An integrated strategy for Doesburg in the Ijssel River Area

Proposing flood risk management in a model-policy nexus

EPA 1361 - Model-Based Decision Making

17-06-2022

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Executive summary

This study is conducted to advice Dike ring Doesburg, concerning the Ijssel River flood problem. Due to climate change water levels have been rising in the Ijssel River located in the east of the Netherlands. These rising water levels increase the flood risks for the areas located closely to the river. Multiple policies can be implemented to mitigate the risks for the surrounding areas and the problem is a complex and uncertain one. A good way to advice on these kinds of problems is to explore scenarios and uncertainty through exploratory modelling.

Based on the three objectives of Dike ring 1, Doesburg – 1). Protecting the lives of the population 2). Protecting the livelihood of the population 3). Keeping in mind economic constraints, this report presents an advice integrating various strategies to tackle the flood risk along the IJssel River. Keeping in mind the preferred strategy of the client being dike heightening to preserve the farmlands while ensuring safety.

Through using the model provided by Ciullo et al. (2019) in the EMA Workbench exploratory modelling techniques were used. The analysis started with open exploration with and without policies and comparing the results. Next up the multi-scenario MORDM framework was executed for optimization. This resulted in the following findings: Based on the signal-to-noise robustness metric constructing dikes does not lower the number of deaths in Doesburg but evaluating based on the maximum regret robustness metric it results in lower damage and casualties in both Doesburg and outside. As expected, there is not one perfect solution due to the uncertainty, complexity, and multi-actor aspect of the problem.

Adhering to the three objectives as stated in the problem formulation (section 1.3), we provide three policy paths Doesburg could choose from. The first focusing on ensuring maximum safety for the dike ring, the second focusing on the livelihoods of the people living in the area and the third offering an alternative incorporating economic considerations. The client is made aware of the best possible approach based on his objectives and is informed that there is room for the client to compromise with other actors and it is certainly necessary to make trade-offs between the different policies to come to a well-supported, adaptive, and effective policy strategy.

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1. Problem framing

Being the largest river exclusively on Dutch grounds, originated over 1500 years ago and once the main connector of the then flourishing 'Hanzesteden', the Ijssel River has huge historical, economic and social value for the region. However, the threat of rising sea levels is lurking, consequently increasing the risk of flooding. On the one hand this has always been the case, since the Netherlands finds itself largely below sea level. On the other hand, however, the predominant scientific paradigm states that climate change has amplified the flood risk due to shrinking flood plains of rivers, melting glaciers and extreme weather conditions leading to more frequent and heavier rainfall (de Bruijn et al.,2015; Rijkswaterstaat, 2022).

It becomes crucial then to address the increased flood risk, to protect the lives and livelihoods of those neighbouring the Ijssel. That said, defining 'the best way forward' has proven to be disputable. Traditionally, the Dutch have known a technocratic 'control paradigm' of risk reduction (Rijke et al., 2012). The focus was on reducing or even eliminating any kinds of uncertainty. Nevertheless, over the past years it has become clear that nature cannot always been controlled by humans. Moreover, the idea of looking at behaviour, vulnerabilities and people to decrease risk became increasingly popular (Folke, 2006; Warner et al., 2003). By now, most scientists agree that 1. risk, especially in deeply complex problems, cannot be eradicated entirely and 2. there are multiple people and stakeholders involved who need to be acknowledged and work together.

This report is specifically dedicated to the Dike ring 'Doesburg', one of the five main locations under threat near the Ijssel River. The report advises on how the Dike ring can best deal with flood risk. Following the line of reasoning above, firstly, the idea is not to eradicate but to minimise risk, whilst also showing the trade-offs. This will be done by making calculated model-based analyses, based on the available information yet recognising and incorporating deep uncertainty. Secondly, we reflect on how the Dike ring can understand and include the views of various key-stakeholders, since drafting a plan is one thing, but implementing it effectively needs willingness and cooperation of those involved.

1.1 Case study context: Room for the River Project

In 2006, the Dutch Senate approved the 2.2 billion Euro "Room for the River" programme. The programme was initiated to change the Dutch strategy from merely strengthening and heightening dikes, to creating more space for rivers to flow (Rijkswaterstaat, 2022). Various measures were thought of, summarised in figure 1, and many were completed. That said, flood risk management requires continuous attention as flood risk continues to grow. Therefore, this report proposes a contemporary strategy to deal with flood risk management.

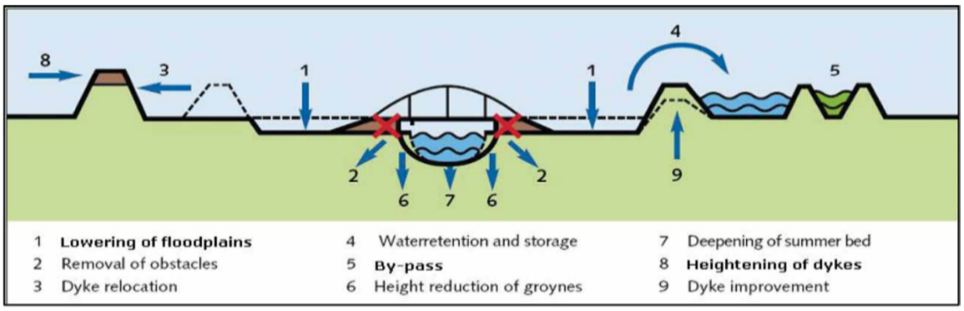


Figure 1: Different measures applied in 'Room for the River' programme. Source: Ciullo et al., 2019

One of the rivers at stake in the Netherlands is the Ijssel River, a branch of the Rhine River flowing north for about 125 km before discharging into the IJsselmeer (Ciullo et al., 2019). The present study focuses on the area around the river, thereby specifically zooming in on Dike ring Doesburg (A1), located upstream the river Ijssel and depicted in figure 2.

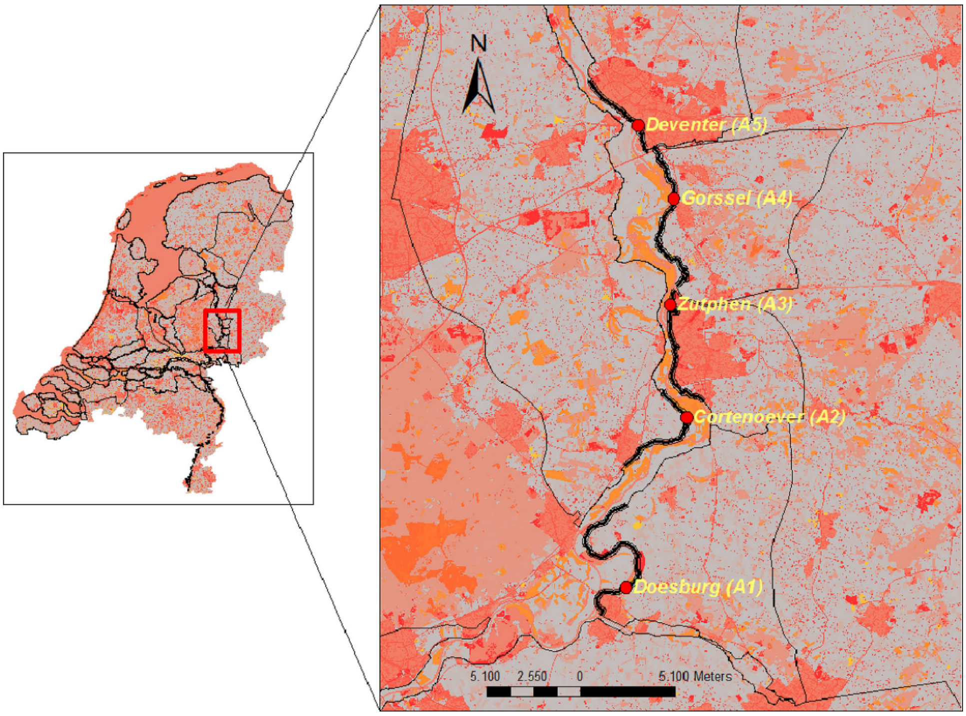


Figure 2: The Study area. Red dots indicate locations of interest, each representative of a given stretch (thick black lines). Each stretch is part of a larger embankment system, in Dutch called "Dijkring". Source: Ciullo et al., 2019.

1.2 Multi-actor nature

Before zooming in on Dike ring Doesburg, it is important to realise that flood management is not just about flood measures, but also about actors and their interests (Bruijn et al., 2015). Where the first measures of the room for the river project were praised for their novel approach, they were also occasionally questioned by engineers, economists and politicians (Rijke, 2015). Therefore, this report aims to include multiple policy angles and perspectives; including damage, costs and the loss of life.

The main stakeholders identified in the Ijssel River case are mapped in figure 3. Appendix A gives a more detailed clarification of these actors, their interests and possible trade-offs. Most importantly, note that the actors generally agree on minimising deaths, costs and damage for the region. However, their priorities differ, as well as the policies they would like to implement to achieve their goals. For instance, widening the river cuts into farmland, thus decreasing the profit of the farmers living around. Implementing an early warning system is useless if the warnings do not reach the people in time. And heightening a dike may proof counter effective if it is only done upstream, potentially causing higher water levels downstream.

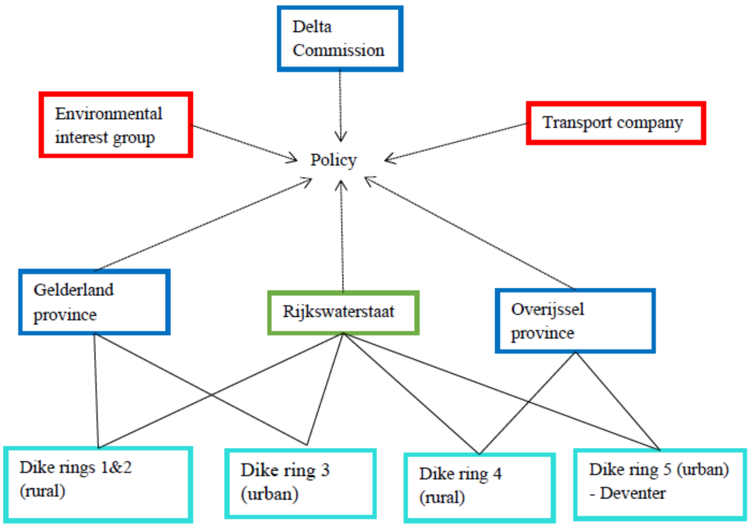


Figure 3:: Key-stakeholders Ijssel River flood risk Management. Source: Project definition, Kwakkel, 2022

1.3 Objectives

Since the study is conducted to advice the Dike ring of Doesburg, it is important to understand the problem from their perspective. Dike ring Doesburg largely consists of rural area, located in the province of Gelderland.

1). The first and foremost aim is to make sure the people are protected. This will be done by looking at minimising the expected number of casualties. That said, not just the lives of people need to be protected, but their livelihoods as well. Therefore, 2). The second objective is to minimise damage to people's livelihoods. This includes damage caused by policies. For example, Room for the River causes the lands of the local farmers to disappear. Without fair compensation this policy is not an option. Finally, having made clear that lives and livelihoods are the most important objectives, the Dike ring does not have limitless resources. To make sure measures are made within economic reason, 3). the third objective is to research the costs of possible investments.

Based on the above, the area also deals with uncertainties the stakeholders cannot directly influence, yet might influence reaching the objectives. Therefore, in the analysis, we have distinguished five uncertainties. Out of the available policy options to combat flood risk, this report will focus on three key areas of possible interventions. An overview of the uncertainties, potential interventions and outcomes of interest will be presented in section 2.1. The measures, either combined or separate from one another will be researched for the final strategy. Ultimately, the aim is to present an integrated strategy, offering well-balanced trade-offs between measures to minimise deaths and impact on livelihoods, though keeping in mind the costs and acknowledging uncertainties at hand.

