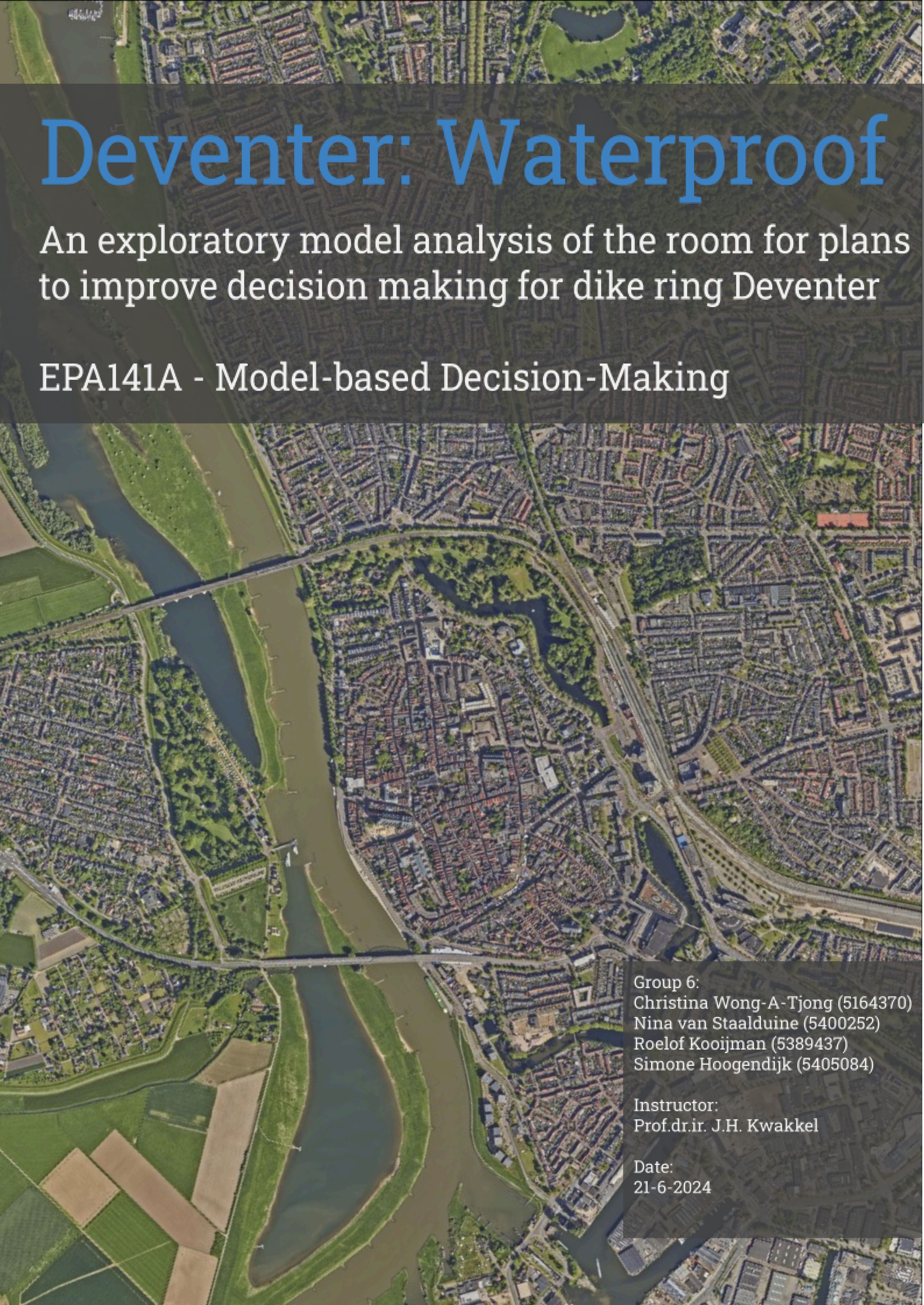

Deventer: Waterproof

An exploratory model analysis of the room for plans to improve decision making for dike ring Deventer

EPA141A - Model-based Decision-Making

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Summary

The Netherlands faces flood risks due to rising sea levels, melting glaciers and extreme weather conditions. This report provides policy advice for flood risk management along the Ijssel river in Deventer. The main goals for Deventer are to minimise human flood risk, flood damage and evacuation costs in the major urban area. However, a collaborative approach is needed with different stakeholders, including local, regional and national parties, as there are different interests and interpretations of the problem. That is why general goals of various stakeholders are also taken into account to analyse the problem and develop a robust flood management strategy. Using the Exploratory modelling technique for sensitivity analyses, scenario discovery, directed search and robustness analyses three different strategies arise.

In terms of overall minimisation of damages and deaths, the first strategy is the most effective. Here, the floodplain Welsummer must be created directly and Tichelbeekse within 150 years. Additionally, the Zutphen dike ring Zutphen will be heightened with 40 cm. The downside is that it is the most expensive strategy. This option is the most secure to prevent casualties and potential reparation costs due to floods. Then, there is the second strategy which solemnly entails raising the Zutphen dike with 50 cm. This is significantly cheaper than the first strategy. However, it is not a waterproof solution compared to the first one. The casualty and damage risk get minimised, but not to the same extent as the first strategy. Lastly, there is the third strategy which has similar performance as the second strategy. This strategy includes the creation of floodplain Tichelbeekse within 75 years but only raises the dike of Zutphen by 20 cm.

If costs are considered less relevant, the first strategy is the most promising one. When costs are crucial, it must be considered if adding a floodplain is better than only heightening the Zutphen dike. Considering the involved stakeholders, creating a floodplain will be against the wishes of dike ring Gorssel, but in favour of environmental interest groups and the waterboard. The final choice will thus strongly depend on the existing dependencies between Dikering Deventer and these stakeholders.

Content

1 Problem framing

1.1 Context

The Netherlands is highly susceptible to flooding, not only from the sea but also from its rivers. Due to climate change, periods of heavy rainfall and snowmelt have become more frequent, leading to higher water levels in our rivers (Ministry of Infrastructure and Water Management, n.d). Rising sea levels, melting glaciers and extreme weather conditions set flood protection high on the agenda (De Bruijn et al., 2015).

In response to severe floods in the nineties, the Dutch government initiated the ‘Room for the River’ project to mitigate the flood threats in the Netherlands (Rijke et al., 2012). This project represented an innovation compared to previous strategies. For a long time, the Netherlands only focused on raising and strengthening dikes (De Bruijn et al., 2015). However, experts realised this approach could not continue indefinitely. As the name suggests, the ‘Room for the River’ project, aims to give rivers more space rather than confining them.

The ‘Room for the River’ project consists of various measures. For the flood-prone areas around the IJssel river, three different measures are being evaluated for each location. First, creating floodplains. Second, implementing a warning system which gives a warning prior to a threat allowing time for evacuation. Third, raising and strengthening the dikes.

The project employs a new collaborative approach, bringing together people from different parts of government, such as those focusing on water safety, planning, agriculture and nature at national, regional and local levels (Rijke et al., 2012).

There are five locations of interest; Doesburg, Cortenoever, Zutphen, Gorssel and Deventer. Deventer is a major urban area within Dike Ring 5. This region aims to minimise flood risk in general, especially for its specific area. Given that Dike Ring 5 is close to a heavily populated area, it is believed this region should endure a lower flood risk compared to rural areas, where a potential flood would endanger far fewer people.

Therefore, the main objective of Dike ring 5, while working on the flood management strategy, is to presume the safety of the region and the citizens more than anything else. This research will be conducted with Deventer’s objectives of minimising the number of deaths in the region, minimising the annual flood damage and minimising evacuation costs in mind.

While analysing the different flood management strategies for Dike ring 5, it is important to consider several uncertainties. These include the discount rate for calculating damages, the type of flood wave, the final extent of the breach width, the probability the dike will fail and how fast the breach grows over time.

1.2 Political arena

Many different stakeholders are involved in the establishment of the Ijssel flood risk management strategy. To create a strategy that satisfies the needs of every stakeholder, collaboration is essential. Within the political arena discussion takes place on several levels. The national level includes Rijkswaterstaat, the Delta commission, environmental interest groups, transport companies and both the provinces of Gelderland and Overijssel. Deventer depends on the province of Overijssel for representation of their objectives within the national debate, as the province is responsible for all the inhabitants and stakeholders in its province. The stakeholders within the province of Overijssel, like waterboards and other dike rings, form the regional political Arena.

At each level, collaboration is needed to come to an agreement on an appropriate flood risk management strategy. As Deventer is a city within dike ring 5, this actor is involved in the decision-making process on the regional level. Together with dike ring 4 and the corresponding waterboard a plan has to be made, which the province of Overijssel can put forth in the national debate. Next to discussions on the regional level, integration with other layers, including the province, is crucial to realise a satisfactory flood risk management strategy (Bosoni et al., 2021).

As Deventer is the biggest city within the province of Overijssel, dike ring 5 represents the most citizens, making it the most crucial dike ring to minimise the human risk associated with flooding. This contrasts dike ring 4, where the main concern is protecting agricultural companies from the possible arrival of floodplains or drought, since dike ring 4 contains mostly agricultural companies. Lastly, the Waterboard is responsible for the water quality and maintenance of the dikes that keep the water in its riverbeds. The Waterboard's main priority is keeping the dikerings intact and protect the citizens that live behind them. The waterboard supports the room for the river projects, as they state that solemnly increasing dike rings would cause droughts, while room for the river would counter floods.

Lastly, as Deventer is a medium-sized city, dike ring 5 has a potential ally in the province of Overijssel. Similar to dike ring 5, the province of Overijssel wants to improve water safety and secure the living and working environment (Provincie Overijssel, n.d.). As the province of Overijssel has a lot of influence, it is important to collaborate with this actor in order to achieve the goals of dike ring 5. In the IJssel delta project for example, the province of Overijssel has played a coordinating role and developed a plan in close collaboration with other stakeholders (Sokolewicz et al., 2011).

On the national level, Rijkswaterstaat is responsible for setting up a proposal for a flood risk management strategy, as this actor is an executive agency of the Ministry of Infrastructure and Water Management. Rijkswaterstaat aims to protect our country against flooding and to ensure a sufficient supply of clean water (Ministerie van Infrastructuur & Waterstaat, 2023). To be able to come to a consensus, it is important that dike ring 5 also takes the goals of Rijkswaterstaat into account when formulating a problem statement.

Another strongly opinionated stakeholder on a national level is the environmental interest groups. These groups believe that the best solutions include Room for river floodplains.

They state that floodplains create new natural environments which will make the area more interesting for tourism.

1.3 Problem formulation

What is most important for the Deventer dike ring is protection of its inhabitants. Deventer is a densely populated city with over 100.000 inhabitants (Centraal Bureau voor de Statistiek, n.d.), making it crucial to minimise the human risk associated with flooding. The expected number of deaths caused by floods in the area of Deventer is a critical measure for assessing this risk.

Furthermore, not only people's lives should be saved, but their living environments as well. Floods can damage or destroy homes, buildings, roads, bridges, et cetera. The expected damage of a flood is a measure that provides insights into the financial impact and economic risks that are associated with a flood of the Deventer dike ring. The expected flood damage to the historical and cultural city-centre of Deventer, and the surrounding neighbourhoods should be kept to a minimum. Moreover, evacuating 100,000 people would be an enormous challenge and extremely costly. Evacuation should be avoided, which means that evacuation costs should be kept to a minimum. Strong flood protection in the Deventer area is therefore crucial.

The Deventer dike ring, however, is not the only important actor in this situation. It needs to keep in mind the objectives of the national and other regional stakeholders. For the national stakeholders, the funding of the policy is important. Deventer itself does not have to contribute financially, but policies that are extremely expensive will not be accepted by the funding stakeholders. Secondly, from a national perspective, the stakeholders could take a utilitarian perspective and choose for the solutions which are the most effective in Deventer. Therefore, the analysis will also take into account outcomes on a more general level. Furthermore, it tries to find the least expensive policy plan that meets the main requirements of Deventer.

For the regional level, Dikering Deventer, the waterboard and province share similar main objectives. The waterboard and province want overall minimised deaths and damages in the province. This can be achieved by ensuring the safety of dikering 5 since this dikering protects Deventer, having the most inhabitants. Therefore, the objective that must be minimised is the expected number of annual deaths and damages. Accommodating the objective of Dikering 4 is hard because of tension with the environmental groups. Dikering 4 does not want any room for the river plans, because that endangers agricultural businesses. However, the environmental groups value the natural benefits of floodplains which are included in the room for the river plans. Because of these tensions no specific constraints will be defined at forehand. Thus combining the objective leads to the following objectives for the analyses:

- Minimise expected number of deaths in Deventer area
- Minimise expected annual damage in Deventer area
- Avoid the use of early warning system
- Minimise expected number of deaths in all 5 dike rings
- Minimise expected annual damage in all 5 dike rings

- Minimise total Investment costs in all 5 dike rings

With taking the objectives mentioned above into account, this paper aims to answer the following research question:

“What robust policies can be implemented for Dike ring 5 to minimise the flood risk and ensure the safety of Deventers’ inhabitants, while taking into account the economic effects, the objectives of the important stakeholders and the deep uncertainty of the system?

2. Approach

To analyse the impact of different strategies in flood management for Deventer, a simulation model will be used. By running this model with different combinations of policy levers, their effects can be explored. The simulation model follows the XLRM framework. In this framework the X is for the factors outside the control of the decision-makers, L stands for the policy levers, R stands for the relationship inside the system and M stands for the performance metrics (Kwakkel, 2017).

