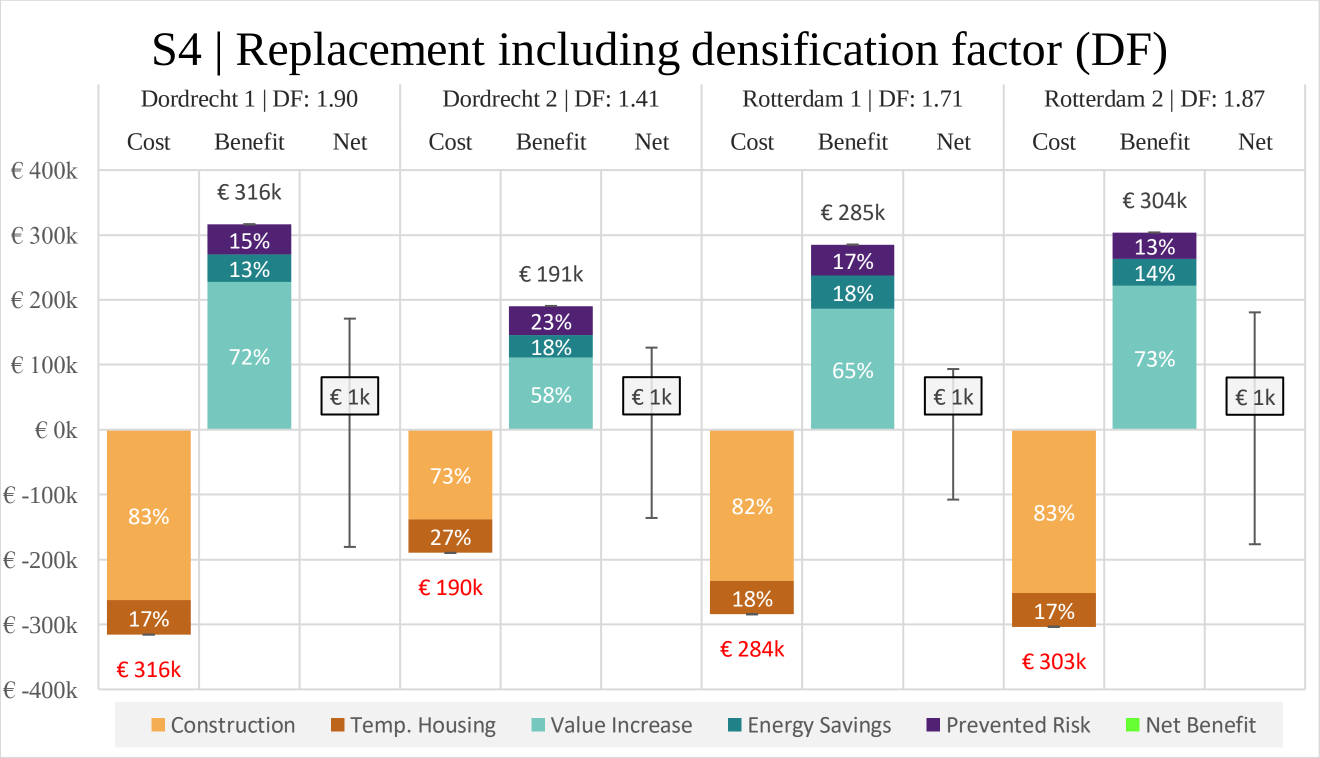

Figure 32:Net Present Value of the Replacement including densification Strategy (S4)

Adaptation strategy S4 does include the valuable measure of generating extra square meters of living space compared to S3. It is designed in a reverse-engineered manner to determine the required densification parameter that leads to a net benefit (positive net result). The net benefit depicted in the figure provides limited information; however, it confirms that with the given densification factors (DFs) of 1.90, 1.41, 1.71 and 1.87 respectively, a positive net result is consistently achieved. Furthermore, the densification factor increases with residence size. This adaptation strategy will always prove cost-effective when a DF that is larger than the minimum DF is applied.

Increasing the densification factor further enhances the net benefit obtained. Notably, larger houses necessitate more drastic measures, demanding substantial investments. This is reflected in the increasing DF for increasing residence size. Consequently, the magnitude of investments directly impacts the range of potential outcomes, which typically falls between € 200k and € 350k, with upper and lower limits equidistant from the expected net result (around 0k).

The replacement including densification strategy provides the opportunity to increase on potential net benefit by increasing the DF. This makes this strategy applicable in most situations. The drawback of this strategy however is twofold. Firstly the character of the neighbourhood changes as not only newer houses but also larger houses are built back. Secondly, larger houses offer space to more people and when the densification factor is not (only) applied to increase the size of the residences but (also) the amount of residences, the neighbourhood must be able to service more people. Increasing stress and strain on public spaces and services. The minimum required DFs to generate an expected positive net result are between 1.5 and 2 which means that solely constructing a basement will not be enough and likely the amount of residences in the case study area needs to increase to accompany for the required DF to make this adaptation strategy cost-effective.

4.6 Summary table of results

Provided below is a table to summarise the results form the previous paragraphs in this chapter for ease of comparison.

Table 23: Summary table of the net result of the adaptation strategies per case study area

	Dordrecht 1	Dordrecht 2	Rotterdam 1	Rotterdam 2
S0 (Baseline)	€ 47k	€ 48k	€ 45k	€ 40k
S1	€ 83k	€ 41k	€ 70k	€ 81k
S2	€ 25k	€ 39k	€ 41k	€ 7k
S3	€ 67k	€ 32k	€ 54k	€ 69k
S4	€ 1k (DF: 1.90)	€ 1k (DF: 1.41)	€ 1k (DF: 1.71)	€ 1k (DF: 1.87)

Table 23 above shows that favourable results where the net results is positive (benefits outweigh the costs) are only achieved under S2 and S4. The renovation strategy with extra investments and the replacement strategy with densification respectively.

4.7 Sensitivity analysis

This thesis is constructed to investigate the cost-effectiveness of various adaptation strategies in relation to location specific characteristics by calculating the costs and benefits of the adaptation strategies for four different case study areas. To do so multiple assumptions are made to come to a solid calculation. To investigate the impact of one of these assumptions a sensitivity analysis is performed on the time horizon.

4.7.1 Time horizon

The time horizon of 2050 is chosen mainly for its convenience of available data on land subsidence related risk until this period. However, this seems rather arbitrary. A longer time horizon will lead to different results for a number of reasons.

Firstly, all FCFs are discounted by a discount factor which after 28 years equals 0.454. This means that cash flows beyond this period are likely not negligibly small. For this reason we take a time horizon of 2100 for this sensitivity analysis. The corresponding discount factor is 0.149 so only 15% of the FCFs in 2100 remains after discounting back to 2023.

Secondly, the costs of all adaptation strategies with the exception of the baseline occur within the first years of the time span of the NPV calculation used in this study. However, the benefits consist of yearly occurring FCFs until perpetuity namely: energy savings and the prevented pluvial flood risk. Furthermore, the energy savings are projected to increase in accordance with the index factor of 2%.

In light of the scarcity of time and resources, the sensitivity analysis of the time horizon is performed only on the case study area of Rotterdam 2. Table 24 below provides a quick overview of the changes in cost (Δ Cost), benefit (Δ Benefit) and net result (Δ Net) between the NPV calculations with a 2050 and 2100 time horizon.

Table 24: Sensitivity analysis of time horizon shift to 2100 for Rotterdam 2

Strategy	Net 2050	Δ Cost	Δ Benefit	Net 2100
S0	€ -40k	€ -5k	€ 0,00	€ -46k
S1	€ -80k	€ 0k	€ 5k	€ -76k
S2	€ -7k	€ 0k	€ 46k	€ 39k
S3	€ -69k	€ 0k	€ 67k	€ -2k
S4	€ 0k	€ 0k	€ 62k	€ 62k

Table 24 confirms that the costs of the adaptation strategies where measures are proposed (S1, S2, S3 and S4) remains unchanged while for the baseline (S0), where costs equal the unprevented risk, show an increase in cost. Land subsidence risks occur beyond 2050 and the risk of pluvial flooding occurs every year, increasing the cost for S0 as unprevented risk while simultaneously adding to the benefits of the other strategies as prevented risk.

The benefit of S1 only contains prevented risk and is thus equal to the change in prevented land subsidence risk whereas the benefits for S2, S3 and S4 increase even further. This can directly be related to the energy savings that continue after 2050.

Table 24 undoubtedly shows all adaptation strategies where action is taken to address land subsidence related risk to real estate (S1, S2, S3 and S4) the net result improves considerably because the costs remain unchanged and the benefits increase. The impact of this can be decisive. The negative net result for adaptation strategy S2 (renovation including additional investments) has turned into a net benefit, rendering this adaptation strategy cost-effective when a time horizon of 2100 is used.

The choice of a longer time horizon can thus prove beneficial but it must always be reflected on in terms of practical use. The houses in this sample are already over 100 years old. Another 28 until a time horizon of 2050 is much more realistic than another 78 years. Within this period other problems can arise that require demolition or major renovation, consequently compromising the business case.

5 Discussion

The occurrence of localized land subsidence poses significant challenges to residential real estate, necessitating effective and cost-efficient adaptation strategies. The discussion offers space to summarize key findings, share interpretations, discuss implications and address limitations. Lastly some recommendations are made to progress research on the topic of localised land subsidence related damage to real estate.

5.1 Key findings

The central discovery of this research is that the relationship between localised land subsidence consequences and residential characteristics is decisive when choosing a cost-effective strategy to adapt to its consequences. Multiple strategic solutions exist and none of them is the sole best solution for the entirety of the possible problems.

The land subsidence damages consists predominantly of damage to the foundation in the form of pile rot or for wooden pile foundations and differential settlements for shallow foundations. Dewatering risk and pluvial flood risk only amount for a small portion of the total which amounts to over € 40,000 for all case study areas. A strategy resembling the baseline situation where no adaptation measures are implemented and the maintenance costs that arise are accepted is not favourable.

Renovation of the property is only cost effective when additional measures are proposed. The cost of solely renovating the property to prevent land subsidence related damages is more than double the prevented risk. Consequently, renovation without additional investments is less favourable than the baseline.

Constructing extra square meters of living space addresses this disparity and proves to be the most valuable measure whereby inserting an extra floor is more cost-effective than constructing a basement. In some situations this measure individually can turn the net result positive but adding measures to transition from a less favourable energy performance label to an A-Label is advised as this measure proves cost-effective across case study areas. Because of the drastic measures this strategy requires a large investment resembling 75% of the current housing prise but taken together, the adaptation strategy of renovation including additional investments to increase square meters of living space and transition to an A-label is a cost-effective strategy in three of the four cases.

Replacement of the buildings with new construction is not cost-effective without applying a densification factor. The benefits from a BENG standard home do not outweigh the construction cost. However, the expected net result can be made positive by applying a densification factor no larger than 2.0 depending on the size of the residence. Where this factor increases with growing residence size.

A further time horizon provides increased risk and increased energy saving. This means the baseline becomes more negative as unprevented risk increases whereas net result of the other adaptation strategies improves as prevented risk and energy savings are increased. This shift in time horizon has a large enough impact to render previously cost-inefficient adaptation strategies to be cost-efficient.

5.2 Interpretations

Land subsidence poses a large threat both in severity of consequence as in size. Estimation of 12,5 %to 25% of properties that will need to deal with land subsidence is incredible. A baseline situation where no action is undertaken potentially leaves a heavy financial burden for homeowners to bear so they are in dire need of solutions that pose economically favourable outcomes (i.e. an action perspective). Although it is likely that the costs materialize between now and the time horizon, it is very difficult to predict when. Homeowners are likely tempted to take on the risk when they intent to reside in the house for a short period of time. This opportunistic behaviour results in homeowners kicking the can regarding land subsidence related damage to their real estate. Breaking through this barrier requires enormous investments in terms of money, but also in research and development of new technologies, methods, policies and awareness creation. This problem appeals to a multitude of organisations including policy makers, financial institutions and academic institutions to play a role in shaping the residential housing market in the Netherlands for the future and for the better.

The findings are understood to show a clear relationship between localised land subsidence related risk and possible solutions that can be weighed up on the basis of their cost-effectiveness. Specific situations require specific solutions. Per case a choice must be made between renovation with additional investments and replacement with densification.

Renovation with additional measures poses quite a challenge technically but also planning wise and project management wise. The complexity of this approach can be regarded as a risk which is reflected in the spread between worst and best case outcomes. Opposingly this combination of activities provides opportunities for further synergies to be explored. Already this thesis has shown that renovation without transition to a more beneficial energy performance label is a waste.

