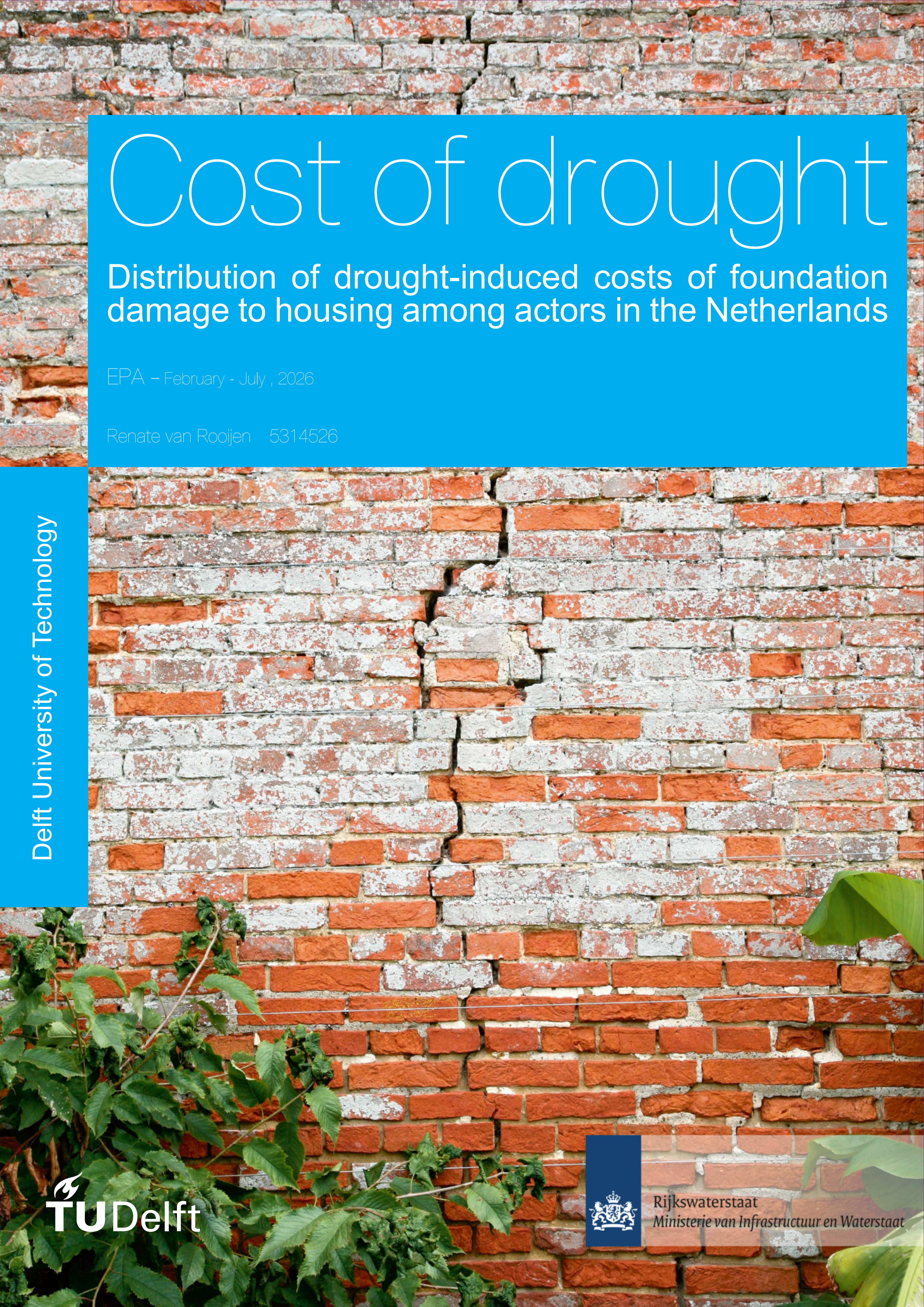

Cost of drought

Distribution of drought-induced costs of foundation damage to housing among actors in the Netherlands

EPA – February - July , 2026

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Ministerie van Infrastructuur en Waterstaat

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by

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Renate van Rooijen 5314526

to pass the master thesis course
at the Delft University of Technology,

Project duration:	February, 2026 – July, 2026	
Under the Guidance:	Prof. Dr. T. Filatova,	TU Delft, chair, first supervisor
	Prof. Dr. M. E. Warnier,	TU Delft, second supervisor
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Abstract

This thesis aims to explore risk of climate damage to housing, in particular the effects of drought to foundations of housing in the Netherlands. This thesis has been conducted between the TU Delft and Rijkswaterstaat. Due to climate-induced droughts, water levels in the Netherlands increasingly drop too low, exposing foundations of houses and triggering the rotting process of the wooden foundation piles. This causes damage and a higher risk of subsiding houses. Due to drought last summers approximately 425.000 houses are at risk of subsiding due to damage to the foundation. This can go up to 687.000 houses if climate change is taken into account (KCAF, 2026).

This poses a significant financial burden for individual homeowners, because the costs are between €50.000 to sometimes €150.000 (KCAF, 2026). Not everyone can afford this. A solutions to overcome this, could be a subsidy, a nudge towards repair, or an insurance policy for these sorts of problems. This thesis has explored and evaluated the possibilities and effects of redistributing the costs by different policies.

With a higher risk of disasters, how should the Dutch government and other involved actors handle this? The following research question is answered:
How do alternative Dutch compensation policies for drought-induced foundation damage influence homeowner adaptation behaviour and the distribution of foundation damage over time?
To address this research question, I developed a spatially explicit agent-based model (ABM) and integrated available spatial data on climate-induced foundation damage and possible private adaptation behaviour. In the model the homeowner's behaviour, the government, insurance and banks are included as agents. With this method different policy levers are tested and evaluated. The main findings are that the main barrier for homeowners with foundation damage is not the behavioural factors constraining the adaptation, but the financial capabilities. When a repair to the foundation damage is postponed, the costs increase. To keep the total costs of foundation damage to a manageable level, a policy that helps the homeowners financially is recommended. There are different views on if homeowners should get financial help for the repairs. There is agreement on helping homeowners who do not have the assets. A targeted subsidy is a good option to help those households. An insurance policy will also help keep the costs down. The feasibility of an insurance policy with a premium that homeowners are willing to pay, is something that has to be explored in further research, especially an insurance policy that is mandatory for every houseowner. A combination of an insurance and subsidy is most effective in keeping the total costs down and realizing the most repairs. This thesis adds to the research field of policy analysis that researches natural disasters using ABM. It fills a research gap of using ABM for drought induced damage to housing. The novelty is that this research is using agent based modelling for drought-induced foundation damage to housing, by combining the physical damage data under a climate scenario, with private adaptation responses of different households, and various policies supported by government and the financial sector. This enables the assessment of the distribution of climate costs across different locations and actors.

Contents

1

Introduction

The climate is changing and the consequences are coming. Even more than the disasters we have already experienced. The frequency and intensity of extreme weather events are increasing (Intergovernmental Panel on Climate Change (IPCC), 2026). This causes a change in agriculture, precipitation, rise of the sea levels, flooding of coastal areas, more frequent and extreme droughts and heavy winds. This grand challenge is already affecting big parts of the world, including the Netherlands. Climate change and its effects are a big wicked problem, the current situation shows a collective action problem with multiple actors with misaligned incentives.

1.1. Societal relevance

Last year was one of the top 10 driest summers ever measured. An average of 155 millimetres of rain fell, which is 30 percent less than average. Last summer (2025) has also entered the top 5 of the warmest summers ever measured in the Netherlands (NOS, 2025). These records indicate a significant increase in climate extremes.

This has got severe consequences; there are extreme droughts but also moments of heavy downpour. A recent example of a consequence, is during the drought in 2022 there was a chance houses were going to subside due to a low ground water level. One million houses are prone to get damage due to drought. They predict that this will happen to even more houses in the future (NOS, 2022).

This is also why the program ”Strategische Verkenningen” from Rijkswaterstaat is interested in this topic. The climate damage in the Netherlands will increase on multiple fronts. With this program, Rijkswaterstaat would like to look forward to see how we, as a society, can handle this. Additionally, Rijkswaterstaat is managing the rivers, and has an impact on the groundwater levels in those areas.

1.2. Policy gap

Due to drought, people will face damages; to their homes, to crops, or to infrastructure. This damage can be caused by a lot of different factors. A policy on how to handle this damage and how the costs are being divided is not in place yet. It is a complex system to make policy on. There are several climatological impacts with different effects, and multiple interacting factors, stakeholders and uncertainties. Firstly it is uncertain when and where a disaster will happen next. But there is one constant, a next disaster will take place somewhere in the future. The complexity lies in the amount of actors, there are the homeowners, but also the insurance companies, municipal governments, national governments, big polluters, et cetera. They all have a role in this problem, but currently the homeowner is a lot of times the one paying for the climate damage. This thesis will look at possible ways to divide the costs of drought damage to housing.

The policy gap in this problem is that there is no national framework for climate-related damage distribution, there is no insurance that covers damage on houses due to drought.

Lastly there is a misalignment of incentives among homeowners, insurers, governments and polluters.

1.3. Scientific gap

Scientifically this study contributes to the literature on climate adaption policies and disaster risk distribution by using an Agent Based Model (ABM) for drought risk. ABM's are widely used for flood adaptation, their application to drought induced foundation damage remains under-researched. Because this is a problem particular to the Netherlands. This thesis will fit into the knowledge gap of using ABM's for drought induced foundation damage. By combining knowledge on ABM's in the housing market and natural disasters, this research will contribute to the existing Agent Based Models. This will be the first Agent Based Model for drought-induced foundation damage to housing.

1.4. Drought damage to housing

There are several types of drought damage, amongst the ones visible in Figure 1.1. The foundation damage considered in this research is pile rot. This occurs when houses are built on wooden piles, and the water level is too low, a part of the pile is exposed. This will cause the pile to rot. This is a type of damage that has been known for a long time. The consequences and costs are very big. There are already a lot of houses at risk currently, there will be more houses at risk in the future. In Figure 1.2a the risk in 2050 is shown. The klimaateffectenatlas provides data on the risk of drought-induced foundation damage. It shows the risk on pile rot but also on another damage,'verschilzetting', also called differentiation. This damage will not be included in this research, but also frequently happens in the Netherlands. A schematic view of those damages can be seen in 1.1.

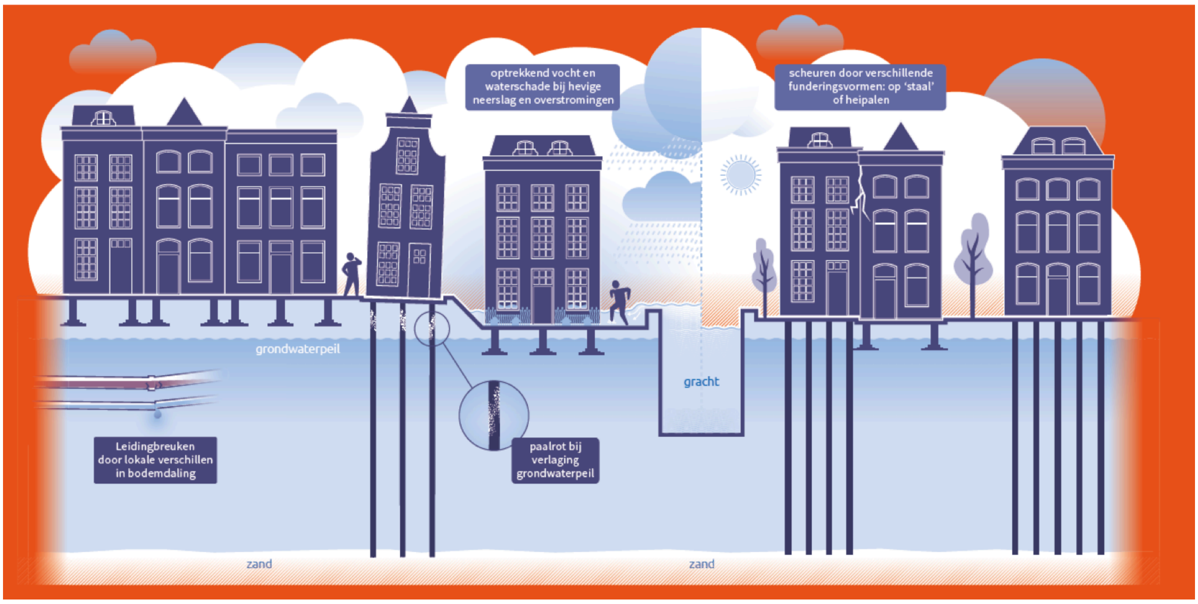
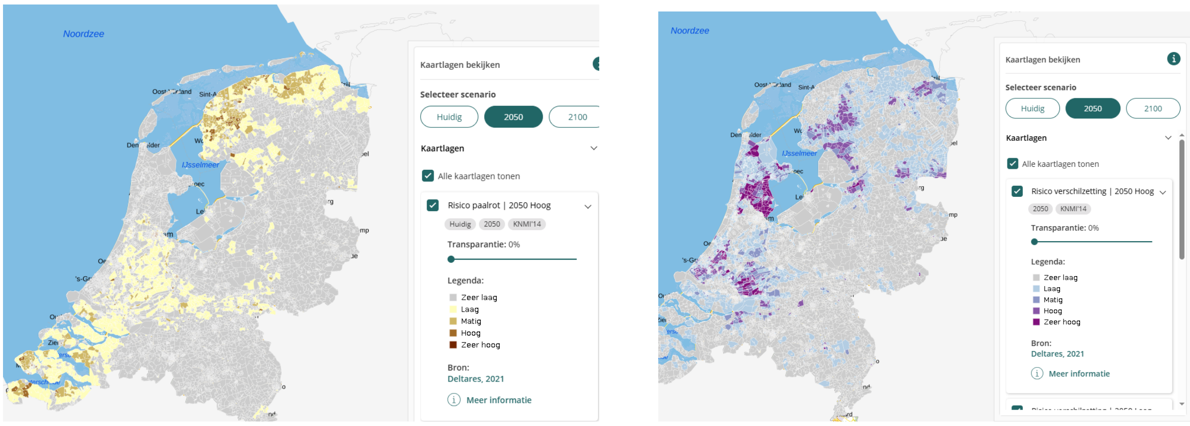


Figure 1.1: *Schematic picture of foundation damages (Kok and Angelova, 2020)*



(a) *Pile rot risk in the Netherlands source: (Klimaateffectatlas, 2026)*

(b) *Differentiation risk in the Netherlands source: (Klimaateffectatlas, 2026)*

Figure 1.2: *Comparison of climate effect risks in the Netherlands. Shown in a map from the Klimaateffectenatlas.*

These maps in Figure 1.2 show the risk. That does not necessarily have to mean that a lot of houses already face problems. But they do, KCAF (2026) has a map that show the amount of reports made per part of the Netherlands. This map can be seen in Figure 1.3. As seen in the map, large parts of the Netherlands already see and feel their homes subsiding due to drought induced foundation damage.

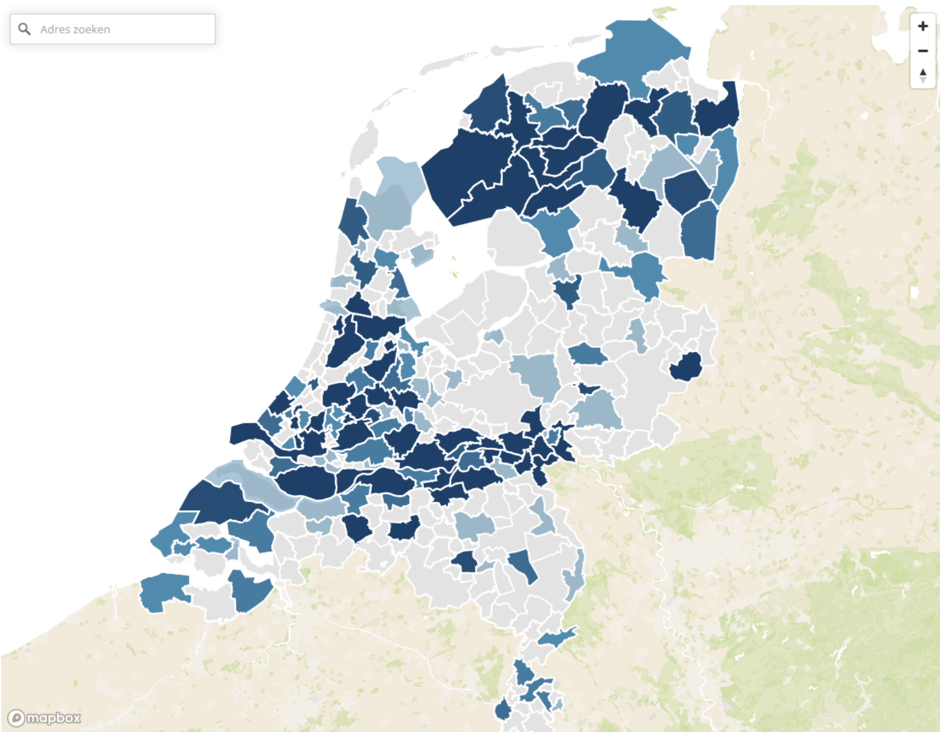


Figure 1.3: *Amount of reports of foundation damage per part in the Netherlands (KCAF, 2026). Big parts of the Netherlands are already facing high amounts of damage.*

1.5. Aim

This thesis aims to develop an analytical framework to evaluate how climate-related housing damages, especially drought can be distributed across stakeholders, and to recommend policy options for the Dutch context.

To address this I will apply methods from the Engineering Policy Analysis (EPA) curriculum to do an extensive stakeholder analysis and use an ABM to model the possible outcomes. This study contributes to the climate adaptation policy research field.

The involved actors are the homeowners, homeowner associations, insurance companies, municipal governments, provincial governments, national governments, banks, waterboards and big polluters. The role of these actors will be identified and modelled to find the interplay between them. Due to a time constraint, not all actors will be included in the model. The used actors are the homeowners, insurance companies, the government as one actor and lastly, the bank.

The output of the model will be multiple things: the behaviour of the homeowners to drought damage to their house, the total costs, the amount of houses damaged, the amount of houses repaired, the response of the system to policies. The other output is my learning curve, and the experience I gain by overcoming several difficulties by modelling.

This thesis will create a recommendation on how to handle climate-related damages under different policy scenarios and with different actor responsibilities. This can support Dutch policymakers in the future in developing national climate-risk compensation frameworks. By using the existing knowledge from drought ABM's on agriculture and from ABM's on housing markets, a ABM that looks at drought-induced foundation damage will be created. This will fill a scientific gap on how to approach this topic using an Agent Based Model.

2

State-of the art

2.1. Approach

In this section a brief literature review is given. The database Google Scholar is used, Scopus gave less articles with the same keywords. There is not much academic literature on this exact case, but there is a lot of grey literature, Google Scholar also shows those, that is why Google Scholar has been used. The articles form 2010 to 2026 are included. The articles on the technical side of how foundation damage occurs, are not included. Neither are the articles about different drought conditions and foundation damages than from the situation in the Netherlands. Behaviour from other countries is included because those are also relevant in this context. A lot of relevant published articles were found by keyword strategies. All the literature is categorised by the KAVV method. In each article the key quote, the argument, method, a question and the connection to the research is established. This ensures structure in the literature review. The question of the KAVV is especially important, because this directs what I am going to research further. This is a way of structuring the literature to group the articles and find the connections. The literature is sorted in paragraph with different key concepts, with corresponding search terms.

2.2. Key concepts

The key concepts divide the literature research into smaller pieces, this ensures that every aspect of the subject is being explored thoroughly.

2.2.1. Current situation

The current situation is assessed by looking at how the costs and actors involved in climate damage to houses currently are. Starting with insurers, then going into different policies, and the connection from drought damage to foundations to climate change.

The insurance interest group, verbond van verzekeraars, has an overview on their website from what insurance companies insure (Verbond van verzekeraars, 2025). This interest group says to represent 95% of all insurance companies in the Netherlands. There are a lot of climate-related damages to houses that are not insured. A short list of the things that are not insured:

- Rain damage: Damage due to a rise in the groundwater level
- Flood damage: Homes in areas outside the dikes.
- Flood damage: Damage caused by water from the sea, a river, or an inland waterway, due to a primary flood defence that has overflowed or failed.
- Drought damage: Damage to a house's foundations due to drought

This also implies that other damages are insured. The literature shows an effect that comes from insuring. When properties are insured, it might make homeowners take bigger risks, since it is insured anyway. This is described as the safe development paradox (Haer et al., 2020).

Mathur and Paul (2022) also find that if homeowners know more about the insurance of their homes, they will feel less vulnerable towards catastrophic events. As a result of this, people will sooner buy homes in catastrophic prone areas. This shows that insurance is a way of distributing the costs, but it might have unwanted side-effects.

2.2.2. Available policies on the matter

Wet tegemoetkoming schade bij rampen (Wts) (Ministerie van Justitie en Veiligheid, 2024), the cabinet can help people who suffered material damage after a disaster. This is for all damage that is not insurable. This does not concern all not insurable things mentioned above, this law only applies for a disaster. Damage to a foundation due to drought is not a disaster, since there are no lives in danger, and it happens gradually. Kamara et al. (2020) state that in Eswatini and Lesotho the current policy response is focused on reducing vulnerability. Whilst a better understanding of resilience against drought has to be created. This will motivate policymakers to start making resilience the policy goal instead of reactive interventions (Kamara et al., 2020). Even though this research is conducted in Eswatini and Lesotho, this is also applicable to the Dutch scenario. The Wts is an example of a reactive intervention. But there is no policy for long-term resilience yet. This is a policy gap, because how should the Dutch government handle this slowly growing damage, in a resilient policy instead of a reactive intervention?

2.2.3. Connection climate change to drought

The KNMI states, dry summers are more likely to happen because of the changing climate KNMI (zd). This report also shows that less water in the rivers in the future will amplify the drought. The summers are becoming dryer and stay dry for a longer time. This leads to water shortages, that are linked to climate change. When there is a water shortage, the ground water level can be depleted so that water can be used. However a lot of homes are not built for that. The foundation of houses with wooden foundations will rot if they come into contact with air. Using the framework from Machairas and van de Ven (2023), this drought damage falls into the groundwater drought category. This research has done a comprehensive vulnerability analysis and shows that in Leiden a lot of buildings are at risk of subsidence due to groundwater drought. Kenniscentrum Aanpak Funderingsproblematiek (KCAF) estimates that at least one million houses in all of the Netherlands are on the verge of subsiding due to low groundwater levels (KCAF, 2026).