1.4 Report outline

Chapter two delineates the deep uncertainty methods used to come to the final advised strategy. The rationale behind these methods will be discussed, based on literature and motivated by the objectives above. **Chapter three** thereafter dives into the results of the models, though carefully substantiating which results are and which are not relevant for the main conclusions and policy considerations. **Chapter four** critically discusses the findings of the report, thereby reflecting on the limitations and suggesting opportunities for improvement. Finally, **chapter five** draws back to the main objectives. After careful consideration of the results and critical reflection, the concluding chapter formulates a clear strategy advice to reduce flood risk in the Ijssel River area.

2. Approach

The report is based on model-based decision support. The nature of modelling is exploratory, given the deeply uncertain nature of the problem (Kwakkel & Haasnoot, 2019). The research approach addresses uncertainty explicitly, to offer computational decision support for decision making under deep uncertainty and robust decision making (EMA workbench documentation, 2022; Moallemi et al., 2020).

2.1 The implemented flood risk model

To analyse the impact of the three identified options for policy measures a simulation model by Alessio Ciullo is used as a base (Ciullo, de Bruijn, Kwakkel & Klijn, 2019). The model assesses damage, the number of casualties and costs. Note that the measures could be implemented simultaneously, but also individually or differentiated per location. Since the report is written for Dike ring Doesburg, location 1 will be looked at specifically in the modelling results. The outcomes of interest are therefore specified for Dike ring 1 and based on their objective (section 1.3).

An overview of the uncertainties, policies under study and outcomes of interest can be found in table 1. A more detailed description of the model parameters can be found in appendix B.

Table 1: Uncertainties, policy options and outcomes of interest in the case of the Ijssel River flood prone areas

Uncertainties	**Policy options under study**	**Outcomes of Interest/measures**
Flood wave shape	Dike heightening	Expected annual damage for dike ring 1
Dike failure probability	Early warning	Expected number of casualties for dike ring 1
Final breach width	Room for the river	Dike investment costs for dike ring 1
Breach width model		Total expected annual number of deaths
Discount rate		Total annual damage

The outcomes directly affecting Dike ring 1 are of major concern to the Dike ring, resulting in the first three measures. However, having a significant number of casualties or damage to the rest of the area will also be very disruptive, that is something that should be avoided. Seeing the last two objectives are not output by the model directly, a function has been developed that aggregates over time and location.

2.1.1 XLMR Framework

This model-based decision support is based on the XLMR Framework, which stands for External Factors (X), policicy levers (L), performance metrics (M) and Relationships in the system (R), also represented in figure 4. The above-mentioned uncertainty factors are the external factors. The policies under study are called policy levers. The mathematical expressions linking the external factors and policy levers are the relationships and compute the performance metrics.

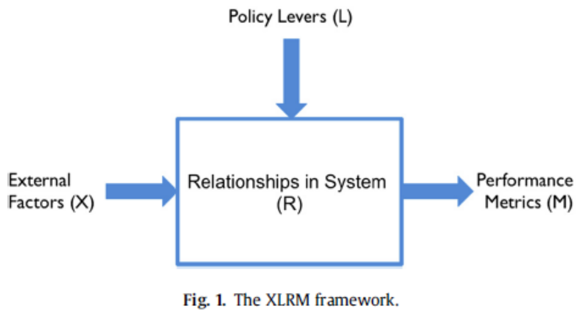


Figure 4. Schematic overview of XLMR Framework. Source: Kwakkel, 2017.

2.1.2 EMA Workbench

The model is implemented in the open-source Exploratory Modelling and Analyses (EMA) workbench (Kwakkel, 2017). The workbench is implemented in python and enables to easily perform with "existing models, identify the policy-relevant uncertainties, assess the efficacy of policy options, and iteratively improve candidate strategies" (Kwakkel, 2017). Within the ema workbench, a point in the uncertainty space is considered a scenario. Scenarios are driven by uncertainties. A point in the decision space is represented by a policy, driven by levers. A combination of both scenarios and policies is called an experiment. (Kwakkel, 2017).

2.2 Modelling approach

Using various techniques, the exploratory analysis will lead to optimal scenarios under various (combinations of) measures whilst taking into consideration the uncertainties and sensitivity of the policy levers. Using the multi-scenario MORDM framework, robustness is considered during the modelling process. The scenarios used on this framework, will be based worst cases.

2.2.1 Open Exploration

The EMA workbench provides two approaches called 1). Open exploration and 2). Directed Search to map the relationship between the uncertainties, policy levers and the outcomes. Open exploration systematically samples the uncertainty- and/or decision space, under a whole range of possible solutions to the various uncertainties (Bankes, 1993). In the results, we commence by exploring the model outcomes without any policies and call this the base-case. For multi-scenario MORDM, the combination of uncertainties (scenarios) which give the worst outcome, need to be found. With open exploration, we will find the thresholds of the scenario's need to cross in order to consider them worst cases. After, the base-case is compared to a situation where policies are applied.

2.2.1.1 Scenario Discovery and Policy Exploration

Scenario Discovery and Policy Exploration is conducted using Patient Rule Induction Method (PRIM) algorithm which is a subspace partitioning method provided by the EMA workbench. The PRIM algorithm also known as the "bump-hunter" algorithm, narrows down the subspace by locating high density regions containing sampled outcomes of interest. The resulting Peeling trajectory gives boxes containing PRIM is preferred over subspace partitioning methods such as CART (Classification and Regression Tree) as PRIM algorithm is more user-interactive and requires lesser work by the analyst to create box sets that have high interpretability (Bryant et al 2010). The worst-case scenario is discovered by limiting the outcomes to the highest percentile. For policy exploration, 100 random policies over 400 scenarios are generated and the result of this exploration is called the 'random policy case'. These policies are then explored using PRIM.

2.2.1.2 Sensitivity Analysis

Next, we perform sensitivity analysis providing insights in the impact of uncertainties on the model output (Razavi et al. 2021). One of the more advanced sampling techniques for global sensitivity is Sobol (EMA Workbench documentation, 2022), and is implemented in the workbench which can be analysed using SAlib. Global sensitivity is more interesting for this model than one-at-a-time sensitivity, due to the high number of uncertainties (Jaxa-Rozen & Kwakkel, 2018). Sobol itself is based on variance decomposition and tells us information about how the total variance of the model output is explained by a variable on its own or with its interactions.

2.2.2 Multi-scenario MORDM Framework

The second approach is to search through the space in a directed manner, using a type of optimization. For this report to ensure robust decision-making, we use a commonly used planning framework incorporating optimization: the Many-Objective Robust Decision-Making Framework (MORDM) (Watson, 2017). MORDM is a bottom-up framework that integrates Multi-objective Evolutionary Algorithms (MOEA) optimization with the RDM framework (Watson, 2017). It is important to note that there are alternatives to using multi-scenario MORDM. One of these is Many-Objective Robust Optimization (MORO). However, compared to MORO, MORDM is less computationally expensive and it gains insight into the robustness-optimality trade-off which MORO does not (Bartholomew & Kwakkel, J2020). Therefore, because it still attains reasonable robustness after re-evaluation, we choose MORDM as a pragmatic balance between robustness and optimality.

The MORDM framework has four phases to incorporate various decision analytical methods:

1. Problem formulation,
2. Generate candidate solutions,
3. Re-evaluate under deep uncertainty,
4. Scenario discovery

Phase 1: Problem formulation

The first phase is largely done by defining the XLMR components. The impact of floodings in the future for the whole area are important for the model behaviour. The base case will be fully disaggregated over location and time, and then aggregated again to get the outcomes of interest. Thereby, we will use the open exploration to better understand the model and inform the problem formulation going into the directed search thereafter.

Phase 2: Directed search to generate alternatives

In the search phase, we need to generate a set of worst-case scenarios based on the data that was generated by running the model without policies in the uncertainty space. We then search over the decision levers given a set of scenarios (documentation EMA workbench, 2022). This results in a Pareto-approximate set, representing a (large) set of candidate policies (Watson, 2017).

The worst cases scenarios are the scenarios which exceed the thresholds of all objectives, which resulted from the open exploration. For each objective, the worst-case scenarios are ranked from best to worst outcomes. The sum of these ranks indicates the overall place of scenarios on the worst ranking list. The 5 worst cases are chosen and used for the Multi-scenario MORDM. If the set of policies work in these worst cases, the client can be moderately guarantee that they will also be effective under the rest of the scenarios.

In order to run the optimization, the following hyperparameters have to be tuned: (1) explore alternative values for epsilon and (2) evaluate the convergence. By having a smaller epsilon value, we retain more solutions. Evaluating the value for epsilon, so the granularity of the of finding solutions, is a matter of case specific concerns as well as runtime. We have evaluated that by looking at the parallel coordinate plots and see which would better fit our case.

Assessing the convergence can be done by using different numbers of function evaluations. The workbench supports both epsilon progress and hypervolume, so we will evaluate both. In order to check for the hypervolume, we have to define the minimum and maximum values for each outcome of interest. We do this by looking at the data from open exploration (the base case without policies and the case with 100 random policies). Then, if we have found a reasonable value for epsilon and if we see that the optimization has converged, then we show a trade-off plot for the outcomes.

If hypervolume and the epsilon progress are converged, we can re-evaluate the found candidate policy solutions under deep uncertainty.

Phase 3: Re-evaluate candidate solutions under deep uncertainty

A trade-off analysis is performed to expose the solution set to a range of plausible values for variables that represent deep uncertainties (Watson, 2017). We use Latin Hypercube Sampling (LHS) to re-evaluate each candidate solution over 1000 scenarios. LHS samples variables within specified ranges to generate plausible States of the World (SOWs) to explore the effects of uncertainties. The evaluation of decision options then will be done based on trade-offs to enhance their robustness (Eker & Kwakkel, 2018).

Phase 4: Scenario Discovery

In this phase we evaluate the robustness of policies and identify the vulnerabilities. Different robustness metrics capture different aspects and trade-offs of the policies. Moreover, preferences of policy makers might change over time, so it is essential to use various metrics. Generally, a distinction can be made between two types of robustness metrics: robustness metrics that evaluate the absolute or the relative performance also known as regret (McPhail et al., 2018). Therefore, we have included two robustness metrics. Firstly, we use the signal-to-noise ratio, a descriptive statistic that measures the absolute performance value. For each policy option we firstly calculate the mean and the standard on each objective. Seeing as we want to minimize our objectives, we then multiply them to get the signal-to-noise ratio. Secondly, we use maximum regret. This measures the relative performance of each policy on each objective. Regret calculates the distance between the performance of a policy in a specific scenario and the best possible policy in that scenario.

2.2.3 Visualisation Workflow

In figure 5, a visualisation of the Multi-Scenario MORM modelling approach is given. Open exploration will be done first to get an understanding of the model and finding the first steps which are later on needed for worst case scenario selection (2a). Then MORM is performed of which a integrated flood risk strategy can be derived.

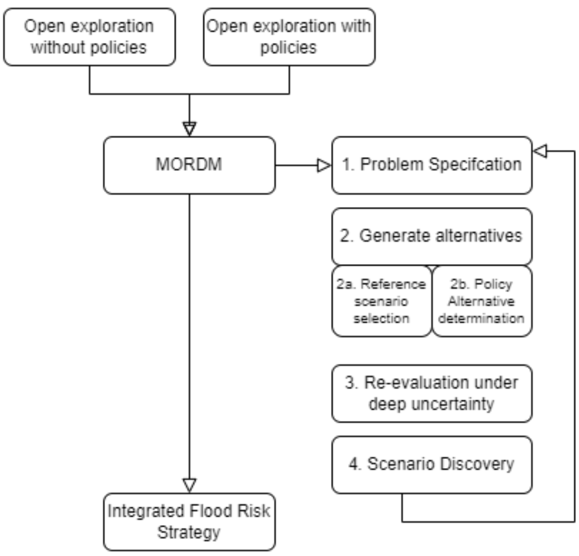


Figure 5. Workflow modelling approach

3. Results

In this chapter the results of the exploratory modelling approach for the IJssel model will be presented. First the open exploration provides insight in the behaviour of the model and scenario exploration. Then the optimization results will be provided supported by robustness metrics.