Circumstance can prevail where it is better to opt for demolition. Making way for a new house without these land subsidence related problems. This tabula rasa provides plenty of opportunities to increase net benefit compared to replacing old with similar but new, even outside densification as is the case with other urban development projects. When densification is applied, one must be mindful of the impact it has on the character and the social fabric of a neighbourhood. Even if renovation with additional measures provides a negative net result, policy makers can decide to weigh this deficit against the value of keeping the characteristics of the neighbourhood intact.

5.3 Limitations

This thesis knows of the abundance of limitations. Firstly, this study does not incorporate the entire set of costs and benefits that perfectly represents the actual situation. Foundation risk, pluvial flood risk and dewatering risk are quantified in monetary terms but risks such as the welfare related costs are excluded. One can think of the experienced discomfort related to temporary housing like the hassle of moving, increased travel time and emotional distress of leaving the familiar and comfortable confines of your own house. On the scale of the case study area welfare impacts include alteration of the character of the neighbourhood, environmental impact of construction work via pollution, emission, waste and energy consumption. On the other hand, benefits also include nonmonetary items such as architectural value, improved comfort, quality and satisfaction of the end result and peace of mind knowing that the renovated or replaced residence is future proof. These risks and opportunities must be acknowledged and discussed in policy formation and decision making but for comparison by means of a monetary cost-benefit analysis as deployed in this study these factors are not quantified.

Another risk that is not incorporated is the possible devaluation of the residence when nothing is done to adapt to land subsidence. Currently the cost of foundation related damage is not represented in the housing price but with growing awareness of the problem this is likely to change. With more buyers realizing the costs related to this issue they are less willing to pay the asking price. The effect of this process in time is difficult to predict and hence not incorporated into calculations. It must be noted that this effect only improves the outcome of the adaptation strategies (net result is more favourable).

With regards to data quality, many sources provide coarse data on land subsidence and foundation issues. The Nationaal Watermodel or the Klimaateffectenatlas.nl provide maps with data averaged out over neighbourhoods. Asset specific data is not available. This limits the specificity of the outcomes. It is key to understand that this research is aimed to investigate the cost-effectiveness of land subsidence adaptations strategies for which such coarse data is often sufficient. For this reason this study makes no asset specific claims with regards to the cost effectiveness of adaptation measures but instead aims to build an understanding of the problem and the solution space to generalize the findings. Also the small sample size of only four case study areas limits the ability for claims outside of the area of interest and the inevitability of a cost figure of inserting an extra floor in between existing floors for residences with wooden pile foundations might have skewed the data.

Furthermore, most of the data that is used is dependent on a specific residential characteristic. For example, energy savings is related to the current energy performance label of the residence but not its size while it is conceivable that larger properties have more to gain from improving their energy performance than smaller properties.

Another limitation of the applicability of this results is the heterogeneous nature of residences. Even within a neighbourhood where originally the same houses were build, we find many discrepancies between them. Examples include extensions, garages, canopies and garden sheds just to name a few. Indoors we can find similar discrepancies in the form of kitchens and bathrooms for example. These discrepancies are obstacles to overcome when looking for a generalized approach for the entire neighbourhood.

The results themselves are dependent on price dynamics. Assumptions regarding the discount factor, construction cost and energy price indexes influence the outcomes of the NPV calculations. Price dynamics are notoriously hard to predict. When a farther time horizon is considered the uncertainty of these price dynamics and consequently the results increases.

Similarly, the choice of climate scenarios greatly influences the projected risk impacts and hence the cost-effectiveness of all adaptation strategies. Furthermore, the climate scenario in this thesis does not account for non-climatic developments such as the availability of financial resources, technologies, skilled people to use the resources and technologies, access to information and legal, social and organisational arrangements. An adaptation policy framework approach does aim to map these non-climatic developments and monitors these to readjust the projected future outcomes. It must be noted that the increased effort required for this approach is not likely to outweigh the increased effectiveness of the projections to reflect reality.

During the practical implementation of any of the adaptation strategies many more problems will arise that need to be addressed for the adaptation strategies to be successful. An example of such a problem is when under either of the replacement adaptation strategies the building, and in case the homeowners have a mortgage the collateral, is destroyed and only after three years a new structure will arise. When applying this strategy on a larger scale this problem can pose serious financial risks for the mortgage provider.

5.4 Implications

Judging from the size of the financial burden due to land subsidence related damage to residential real estate, many homeowners are likely to get into financial distress. On top of that, many homeowners will be caught off guard as for most houses the state of the foundation remains unknown. This can lead to unpleasant situations where some homeowners cannot pay for repairs or even default on their mortgage. This is troublesome for the banks and if impactful enough the Dutch economy at large, but also for municipalities as neighbourhoods become impoverished due to negligence of maintenance. This study exemplifies the chain reaction and hence the far reaching consequences of land subsidence related damage to residential real estate.

The key findings of this research can be used to open the debate on land subsidence as it shows that options with net benefits instead of only sunk cost exist and can work. On paper favourable, remunerative outcomes are plausible. Municipalities are cautious of engaging in conversations with residents of houses that experience land subsidence consequences without an action perspective to propose residents that can help improve their current situation. They want to avoid being the barer of bad news and want to provide practical and favourable solutions to their residents. This study provides all parties involved with an action perspective as two adaptation strategies can provide favourable outcomes for residents that might either feel stuck in their current situation. This piece can function as a starting point for an open dialogue with residents, investors, municipalities and other stakeholders on how to realize one or a mix of these adaptation strategies.

Besides private home owners, land subsidence affected houses can also be owned by housing corporations. The cost-benefit analysis in this study not only shows that a favourable outcome can be achieved via densification when replacing the current houses and by renovation with extra investments, it also contributes to the understanding of the financial realisation of these strategies. By showing the build up of the benefits, a distinction can be made between the value increase of the residence and the avoided costs (prevented risk and lower energy bill). The first take effect on relatively short time span of a few years whereas the later are only marginal contributions per year but accumulate over time. In other words, adaptation strategies based on prevented cost are more difficult to finance. This implies that for housing cooperations, who are more likely to own the residence for the duration of the timespan applied in this study (until 2050), the avoided costs are more important than for owner-residents who aim to sell their house after only a few years. In practice the renovation strategy seems more applicable to houses owned by housing cooperations than those owned privately.

On the theoretical side the implications have shown there to be a relation between the land subsidence related risks of pile rot, differential settlements, pluvial flood risk and dewatering risk and the cost-effectiveness of various adaptation strategies. Strategy four of replacing the structure and densifying that what you build back is relatively similar to other new construction projects but the many more theoretical improvements can be made regarding the combined approach of strategy 2 by renovating the foundation, jacking up the house, restructuring the entire building to accommodate more square meters of living space and improving on energy efficiency. So many topics come together on this cross roads and theoretical exploration of the solution space and the interactivity of certain operations can vastly improve overall benefits and therefor cost-effectiveness of similar adaptation strategies.

It proves useful to investigate multiple approaches and asses their cost-effectiveness. This being said, addressing land subsidence by exclusively renovating the foundation is, for as far as the characteristic differences in the samples go, a foolish endeavour. Benefits can be generated when one places land subsidence issues in a broader context including the housing crisis, energy transition and sustainability movement.

This study demonstrates the size of the cashflows involved in the process of transitioning towards a situation where land subsidence related consequences are adapted. Taken together with the size of this issue (more than 1 million houses) it can motivate private companies to develop new methods and techniques that open up new possibilities and/or cut costs of interventions drastically. There is plenty of room for development regarding this specific issue both technically and economically. This study does not account for such developments over time similarly as climate scenarios do not do this.

6 Conclusion

This thesis is concluded by restating the research questions, elaborating on the significance of this research and providing recommendations for future direction.

6.1 Answering research question

The thesis has answered the first sub-questions regarding risk estimation as a combination of foundation risk and pluvial flood risk and the second sub-question regarding the available adaptation strategy options in chapter 2. The third sub-question of calculating the net-benefit per adaptation strategy is resolved in chapter 4. Together they provide a basis to answer the main research question.

The research question: "*What constitutes a cost-effective adaptation strategy to land subsidence related damage to residential real estate?*" has one overarching answer and two separate alternatives. Whether renovation or replacement is preferred, a cost-effective adaptation strategy utilize additional measures that require additional investments to provide a positive net benefit.

For renovation bases adaptation strategies this means constructing extra square meters when renovating the foundation of the house and simultaneously adopting measures to improve on the energy performance of the building.

For replacement based adaptation strategies this means applying a densification factor to increase the current amount of square meters of living space by increasing the residences that is build back, building back more residences or a hybrid option.

6.2 Significance

The results provide an action perspective for homeowners and other stakeholders such as policy makers and financial institutions. It shows not only that cost-effective adaption to land subsidence related damage to residential real estate exists but puts two alternative strategies forward and substantiates their approach and relative cost-effectiveness in relation to residential characteristics. It serves as a basis for open discussions between stakeholders on this subject now possible solutions have been laid out theoretically. It serves as a basis for relative comparison, not exact calculations of costs and benefits.

With current dynamics in the housing market where investors are weary of changing regulations regarding renting out apartments, it can prove interesting to invest in land subsidence adaptation strategies on the basis of this study. Attracting financers is key to realize the favourable adaptation strategies put forward by this study and with favourable outcomes this is possible. Even more so when the fact that these land subsidence affected houses are located within cities and city centres is taken into account. These prime locations usually are not usually up for development and when renovation is applied, residences not necessarily have to be acquired when an agreement can be found with residents for them to move back after works have been completed. This drastically reduces the cost of investment and helps attract investors.

This study puts two tools in the toolbox which policy makers can deploy to deal with land subsidence affected areas: renovation with additional investments and replacement with densification. Together with all other stakeholders a decision can made to deploy one or the other depending on the structures in the area of interest. For instance, monumental buildings that are to be preserved can be adapted using the renovation with extra investments strategy whereas for other buildings a replacement with densification can be applied. This increases the options and thus solution space for all involved parties to work with.

6.3 Recommendations

With more and more houses added to the list of being at risk to land subsidence, it is essential to build upon this action perspective for residents of these houses. The next step would be to start the discussion with all relevant stakeholders on the topic of land subsidence related damage to residential real estate by putting the two cost-effective adaptation strategies on the table for consideration.

The next step would be to put the cost-effective adaptation strategies to the test by organizing two practical case studies. One where renovation with additional investments is applied and the other where renovation with densification is applied. Testing the two cost-effective adaptation strategies in practice would provide useful insights on the additional costs and benefits that are overlooked by this thesis and the will unveil all other obstacles that have to be overcome outside of the financial cost-effectiveness and can verify or dismiss claims made by this thesis.

Scholar can further this research by diving deeper in to the possibility of combining various renovation and upgrade techniques and construct an integrated approach for addressing land subsidence related damages in the broader economic perspective to maximise potential synergies. Academic research can help improve damage estimation by modelling the physical processes of pile rot, differential settlements and dewatering risk in more detail. Specifically the first two as they are the primary contributors to the land subsidence related consequences. There is much to be gained with regards to the certainty and effectiveness of these damage estimation methods.

Furthermore, the sensitivity analysis concerning the time horizon has shown that a time horizon beyond 2050 improves the cost-effectiveness of all adaptation strategies with exception of the baseline. Investigating the optimal time horizon to reflect practical implications can improve the results provided by this study.

Similarly, the monetization of costs and benefits by extending research on relevant pricing can be improved. Bringing in more experts can help solidify cost and benefit estimates and help reduced the solution space of the net result.

To improve on the data quality, this thesis urges to increase the amount of foundation surveys either by improving public availability of existing survey from archives or by persuading homeowners or potential buyers to request a foundation survey. The latter proves problematic because homeowners might behave opportunistic and do not want to know what the underlying risk is that they are facing because it is difficult to predict when these costs materialize, as this thesis has confirmed.