2.2.4. Human behaviour and risks

An important factor in an ABM model is the human behaviour. Humans behave differently under different circumstances. Sen (2021) state that the decisions of individuals are irrational and inadequate, influenced by biases, overconfidence and nudges. This paper encourages for behavioural issues to be given recognition when developing disaster reduction policies. Wens et al. (2019) have made a framework for how to include human behaviour into the evaluation of risks. This article highlights the advantages of using an ABM to model drought. Bryan et al. (2019) have defined decision-stages that show how individuals respond to drought. This clearly shows the irrationality of human decision-making. Slotter et al. (2020) use the theory of planned behaviour to find the factors that influence if homeowners have the intention to mitigate. Some factors are the intention of the homeowners and the influence of others. van Valkengoed and Steg (2019) also find that the descriptive norms of the environment are an important factor, this paper also identifies negative affect, perceived self-efficacy and outcome efficacy as factors associated with adaptive behaviour to drought. Guo et al. (2021) find that location is a good predictor for preparedness to disasters, and that people who migrate to a place are better prepared than the people who already lived there. They also identified a gap between men and woman, men are generally better prepared. Mallick et al. (2022) found the same gap between the genders. Those researches were conducted in China and Bangladesh, there is a gap in the literature whether this is also the case in the Netherlands. In the research of Kusuma et al. (2019) the undervaluing of catastrophic insurance is highlighted. They state that insurance has the potential to give incentives for risk mitigation behaviours, although this research has been done on agriculture and not on housing, this is a valuable insight to the potential that insurance has. People with an insolvent socioeconomic status are at higher risk to drought than others (Salam et al., 2021). This research also found that the mean level of perceived risks is according to the actual level or risk.

To capture human behaviour these loose papers will give an idea of which behaviour the model will show. Behavioural theories are better fitted to describe behaviour in an ABM. There are several theories that are useful for this case. A few examples are the theory of planned behaviour, prospect theory and protection motivation theory. The latter has especially been used a lot in combination with natural disasters and ABM. Jin et al. (2026); McEligot et al. (2019); Schrieks et al. (2021) have used this combination. Protection Motivation Theory (PMT) consists of two parts, the threat appraisal and coping appraisal. If those two factors are high enough, the agent will have enough motivation to act (Maddux and Rogers, 1983). Schrieks et al. (2021) have written a review of behavioural theories in drought-risk assessment in an agricultural setting. This is a similar case, they have found that multiple drought risk assessments have been done using PMT. Some of those studies did not have all survey data available, and in those scenario's proxy variables can be used to include the human behaviour.

2.2.5. Policy instruments

There are different policy instruments that can be included to soften the financial blow for individual households with foundation problems. Filatova (2014) states that there are several market based instruments that can help stimulate individual adaptation. The systemic review looks at different instruments and their effectivenesses. Some examples are taxes, subsidies and insurances. Logar and van den Bergh (2013); Merrett (2004) also deem market valuation instruments appropriate while Logar and van den Bergh (2013) highlight that pre-impact mitigation measures has to be enacted as well. Han and Peng (2019) state that public participation in local risk mitigation is of utmost importance. In this article the importance of the integration of local governments with residents and insurance in coastal adaptations to floods. Hurlbert and Gupta (2019) have made an overview of available policy instruments that policymakers in the Netherlands can use to handle drought. Such as water licence, insurances and irrigator associations. Their effectiveness is tested in case studies in different countries.

2.2.6. ABM

There are a lot of articles where flood risk is modelled using an ABM (Tonn and Guikema, 2018; de Koning et al., 2019). Akhbari and Grigg (2013) show how an ABM in the context of water management can be useful to show conflicting actors. There are studies done on drought in combination with agriculture (Badillo-Márquez et al., 2021; Salimi et al., 2026; Schrieks et al., 2021; Wens et al., 2020). There are not a lot of studies that model drought in combination to housing damage to foundations. This is a knowledge gap. There is a framework to include adaptation decisions and the exposure, hazard and vulnerability of drought into risk assessment Wens et al. (2019). This is not necessarily made to apply to housing, but it has the possibility.

Wens et al. (2019) recommend including more stakeholders into an ABM, which is what this research aims to do. Furthermore this framework can be applied to drought risk to housing due to pile rot.

2.3. Knowledge gap

In the literature several knowledge gaps have been identified. There is a lot of knowledge on the process of rotting foundations and other drought-induced foundation damages. How the costs of the foundation damage can be assessed remains unclear. Moreover, there are a lot of policies available on damage to housing. For this case there are currently no adequate policies. Additionally, the question if the costs should even be distributed and how this plays out in the future has not been researched in the context of drought-induced foundation damage. If there are unwanted side effects from distributing costs is an important question to ask. Lastly, there are several policy instruments described in the literature. They have been researched in another context. What policy instruments governments, insurers and banks have to mitigate the damage due to pilerot and what the results of these instruments are, remain a knowledge gap in the current literature.

This gap is important to fill because this is something that the Netherlands will face in the near future. The implications of this development are hard to oversee.

3
Research Question

The goal of this thesis is to explore the possible policies that handle climate damage to housing. The research is going to investigate how human behaviour shapes long-term drought damage risks to housing in a region of the Netherlands. Existing studies analyse drought damage or individual adaptation measures. A study on how compensation policies by the government can be designed and or a policy for insurers to redistribute long-term risk and responsibility amongst actors under behavioural adaptation is still not done. This is a research gap. To fill this gap the following research question is formulated:

'How do alternative Dutch compensation policies for drought-induced foundation damage influence homeowner adaptation behaviour and the distribution of foundation damage over time?'

3.1. Subquestions

- SQ 1: What policy instruments do homeowners, governments, insurers and banks have to mitigate the damage to houses due to drought and what are the outcomes of these instruments?
- SQ 2: What are different views on how the costs of drought-induced foundation damage should be distributed?
- SQ 3: What are the barriers that hinder homeowners in repairing foundation damage?
- SQ 4: How do different damage compensation policies influence homeowners over time under climate driven changes?

3.2. Method

This research question will be answered using ABM. ABM is ideal for testing policies over time, whilst including human behaviour. This is exactly what this research question asks for. The opportunity to include all actors and seeing how their interactions evolve and influence each other over multiple time steps.

The research question has to be answered in a way that heterogeneous actors, feedback loops and adaptive behaviour are included over time. This method fits this research because it is able to include behavioural patterns such as the safety paradox (Haer et al., 2020) and irrational individual decisions. This way of modelling will help finding emergent phenomenons that come from different policies. As Nikolic et al. (2013) states, ABM is a good way to model large socio-technical problems. This is very fitting in this case. Wens et al. (2019) show the potential for ABM in modelling drought in combination with human behaviour clearly, since an ABM can include risk equation, socio-hydrologic factors and the influence of risk on the decision-making behaviour of individuals.

3.3. Alternative research designs

Alternative approaches were also considered. System dynamic modelling has also been looked at. This method is also able to represent feedback loops. It is however not able to represent the heterogeneity among households, the differential exposure, and behavioural choices individuals make. These are all important factors in the housing risk in the Netherlands.

3.4. Limitation and mitigation

The first limitation is behavioural simplification. Human behaviour is infinitely complex. It has to be simplified into decision rules, these may not capture the real-world complexity. In order to address this, all the behavioural assumptions will be grounded in empirical literature. A sensitivity analysis will also be conducted to see which assumptions have a big affect on the outcomes.

Another limitation is the data. Empirical data on damage to housing and the behavioural response to the damage is limited. The model will focus on reproducing facts instead of calibrating the model to precise damage values. The model will be able to output trends, but not exact values.

The external validity can also pose a limitation. This model is developed in a specific Dutch context. The question is if this is applicable in other regions. By modelling behavioural mechanisms and interactions, the insights are expected to be conceptually usable in similar socio-technical systems.

Lastly, the uncertainty in future climate conditions and their corresponding policy responses will induce an additional uncertainty. This will be addressed trough scenario analysis and by checking the robustness of the model. This will allow the exploration of varying scenario's, instead of only a single outcome.

These things will be taken into account during the modelling phase of this thesis. Afterwards those limitations are reflected on in the discussion.

4 Research Design

4.1. Model design

The ABM is conceptualised using the method from Nikolic et al. (2013). The workflow will be as described in 4.1. An ABM consists of agents who interact with each other within an environment. Showing the dynamic interactions between heterogenous actors involved in housing-related climate risks is something that can be modelled using an ABM. The purpose of the model is to research how individual and institutional decision-making in combination with policy instruments, will lead to patterns in housing risk and adaptation in combination with drought, with a specific focus on drought-induced foundation damage to houses.

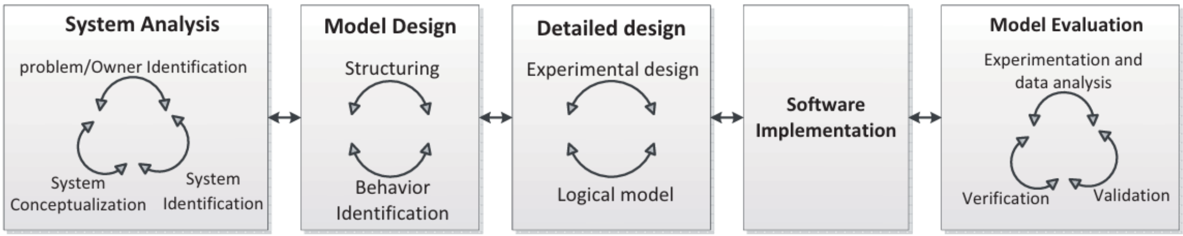


Figure 4.1: *Modelling scheme that has been used from Nikolic et al. (2013), that shows the design cycle of making an Agent Based Model. First system analysis, then model design, the detailed design, software implementation and lastly model evaluations.*

4.2. Agents

This model includes four types of agents: homeowners, local governments, banks and insurers. Each agent has different attributes, decision-making rules and behavioural actions. This research only looks at homeowners and their behaviours, since they are the biggest part of the Dutch housing sector. But they are influenced by the other involved agents.

4.2.1. Homeowners

The homeowners represent households who own residential properties in areas that are exposed to drought risks. Homeowners are heterogeneous with respect to their risk perception, financial capacity, previous experience, in the foundation type of their house and access to financial and technical adaptation measures. The behavioural patterns that the homeowners will show will be described by the PMT. Over time homeowners adapt their behaviour to the experienced damage, policy instruments, insurance schemes and changes in the perceived risk. As a basis for the behaviour, in an ideal world a survey had been conducted to establish the parameters for the PMT. In reality, due to time constraint, this has not been done. But a proxy using flood risk perception data has been used.

4.2.2. Homeowner behaviour

Human behaviour is difficult to simulate. The possibilities have been touched upon in the state of art. Using Protection Motivation Theory, the behaviour will be modelled. The factors already identified are previous experience, risk communication, financial instruments and technical instruments. PMT is commonly used to study private climate change adaptation behaviour empirically. This can be done using household surveys Taberna et al. (2023); van Duinen et al. (2016). Increasingly, behaviour of agents in ABMs is not only grounded in theories, like PMT, but also rely on empirical micro data from surveys. Due to time limitations, a survey for this exact case has not been done, a proxy has been used. The values that have been used come from a survey that determined the PMT values for flooding in the Netherlands (Filatova et al., 2022). Drought risk and flooding risks do have a different nature. Droughts happen gradually over time, whilst a flood comes all of a sudden and is gone after. The perception of drought in the Netherlands is also on another level than flood risk. It is well known that the Netherlands is below sea level. It is not common knowledge that we also have droughts that can have foundation damage as a consequence. It would be relevant to determine the PMT values for drought risk in further research. Even though there are differences, there are enough similarities, like the fact that they both cause damage, are happening more frequent due to climate change et cetera, that this proxy is deemed suitable for this research.

4.2.3. Bank

Another agent is the bank. In this model this agent will act rationally and is not dependant on behavioural stimuli. The bank will purely look at the available assets to determine whether a homeowner can get a loan. In this model, the bank will look a combination of the WOZ-worth, mortgage debt, available money on the bank and other money-related assets to determine if a homeowner can get a loan.

4.2.4. Insurer's behaviour

Insurers can adjust premiums, coverage conditions and withdrawal decisions. They can play a key part in the financing of those risks. The costs might not become lower by insuring, but at least they will be divided amongst a bigger group. There is a interplay between insuring and risk-taking that will be explored in the model. One constraint has been added, the premiums paid and the coverage given to the homeowners have to be balanced, if an insurance is not feasible, the insurers will not offer it as as insurance.

4.2.5. Governments

Governments are decision-making agents who decide who to give subsidies and where to invest in infrastructure. They are also responsible for the communication. The governments can have an influence with it's available instruments on the objective risk and the subjective risk perception. Which tools governments have will be found in the literature, but the outcome of the behavioural response will come apparent by the model. In this model the government will have two tools available, nudge, that plays into their communication and information giving role. The government will also have the ability to give out subsidies.

4.2.6. Fonds Funderingsherstel

This fund is funded by the government already. Fonds funderingsherstel is a fund that gives out loans to households who cannot get a loan themselves. They help households who cannot get market-compliant loans, and give them this alternative. This fund has not been available in all parts of the Netherlands, recently more money has been added to the fund to make it nationally available. There are some limits, this Fund has a limited budget, and there are some conditions homeowners have to meet before they can get a loan. This one has been modelled separately because it is an already existing financing option, not a new policy to test.

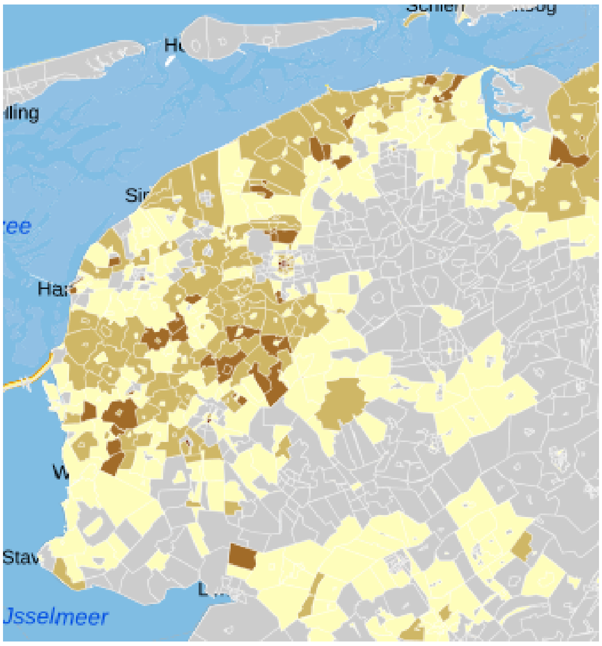


Figure 4.2: *This figure shows the pile rot risk in Friesland. A clear band of high risk area can be seen on the south east side. This image shows why Friesland is an interesting part to look at. The darker coloured parts are the areas with more risk at pile rot.*

4.2.7. Vulnerable areas

This part is not about an agent but about the environment the agents operate in. There are already a lot of maps on this. The klimaateffectenatlas shows which areas in the Netherlands are prone to pile rot right now, in 2050 and in 2100 (Klimaateffectatlas, 2026). Deltares has a report on damages from water shortages in urban areas (Hoogvliet et al., 2012). This report gives an insight to the problem including a few maps that show the vulnerable areas. Kok and Angelova (2020) show in another Deltares report what the impact of drought is to foundations. This is essential for determining the grid of the ABM since it will be modelled after an existing area in the Netherlands.

4.2.8. Climate risk

It will be very informative to run the model over time. The intended running time is 30 years. This will be long enough to see the effects of measures, but is short enough that it does not cause unnecessary uncertainty. This will help determine whether a policy is one to be recommended. There are different datasets available, one with the current state of the climate, one with a lot of climate change in 2050 and one with not a lot of climate change in 2050.

4.2.9. Environment

The environment will represent a spatially explicit urban area in the Netherlands that is vulnerable to drought impacts. The spatial units will correspond to the chosen area and its exposure to climate hazards, foundation vulnerability and existing infrastructure. A lot of maps and data on the exact state of the environment is already available. The research will be conducted in Friesland, because this province has two different types of drought damage, pile rot and differentiation. The plan at first was to also add that damage in. That was not feasible, so the research has only been conducted on pile rot. In the future differentiation can also be added in. The information from the klimaateffectenatlas as seen in Figure 4.2 is used to model the risks in an area.

4.2.10. Dynamics

The model is dynamic and operates over multiple discrete time steps, each representing a fixed period of a year. At each time step, agents can be updated into a different state. So that over multiple time steps the adaptation process can be found. the emerging system will show the behaviour over time with repeated interactions under changing conditions. For the behavioural aspect Bryan et al. (2019) have described decision stage where individuals respond to drought. This will be a first step in defining the behaviour.

4.3. Model flowchart

The model concept has been visualized as shown in figure 4.3. This clearly shows the order in which things occur in a time step. This flowchart is construced by looking at different reports on drought risk to foundations over time (KCAF, 2026; Kok and Angelova, 2020; ABN AMRO, 2026). The following steps have been identified in the reports:

1. Determine the risk of a house
2. Investigate if the house is already damaged (or will be in five years)
3. Find financing options
4. Repair the house (if feasible)

This order has been the starting point for the flowchart. This one also includes the initialization and updating step that agent based models have. This representation is very focussed on the means of financing the damage to houses. This has been chosen because that is in line with the research question. An alternative would be to focus even more on the behaviour, small drought mitigation measures, or even focus on another actor. This chart would look very different if it was made from the perspective of a government, bank or insurer. It would give those agents more depth aside from one function to determine if the homeowner will get money. For example the warning and informing role from the government, or its influence over the groundwater levels could be added into that model. This method using the homeowner is deemed the most suitable for the research question.

4.3.1. Description of the model flowchart

This section will talk trough the steps that the flowchart is taking as can be seen in figure 4.3. First the model is initialized. The groundwater level is determined. In the model this is done by the value assigned to a house from the klimaateffectenatlas. Because this will have an impact on how many houses are at risk of foundation damage. If there is no risk, the house is updated, homeowner's perception is updated and this homeowner goes to the next time step. If, however, the foundation is exposed, the protection motivation theory will assess whether the homeowner will come into action. If the homeowner decides to take action, the financing is to be found. Afterwards the house damage and worth is updated and the homeowner's perception.

The PMT has a separate graph that shows what the homeowner will do. The combined threat and coping appraisal will determine whether the homeowner will consider getting into action. This can be seen in figure 4.4. A regression model is used as threshold for getting into action, or doing nothing. This has been based on the building block from Verbeek and Filatova (2026).

The scenario with the insurance has also been visualised in figure 4.5. The yellow boxes show the added options. In figure 4.6 a flow with a subsidy is included. The subsidy and insurance comes before the PMT, because having and not having a subsidy or insurance will change the coping appraisal.

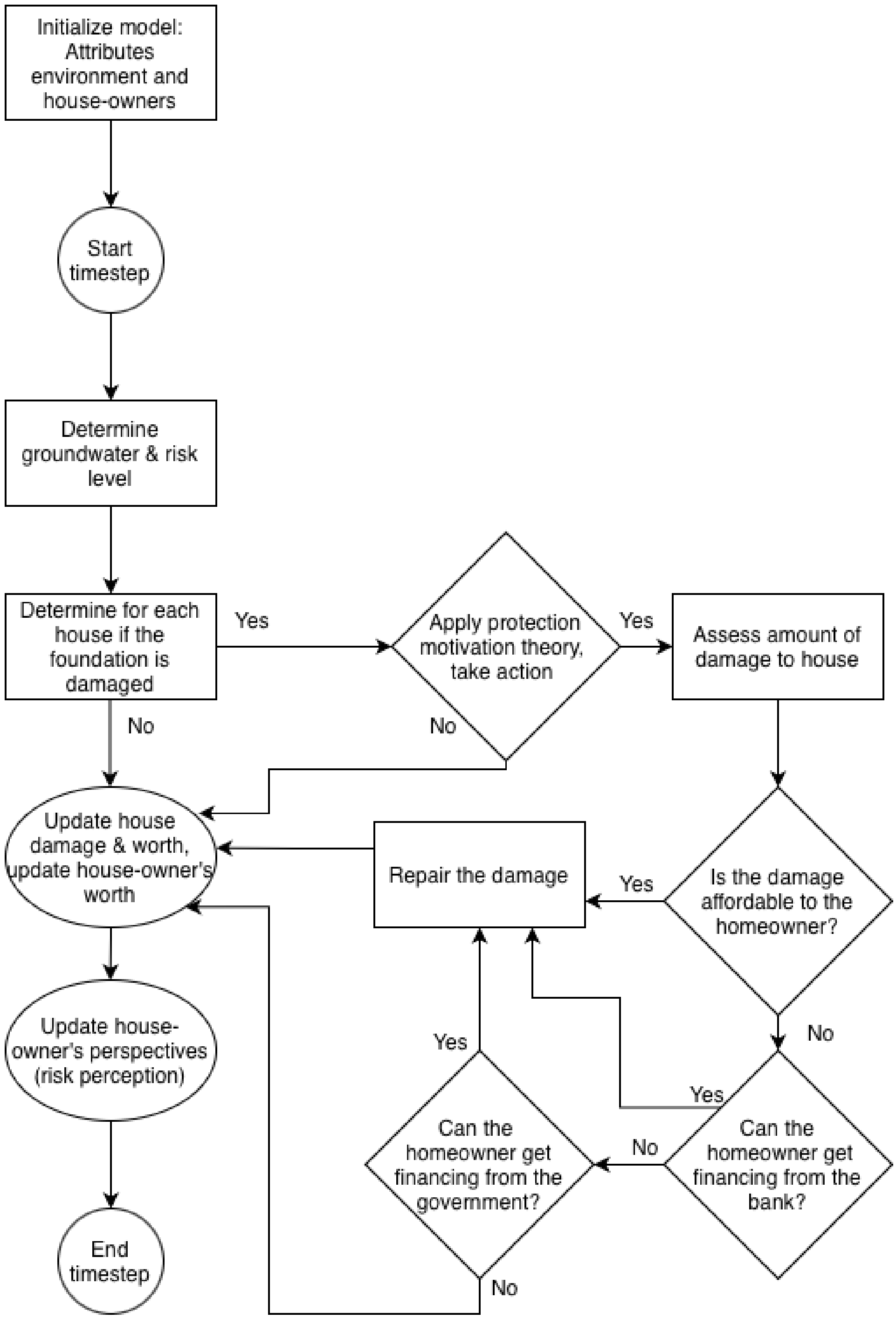


Figure 4.3: *Visualization of general flow of the Agent Based model. It shows the steps the homeowners take in the model. Starting with initialization, where the homeowners gets all the attributes and the environment is made. Then the risk level is obtained. Depending on if the homeowner has a damaged foundation, the protection motivation theory is activated. If so, the homeowners goes into the financing part where it looks for ways to finance the damage. It ends with updating the aspects of the homeowner and environment (groudwater and risk level). Then the model is ready for the next timestep.*