3.1 Open Exploration

3.1.1 Base-case Exploration

Deaths and Damage

The violin plots below show that expected number of casualties has varies over the scenarios. The biggest bulk (so the most scenarios) results in two casualties. This and everything above needs to be minimised. Therefore, we set the threshold for the worst-case scenarios on 2 people. There is also quite some variation between the scenarios for expected annuals damage; a lot of the scenarios lie around and above the €2,500,000,000. The threshold for the worst-case scenarios for Annual Damage will be set on this point, since we do not want to end up in those scenarios.

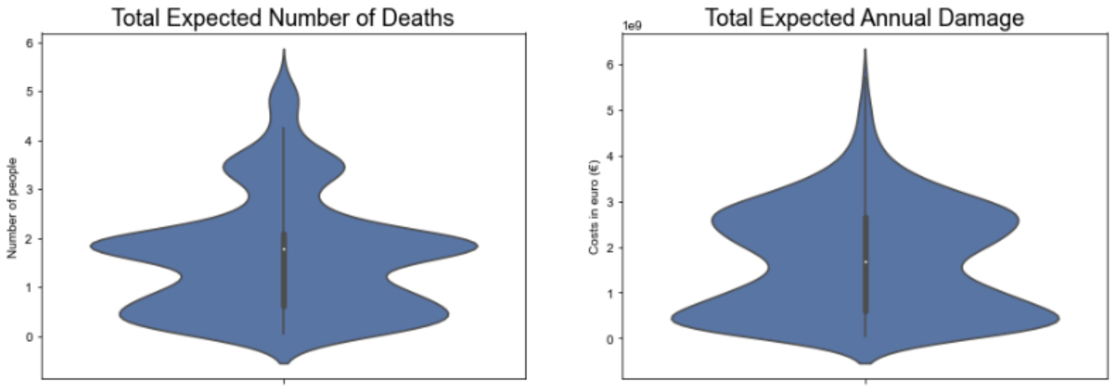


Figure 6: Base-case exploration for total number of deaths and annual damage

Deaths and damage per location

To see which Dike ring is the most vulnerable to flooding and therefore generates the most casualties and/or damage, the next step is to only aggregate over time and compare the Dike rings with each other. The first figure below shows that both Dike ring 1 and 3 have scenarios with high number of casualties. The expected number is higher for Dike ring 3, but the number of scenarios expecting casualties is higher for Dike ring 1. Our client does not want to end up in the scenario of the top bulk. Therefore, the threshold will be set at 1.5 people for Dike ring 1.

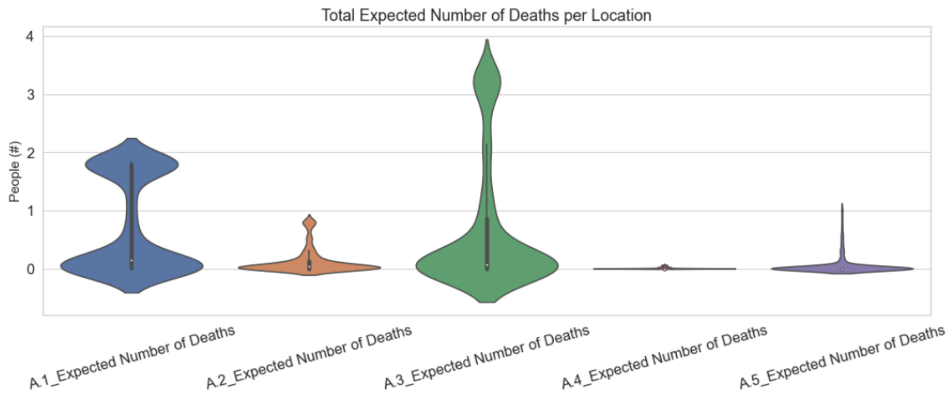


Figure 7: Base-case exploration Expected Number of Deaths per location

The second figure shows that Dike ring 1, the client of this report, has the highest expected damage of all dike rings. Most of the scenarios do not expect damage or small damage, but there is again a bulk of some scenarios showing a damage of €2,000,000,000 or higher.

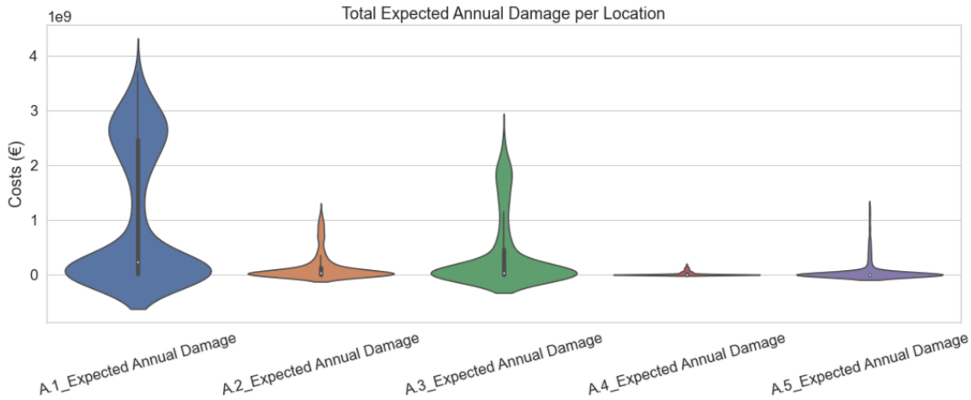


Figure 8: Base-case exploration Expected Annual Damage per location

A selection of scenarios which perform the worst under certain uncertainties, will be made according to the following thresholds. As seen, quite a big portion of scenarios (26-35%) have objective values that are high.

Table 2: Threshold value of each objective

Objective	**Threshold value**	**% of total scenarios if exceeded**
Total Expected Number of Deaths	2 people	26%
Total Expected Annual Damage	€2,500,000,000	30%
A.1 Expected Number of Deaths	1.5 people	35%
A.1 Expected Annual Damage	€2,000,000,000	33%

3.1.2 Open exploration base-case versus policies

Comparing the base-case without policies to scenarios with policies shows that implementing policies will significantly influence the system. However, this comparison only generates insight into the random policies and not on sets of policies or policy measures. Underneath, two examples can be found, specifically zoomed in the first two objectives for Dike ring 1. The violin plots show that the deaths are much higher without policies, and the damage is much lower. Other figures can be found in appendix C (the scenarios influenced by policy are aggregated to policy scenarios and 100 policy combinations are evaluated). Of all objectives, only investment costs show a different pattern. Naturally the investment costs were zero in the base case, since without policy no costs have to be made. Once policies are applied, investment costs obviously rise, though most are lower than €250,000,000.

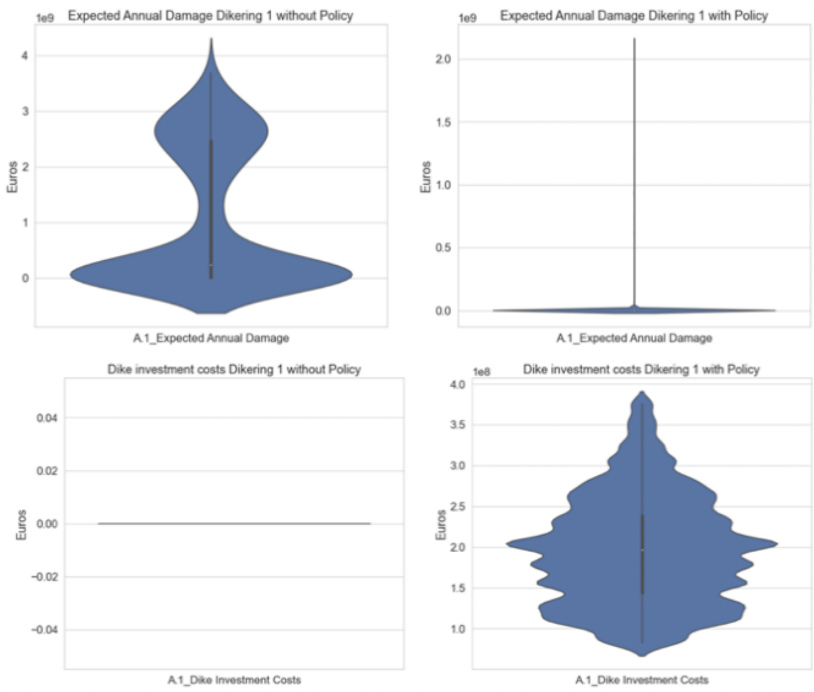


Figure 9: 1 Comparison base-case with policies

Because the plots above do not provide insights in the quantity of scenarios for 0 or more deaths, damage and investment costs, histograms are made as well. These can be found in Appendix C.

3.1.3 Scenario Discovery

The base case exploration discussed in section 3.1. corroborates the need to identify scenarios that result in inadmissible outcomes. Primarily two outcomes were monitored to discover the uncertain variables that made the most impact on the outcomes i.e The Total Annual Deaths, The Total Annual Damage. The other outcomes were not considered as in the base case, the policy implementation costs would be zero. PRIM algorithm was used to sample these outcomes. Although a density of over 80% would be ideal, the chosen result box of scenarios has a coverage of 62% and a density of 74%. A scatter plot illustrating the selection of box 11 is attached in Appendix D.

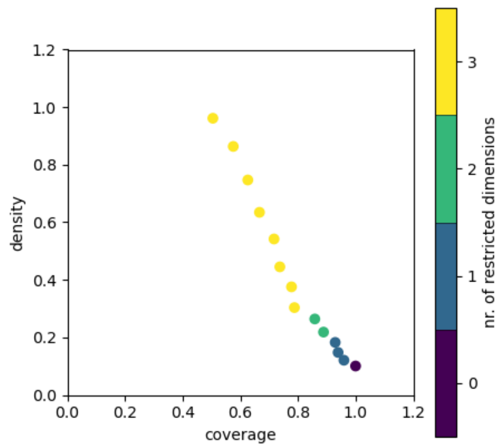


Figure 210: PRIM uncertainties box

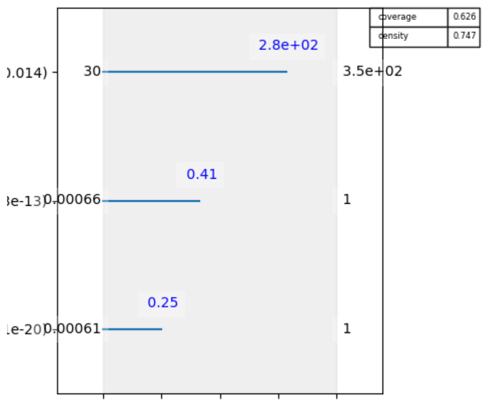


Figure 11: PRIM uncertainties box inspection

The outcomes of the PRIM analysis are illustrated in the table 3 below. There are three restricted dimensions or uncertainties. We notice that Dike Failure Probability at A.1 Doesburg (<0.41) and A.3 Zutphen (<0.25) are seen as the two most vulnerable uncertainties as a Dike failure would result in immense damage to property and loss of life in these urban cities. We assume that this is these two dike rings being higher up the stream, if their probability of failure was high, would result in greater damage downstream due to the increased water flow. A Dike Breach at A.1 Doesburg of about 30 – 280 dm would also result in heavy loss as well. All the stated uncertainties were considered for the selection of worst-case scenarios as their P-value, that determines the significance of the uncertainty, lesser than 0.05. The worst cases were selected and ranked, then further used for the optimization of the policy levers.

Table 3 : PRIM analysis on base case

Uncertainty	Description	P-Value	Range
A.1 Bmax	Dike Breach width at A.1 Doesburg in (dm)	0.014	[30 - 280]
A.1 pfail	Dike Failure Probability at A.1 Doesburg	3.00E-13	[0.00066 - 0.41]
A.3 pfail	Dike Failure Probability at A.3 Zutphen	6.10E-20	[0.00061 - 0.25]

3.1.4 Policy Exploration

The policy levers from the random policy are explored and compared with the base case in the open exploration in section 3.1. It is noticeable that the policy levers reduce the total annual damage and the deaths. The aim of this section is to minimize the investment into policy levers while keeping the results of the outcomes in check or simply acquire cost efficient policy levers. PRIM was executed on 'random case' with 100 randomly generated policy levers on 400 scenarios, resulting in a box selection of coverage only 46% and a density of approximately 60%.