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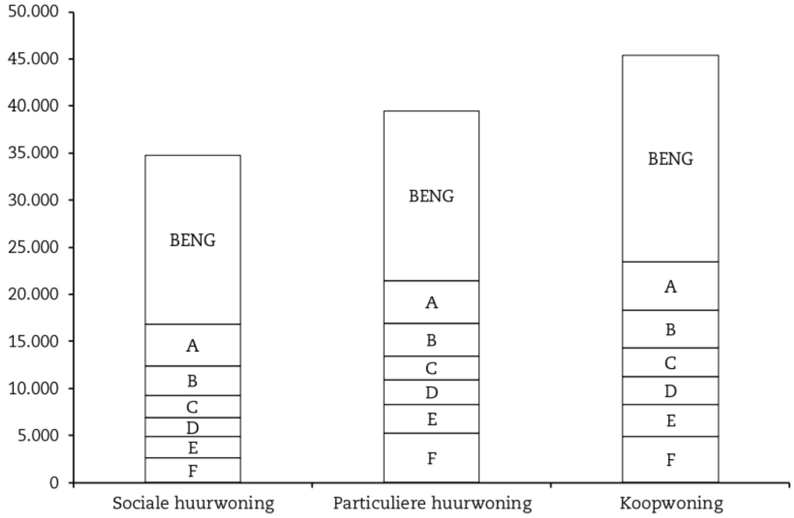
Appendices

Appendix A Investment costs and savings for transitions in energy label

Investment costs in euro () per residence for different steps towards energy neutrality (https://www.eib.nl/pdf/EIB-notitie_Klimaatbeleid_en_de_gebouwde_omgeving.pdf)

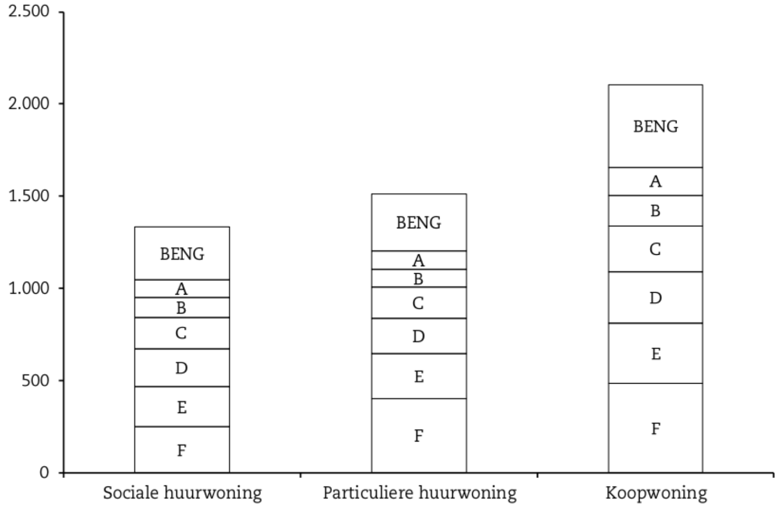
Figuur 1 Investeringskosten per woning van verschillende stappen richting energieneutraliteit, in €



Bron: ECN/ EIB

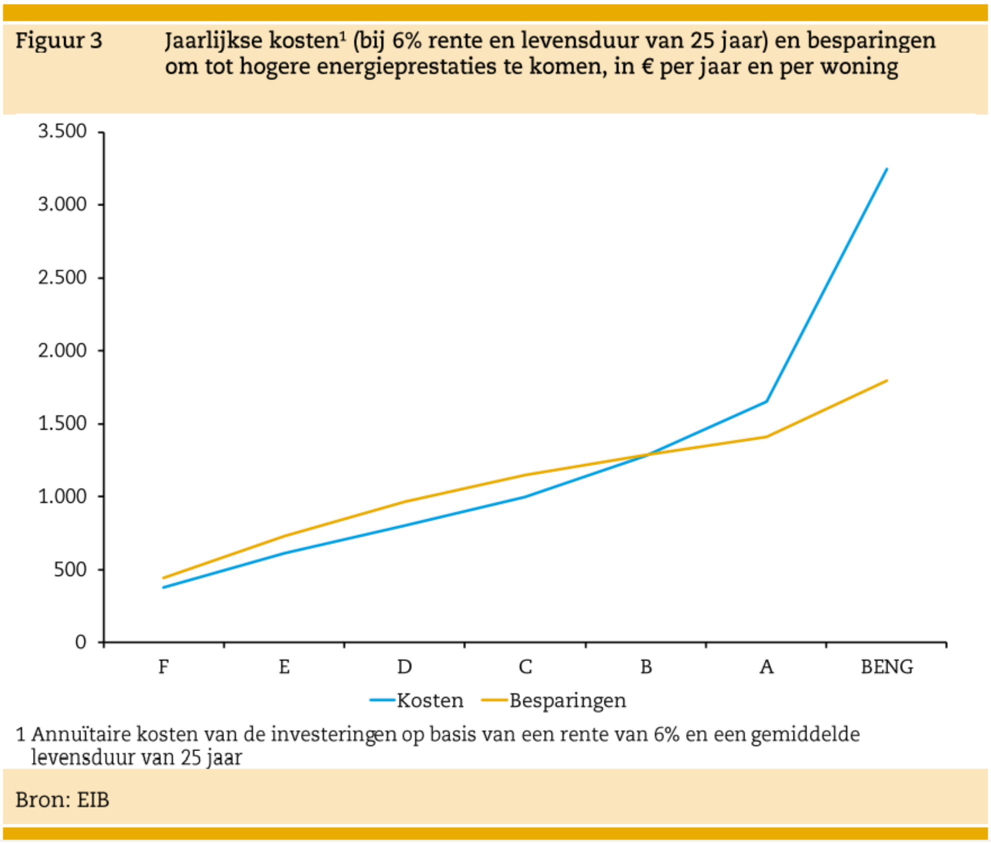
Savings for different steps towards energy neutrality, in euros per residence

Figuur 2 Gemiddelde energiebesparing per labelstap, in € per woning per jaar



Bron: ECN / EIB

Yearly cost and saving to get to higher energy performance, in euros per year per residence



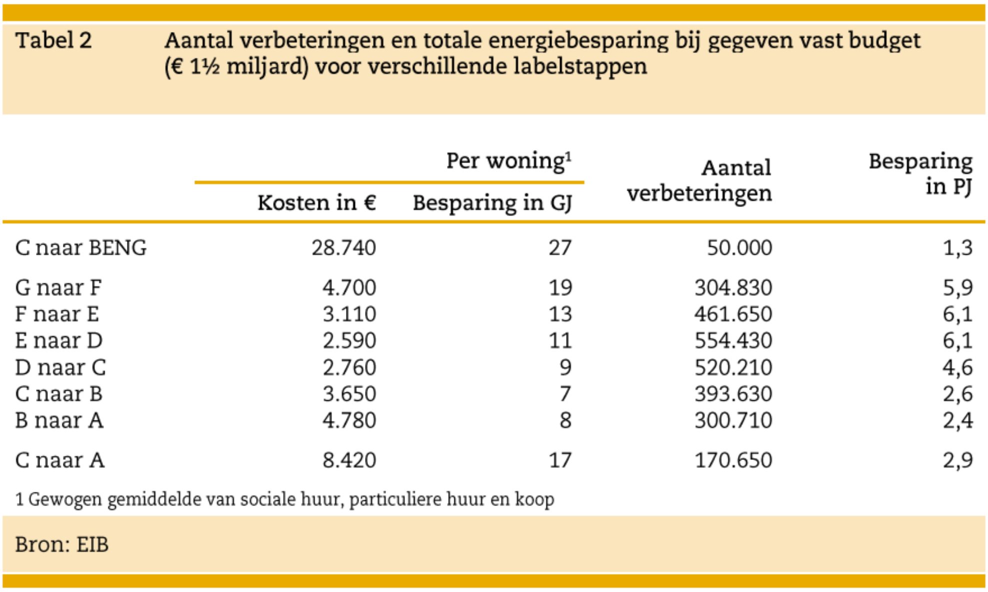
Figuur 3 Jaarlijkse kosten[1] (bij 6% rente en levensduur van 25 jaar) en besparingen om tot hogere energieprestaties te komen, in € per jaar en per woning

1 Annuïtaire kosten van de investeringen op basis van een rente van 6% en een gemiddelde levensduur van 25 jaar

Bron: EIB

Amount of improvements and total energy savings for given budget (1,5 billion euro) for various steps in labels

Includes cost of transition per step in label and projected energy savings.



Tabel 2 Aantal verbeteringen en totale energiebesparing bij gegeven vast budget (€ 1½ miljard) voor verschillende labelstappen

	Per woning[1]		Aantal verbeteringen	Besparing in PJ
	Kosten in €	Besparing in GJ		
C naar BENG	28.740	27	50.000	1,3
G naar F	4.700	19	304.830	5,9
F naar E	3.110	13	461.650	6,1
E naar D	2.590	11	554.430	6,1
D naar C	2.760	9	520.210	4,6
C naar B	3.650	7	393.630	2,6
B naar A	4.780	8	300.710	2,4
C naar A	8.420	17	170.650	2,9

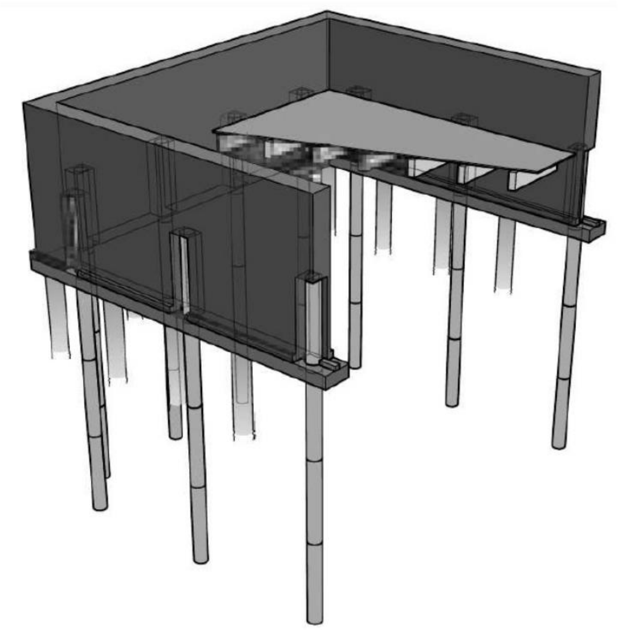
1 Gewogen gemiddelde van sociale huur, particuliere huur en koop

Bron: EIB

Appendix B Construction methods for foundation renovation

1 Strengthening by adding piles

1.1 Hydraulic cylinders anchored to the floor press foundation piles down. Can be installed right underneath the walls (free from vibrations).