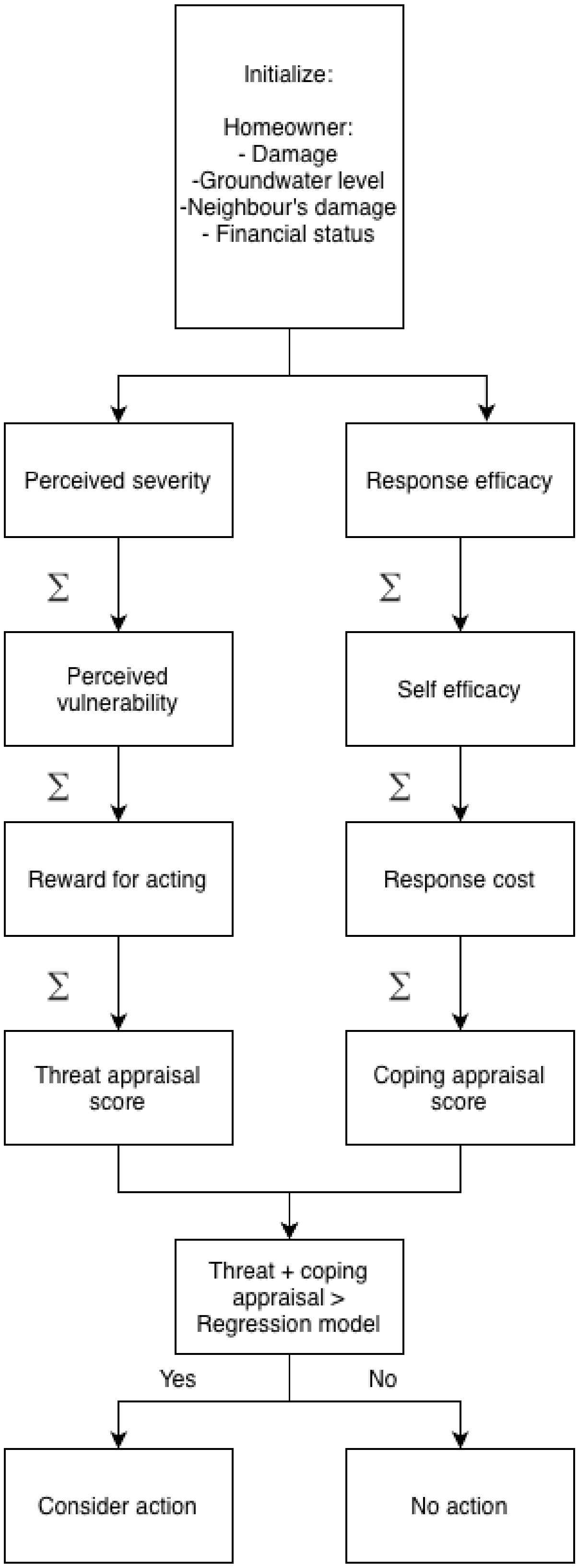


Figure 4.4: *Flow chart diagram illustrating household agent cognitive process of decision making on whether to adapt or not to climate-induced hazard. This process relies on the Protection Motivation Theory from psychology that explains how people make choices when facing risks.*

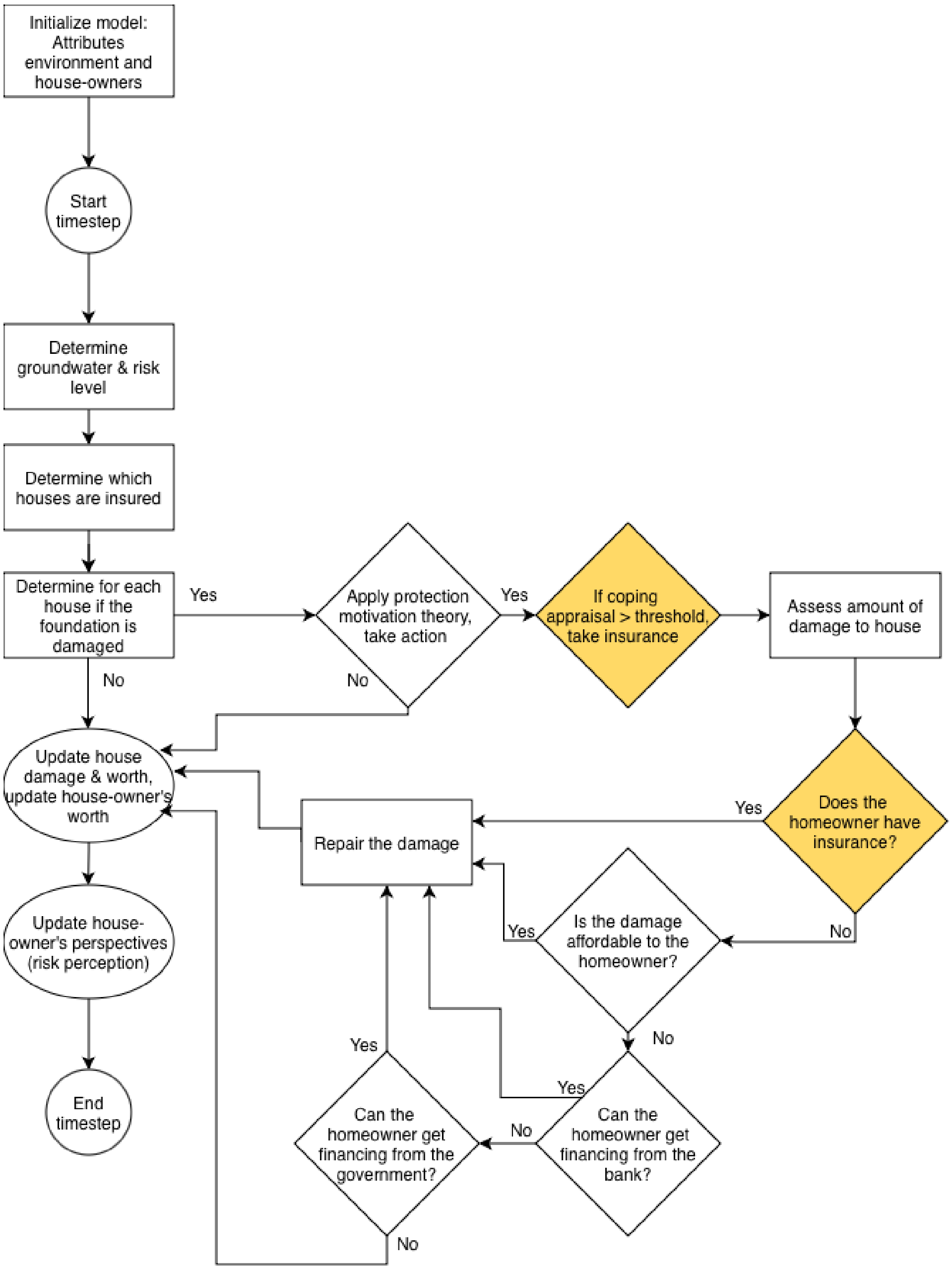


Figure 4.5: *Visualization that includes insurance. This is derived from the visualization in figure 4.3. With two additions, the option to get insurance and the assessment if a person has insurance. Those additions are marked in the yellow shapes.*

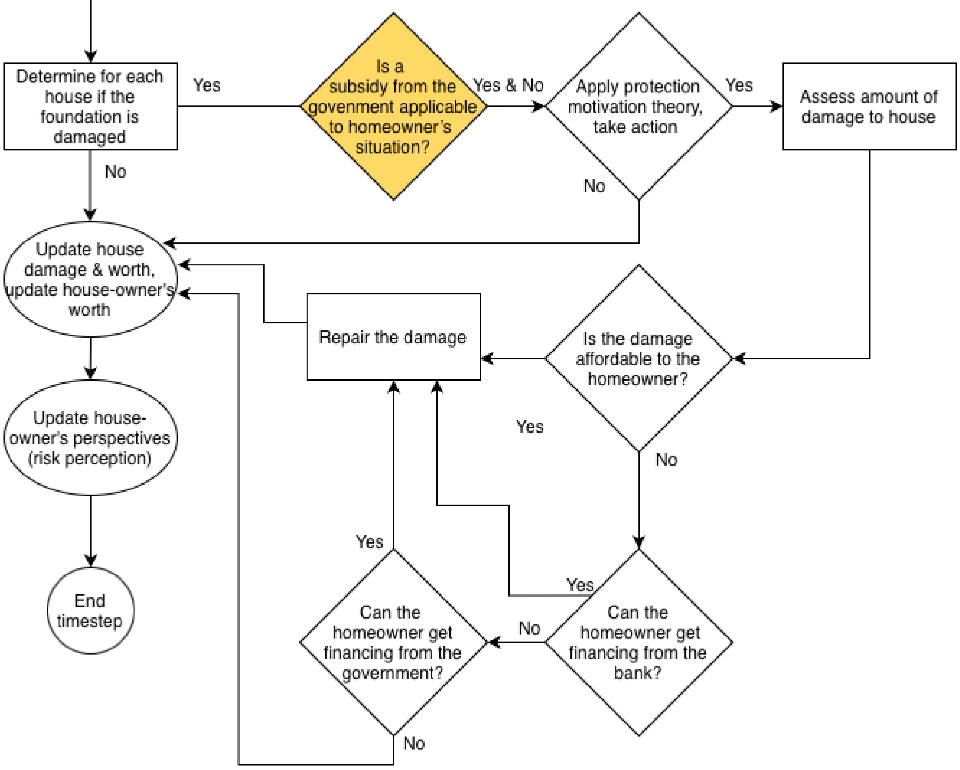


Figure 4.6: *Visualization that includes government subsidy. This is derived from the visualization in figure 4.3. The addition is the yellow shape in which the homeowner have the chance to get a subsidy.*

4.4. Model Calibration

The data that has served as input for the model can be seen in appendix A. These values in the datasets have been formatted in such a way that they can be put into the model. Not all data was readily available and at the right scale. Some data was available on neighbourhood level, some on municipality and some on a national level. In order to make this work, the municipality level has been chosen. On a neighbourhood level a lot of extra assumptions have to be made, and on a national level the extremes will be averaged out. This is because there is no pilerot risk in all parts of the Netherlands. To create the environment, the neighbourhood data from the klimaateffectenatlas has been combined to form the municipalities. Two municipalities have been selected to compare, Leeuwarden and Sudwest-Fryslan. They have been chosen based on the fact that one has more pile rot risk than the other. Another difference is that one is more urban (Leeuwarden) than the other. The house worth and amount of houses are already in the right scale, on a municipal level. The national values have been scaled and distributed and shifted to the needed distributions. By using a structured method, the synthetic population has been created. The exact method is described in appendix A.1. For the behaviour of the homeowners, PMT data has been used from a survey that looked at the risk perception of people in the Netherlands regarding floods. This is not the same as drought. More research is necessary to find the exact values of the homeowners. Because this is the closest thing to the needed PMT values, this has been used. The calibration of those values also requires more research, that is why those values have not been altered.

4.5. Sensitivity analysis

Some values needed calibration after the inputs have been processed. The most important ones are the repair cost growth rate, the threshold for action immediately and action in five years. These have been varied in a sensitivity analysis. This can be found in appendix B. The most sensitive output value is the amount of money the bank loans to the homeowners. This can be explained by the strict conditions the bank has to give homeowners a loan. A lot of homeowners are very close to meeting the conditions, that even a little change in a threshold can make the difference. The other values are not so sensitive to those input changes.

4.5.1. Model output

Key model outputs will include changes in household adaptation levels, the insurance coverage, government investment strategies and overall costs, and their distribution. By running the model with different scenarios, the comparison between different compensation schemes and insurance policies can be assessed over time. The output will not predict exact numbers, but this ABM will help identifying trends and behavioural aspects when homeowners are faced with foundation damage induced by drought.

The model is critically evaluated to ensure the credibility of the agent-based model. This step is needed to assess whether the model is used correctly and if the real-world dynamics are accurately represented. By checking the model and its outcomes multiple times, the model will be verified and debugged. Under simplified conditions the model is tested to confirm that the model behaves as expected. This will ensure useable model outputs.

5 Modelling

This chapter will expound on the choices made during the implementation of the conceptual design discussed in the previous chapter and its operationalization in the code. For my thesis I have decided to code it in Python using the Mesa package. Mesa is a Python package designed for the purpose of making Agent Based Models. To visualize and clarify the model and its workings, a schematic view of the model can be seen in figure 5.1. The schematic view shows the exact steps the code is taking in the model. It has been based on the prior shown flowchart in figure 4.3. The model consists of the following four stages:

1. Initialization
2. Inspection
3. Financing
4. Updating agents

The base scenario is the one where no policy is active. This will be called the base case from now on. It is the situation described below. The model description is also valid for the cases in which the scenario is active, but then the policy is added.

5.1. Initialization

The first thing that happens during the initialization is the creation of the synthetic population as described above. The houses and homeowners are given their properties. The homeowners get financial attributes such as their assets, and income. They also get behavioural properties from the PMT-values. They then get assigned a house, this is done by binning. The homeowners and houses are put into 5 bins. Within a bin they are randomly matched on their financial abilities, assets for the homeowner, and woz-worth for the houses. This is done to correlate the WOZ worth of the house with the assets of the homeowners. They should not match perfectly, however, they should have some correlation to each other. The houses also have a pilerot risk. This is enough to start running the model.

5.1.1. Grid

Networkx grid has been used. The exact spatial coordinates are not as important with drought as it is with flooding. Because a flood happens in a certain area. Droughts too, but a house will not have negative effects if the house has a good foundation. This is in contrast to a flood, that will impact a whole area. The data is also not disaggregated enough to create something spacially explicit. There is only data per neighbourhood available, that is also based on an assumption of how many houses with wooden piles are in each part. As much as possible this data has been used to create an area with the aspects of Leeuwarden.

5.2. Inspection

If the PMT values are high enough that a homeowner will act, the first step is to get an inspection. This will determine if the foundation is damaged at all, or if the homeowner is acting even though it may not be necessary. Currently the inspection is done each timestep, this is because the PMT values are changing, if the agent has other PMT values then in the previous step, it might be the case that this person will act the next timestep around.

There are three possible outcomes for the inspection:

- **No action needed**: The damage threshold is not reached. The homeowner will do nothing.
- **Action in five years**: The damage threshold for action in five years is reached. After five years it will automaticallly swich over to the immediate action state.
- **Immediate action**: The homeowner either exceeds the immediate action threshold, or the homeowner has gotten the state action in 5 years, 5 years ago. The homeowner is aware of the damage and will try to repair this. The homeowner will go into the financing damage phase, to find a mean to pay for the damage.

The sensitivity of this threshold can be found in appendix B. Side note, if there is damage but the homeowner does not have a big enough incentive to act, one point will be added to the neglected steps. this is because if the homeowner does nothing, the costs for repairing the damage will increase. Even though an inspection has not been done, the damage will not be ignored by the model. The same goes for the case in which no financing options to repair the damage have been found.

5.3. Financing

The financing goes by asking the questions below in the following order:

1. Does the homeowner have enough available money in their own pocket?
   If yes, pay the damage costs from the money out of their own pocket. Otherwise continue to the bank.
2. Can the homeowner get a loan from the bank?
   If yes, pay the damage costs from the bank loan. Otherwise continue to the Fonds Funderingsherstel.
3. Can the homeowner get a loan from Fonds Funderingsherstel?
   If yes, pay the damage costs from the money from Fonds Funderingsherstel. Otherwise continue to the last question.
4. If all prior options have failed, the repair is deemed too expensive for the homeowner.

The bank only gives out a loan if the homeowner passes the requirements from equations 5.1 to 5.3. These assumptions are based on the fact that the bank will not loan more money than the house worth. The expanded explanation from the homeowners' properties can be found in appendix A.1.

$$mortgage\_debt < 0.8 * house.woz \tag{5.1}$$

$$loan\_amount < 0.5 * house.woz \tag{5.2}$$

$$homeowner\_available\_money > 0.1 * loan\_amount \tag{5.3}$$

The requirements from Fonds Funderingsherstel are a lot less strict. The requirement is described in equation 5.4. The condition that the homeowner has to meet, is that the debts of a homeowner cannot become more than twice the amount of the WOZ value. The fund was first for only certain municipalities. The government has added €20 million to make the money nationally available Rijksoverheid (2025). There is a cap, the government cannot give out more money than they have budgeted for. The cap in the model is €20 million, only a part of this is for Friesland. The proportion of 1/6 of this national cap is what Fonds Funderingsherstel can give out in Friesland. This cap is not reached during the runs.

$$mortgage\_debt + loan\_amount < 2 * house.woz \tag{5.4}$$

When a homeowner does not meet any of those three requirements, the homeowner cannot afford a repair. The homeowner will get into the repair too expensive phase. Because the economic status of homeowners does not change, the homeowner is not able to leave this group. The homeowner will get a plus one for neglected steps. If it turns out that the house has foundation damage, the worth of the house will decrease by 12%. This is what happens to this group of homeowners (ABN AMRO, 2026).

There is one more option. That is the case where the homeowner did not go for an investigation, even though their house is damaged. This homeowner will also get +1 in the amount of neglected steps. This will increase the costs to fix the house. As can be seen in formula 6.5.

$$cost = base\_cost * (1 + (cost\_growth\_rate * neglected\_steps) \tag{5.5}$$

When a homeowner is able to successfully repair their house, the risk is decreased by 50% and the risk label is reduced to its lowest level. The WOZ worth of the house is also restored.

5.4. Behaviour

The PMT used in the model has been built by using the reusable building block from Verbeek and Filatova (2026). All actions and interactions that happen within the model will influence the perceptions of the agents. Table 5.1 shows the changes the PMT values go trough. This table is based on assumptions. For example, if a homeowner has gone for an inspection, and the outcome is no action, the perceptions change in such a way that the homeowner is reassured. The probability, worry, cost and damage decrease, and the self efficacy grows slightly.

Table 5.1: *Table with the PMT Event Deltas. The event deltas describe how much a certain property changes when events occur. For example, in case of no action, the perception of the flood probability decreases with -0.05.*

Event	Flood probability	Flood damage	Worry	Response efficacy	Self efficacy	Cost
inspect_no_action	-0.05	-0.03	-0.10	0.000	0.05	-0.02
inspect_action_5y	0.03	0.04	0.08	0.004	0.000	0.03
immediate	0.08	0.12	0.15	0.006	-0.004	0.04
success_self_fund	-0.05	-0.04	-0.08	0.01	0.004	-0.06
success_bank_loan	-0.05	-0.04	-0.08	0.10	0.004	0.06
success_gov_loan	-0.05	-0.04	-0.08	0.010	0.004	0.06
missed_inspection	0.03	0.04	0.06	0.01	-0.003	0.03
repair_too_expensive	0.04	0.04	0.10	-0.002	-0.010	0.12

5.5. Updating agents

The agents are updated with a new WOZ value, new available money, loan, a repaired foundation, new PMT values or a higher neglected steps amount. These updated numbers are used again in the next timestep. In this case the risk and damage do not change over time, nor does the economic status of a homeowner. This can be included in further reseach.

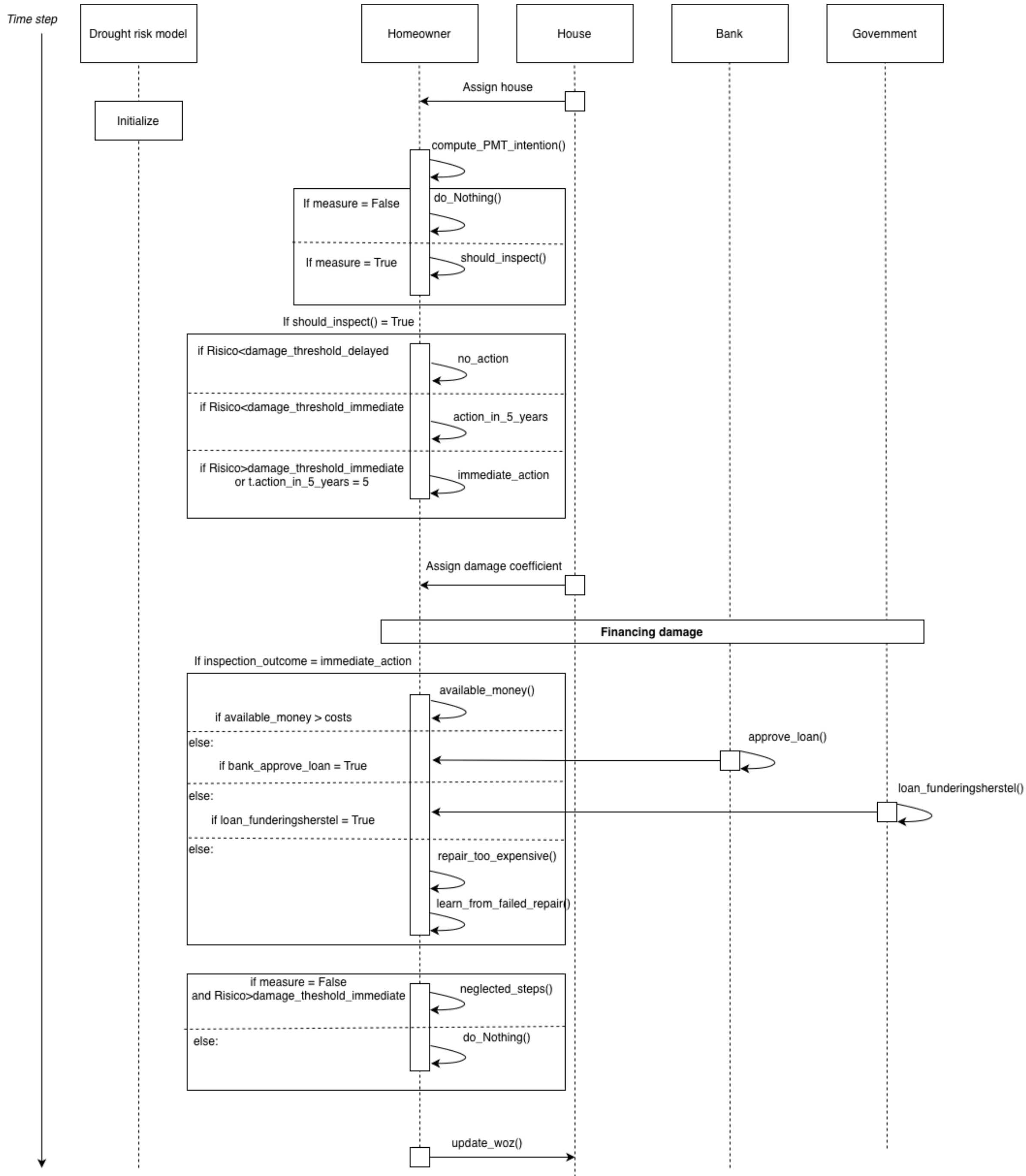


Figure 5.1: *Sequence diagram of the model. This diagram shows step by step what is happening in the model. The function names can be seen in the diagram. The blocks show the functions activated. Firstly the PMT intentions, whether a homeowner is going to inspect. And later on the scheme in which it can be seen which financing options a homeowner has. Ending with the function that makes the costs of repair higher after negligence.*

5.6. Policies

There are three policies that have been implemented. They are an insurance policy, a subsidy and a nudging policy. The insurance comes from insurance companies, and the subsidy and nudging are done by the government. This comes on top of the base case, where people can already fund their damages by their own money, a bank loan and money from Fonds Funderingsherstel, as implemented in the flowchart.