Given the deep uncertainty characterising decision-making for the Ijssel river flood management, it is important to adopt a robust approach. To provide the Deventer with a successful strategy, Exploratory Modelling will be used. Exploratory Modelling is the use of computational experiments "to explore the implications of varying assumptions and hypotheses" (Banks, 1993). This approach will be executed by using the Exploratory Modelling Workbench, which is an open-source library for the coding language Python (Kwakkel, 2017).

2.1 Open exploration

In this section, the open exploration methods are discussed. First, open exploration is applied to the scenario space. This entails that a wide set of scenarios is explored without policy interference. Thus, the uncertainties are varied and the policy levers are kept constant. Second, the policy space is explored. Hereby, the policies are analysed without taking into account the uncertainties. Thus, when applying open exploration to the policy space, the uncertainties are based on two reference scenarios, while the policy levers are varied.

2.1.1 Scenario space

The open exploration of the scenario space consists of two steps: sensitivity analysis and scenario discovery. The sensitivity analysis provides insight into how the uncertainties affect the outcomes, whereas the scenario discovery can be used to identify policy-relevant scenarios.

2.1.1.1 Sensitivity Analysis

To analyse how sensitive the outcome variables are to the uncertainties, a sensitivity analysis has been conducted. A sensitivity analysis is important as it shows how uncertainties influence a system; this can also be used to remove uninfluential factors from subsequent analyses (Razavi et al., 2021). In this analysis, two techniques are used: Extra-Tree algorithm and Sobol. The Extra-Tree algorithm creates decision trees which divide the data into different clusters. When these classes are established the variables in the tree that have the biggest role in getting the data from the uncluster impure state to the cluster pure state have the biggest importance. This metric is called the Gini importance (Breiman et al., 1984). To ensure that all variables are considered, randomness is added by combining randomly selected variables with randomly identified cutting points for each node (Jaxa-Rozen & Kwakkel, 2018). To create a set of experiments that fill the scenario space effectively, the Latin Hypercube sampling technique is used (Sanchez & Wan, 2015).

Herefore, experiments are conducted by running 50.000 scenarios. After the experiments are conducted, the Extra-Tree algorithm is performed and feature scoring is applied to see how each of the uncertainties influences the KPI's. Based on these feature scores, the uncertainties that are most impactful can be further analysed using the sobol analysis.

At first glance, doing a sobol analysis, after determining feature scores with an Extra-Tree algorithm, could seem excessive. However, compared to the Extra-Trees algorithm, Sobol can more accurately estimate the importance of the uncertainties and take into account possible second-order effects (Jaxa-Rozen & Kwakkel, 2018). The reason the Extra Trees algorithm is applied first, is that Sobol is computationally heavy with a lot of uncertainties, which will now be reduced by using the Extra Trees algorithm.

The Sobol technique bases its feature importance on the amount of variance the uncertainties have for the output variables. In this sensitivity analysis, both the first- and second-order effects of the uncertainties are taken into account. The total effect is the effect of a specific uncertainty on a specific outcome due to both the first-order and second-order effects. These effects indicate how much the uncertainty contributes to the variance of the outcome variable (Jaxa-Rozen & Kwakkel, 2018). In this analysis the Sobol technique is used by running 150.000 scenarios. The higher the calculated contribution, the more influential the uncertainty is. Now, the most influential uncertainties can be used for scenario discovery.

2.1.1.2 Scenario discovery

Scenario discovery is a model-based approach to identify policy-relevant scenarios under conditions of deep uncertainty (Kwakkel & Cunningham, 2016). The goal of scenario discovery is to help decision-makers better understand the potential strengths and weaknesses of various strategies by summarising a wide range of possible future states (Bryant & Lempert, 2010). A key tool in scenario discovery is the Patient Rule Induction Method (PRIM); a bump-hunting algorithm that was first developed by Friedman and Fisher (Friedman & Fisher, 1999). PRIM works by incrementally "peeling" away thin faces of the input space to uncover high-density regions, effectively identifying scenarios that are both informative and relevant (Bryant & Lempert, 2010). The method is advantageous because it is highly interactive, allows for the exploration of different scenario options and provides visualisations that help balance the three crucial measures of scenario quality: coverage (how complete the scenarios capture the cases of interest), density (measures the purity of the scenarios) and interpretability (the ease with which the scenarios can be understood and used by decision-makers) (Bryant & Lempert, 2010). The PRIM algorithm will be conducted on a set of 15000 runs. The threshold value is 0.8 to filter only the boxes that have a good combination of coverage, and density. The peeling alpha value for the PRIM will be 0.1. The peeling alpha defines with which size the PRIM boxes get decreased.

As Deventer wants to protect its inhabitants, it is important that even in a worst case scenario, the safety of Deventers is ensured. It is therefore relevant to search for policies that are successful in unfavourable scenarios. To define these worst case scenarios, PRIM is used to identify a region that captures the scenarios in which the highest expected number of deaths and highest annual damage of the Deventer dike ring occur. This region consists of scenarios that are located in the top 20th percentile of the number of deaths or the top 20th percentile of the annual damage of the Deventer dike ring.

Next to the objectives of Deventer, it is also important to incorporate the objectives of other actors, like Rijkswaterstaat, as they are the one that set up the final policy proposal. By incorporating their objectives, a solution may be found which is favourable for both Deventer as well as Rijkswaterstaat. To incorporate this, a second PRIM box is established which captures the worst-case scenarios for the total number of deaths and the total damage. From each box the scenario that is located in the middle is selected, which will be used later to search for candidate strategies.

Compared to other methods like the Classification and Regression Tree (CART) algorithm, PRIM is preferred for several reasons. CART produces results comparable to those of PRIM. However, CART requires less user interaction and demands more effort from the analyst to construct box sets that are highly interpretable (Lempert, Bryand and banks).

2.1.2 Policy space

As the scenario space is now explored, the next step is to look at the policy space. Similar to the open exploration of the scenario space, a sensitivity analysis is conducted to analyse the effect of the different policies on the outcomes.

2.1.2.1 Sensitivity analysis

The sensitivity analysis for the policy space is conducted similarly to the sensitivity analysis for the scenario space. First, experiments are performed using Latin Hypercube sampling and running 25.000 different lever combinations per reference scenario, so 50.000 in total. It is important to note that in these scenarios the uncertainties are fixed and only the policy levers are varied. After the experiments are conducted, feature scoring is applied, by making use of the Extra-Tree algorithm to see how each of the policy levers influences the model outcomes. Based on these feature scores, the policy levers that are most impactful can be selected and analysed further.

2.3 Direct search

As both the scenario and policy space are explored, the most desirable policies can be determined, based on the defined scenario and policy space. To determine the robustness of the different candidate strategies, the policies need to be evaluated over multiple scenarios. To find a set of desirable and robust candidate strategies, a Many-Objective Robust Decision making algorithm (MORDM) is used. MORDM consists of four steps: (1) formulating the problem, (2) searching for candidate strategies using Many Objective Evolutionary Algorithm (MOEA), (3) assessing the robustness of each candidate strategy among multiple objectives and (4) improving the candidate solutions by applying scenario discovery (PRIM) (Eker & Kwakkel, 2018; Bartholomew & Kwakkel, 2020).

Other methods to assess the robustness of candidate strategies are Multi-scenario MORDM and Many-Objective Robust Optimization (MORO). When applying Multi-scenario MORDM, additional scenarios are selected for which a search is also performed. These scenarios are selected based on the performance of the previously found candidate strategies and can be used as new reference scenarios on which direct search can be applied.

While in multi-scenario MORDM direct search is applied multiple times on different scenarios, MORO already includes multiple scenarios in the search phase. This means that the robustness of each candidate strategy is approximated over the entire scenario space, by calculating it on a sample of scenarios (Bartholomew & Kwakkel, 2020). As Multi-scenario MORDM and MORO both include multiple scenarios in either the search phase or a subsequent iteration, the chance of finding robust candidate strategies increases.

To increase the chance of finding robust solutions, MORDM will be conducted for two iterations, using two different reference scenarios. This approach is inspired by the MORO algorithm, as MORO also includes multiple scenarios in the search phase. The reason MORDM is chosen instead of MORO or Multi-scenario MORDM is that conducting MORDM with two reference scenarios already led to quite robust policies. On top of that, MORDM with two reference scenarios has significantly less computational time than MORO or Multi-scenario MORDM.

2.3.1 Problem formulation

In the open exploration phase, the relationship between the input and the output variables has been analysed. Based on the results of this analysis only the most influential uncertainties and policy levers are taken into account.

2.3.2 MOEA

The Many Objective Evolutionary Algorithm (MOEA) searches over the policy levers to find candidate strategies that yield desirable outcomes. In this phase of the analysis the MOEA will be applied to one reference scenario, in which the policies will be optimised. Within the development of a MOEA there are three different goals: (1) convergence to the true Pareto-optimal front, (2) maintenance of a well-distributed set of non-dominated solutions and (3) high efficiency and low computational time (Deb et al., 2005). A Pareto-optimal front consists of several solutions that are not dominated by any other solution (Kasprzyk et al., 2013). The second goal is that the solutions within this Pareto-optimal front should be well-distributed, as the purpose of the optimization process is not to identify a single optimal solution, but a set of solutions that is distributed with a uniform density over the Pareto front (Maier et al., 2019).

To sort the solutions, a non-dominated sorting genetic algorithm (NSGA) is used. This algorithm sorts solutions based on their level of non-domination and the distance to their neighbours. A solution is non-dominated when there is no other solution that scores better on every objective. Thus, when a solution is dominated, there is a dominating solution that exceeds in every objective. Weak-dominance occurs when a non-dominated solution is better than or equal to another solution. A set of non-dominated solutions that don't dominate each other is called a set of Pareto-optimal solutions, in other words the Pareto front.

In the NSGA-II algorithm there is an initial population of solutions, also called individuals. The algorithm constantly combines two of these individuals to generate a new solution.

These solutions are then classified based on two conditions: the level of non-domination and the crowding distance (Kollat & Reed, 2005). The selection process of the new population goes as follows: (1) individuals with a higher level of non-domination are prioritised and (2) individuals with an equal non-domination level, but with a higher crowding distance are prioritised (Lee, 2019). Once a new population is selected, the process will start over. This cycle continues until the Pareto-front has converged, which means it doesn't change anymore when passing the new population to the algorithm.

In this analysis an ε-NSGA-II algorithm is used, to achieve a well-distributed Pareto front. This algorithm makes use of ε-dominance, which gives the modeller the ability to assign a relative importance to each objective, also called the ε-value (Kollat & Reed, 2005). Therefore the algorithm makes use of a grid, consisting of equally-sized blocks along the axes of the different objectives. The ε-values then determine the shape of the Pareto-front, as this front now follows the grid-structure. A high ε-value results in a course grid, whereas a low ε-value results in a fine grid. Subsequently, non-domination sorting is conducted, where solutions that are dominated within a grid block are not taken into further consideration. Once the Pareto-front has converged, the algorithm has come to a set of desirable solutions for the defined reference scenario. This set of candidate solutions can be further reduced by filtering on outcome. According to Deventer's mandate, evacuation should be avoided, leading to eliminating strategies where the expected evacuation costs are higher than 0.001.

To ensure that the Pareto-front converges and becomes stable the optimizer will first be run with 50.000 number of function evaluations (nfe). If this is not enough, the nfe will be increased. Additionally the algorithm will be run with multiple seeds to avoid the chance that the solution gets stuck in local optima and ensuring that, after merging the seeds, there will be a proper distribution over the Pareto-front.

2.3.2 Robustness analysis

The third step of the MORDM algorithm is to evaluate the robustness of the identified candidate strategies. In this step the Latin Hypercube sampling technique is used to generate a set of scenarios that evenly represents the uncertainties. With this set, the robustness of the candidate strategies and the effect of the uncertainties on this robustness can be assessed (Kasprzyk et al., 2013). In this analysis the robustness metrics that will be used are the signal-to-noise ratio and the maximum regret. The signal-to-noise ratio gives an indication of the variation of the outcomes over different scenarios, whereas the maximum regret indicates the difference in performance between the current policy and the best policy in a certain scenario (Kwakkel et al., 2016).

The reason the signal-to-noise ratio is chosen over other metrics, is that this metric captures both the average and the standard deviation of the candidate solution. By taking the standard deviation into account not only the average performance, but also the range of the performance of the candidate solutions becomes clear. The maximum regret metric is applied as this shows how a certain solution performs, compared to the best solution for that specific scenario. This also shows how far the best and worst solution are apart and how much impact making a less favourable choice has.

2.3.2.1 Signal-to-noise ratio

The first metric that is applied is the signal-to-noise ratio. This ratio indicates the variance of an outcome given a specific policy. The aim is to keep this variance as low as possible, as a narrow range of uncertainty shows robustness (Kwakkel et al., 2016). When the objective needs to be minimised, the signal-to-noise ratio is calculated by multiplying the mean and the standard deviation, as both the mean and the standard deviation needs to be as low as possible. When maximising the objective, the signal-to-noise ratio is calculated by dividing the mean by the standard deviation, as the mean needs to be maximised, while having a minimal standard deviation. Thus, in case of maximisation of the objective, a high signal-to-noise ratio indicates robustness, while in case of minimisation, a low signal-to-noise ratio is preferred.

