Flood Risk Management Plan
IJssel river

EPA1361 Model-based Decision-making

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Abbreviations

CART	Classification and Regression Tree
EMA	Exploratory Modelling and Analysis
FS	Feature Scoring
GSA	Global Sensitivity Analysis
KPI	Key Performance Indicator
LHS	Latin Hypercube Sampling
MORDM	Multi-Objective Robust Decision Making
MORO	Multi-Objective Robust Optimization
PRIM	Patient Rule Induction Method
RfR	Room for the River

Management summary

The Room for River projects are part of a strategy comprising both technical innovation and policy stakeholders, it requires extensive analysis, balancing decision-making in a multi-actor environment. In this report, a succession of steps is described to make a comprehensive analysis of the decision and its effects. Then a policy advice is given to Rijkswaterstaat for implementation in the IJssel delta.

Main policy advice for Rijkswaterstaat

Table 5 - policy advice

Policy 1	
RfR	Dikes 1,2 and 4
Dike heightening	Area 5
Early Warning system	4 days
Problem formulation	3

Formulated together with Rijkswaterstaat with input of all actors and considerations. Implemented immediately, this policy advice is based on the principle of minimum risk with arguably quite drastic measures.

Next, the steps to get to this workable policy are briefly touched upon.

Problem operationalization

Described in chapter 2, the problem is operationalized and an overall overview of method is given to support decision making.

Open exploration

This method is used as an alternative to the traditional *predict and act* approach of modelling. The goal of open exploration is to discover the patterns and inner-workings in the behaviour of the model under different scenarios and policies. Open exploration is performed by running the base case through a lot of scenarios and policies. The base case is essentially the model without any levers. This means no dike heightening, no warning system and no extended room for the river.

Optimization

In chapters following the open exploration, analysis steps are taken: scenario discovery, sensitivity analysis and optimization to arrive at a comprehensive solution to the policy advice issue.

Political reflection

A political reflection is written to evaluate different stakeholders and the process in which the policy advice has been materialised.

1. Introduction

The flood of 1953 is considered as the greatest natural disaster to occur in the Netherlands in the 20th century (Rijkswaterstaat, 2022). Large parts of the country were flooded because of the unforeseen combination of heavy storm and spring tide. The disastrous event claimed the lives of 1,836 people and caused significant infrastructural damage. Chronology of this event has been well documented and analysed, which gives us an opportunity to reflect its consequences on the current situation and develop solutions that would prevent such disasters.

A third of the Netherlands lies below sea level. The past event demonstrated the vital importance of protecting the country properly against flooding. It was concluded that one of the main reasons for the severe flooding was the poor condition of dykes, which lead to many breaches and heavy water inflow. The adaptation of stricter safety standards led to a continued advancement of the flood protection system. One of the recent measures adapted in the Dutch water management portfolio is Room for the River (RfR) (Rijke et al., 2012). The RfR concept focuses on rivers' overflow impact mitigation by constructing designated floodplains. This approach could be seen as an alternative to the more conventional building and heightening of dikes. (De Bruijn et al., 2015).

Basically, what makes the RfR strategy stand out when compared to the conventional flood protection measures is the adaptation of the resilience concept. One of the key elements of this strategy is the ability to return to the pre-flood state with minimal financial and social consequences (Warner et al., 2012). The RfR concept utilises the flood-suppressing qualities of the natural surroundings by including them in the design.

Another important feature that is incorporated in the RfR strategy is the adaptation of the multi-actor network governance. It entails including actors that are affected by the development but might not be on the same hierarchy level. Accordingly, including relevant actors in the decision-making process is essential for successful policy adaptation. It might make the decision-making process more complex, since there is an extensive amount of interest groups and different opinions, it also provides insights in groups that might compromise the decision-making process (De Bruijn et al., 2015).

In this report, the case of the Ijssel River is described which includes multiple Dutch regions that Ijssel is flowing through. Due to the increasing pressure of climate change on flood risk in the Netherlands a new water management policy is needed for this specific case. To tackle the arised complexity, a model-based exploratory approach is used to aid the decision-making process and develop an optimal policy combination.

1.1 Problem Description

In the Netherlands, the history of reclaiming land from the water system has been long and storied. However, climate change and increased volatility in weather behaviour now require the opposite to take place. Water management in the Netherlands in recent years has been focussed on allowing the water system to move more freely throughout the low countries.

Water management in the Netherlands

Innovation, policy and strategy are aspects which are central to this report and are incorporated into every aspect of the analysis. Central is the weighing of advantages and disadvantages of the multiple implementations of the project solutions while incorporating wishes of different stakeholders.