5.6.1. Insurance

A lot of things in the normal day life can be insured. This creates a sense of security, since when the insured object has gone missing or is broken, the insurance pays part of the replacement costs. Insurers do not insure everything, simply for the reason that insuring some things is not very feasible. Currently for housing damage in relation to drought, houses can only be insured for fires (Verbond van verzekeraars, 2025). This policy explores what will happen if houses could also be insured against foundation damage. The insurance policy is designed in the following way:

1. If the homeowner has an incentive to do something, the homeowner gets an insurance.
2. Insurance premium is equal to the predetermined premium factor multiplied by the WOZ worth of the house
3. The Homeowner pays the insurance premium each timestep. If this is not possible, the insurance will end.
4. If there is a damage, the insurance will cover 70% of the costs.

5.6.2. Subsidies

One of the instruments that can be used by the government is subsidies. There is some debate on whether this is fair van 't Klooster and Hochstenbach (2026). It is a commonly used instrument as described by Filatova (2014). The report by AFM (2026) describes a case where the government gives a 30% subsidy of the total damage costs. This has been the starting point. The subsidy has been implemented in the following way:

1. When the homeowner gets the verdict that immediate action is needed after investigation the financing options are assessed.
2. The costs are decreased by 30%. This ensures that more people are able to finance the damage out of their own pockets, with a bank loan and with Fonds Funderingsherstel.
3. The costs of this subsidy are logged to see the expenses of this policy.

5.6.3. Nudging

Another thing the government can do is create awareness. By showing the risks and the scale of the problem, the government can try to nudge people to start acting earlier. The goal of this policy would be to get people to investigate their damage sooner. This would give the effect that there will be less neglected steps. Which in turn will keep the total foundation damage costs down. Another advantage is the fact that this measure does not cost a lot of money. The government would not be paying for people's foundation damage on a large scale. This policy is implemented in the following way:

1. Before it is established if the homeowner is going to act, the values are altered by the nudge.

2. The worry, cost perception and the perception of the drought risk and damage increase slightly.
3. When the homeowners decide to act or not, this nudge will influence the factors a bit.

5.7. Targeted policies

The policies described before will also be altered to target a specific group. This is done because a generic policy might help overall, but it still might be the case that it helps the people who do not need it. For the targeted policies an extra filter in the subsidy and insurance policy will be added.

5.7.1. Targeted subsidy

The targeted policy will work the same as before, except for the fact that the subsidy will only be given out to homeowners who have smaller amount of assets than 50.000 euros. This is chosen because this is the nation-wide mean of assets. The idea is that this will help give out the subsidy to the people who cannot afford it themselves, but not to the wealthy.

5.7.2. Targeted insurance policy

For the insurance it will be the other way around. Insurers generally do not insure very high risk endeavours. This is why drought damage to foundations already is not insurable anymore. This is why the houses with the highest two risk labels will be excluded from the insurance scheme.

5.8. Run amount

Because of the stochastic nature of ABM, multiple runs with the same settings have to be done. To establish the amount of runs, the method from Lorscheid et al. (2012) has been used. This article states that using the coefficient of variation can be a good measure.

$$c_v = \frac{s}{\mu} \tag{5.6}$$

When running with different seeds, this coefficient eventually stabilizes. The runs and their outcomes can be found in appendix A.2. A lot of runs will limit the impact of the stochastic nature, the problem is that this also needs a lot of computing power and time to run. This is why the amount of runs and the output should be balanced. The run amount that has been found in this way is 50. This will be the amount that is used in the results section.

5.9. Design of experiments

In order to answer the research question multiple experiments have been made. The experiments can be seen in table 5.2. Due to limited time, not all combinations have been looked at. Choices have been made. The experiments are in service of answering the research question; finding different distributions of the costs of drought-induced foundation damage, and looking at the adaptation behaviour of homeowners. Below the reasoning behind the experiments is explained.

- **E0:** This is the first experiment. By testing it on the municipality of Leeuwarden and on the current data it can be compared with another municipality to see the difference and to find the municipality that can be used for the base case.
- **E1:** This is the experiment that has been run on the same dataset, but on another municipality. This can be compared to E0 to establish which municipality will become the base case.

- **E2: (Base case)** After the municipality has been chosen, a dataset must be selected. This experiment is conducted on the 2050 dataset with high climate change consequences.
- **E3:** The data from the 2050 low climate change conditions has also been used. This can now be compared to E0, and E2 to select the base case.
- **E4:** The next step is to compare the base case to the policies. In this experiment the insurance policy is tested. This will answer the main research question.
- **E5:** This experiment is conducted to find out if a subsidy is effective in distributing the costs.
- **E6:** This experiment will show if a nudge is an effective policy. By altering the homeowner behaviour, it can be established whether the adaptation behaviour is the main barrier in the homeowner behaviour.
- **E7:** To make the policy options more realistic, a targeted policy for the insurance is designed. Insurers usually do not insure high risk situations if they are not feasible. To see what would happen if the high risk groups are excluded from the insurance, this experiment is conducted.
- **E8:** This experiment shows the effect of targeting the subsidy to homeowners who are less well of financially. This is done to see what would happen to the distribution.
- **E9:** To see what the effects of helping homeowners financially and helping their adaptation behaviour, a policy combination is designed. This experiment will show what the effects of combining the nudge with the insurance is.
- **E10:** This experiment will show what the effects of combining subsidy and the nudge will do.
- **E11:** This experiment is conducted to see what would happen if the subsidy and insurance are combined. This is informative because this shows what happens when the costs are distributed over one extra actor.

Table 5.2: *Table with the design of experiments. These experiments have been designed to answer the research question. E2 is the base case to which all policies are compared to see what is the most effective policy to distribute the costs of drought-induced foundation damage to houses.*

	Municipality	Dataset	Insurance	Subsidy	Nudge
E0 (Baseline)	Leeuwarden	Current	0	0	0
E1 (Baseline)	Súdwest-Fryslân	Current	0	0	0
E2 (Climate scenario)	Leeuwarden	2050 High	0	0	0
E3 (Climate scenario)	Leeuwarden	2050 Low	0	0	0
E4 (Policies)	Leeuwarden	2050 High	1	0	0
E5 (Policies)	Leeuwarden	2050 High	0	1	0
E6 (Policies)	Leeuwarden	2050 High	0	0	1
E7 (Targeted policy)	Leeuwarden	2050 High	Targeted	0	0
E8 (Targeted policy)	Leeuwarden	2050 High	0	Targeted	0
E9 (Policy combinations)	Leeuwarden	2050 High	1	0	1
E10 (Policy combinations)	Leeuwarden	2050 High	0	1	1
E11 (Policy combinations)	Leeuwarden	2050 High	1	1	0

5.10. Distribution

The research question that concerns the different views on how the costs from drought-induced foundation damage should be distributed cannot be answered by modelling. In order to answer this research question, a literature review has been conducted that can be found in chapter 7.7.

6 Validation

In this section the validation of the model is done. This is by using the method described by Sargent (1987). This article states that a model can be seen as valid if the accuracy is within an acceptable range that is acceptable for the purpose of the model. Several methods are used to validate the model as described in the paper.

- **Animation:** By looking at the graphs that the model produced the behaviour is seen and analysed.
- **Historical Data Validation:** In the appendix the data produced by the model is compared to existing numbers.
- **Internal Validity:** A lot of runs have been done to find the variability of the stochastics within the model. The conclusion is that there is not a high amount of variability.
- **Parameter Variability - Sensitivity analysis:** This has been done and is described in the result section.
- **Trances:** Behaviour of individual values within the model has been traced to see if the model logic is correct.

Another thing Sargent (1987) suggests is looking at the conceptual model validation. Checking to see if the concepts and relations are correct. For most of the assumptions sources are found, otherwise they have been explicitly stated.

Figure 5.1 shows the computerization of the model. This is based on the prior model conceptualisation. This shows that the computerized model verification does not differ much from the concept. Dynamic testing has been done to ensure that it has been implemented correctly. This has been checked by tracing individual values and looking carefully at the outcomes of each function.
Lastly Sargent (1987) describes the operational validity. This is about determining if the models output has the needed accuracy. The validation tools that have been used all contribute to establishing the operational validity. The articled describes that the main criterion is whether the thing that is being researched is observable. In this case the intended outcomes are observable. By using graphs to see the outcomes and looking at the batch mean, the model is validated.

7

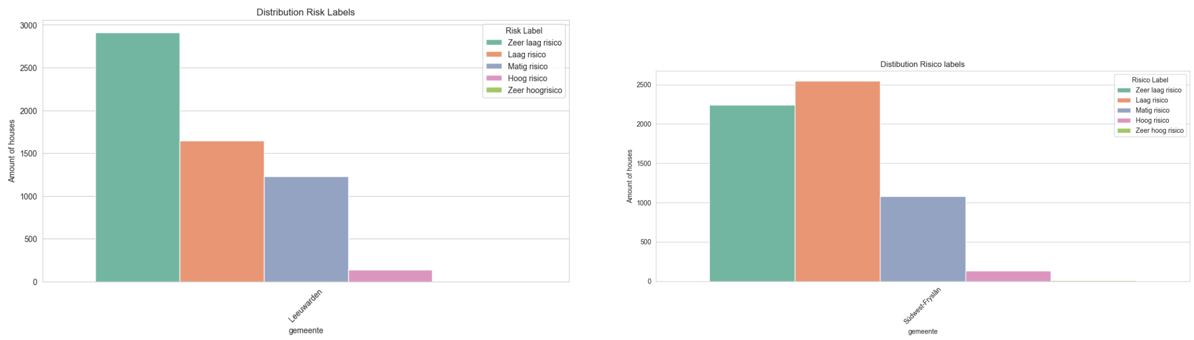
Results

The results are found by running the model methodologically in multiple experiments. The Baseline experiments are used to choose which municipality the other tests will be run on. The climate scenario experiments will be used to determine on which climate scenario the policies will be tested on. Lastly the policies will be tested on the chosen municipality and climate scenario.

7.1. Baseline

The first experiments that have been conducted are the ones to establish the baseline. This is done for two municipalities in Friesland. This is to compare a high-risk with a low-risk area. Súdwest-Fryslân is an area with a relatively low pilerot risk, but not one without risk. Leeuwarden has a lot of buildings in the city center with a high risk of pilerot. Due to limited time, one is chosen to go forward with. Since this research is about finding the means of how to divide the costs of drought damage to foundations, the municipality with the highest damage and highest accompanying costs is chosen to go forward with.

The division of the risk labels per municipality can be seen in figure 7.1. What stands out is the fact that Súdwest-Fryslân has more in the low risk category than in the very low risk category. Leeuwarden has the most in the lowest category and the least in the high risk category. This municipality does have more homeowners in the higher risk categories in general.

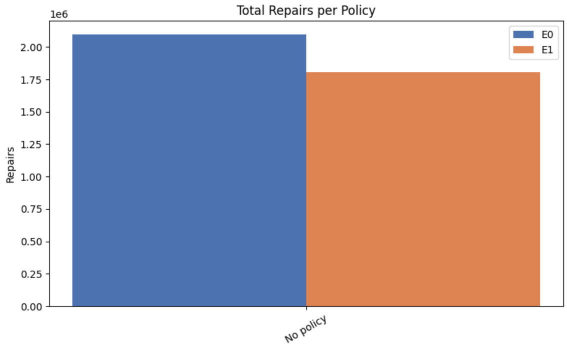


(a) *Distribution of risk labels per category for the municipality of Leeuwarden.*

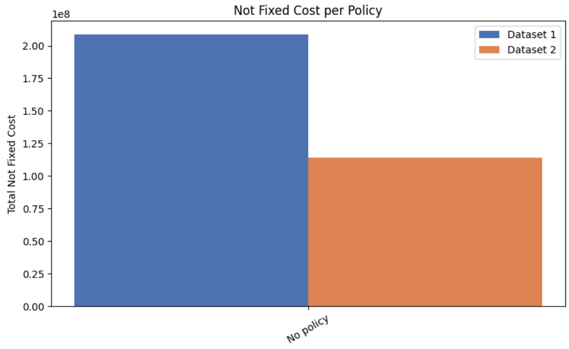
(b) *Distribution of risk labels per category for the municipality of Súdwest-Fryslân.*

Figure 7.1: *Figure where the distribution of risklabels among the two municipalities can be seen. The labels go from very low risk, to very high risk. This is done in order to determine on which municipality the simulations are going to be run.*

To choose the municipality this research is going to focus on, the results are compared. This can be seen in 7.2. The municipality of Leeuwarden (E0) has the most repairs, and the highest not fixed costs. Because of this, it has been chosen to go forward with the municipality of Leeuwarden.



(a) *Barplot that compares the total amount of repairs between the two municipalities. E0 represents the amount of repairs in Leeuwarden and E1 represents the amount of repairs in Sudwest-Fryslan.*

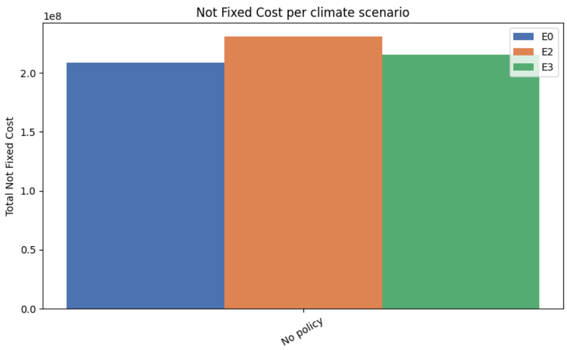


(b) *Barplot that compares the total amount costs from the not fixed houses between the two municipalities. E0 represents the amount of not fixed damage costs in Leeuwarden and E1 represents the amount of not fixed damage costs in Sudwest-Fryslan.*

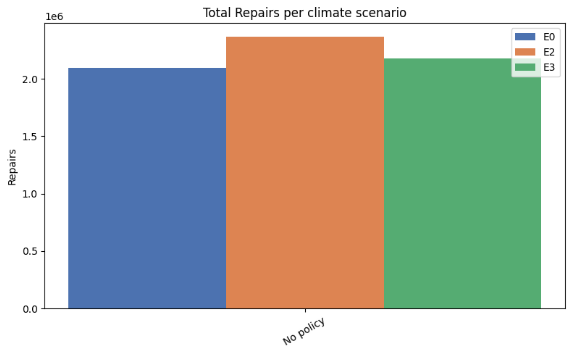
Figure 7.2: *Comparison of repairs and not fixed damage costs between municipalities E0 = Leeuwarden, E1 = Sudwest-Fryslan. Leeuwarden has more repairs and more not fixed costs. This means that Leeuwarden is the more interesting municipality to look at trough the eyes of cost distribution.*

7.2. Climate scenarios

The data from the klimaateffectenatlas contains multiple climate scenarios, the current one, a scenario from 2050 with a lot of climate change (2050 high) and one in 2050 where climate change does not play a too big of a role (2050 low). To test the policies on, one of those climate scenario's will be chosen. Experiment E2 is conducted on the data from the 2050 scenario with high risk, E3 in 2050 with a low risk, and E0 has been run with the current climate scenario.



(a) *Not fixed damage costs comparison between the climate scenarios*



(b) *Total repairs comparison between the climate scenarios*

Figure 7.3: *Comparison of repairs and not fixed damage costs between climate scenarios. E0 = current, E2 = 2050 high, E3 = 2050 low. The scenario with 2050 high climate conditions has the most not fixed costs and the highest amount of repairs. Thus the case in which it will be the most informative to look at in this research.*

In this case the scenario with the highest repairs and the highest costs, is the scenario in Leeuwarden with the 2050 high climate change dataset. This one has been chosen as the base case to conduct the other tests on.

7.3. Policies

In this section the results of the policy runs are observed. The case with the insurance, subsidy and nudge, also called E4, E5 and E6 respectively. Experiments E4, E5 and E6 are compared to the baseline of E2. This is done to evaluate the experiments that have been conducted.

They have been plotted next to each other in figures 7.4 and 7.5. The first shows the total costs and their distributions over time. This model has been run over 30 years. What stands out is the amount of not fixed costs. They accumulate each year. This is because more homeowners get damaged foundations over time, but also the damages become more expensive after negligence. The two policies that help people pay their damage, the subsidy and insurance, have a notably lower amount of total costs. To see how those costs are distributed over time and amongst the actors, their division is seen in figure 7.5. The subsidy and the insurance both have a higher total amount of costs, this is because more houses are repaired. What also helps is the fact that with those policies there is another actor to distribute the costs over. What also stands out is that the insurance is paying a large part of the costs. Because of this the share of money paid by the households, the bank and Fonds Funderingsherstel is much lower.

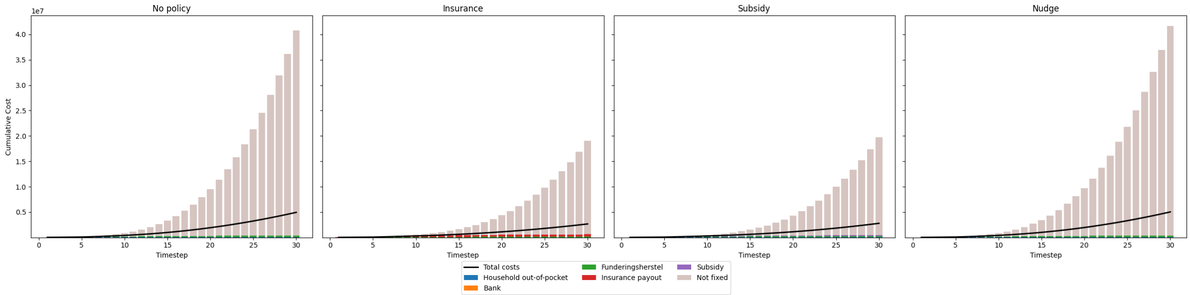


Figure 7.4: *A bar chart of the four policies and their total costs next to each other over a timespan of 30 years. The not fixed costs are a big part of the total costs in each of the policies. Even more so for the experiment without policy and the one with a nudge.*

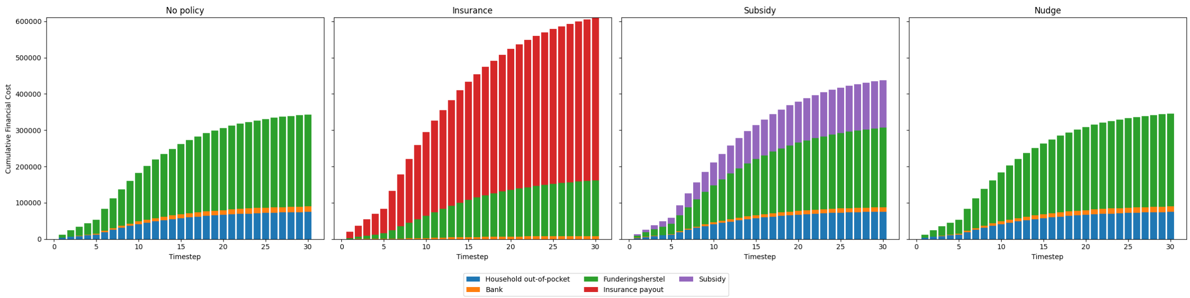


Figure 7.5: *A stacked bar chart of the division of the costs amongst the actors in the policies over a timespan of 30 years. These are all the costs that have been made to repair the foundation damage.*

Another chart that shows the distribution of cost clearly is seen in figure 7.6. What stands out is the fact that the insurance has paid for such a big part of the damage. The premiums that have been paid to the insurers cannot be seen in this graph. The base policy and the nudge policy have the same distribution. The subsidy takes away a small part of the money paid by Fonds Funderingsherstel. The part paid by the subsidy is less substantial than the part paid by the insurance in the case of the insurance policy. This can be explained by the fact that the policy helps to pay for 30% of the costs, and the insurance covers 70%, but does get a premium in return.

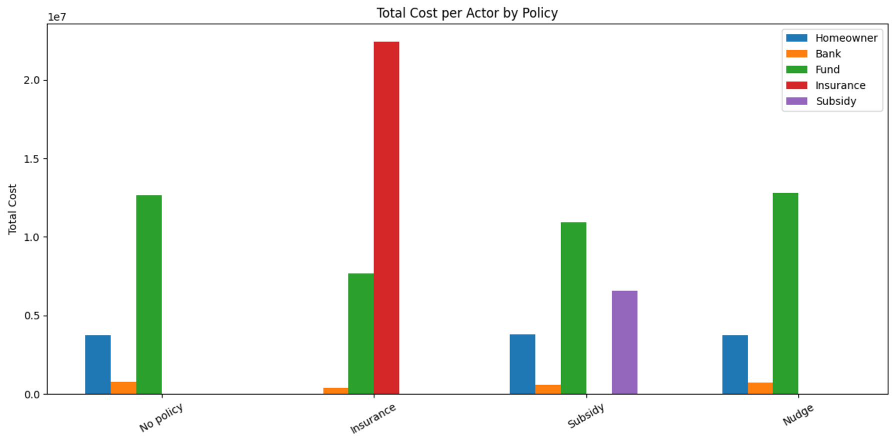
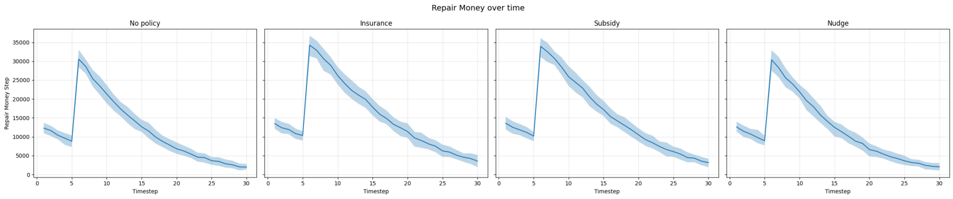


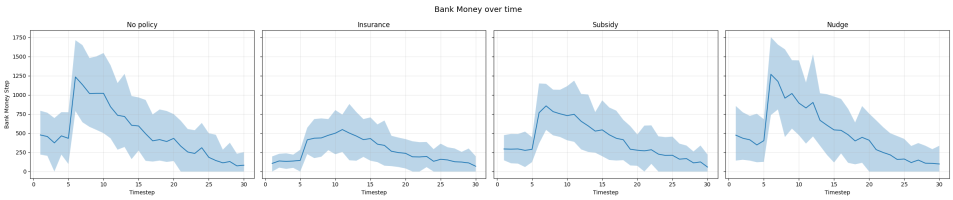
Figure 7.6: *Bar charts sorted per policy of which actor paid for the foundation damage. On the X-axis the policies are clustered and the costs per actor can be seen. The insurance has a very high amount that stands out. In all cases Fonds Funderingsherstel plays a big part in financing the damage.*

7.3.1. Costs

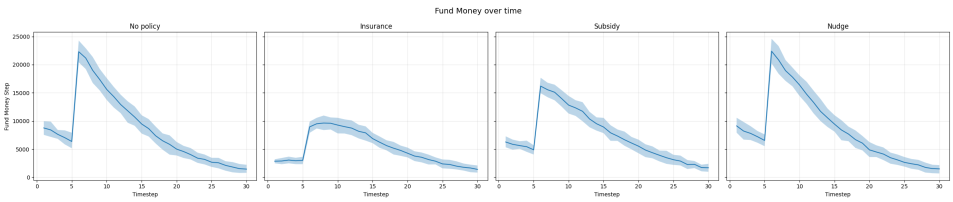
The repair money over time is about the same for each policy. The money that banks have given out is more in case of no policy and the nudge policy. It is notably less in case of the insurance. The same goes for the money from Fonds Funderingsherstel. The sudden spike at 5 years can be explained by the fact that a lot of homeowners have gotten a 'repair in 5 years' in the first timestep. After 5 years all those people in this group that have investigated will immediately go to the financing options. This explains the increase. What stands out is that there are significantly less bank and Fonds Funderingsherstel loans in the case of the insurance. In the case of the subsidy, there are also less, but not as drastic as it is in case of the insurance.