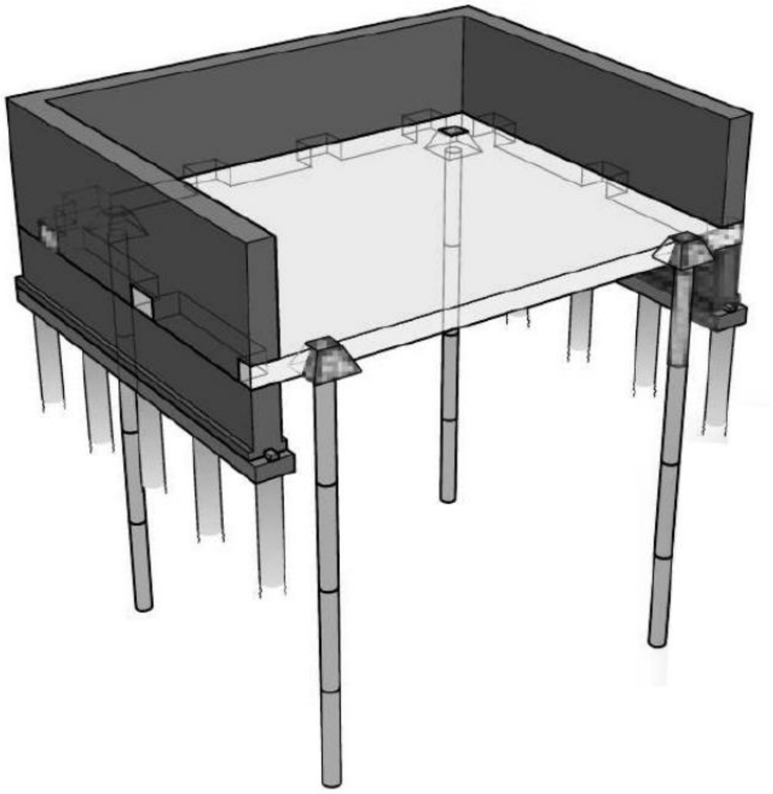


1.2 Mechanical drill on tracks drills down foundation piles from inside the building (free from vibrations).

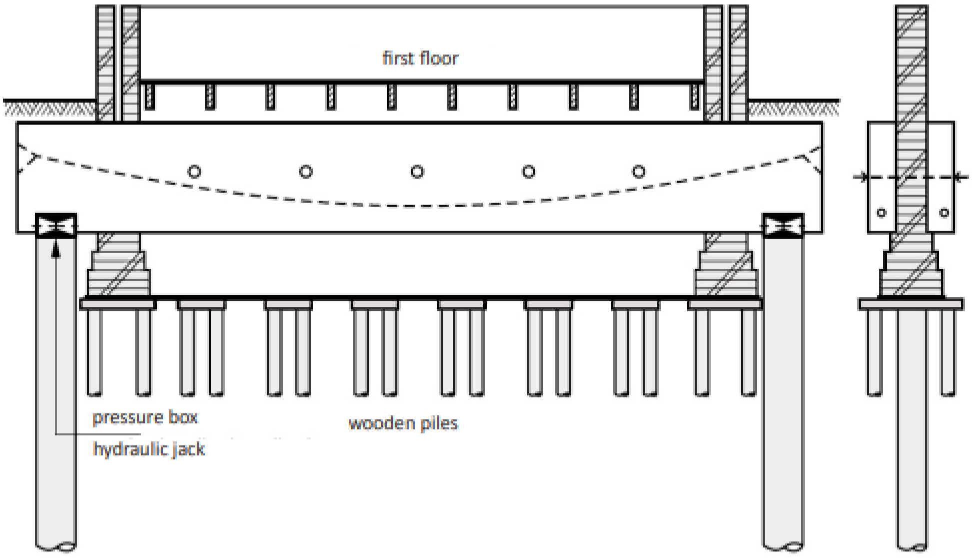
2 Lowering wooden pile heads

Steps for renovating wooden pile heads by lowering the existing wooden heads and replacing them by concrete ones. From left to right, top to bottom: Rotten pile head, Pile head sawn off and replaced with formwork and steel reinforcement, Closed off formwork ready to be poured, New concrete pile head after drying.

3 Floor slab piling (tafelmethode)
Old structure is carried by newly formed concrete floor that rest on new concrete piles



5 Pile foundation with prestressed concrete beams
Beams carry the old structure, resting on newly formed concrete piles.



Appendix C Data tables for the case study areas

Dordrecht 1

Parameter	**Value**	**Unit**	**Range**
Asset specific characteristics			
Residence type	Terraced		
Population size	57	houses	
Foundation type	Shallow		
Completion	1900 to 1930	year	30 years
Age building	93 to 123	year	30 years
Age building (in 2050)	120 to 150	year	30 years
Living space (total m^2)	79	m^2	
Surface area (ground floor)	50	m^2	
Property value	250.000	€	+/- 10%
price per m2 (living space)	3.165	€/m^2	
Energy Label	E		D,E,F
Ownership	Private		
Residents	Owners		
Number of floors	1		
Attic	Yes		
Basement	No		
Partial basement	No		
Height of doorstep (relative to ground level)	10	cm	+/- 5 cm
Soil type underneath structure	Clay		
Thickness fill layer	0 to 1	m	+/- 50%
External parameters			
Land subsidence rate	3,5	mm/year	+/- 1mm/year
Variance in settlement rates	Average		
Dewatering depth	60	cm	+/- 5 cm
GHG increase 2050	0	cm	+/- 25cm
Dewatering depth 2050	60	cm	
Inundation height (1 in 100 year event)	> 30	cm	+/- 15%

Dordrecht 2

Parameter	Value	Unit	**Range**
Asset specific characteristics			
Residence type	Terraced		
Population size	17	houses	
Foundation type	Shallow		
Foundation risk			
Completion	1880 to 1890	year	10 years
Age building	133 to 143	year	10 years
Age building (in 2050)	160 to 170	year	10 years
Living space (total m^2)	56	m^2	
Surface area (ground floor)	32	m^2	
Property value	200.000	€	+/- 10%
price per m2 (living space)	3.570	€/m^2	
Energy Label	F		E,F,G
Ownership	Corporation		
Residents	Renters		
Number of floors	1		
Attic	Yes		
Basement	No		
Partial basement	No		
Height of doorstep (relative to ground level)	10	cm	+/- 5cm
Soil type underneath structure	Clay		
Thickness fill layer	0 to 1	m	+/- 50%
External parameters			
Land subsidence rate	4	mm/year	+/- 1mm/year
Variance in settlement rates	High		
Dewatering depth	70	cm	+/- 5cm
GHG increase 2050	0	cm	+/- 25cm
Dewatering depth 2050	70	cm	
Inundation height (1 in 100 year event)	10	cm	+/- 15%

Rotterdam 1

Parameter	Value	Unit	Range
Asset specific characteristics			
Residence type	Terraced		
Population size	62	houses	
Foundation type	Shallow		
Foundation risk	1 to 5 (high)	% at risk	
Completion	1909 to 1927	year	18 years
Age building	96 to 114	year	18 years
Age building (in 2050)	123 to 141	year	18 years
Living space (total m^2)	78	m^2	
Surface area (ground floor)	45	m^2	
Property value	250.000	€	+/- 10%
price per m2 (living space)	3.205	€/m^2	
Energy Label	F		E,F,G
Ownership	Private		
Residents	Owners		
Number of floors	2		
Attic	Yes		
Basement	No		
Partial basement	No		
Height of doorstep (relative to ground level)	15	cm	+/- 5cm
Soil type underneath structure	Clay/Peat		
Thickness fill layer	0 to 1	m	+/- 50%
External parameters			
Land subsidence rate	3	mm/year	+/- 1mm/year
Variance in settlement rates	Average		
Dewatering depth	7	cm	+/- 5cm
GHG increase 2050	0	cm	+/- 25cm
Dewatering depth 2050	7	cm	
Inundation height (1 in 100 year event)	20	cm	+/- 15%

Rotterdam 2

Parameter	Value	Unit	Range
Asset specific characteristics			
Type of residence	Terraced		
Population size	250	houses	
Type of foundation	Wooden pile		
Foundation risk	5 tot 30	% at risk	
Completion	1901 to 1912	year	11 years
Age building	111 to 122	year	11 years
Age building (in 2050)	138 to 149	year	11 years
Living space (total)	77	m^2	
Surface area (ground floor)	45	m^2	
Property value	250.000	€	+/- 10%
price per m2	3.246	€/m^2	
Energy Label	E		C,E,G
Ownership	Private		
Rent/own	Owners		
Number of floors	2		
Attic	Yes		
Basement	No		
Partial basement	No		
Height of doorstep relative to surface level	17	cm	+/- 5cm
Depth of pile head (relative to NAP)	-258	cm	+/- 5%
External parameters			
Land subsidence rate			
Variance in settlement rates	High		
GHG (relative to NAP)	-204	cm	
GLG (relative to NAP)	-241		+/- 25cm
Pile head cover	17	cm	+/- 5cm
Dewatering depth	117	cm	+/- 5cm
Inundation height 1 in 100 year event	15	cm	+/- 15%

Appendix D Net Present Value (NPV) calculations

This appendix includes the tables for the NPV calculations per adaptation strategy (Baseline, Strategy 1: Renovate, Strategy 2: Renovate with extra investments, Strategy 3: Replace, and Strategy 4: Replace and densify) in order of case study area (Rotterdam 1, Rotterdam 2, Dordrecht 1 and Dordrecht 2).

	Dordrecht 1 | Baseline		
	Net Benefit		
Year	Risk	Prevented Risk	Net Benefit
2023	€ 104,92	€ 0,00	-€ 104,92
2024	€ 102,36	€ 0,00	-€ 102,36
2025	€ 99,86	€ 0,00	-€ 99,86
2026	€ 97,43	€ 0,00	-€ 97,43
2027	€ 95,05	€ 0,00	-€ 95,05
2028	€ 92,73	€ 0,00	-€ 92,73
2029	€ 90,47	€ 0,00	-€ 90,47
2030	€ 88,26	€ 0,00	-€ 88,26
2031	€ 86,11	€ 0,00	-€ 86,11
2032	€ 84,01	€ 0,00	-€ 84,01
2033	€ 81,96	€ 0,00	-€ 81,96
2034	€ 79,96	€ 0,00	-€ 79,96
2035	€ 78,01	€ 0,00	-€ 78,01
2036	€ 76,11	€ 0,00	-€ 76,11
2037	€ 74,25	€ 0,00	-€ 74,25
2038	€ 72,44	€ 0,00	-€ 72,44
2039	€ 70,67	€ 0,00	-€ 70,67
2040	€ 68,95	€ 0,00	-€ 68,95
2041	€ 67,27	€ 0,00	-€ 67,27
2042	€ 65,63	€ 0,00	-€ 65,63
2043	€ 64,03	€ 0,00	-€ 64,03
2044	€ 62,47	€ 0,00	-€ 62,47
2045	€ 60,94	€ 0,00	-€ 60,94
2046	€ 59,46	€ 0,00	-€ 59,46
2047	€ 58,01	€ 0,00	-€ 58,01
2048	€ 56,59	€ 0,00	-€ 56,59
2049	€ 55,21	€ 0,00	-€ 55,21
2050	€ 44.750,44	€ 0,00	-€ 44.750,44
	€ 46.843,59	€ 0,00	-€ 46.843,59

	Dordrecht 1 | Strategy 1			
	Net Present Value of Expected Outcome			
Year	Renovation	Temp. Housing	Prevented Risk	Net Benefit
2023	€ 121.000,00	€ 8.750,00	€ 104,92	-€ 129.645,08
2024	€ 0,00	€ 0,00	€ 102,36	€ 102,36
2025	€ 0,00	€ 0,00	€ 99,86	€ 99,86
2026	€ 0,00	€ 0,00	€ 97,43	€ 97,43
2027	€ 0,00	€ 0,00	€ 95,05	€ 95,05
2028	€ 0,00	€ 0,00	€ 92,73	€ 92,73
2029	€ 0,00	€ 0,00	€ 90,47	€ 90,47
2030	€ 0,00	€ 0,00	€ 88,26	€ 88,26
2031	€ 0,00	€ 0,00	€ 86,11	€ 86,11
2032	€ 0,00	€ 0,00	€ 84,01	€ 84,01
2033	€ 0,00	€ 0,00	€ 81,96	€ 81,96
2034	€ 0,00	€ 0,00	€ 79,96	€ 79,96
2035	€ 0,00	€ 0,00	€ 78,01	€ 78,01
2036	€ 0,00	€ 0,00	€ 76,11	€ 76,11
2037	€ 0,00	€ 0,00	€ 74,25	€ 74,25
2038	€ 0,00	€ 0,00	€ 72,44	€ 72,44
2039	€ 0,00	€ 0,00	€ 70,67	€ 70,67
2040	€ 0,00	€ 0,00	€ 68,95	€ 68,95
2041	€ 0,00	€ 0,00	€ 67,27	€ 67,27
2042	€ 0,00	€ 0,00	€ 65,63	€ 65,63
2043	€ 0,00	€ 0,00	€ 64,03	€ 64,03
2044	€ 0,00	€ 0,00	€ 62,47	€ 62,47
2045	€ 0,00	€ 0,00	€ 60,94	€ 60,94
2046	€ 0,00	€ 0,00	€ 59,46	€ 59,46
2047	€ 0,00	€ 0,00	€ 58,01	€ 58,01
2048	€ 0,00	€ 0,00	€ 56,59	€ 56,59
2049	€ 0,00	€ 0,00	€ 55,21	€ 55,21
2050	€ 0,00	€ 0,00	€ 44.750,44	€ 44.750,44
	€ 121.000,00	€ 8.750,00	€ 46.843,59	-€ 82.906,41