2.3.2.2 Maximum regret

The second metric that is applied on the found candidate strategies is maximum regret; the difference between the performance of a specific policy and the best-performing policy in a specific scenario. It indicates the amount of 'regret' a policymaker would have when he did not choose the best performing policy for the scenario that eventually became reality. Thus, a lower value of regret means a more robust policy. As the goal is to minimise the maximum regret, this metric is also called Minimax regret (McPhail et al., 2018).

2.3.4 Scenario discovery

Once a set of robust candidate strategies is identified, these strategies are improved using scenario discovery. With the use of PRIM, the uncertainty regions in which the candidate strategies are unsuccessful can be identified (Eker & Kwakkel, 2018). Similar to the scenario discovery of the open exploration phase, two separate boxes are identified. One box contains the top 20th percentile of the number of deaths or the highest annual damage of the Deventer dike ring and the other box contains the top 20th percentile of the total number of deaths or the total amount of damage. The difference is that in this case relevant scenarios are identified based on the candidate strategies that were found by applying MOEA, while in the open exploration phase, the relevant scenarios were based on a zero-policy. A zero-policy is a strategy in which no policy measures are taken and in which all levers are set to zero. For each box the performance of the candidate strategies is evaluated.

2.4 Analysing the candidate strategies

Based on the results of the robustness metrics and scenario discovery, a final set of candidate solutions will be selected. Based on the robustness metrics, the three best policies are picked by filtering out policies with the best robustness scores over all the outcomes. The policies are first filtered on signal to noise ratio and second on maximal regret. For both metrics holds that the lower the score, the better the outcome. The worst policies, with a metric score higher than a certain threshold for any outcome, are eliminated.

Then, using the scenario discovery, it is controlled if the candidate policies are able to yield favourable results for all the possible outcomes. If there are still scenarios for which the candidate policies fail to meet the objective, a second iteration of the NSGAII will be done using the candidate policies as a starting point to make them suitable for the scenarios. If the candidate policies do meet the objectives, the final policies can be picked as proposed solutions. A trade-off for these solutions can be made by reflecting on how the candidate solutions fit in the political arena.

3. Results

In this chapter, the results needed to answer the research question are discussed. First, the results of the open exploration in the scenario space are discussed, after that the open exploration of the policy space is discussed and lastly the results from the directed search are analysed. These results can also be found on the GitHub page and the model specifications used can be found in Appendix A.

The most important objectives are the ones for Deventer; minimising the number of deaths, the annual damage and the evacuation costs. But also more general objectives of Rijkswaterstaat are taken into account; minimising the number of deaths and damage in all five dike rings. These objectives are aggregated.

3.1 Open Exploration Scenarios

Below the results of the open exploration of the scenario space can be found. By using Extra Trees feature scoring, the most relevant uncertainties in the model were identified. These uncertainties were then used in the sensitivity Sobol analysis. After that, the scenario analysis was executed using PRIM

3.1.1 Sensitivity Analysis Scenarios

In Appendix B the outcomes of the sensitivity analysis can be found. From the Extra-Tree algorithm it becomes clear that for the objectives of Deventer, the following uncertainty is clearly of most importance: the probability that dike 5 will withstand the hydraulic load. Both the expected number of deaths and the expected annual damage in dike ring 5 are primarily influenced by this uncertainty. Although of less importance, the chance of dike ring 1 and 3 to withstand the hydraulic load also influences the objectives of Deventer. For the overall objectives, considered by Rijkswaterstaat, the possibility that dike 1 and dike 3 will withstand the hydraulic flood are primarily important.

The Extra Tree algorithm is also used to evaluate the importance of the 20% worst-case scenarios for the Deventer dike ring specific outputs and the general outputs. For the worst-case scenarios for the Deventer dike ring, the chance of withstanding for dike 4 had a significant feature score. For the worst cases of the general output, it was notable that the discount rates for the three timesteps became significant. The discount rate defines how expensive it is to rebuild damages after a flood. Besides the identified important uncertainties, the uncertainties identified for the worst scenarios will also be included in the Sobol analysis.

The uncertainty outcomes from the feature scoring above are used in the Sobol analysis. Included are the failure of dike ring 2 and the three discount rates (for calculating the present day values of damages). These were also considered relevant factors.

From the Sobol Analysis it becomes clear that all uncertainties have negligible effects for the expected evacuations costs and total investment costs. Furthermore, for the expected number of deaths and the expected annual damage for Deventer, failure of dike ring 5 is the dominant parameter to which the model is sensitive. And although less than dike ring 5, also the other dike rings can have an impact on the Deventer outcomes. Moreover, failure of dike ring 1 and dike ring 3 are the two dominant parameters to which the general objectives, considered by Rijkswaterstaat, are sensitive. Lastly, no uncertainties have a significant second order effect on the outcomes.

3.1.2 Scenario Analysis

Scenario discovery was used to develop scenarios under conditions of deep uncertainty (Kwakkel & Cunningham, 2016). PRIM was executed to identify subspaces in the uncertainty space where implemented policies perform poorly. The PRIM analysis gives multiple results. Of these results, the most favourable one was chosen. Explanations of this choice can be found in appendix B.

Firstly, PRIM was executed for the important outcomes for Deventer: 1) expected number of deaths and 2) expected annual damage and for the top 20 percentile worst-cases. The worst-case scenarios for Deventer are the ones in which dike ring 2, dike ring 3 and dike 4 have a small chance of breaking. The dike ring of Deventer (dike ring 5), then has a big chance of breaking. This can be explained by the fact that all water flows through to Deventer, resulting in a higher probability that the dike cannot handle all this water. This leads to more deaths and damage in this area.

PRIM was also executed for the general outcomes: 1) total expected number of deaths, 2) total annual damage and 3) investment costs. Again, for the top 20 percentile worst-cases. The outcome here is different. Only dike ring 3 is important to represent the 20% worst-case scenarios. Breaking of dike ring 3 will result in the highest number of deaths and damage.

These two PRIM analyses result in two reference scenarios. One conducted with important outcomes for Deventer and one conducted with important outcomes in general; resulting in a broader scope for the exploration of the policies and the directed search.

3.2 Open Exploration Policies

3.2.1 Sensitivity Analysis Policies

After the open exploration of the scenarios, an exploration of the policies was conducted to see which policies work best in the scenarios and which policies are most relevant to research in the directed search. To do this, again a sensitivity analysis was performed. This was done by running experiments with the two reference scenarios. The detailed results of this analysis can be found in appendix C.

It became clear that the annual damage and the expected number of deaths for dike ring 5 of Deventer are strongly influenced by increasing dike 5. This is explainable, because in the scenarios, dike 5 had a high chance of breaking. Furthermore, an early warning system will strongly influence the number of deaths in Deventer. Making sure inhabitants are evacuated in time, will reduce the amount of deaths. It is notable that the early warning system seems effective, since this is a policy that dijkring 5 wants to avoid. However, the main objective is to minimise potential deaths and damages and if the early warning system proves to achieve this then it is acceptable. And although of less influence, also room for the river project 3 influences the outcomes for Deventer.

For the evacuation costs, the three policy levers that influence this outcome the most are an increase of dike 3, implementation of the early warning system and an increase in dike ring 5. It can be expected that the increase of dike ring 3 and 5 influence the early warnings system positively because when the dikes are higher the warning systems do not have to be used that often.

Looking at the general objectives, it became clear that the total annual damage is mainly influenced by an increase of dike 3 at the beginning. Also this is logical, as breaking of dike 3 was important for the general outcomes in the worst-case scenarios. After raising dike 3, raising of dike 5 and room for the river at location 2 have some influence on the total annual damage. The total expected number of deaths is also mainly influenced by a dike increase of dike 3 at the start. Next to that, the early warning system is of importance for this outcome.

Now both the scenario and policy space are explored and the most desirable policies are determined. All the above mentioned policies will be evaluated over multiple scenarios to determine the robustness of these different candidate strategies. The results of the MORDM for the robust candidate strategies can be found in section 3.3.

3.3 Directed Search

After the open exploration of scenarios and policies, an optimization can be done to find the most relevant policies in the most relevant scenarios. The optimization was run on TU Delft's supercomputer. The results for the convergence metrics, as can be seen in appendix D, show that for both scenarios, all the metrics for all the seeds stabilise. This means that there is indeed convergence. The seeds seem to converge to rather similar solutions, as the lines head to rather similar values.

After merging the candidate solutions from different seeds, using epsilon non dominance, there were 34 candidate solutions for scenario 0 and 51 for scenario 1. After joining all these candidate solutions, and removing duplicate ones, 49 candidate solutions were left. As Deventer wants to avoid evacuation, a constraint was added saying that Expected evacuation costs have to be smaller than 0,001, leaving 15 candidate policies for further evaluation.

3.3.1 Robustness

After running 6000 experiments (with Latin Hypercube Sampling), the robustness of the 15 candidate solutions can be analysed. First, the signal to noise ratio was analysed. The normalised signal to noise ratio for each candidate policy and each outcome is given in figure 1.

Figure 1 shows that the 15 candidates have a wide variety of signal to noise ratios. In this case holds that the lower the ratio, the better the outcome. The ideal policy would score 0 for every outcome. However, in reality that is not feasible, and trade-offs have to be made between outcomes.

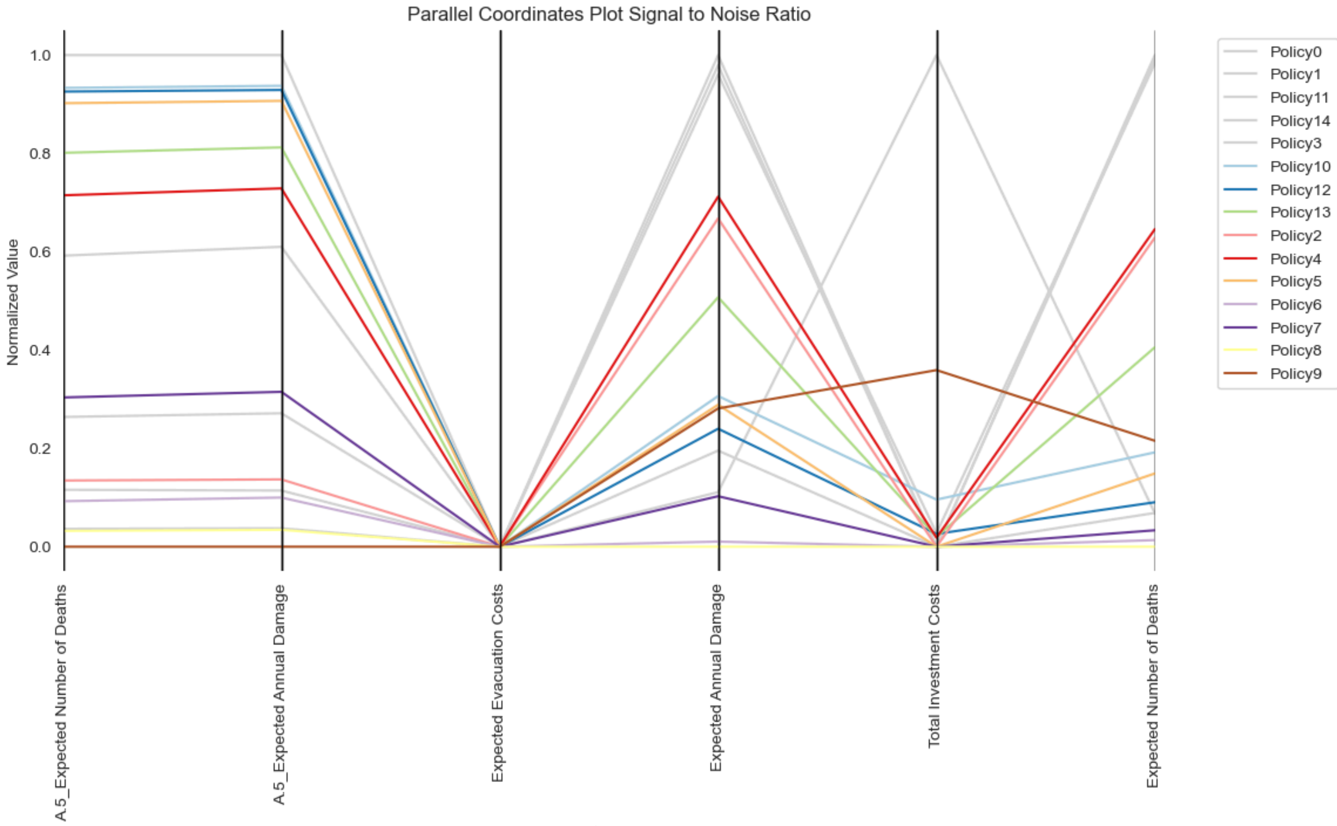

Figure 1: Parallel Coordinates for the 15 candidate policies and their Signal to Noise ratio for each of the outcomes

Figure 1 shows that the trade-offs are mainly to be made between deaths, damages and costs. To filter out more policies, all the policies that have a normalised signal to noise ratio higher than 0.95 for any of the outcomes are eliminated. These eliminated policies are indicated with a grey line in figure 1. The coloured lines indicate the remaining 10 candidate policies, of which the maximum regret score is also analysed. These maximum regret scores are depicted in figure 2.