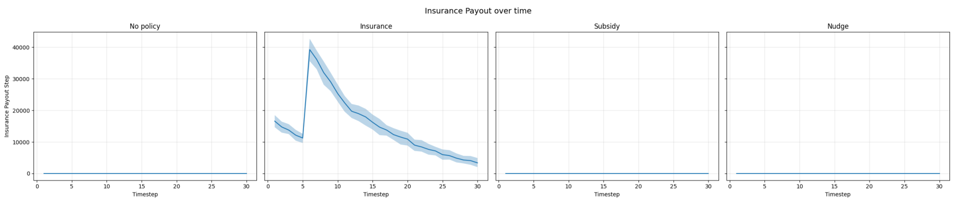
(a) *The amount of money spent repairing damage to foundation damage by the money that the individual homeowners already possessed. This can be viewed for all 4 policies.*



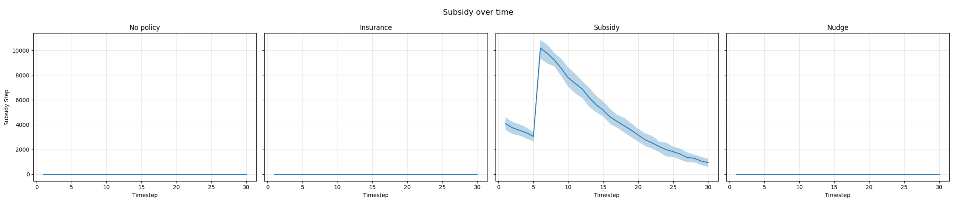
(b) *The amount of money banks loaned for repairing damage to foundation damage. This is shown for all the 4 policies.*



(c) *The amount of money spent by Fonds Funderingsherstel on repairing the foundation damage. The amount can be seen for all 4 policies.*



(d) *Insurance payout over time. There only was insurance in the case of the insurance policy, which can be seen in the graph.*

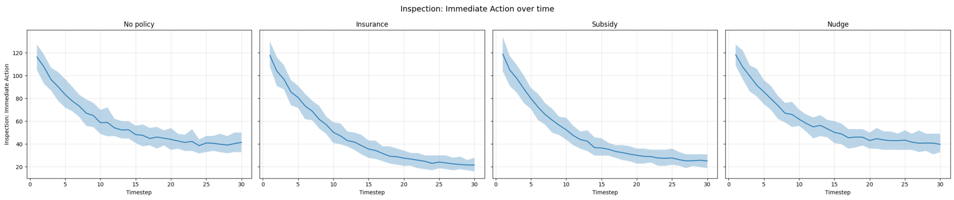


(e) *Subsidy payout over time. There only was subsidy in the case of the subsidy policy, which can be seen in the graph.*

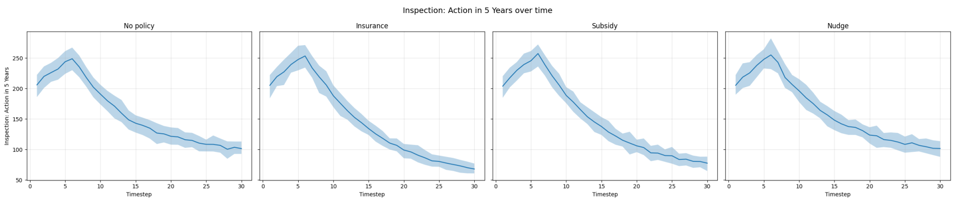
Figure 7.7: *The money paid per actor split out per step. This is not cumulative but the payout per step. Especially in the payout money from the bank over time there is a bigger uncertainty. The line shows the mean per step, the blue band around the unceirtainty from the stochastic nature of ABM*

7.3.2. Inspection outcomes

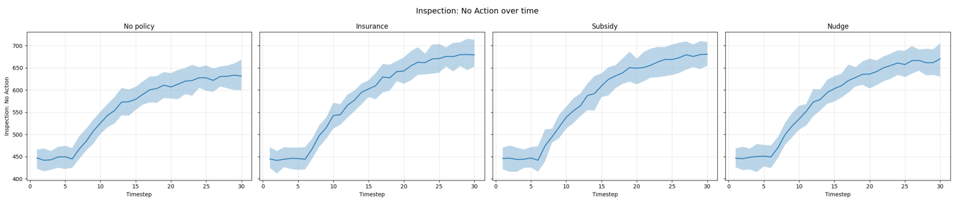
Inspection outcomes per timestep for all the policies can be seen in figure 7.8. All of the policies show a same trend. The amount of inspection outcome that is immediate action decreases over time. The action needed in 5 years increase up to 5 years, then also decreases. The inspection outcome that no action over time is necessary keeps growing, and eventually stabilizes. Since the risk labels do not change in this way of modelling, it makes sense that all the investigation outcomes eventually stabilize. It is also because at a certain point everyone will have had the incentive to act, so everyone will have already undergone an investigation.



(a) *Number of homeowners who after the damage investigation received the verdict 'immediate action'.*



(b) *Number of homeowners who after the damage investigation received the verdict 'action in five years'.*



(c) *Number of homeowners who after the damage investigation received the verdict 'immediate action'.*

Figure 7.8: *Inspection outcomes for the policies divided into the three outcomes, immediate action, action in 5 years and no action needed. The line shows the mean per step, the blue band around the uncertainty from the stochastic nature of ABM.*

7.3.3. PMT values

Figure 7.9 shows the plots for the PMT values per policy. In section B.2 in the appendix, the individual plots per policy and their average over the 50 runs can be seen. When looking at the flood probability in Figure 7.9, flood damage, worry and cost, the nudge policy stands out. Over time this line increases a lot, while the other lines stay relatively flat. This is because the nudge directly influences the PMT values. What also stands out that when looking at the response efficacy and self efficacy, the subsidy and insurance are much higher than the base scenario and the nudge. This can be explained by the fact that the homeowners who have been able to successfully repair their home perceive a higher response and self efficacy. Because in those two policies more homeowners have been able to repair their homes, the efficacy for those two policies are higher.

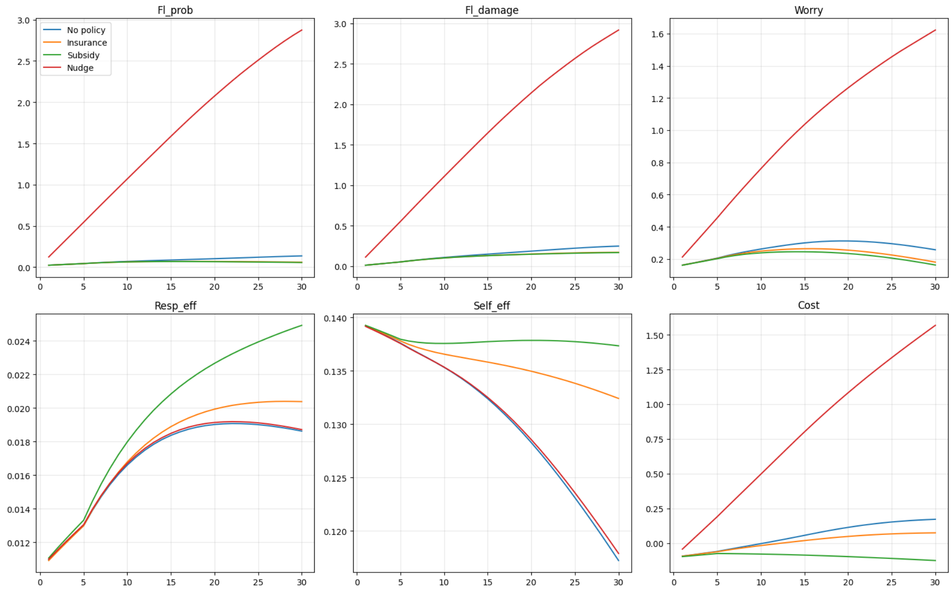


Figure 7.9: *PMT values per factor for all of the policies. The flood probability, flood damage, worry, response efficacy, self efficacy ant the costs. Especially the values from the nudge policy stand out.*

7.3.4. Viability of the insurance

To see if the insurance is profitable, the premiums that have been paid and their respective payouts have been tested in a sensitivity analysis. This can be seen in figure 7.10. What stands out is the fact that the insurance is more times not profitable than that it is. With a high premium that is 0.2 or higher of the WOZ worth, the costs can be borne. But the coverage amount cannot become too high, with the coverage that has been used 70% of the damage, a very high premium is needed to make this profitable. Another option is to make more people take an insurance, this will also help with bearing the costs.

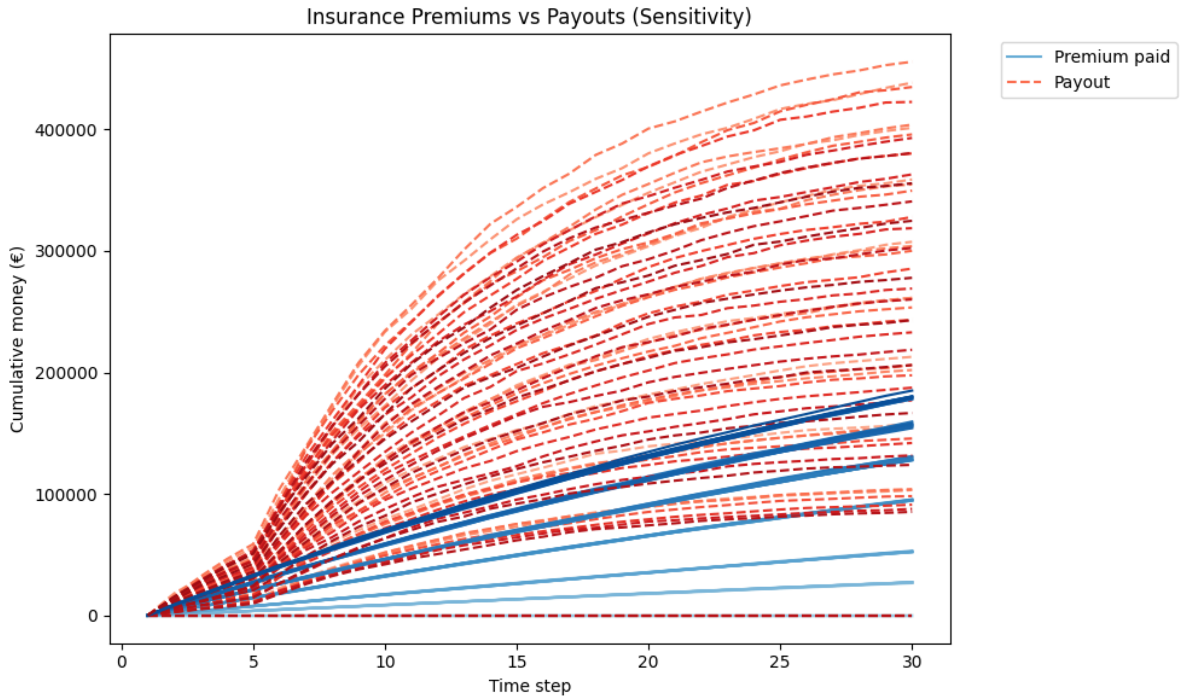


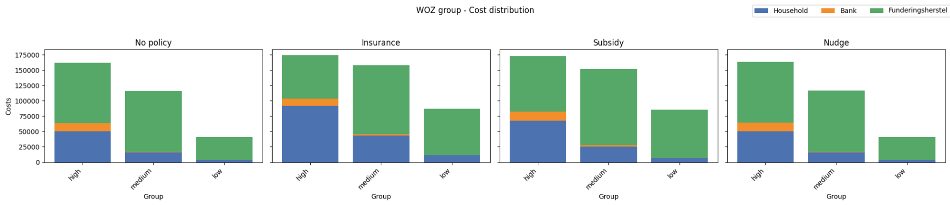
Figure 7.10: *Sensitivity analysis where the insurance premium is varied: [0, 0.05, 0.1, 0.2, 0.3, 0.4,0.5] and also the insurance coverage share: [0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9,1]. There are cases in which the insurance premiums are more than the insurance payout, in most of the cases the insurance it is not profitable.*

7.3.5. Policies divided into groups

To see how the policies affect different groups, the homeowners are grouped on different aspects. On the amount of available money, WOZ-worth of their houses and in the risk group. All those groups are made by dividing the homeowners in three groups, high, medium and low. The results can be seen in the upcoming sections.

WOZ-value

Figure 7.11a shows the distribution of costs for the houses with different WOZ values. What can be seen is that the homeowners with the high WOZ-value have to pay more costs, this is because they have more means available to repair the damage, so they will make more repair costs. The high WOZ group pays off their repair costs largely by their own money and a bank loan, and by Fonds Funderingsherstel. The middle group is less able to finance the damage by own money and is also less likely to get a loan from the bank. They also finance a lot of damage trough Fonds Funderingsherstel. The lower group is not as able to pay for the damage as the other groups. But when they are able to, they finance it with Fonds Funderingsherstel. When comparing amongst the policies, it can be seen that in the case of an insurance or subsidy, more people are able to finance their damage using also their own money. When looking at figure 7.11b, it can be seen that especially the homeowners with a high WOZ-value profit from the insurance, the lower the WOZ-value the less insurance is received. Almost the same goes for the subsidy, the high and medium households get more subsidy than houses with a low WOZ-value.



(a) *Cost distribution amongst homeowners sorted into three groups based on the WOZ value of the houses.*

(b) *Distribution of the subsidy and insurance money splitted over the groups based on WOZ value of the houses.*

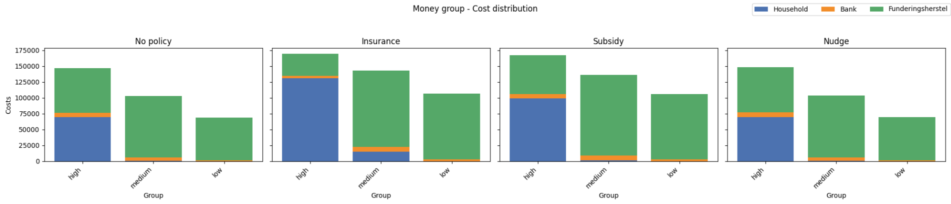
Figure 7.11: *The results are sorted into groups to see how different policies affect different groups. In this case, the distribution of the costs per policy are sorted into groups based on WOZ value. The group with the highest WOZ value is also the group who can pay the biggest share of the repair costs from their own money.*

Available money

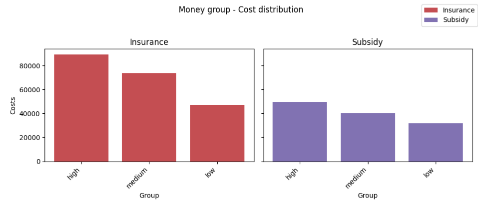
Figure 7.12a shows the distribution of costs where the homeowners are sorted amongst the available money of the homeowners. This has been made because the first step of financing foundation damage, consists of looking at the available money to determine whether the damage can be paid for by the homeowner. This can be seen in the graphs, the homeowner with a high availablity of money can largely pay for the damage themselves. The other groups are not able to finance it trough their own money. In the high and medium group, a proportion of the people can get a bank loan. The group with a low availability of money has to rely on Fonds Funderingsherstel. When comparing the amount paid for by the insurance and the subsidy in figure 7.12b, the same trend can be seen as when the money was divided to WOZ-value of the homes, that the people with more financial means also get a higher amount of subsidy and insurance.

Risk groups

When dividing into groups based on risk, a different picture is gathered than when sorting on financial capabilities. This can be seen in figure 7.13a. The damage in the high risk group is much higher, that is why there are more costs to divide in that segment. There is some damage in the medium group, but not nearly as much. The money is distributed the same way in the two groups, but there is just more damage in the high risk group. When looking at the distribution amongst the policies in figure 7.13b the high risk group gets a lot of insurance and subsidy, and the medium group even less, the low risk group gets nothing. This is proportional to the damage within those groups.

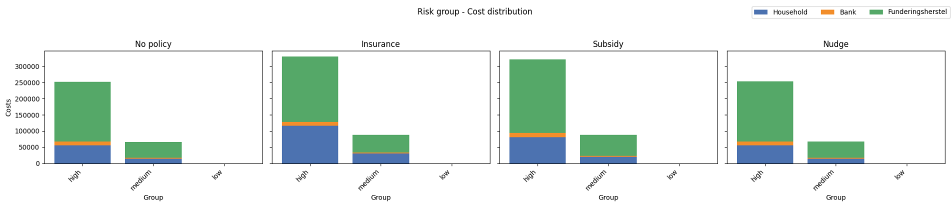


(a) *Cost distribution amongst homeowners sorted into three groups based on the Available money of the homeowners.*

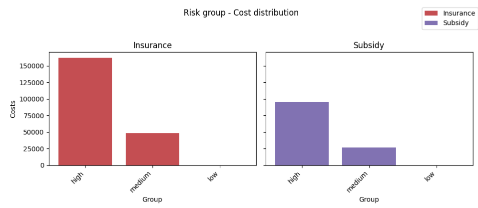


(b) *Distribution of the subsidy and insurance money splitted over the groups based on available money of the homeowners.*

Figure 7.12: *Distribution of costs per policy sorted into groups based on available money of homeowner. The group with the most available money is able to pay the biggest share of their costs out of their own pocket.*



(a) *Cost distribution amongst homeowners sorted into three groups based on the risk label of the house.*



(b) *Distribution of the subsidy and insurance money split over the groups based on the risk label of the house.*

Figure 7.13: *Distribution of costs per policy sorted into groups based on risk label of the house. This is done to see if the risk labels affect the costs. The houses with no risk, also have no damage.*

7.4. Policy targeting

In this section the experiments E7 and E8 are evaluated. The polices are designed to target a specific group. In the case of insurance (E7), the insurance business usually only insure profitable cases. High risk to very high risk houses, will be excluded. The premium they would pay would never cover the reparation costs. To explore this scenario, the high risk and very high risk houses are excluded from the insurance policy.

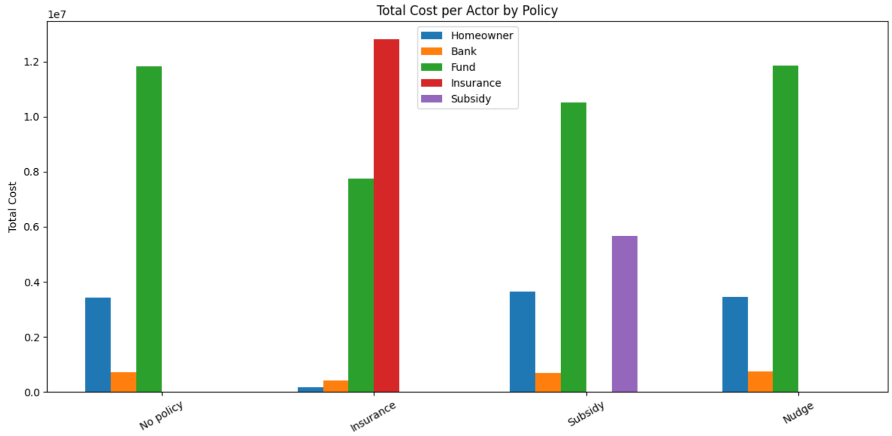


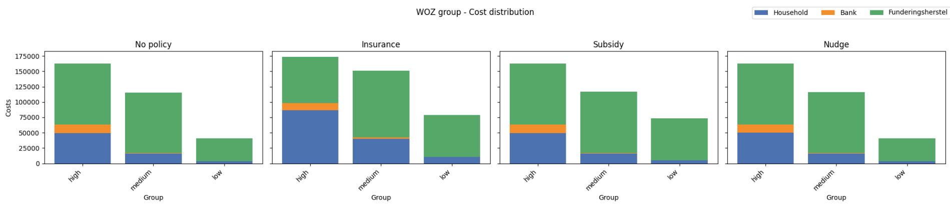
Figure 7.14: *Total costs per policy, the insurance policy and subsidy policy are targeted. The homeowners in the top two tiers of risk are excluded in the case of the insurance. In the case of the subsidy, every homeowner with more then average assets worth are excluded.*

The first thing that stands out, when comparing figure 7.14 to figure 7.6, is that in the targeted policy less money is spent. This is the case for the insurance, but also for the subsidy. Since the target is a 'filter' that excludes certain households, this is correct.

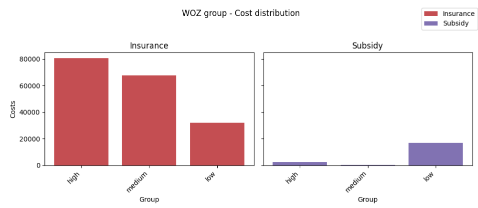
In the subsidy case (E8), the government would like to help people who cannot afford it, and not the ones who have the money already anyway. The subsidy only becomes available for people who have less assets than average. Since this policy is made for certain groups, the results will be splitted out into the prior groups again to see the differences.

WOZ-value

When looking at figure 7.15 especially the subsidy case looks different. There is much less subsidy given out and the subsidy that has been paid has been to people on the low WOZ-worth group and partly in the high. This shows that the target worked to redistribute the subsidies in such a way that it is not the group with a high WOZ-worth gets the most subsidy. The insurance graph does not seem to have changed compared to the non-targeted policy.



(a) *Cost distribution amongst homeowners sorted into three groups based on the WOZ value of the houses. The policies are the no policy, targeted insurance, targeted subsidy and the nudge*

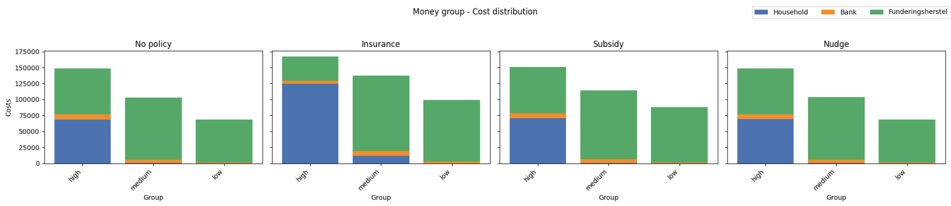


(b) *Distribution of the subsidy and insurance money splitted over the groups based on the WOZ-value of the house.*

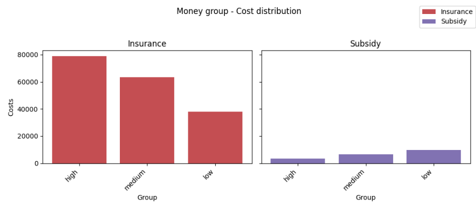
Figure 7.15: *Distribution of the targeted subsidy and targeted insurance money splitted over the groups based on WOZ value of the houses*

Available money

When looking at the targeted policy trough the eyes of the availability of money in figure 7.16, the insurance money shows the same trend as in the last case. The homeowners with a lot of money get more money than the homeowners with less available money. Looking at the subsidy, the trend has changed. There is a rising trend, the homeowners with a lot of money get less subsidy than the ones with less available money. By selecting on assets, not a complete overview of the financial capabilities of a homeowner is found. Other options may work better to accurately target the households who cannot afford it.