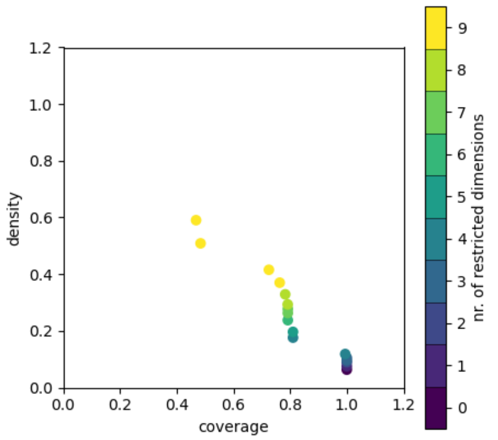


Figure 312: PRIM on policy levers box

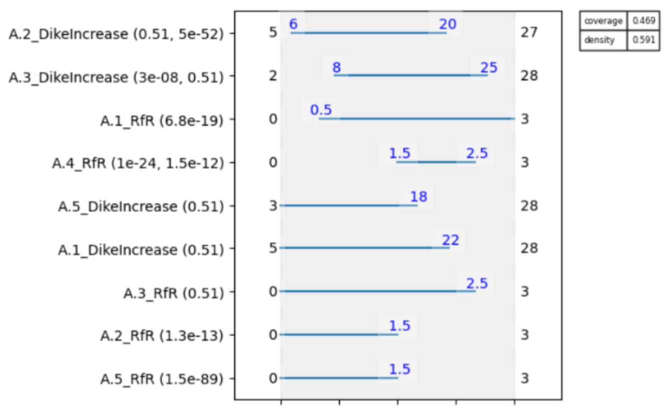


Figure 13: PRIM on policy levers box inspection

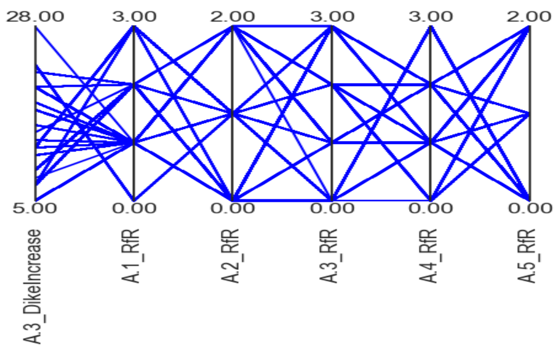
The table 3 below depicts the restricted dimensions of the PRIM analysis on the random case. Only the selected policies that are significant are listed. As seen in fig 13 there are 9 restricted parameters present ranging from Dike Heightening at different Dike rings to RfR policies. However, the p-values of 4 of these restricted dimensions is > 0.05. Thus, they are insignificant, they are removed from the analysis and the 5 policy levers of RfR at the different dike rings and A.3_DikeIncrease at Zutphen, is considered. The figure 14 is a Parcoords plot that depicts the trade-offs between the selected policy levers. The Dikeincrease policy lever of A.3 Zutphen plays a crucial role in the analysis as it ranges from 8 dm – 25 dm as this is a trade-off to the Room for the River at A.3 Zutphen. The policy levers that are desired are compared over the undesired policies in the histogram in figure 15. We can notice that A.3DikeIncrease is spread over 0-30 dm and we see that the desired policies have room to play from

10 – 20 dm, therefore decreasing the overall investment into the policy levers. Therefore, we can see that though these policies are of high investment, it is not necessary to implement the policy levers to the maximum extent.

Table 4 : PRIM Analysis on Policy levers

Policy Levers	Description	P-Value	Range
A.3 DikeIncrease	Dike Heightening in A.3 Zutphen in (dm)	3.00E-08	[8 - 25]
A.1 RfR	Room for the River at A.1 Doesburg	6.80E-19	[0.5 - 3]
A.2 RfR	Room for the River at A.2 Cortenoever	1.30E-13	[0-1.5]
A.4 RfR	Room for the River at A.4 Gorssel	1.00E-24	[1.5-2.5]
A.5 RfR	Room for the River at A.5 Deventer	1.50E-89	[0-1.5]

Explanation



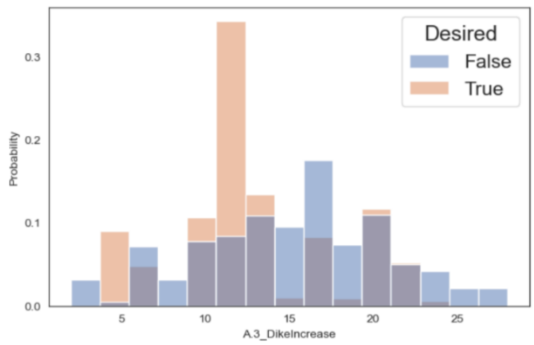


Figure 414: Trade offs over selected policy levers for "random policy case" *Figure 15: Comparison of desired policy lever A.3 DikeIncrease*

3.1.5 Sensitivity Analysis

The sensitivity analysis indicates the effects of uncertainties (as inputs) on the model output. In our case, the figures underneath show the results of uncertainty variables for expected casualties aggregated over time and expected damage aggregated over time and location. The analysis is based on the base-case without policy to truly see the effect of the uncertain values on the system for 1000 scenarios. The blue bar represents S1 showing the first-order effect (i.e., the effect of the variable on its own), on the output by a single model input. The orange bar represents ST, which shows the total order effect and higher order interaction on the output. When ST is substantially higher than S1, there are most likely higher order variances occurring. ST, therefore, indicates the interactions. The figure below shows that dike failure for dike ring one has the biggest impact on the system. Since S1 and ST are not very different interaction do not have a big effect. This makes sense since there are no other uncertainties with high impact. There are similar results for number of casualties, to be found in appendix C. For the aggregated view over time and location, the uncertainties dike failure for dike ring 1 and dike failure for dike ring 3 have the highest impact on the total expected number of casualties. This aggregated view provides insights of these dike failures directly on the whole system. A bigger difference can be seen between S1 and ST, so this might impact on the system might have to do with interaction, although the differences are not very big.

Something noteworthy from this sensitivity analysis is that dike ring 1 and 3, compared to other dike rings, did have higher number casualties in the base-case. Since the dike failure of both dike rings have the most impact on the system, it might be wise to adjust policy to that.

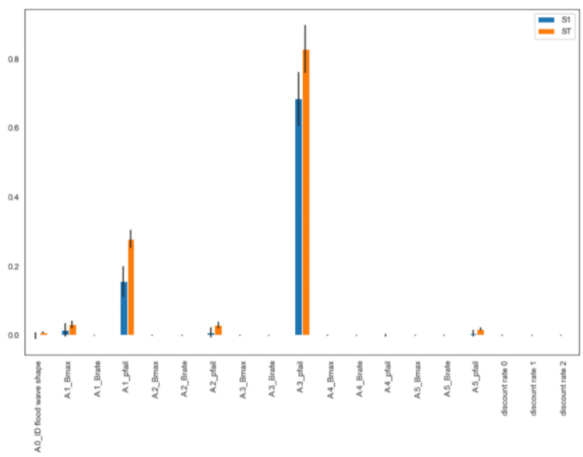


Figure 16: 5 Effect of uncertainties on expected annual damage (aggregate time)
Figure 17: 6 Effect of uncertainties on expected number of casualties (aggregate time and location)

3.2 Multi-scenario MORDM

3.2.1 Problem formulation and generating the worst-case scenarios

A problem formulation based on the five objectives was created. This modified problem formulation can be found in the Github.

The thresholds which were established in the open exploration, were used to select the scenarios that perform the worst under certain uncertainties. Then, these selected scenarios were sorted and the 5 worst case scenarios were used for Multi-scenario MORDM.

3.2.1 Epsilon value exploration and convergence check

By having a smaller epsilon value, we retain more solutions. The epsilon values were based on the lowest value (except for 0) found in the “scenarios with policies” case. Secondly, the HyperVolume Space was defined. The minimum and maximum values for each of the 5 objectives are based on the base case and the “scenarios with policies” case. The convergence of the algorithm will be checked by evaluating both epsilon progress and hypervolume, which is displayed in the figure below.

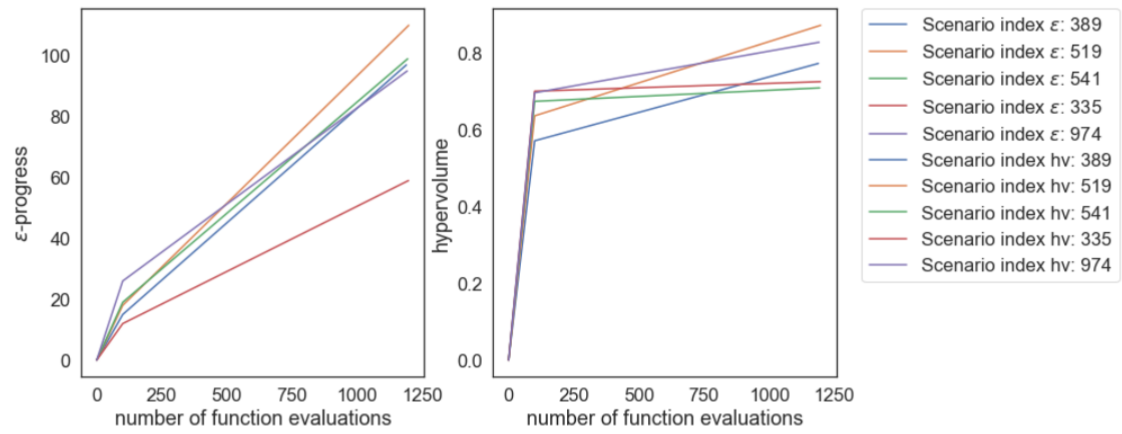


Figure 18: Convergence check of the algorithm (with matrices epsilon-progress and hypervolume).

If the optimization has converged, the found set of solutions can be re-evaluated. We can see that the hypervolume has converged. The epsilon progress has not yet converged, but due to time constraints, we were not able to run it with higher function evaluations.

3.2.2 Candidate set of solution based on worst-case scenarios

After generating a candidate set of policies based on the worst-case scenarios, parallel plots provide insight in potential trade-offs of policies. The parallel plots of all scenarios can be found in Appendix D. Under all worst-case scenarios with the candidate policies, the Expected Number of Deaths in A.1 is 0. In the majority of the scenarios with the candidate policies, the Expected Number of Deaths aggregated over all location is too. Here, the parallel plot of scenario 5 is analysed, which contains a few policies where the aggregated Expected Number of Deaths is not 0. The parallel plot below shows that the higher dike investment costs lead to a lower Expected Annual Damage in A.1. It is interesting to see however that investing in dikes in A.1 does not affect the Expected Number of Deaths in A.1, but it does lead to fewer deaths outside A.1.

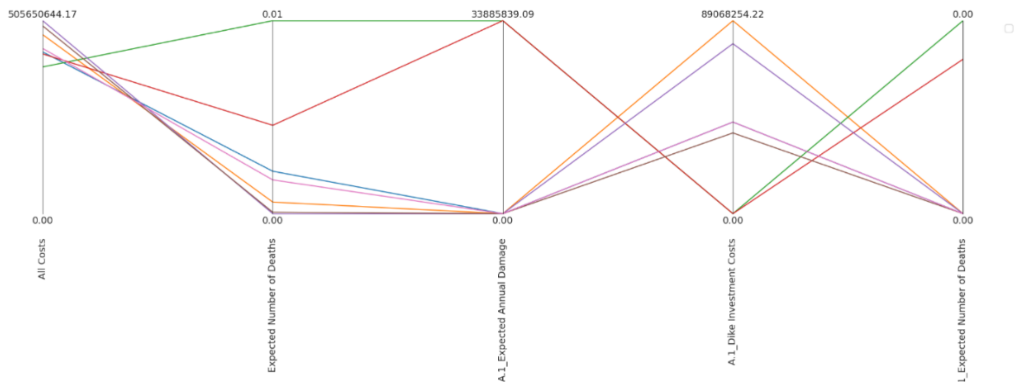


Figure 19 7: Parallel coordinates plot set of policies scenario 5

3.2.2 Robustness of candidate set of solutions

We selected eight candidate policies based on a number of constraints. We tested each of these policies under 1000 scenarios to evaluate it in the uncertainty space and then evaluate its performance using the robustness metrics.