As the maximum regret scores are also to be minimised, the candidate policies can again be filtered. The candidate policies that have a maximum regret score of more than 0.975 for any of the outcomes are eliminated, leaving the final 3 candidate policies: policy number 7, 10 and 12.

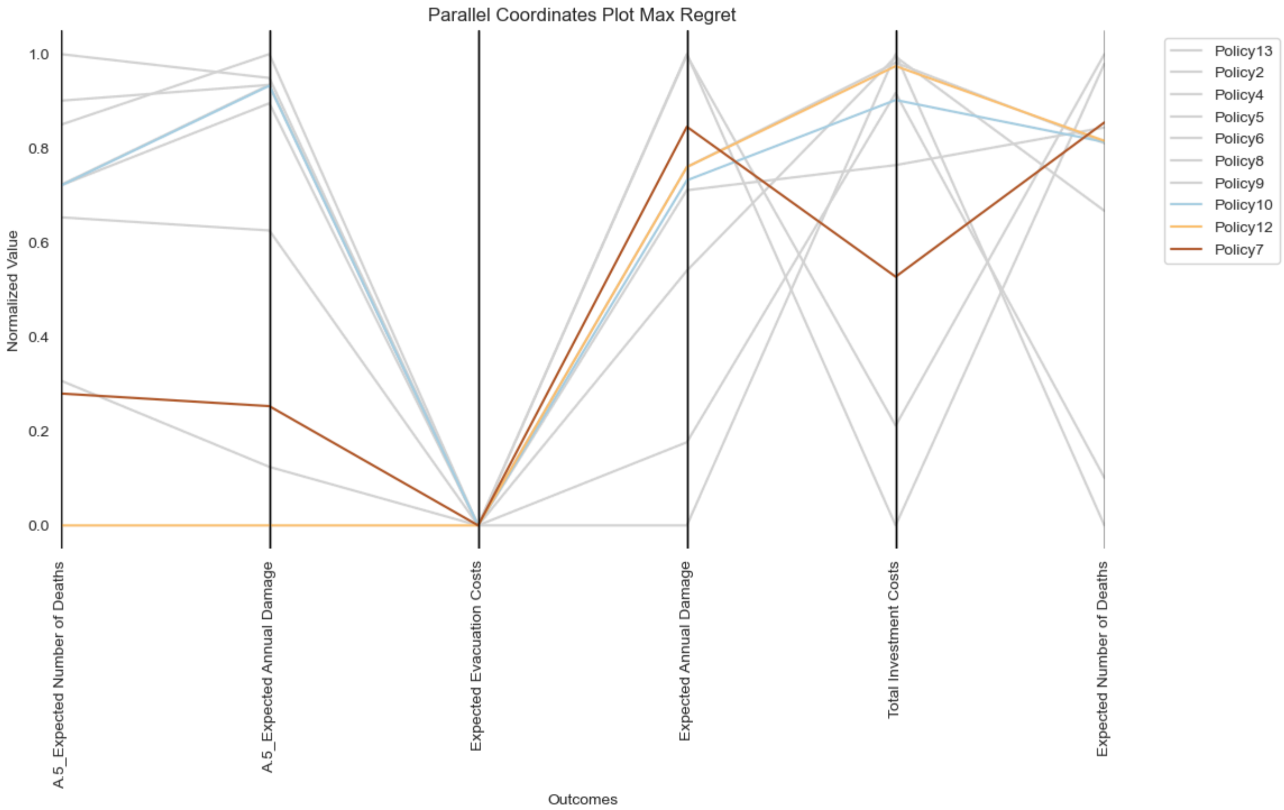

Figure 2: Parallel Coordinates for the 10 candidate policies (after filtering on signal to noise ratio) and their maximal regret score for each of the outcomes

The exact specifications of the policy levers of the final three policy strategies can be found in appendix E. All three policies include a dike increase for dike ring 3 at step 0. Policy 7 and 10 make a combination of the dike ring 3 increase and Room for the River projects. Policy 7 includes heightening the A3 dike by 40cm, Room for the River at location 2 at timestep 2 and Room for the river at location 3 at timestep 0. Policy 10 heightens the A3 dike by 20 cm, but only includes the Room for the River project at location 2, timestep 1. The only policy lever for policy 12 is the increase of dike ring 3 by 50 cm, which is the highest increase of the three policies.

The final three policies and their mean (non-normalised) outcomes are shown in table 1. It is good to note that the expected evacuation costs are all zero, because this was a pre-defined constraint. The table shows that the expected number of deaths in Deventer are relatively low for all policies. However, policy 7 does have half the expected casualties in Deventer compared to the other two. The expected annual damage in Deventer for policy 7 is also about half the value of the other policies. Both the expected annual damage and the expected number of deaths in the entire region are in a quite similar range for all three policies. However, policy 7 does, again, score the best for these two outcomes. The only point of concern for policy 7 is the relatively high investment costs. These are more than 3 times as high as policy 10 and almost six times as high as policy 12.

Table 1: Final three policies and their mean outcomes

Policy	A.5_Expected Number of Deaths	A.5_Expected Annual Damage	Expected Evacuation Costs	Expected Annual Damage	Total Investment Costs	Expected Number of Deaths
Policy7	0,043	49.200.000	0	1.240.000.000	178.000.000	0,89
Policy10	0,083	92.300.000	0	1.360.000.000	53.000.000	1,05
Policy12	0,082	91.500.000	0	1.340.000.000	29.000.000	0,99

Looking at table 1 and not considering costs, policy 7 seems the most favourable one. As the results of the policy are relatively good, the decision whether this policy will be implemented mainly depends on the funding parties' budget. As policy 7 is significantly more expensive than the other policies, thus increasing risk of it not being implemented, it is good to also take the other two policies into account. From the mean outcomes, policy 12 seems to dominate policy 10. However, it is good to note that policy 12 only increases dike ring 3, but does not make room for the river. Policy 10 does include a Room for the River project, making it a more favourable option for many stakeholders in the political arena. While policy 12 scores better than policy 10 in the model, it does not mean that it is supported in the political arena and thus scores better in real life. In appendix E the performances of the three policies are visualised using a boxplot.

3.3.2 Scenario discovery

As the three candidate solutions are found based on two reference scenarios, it is important to assess in which scenarios the candidate solutions are less successful. By applying scenario discovery the uncertainty regions in which the solutions are most vulnerable can be identified. The PRIM algorithm is conducted to determine the top 20th percentile of scenarios in which the most annual damage and number of deaths for either dike ring 5 or in total occurs. Figure 3 shows the performance of each policy on the objectives for dike ring 5 and in total in the top 20th worst case scenarios. These plots show that even in the worst case scenario, the average number of deaths and annual damage is relatively low. On average the total expected annual damage remains below 1 billion euros and the expected number of deaths remains below 1. Because of these relatively low numbers, a second iteration of the MORDM algorithm is not deemed necessary.

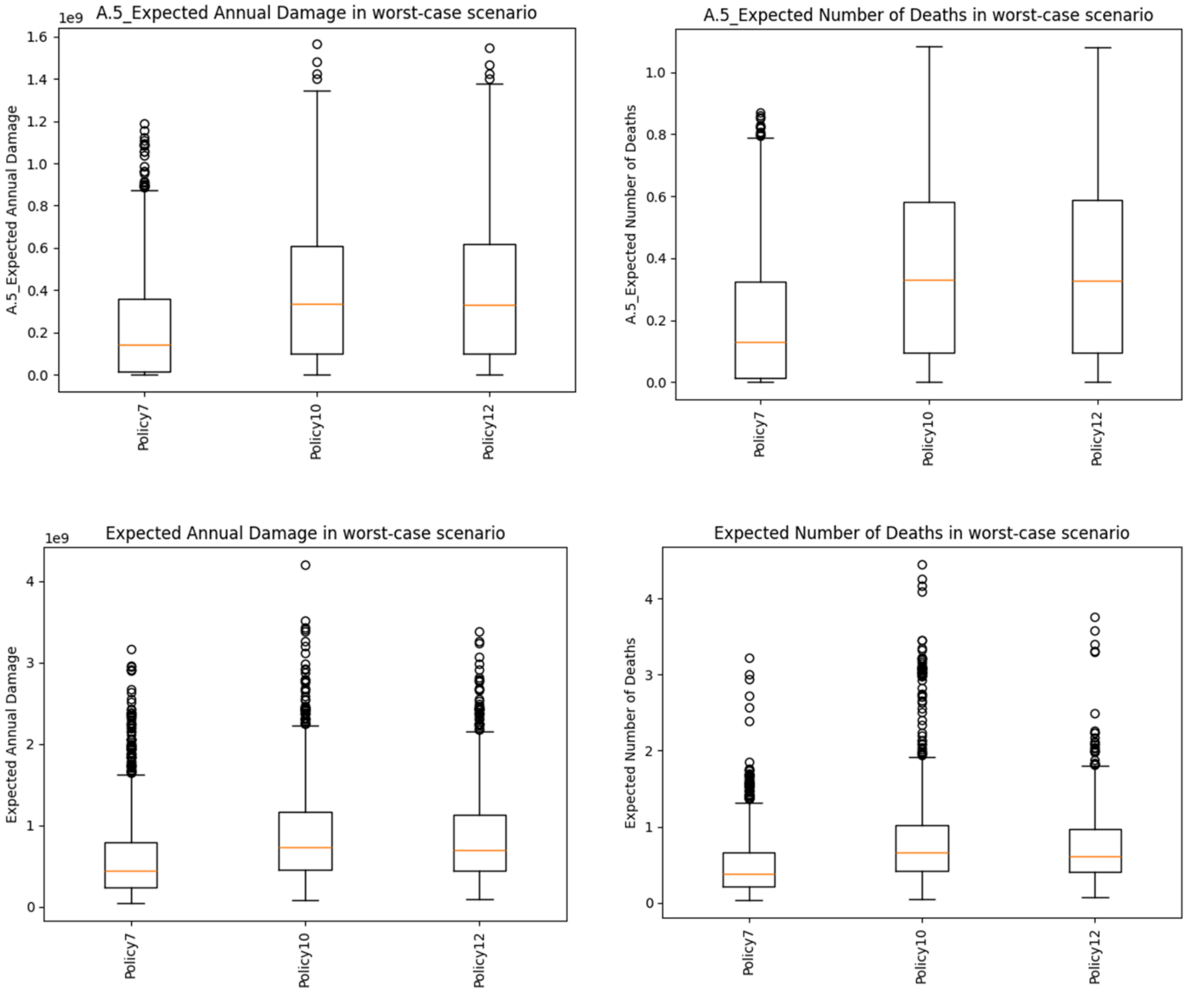

Figure 3: The expected annual damage and number of deaths for the Deventer dike ring in the worst case scenarios for each candidate solution

The performance of the candidate solutions on the total investment costs is not visualised as these costs are independent of the uncertainties. The expected evacuation costs are not taken into account as solutions where evacuation costs are made, were filtered out. Thus, for the current candidate solutions the evacuation costs remain zero.

4. Conclusion

The Ijssel river is one of the main rivers in the Netherlands and with ongoing climate change and global warming, it is crucial to protect the regions along the Ijssel river against floods. Deventer, part of dike ring 5, is one of the bigger cities along the Ijssel. Therefore, strong flood protection for dike ring 5 is essential to limit flood harm done to Deventer's inhabitants. This paper aimed at answering the following question: *"What robust policies can be implemented for Dike ring 5 to minimise the flood risk and ensure the safety of Deventers' inhabitants, while taking into account the economic effects, the objectives of the important stakeholders and the deep uncertainty of the system?*

Protecting the Ijssel river is a project with a political arena including many stakeholders with different views. While waterboards and environmental interest groups, for instance, support Room for the River projects, transport companies and dike ring 4 oppose it. As Rijkswaterstaat is the main stakeholder, deciding on the final policy, its objectives were taken into account in the modelling and analysis. The final objectives were to minimise Deventer's and the entire region's flood casualties and damages, minimise evacuation costs and total investment costs.

After analysing multiple policy strategies in the various deep uncertainties of the system, three final policies were selected based on their performance on the earlier mentioned objectives. According to the model, the policy that implements a 40 centimetre dike increase near Zutphen and Room for the river at Tichelbeekse (extreme long-term) and Welsummer (short-term) would lead to the most favourable outcomes regarding casualties, damages and evacuation costs. This is, however, the most expensive policy of the three, with an expected investment of 178 million euros.

Implementing a 50 centimetre dike increase near Zutphen would be the least expensive policy, with 29 million euros, but this would go at the expense of expected casualties and damages according to the model. The last policy, with Room for the river in Tichelbeekse (long-term) and a 20 cm dike increase near Zutphen, has similar expected casualties and damages as the solemn 50 cm Zutphen dike increase. This policy is expected to cost 53 million euros.

While the first policy, with Room for the river at Tichelbeekse and Welsummer and a 40 cm Zutphen dike increase, would probably lead to the most preferable results, it is important to note that the budget for this project is limited. The other two policies are less expensive, but they could cause more casualties and damages. To choose between these two policies, it is crucial to have a good understanding of the political arena, to ensure enough support for the chosen policy. In the end, the chosen policy must balance budget constraints and political support to ensure Deventer's well-being and protection against future floods.

5. Discussion

The purpose of this report was to use Exploratory Modelling and Analysis to find optimal policy combinations for the goals of Deventer. The model and the analysis contain inaccuracies and limitations in what they consider. These inaccuracies and limitations have their roots in two sources, the model analysis part and the decision-making part. For both, the main limitations will be given.