The Room for River projects are part of a strategy comprising both technical innovation and policy stakeholders, it requires extensive analysis, balancing decision-making in a multi-actor environment. In this report, a succession of steps is described to make a comprehensive analysis of the decision and its effects. Then a policy advice is given to Rijkswaterstaat for implementation in the IJssel Delta. First the problem is framed, then the methods and approach are explained and supported. The results of these analysis and modelling actions are subsequently set out and the results are discussed. Finally, the conclusions of the project are presented and a recommendation is given.

1.2 Problem Framing

The Room for the River project is a case study in the water management policy issues that originates from the issues that increased urbanisation and climate change brings to the surrounding regions. The aim of the project is to have a data-driven multi-actor decision process to analyse, evaluate and execute different scenarios and solutions to combat flooding in extreme circumstances. This, resulting in a comprehensive water management policy to be implemented by the different stakeholders.

To be able to formulate a strategy and begin analysis, an overview of different stakeholders and the tools available to these actors have to be mapped. As this project is one that is vertically integrated over the entire hierarchy of stakeholders, with actors in vastly different capacities and scopes, interests of these parties can conflict in the eventual outcome of the project.

The model assessment will be based on multiple indicators that will be carefully designed to predict impacts from certain decisions or policy combinations. According to Prof. Kwakkel, assigning a weighing factor for each interest might not be the optimal approach. Instead, we will try to see what is the contribution of each action to the general satisfaction of stakeholders.

Students will be provided with a simulation model that assesses economic damage and number of casualties at several locations located along the IJssel river.

There are multiple stakeholders that will be affected by the decision, interconnected in the national and regional political arena. Building on the given mandates, these parties will try to extract the maximum effectiveness for their policy in the debate.

2. Approach

2.1 Problem operationalization

This projects' aim is to develop a flood risk management plan for the upper branch of the Ijssel River in the Netherlands applying the notions on decision-making under (deep) uncertainty. According to Hall et al. (2003) is the Flood Risk Management (FRM) the process of gathering data and information, risk assessment, appraisal of options, and making, implementing and reviewing decisions to reduce, control, accept or redistribute risks of flooding. A flood is an overflow of water that submerges land that is usually dry. The approach of this study is related to exploratory modelling, which is applicable for complex systems with a deeply uncertain context where human reasoning alone is incapable of handling, a computer-assisted reasoning is needed. Since this project is realised to provide the Netherlands with a policy analysis framework based on an exploratory model, a classification of uncertainties can be made. The classification has two fundamental dimensions according Walker et al. (2003):

- "Location: where the uncertainty manifests itself within the policy analysis framework
- Level: the magnitude of the uncertainty, ranging from deterministic knowledge to total ignorance"

To ensure exploratory modelling, the analysis is conducted using the exploratory modelling workbench by Kwakkel, which is an open source Python library (2017). This type of modelling is used because no valid predictive policy analysis model can be built for the flooding of the Ijssel River. This research method focuses on the analysis and reasoning of the behaviour of the system rather than predicting the system (Walker & Kwakkel, 2013). The Exploratory Modelling and Analysis (EMA) method explores multiple scenarios that involve different scenarios. With the help of different experiments it is possible to investigate how the system behaves under specific conditions. It provides a wide overview of the implications on decision-making under the various uncertainties - it captures known uncertainties by systematically exploring the impact of a range of defined assumptions by means of intensive computational experiments (Maollemi et al., 2020). Based on the possible outcomes, the policy can be adjusted accordingly as EMA contributes to providing new knowledge about the policy adjustments that need to be made to create satisfactory results for the various scenarios (Walter & Kwakkel, 2013).

The theoretical XLRM framework (Lempert et al., 2003) behind exploratory modelling is slightly adapted by Ciullo et al., (2019) and shown in figure 1. Using this theory, the problem formulation from the previous chapter can be converted into model terms. There are four terms that are considered in this framework:

- Policy Levers (L): policy instruments under exploration by decision-makers
    - Dike heightening
    - Early warning system
    - Room for the River (RfR)

- External factors (X): uncertainties outside the control of the decision-maker
  - Flood wave shape
  - Dike failure probability
  - Final breach width
  - Breach width model
  - Discount rate
- Measures (M): outcomes of interest which represent the performance of the policy
  - Expected annual damage
  - Expected investment of casualties
  - Dike investment costs
  - Evacuation costs
  - Room for the river costs
- Relationship (R): relationships between the uncertainties, policies and outcomes

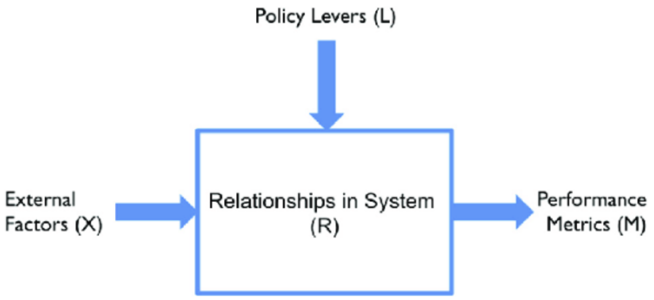


Figure 1 - The XLRM framework (Ciullo et al., 2019)

The analysis is performed for five different locations of interest (Table 1). Each city is located within a different dike ring (Figure 2).