Signal to noise ratio
The parallel plot below shows that there are few trade-offs based on the signal-to-noise ratio. The ideal solution would be a solution that has the lowest signal-to-noise ratio for all objectives. The pink line shows to be most efficient and effective.

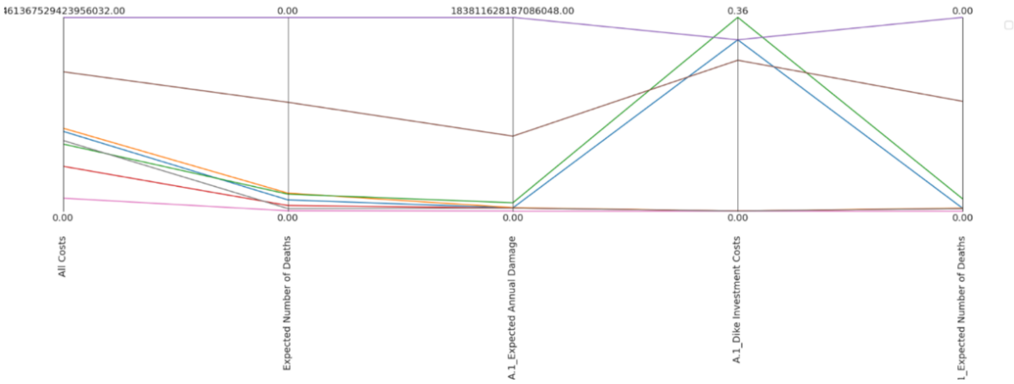


Figure 208: Parallel coordinates plot signal-to-noise ratio

Maximum regret

Maximum regret is a relative robustness metric. It shows, for every scenario, how well a policy performs versus the how well the best policy performs in that scenario. We want to minimize the outcomes. In the way that we calculated the maximum regret, it is most favourable to achieve the lowest maximum regret.

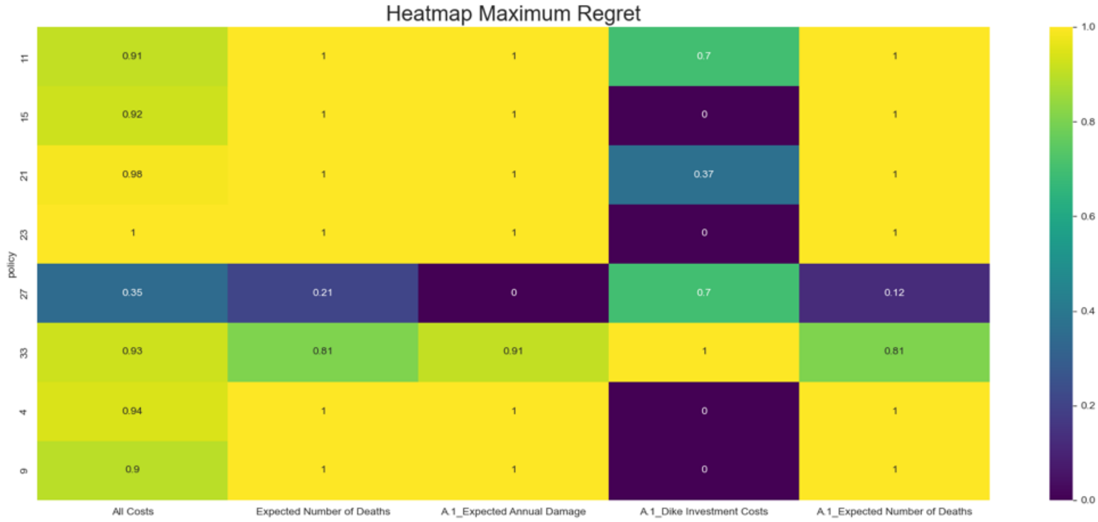


Figure 219: Heatmap Maximum Regret

We can see clear trade-offs between policies. Policy 27 performs well on the majority of the objectives, but would result in relatively high Dike Investment Costs for A.1. Moreover, there seems to be a trade-off between A.1 Expected Annual Damage and A.1 Expected Number of Deaths on the one hand and A.1 Dike Investment Costs on the other.

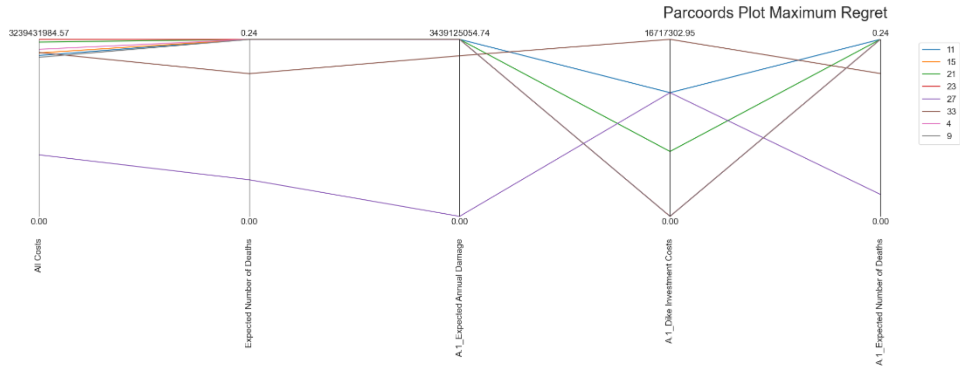


Figure 2210: Parallel coordinates plot Maximum Regret

4. Discussion

Before a conclusion is drawn it is important to discuss the limitations of the model and the research as well as substantiating implications of some of the choices and giving directions for future improvement. These considerations come from limitations in both the methodology and the decision arena. Both types of limitations and implications will be discussed in the next section and embedded in literature, followed by suggestions for future work thereafter.

Limitations and implications methodology and decision arena

First, due to the short period of time in which this project was conducted, there was a limit in the number of analyses and iterations done. Ideally, we would have gone back and optimized again, to make the conclusions even more solid and robust (Bartholomew & Kwakkel, 2020). That said, the idea is to recommend an adaptive planning strategy. Therefore, additional iterations could and even should be done again in the future, potentially including new state of the art data that presents itself later on.

Something similar applies to the number of function evaluation that were run. Due to computational time versus time available, only 2,000 NFEs were run. Ideally a higher number of NFEs would have been chosen (EMA workbench documentation, 2022). This would have resulted in a model that was converged better. Moreover, the size of the set of candidate policies was reduced to 8 policies. These 8 policies were then evaluated over 1000 scenarios. Ideally, both numbers, but especially the number of scenarios, should be substantially higher to be able to offer solid advice.

An important decision made in the modelling process, was the choice for aggregation level. Based on the objectives of dike ring Doesburg, the choice was made to aggregate over time as the timeframe was not of added value for the outcomes of interest. Due to this aggregation the results show damage, costs and casualties over the whole timeframe of 200 years (3 timesteps aggregated). Without this aggregation the outcomes would be presented for each timestep.

Looking at the decision arena, it is important to remember that the problem at stake is a wicked one. Multiple stakeholders are involved and decisions made individually influence others. The first three outcomes of interest in the model are specified for dike ring 1. Nevertheless, implementing policies which results in lower casualties and/or damage for dike ring 1, does not necessarily need to be the best or only solution for the rest of the region. This is one of the reasons why total damage and casualties are included in the research. This way it can be checked if a certain policy does not affect entire area disadvantageously.

Suggestions for future work

As mentioned in the limitations, this research aggregated the data over time. It might be interesting to have a look at the specific timesteps and therefore not aggregate over time. This would result in output for each timestep and could be used to determine usefulness of policies over periods of time. It might be the case that some policies work well on short term, but other policies perform better on long term. This is not yet included in this research.

Model-based scenario development through the EMA Workbench is a way to incorporate uncertainty factors to explore future pathways. This is mentioned as one of the major advantages of model-based scenario development over intuitive approaches based on qualitative knowledge and expert insights (Van Notten et al., 2003 cited in Eker & Kwakkel, 2018). That said, it is important to iteratively evaluate the system performance, with the aim of basing the strategy on outcomes that perform adequately irrespective of changes in future conditions/under a range of plausible conditions (Maier et al., 2016;

McPhail et al., 2018). It would be interesting to evaluate the model and its impacts based on a different set of uncertainties in the future, to evaluate system's performance under these changing conditions. Finally, it would be interesting to research the perceptibility of both the problem owner and the various stakeholders to the proposed policy measures. This with the rationale that actual implementation will only happen after attaining a certain degree of consensus and cooperation.

5. Conclusions

Due to its location at the Ijssel River, Doesburg is facing potentially severe flooding threats. It is in their best interest to keep the casualties and the damage to a minimum. Doesburg also wants to prevent these harms from happening in other cities and towns along the Ijssel River. There are several policy measures that can be taken both by Doesburg itself as well as by other actors to prevent or reduce the risk of flooding. However, prior to implementing flood measure policies, the effectiveness of these policies must be determined. Using the flood risk model from the Ijssel River developed by Alessio Ciullo (Ciullo et al., 2019), various analyses have been conducted to ultimately advice the government of Doesburg on their policy options. Note that the analyses acknowledge and incorporate the wickedness and uncertainties accompanying the area's flood risk.

Open exploration shows that Doesburg (together with Dike ring 3) is the most vulnerable to flooding. There is a batch of scenarios resulting in high damage and high casualties. It is striking that these batches of scenarios result in extremes. The bulk of the scenarios has low damage and/or casualties, but also the bulk of the scenario results in high amount damage and casualties. There is only a very small middle ground. Running the model with random policies versus with no policies at all, shows that policies can significantly reduce the risk and/or the consequences of flooding.

The vulnerability analysis tests how uncertainties in the base-case (running the model without policies) impact the system. The results from the vulnerability analysis show that the uncertainties regarding dike failures at dikering 1 have the highest impact on the Expected Annual Damage. In addition, the uncertainties regarding dike failures at dikering 1 and 3 have the highest impact on the Expected Number of Deaths. This would indicate that it is in Doesburg's best interests to fortify their dikes and maybe also the dikes of Dike ring 3.

The PRIM algorithm implementation for Worst Case Scenario Discovery and Policy Exploration led to many insights on the functioning of the dike model. It was discovered that the policy levers do not have to be implemented completely to achieve the most efficient outcomes. Similarly, the worst-case scenarios were highly sensitive to the uncertainties such as Probability of Dike failure at A.1 and Probability of Dike Failure at A.3.

The Multi-Scenario Multi-Objective Robust Decision Making (MORDM) analysis shows that carefully designed policies can result in a very minimal expected number of deaths for Doesburg, as well as for the other dike rings. In the MORDM, firstly, a set of worst-case scenarios was developed. Secondly, a set of candidate policy options was generated. After which the performance of these promising policies was tested under many scenarios. Lastly, their performance was evaluated using robustness metrics. Several trade-offs have been distinguished, based on these analyses.

Integrated Policy Strategy Advice
Adhering to the three objectives as stated in the problem formulation (section 1.3), we provide three policy paths Doesburg could choose from. The first focusing on ensuring maximum safety for the dike ring, the second focusing on the livelihoods of the people living in the area and the third offering an alternative incorporating economic considerations.

1. Safety alternative – This policy is aimed at protecting the lives of the people i.e. minimizing the death of people of Doesburg and minimizing the damage that can be caused due to flooding in Doesburg. This puts the safety of the citizens of Doesburg as the first priority, this would mean that this is a long term policy and may require the farmers to relocate to make room for the expansion of the river Ijssel and implement the RfR policies.