5.1 Model analysis limitations

Various limitations can be found throughout the analysis and they are highlighted following the structure shown in the methodology. Starting with the scenario discovery for both the scenario and policy space. The Extra Trees algorithm was executed with the default parameter configuration of the function. Adding extra decision trees or forcing a certain depth of the tree could have resulted in more accurate results. Additionally, if the Sobol analysis was done with more samples, the using Extra Trees would have been redundant. For the Sobol analyses the number of samples could have been higher making the result more reliable. A limitation specifically for the open exploration for policies, is that the analysis is done using only two reference scenarios. To get a more complete overview, randomly picked scenarios could have been taken into account.

For the scenario discovery phase, the selection of reference scenarios could be improved. Currently, the centre points of the two PRIM boxes have been taken. This way the full space of interest gets overly simplified. A more sophisticated method uses an optimization-based selection procedure which optimises the diversity of scenarios (Eker & Kwakkel, 2018). This could be used to yield more interesting reference scenarios which could be used in the direct search.

To ensure that the NSGA-II optimizer has found the best solutions, convergence metrics were used. Unfortunately, the Hypervolume metric was not taken into account. Compared to generational distance and the epsilon indicator metrics, the hypervolume metric can take into account the diversity of solutions over the solution Pareto-front. This could have ensured that no gaps in the Pareto front were present. It was not implemented because incorporating it in the used code was too complex and hypervolume introduces extra computational weight. Another shortcoming, which is more connected to MORDM, is that the candidate solutions do not consider the specific objectives of other stakeholders. In future research it could evaluate which of the policies reduces the damage and deaths for dike ring 4 of Gorssel.

Lastly, from the analyses, it becomes apparent that the policy lever of raising dike ring 3 is very effective. Unfortunately, it is not clear why this specific lever has such a good effect on the deaths and damages for the general and dike ring 5 outcomes. Currently, the only explanation is that the state of dike ring 3 is very bad and in need of improvement, but this is uncertain. Future research could examine why raising dike ring 3 is so effective.

5.2 Decision-making limitations

Firstly, is the small number of outcomes used throughout the analysis. The current outcomes cover the needs of Deventer and some general objectives of Rijkswaterstaat. To accommodate the interest of other stakeholders, other objectives could have been included. Take for example the outcomes for the damage and deaths for the dike ring 4. Including these outcomes could make the policies more convincing for dike ring 4. Another way to consider interests is by adding specific constraints which align with an actor. To do this more knowledge must be gathered on the various stakeholders and their perspectives on the system the model represents. An approach to accomplish this is comparative cognitive maps where the various stakeholders create a mental model of the systems which includes aspects of how they think how the model works, what the input and what the interested outcomes of the systems are. Then these mental maps can be compared leading to an overview of the objectives of all the stakeholders (Hart, 1976). This could be used as a better foundation to base the problem formulation on and include more specific needs of different actors.

The policies that come forward from the analysis are static. Making them less suitable for when uncertainties shift their values over time. This can be avoided by selecting various policies that are optimal for scenarios with different values for uncertainties. With these policies a dynamic adaptive policy pathway (DAPP) could be made. A DAPP provides a plan that describes which initial policies must be implemented and under which circumstances the initial policies must be altered when future uncertainties change (Haasnoot et al., 2013).

Besides the policies being static they are only focused on a limited spatial scope. The model only takes the five dike rings and the main stakeholders interested into account. However, the Ijssel does not start in the Netherlands and cities in Germany also experience flooding. In future work the current model could be extended to include objectives of Germany.

Lastly, it must be noted that this report provides policy to avoid the consequences of the river flooding but the source problem of this flooding is not addressed. The European Environment Agency states that climate change will increase the severity of flooding. While rising dikes and creating floodplains will bring safety for the coming years it will not solve the source of the problem (European Environment Agency, 2024). Efforts must be made to evaluate the increase of flood severity of climate change to determine the future costs and if mitigation measures are financially responsible compared to tackling the root problem.

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Appendix

Appendix A: Locations of interest and model outcomes and uncertainties

In Table A.1 the variable names of the five dike rings are linked to the locations of the dike rings.

Table A.1: Locations names corresponding to used model names

Location	**Model name**
Dikering Doesburg	A1
Dikering Cortenoever	A2
Dikering Zutphen	A3
Dikering Gorssel	A4
Dikering Deventer	A5

In Table A.2 the outcome variables that are used in this analysis are presented. Both the variable name, as well as the description and dimension are included.

Table A.2: Description of the used objective values

Outcome	**Description**	**Dimension**
A.5_Expected Annual Damage	Discounted expected annual flood damage in dike ring 5	Euro
A.5_Expected Number of Deaths	Expected annual number of casualties due to floods in dike ring 5	Person
Expected Evacuation Costs	Costs of evaluation based on the number of people and the duration they have to leave their home	Euro
Expected number of deaths (in all 5 dike rings)	Expected annual number of casualties due to floods in all five dike rings	Person
Expected annual damage (in all 5 dike rings)	Discounted expected annual flood damage in all five dike rings	Euro
Total investment costs	The total investment costs of all the dike heightening project, the total investment costs for the Room for the River projects and the total expected evacuation costs	Euro

The uncertainties are presented in table A.3. For each uncertainty, the variable name, possible values, a description and the dimension are incorporated.

Table A.3: Description of the uncertainty values

Uncertainty	Values	Description	Dimension
discount rate {timestep}	1.5, 2.5, 3.5, 4.5	discount rate for calculating present-day value of damages	Dmnl
A.0_ID flood wave shape	0-132	A normalised curve describing the shape of the incoming flood wave over time. There are 132 predefined curves	Dmnl
A.{dike_ring}_Bmax	30-350	The final extent of the breach width. The greater the width, the larger the volume of water that enters the floodplain per unit of time	Metres
A.{dike_ring}_pfail	0-1	The probability that the dike will withstand the hydraulic load	Dmnl
A.{dike_ring}_Brate	0, 1.5, 10	How fast the breach grows over time	1/day

Table A.4 presents the Room for the River strategies that are corresponding to the strategy numbers used in the model.

Table A.4: shows which number corresponds to which location for the room for the river plans

Rfr strategy number	Rfr strategy name
0	Olburgen
1	Havikervaard
2	Tichelbeekse
3	Welsummer
4	Obstakelverwijdering

In Figure A.1 the locations of the Room for the River projects are visually presented.

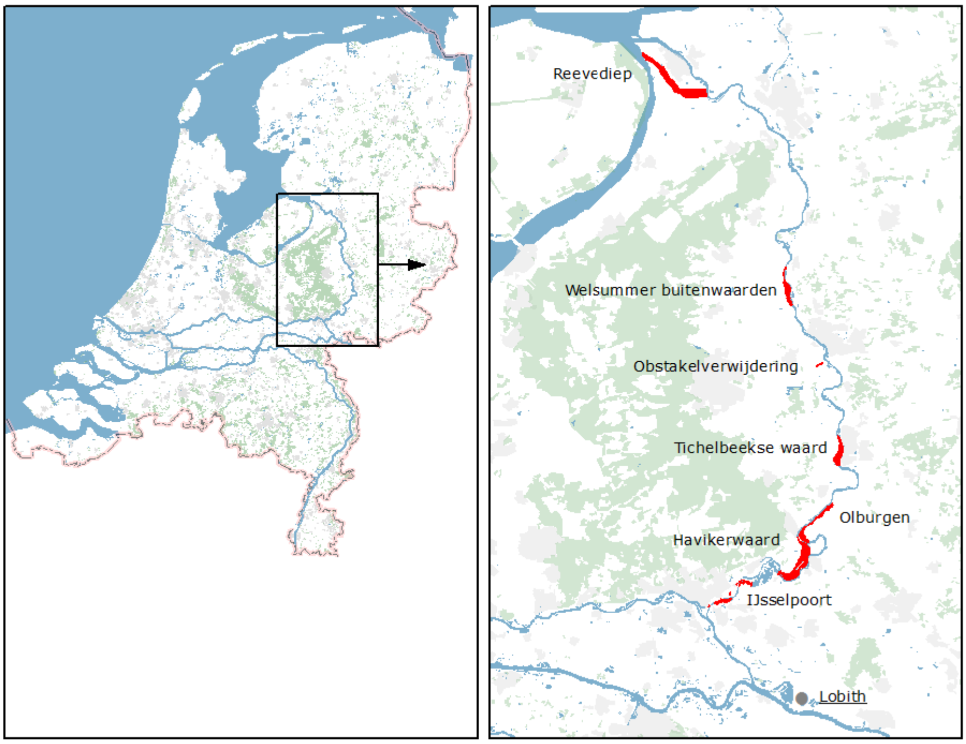


Figure A.1: Locations Room for the river Projects

Appendix B: Open Exploration Scenarios

In this appendix the results of the open exploration phase of the scenario space are presented in more detail.

Extra-Trees analysis

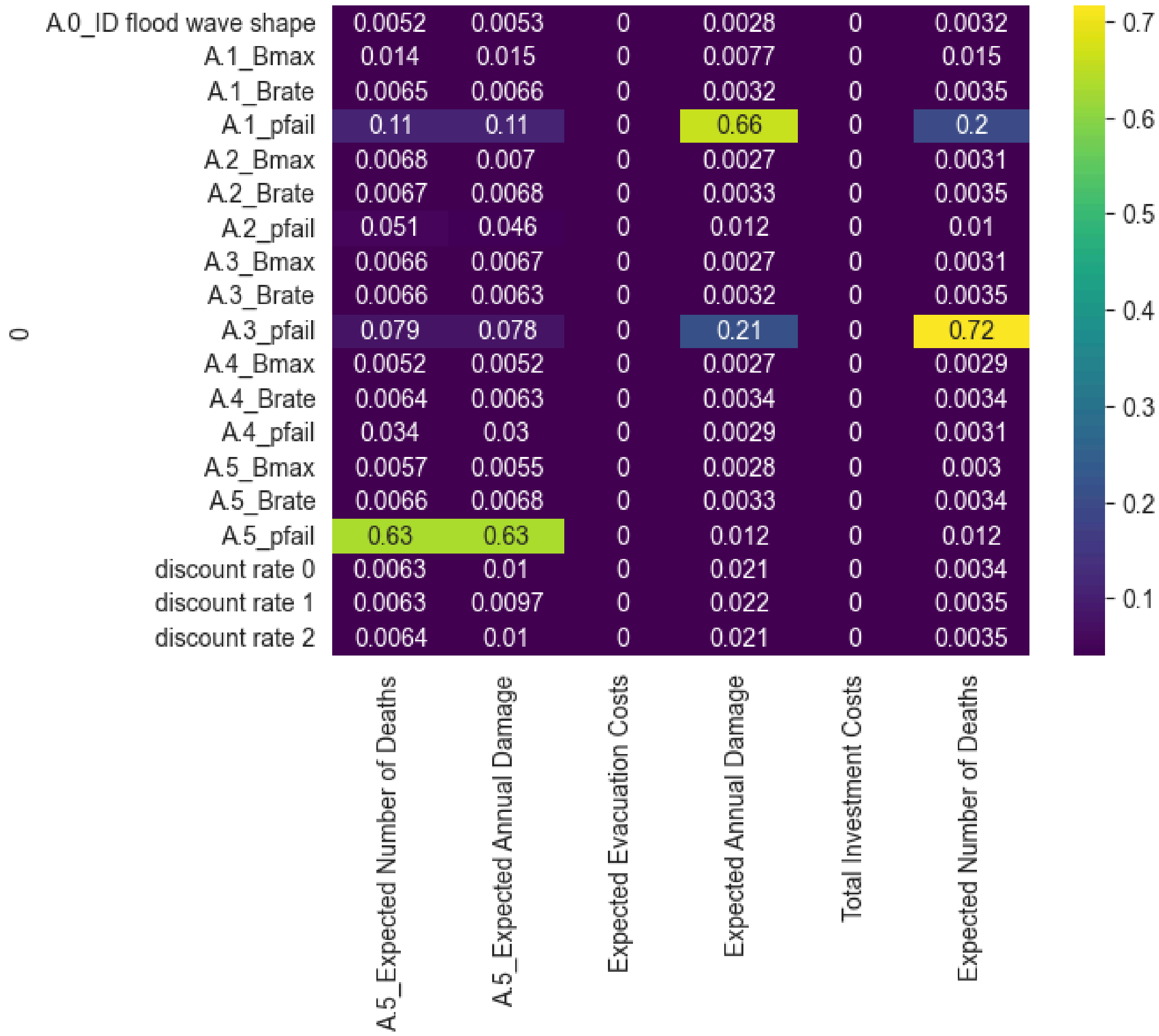


Figure B.1: Feature scoring Extra Trees heatmap for policies

From the feature scoring using Extra Trees it becomes clear that for the objectives of Deventer, the following uncertainty is clearly of most importance: A.5_pfail. Which is the probability that the dike will withstand the hydraulic load. With a score of 0.63, both the expected number of deaths and the expected annual damage for dike ring 5 are primarily influenced by this uncertainty. Although of less importance, the chance of dike ring 1 and dike ring 2 to withstand the hydraulic load also influences the objective of Deventer.

For the overall objectives, considered by Rijkswaterstaat, the probability that dike 1 and dike 3 will withstand the hydraulic flood is primarily important. With a score of 0.66, the probability of dike ring 1 to withstand is most important for the expected annual damage. With a score of 0.72, the probability that dike 3 will withstand the hydraulic load is most important for the expected number of total deaths.