Dordrecht 1 | Strategy 2

Net Present Value of Expected Outcome

Year	Renovation	Temp. Housing	Transition	Extra m2	House price	Energy Savings	Prevented Risk	Net Benefit
2023	€ 156.750,00	€ 17.500,00	€ 19.795,00	€ 118.670,89	€ 26.000,00	€ 1.050,00	€ 104,92	-€ 48.219,19
2024	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.044,88	€ 102,36	€ 1.147,24
2025	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.039,78	€ 99,86	€ 1.139,64
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.034,71	€ 97,43	€ 1.132,13
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.029,66	€ 95,05	€ 1.124,71
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.024,64	€ 92,73	€ 1.117,37
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.019,64	€ 90,47	€ 1.110,11
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.014,67	€ 88,26	€ 1.102,93
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.009,72	€ 86,11	€ 1.095,83
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.004,79	€ 84,01	€ 1.088,80
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 999,89	€ 81,96	€ 1.081,85
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 995,01	€ 79,96	€ 1.074,97
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 990,16	€ 78,01	€ 1.068,17
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 985,33	€ 76,11	€ 1.061,44
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 980,52	€ 74,25	€ 1.054,77
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 975,74	€ 72,44	€ 1.048,18
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 970,98	€ 70,67	€ 1.041,65
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 966,24	€ 68,95	€ 1.035,19
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 961,53	€ 67,27	€ 1.028,80
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 956,84	€ 65,63	€ 1.022,47
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 952,17	€ 64,03	€ 1.016,20
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 947,53	€ 62,47	€ 1.009,99
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 942,91	€ 60,94	€ 1.003,85
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 938,31	€ 59,46	€ 997,76
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 933,73	€ 58,01	€ 991,73
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 929,17	€ 56,59	€ 985,76
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 924,64	€ 55,21	€ 979,85
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 920,13	€ 44.750,44	€ 45.670,58
	€ 156.750,00	€ 17.500,00	€ 19.795,00	€ 118.670,89	€ 26.000,00	€ 27.543,32	€ 46.843,59	€ 25.012,80

	Dordrecht 1 | Strategy 3						
	Net Present Value of Expected outcome						
Year	Demolition	Temp. Housing	Construction	Value Residence	Energy Savings	Prevented Risk	Net Benefit
2023	€ 250.000,00	€ 21.000,00	€ 138.250,00	€ 0,00	€ 1.585,00	€ 104,92	-€ 407.560,08
2024	€ 0,00	€ 21.307,32	€ 0,00	€ 0,00	€ 1.577,27	€ 102,36	-€ 19.627,69
2025	€ 0,00	€ 10.809,57	€ 0,00	€ 285.544,32	€ 1.569,57	€ 99,86	€ 276.404,19
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.561,92	€ 97,43	€ 1.659,34
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.554,30	€ 95,05	€ 1.649,35
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.546,72	€ 92,73	€ 1.639,45
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.539,17	€ 90,47	€ 1.629,64
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.531,66	€ 88,26	€ 1.619,93
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.524,19	€ 86,11	€ 1.610,30
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.516,76	€ 84,01	€ 1.600,77
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.509,36	€ 81,96	€ 1.591,32
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.502,00	€ 79,96	€ 1.581,96
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.494,67	€ 78,01	€ 1.572,68
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.487,38	€ 76,11	€ 1.563,49
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.480,12	€ 74,25	€ 1.554,37
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.472,90	€ 72,44	€ 1.545,34
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.465,72	€ 70,67	€ 1.536,39
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.458,57	€ 68,95	€ 1.527,52
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.451,45	€ 67,27	€ 1.518,72
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.444,37	€ 65,63	€ 1.510,00
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.437,33	€ 64,03	€ 1.501,35
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.430,32	€ 62,47	€ 1.492,78
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.423,34	€ 60,94	€ 1.484,28
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.416,39	€ 59,46	€ 1.475,85
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.409,49	€ 58,01	€ 1.467,49
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.402,61	€ 56,59	€ 1.459,20
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.395,77	€ 55,21	€ 1.450,98
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.388,96	€ 44.750,44	€ 46.139,40
	€ 250.000,00	€ 53.116,88	€ 138.250,00	€ 285.544,32	€ 41.577,29	€ 46.843,59	-€ 67.401,68

Dordrecht 1 | Strategy 4 (Extra: 68 m2, Densifcation: 1.90)

Net Present Value of Expected outcome

Year	Demolition	Temp. Housing	Construction	Value Residence	Energy Savings	Prevented Risk	Net Benefit
2023	€ 250.000,00	€ 21.000,00	€ 262.500,00	€ 0,00	€ 1.585,00	€ 104,92	-€ 531.810,08
2024	€ 0,00	€ 21.307,32	€ 0,00	€ 0,00	€ 1.577,27	€ 102,36	-€ 19.627,69
2025	€ 0,00	€ 10.809,57	€ 0,00	€ 478.015,65	€ 1.569,57	€ 99,86	€ 468.875,52
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.561,92	€ 97,43	€ 1.659,34
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.554,30	€ 95,05	€ 1.649,35
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.546,72	€ 92,73	€ 1.639,45
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.539,17	€ 90,47	€ 1.629,64
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.531,66	€ 88,26	€ 1.619,93
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.524,19	€ 86,11	€ 1.610,30
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.516,76	€ 84,01	€ 1.600,77
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.509,36	€ 81,96	€ 1.591,32
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.502,00	€ 79,96	€ 1.581,96
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.494,67	€ 78,01	€ 1.572,68
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.487,38	€ 76,11	€ 1.563,49
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.480,12	€ 74,25	€ 1.554,37
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.472,90	€ 72,44	€ 1.545,34
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.465,72	€ 70,67	€ 1.536,39
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.458,57	€ 68,95	€ 1.527,52
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.451,45	€ 67,27	€ 1.518,72
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.444,37	€ 65,63	€ 1.510,00
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.437,33	€ 64,03	€ 1.501,35
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.430,32	€ 62,47	€ 1.492,78
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.423,34	€ 60,94	€ 1.484,28
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.416,39	€ 59,46	€ 1.475,85
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.409,49	€ 58,01	€ 1.467,49
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.402,61	€ 56,59	€ 1.459,20
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.395,77	€ 55,21	€ 1.450,98
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.388,96	€ 44.750,44	€ 46.139,40
	€ 250.000,00	€ 53.116,88	€ 262.500,00	€ 478.015,65	€ 41.577,29	€ 46.843,59	€ 819,65

	Dordrecht 2 | Baseline		
	Net Benefit		
Year	Risk	Prevented Risk	Net Benefit
2023	€ 20,72	€ 0,00	-€ 20,72
2024	€ 20,22	€ 0,00	-€ 20,22
2025	€ 19,73	€ 0,00	-€ 19,73
2026	€ 19,24	€ 0,00	-€ 19,24
2027	€ 18,78	€ 0,00	-€ 18,78
2028	€ 18,32	€ 0,00	-€ 18,32
2029	€ 17,87	€ 0,00	-€ 17,87
2030	€ 17,43	€ 0,00	-€ 17,43
2031	€ 17,01	€ 0,00	-€ 17,01
2032	€ 16,59	€ 0,00	-€ 16,59
2033	€ 16,19	€ 0,00	-€ 16,19
2034	€ 15,79	€ 0,00	-€ 15,79
2035	€ 15,41	€ 0,00	-€ 15,41
2036	€ 15,03	€ 0,00	-€ 15,03
2037	€ 14,67	€ 0,00	-€ 14,67
2038	€ 14,31	€ 0,00	-€ 14,31
2039	€ 13,96	€ 0,00	-€ 13,96
2040	€ 13,62	€ 0,00	-€ 13,62
2041	€ 13,29	€ 0,00	-€ 13,29
2042	€ 12,96	€ 0,00	-€ 12,96
2043	€ 12,65	€ 0,00	-€ 12,65
2044	€ 12,34	€ 0,00	-€ 12,34
2045	€ 12,04	€ 0,00	-€ 12,04
2046	€ 11,74	€ 0,00	-€ 11,74
2047	€ 11,46	€ 0,00	-€ 11,46
2048	€ 11,18	€ 0,00	-€ 11,18
2049	€ 10,91	€ 0,00	-€ 10,91
2050	€ 44.383,78	€ 0,00	-€ 44.383,78
	€ 44.797,24	€ 0,00	-€ 44.797,24

	Dordrecht 2 | Strategy 1			
	Net Present Value of Expected Outcome			
Year	Renovation	Temp. Housing	Prevented Risk	Net Benefit
2023	€ 77.440,00	€ 8.750,00	€ 20,72	-€ 86.169,28
2024	€ 0,00	€ 0,00	€ 20,22	€ 20,22
2025	€ 0,00	€ 0,00	€ 19,73	€ 19,73
2026	€ 0,00	€ 0,00	€ 19,24	€ 19,24
2027	€ 0,00	€ 0,00	€ 18,78	€ 18,78
2028	€ 0,00	€ 0,00	€ 18,32	€ 18,32
2029	€ 0,00	€ 0,00	€ 17,87	€ 17,87
2030	€ 0,00	€ 0,00	€ 17,43	€ 17,43
2031	€ 0,00	€ 0,00	€ 17,01	€ 17,01
2032	€ 0,00	€ 0,00	€ 16,59	€ 16,59
2033	€ 0,00	€ 0,00	€ 16,19	€ 16,19
2034	€ 0,00	€ 0,00	€ 15,79	€ 15,79
2035	€ 0,00	€ 0,00	€ 15,41	€ 15,41
2036	€ 0,00	€ 0,00	€ 15,03	€ 15,03
2037	€ 0,00	€ 0,00	€ 14,67	€ 14,67
2038	€ 0,00	€ 0,00	€ 14,31	€ 14,31
2039	€ 0,00	€ 0,00	€ 13,96	€ 13,96
2040	€ 0,00	€ 0,00	€ 13,62	€ 13,62
2041	€ 0,00	€ 0,00	€ 13,29	€ 13,29
2042	€ 0,00	€ 0,00	€ 12,96	€ 12,96
2043	€ 0,00	€ 0,00	€ 12,65	€ 12,65
2044	€ 0,00	€ 0,00	€ 12,34	€ 12,34
2045	€ 0,00	€ 0,00	€ 12,04	€ 12,04
2046	€ 0,00	€ 0,00	€ 11,74	€ 11,74
2047	€ 0,00	€ 0,00	€ 11,46	€ 11,46
2048	€ 0,00	€ 0,00	€ 11,18	€ 11,18
2049	€ 0,00	€ 0,00	€ 10,91	€ 10,91
2050	€ 0,00	€ 0,00	€ 44.383,78	€ 44.383,78
	€ 77.440,00	€ 8.750,00	€ 44.797,24	-€ 41.392,76

Dordrecht 2 | Strategy 2

Net Present Value of Expected Outcome

Year	Renovation	Temp. Housing	Transition	Extra m2	House price	Energy Savings	Prevented Risk	Net Benefit
2023	€ 100.320,00	€ 17.500,00	€ 24.725,00	€ 85.714,29	€ 25.600,00	€ 970,00	€ 20,72	-€ 30.239,99
2024	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 965,27	€ 20,22	€ 985,49
2025	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 960,56	€ 19,73	€ 980,29
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 955,87	€ 19,24	€ 975,12
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 951,21	€ 18,78	€ 969,99
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 946,57	€ 18,32	€ 964,89
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 941,95	€ 17,87	€ 959,82
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 937,36	€ 17,43	€ 954,79
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 932,79	€ 17,01	€ 949,80
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 928,24	€ 16,59	€ 944,83
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 923,71	€ 16,19	€ 939,90
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 919,20	€ 15,79	€ 935,00
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 914,72	€ 15,41	€ 930,13
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 910,26	€ 15,03	€ 925,29
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 905,82	€ 14,67	€ 920,48
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 901,40	€ 14,31	€ 915,71
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 897,00	€ 13,96	€ 910,96
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 892,62	€ 13,62	€ 906,24
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 888,27	€ 13,29	€ 901,56
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 883,94	€ 12,96	€ 896,90
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 879,63	€ 12,65	€ 892,27
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 875,33	€ 12,34	€ 887,67
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 871,06	€ 12,04	€ 883,10
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 866,82	€ 11,74	€ 878,56
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 862,59	€ 11,46	€ 874,05
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 858,38	€ 11,18	€ 869,56
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 854,19	€ 10,91	€ 865,10
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 850,03	€ 44.383,78	€ 45.233,80
	€ 100.320,00	€ 17.500,00	€ 24.725,00	€ 85.714,29	€ 25.600,00	€ 25.444,78	€ 44.797,24	€ 39.011,30