(a) *Cost distribution amongst homeowners sorted into three groups based on the money availability of the homeowners. The policies are the no policy, targeted insurance, targeted subsidy and the nudge*

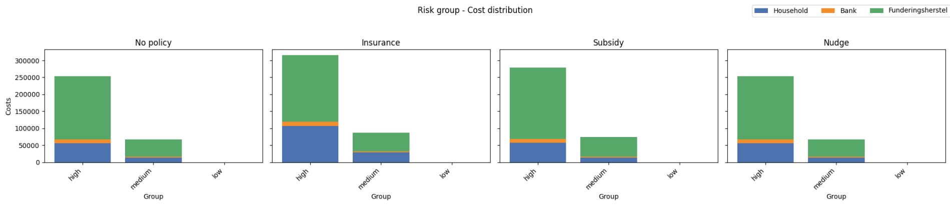


(b) *Distribution of the subsidy and insurance money splitted over the groups based on the availability of money.*

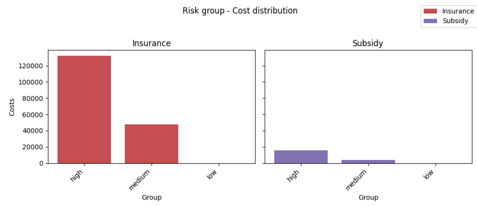
Figure 7.16: *Distribution of the targeted subsidy and targeted insurance money splitted over the groups based on available money of homeowners*

Risk labels

When looking at the risk labels, it is expected to see a difference in the insurance, this did not happen. The insurance looks comparable to the case with no target. This can be explained by the fact that there are not that many houses in the higher risk label groups. It did have an effect, since the total amount of money spent by the insurance is higher as established in the overall comparison. The subsidy amount is also notably lower, as seen in the other groups.



(a) *Cost distribution amongst homeowners sorted into three groups based on the risk label of the house. The policies are the no policy, targeted insurance, targeted subsidy and the nudge*



(b) *Distribution of the subsidy and insurance money splitted over the groups based on the risk label of the house*

Figure 7.17: *Distribution of the targeted subsidy and targeted insurance money with the groups based on available money of homeowners*

7.5. Policy combinations

The nudge has marginally more repairs than the case with no policy, but it does not take away the financial barrier to repair one's home. This is why policy combinations are also explored. The subsidy and insurance are able to overcome the financial barrier. It might be the case that these combinations could give even better results. The nudge will stimulate the homeowner adaptation, while another policy can help overcoming the financial barrier. The first three plots in figure 7.18 look similar to those prior. The extra nudge in the insurance and subsidy scenario does not seem to drastically change the outcome. The policy combination in which the insurance and the subsidy are combined, however, does really look different. The overall costs are much higher. This suggests that more people are able to pay for their foundation damage, and have done so. This can be seen in figure 7.19. The amount that is not fixed is enormous in the case without a policy, in the two combinations with a nudge it is halved. In the case of the combined insurance and subsidy it has become a lot smaller. Figure 7.20 zooms in on the x-axis. The combined insurance and subsidy money help keep the costs down. The amount of insurance money is smaller than in the insurance-nudge scenario, and the amount of subsidy money is about the same as it is the case in the nudge-subsidy case. Since more actors are contributing, the total amount of costs can be distributed better and results in lower total amount of not fixed costs.

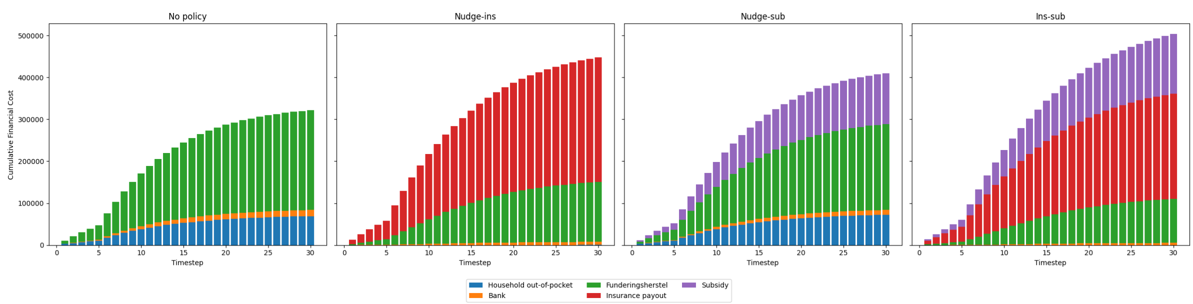


Figure 7.18: *Cost distribution over time for all the policy combinations. The distribution is shown in stacked bars. The combined policy has paid the highest costs.*

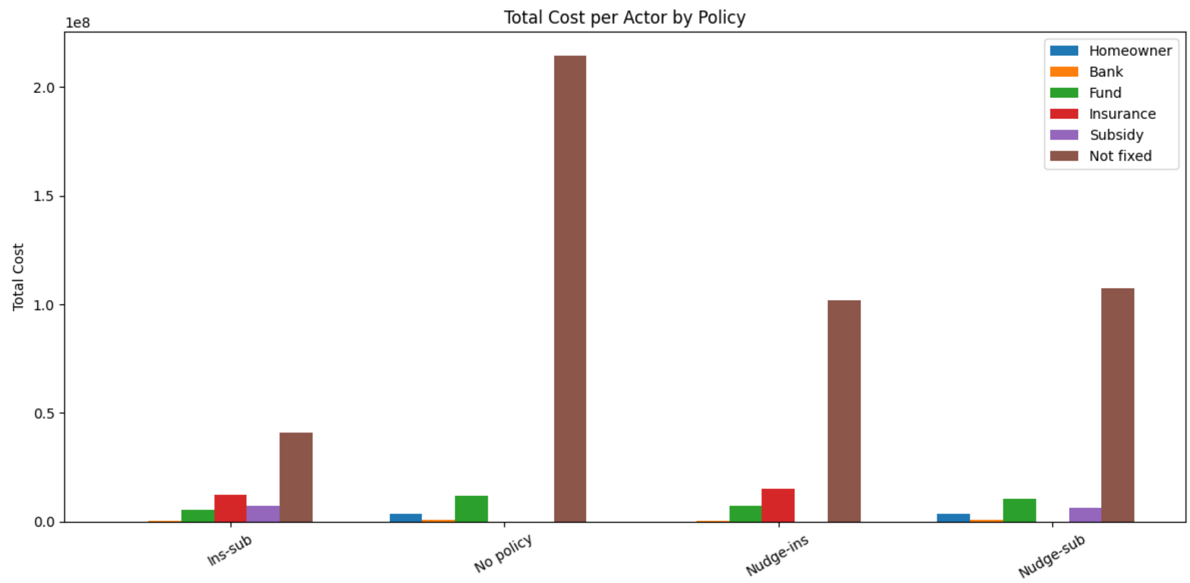


Figure 7.19: *Cost distribution over the actors of the policy combinations, the total amount of not fixed costs are also accounted for in this bar plot. The not fixed bar is especially high in the case without a policy. In the case of a policy it decreases significantly and in the case of a subsidy and insurance it decreases eaven more.*

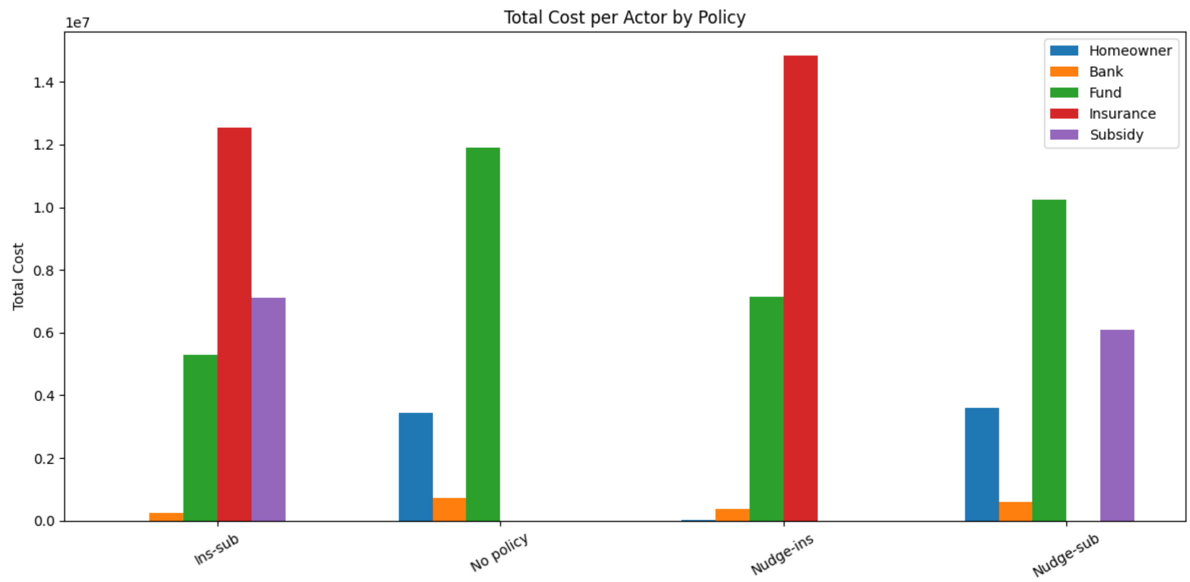


Figure 7.20: *Cost distribution over the actors of the policy combinations. This shows the costs per actor better then figure 7.19.*

7.6. Final comparison

The different scenarios have been compared to each other in the light of amount of repairs, this can be seen in figure 7.21. This shows that the policy combination where there is an insurance plus subsidy, realizes the most repairs. This is closely followed by the insurance, and subsidy policy option. When looking at figure 7.22 all the costs yet to come from the not fixed homes can be seen. This gives almost the same order as the amount of repairs. This also shows the difference more clearly, since the amounts differ a lot between the policies. Doing nothing, or only encouraging homeowners to start doing something will not solve the problem of foundation damage.

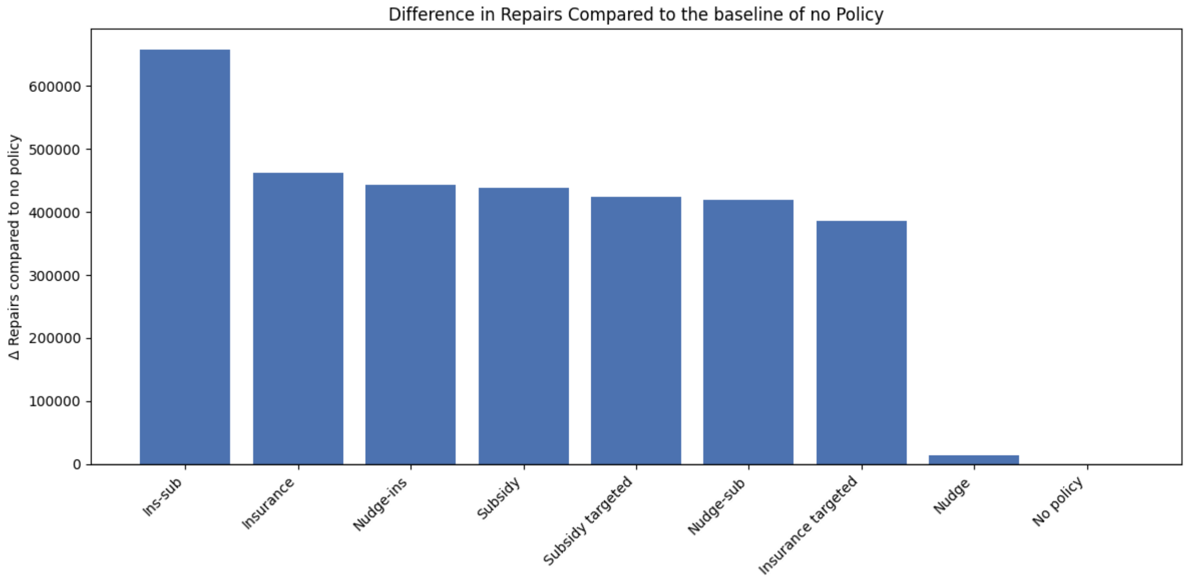


Figure 7.21: *Delta of the amount of repairs across all experiments. The amounts are the policy - no policy. The case of no policy the least repairs are performed. In the case of an insurance with a subsidy at the same time the most repairs are done.*

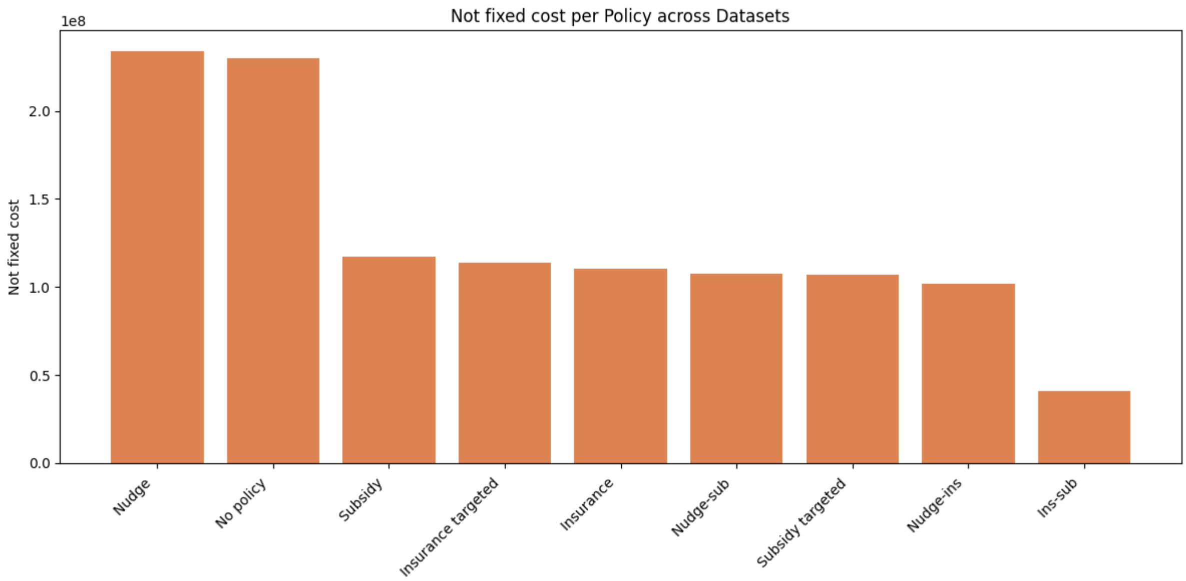


Figure 7.22: *Total amount of costs from the not fixed houses. The costs of not fixed houses is the highest with the nudge and no policy. It is the least in the case of an insurance policy together with a subsidy.*

7.7. Distribution of costs

In this section the subquestion on if costs should be distributed and which different views there are on this subject is answered. The problem, and at the same time, the advantage of distributing of costs, is that more people contribute to paying the costs. The advantage is that the payment share becomes smaller for everyone. The problem can be that people who are not responsible for the costs are also contributing to paying those costs. For example, when using a national subsidy, renters are also contributing to the costs that homeowners are paying. while at the same time homeowners have a lot of financial benefits that renters do not.

7.7.1. Debate on the distribution of costs

van 't Klooster and Hochstenbach (2026) have looked at the Dutch housing sector and the politics of climate adaptation trough a macro-financial lens. They clearly show the different views and the fact that asset owners in the housing sector have different opinions on how to approach climate adaptation. They state that property owners would prefer options where they do not have to pay for the costs they have incurred, by transferring the bill to the "public balance sheet". The main conclusion of the article is that homeowners can handle the damage to their houses because they have been building wealth from paying down their mortgages, in contrast to renters who have been paying their landlord. This should be enough to pay for the damage. The article also states that the costs of the risks to the housing sector are manageable, that the insurance companies can absorb the claims and that the banks have enough financial assets to handle the climate damage. The article does state that the small group who does not have enough assets to pay for their foundation damage, should get help financing the damage. In the next section, all the actors and their interests and statements about this topic will be discussed.

Banks
In a report from the banking sector multiple banks have looked at climate change and the Dutch housing market (Bani et al., 2024). The banks state that the costs of climate change in the housing market can be absorbed by the society, but that for certain regions and individuals the costs will not be manageable. Climate change can fuel inequality in the housing market, since the wealthier households will move to a place with less climate risk, or have the money for more adaptation measures. This is something to take into account. For solving the problem of climate damage to houses, the banking sector sees a big role for Fonds Funderingsherstel. They would like to see the fund cover all the regions and more types of damages. That this is in their interest, and makes a lot of sense, since it is their mortgage portfolio at risk. If they were to bear the costs of this problem, that would not be profitable for them. Since the main goal from the banks is to make money, of course they do not see a big role for themselves in terms of paying for foundation damage to housing.

Insurance
Verbond van verzekeraars would like to see a national approach to this problem (Verbond van Verzekeraars, 2025). They would like to see a central approach to the problem with clear laws, and structural financing. When asked for what the role of insurers in this problem is, they state a lot of things but they do not state anything about insuring the damage. AFM (2021) does see a role for the insurers. They recommend that the government and the insurance sector jointly explore possible solutions. One approach could be to specify in the law which damage and losses the government can payout, or to look at making certain types of insurance cover mandatory. Insurers are commercial businesses, their main driver is making profit. If insuring houses with pilerot is not financially profitable, they will not do so. When a central approach is put in place that would make the insuring of foundation damage profitable, they will be the first in line to create an insurance policy.

Insureability of climate damage
AFM (2021) states that a the price of a fair insurance premium is calculated by quantifying the risks the costs and looking at the frequency of disaster occurrence. And what also helps if the damages do not occur at the same time. These are very difficult conditions for climate related

risks, that explain why these things are not covered anymore. Up to 2016 there were some insurance policies that covered drought risks, but currently there is no insurer that offers foundation as coverage. Doll et al. (2025) state that insurers are becoming increasingly dependent on investment returns, due to the declining premium incomes. What makes something insurable is to be able to accurately assess risks, the potential claims burden. The premiums that people are willing to pay may be insufficient to cover all the damage claims. That is one of the reasons that foundation damage is currently not insureable anymore.

Government
The government has also published a report with recommendations for their own role in this problem (van Kempen, 2025). The report identifies three stages, one where the market can sort out the problem, one where the government starts helping, and finally the one where the government takes the lead. The main points are better information provision, help with more financing options, give the waterboard a louder voice in spatial planning and get more execution capacity in this case. The government has many interests in this case. They are already dealing with a housing shortage, it is in their best interest that the houses that already exist remain habitable. If there is social support for this problem, a subsidy is an option. The problem is that they do not have infinite money, the money spent here comes from somewhere.

All the actors involved are pointing to each other for who should pay for the foundation damage, because they have other interests. There is no consensus on if and how the costs should be distributed. There is one thing they all agree on, that is that the households who do not have the financial capacity to pay for the foundation damage, should get financial help.

8 Conclusion

In this chapter the research question will be answered. My research question was: ***'How do alternative Dutch compensation policies for drought-induced foundation damage influence homeowner adaptation behaviour and the distribution of foundation damage over time?'***

This question consists of two parts, how do policies influence the homeowner adaptation behaviour and how policies distribute the costs from foundation damage. In the sections below the two parts will be answered.

8.1. Homeowner adaptation

When looking at the results from the homeowner adaptation behaviour, the following things can be concluded:

- The limiting factor that homeowners experience is not their behaviour, but their financial capabilities.
- The behavioural policy, the nudge, does not work for the prior named reason.
- To fully answer this research question, more research is needed. Then the behavioural data can be found from drought risk perception, and can be included in this model.

8.2. Distribution of the costs

From the distribution of foundation damage over time, more matters can be concluded. The following things have been found:

- An insurance policy is effective in distributing costs. But in order to make it feasible, a sky high premium is needed. This makes it an unrealistic scenario.
- A subsidy is also an effective way of distributing the costs. If the bill from foundation damage should be transferred to the public budget is a whole other question. A targeted subsidy is a good middle way, effective and not very expensive to the public.
- The nudgeing policy does not help in distributing the costs better.

This question can also be answered by looking at the different actors and looking per actor at their views on the distribution of the costs:

- **Homeowners:** A financial policy will help keep the total costs down for the homeowners. It will also distribute the costs among the homeowners and will help realising more repairs.
- **Government:** Fonds Funderingsherstel already helps a great deal of homeowners with paying for their foundation damage. There societal support for a targeted subsidy can be found, and this is a relatively cheap option. Since the nudge is not effective, the government should not implement this.

- **Insurers:** An insurance policy is effective in distributing the costs. But this is not financially viable.
- **Combined insurance and subsidy policy:** This is the policy option that has realised the most repairs. It also keeps the total costs at the lowest level. By joining the forces of the insurers and the government, a precedent can be set for other actors to also start contributing.

8.3. Subquestions

In this section the subquestions will be answered. These have been used to support the arguments for answering the main question.

SQ1: What policy instruments do homeowners, governments, insurers and banks have to mitigate the damage to houses due to drought and what are the outcomes of these instruments?
This research has looked at the following instruments: a subsidy, insurance and a nudge. Both the subsidy and the insurance resulted in a lower amount of total costs and a higher amount of repairs. One side effect of the insurance, is that this policy replaced the share that homeowners themself paid. The nudge policy was not effective, it did not change much when compared to the base case, in which no policy was active.

SQ 2: What are different views on how the costs of drought-induced foundation damage should be distributed?
This question has been answered in the last section of the results. In summary, the insurance and the banks would like to see a big role for the government in solving this. This is in line with their motive to make profit. Homeowners would also like to see financial help. van 't Klooster and Hochstenbach (2026) state that the homeowners have been building wealth from paying down their mortgage, so most of the homeowners should be able to pay for it themselves. The government is already facilitating Fonds Funderingsherstel. They have been advised to handle this problem in different stages, ranging from not doing much to intervening in the market. They do all see a need to help the households who cannot afford to pay for the foundation damage.

SQ 3: What are the barriers that hinder homeowners in repairing foundation damage?
The biggest barrier is the finance. The homeowners who end op in the phase where they cannot repair their house, do not end up there because they do not have the incentive to act. They end up there because they simply do not have the money.