Furthermore, it is important to note that none of the uncertainties have any effect on the expected evaluation costs for Deventer and the total investments costs. The reason being that all policies are set to zero, so no evacuations or investments take place. In the Sobol analysis all factors with a score above 0.05 are taken into account. This results in the fact that the probability of dike 2 to withstand is also taken into account. From the figure, it becomes clear that the three discount rates (for calculating the present day value of damages) have scores lower than 0.05 for all the important outcomes. However, they are still used in the Sobol analysis, because they are relevant for the outcomes of Rijkswaterstaat.

Sobol Analysis

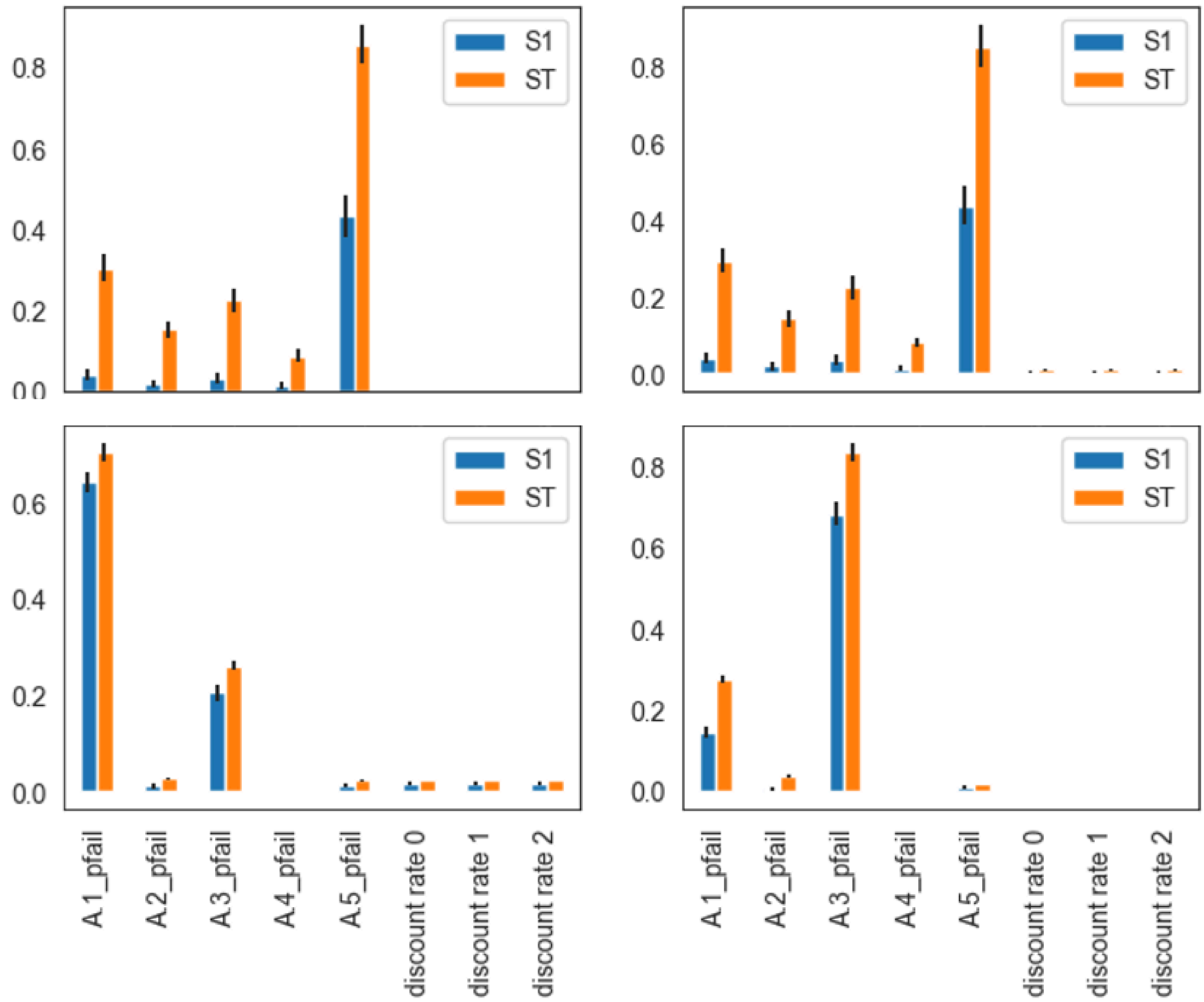


Figure B.2 First-order and Total order Sobol scores where S1 shows the first order and ST the total order.

In Figure B.2, the results from the Sobol analysis are shown. The figure shows the total order of effects (orange) and the first order effects (blue). The black line indicates the error bar around the estimated effect and the values indicate how the uncertainties contribute to the output variables. For the expected evaluation costs and the total investment costs, all factors have negligible effects, indicating that none of these uncertainties significantly influence the expected evaluation costs.

For the expected number of deaths and the expected number of annual damages for Deventer, the failure of dike ring 5 is the dominant parameter to which the model is sensitive. Although less than dike ring 5, the other dike rings can also impact these outcomes. It is notable that there is a bigger difference between the first-order and total-order effects here. This indicates that the influence on the outcomes is not just direct but also involves interaction effects.

For the general objective ‘expected annual damage’, failure of dike ring 1 shows the highest impact. But also important is the failure of dike ring 3. For the general objective ‘expected number of deaths’ the opposite happens. Failure of dike ring 3 is more important than failure of dike ring 1. The other uncertainties have negligible impact. Failure of dike rings 1 and 3 are the two dominant parameters here. The relatively small difference between the first-order effects and total-order effects suggests that most of the sensitivity is due to direct effects rather than interaction effects.

Scenario Analysis

Scenario discovery was used to develop scenarios under conditions of deep uncertainty (Kwakkel & Cunningham, 2016). PRIM was executed to identify subspaces in the uncertainty space where implemented policies perform poorly. Firstly, PRIM was executed for the important outcomes for Deventer: 1) expected number of deaths and 2) expected annual damage and for the top 80 percentile worst-cases.

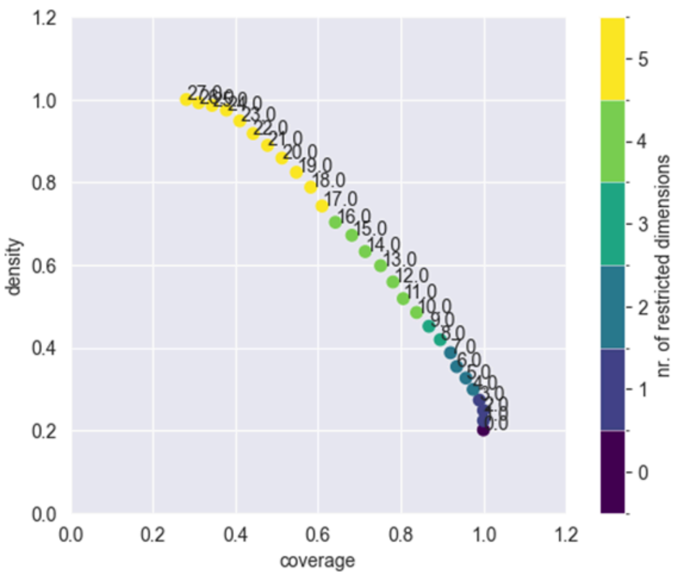
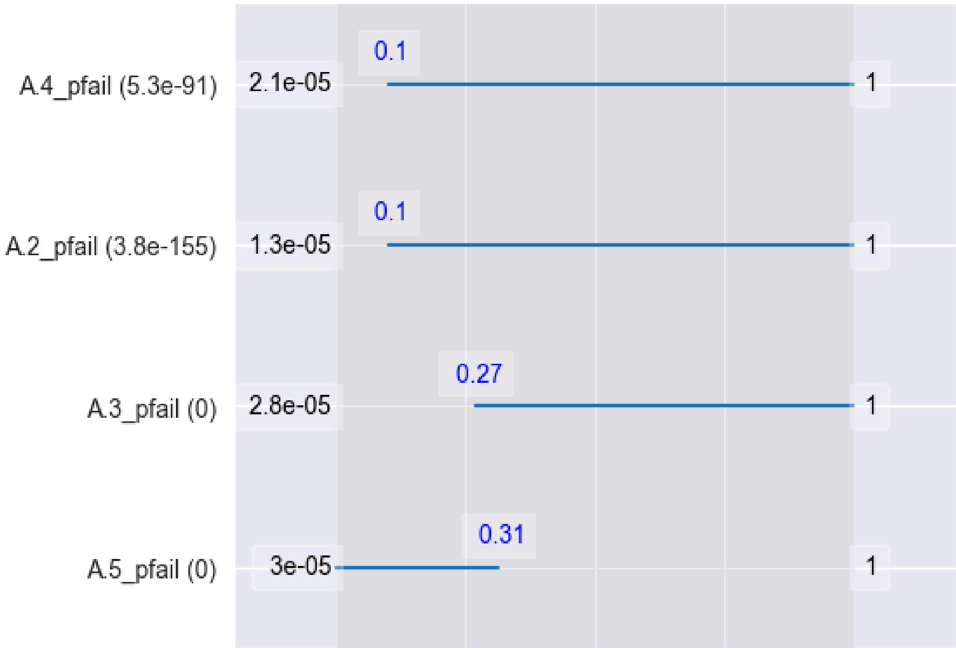


Figure B.3: PRIM trade-off curve (dike ring 5 outcomes)

In figure B.3 the trade-off curve of PRIM for the important outcomes of dike ring 5 is shown. In this case, the 16th box was used to analyse. The density of this box is not the highest (around 70%), however it is still chosen because it has fewer dimensions than the other boxes with a higher density. These fewer dimensions make it easier to understand.



coverage	0.719
density	0.779

Figure B.4: Table inspection box 16 (dike ring 5 outcomes)

The table in figure B.4 shows the box limits. The coverage value of 0.642 indicates that 64.2% of the relevant scenarios are covered by this box. The value of 0.703 for the density indicates that 70.3% of the scenarios within this box are relevant. As the quasi-p value of all the parameters are lower than 0.05, they can all be considered significant. From the table it can be concluded that failure of dike 3 and failure of dike 5 have a higher influence of defining the box compared to failure of dike ring 2 and dike ring 4.

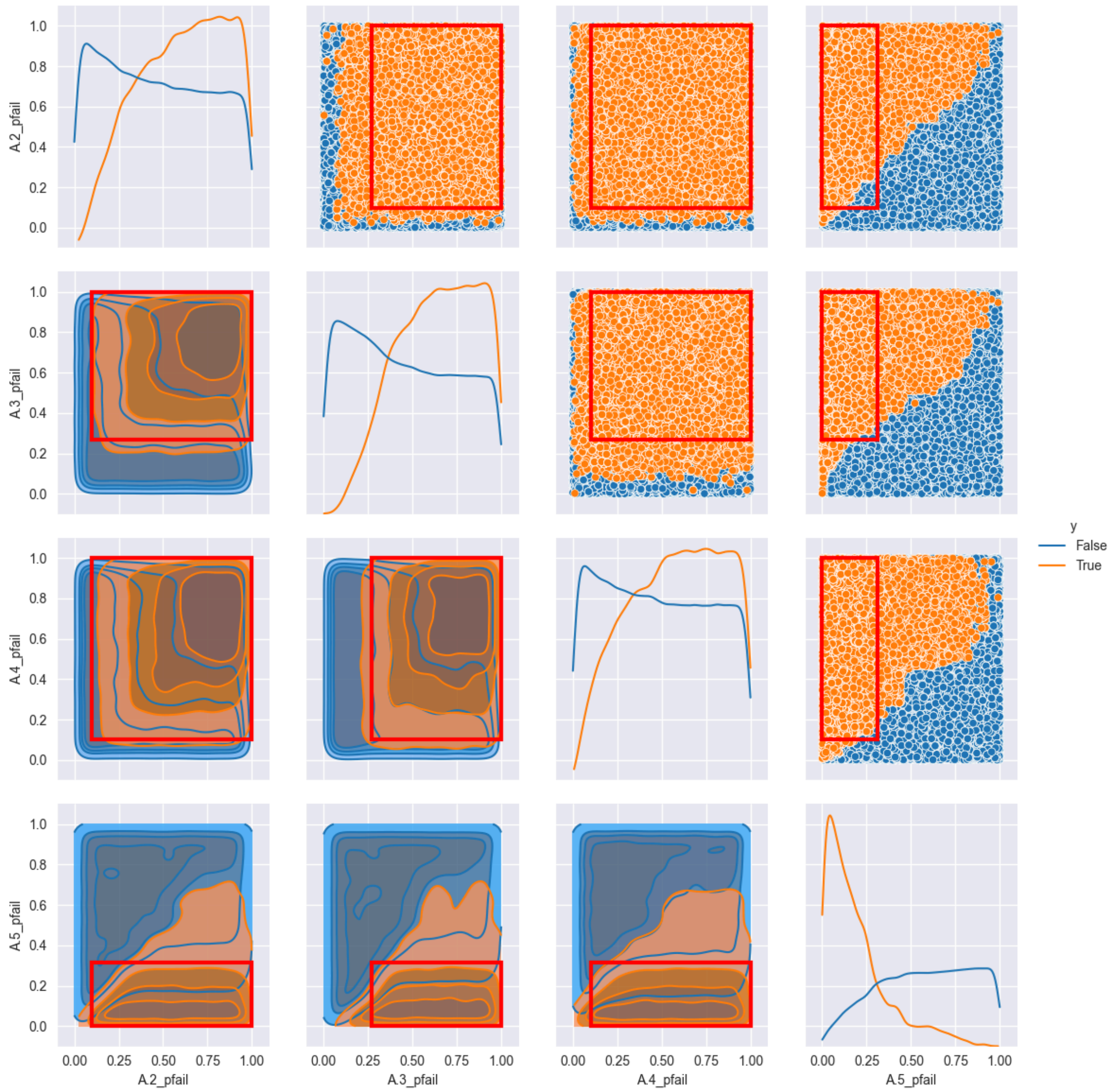


Figure B.5: PRIM pair plot (dike ring 5 outcomes)

In figure B.5, the PRIM pair plot outcomes are shown. From the pair plot can be derived how outcomes correlate with each other. The cases of interest are shown in orange and the cases not of interest are shown in blue. On the diagonal the Gaussian Kernel density is given for both cases. The red squares indicate the identified box limits for each pair of parameters.