Dordrecht 2 | Strategy 3

Net Present Value of Expected outcome

Year	Demolition	Temp. Housing	Construction	Value Residence	Energy Savings	Prevented Risk	Net Benefit
2023	€ 200.000,00	€ 21.000,00	€ 98.000,00	€ 0,00	€ 1.320,00	€ 20,72	-€ 317.659,28
2024	€ 0,00	€ 20.487,80	€ 0,00	€ 0,00	€ 1.313,56	€ 20,22	-€ 19.154,03
2025	€ 0,00	€ 9.994,05	€ 0,00	€ 237.953,60	€ 1.307,15	€ 19,73	€ 229.286,43
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.300,78	€ 19,24	€ 1.320,02
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.294,43	€ 18,78	€ 1.313,21
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.288,12	€ 18,32	€ 1.306,43
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.281,83	€ 17,87	€ 1.299,70
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.275,58	€ 17,43	€ 1.293,02
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.269,36	€ 17,01	€ 1.286,37
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.263,17	€ 16,59	€ 1.279,76
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.257,00	€ 16,19	€ 1.273,19
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.250,87	€ 15,79	€ 1.266,67
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.244,77	€ 15,41	€ 1.260,18
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.238,70	€ 15,03	€ 1.253,73
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.232,66	€ 14,67	€ 1.247,32
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.226,64	€ 14,31	€ 1.240,95
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.220,66	€ 13,96	€ 1.234,62
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.214,71	€ 13,62	€ 1.228,33
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.208,78	€ 13,29	€ 1.222,07
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.202,88	€ 12,96	€ 1.215,85
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.197,02	€ 12,65	€ 1.209,66
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.191,18	€ 12,34	€ 1.203,52
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.185,37	€ 12,04	€ 1.197,40
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.179,58	€ 11,74	€ 1.191,33
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.173,83	€ 11,46	€ 1.185,29
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.168,10	€ 11,18	€ 1.179,28
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.162,41	€ 10,91	€ 1.173,31
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.156,74	€ 44.383,78	€ 45.540,51
	€ 200.000,00	€ 51.481,86	€ 98.000,00	€ 237.953,60	€ 34.625,88	€ 44.797,24	-€ 32.105,13

Dordrecht 2 | Strategy 4 (Extra: 23 m2, Densifcation: 1.41)

Net Present Value of Expected outcome

Year	Demolition	Temp. Housing	Construction	Value Residence	Energy Savings	Prevented Risk	Net Benefit
2023	€ 200.000,00	€ 21.000,00	€ 138.250,00	€ 0,00	€ 1.320,00	€ 20,72	-€ 357.909,28
2024	€ 0,00	€ 20.487,80	€ 0,00	€ 0,00	€ 1.313,56	€ 20,22	-€ 19.154,03
2025	€ 0,00	€ 9.994,05	€ 0,00	€ 311.251,81	€ 1.307,15	€ 19,73	€ 302.584,63
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.300,78	€ 19,24	€ 1.320,02
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.294,43	€ 18,78	€ 1.313,21
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.288,12	€ 18,32	€ 1.306,43
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.281,83	€ 17,87	€ 1.299,70
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.275,58	€ 17,43	€ 1.293,02
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.269,36	€ 17,01	€ 1.286,37
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.263,17	€ 16,59	€ 1.279,76
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.257,00	€ 16,19	€ 1.273,19
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.250,87	€ 15,79	€ 1.266,67
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.244,77	€ 15,41	€ 1.260,18
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.238,70	€ 15,03	€ 1.253,73
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.232,66	€ 14,67	€ 1.247,32
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.226,64	€ 14,31	€ 1.240,95
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.220,66	€ 13,96	€ 1.234,62
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.214,71	€ 13,62	€ 1.228,33
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.208,78	€ 13,29	€ 1.222,07
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.202,88	€ 12,96	€ 1.215,85
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.197,02	€ 12,65	€ 1.209,66
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.191,18	€ 12,34	€ 1.203,52
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.185,37	€ 12,04	€ 1.197,40
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.179,58	€ 11,74	€ 1.191,33
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.173,83	€ 11,46	€ 1.185,29
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.168,10	€ 11,18	€ 1.179,28
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.162,41	€ 10,91	€ 1.173,31
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.156,74	€ 44.383,78	€ 45.540,51
	€ 200.000,00	€ 51.481,86	€ 138.250,00	€ 311.251,81	€ 34.625,88	€ 44.797,24	€ 943,07

	Rotterdam 1 | Baseline		
	Net Benefit		
Year	Risk	Prevented Risk	Net Benefit
2023	€ 58,29	€ 0,00	-€ 58,29
2024	€ 56,87	€ 0,00	-€ 56,87
2025	€ 55,48	€ 0,00	-€ 55,48
2026	€ 54,13	€ 0,00	-€ 54,13
2027	€ 52,81	€ 0,00	-€ 52,81
2028	€ 51,52	€ 0,00	-€ 51,52
2029	€ 50,26	€ 0,00	-€ 50,26
2030	€ 49,03	€ 0,00	-€ 49,03
2031	€ 47,84	€ 0,00	-€ 47,84
2032	€ 46,67	€ 0,00	-€ 46,67
2033	€ 45,53	€ 0,00	-€ 45,53
2034	€ 44,42	€ 0,00	-€ 44,42
2035	€ 43,34	€ 0,00	-€ 43,34
2036	€ 42,28	€ 0,00	-€ 42,28
2037	€ 41,25	€ 0,00	-€ 41,25
2038	€ 40,25	€ 0,00	-€ 40,25
2039	€ 39,26	€ 0,00	-€ 39,26
2040	€ 38,31	€ 0,00	-€ 38,31
2041	€ 37,37	€ 0,00	-€ 37,37
2042	€ 36,46	€ 0,00	-€ 36,46
2043	€ 35,57	€ 0,00	-€ 35,57
2044	€ 34,70	€ 0,00	-€ 34,70
2045	€ 33,86	€ 0,00	-€ 33,86
2046	€ 33,03	€ 0,00	-€ 33,03
2047	€ 32,23	€ 0,00	-€ 32,23
2048	€ 31,44	€ 0,00	-€ 31,44
2049	€ 30,67	€ 0,00	-€ 30,67
2050	€ 46.440,75	€ 0,00	-€ 46.440,75
	€ 47.603,61	€ 0,00	-€ 47.603,61

	Rotterdam 1 | Strategy 1			
	Net Present Value of Expected Outcome			
Year	Renovation	Temp. Housing	Prevented Risk	Net Benefit
2023	€ 108.900,00	€ 8.750,00	€ 58,29	-€ 117.591,71
2024	€ 0,00	€ 0,00	€ 56,87	€ 56,87
2025	€ 0,00	€ 0,00	€ 55,48	€ 55,48
2026	€ 0,00	€ 0,00	€ 54,13	€ 54,13
2027	€ 0,00	€ 0,00	€ 52,81	€ 52,81
2028	€ 0,00	€ 0,00	€ 51,52	€ 51,52
2029	€ 0,00	€ 0,00	€ 50,26	€ 50,26
2030	€ 0,00	€ 0,00	€ 49,03	€ 49,03
2031	€ 0,00	€ 0,00	€ 47,84	€ 47,84
2032	€ 0,00	€ 0,00	€ 46,67	€ 46,67
2033	€ 0,00	€ 0,00	€ 45,53	€ 45,53
2034	€ 0,00	€ 0,00	€ 44,42	€ 44,42
2035	€ 0,00	€ 0,00	€ 43,34	€ 43,34
2036	€ 0,00	€ 0,00	€ 42,28	€ 42,28
2037	€ 0,00	€ 0,00	€ 41,25	€ 41,25
2038	€ 0,00	€ 0,00	€ 40,25	€ 40,25
2039	€ 0,00	€ 0,00	€ 39,26	€ 39,26
2040	€ 0,00	€ 0,00	€ 38,31	€ 38,31
2041	€ 0,00	€ 0,00	€ 37,37	€ 37,37
2042	€ 0,00	€ 0,00	€ 36,46	€ 36,46
2043	€ 0,00	€ 0,00	€ 35,57	€ 35,57
2044	€ 0,00	€ 0,00	€ 34,70	€ 34,70
2045	€ 0,00	€ 0,00	€ 33,86	€ 33,86
2046	€ 0,00	€ 0,00	€ 33,03	€ 33,03
2047	€ 0,00	€ 0,00	€ 32,23	€ 32,23
2048	€ 0,00	€ 0,00	€ 31,44	€ 31,44
2049	€ 0,00	€ 0,00	€ 30,67	€ 30,67
2050	€ 0,00	€ 0,00	€ 46.440,75	€ 46.440,75
	€ 108.900,00	€ 8.750,00	€ 47.603,61	-€ 70.046,39

	Rotterdam 1 | Strategy 2							
	Net Present Value of Expected Outcome							
Year	Renovation	Temp. Housing	Transition	Extra m2	House price	Energy Savings	Prevented Risk	Net Benefit
2023	€ 141.075,00	€ 17.500,00	€ 24.725,00	€ 108.173,00	€ 32.000,00	€ 1.410,00	€ 58,29	-€ 41.658,71
2024	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.403,12	€ 56,87	€ 1.459,99
2025	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.396,28	€ 55,48	€ 1.451,76
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.389,47	€ 54,13	€ 1.443,59
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.382,69	€ 52,81	€ 1.435,49
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.375,94	€ 51,52	€ 1.427,46
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.369,23	€ 50,26	€ 1.419,49
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.362,55	€ 49,03	€ 1.411,59
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.355,91	€ 47,84	€ 1.403,74
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.349,29	€ 46,67	€ 1.395,96
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.342,71	€ 45,53	€ 1.388,24
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.336,16	€ 44,42	€ 1.380,58
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.329,64	€ 43,34	€ 1.372,98
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.323,16	€ 42,28	€ 1.365,44
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.316,70	€ 41,25	€ 1.357,95
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.310,28	€ 40,25	€ 1.350,52
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.303,89	€ 39,26	€ 1.343,15
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.297,53	€ 38,31	€ 1.335,83
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.291,20	€ 37,37	€ 1.328,57
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.284,90	€ 36,46	€ 1.321,36
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.278,63	€ 35,57	€ 1.314,20
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.272,39	€ 34,70	€ 1.307,10
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.266,19	€ 33,86	€ 1.300,04
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.260,01	€ 33,03	€ 1.293,04
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.253,86	€ 32,23	€ 1.286,09
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.247,75	€ 31,44	€ 1.279,19
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.241,66	€ 30,67	€ 1.272,33
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.235,60	€ 46.440,75	€ 47.676,35
	€ 141.075,00	€ 17.500,00	€ 24.725,00	€ 108.173,00	€ 32.000,00	€ 36.986,74	€ 47.603,61	€ 41.463,35

Rotterdam 1 | Strategy 3

Net Present Value of Expected outcome

Year	Demolition	Temp. Housing	Construction	Value Residence	Energy Savings	Prevented Risk	Net Benefit
2023	€ 250.000,00	€ 21.000,00	€ 136.500,00	€ 0,00	€ 1.940,00	€ 58,29	-€ 405.501,71
2024	€ 0,00	€ 20.487,80	€ 0,00	€ 0,00	€ 1.930,54	€ 56,87	-€ 18.500,40
2025	€ 0,00	€ 9.994,05	€ 0,00	€ 285.544,32	€ 1.921,12	€ 55,48	€ 277.526,87
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.911,75	€ 54,13	€ 1.965,87
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.902,42	€ 52,81	€ 1.955,23
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.893,14	€ 51,52	€ 1.944,66
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.883,91	€ 50,26	€ 1.934,17
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.874,72	€ 49,03	€ 1.923,75
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.865,57	€ 47,84	€ 1.913,41
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.856,47	€ 46,67	€ 1.903,14
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.847,42	€ 45,53	€ 1.892,95
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.838,40	€ 44,42	€ 1.882,83
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.829,44	€ 43,34	€ 1.872,78
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.820,51	€ 42,28	€ 1.862,80
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.811,63	€ 41,25	€ 1.852,88
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.802,79	€ 40,25	€ 1.843,04
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.794,00	€ 39,26	€ 1.833,26
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.785,25	€ 38,31	€ 1.823,56
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.776,54	€ 37,37	€ 1.813,91
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.767,87	€ 36,46	€ 1.804,34
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.759,25	€ 35,57	€ 1.794,82
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.750,67	€ 34,70	€ 1.785,37
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.742,13	€ 33,86	€ 1.775,99
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.733,63	€ 33,03	€ 1.766,66
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.725,17	€ 32,23	€ 1.757,40
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.716,76	€ 31,44	€ 1.748,20
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.708,38	€ 30,67	€ 1.739,06
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.700,05	€ 46.440,75	€ 48.140,80
	€ 250.000,00	€ 51.481,86	€ 136.500,00	€ 285.544,32	€ 50.889,55	€ 47.603,61	-€ 53.944,37

Rotterdam 1 | Strategy 4 (Extra: 55 m2, Densifcation: 1.71)