SQ 4: How do different damage compensation policies influence homeowners over time under climate driven changes?
This subquestion needs further research. Due to data unavailability these sorts of behaviour have not been observed accurately enough to make conclusions.

9

Discussion

The aim of this research is to find ways to redistribute the costs of drought-induced foundation damage and adaptation behaviours of homeowners over time. This has been done by using an Agent Based Model to simulate the dynamics. Different policy instruments are available for distributing the damage costs. This research has focussed on an insurance policy from insurers, a subsidy from the government and lastly a nudge from the government.

One of the main findings of this research is that due to the rising costs when repairs are neglected, it is cheaper in the long term to repair all the foundation damage immediately. A small part of the homeowners is able to pay for the damage out of their own pocket, most will need help, from either the bank or Fonds Funderingsherstel. Even with those options there is still a group that is not able to pay for the damage.

Different policy options have been tested to find a desirable policy. The nudge, where homeowners are simply given more incentive to act does not work. This is because the main barrier for repairing foundation damage has turned out to be the financial means. The adaptation behaviour is not the limiting factor.

9.0.1. Policy options

The insurance policy is one that keeps the total costs down. A lot of the damage is repaired instantly, this helps to keep the total costs down. The downside of this policy is that the insurance scheme is not very profitable for the insurance companies. The insurance policy is modelled in such a way that there must be more premium paid than insurance money spent. In the case of drought induced foundation damage, this does make the premium very high. This is probably why foundation damage is not insurable anymore. This is a policy that distributes the costs of foundation damage over multiple actors. A big part of the costs however, is carried by the insurance. This is done by high premiums and high coverage rates. AFM (2021) states that another thing that can be looked at is to make the insurance of certain things mandatory. The feasibility and options of this insurance can be looked at in further research.

For the subsidy policy, the government would pay 30% of the damage costs. Because the damage can be repaired immediately, the neglected repair costs will not add up to high amounts. Although effective, the question if the government should even help pay for this is posed. van 't Klooster and Hochstenbach (2026) do not think that a subsidy for all homeowners is a solution, but Verbond van Verzekeraars (2025) do see a role for the government in this. Both the reports do have a consensus on helping the homeowners who cannot afford it themselves, this would suggest using the targeted version of a subsidy. This research has also explored only helping the homeowners with a below average amount of assets. This research finds that a targeted policy has great potential to reach the homeowners who cannot pay for it, and while doing so keeping the costs of the subsidy for the society relatively low. It is an effective way to help homeowners in need while keeping costs relatively low. The method of how this group can be reached in the best way can be assessed in further research.

A combination of the insurance and the subsidy policy has also been experimented with. This results in the most repairs and the lowest amount of not fixed costs, in comparison to the other policies. By combining those two options the government can set a precedent for actors in the financial sectors to follow and help solving this wicked problem. This is also one of the options the AFM (2021) proposed, a combination of government and insurers. This is the scenario in which the most repairs are done and the not fixed costs are kept at its lowest level.

9.1. Place in scientific discourse

Damage to foundations due to increasing drought is a problem that is facing the Netherlands today. There is not a lot of scientific literature on this topic because this is a problem specific to the Netherlands. The details on how foundations start rotting are clearly described in the literature. The way the society handles this problem not. This research adds to the existing grey literature from Deltares, the KCAF, by using that knowledge in an Agent Based Model. This thesis contributes to the drought risk ABMs that have focussed on agriculture such as the one from Wens et al. (2019), by expanding it to the housing market and including drought-induced damage to foundations. The novelty of this research is the use of ABM's in drought-induced damage to housing. This has not been done before. This research shows the possibilities and potential for further studies on drought-induced damage to foundations in combination with ABM's. By combining risk data under a certain climate scenario with adaptation behaviours of households and multiple policy options, the assessment of the distribution of climate costs can be enabled, in different locations and across involved actors.

9.2. Limitations

This research has several limitations: the first one being the used data. The article from Sargent (1987) states that data validity is an important thing to keep in mind when building a model. This is a concern since the data used for this model is far from perfect due to no publicly available data about the exact people in Friesland. The synthetic population is ultimately an estimate. Secondly the data on risks. The risk data already includes a money component. This article uses the risk multiplied by the estimated costs. But in the risk value from the klimaateffectenatlas some measure of costs is already included. Due to this the money is overrepresented in this value. It has been normalised, to only include the relative risk. This was the best option for risk assessment on this level, it is still deemed a suitable proxy.

Another limitation is the modelling process. Firstly, the economic status of an agent does not change. This is under the assumption the the costs of the repair will increase faster than the savings from this agent. This means that once an agent cannot pay for the damage, it will not be able to for the whole run. This is because all the financial options have been exhausted and after all those options there are no left. The economic properties do not change, so the homeowner cannot escape not being able to finance the damage. Another factor is the way of modelling, the bank and the fund are really strict, while in reality it is the case that they might be more lenient. Especially since the income data has not been used to determine if someone can get a loan, while this does play a role. This research has used the assets and average debts of someone. Moreover, this research has included 'the government'. This is way more complex, there are several parts of the government included in this problem. In this case the government consists of the municipality, the waterboards, the provincial government and the national government, where they all play a role.

When reflecting on the earlier named limitations in the research question chapter, it becomes clear that these factors proved to be a limitation to the research. But not as big as expected at the start those limitations are: the behavioural simplification; the data; external validity and the uncertainty in future climate conditions. The behaviour is simplified, but modelled after an existing theory, PMT. The limitations of the data have already been discussed.

In case of the external validity, the research has focussed on a small part of the Netherlands. With enough data this can also be used in all other parts of the Netherlands. This is not a frequent occurring problem elsewhere. So it is not applicable in other countries. Lastly, the uncertainty in the future climate conditions. This has been omitted by using the climate scenario from the klimaateffectenatlas. This data has its uncertainties, but within reasonable boundaries.

The prior named limitations show that the actual numbers are not representative of the real world, the trends however are. In further research these findings can be validated. More research is needed to explore the policy options further and to see if there are other implementation options, such as a mandatory insurance, or a tax. Another recommendation is to not only look at the pile rot, but to also include differentation as foundation damage. This is also something that poses a risk for house subsidence in the Netherlands. And lastly, most experiments have been run in Leeuwarden with the 2050 high risk climate scenario. It would be interesting to run the experiments on other municipalities and climate scenarios to compare the results.

9.3. Recommendations

For a following research on this topic the following recommendations follow from this thesis:

- Separate governmental bodies to see their different roles and interests in this problem. For example, the waterboards, local municipalities, the province boards and the national government each as a separate actor.
- Include big polluters. They are making economic profit whilst polluting the earth. In further research it is interesting to see if and how this actor can be included in the distribution of costs from climate change to housing.
- In this research only the homeowners are included, no renters, public buildings or commercial facilities are taken into account. The homeowners are a large piece of the housing market, so it is grounded. Including all kinds of buildings is a good place to start further research on.
- The dynamics of the housing market can also be included in another study on this topic. In some cases it is plausible that a homeowner might want to move, to avoid future foundation damage. This is not an option in this model This could create different dynamics in the model, such as a safe development paradox that an insurance policy can give Haer et al. (2020). Due to the fact that moving is not an option, this dynamic is not established in the current model. This calls for more research.
- Establish the data needed for the PMT that is based on drought risk to see if and how it changes these outcomes.
- For the targeted subsidy, determine how and in what way the people who cannot pay for the foundation damage themselves can be targetted.
- Look into a mandatory insurance policy, see if this would make the insurance feasible.

9.4. Policy Implications

The following findings from the research have the following policy implications:

General policy implications:

- Implementing a policy that financially helps homeowners will keep the total costs for the homeowners down. It will also help realizing more repairs amongst homeowners.
- By distributing the costs over multiple actors, by for example an insurance and subsidy policy, the most repairs and least total costs can be realised.

Policy implications for insurances:

- An insurance policy distributes the costs among a lot of homeowners. In order to cover a big part of the damage, a high premium is necessary. The feasibility of such an insurance scheme can be researched further. It is not financially viable in this research. Excluding the houses in the top two tiers of the highest risk does not solve this problem.

Policy implications for the government:

- A subsidy is also an effective way to distribute the costs. The costs go from solely the homeowners, to also a share paid for by the taxpayers. This also helps keeping the costs down, and distribute it amongst more actors. There is a debate on if the public should be paying for homeowners, who are already reaping financial benefits because they own a house.
- A targeted subsidy has more support. This subsidy is still effective in keeping the total costs for homeowners down. By only helping the one's who need it, the costs for society are limited, while the benefits for distributing the costs are present.
- A nudge for a policy is not effective. Because this does not help overcome the financial barrier.

9.5. Concluding statement

This research is a first step in quantifying the risks of pile rot in the Dutch housing sector. Agent Based Modelling is a suitable method to model drought risk problems. This research can be a stepping stone for more work in the future. It shows that it is important to take a measure to avoid the doom scenario where a big part of the houses have rotting foundations. Especially in light of the housing shortage that the Netherlands is already facing and other disasters that will damage houses more frequently due to climate change. The barrier to repairing foundation damage to houses is not the adaptation behaviour of the homeowners, but the financial means. A subsidy or an insurance is effective in keeping the total costs for the homeowners down. The debate on if the homeowners are the only ones who should pay is still ongoing. A targeted subsidy is an option to help the ones in need without a big financial burden on other taxpayers. The way we are heading is one with a lot of rotting foundations. To keep this from becoming a societal problem, measures are needed. Currently the policies that are recommended by involved actors are still reactive policies. The main takeaway from this research is that a policy is needed rather sooner than later. Preferably a proactive policy that will help to break the drought.

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A

Appendix A

A.1. Synthetic population

On the area of Friesland, a lot of data that this research needs is not publicly available. In order to run the model a 'synthetic population' that has the attributes from the people in Friesland has to be made, without having the actual datasets. By doing this, a stylised version is created, by using known distributions and averages, the lack of individual data is bypassed. As Chapuis and Taillandier (2019) state in their literature review, a lot of ABM's use a form of synthetic population. This article notices that not a lot of articles clearly state how the synthetic population in those papers are generated. Since this is not the actual ABM but the data preparation for it. There are, however, some literature syntheses that have summarised which methods there are available.

Aside from the generation method, the quality of the synthetic population depends on the available datasets, and if those come from one or multiple sources. This is because if the large scale data is not accurate, the agents generated from that dataset will also not be accurate at all. It is very inconvenient that big disaggregated do not exist, this has an important reason. As Barthelemy and Cornelis (2012) state, such disaggregated datasets have big privacy concerns.

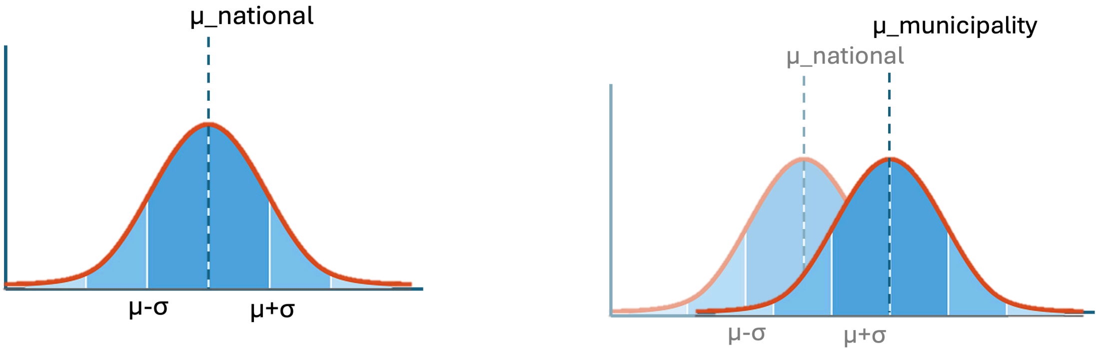
The method described as 'the conventional approach' by Barthelemy and Cornelis (2012) has been used in this case. Merging aggregated date from one source with disaggregated data set from another, to get a detailed dataset for the population of interest. From this dataset, the synthetic population is generated by estimating a distribution and sampling agents by using the estimated distribution. This paper then describes a method for estimating a distribution. For this method, a representative sample of the true population is necessary. This is not something that was available for this research. The sampling used for the synthetic population has been done in a way that the normal distribution is still there, without adding noise. This research has been conducted using the mean and median of the population level data. From those two metrics, the distribution has been constructed. In some instances, the mean and median were known on a national level, but on a smaller level, only the mean was known. In that case the sigma from the national level has been used to find the distribution, but it is being shifted to the known mean from the municipality. This can be seen schematically in figure A.1. The formulas below describe which equations are used for determining the distributions.

$$mean = e^{\mu+\sigma^2/2} \tag{A.1}$$

$$median = e^{\mu} \tag{A.2}$$

$$\mu = \ln(median) \tag{A.3}$$

$$\sigma = \sqrt{(2 * (\ln(mean) - \ln(median)))} \tag{A.4}$$



(a) *Normal distribution for the national level* **(b)** *Shifted normal distribution to the μ of the municipality*

Figure A.1: *Schematic view of the shifting of normal distributions*

A.1.1. House attributes

The available data is shown in table A.1. This section will describe how the data has been processed. The house needs multiple attributes in this model:

- Location
- House worth
- Drought risk
- Drought damage

First off the location, each municipality has a certain amount of houses. When simulating with multiple municipalities together, this is important. In case the model is run over two municipalities, the model calculates the percentage of houses per municipality. This it multiplied by the amount of agents that are being simulated, that is giving the amount of houses per municipality in the model. The house worth comes from (AlleCijfers.nl, nd). This value does not have a median, the distribution is made built on the assumption that $\sigma = 0.5$. For each municipality this distribution is shifted to the corresponding mean.

A.1.2. Homeowner attributes

The homeowner has the following attributes:

- Assets
- A house
- Available money
- Mortgage attributes
- Protection Motivation Theory attributes

The homeowner's assets are bases off of two datasets. Firstly the municipal level from (CBS, 2026b). This dataset contains the mean and median of which the distribution can be created. This contains all the data per municipality. The hassle begins when adding the available money and the mortgage attributes. Those come from two separate national level datasets. The distribution from the available money and mortgage have been made from those

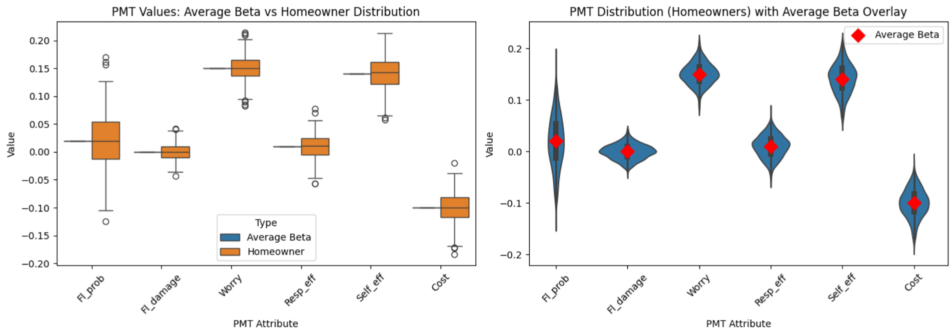


Figure A.2: *PMT distributions, in a boxplot and to see the distribution more clearly*

datasets. They have been shifted to follow the average amount of assets per municipality. The houses have been matched to the homeowners by binning. The houses and the homeowners are binned into 5 categories. Within than bin they are randomly matched. This is done because someone with no assets cannot afford a 1 million euro house, the other way around is also very difficult. To not match them linearly, but to have some randomisation, the binning is used. Otherwise the person with the most assets will also have the most expensive house, whilst this is not necessarily true. For the protection motivation theory there are starting values that usually come from a survey. Due to time limitations, a survey has not been conducted on this topic. Since there is not much other research done on this topic, a proxy has been found. There is a dataset coming from a survey where Dutch citizens have filled in their perceptions not on drought, but on flooding (Filatova et al., 2022). This dataset has been used as a starting point for this research. This dataset included the distribution but also the mean. The created attributes can be seen in figure A.2.

Table A.1: *Data availability*

Data:	Sort of value	Unit	Scale	Source
Pilerot risk	Average		Neighbourhood	(Klimaateffectatlas, 2026)
Percentage of houses with wooden piles	Average	%	Neighbourhood	(Klimaateffectatlas, 2026)
Vulnerability	Average	%	Neighbourhood	(Klimaateffectatlas, 2026)
Worth of owned home	Average, Median	€	Municipality	(CBS, 2026b)
WOZ-worth	Average	€	Municipality	(AlleCijfers.nl, nd)
Amount of houses per municipality	Amount	#	Municipality	(AlleCijfers.nl, nd)
Assets	Average	€	National	(CBS, 2026b)
Assets split	Average, Median	€	National	(CBS, 2026b)
Income, bank and savings balance	Average, Median	€	National	(CBS, 2026b)
Mortgage debt	Average	€	National	(CBS, 2026a)
PMT values	Behavioural parameter		National	Filatova et al. (2022)

A.2. Run amount values

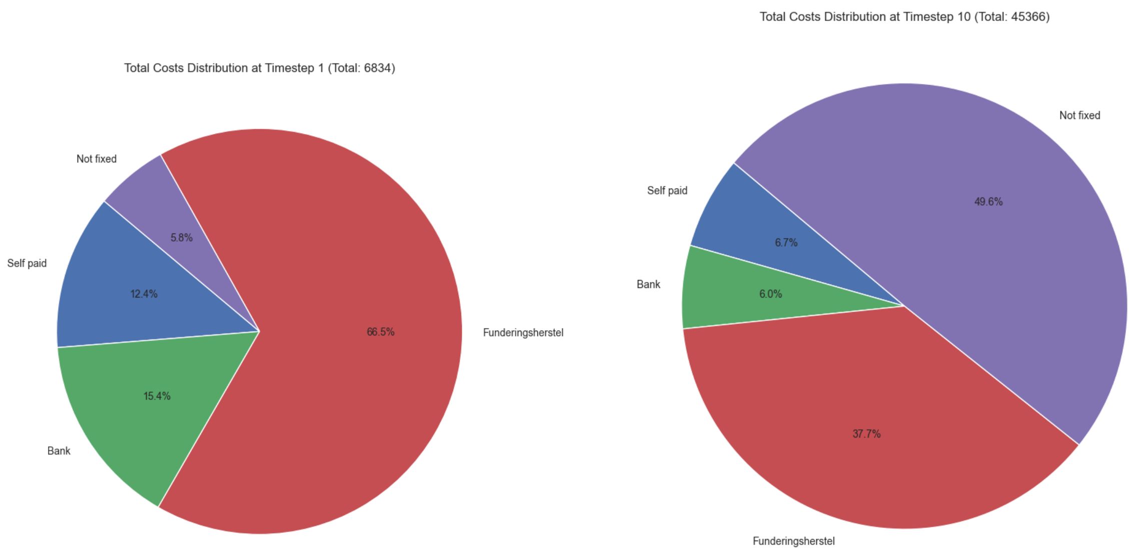
Table A.2: *Determine the seed by using the coefficient of variance*

cv	seed = 1	seed = 10	seed = 20	seed = 30	seed = 40	seed = 50	seed = 100
Repair money	c = 0.73	c = 0.76	c = 0.75	c = 0.75	c = 0.76	c = 0.76	c = 0.76
not fixed costs	c = 0.82	c = 0.83	c = 0.82	c = 0.83	c = 0.82	c = 0.82	c = 0.82
Bank money	c = 0.93	c = 0.88	c = 0.89	c = 0.90	c = 0.89	c = 0.90	c = 0.90
Fund money	c = 0.74	c = 0.76	c = 0.75	c = 0.75	c = 0.75	c = 0.75	c = 0.75

A.3. Comparison to real life data

In this section the verification of the model is done.

The Autoriteit Financiele Markten states that foundation damage cannot be paid directly by a lot of people (AFM, 2026). Those numbers are also useful when verifying the model results. This article states that from the 120.000 buildings with foundation damage, 75.000 people cannot afford to pay for the damage directly. And for 25.000 a loan would not be a responsible option. Calculation back to percentages, this would mean that 65.5 % cannot afford it by their own liquidity and 20.8% would not be able to get a loan. This is something that the model can be verified with. When looking at figure A.3 the percentages per group can be seen. This does not match the exact percentages from the report from the AFM. This is because in the model the amounts start out at 0 and eventually stabilize. What can be seen is that in line with the report, a large part of the agents is not able to pay for the damage straight out of their pockets. And that there is a small percentage that is able to do so. The exact percentages do not match, but they show a similar trend.



(a) *Distribution of payment t=1* **(b)** *Distribution of payment t=10*

Figure A.3: *Cost distribution at t=1 and t=10*

B

Appendix B

B.1. Sensitivity analysis

On several assumptions, a sensitivity analysis has been conducted. Firstly the cost growth rate. This is the rate of how much the repair costs increase after negligence. The biggest difference can be seen in the bank money in figure B.1. With a low threshold the bank money is logically the least, because people need a smaller loan. In the case of a high growth rate, the loan amount grows.

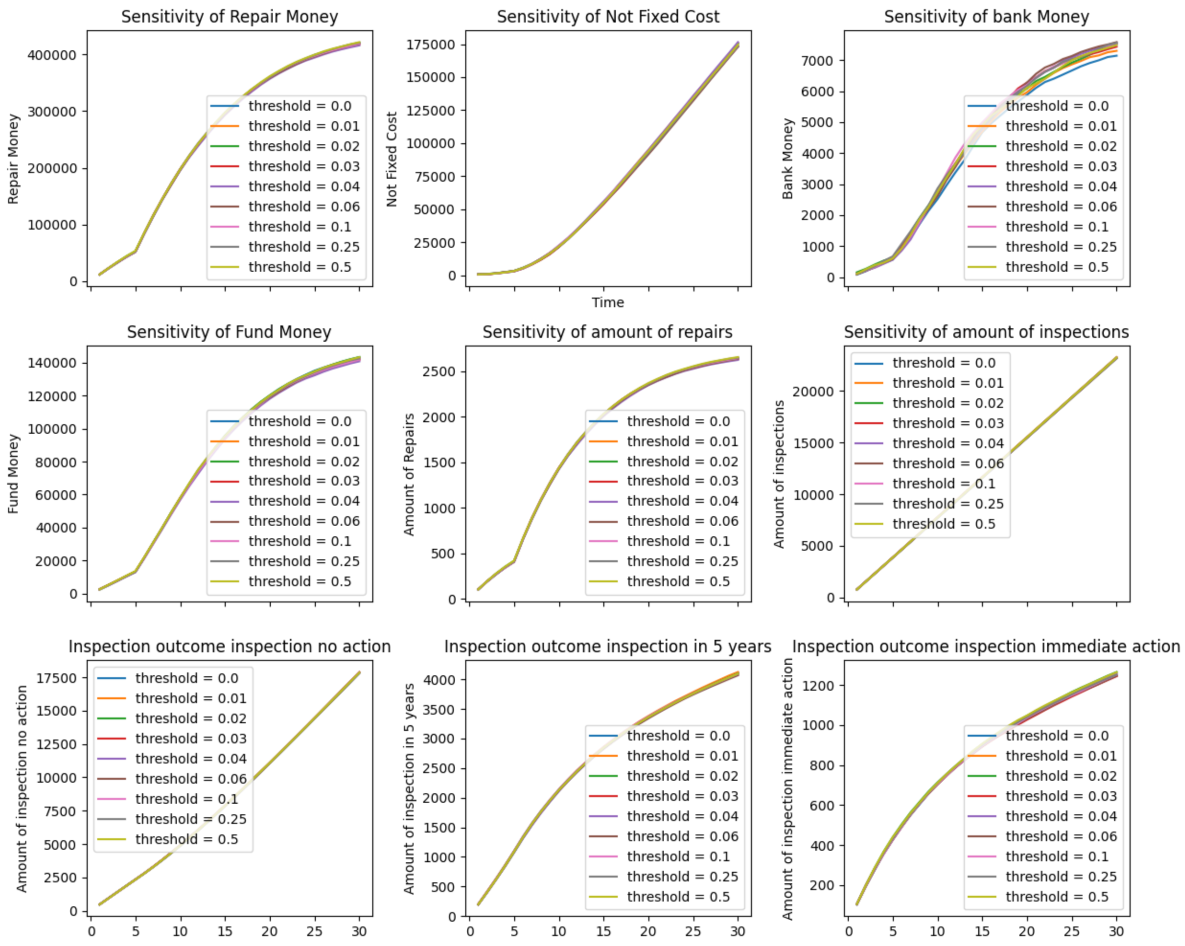


Figure B.1: *Sensitivity analysis on the cost growth rate. In this panel the sensitivity is observed of the costs, and the amount of repairs and inspections.*

The sensitivity analysis of the threshold of immediate inspection can be seen in figure B.2. This is the number of damage at which someone has to repair their home immediately. This value gives a range in the inspection outcome immediate action graph. But also in the amount of bank money given out in loans.