It becomes clear that dike ring 2, dike ring 3 and dike ring 4 have a smaller chance of breaking. Dik ring 5 of Deventer has a higher chance to break. This can be explained by the fact that all the water flows through to Deventer, so there is a higher probability that dike cannot handle the water. Leading to more deaths and damage in that area.

Next to the PRIM analysis with the most important outcomes for Deventer, PRIM was also executed for the general important outcomes: 1) expected number of deaths and 2) expected number of annual damage. The results of this PRIM trade-curve are given in Figure B.6.

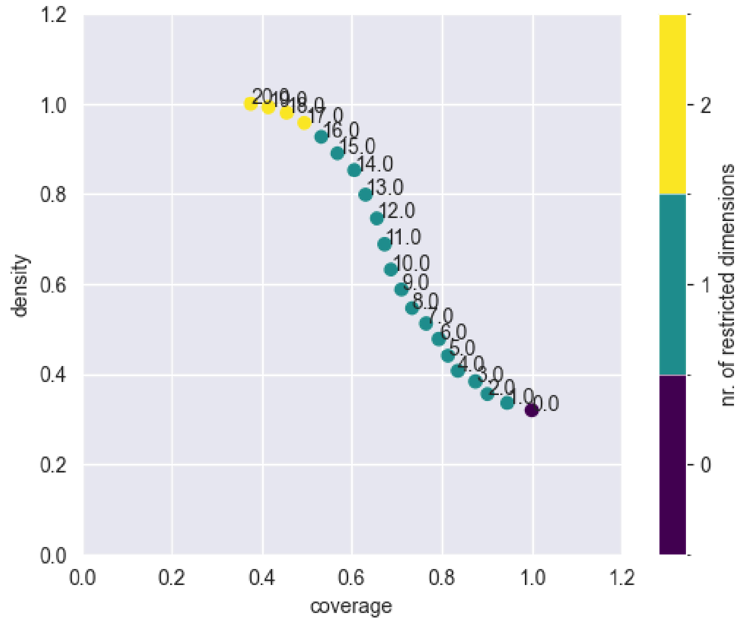


Figure B.6: PRIM trade-off curve (general outcomes)

In figure B.6 the trade-off curve of PRIM for the general is given. In this case, the 12th box was used to analyse. The density of this box is not the highest but almost 80%, which is considered enough. It is chosen because it also has quite a good coverage of around 65%.

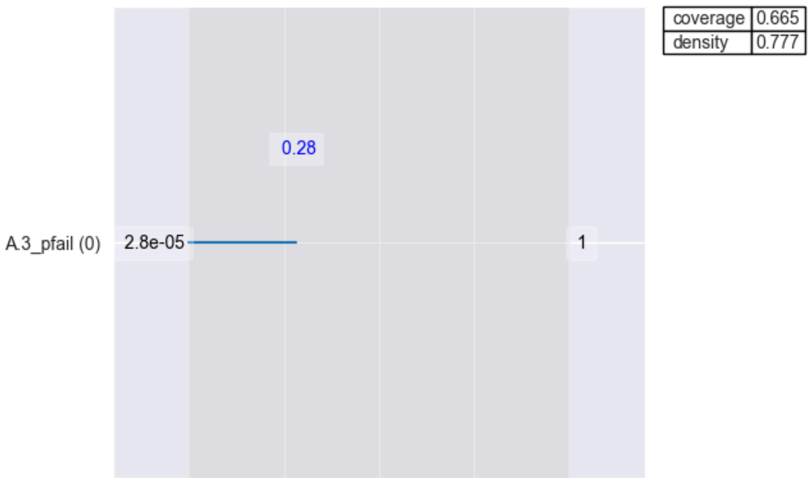


Figure B.7: Table inspection box 12 (general outcomes)

Compared to the inspection of box 16 of the outcomes for the Deventer dike ring, the outcome here is quite different. It becomes clear that only dike ring 3 is important to represent the 20% worst-case scenarios. It means that breaking of dike ring 3 is most important for the general outcomes and can result in the highest number of deaths and the biggest amount of damage.

The PRIM analysis identified important regions in the input space for both outcomes for Deventer and the general outcomes. The midpoints of these regions were calculated, providing central points around which the directed search can be focused. This combined use of PRIM boxes allows for a more focused and broader scope for the directed search.

Appendix C: Open Exploration Policies

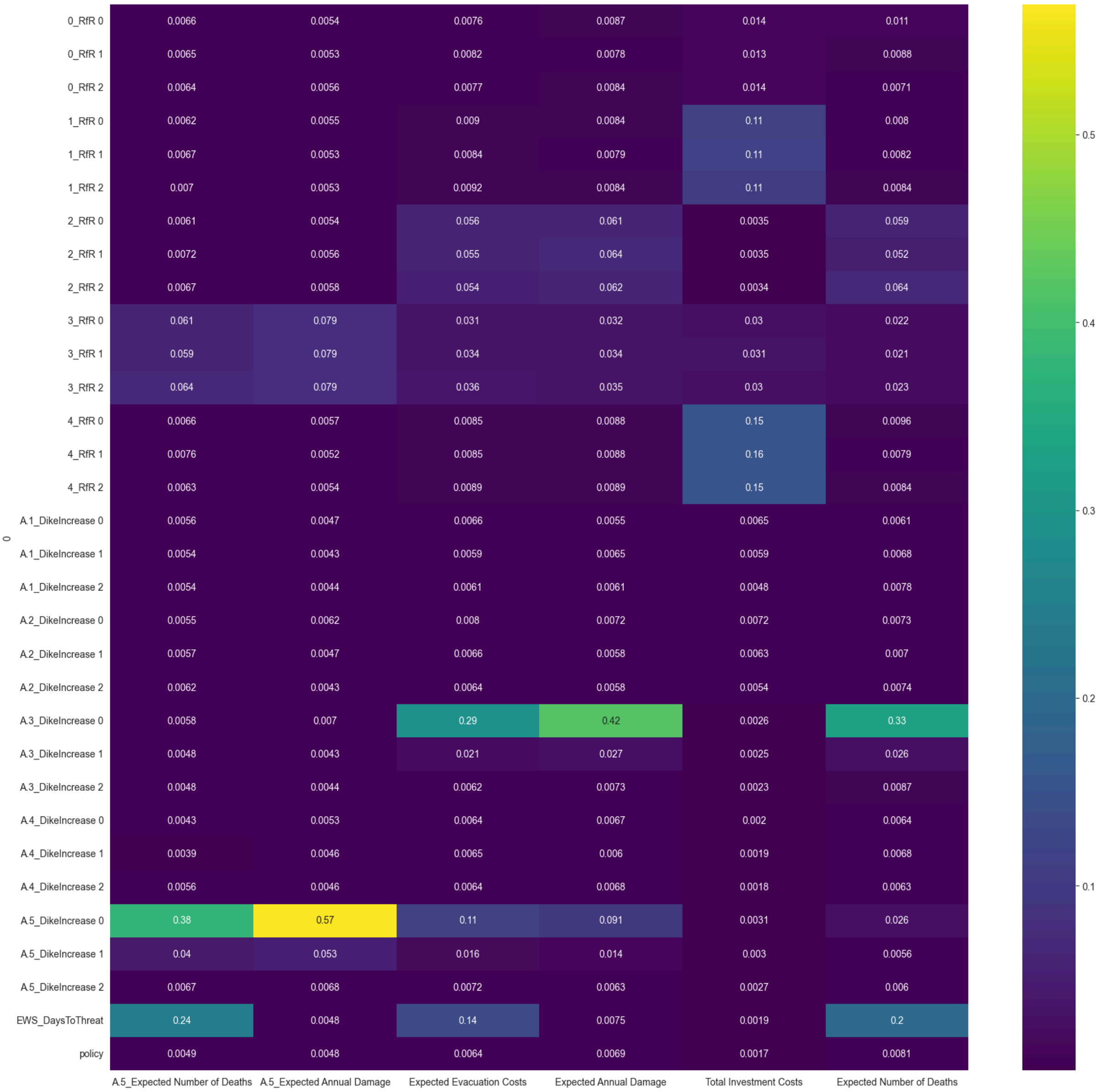


Figure C.1: Feature scoring policies

From figure C.1 it becomes clear that the annual damage and the expected number of deaths for dike ring 5 of Deventer are strongly influenced by an increase of dike 5; with scores of 0.38 and 0.57. This is explainable because in the scenarios dike 5 had a high chance of breaking. Furthermore, an early warning system has quite a high score of 0.24 and will strongly influence the expected number of deaths in Deventer. Making sure inhabitants are evacuated in time, will reduce the amount of deaths. Although of less influence, Room for the River project 3 also influences the outcomes for Deventer.

For the evacuation costs, the three policy levers that influence this outcome most are, an increase of dike 3, implementation of the early warning system and an increase of dike 5.

Looking at the other general objectives it becomes clear that the total annual damage is mainly influenced by an increase of dike 3 at the beginning (it has a score of 0.42). This is logical, as the breaking of dike 3 was important for the general outcomes in the worst-case scenarios. After raising dike 3, raising of dike 5 and room for the river at location 2 have some influence on the total annual damage.

The other general objective, the total expected number of deaths, is also mainly influenced by a dike increase of dike 3 at the start. Next to that, the early warning system is of importance for this outcome. Lastly, for the total investment cost, room for the river project in location 4 is most important with a score of 0.15. The room for the river project in location 4 is also important for the total investment costs. It becomes clear that room for the river projects are more costly than dike heightening.

The policies which will be evaluated over multiple scenarios to determine the robustness of these different candidate strategies are given in Table C.1.

Table C.1: Description of every policy lever which is taken into account

Policy lever	**Values**	**Description**	**Dimension**
2_RfR 0	0-1	Whether to activate the RfR project at location 2 at timestep 0 or not. Once activated, the project remains active.	Dmnl
2_RfR 1	0-1	Whether to activate the RfR project at location 2 at timestep 1 or not. Once activated, the project remains active.	Dmnl
2_RfR 2	0-1	Whether to activate the RfR project at location 2 at timestep 2 or not. Once activated, the project remains active.	Dmnl
3_RfR 0	0-1	Whether to activate the RfR project at location 3 at timestep 0 or not. Once activated, the project remains active.	Dmnl
3_RfR 1	0-1	Whether to activate the RfR project at location 3 at timestep 1 or not. Once activated, the project remains active.	Dmnl
3_RfR 2	0-1	Whether to activate the RfR project at location 3 at timestep 2 or not. Once activated, the project remains active.	Dmnl

EWS_DaysToThreat	0-4	Number of days prior to treat to give a warning. False warnings can undermine trust in the system. The earlier the warning the more time to evacuate, but also the more chance of a false warning	Days
A.3_DikeIncrease 0	0-10	Amount of dike raising for dike A3 at timestep 0	Decimeter
A.5_DikeIncrease 0	0-10	Amount of dike raising for dike A5 at timestep 0	Decimeter
A.5_DikeIncrease 1	0-10	Amount of dike raising for dike A5 at timestep 1	Decimeter

Appendix D: Convergence metrics

The figure below shows the progress of the convergence metrics overtime. The graphs on the left are for the first reference scenario and the ones on the right belong to the second scenario. For both cases it is clearly visible that all seeds converge after 30.000 function evaluations. This is faster than expected and two reasons could explain this. First, is the fact that there were only six objectives taken into account. If there were more objectives, it would have taken longer to convert. Second, there is only trade-off that must be made and that is between the total costs and evacuations cost and the annual damages and deaths. This trade-off is not complex, explaining why convergence is reached fast.