Net Present Value of Expected outcome

Year	Demolition	Temp. Housing	Construction	Value Residence	Energy Savings	Prevented Risk	Net Benefit
2023	€ 250.000,00	€ 21.000,00	€ 232.750,00	€ 0,00	€ 1.940,00	€ 58,29	-€ 501.751,71
2024	€ 0,00	€ 20.487,80	€ 0,00	€ 0,00	€ 1.930,54	€ 56,87	-€ 18.500,40
2025	€ 0,00	€ 9.994,05	€ 0,00	€ 436.553,33	€ 1.921,12	€ 55,48	€ 428.535,88
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.911,75	€ 54,13	€ 1.965,87
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.902,42	€ 52,81	€ 1.955,23
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.893,14	€ 51,52	€ 1.944,66
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.883,91	€ 50,26	€ 1.934,17
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.874,72	€ 49,03	€ 1.923,75
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.865,57	€ 47,84	€ 1.913,41
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.856,47	€ 46,67	€ 1.903,14
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.847,42	€ 45,53	€ 1.892,95
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.838,40	€ 44,42	€ 1.882,83
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.829,44	€ 43,34	€ 1.872,78
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.820,51	€ 42,28	€ 1.862,80
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.811,63	€ 41,25	€ 1.852,88
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.802,79	€ 40,25	€ 1.843,04
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.794,00	€ 39,26	€ 1.833,26
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.785,25	€ 38,31	€ 1.823,56
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.776,54	€ 37,37	€ 1.813,91
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.767,87	€ 36,46	€ 1.804,34
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.759,25	€ 35,57	€ 1.794,82
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.750,67	€ 34,70	€ 1.785,37
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.742,13	€ 33,86	€ 1.775,99
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.733,63	€ 33,03	€ 1.766,66
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.725,17	€ 32,23	€ 1.757,40
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.716,76	€ 31,44	€ 1.748,20
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.708,38	€ 30,67	€ 1.739,06
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.700,05	€ 46.440,75	€ 48.140,80
	€ 250.000,00	€ 51.481,86	€ 232.750,00	€ 436.553,33	€ 50.889,55	€ 47.603,61	€ 814,64

	Rotterdam 2 | Baseline		
	Net Benefit		
Year	Risk	Prevented Risk	Net Benefit
2023	€ 43,72	€ 0,00	-€ 43,72
2024	€ 42,65	€ 0,00	-€ 42,65
2025	€ 41,61	€ 0,00	-€ 41,61
2026	€ 40,59	€ 0,00	-€ 40,59
2027	€ 39,60	€ 0,00	-€ 39,60
2028	€ 38,64	€ 0,00	-€ 38,64
2029	€ 37,70	€ 0,00	-€ 37,70
2030	€ 36,78	€ 0,00	-€ 36,78
2031	€ 35,88	€ 0,00	-€ 35,88
2032	€ 35,00	€ 0,00	-€ 35,00
2033	€ 34,15	€ 0,00	-€ 34,15
2034	€ 33,32	€ 0,00	-€ 33,32
2035	€ 32,50	€ 0,00	-€ 32,50
2036	€ 31,71	€ 0,00	-€ 31,71
2037	€ 30,94	€ 0,00	-€ 30,94
2038	€ 30,18	€ 0,00	-€ 30,18
2039	€ 29,45	€ 0,00	-€ 29,45
2040	€ 28,73	€ 0,00	-€ 28,73
2041	€ 28,03	€ 0,00	-€ 28,03
2042	€ 27,35	€ 0,00	-€ 27,35
2043	€ 26,68	€ 0,00	-€ 26,68
2044	€ 26,03	€ 0,00	-€ 26,03
2045	€ 25,39	€ 0,00	-€ 25,39
2046	€ 24,77	€ 0,00	-€ 24,77
2047	€ 24,17	€ 0,00	-€ 24,17
2048	€ 23,58	€ 0,00	-€ 23,58
2049	€ 23,00	€ 0,00	-€ 23,00
2050	€ 39.555,61	€ 0,00	-€ 39.555,61
	€ 40.427,76	€ 0,00	-€ 40.427,76

	Rotterdam 2 | Strategy 1			
	Net Present Value of Expected Outcome			
Year	Renovation	Temp. Housing	Prevented Risk	Net Benefit
2023	€ 108.900,00	€ 12.250,00	€ 43,72	-€ 121.106,28
2024	€ 0,00	€ 0,00	€ 42,65	€ 42,65
2025	€ 0,00	€ 0,00	€ 41,61	€ 41,61
2026	€ 0,00	€ 0,00	€ 40,59	€ 40,59
2027	€ 0,00	€ 0,00	€ 39,60	€ 39,60
2028	€ 0,00	€ 0,00	€ 38,64	€ 38,64
2029	€ 0,00	€ 0,00	€ 37,70	€ 37,70
2030	€ 0,00	€ 0,00	€ 36,78	€ 36,78
2031	€ 0,00	€ 0,00	€ 35,88	€ 35,88
2032	€ 0,00	€ 0,00	€ 35,00	€ 35,00
2033	€ 0,00	€ 0,00	€ 34,15	€ 34,15
2034	€ 0,00	€ 0,00	€ 33,32	€ 33,32
2035	€ 0,00	€ 0,00	€ 32,50	€ 32,50
2036	€ 0,00	€ 0,00	€ 31,71	€ 31,71
2037	€ 0,00	€ 0,00	€ 30,94	€ 30,94
2038	€ 0,00	€ 0,00	€ 30,18	€ 30,18
2039	€ 0,00	€ 0,00	€ 29,45	€ 29,45
2040	€ 0,00	€ 0,00	€ 28,73	€ 28,73
2041	€ 0,00	€ 0,00	€ 28,03	€ 28,03
2042	€ 0,00	€ 0,00	€ 27,35	€ 27,35
2043	€ 0,00	€ 0,00	€ 26,68	€ 26,68
2044	€ 0,00	€ 0,00	€ 26,03	€ 26,03
2045	€ 0,00	€ 0,00	€ 25,39	€ 25,39
2046	€ 0,00	€ 0,00	€ 24,77	€ 24,77
2047	€ 0,00	€ 0,00	€ 24,17	€ 24,17
2048	€ 0,00	€ 0,00	€ 23,58	€ 23,58
2049	€ 0,00	€ 0,00	€ 23,00	€ 23,00
2050	€ 0,00	€ 0,00	€ 39.555,61	€ 39.555,61
	€ 108.900,00	€ 12.250,00	€ 40.427,76	-€ 80.722,24

Rotterdam 2 | Strategy 2

Net Present Value of Expected Outcome

Year	Renovation	Temp. Housing	Transition	Extra m2	House price	Energy Savings	Prevented Risk	Net Benefit
2023	€ 178.425,00	€ 12.250,00	€ 19.795,00	€ 109.577,92	€ 26.000,00	€ 1.050,00	€ 43,72	-€ 73.798,36
2024	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.044,88	€ 42,65	€ 1.087,53
2025	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.039,78	€ 41,61	€ 1.081,39
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.034,71	€ 40,59	€ 1.075,30
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.029,66	€ 39,60	€ 1.069,27
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.024,64	€ 38,64	€ 1.063,28
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.019,64	€ 37,70	€ 1.057,34
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.014,67	€ 36,78	€ 1.051,44
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.009,72	€ 35,88	€ 1.045,60
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.004,79	€ 35,00	€ 1.039,80
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 999,89	€ 34,15	€ 1.034,04
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 995,01	€ 33,32	€ 1.028,33
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 990,16	€ 32,50	€ 1.022,66
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 985,33	€ 31,71	€ 1.017,04
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 980,52	€ 30,94	€ 1.011,46
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 975,74	€ 30,18	€ 1.005,92
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 970,98	€ 29,45	€ 1.000,43
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 966,24	€ 28,73	€ 994,97
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 961,53	€ 28,03	€ 989,56
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 956,84	€ 27,35	€ 984,18
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 952,17	€ 26,68	€ 978,85
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 947,53	€ 26,03	€ 973,55
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 942,91	€ 25,39	€ 968,30
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 938,31	€ 24,77	€ 963,08
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 933,73	€ 24,17	€ 957,90
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 929,17	€ 23,58	€ 952,75
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 924,64	€ 23,00	€ 947,65
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 920,13	€ 39.555,61	€ 40.475,74
	€ 178.425,00	€ 12.250,00	€ 19.795,00	€ 109.577,92	€ 26.000,00	€ 27.543,32	€ 40.427,76	-€ 6.921,00

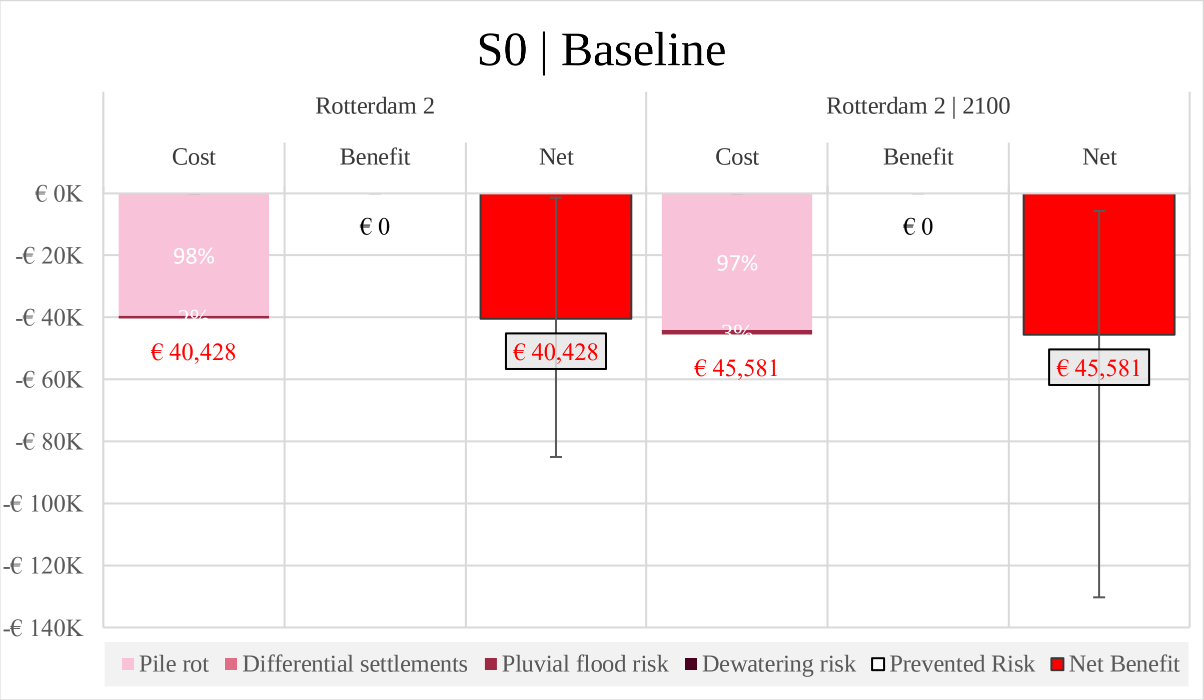
	Rotterdam 2 | Strategy 3						
	Net Present Value of Expected outcome						
Year	Demolition	Temp. Housing	Construction	Value Residence	Energy Savings	Prevented Risk	Net Benefit
2023	€ 250.000,00	€ 21.000,00	€ 134.750,00	€ 0,00	€ 1.585,00	€ 43,72	-€ 404.121,28
2024	€ 0,00	€ 20.487,80	€ 0,00	€ 0,00	€ 1.577,27	€ 42,65	-€ 18.867,89
2025	€ 0,00	€ 9.994,05	€ 0,00	€ 285.544,32	€ 1.569,57	€ 41,61	€ 277.161,45
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.561,92	€ 40,59	€ 1.602,51
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.554,30	€ 39,60	€ 1.593,90
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.546,72	€ 38,64	€ 1.585,35
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.539,17	€ 37,70	€ 1.576,87
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.531,66	€ 36,78	€ 1.568,44
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.524,19	€ 35,88	€ 1.560,07
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.516,76	€ 35,00	€ 1.551,76
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.509,36	€ 34,15	€ 1.543,51
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.502,00	€ 33,32	€ 1.535,31
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.494,67	€ 32,50	€ 1.527,17
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.487,38	€ 31,71	€ 1.519,09
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.480,12	€ 30,94	€ 1.511,06
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.472,90	€ 30,18	€ 1.503,09
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.465,72	€ 29,45	€ 1.495,16
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.458,57	€ 28,73	€ 1.487,30
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.451,45	€ 28,03	€ 1.479,48
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.444,37	€ 27,35	€ 1.471,72
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.437,33	€ 26,68	€ 1.464,00
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.430,32	€ 26,03	€ 1.456,34
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.423,34	€ 25,39	€ 1.448,73
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.416,39	€ 24,77	€ 1.441,17
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.409,49	€ 24,17	€ 1.433,65
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.402,61	€ 23,58	€ 1.426,19
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.395,77	€ 23,00	€ 1.418,77
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.388,96	€ 39.555,61	€ 40.944,57
	€ 250.000,00	€ 51.481,86	€ 134.750,00	€ 285.544,32	€ 41.577,29	€ 40.427,76	-€ 68.682,49