2. Livelihood alternative – This policy is aimed at protecting the livelihood and the farmland of the people of Doesburg therefore it is inclined towards the Heightening of the Dike at Doesburg rather than the RfR policy. This would involve less investment costs as well as Dike Heightening is relatively less expensive when compared to RfR.

3. Economic alternative – This policy alternative strictly prioritizes minimizing the spending of the problem owner. This would involve harsher trade-offs such as increased total annual damage, or possible loss of life.

From the available policies that we have optimized over the worst case scenarios, 3 policy options stand out.

Policy 27 : This policy excels in cost reduction as it invests only in Dike Heightening and not in RfR for A.1. The expected number of deaths and the expected number of deaths in Doesburg are the lowest when this policy is implemented. This policy is also the best as it decreases the annual estimated damage to Nil. Thereby standing out from the rest of the available policy options. It covers all the objectives i.e it is economic, saves the livelihood of farmers and has the least deaths within Doesburg and should be the go to alternative. However, implementation of this policy would involve complexity due to the upstream location of Doesburg. From the model we interpret that A.1pfail uncertainty (Probability of failure of Dike at A.1 Doesburg – is one of the most sensitive uncertainties and when monitored, and reduced with Dike heightening would put the other urban Dike Rings downstream at risk such as Zutphen or Deventer and force them to implement RfR in their respective regions. It would be too irrational to not consider the possibility of a coalition formed aimed at making Doesburg implement RfR for the safety and the harmony of the other urban dike Rings. The coalition forming is further discussed in the Political Reflection.

Policy 33: Alternatively, the policy option 33 can be explored. This policy option implements RfR in the Doesburg Dike ring along with the dike heightening of A.1. This would ensure safety and has relatively less damage and deaths when compared to the other Policy alternatives.

Policy 9: Last but not the least is the Policy option 9. This would involve implementing Room for the River policy in A.1 Doesburg. It would cost the disruption of livelihoods of the farmers but does provide a long-term solution for damage and death prevention not just in Doesburg but all the other dike rings as well.

In conclusion there is enough room for the client to compromise with other actors and it is certainly necessary to make trade-offs between the different policies to come to a well-supported, adaptive and effective policy strategy. The given advice is thus not absolute, because the policy process impacts the results. When implementing this advice, it should be considered that these advises are given based on a model containing uncertainty in the model. The given advice provides a framework, which supplies the client with a firm scientific base to solve the Ijssel River flood problem.

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Appendix A – Mapping of key-stakeholders

Flood management is not just about flood measures, but also about actors and their interests (Bruijn et al., 2015). As this report aims to include multiple policy angles and perspectives the main stakeholders are identified and mapped out. This appendix provides a more detailed clarification of these actors, their interests and possible trade-offs. Most importantly, note that the actors generally agree on minimising deaths, costs and damage for the region. However, their priorities differ, as well as the policies they would like to implement to achieve their goals.

Rijkswaterstaat

The goal of Rijkswaterstaat is to create a safe, liveable and accessible environment in the Netherlands. They do this in combination with other (public) actors (Ministerie van Infrastructuur en Waterstaat, 2022). Since a flooding of the Ijssel would discard all values, Rijkswaterstaat naturally is involved. Rijkswaterstaat is the actor who eventually needs to finance the project, and therefore has a lot of decision power. But overall, they would want to reach a decision in which every other actor feels represented. Rijkswaterstaat is responsible for organising events in which other actors debate about their proposed solution. Eventually Rijkswaterstaat needs to formulate a policy recommendation, for which the other actors need to vote.

Delta Commission

The Delta Commission is a commission of experts that has been established for advice on water safety and water supplies. They provide advice on how the Netherlands stays protected for floodings, water shortages and extreme weather (Ministerie van Infrastructuur en Waterstaat, 2020). This makes the Delta Commission an important actor in the decision arena. Since this commission is established by the Ministry of Infrastructure and Water, Rijkswaterstaat will take their advice very seriously. As actor they do not have to profit of anything, they just want a safe environment for the Netherlands.

Province of Gelderland

The province of Gelderland is situated in the east of the Netherlands and its one of the biggest provinces. In the debates they represent Dike ring 1&2 (Doesburg and Cortenoever) and Dike ring 3 (Zutphen). Being a representative of three smaller actors, their responsibility to protect their objectives well is big. Since Dike ring 1 and 3 are the most flood prone, their preferred measure is dike heightening. Simultaneously, this measure preserves the farmland, which is highly valued in the province.

Province of Overijssel

The province of Overijssel is more on the downstream areas of the Ijssel. Because of the area being rural but also urban, the province wants to protect farmlands but also their businesses and cities. In the debate they represent Dike ring 4 (Gorssel) and 5 (Deventer). The province would prefer Room for the River upstream, thus in Gelderland. Because that will lower the water level downstream. They do not prefer dike heightening upstream, because that causes the level to rise. This is not in line with the preferred policy of Gelderland.

Transport Company

The transport company is a company which operations make use of the Ijssel River for inland shipping. They are impacted by the water height of the river; therefore, they want to make sure the water height remains a certain depth. Room for the river is the least preferable measure since the water height with normal circumstances will decrease. After all this actor does not want to have floodings as well, since this impacts the water level as well and makes the river impassable. Therefore, they will be open for negotiation.

Environmental Groups

Finally, environmental groups are involved which want to maintain a sustainable environment and diverse ecosystem. Since a river has a whole ecosystem around it, they want to make sure this ecosystem does not get jeopardised. They prefer room for the river, since the ecosystem even gets bigger with this measure.

Appendix B – Model Specifications

In this appendix, an overview of the model parameters and their descriptions is given. The model parameters are uncertainties, policy levers and outcomes of interest.

B.1 System uncertainties

	Description	Range	Unit
Flood wave shape	A normalized curve describing the way dis- charges at the most upstream location change over time. There are 140 possible wave shapes.	0 - 140	
Dike failure probability	Probability that the dike will stand the hydraulic load, The higher this number, the ’stronger’ the dike.	0 - 1	
Final breach width	The final extent of the breach width. The larger the width, the greater the volume of water flow-ing into the floodplain.	30 - 350	m
Breach width model	The way the breach width develops over time, with the uncertainty being the growth rate. The final breach width can be reached within 1, 3, or 5 days.	(1, 1.5, 10) for 5,3,1 day respectively	1/day
Discount rate	It determines the present value of the future ex-pected damage. The lower the value, the more damage to future generations is valued.	(1.5, 2.5, 3.5, 4.5)	

B.2 Policy levers under study

	Description	Range	Unit
Dike heightening	Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand.	0 - 10	dm
Early warning	Early warning systems anticipate a threat and help limit damage and/or avoiding deaths. The earlier the alert, the more effective the response, but also the more uncer- tain it is that the event will actually happen. False alerts can be costly and undermine people’ trust into the au- thority. Waiting too long is also problematic as the effi- cacy of late alerts is poor. In the model one can choose how much time in advance to give the alert.	0 - 4	days
Room for the river	RfR projects widen the riverbed thus lowering the water levels associated to a given water volume. There are five RfR projects which can be either	0 - 1	

	implemented or not (1 or 0). Each project corresponds to a profile of water level reductions across locations.		

B.3 Outcomes of interest

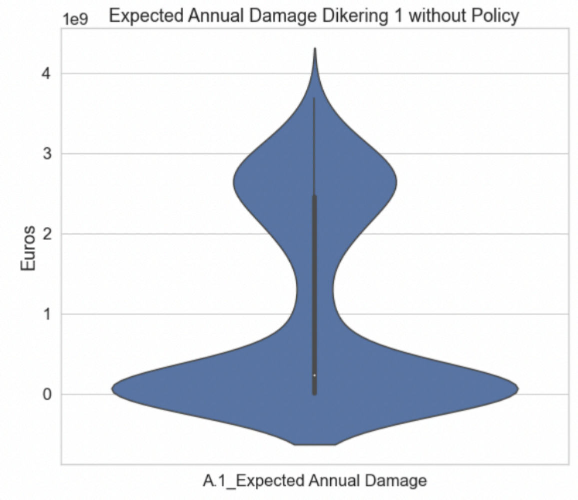
	Description	Unit
Expected annual damage	Expected annual value of flood damage over the planning period. Clearly, for each location, the lower this value, the bet-ter.	€
Expected number of casualties	Same as above but related to the number of casualties.	#
Dike investment costs	Investment costs of raising dikes.	€
Evacuation costs	Function of the number of people evacuated and the number of days they need to be out from home. The estimation is based on the 1995 evacuations in the Netherlands.	€
Room for the river costs	Investment costs for the implemented Room for the river project.	€

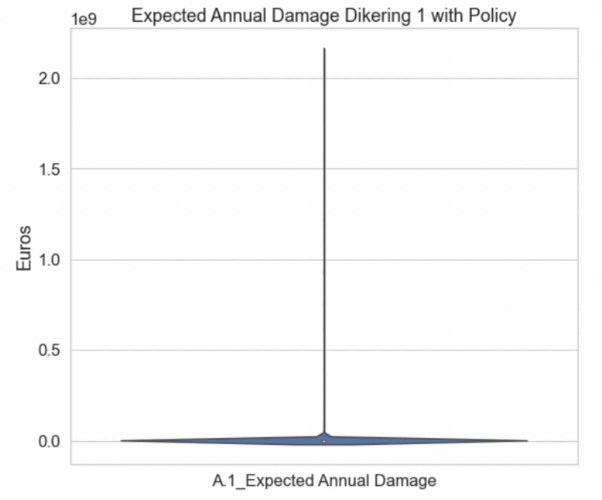
Appendix C – Open exploration

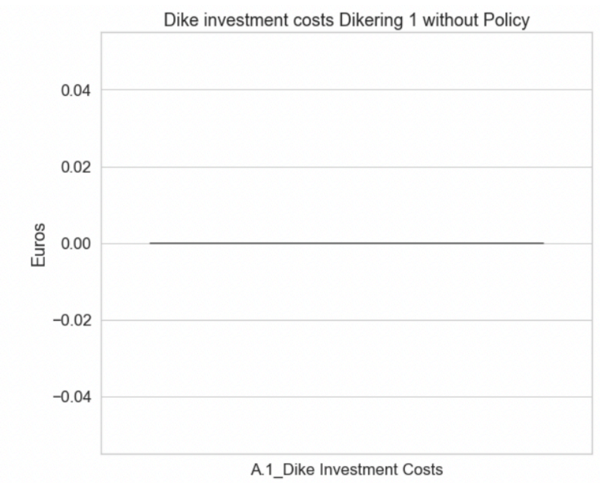
In this appendix further explanation on exploration on the comparison between the base case and the random policy case. Secondly, further explanation about the base case.

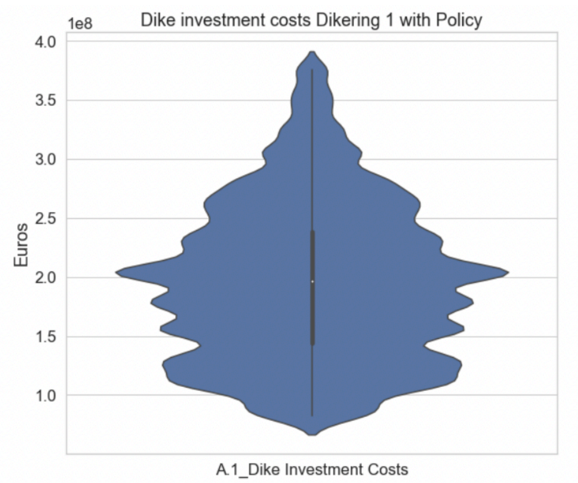
C.1 Exploration policies compared to base case

Violin plots that compare each the base case without policy and random policy case for each of the 5 objectives.