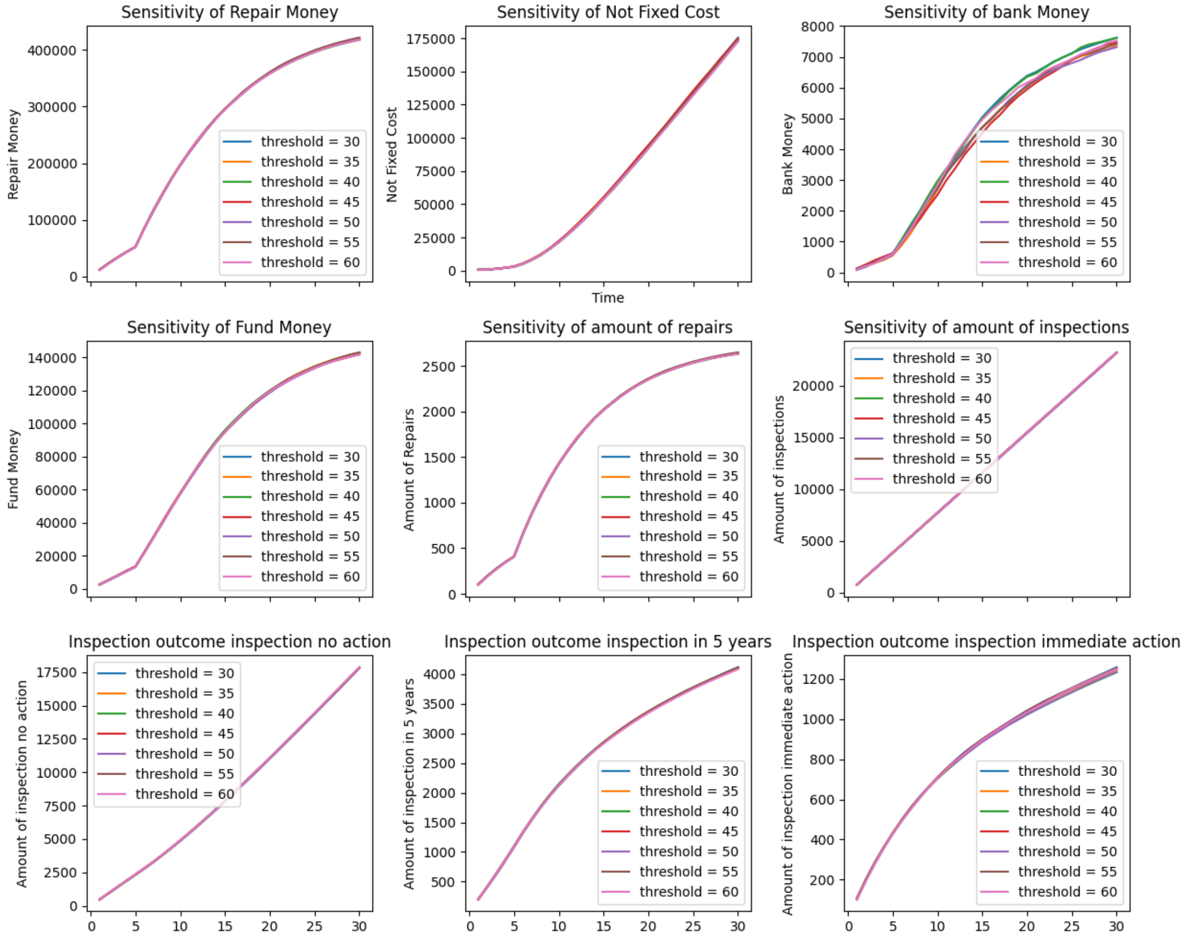


Figure B.2: *Sensitivity analysis on the threshold of immediate inspection. In this panel the sensitivity is observed of the costs, and the amount of repairs and inspections*

The sensitivity analysis of the threshold of action in 5 years can be seen in figure B.3. This is the number of damage at which someone has to repair their home in 5 years. This value gives a range in the inspection outcome action in 5 years graph. But also in the amount of bank money given out in loans even more so in the last options.

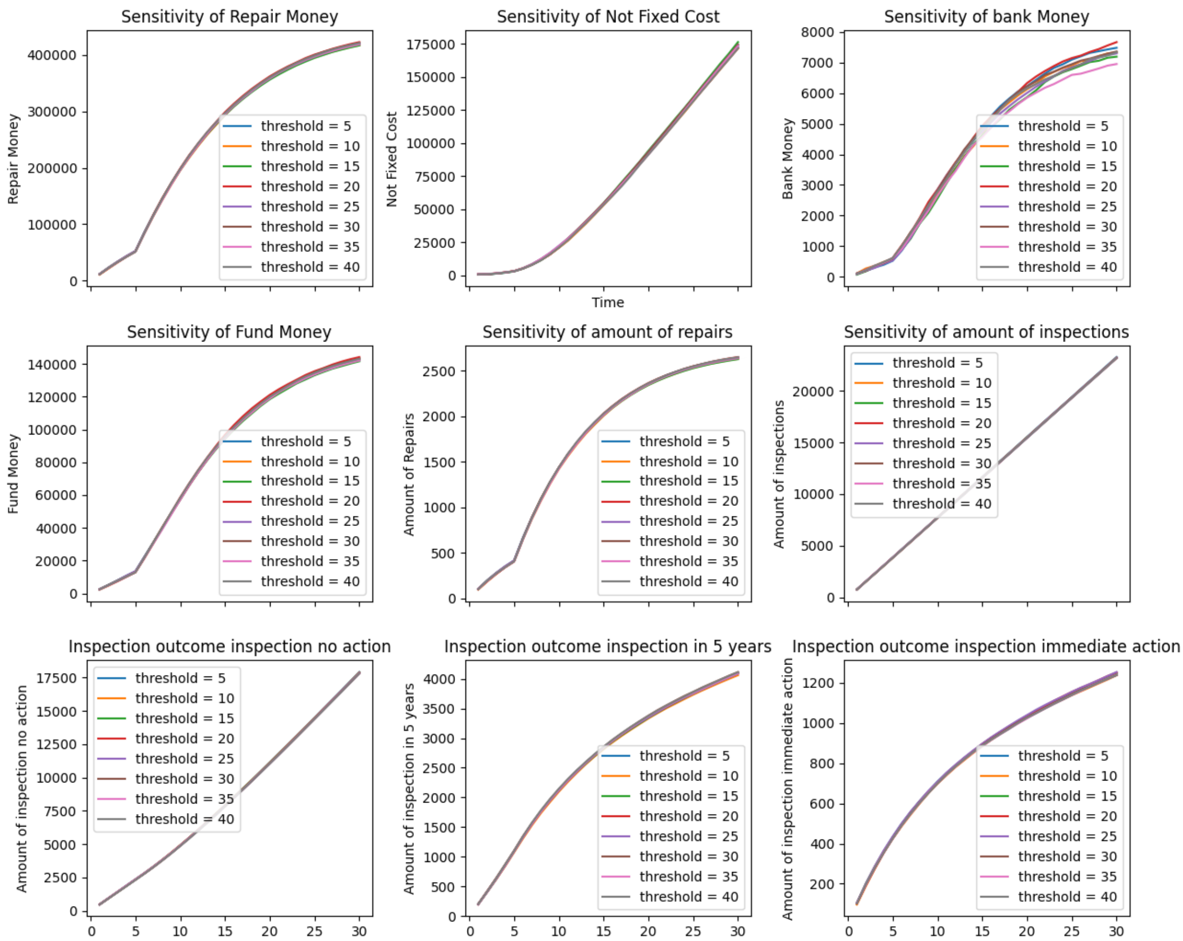
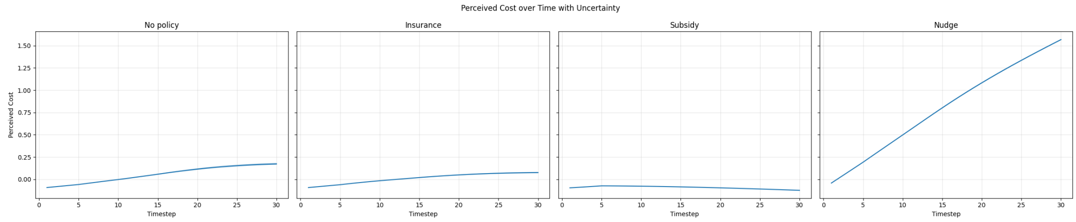


Figure B.3: *Sensitivity analysis on the threshold of action in 5 years. In this panel the sensitivity is observed of the costs, and the amount of repairs and inspections*

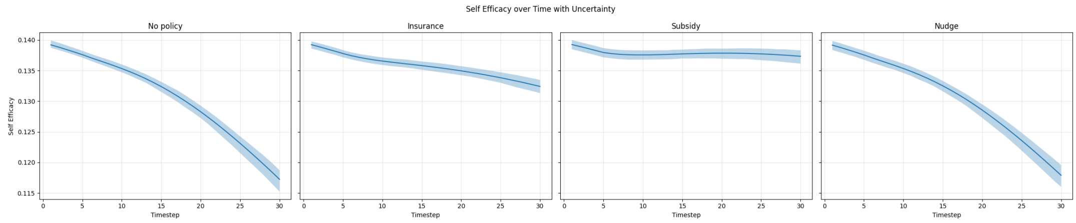
What stands out is the sensitivity of the bank loan amount. Even a slight change in a threshold or in the quicker increase of damage costs, makes a noticeable difference.

B.2. PMT

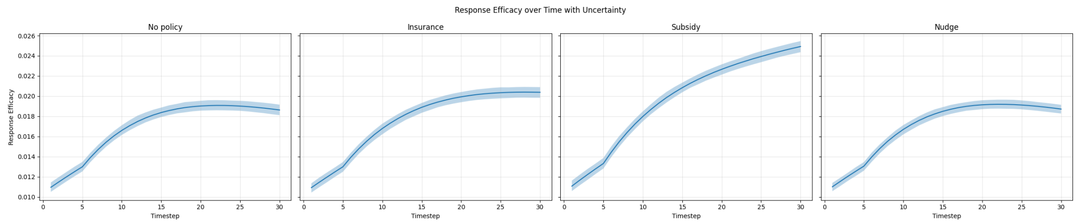
The PMT values for the 4 policies per PMT factor are seen in the figure below.



(a) *This figure shows the perceived cost over time for all 50 runs per policy over a timespan of 30 years.*

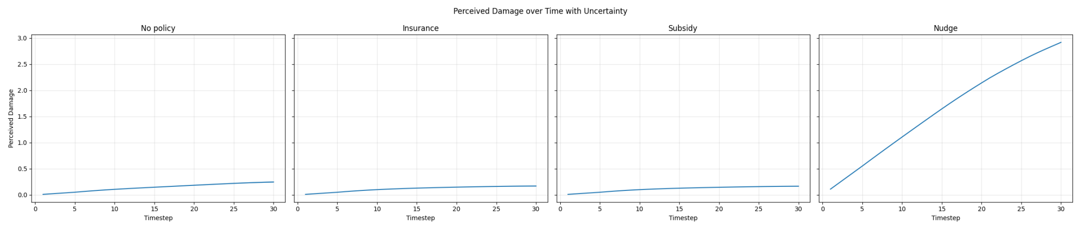


(b) *This figure shows the self efficacy over time for all 50 runs per policy over a timespan of 30 years.*

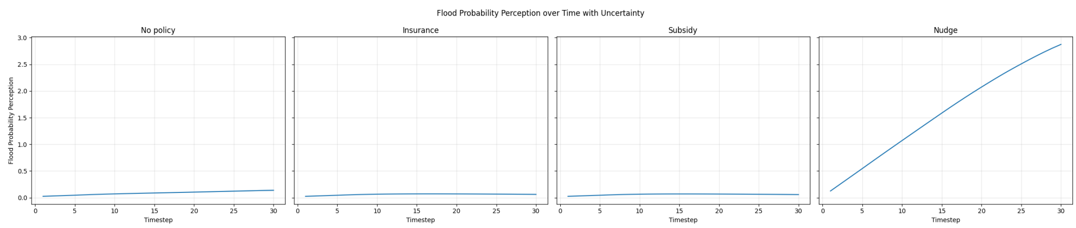


(c) *This figure shows the response efficacy over time for all 50 runs per policy over a timespan of 30 years.*

(d) *This figure shows the worry over time for all 50 runs per policy over a timespan of 30 years.*



(e) *This figure shows the perceived damage over time for all 50 runs per policy over a timespan of 30 years.*



(f) *This figure shows the flood probability perception over time for all 50 runs per policy over a timespan of 30 years.*

Figure B.4: *Individual PMT values per policy over a timespan of 30 years. On the x-axis the timestep in years are shown and on the y-axis the PMT value can be seen.*

C

Appendix C

To summarize the findings, a policy brief has been written. This gives a quick overview of the model, results and finally some policy recommendations.

Policy Brief

Cost of drought

Renate van Rooijen **Supervised by:** Ir. Erna Ovaa (RWS), Prof. dr. Tatiana Filatova (TU Delft)

EXECUTIVE SUMMARY

Climate change is causing more frequent droughts. This is causing damage to foundations of houses in the Netherlands. This research has focused on pile rot to foundations of houses in Leeuwarden in the province Friesland. This study examines how the costs of pile rot can be distributed among different actors, using an agent based model (ABM). The homeowner adaptation behaviour is also analysed. The homeowners, government, banks and insurance have been added as actors. Different distribution policies have been evaluated, a subsidy, an insurance policy and a nudging policy. The policies that involved financial help were most successful. This is because the barrier for repairing foundation damage is not the homeowner's behaviour, but their financial capabilities. The insurance policy is not realistic from an insurance point of view. The subsidy is effective. The question if this should be paid from taxpayers' money is posed. All involved actors agree on helping those who cannot pay for the repairs themselves. The policy that enables this is a targeted subsidy for those who are otherwise not able to afford it.

425.000

Houses are at higher risk of subsiding due to drought (KCAF, 2025).

687.000

Houses will be affected in the future (KCAF, 2025).

DESIGN APPROACH

- Agent Based Model
- 6000 agents
- In Leeuwarden
- The agents use the decision rules described in figure 1.

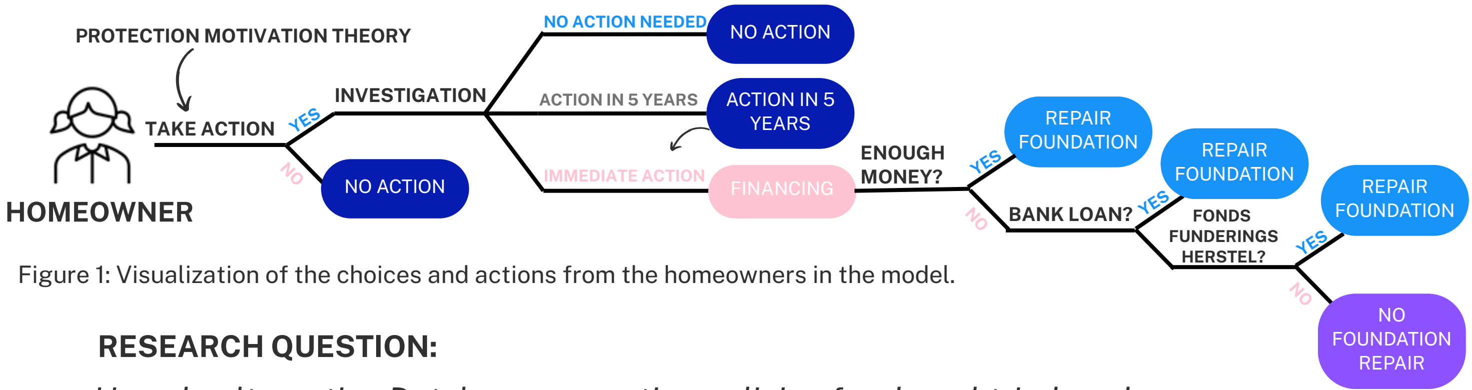


Figure 1: Visualization of the choices and actions from the homeowners in the model.

RESEARCH QUESTION:

How do alternative Dutch compensation policies for drought-induced foundation damage influence homeowner adaptation behaviour and the distribution of foundation damage over time?

PROTECTION MOTIVATION THEORY

Based on how the homeowners perceive the risks they determine to take action - or not. The protection motivation theory describes this in terms of two things, threat appraisal and coping appraisal. How does the homeowner perceive the threat, and is the homeowner capable of doing something about it. Each homeowner starts with PMT values based on a survey on flood risks. After each event those values are altered. This creates the behaviour of the agents.

FINANCING

The homeowner can get financing based on their financial capabilities. In this model the homeowners have to comply to some rules in order to get a loan, or money from the funds. Most homeowners do not have €50.000 - €150.000 ready to repair their foundation. That is what the foundation repairs usually cost (KCAF, 2025). So the homeowners will have to get a loan or help from Fonds Funderingsherstel.

Cost of drought

COSTS PER ACTOR

Figure 2 shows how costs are distributed across actors. Insurance shifts most costs away from homeowners, but requires unrealistically high premiums. In contrast, the subsidy policy results in a more balanced distribution, where both homeowners and the subsidy contribute.

WHO GETS THE SUBSIDY?

To examine who benefits from subsidies, homeowners are divided into three groups based on their financial capacity (Figure 3). Under a general subsidy, wealthier households receive the largest share of support, even though they are more able to finance repairs themselves.

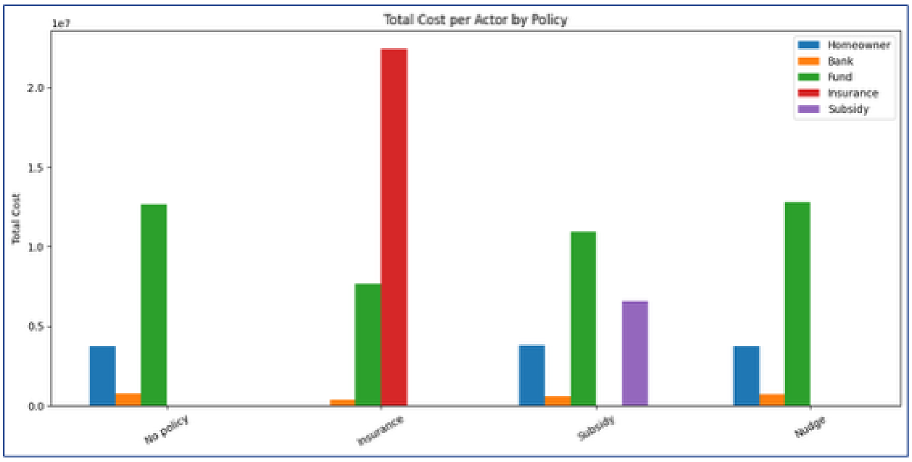


Figure 2: Total costs paid per actor. On the y-axis the total costs are shown. On the x-axis the costs per policy are grouped per actor.

TARGETED SUBSIDY

To address this, a targeted subsidy is introduced, focusing on households with below-average assets. This reduces total costs and changes the distribution significantly: lower-income households receive the majority of support.

CONCLUSION

Main finding

- Barrier to repairing foundation damage is fincancial, not behavioural

Policy effectiveness

- Subsidies increase repairs and reduce total costs
- Insurance is not financially viable
- Nudge is missing a financial help

Distributional effects

- Actors have different incentives and intersts
- A targeted subsidy ensures support and will reach households that cannot afford repairs

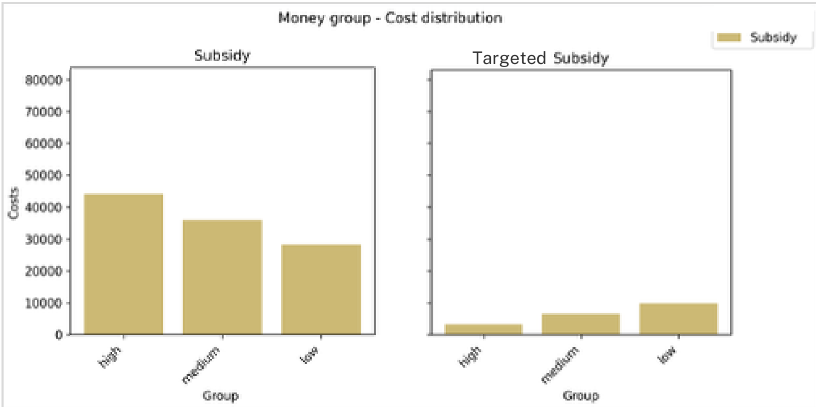


Figure 3: Subsidy money received per group. The groups are divided on their money availability. The households with the most money are in the high group and the ones with the least money in the low group.

POLICY RECOMMENDATIONS

- Implementing a policy **as soon as possible** will keep the total costs down. This is crucial to prevent rising long-term costs
- A subsidy for the homeowners who cannot pay for the damage on their own, **a targeted subsidy**, has societal support, and helps reducing the total damage costs significantly.
- An insurance policy is not feasible for insurance companies, a mandatory insurance can be looked into in further research.
- A nudge policy, eg. awareness campaign, is not enough to solve this problem. The **main barrier for repairing houses is financial.**
- Sharing costs between actors reduces overall damage costs and increases repairs.