	Rotterdam 2 | Strategy 4 (Extra: 64 m2, Densifcation: 1.87)						
	Net Present Value of Expected outcome						
Year	Demolition	Temp. Housing	Construction	Value Residence	Energy Savings	Prevented Risk	Net Benefit
2023	€ 250.000,00	€ 21.000,00	€ 252.000,00	€ 0,00	€ 1.585,00	€ 43,72	-€ 521.371,28
2024	€ 0,00	€ 20.487,80	€ 0,00	€ 0,00	€ 1.577,27	€ 42,65	-€ 18.867,89
2025	€ 0,00	€ 9.994,05	€ 0,00	€ 471.889,80	€ 1.569,57	€ 41,61	€ 463.506,93
2026	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.561,92	€ 40,59	€ 1.602,51
2027	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.554,30	€ 39,60	€ 1.593,90
2028	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.546,72	€ 38,64	€ 1.585,35
2029	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.539,17	€ 37,70	€ 1.576,87
2030	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.531,66	€ 36,78	€ 1.568,44
2031	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.524,19	€ 35,88	€ 1.560,07
2032	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.516,76	€ 35,00	€ 1.551,76
2033	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.509,36	€ 34,15	€ 1.543,51
2034	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.502,00	€ 33,32	€ 1.535,31
2035	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.494,67	€ 32,50	€ 1.527,17
2036	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.487,38	€ 31,71	€ 1.519,09
2037	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.480,12	€ 30,94	€ 1.511,06
2038	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.472,90	€ 30,18	€ 1.503,09
2039	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.465,72	€ 29,45	€ 1.495,16
2040	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.458,57	€ 28,73	€ 1.487,30
2041	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.451,45	€ 28,03	€ 1.479,48
2042	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.444,37	€ 27,35	€ 1.471,72
2043	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.437,33	€ 26,68	€ 1.464,00
2044	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.430,32	€ 26,03	€ 1.456,34
2045	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.423,34	€ 25,39	€ 1.448,73
2046	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.416,39	€ 24,77	€ 1.441,17
2047	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.409,49	€ 24,17	€ 1.433,65
2048	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.402,61	€ 23,58	€ 1.426,19
2049	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.395,77	€ 23,00	€ 1.418,77
2050	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 1.388,96	€ 39.555,61	€ 40.944,57
	€ 250.000,00	€ 51.481,86	€ 252.000,00	€ 471.889,80	€ 41.577,29	€ 40.427,76	€ 412,99

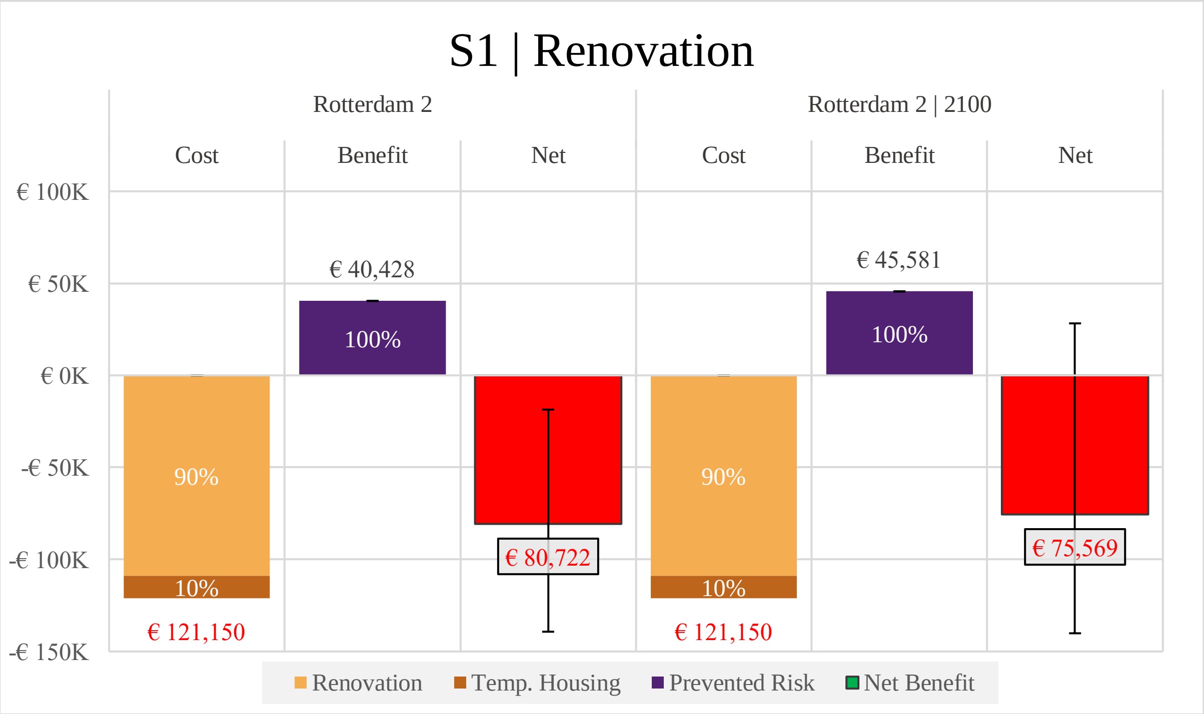
Appendix E Sensitivity Analysis

This appendix provides the Net Present Value calculations each of the adaption strategies and the baseline for case study area Rotterdam in 2050 and 2100 to analyse the sensitivity of the time horizon.]

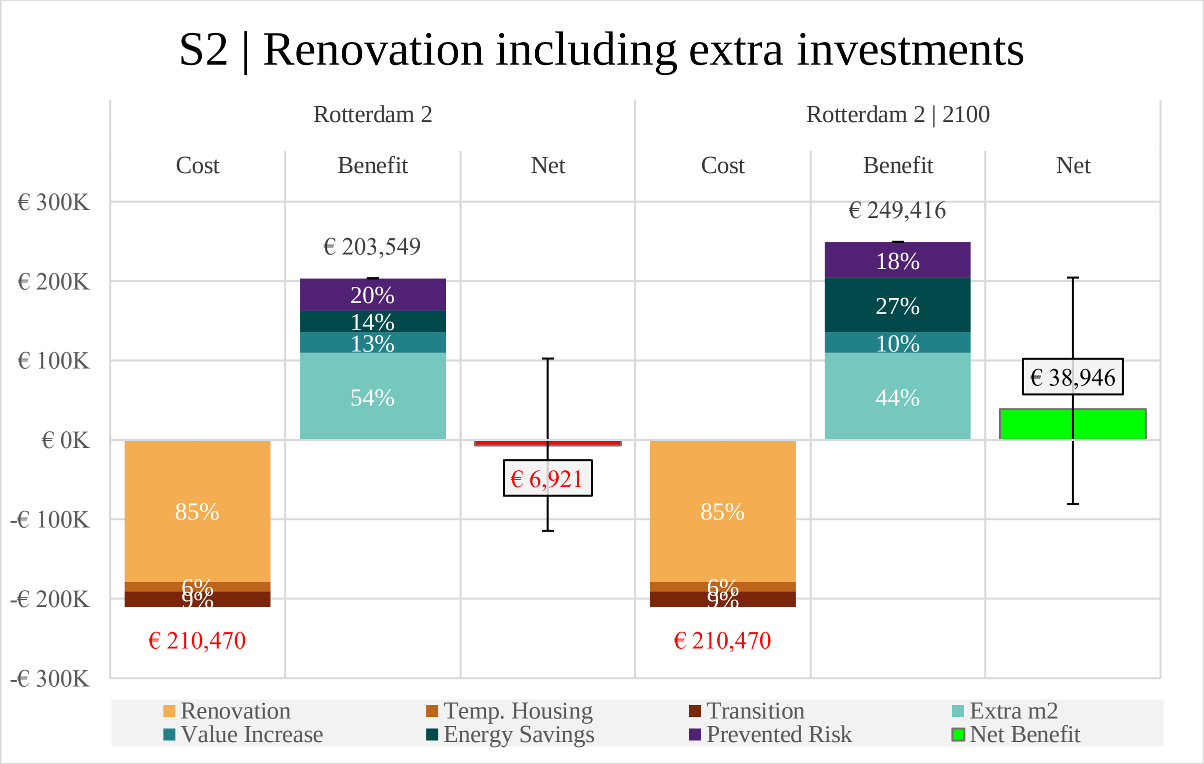
NPV calculation of the baseline to compare different time horizons (2050 vs 2100)



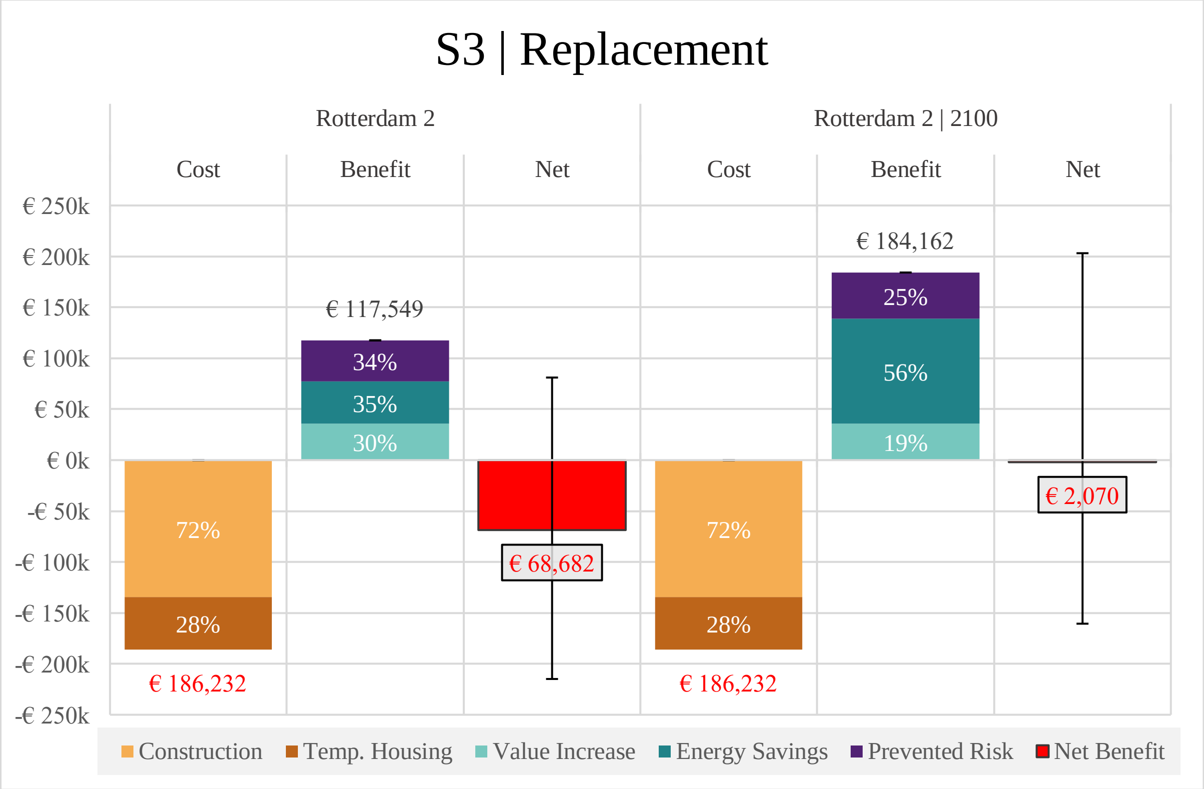
NPV calculation of the Renovation strategy to compare different time horizons (2050 vs 2100)



NPV calculation of the Renovation strategy including extra investments to compare different time horizons (2050 vs 2100)



NPV calculation of the Replacement strategy to compare different time horizons (2050 vs 2100)



NPV calculation of the Replacement including densification strategy to compare different time horizons (2050 vs 2100)