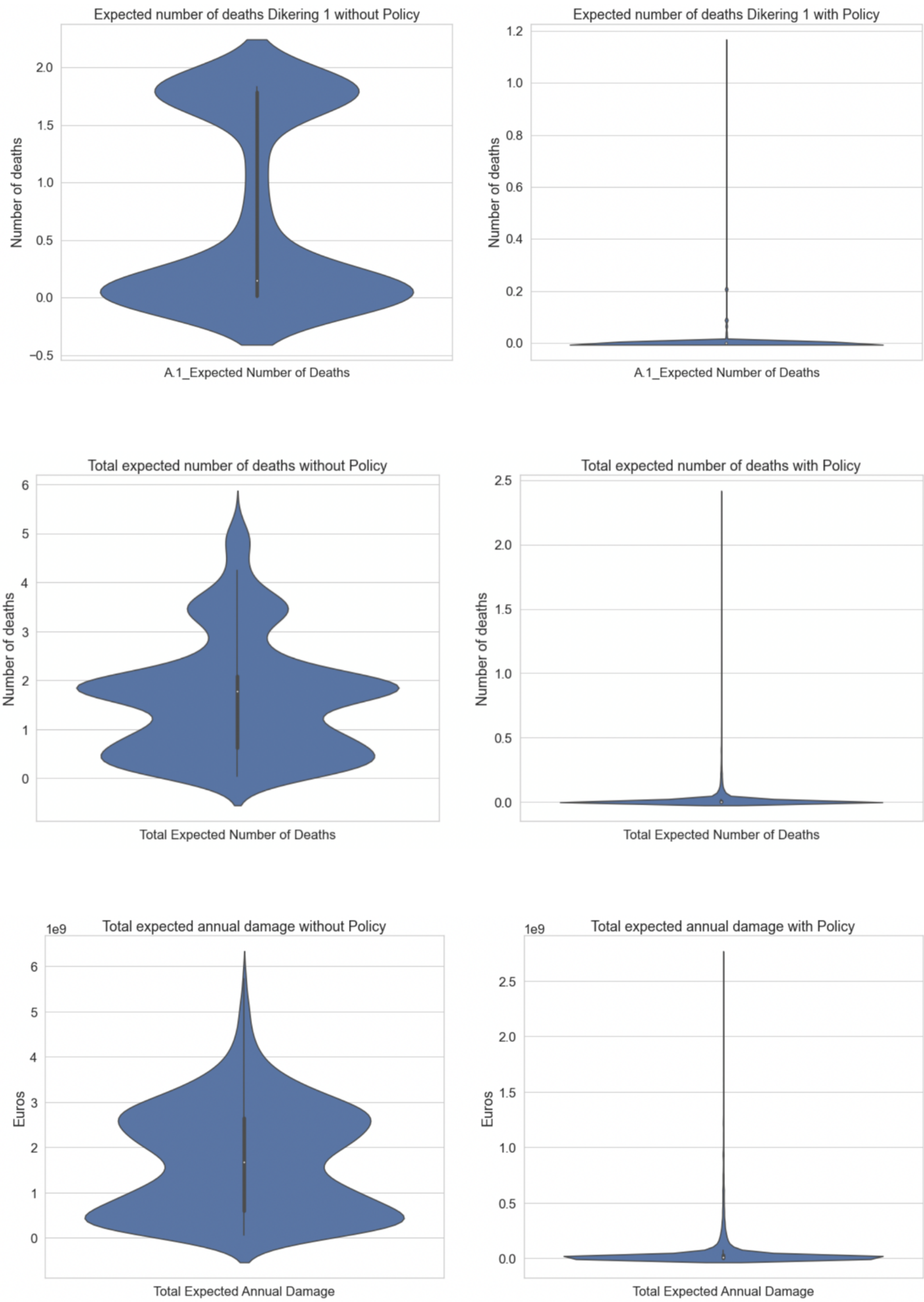
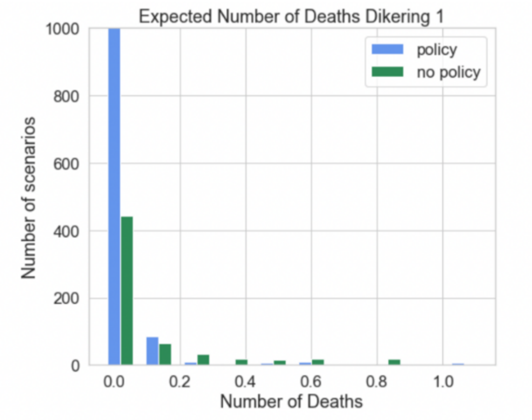
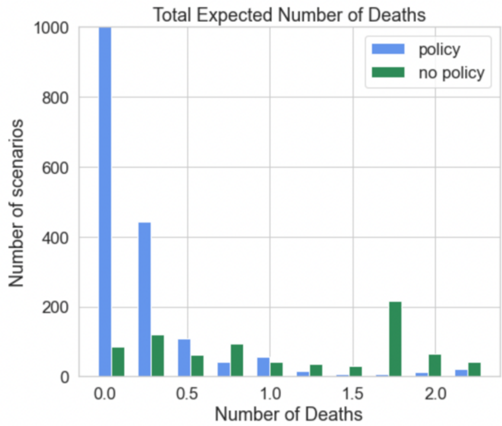


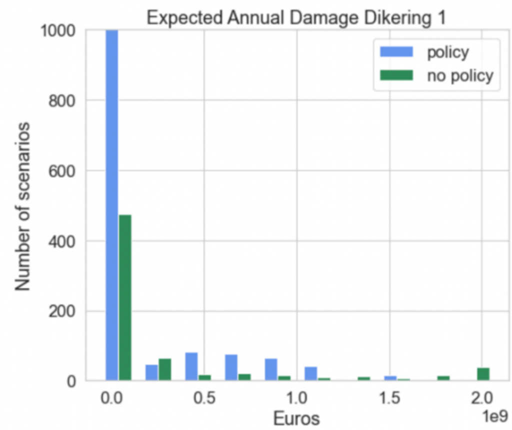
Figure 2311: Comparison of with or without policies

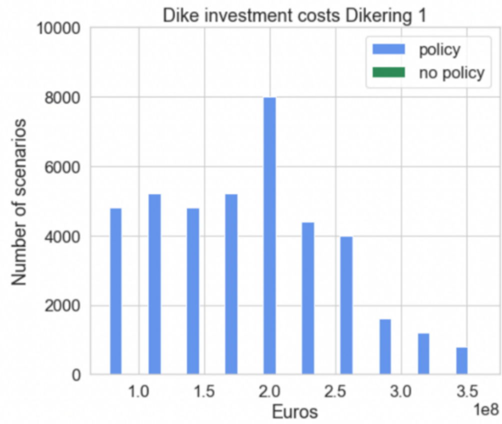
C.1.1 Distribution of scenarios in quantity

Something which has to be considered when looking at these histograms, for the base-case and the policy run there are different numbers of scenarios. The base-case only has 985 scenarios, but the policy run has 40,000 scenarios. This is because all the policies have been aggregated. Since the figures have a limit at 1,000, the blue bars are in comparison to the green ones a factor 40 smaller. Even without this factor we already see a decline in both damage and casualties (pictured above) from both the dikering perspective as the aggregated perspective. The policy run shows that the scenarios with zero casualties are approaching the 40,000. For Dikering 1 it remains below 1 in the aggregated time frame, so 200 years. Some higher numbers can be found in the aggregated view over locations, which is still something important to consider. This might be caused by implementing policy for one dike ring and not for the other resulting in flooding in other regions and therefore causing damage. Similar results are found for expected damage.









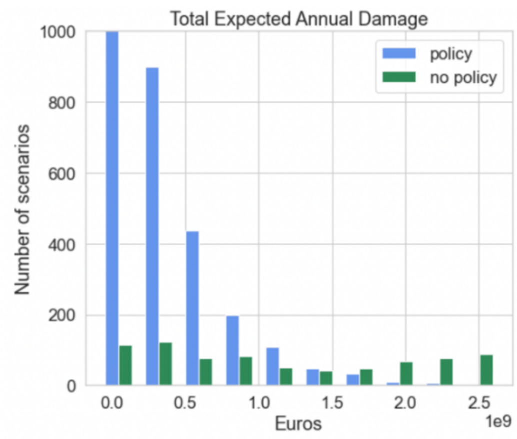


*Figure 24*12*: Comparison of with or without policies*

C.2 Sensitivity analysis

Sensitivity analysis was also done for Expected annual damage and Expected Number of Deaths, aggregated over time and aggregated over time and location

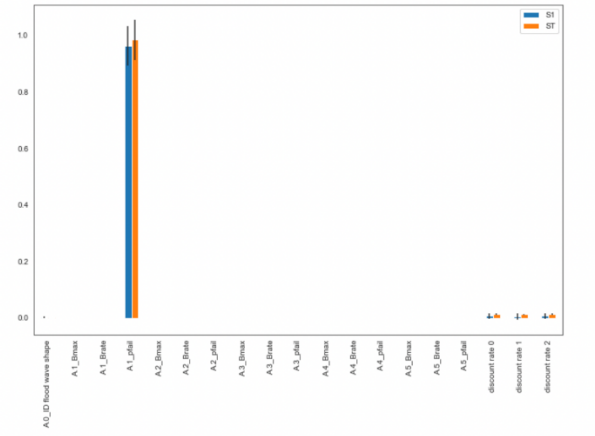


Figure 25: Expected annual damage (aggregate time)

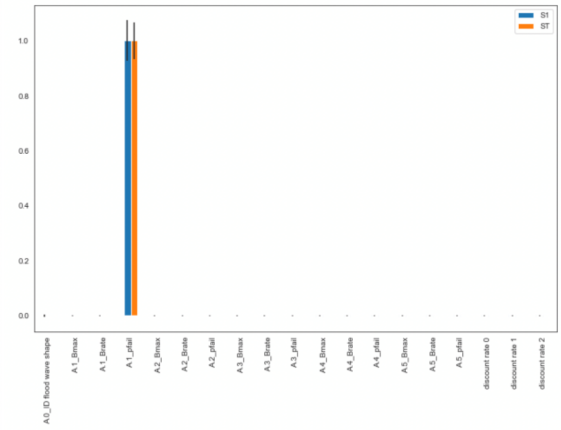


Figure 26:13 Expected number of deaths (aggregate time)

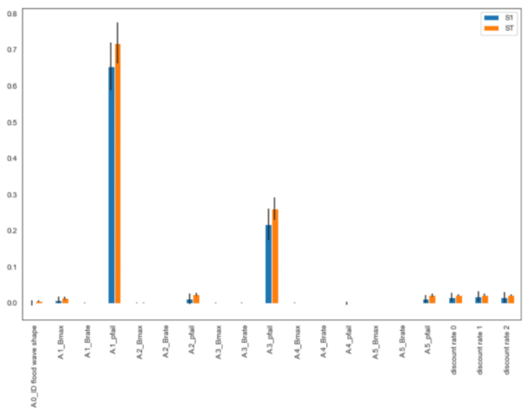


Figure 27: Expected annual damage (aggregate time and location)

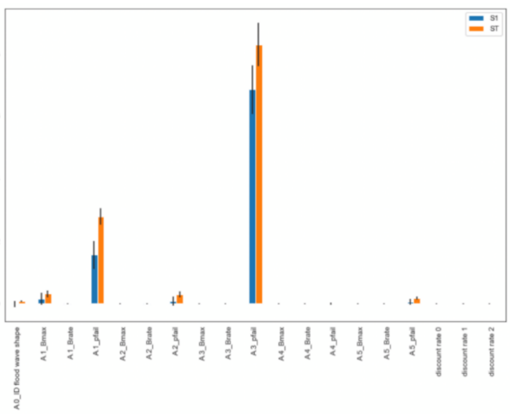


Figure 28: Expected number of deaths (aggregate time and location)

Appendix D – PRIM results scenario discovery

In this appendix the scatterplot of the scenario discovery of PRIM is given.