Table 1 - Locations of interest

Location	**Dike ring**
Doesburg	A1
Cortenoever	A2
Zutphen	A3
Gorssel	A4
Deventer	A5

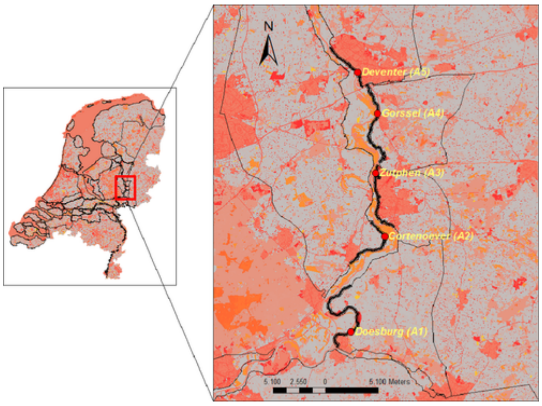


Figure 2- Map Dike Ring (Ciullo et al, 2019)

Key Performance Indicators (KPIs) are used to evaluate the performance of the policy, thus to examine which policies result in the best scenario. In this study, the variables listed below (Table 2) are crucial to analyse which policy levers should be used in the new flood risk management plan. The values that these variables take per policy option are decisive, these values should be minimised by the policy resulting in minimised damage caused by flood.

Table 2 - KPIs

KPI	**Description**	**Unit**
Total costs	Investment costs of dike heightening & damage	€
Number of deaths	Expected number of casualties due to flooding	#
Evacuation costs	Investment costs of preventive evacuation	€
Room for the River costs	Investment costs for the RfR option	€

2.2 Methods

The exploratory model process used in this project consists of three parts; Open Exploration, Vulnerability Analysis and Optimization. The vulnerability analysis is divided in two analyses; scenario discovery and sensitivity analysis. The Multi-Objective Robust Optimization is approached to optimise the robustness of the strategies.

2.2.1 Open exploration

This method is used as an alternative to the traditional *predict and act* approach of modelling. The goal of open exploration is to discover the patterns and inner-workings in the behaviour of the model under different scenarios and policies. Open exploration is performed by running the base case through a lot of scenarios and policies. The base case is essentially the model without any levers. This means no dike heightening, no warning system and no extended room for the river.

The outcomes will be sampled using Latin Hypercube Sampling (LHS). This method of sampling can be used to produce input values for estimation of expectations of output variables (Stein, 1987). LHS is suggested as a tool to improve the efficiency of different importance sampling methods for structural reliability analysis (Olsson, Sandberg & Dahlblom, 2003). This sampling method is typically used to save computer processing time when running simulations. Olsson et al. (2003) claim that "by means of different numerical examples, it is shown that more than 50% of the computer effort can be saved by using Latin hypercubes instead of simple Monte Carlo in importance sampling". Furthermore, running the base case will contribute to evaluate how well policies perform because the outcomes of the base case help by understanding the water management system with no implemented policy.

Problem formulation 3 was used for the open exploration. This problem formulation focuses on the outcomes of the total costs (dike heightening costs and damage costs), the expected number of deaths, the total costs for RfR and the expected evacuation costs. The reason for choosing this problem formulation is that it is most in line with the previously defined KPI's and the wishes of problem owner Rijkswaterstaat. Using problem formulation 3, the open exploration stage is executed by running the model with 100 policies and in 400 scenarios, leading to a total of 40.000 experiments. The product of running these experiments is two datafiles containing the outcomes and the experiments. The information was stored aggregated for each location and KPI specifically.

2.2.2 Scenario discovery

As stated before, the model consists of multiple external factors. These factors combined can result in either desirable or disadvantageous outcomes for the policymakers. Therefore it is of great importance to get more insight into the influence of these external factors on the effect of possible policies in the dike model. For that purpose in this analysis the computer-assisted scenario development, called scenario discovery, is being used.

For the scenario discovery two methods can be used, namely the Patient Rule Induction Method (PRIM) and the Classification and Regression Tree (CART). As Friedman and Fisher (1999) states, PRIM is a "bump-hunter" which seeks "high-density regions" by peeling away thin faces of the input space to generate small regions that contain a higher mean value.The 'peeling' results in boxes that keep getting smaller, as can be seen in Appendix. The CART method provides outputs in the form of a decision tree, where the branches of the tree develop based on a hierarchical set of splitting rules. As in the PRIM method, the output depends on the combinations of the input(Breiman, 1984).