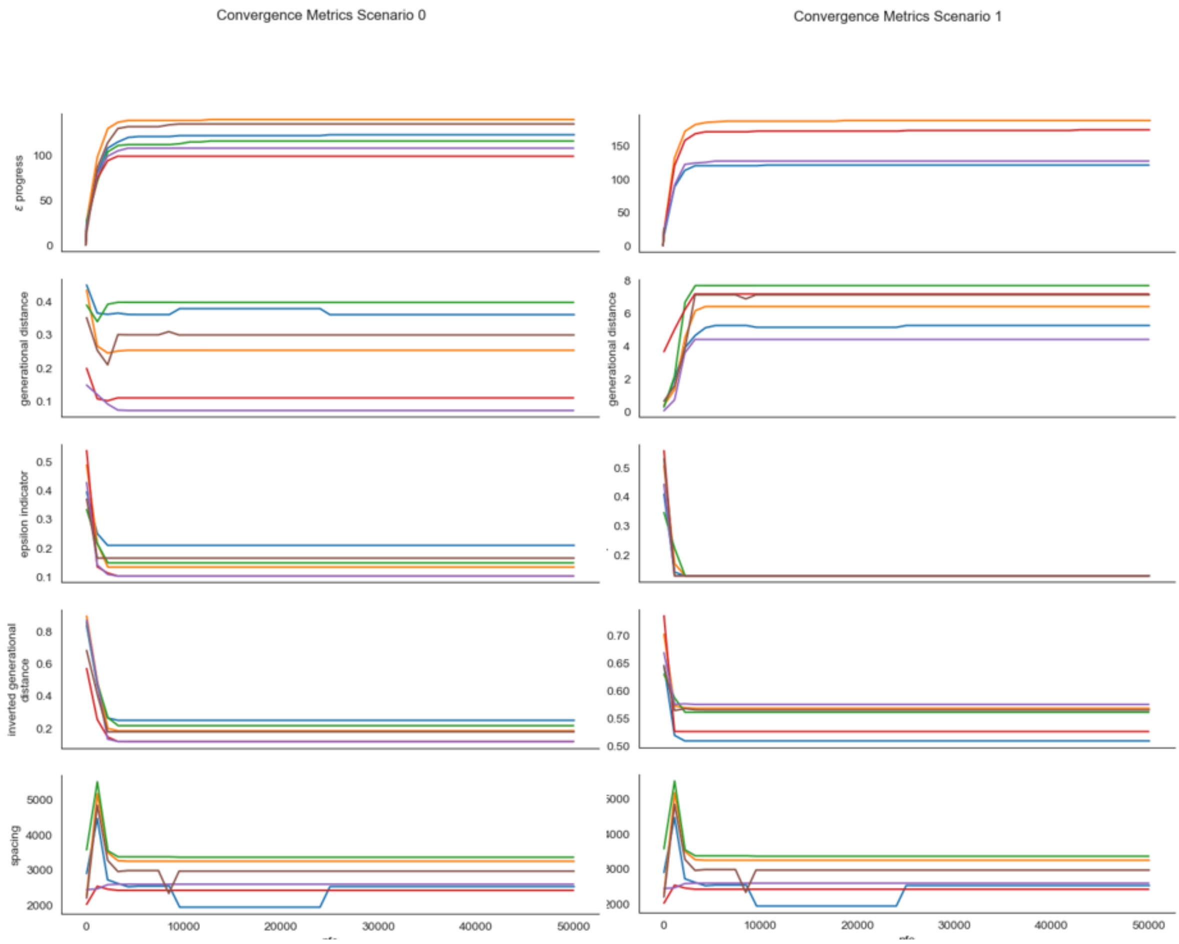


Figure D.1: Boxplot of Expected Annual Damage in dike ring 4

Appendix E: Visualisation candidate solutions

In table C.1 the lever combinations are given per policy.

Table C.1: Description of every policy lever which is taken into account

policy	Room for the River Location 2, timestep 1	Room for the River Location 2, timestep 2	Room for the River Location 3, timestep 0	A3 Dike Increase, time step 0
Policy7	0	1	1	4
Policy10	1	0	0	2
Policy12	0	0	0	5

To visualise the performance of the candidate solutions on each objective, several boxplots are made. In Figure E.1 the expected annual damage of dike ring 5 is shown for each candidate solution. While all policies are quite successful, policy 7 results in significantly less damage than policy 10 and policy 12. Moreover, it can be noted that all candidate solutions have quite some outliers, which suggest that there are scenarios in which the policies do not perform as well as desired.

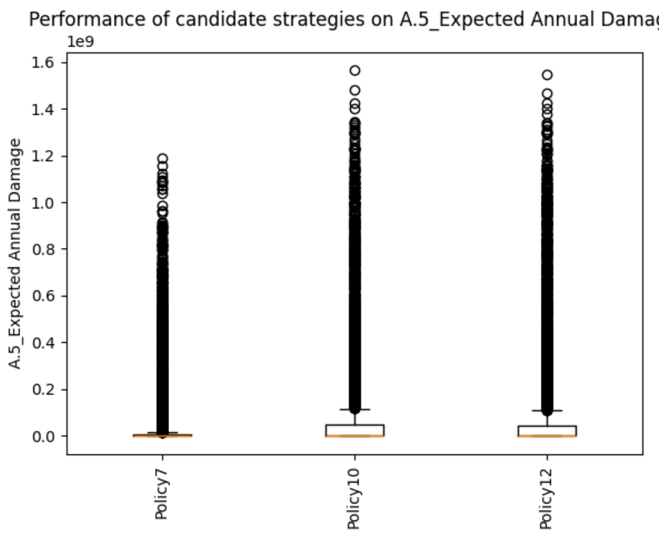


Figure E.1: Boxplot of the expected annual damage in dike ring 5

Figure E.2 shows how the different policies affect the expected number of deaths in dike ring 5. Similarly to Figure E.1, policy 7 results in significantly less number of deaths, compared to policy 10 and policy 12. Once more, the outlying scenarios cover quite an extensive range. Nevertheless, the average number of deaths is almost negligible, making the chance of actual deaths relatively low.

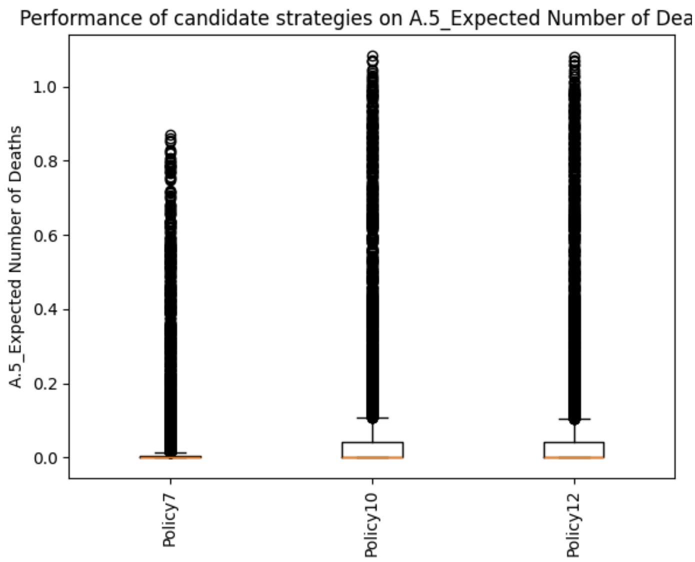


Figure E.2: Boxplot of the expected number of deaths in dike ring

Next to the objectives for dike ring 5, also the general objectives are taken into account. In Figure E.3 the expected annual damage is shown. For all policies it can be noted that the average remains just below 1 billion euros, which is relatively low, considering the fact this is the total damage of all dike rings. Unlike the expected annual damage for dike ring 5, the total expected damage has significantly less outliers, indicating more reliable policies.

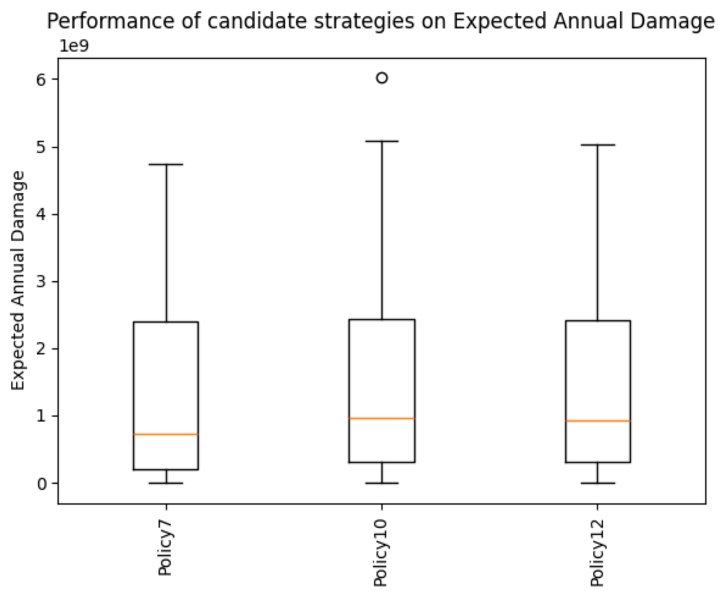


Figure E.3: Boxplot of the expected annual damage

In Figure E.4 it can be seen that the proportions between the different policies are quite similar when it comes to the expected annual damage and the expected number of deaths. Although policy 7 has again a better performance than policy 10 and policy 12, all policies result in less than one death on average.

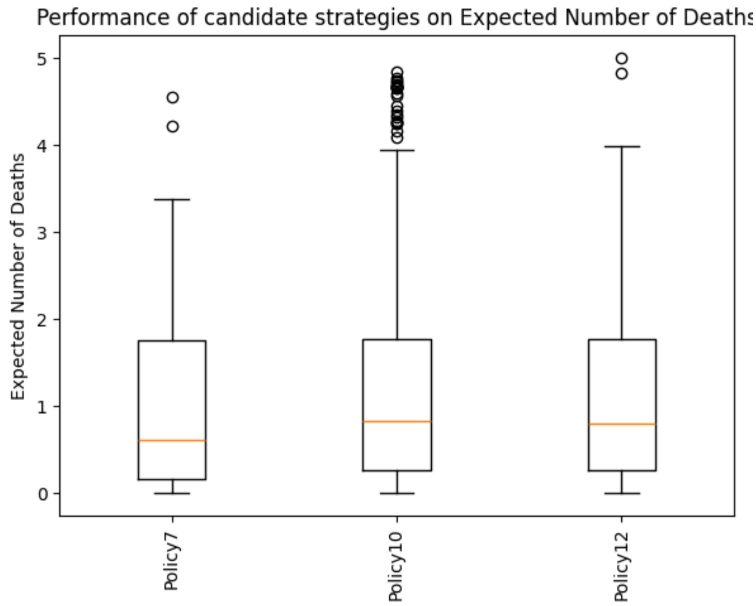


Figure E.4: Boxplot of expected number of deaths

While policy 7 performs best when looking at the annual damage and expected number of deaths, the costs for this policy are the highest. Figure E.5 shows that the investment costs of policy 7 are three times higher than those of policy 10. This indicates that there is a trade-off between the investment costs and the effectiveness of the policy. The reason why the investment costs are constant in this plot, is because these costs are independent of the uncertainties.

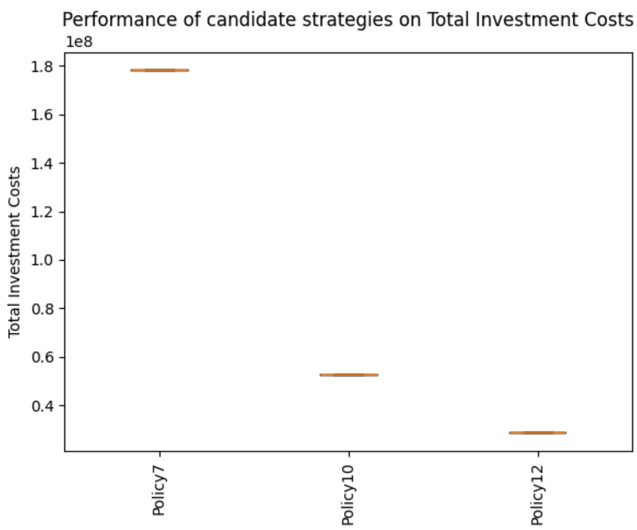


Figure E.5: Boxplot of the total investment costs

The last objective that is of interest is the expected evacuation costs. In Figure E.6 the expected evacuations for the candidate solutions are shown. As all solutions resulting in evacuation costs were filtered out, the current candidate solutions all lead to zero evacuation costs.

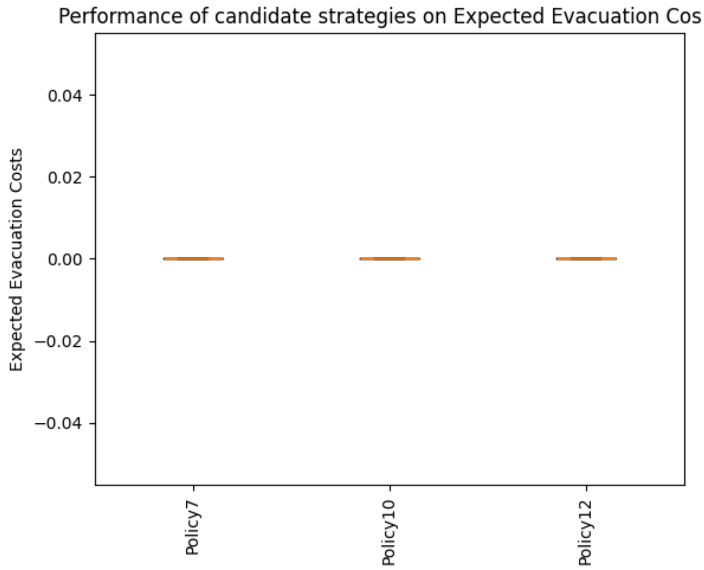


Figure E.6: Boxplot of the expected evacuation costs