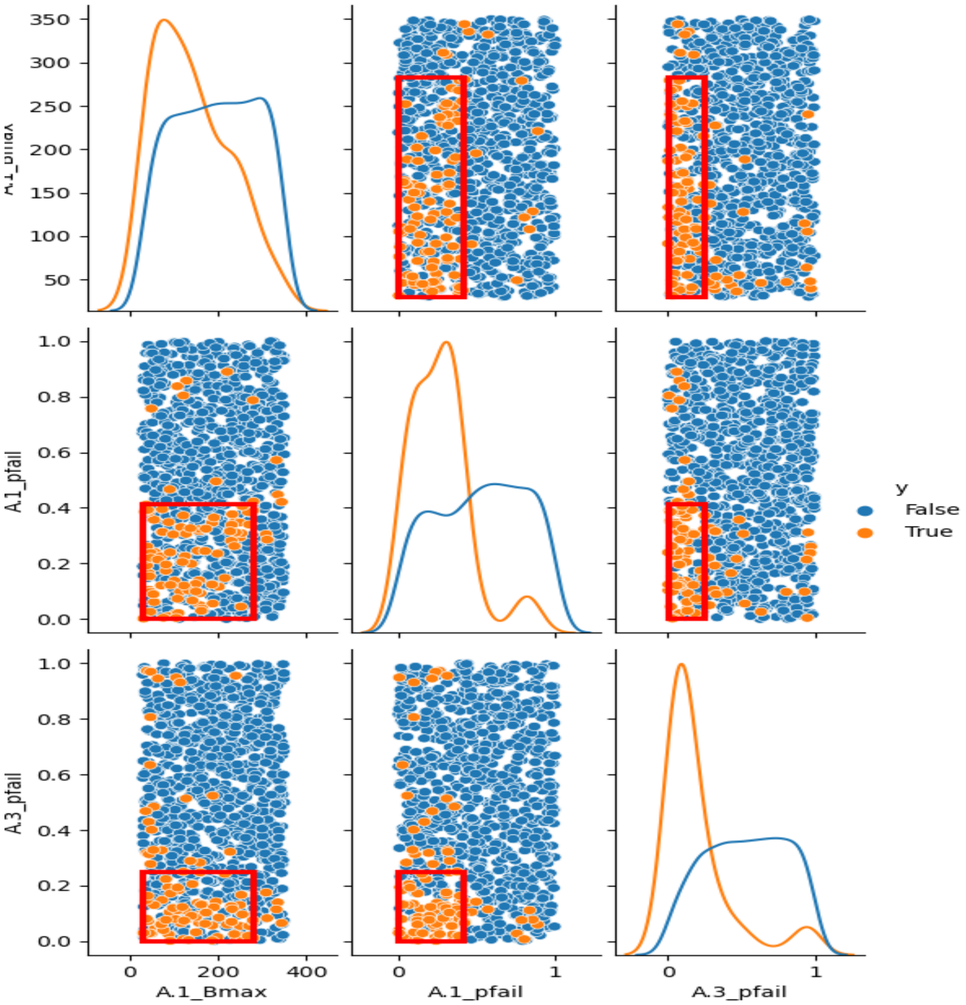


Figure 29: Scatterplot scenario discovery

Appendix E – Multi-Scenario MORDM

Parallel plots different scenarios candidate set of policies.

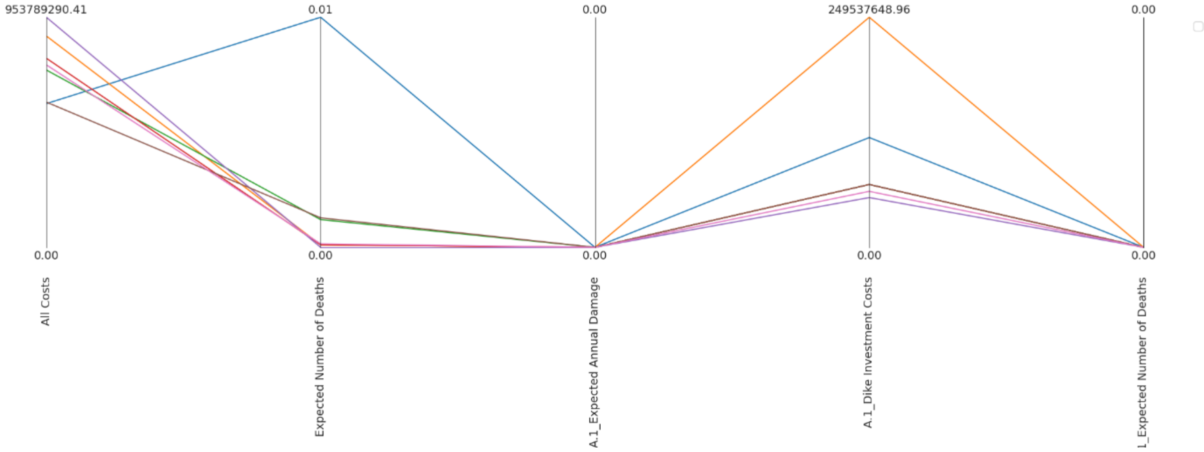


Figure 3014: Parallel plot scenario 1

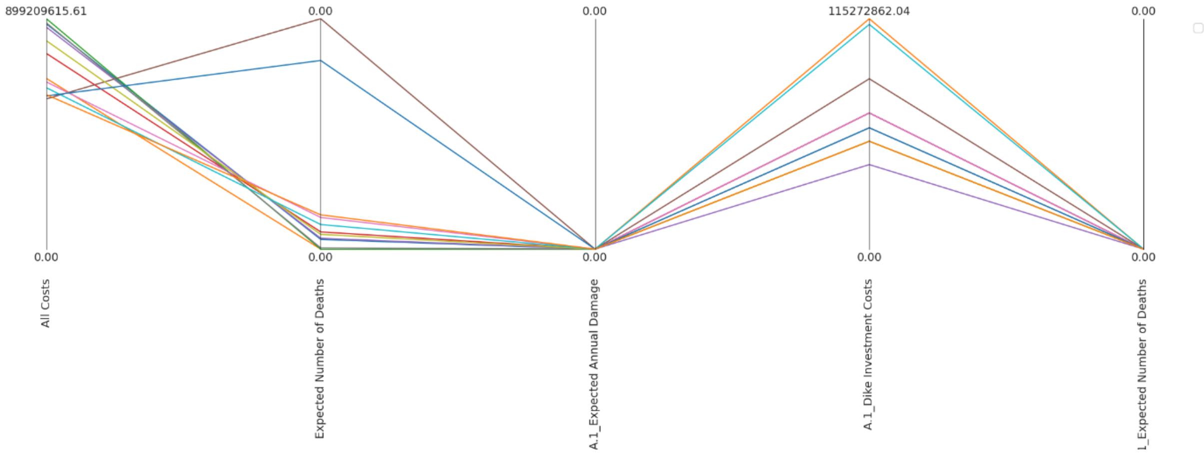


Figure 31: Parallel plot scenario 2

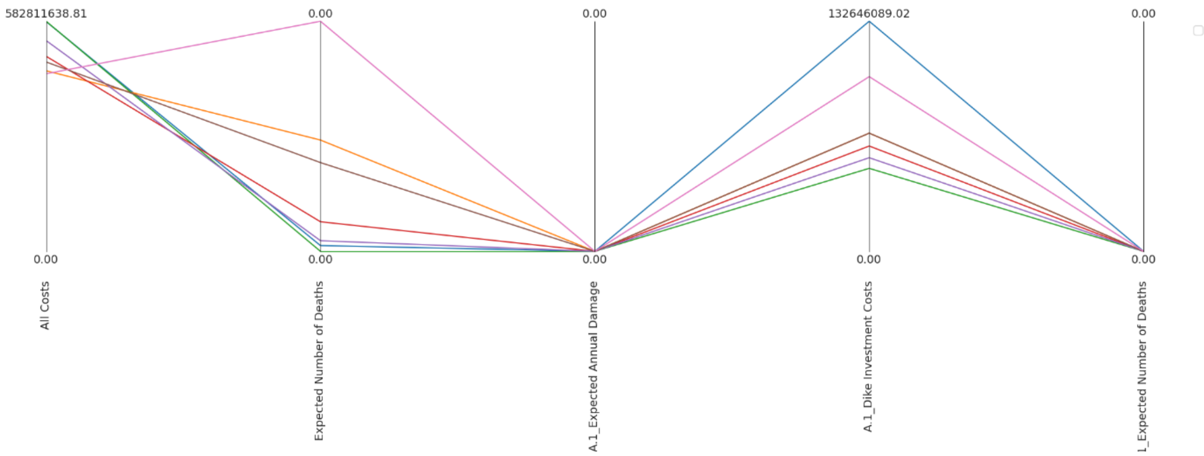


Figure 32: Parallel plot scenario 3

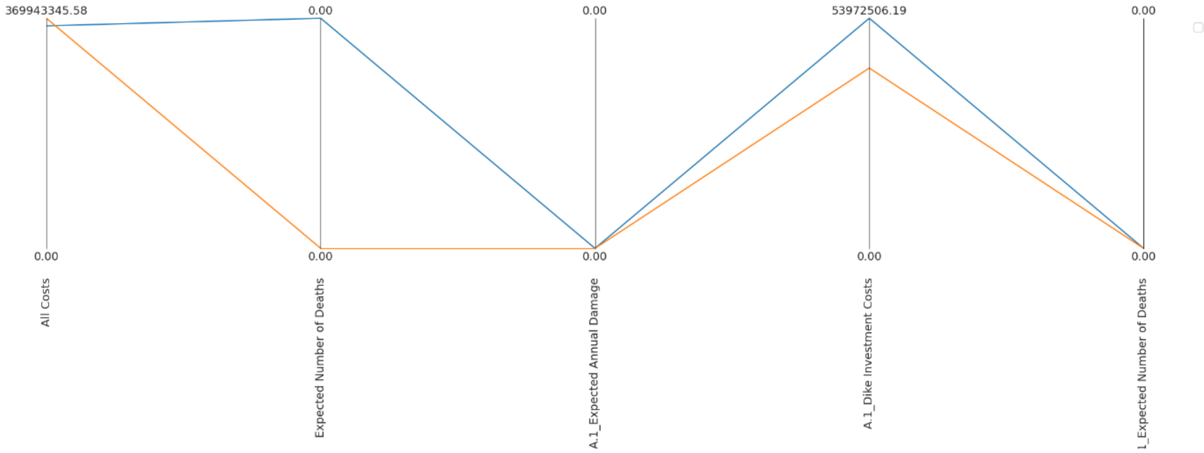


Figure 33: Parallel plot scenario 4

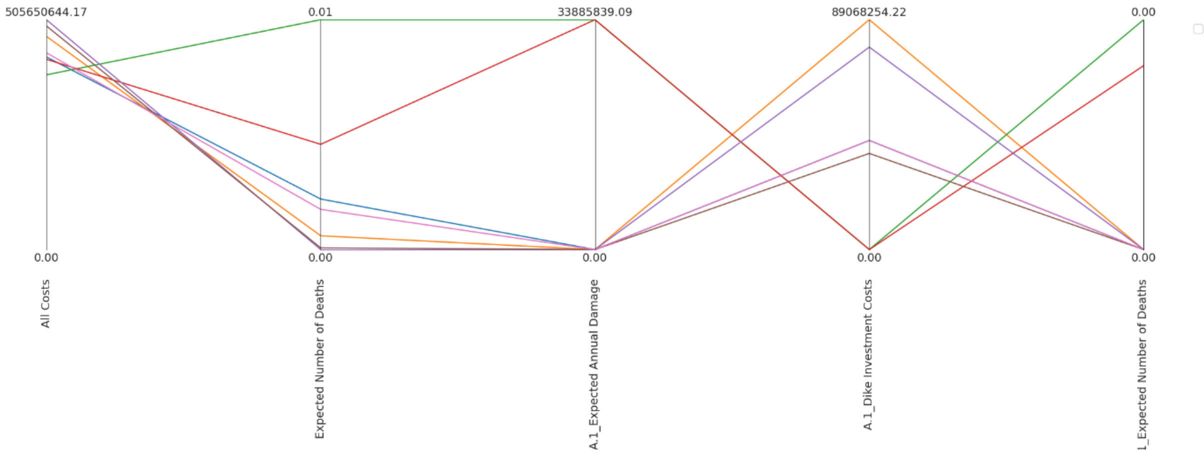


Figure 34: Parallel plot scenario 5