According to Lempert, Bryant, and Bankes 2008, CART seems to generate similar results as PRIM. However, to achieve box sets with high interpretability, the analyst has to put in more work. Therefore in this analysis, because of the magnitude of the data and the associated run time time restrictions, the chosen method is PRIM.
The drawback of this method is that it often leaves out surprising or shocking developments, black swan events and conflicting interpretations of scenarios between actors makes it difficult to arrive at a consensus/trade-offs.

2.2.2.1 Worst case scenarios

In order to get more insight into the different scenarios, the worst case scenarios have to be selected. To do this, different thresholds for the KPIs have been chosen in conversation with Rijkswaterstaat. The maximum values for the KPI's are in total (Table 3), this means for the five different locations together. The goal in to optimise the policies for these worst case outcomes.

Table 3 - Preferred maximum values KPIs

KPI	**Maximum value**
Death	0,005
Total costs	750.000.000
Room for river costs	1.250.000.000
Evacuation costs	50.000

2.2.3 Sensitivity Analysis

The goal of sensitivity analysis is to locate the source of uncertainty in a model. A sensitivity analysis can be used to characterise how model outputs respond to changes in input, with an emphasis on finding the input variables to which outputs are most sensitive (L. Uusitalo, A. Lehikoinen, I. Helle, et al., 2015). To comprehend the complexity of the Dike model, the first order sensitivity index (SOBOL) is used in addition to the feature scoring method. The feature scoring (FS) method is an alternative of the global sensitivity analysis
(GSA) that focuses on the prioritisation of factors. FS is a machine learning technique used to illustrate the influences of various uncertainties and levers to the outcomes. This method can also be used in non-linear relationships between variables in models with a lot of uncertainty (Liu, Q., Homma, T., 2009).

The SOBOl method is based on variance decomposition, so it clarifies he fraction of total variance added by each variable.
Instead of the SOBOL, A linear regression or Extra-trees/Random forests was also possible, but since the dike model is non-linear, the linear regression was not chosen and since Extra-trees/Random forests is a machine-learning technique and its limits are still unknown, the choice was made to also not use this method.

2.2.4 Optimization

The final step of the analysis is to optimise the opportunities to minimise the KPIs so that the damage, expressed in both human lives and costs, is limited. The robust optimization method Multi-Objective Robust Optimization (MORO) is used to determine the desired policy. This method considers a set of scenarios and optimises the robustness of strategies over a specific set of scenarios (Hamarat et al, 2013). An alternative optimization method is Many-Objective Robust Decision Making (MORDM), which uses a single reference scenario (Shavazipour, Kwakkel & Miettinen, 2021). Because this method uses only one scenario, it can result in policies that do not perform optimally in scenarios that are different from the reference because MORDM introduces scenario dependency given that the Pareto approximation only includes solutions optimised in that single scenario (Shavazipour et al., 2021). Multi-scenario MORDM, however, repeats the search for different scenarios that represent conditions that are difficult to address with solutions from the reference scenario.

The MORO method was chosen because, according to Bartholomew & Kwakkel (2020), "this method has a much stronger guarantee of finding solutions in the Pareto optimal set in the robustness space after reevaluation, compared to (multi-scenario) MORDM". Bartholomew & Kwakkel (2020) also claim that "Only in the case of a static policy formulation and a very clear emphasis on robustness, would MORO be the more appropriate method." In this analysis, the goal is to formulate a risk-averse policy option to reduce the total expected damage and casualties in all regions as a solution to possible flooding in the IJssel River. MORO concentrates on the robustness by optimising measures as objective functions over a set of various scenarios which results in multiple solutions (Shavazipour et al., 2021).

3. Results

This chapter consists of the results from the analyses mentioned in the previous chapter. The results and their implications are discussed in the following order: Open Exploration followed by the vulnerability analysis which consists of the scenario discovery and the sensitivity analysis. This chapter concludes with the results of the optimization.

3.1 Open Exploration

First, the base case is analysed. Next, the multiple scenarios with the policy options. Using problem formulation 3, the open exploration analysis is executed by running the model with 100 policies and in 400 scenarios. This resulted in 40.000 different outcomes. From these results, interesting patterns can be extracted. The outcomes are aggregated by location and by KPIs (see Appendix A).

3.1.1 Open Exploration Base Case

The base case is analysed to represent the performance of the current state of the flooding management system without policies implemented, thus levers in the dike model are zero in this scenario. The base case is used in the open exploration and vulnerability analysis to compare the results with the scenarios where policy options are implemented.

In the base case, there is only one scenario given that no policy is applied. The open exploration with the base case is conducted with 1000 experiments. For each dike ring, the four KPIs are calculated. As a result of no policy, for each diked area the investment costs for RfR and evacuation are zero. The total costs and the number of deaths in the base case are not equal to zero (Figure 3). This is because in the current situation without policy, damage can be caused to the environment (e.g. houses and roads destroyed) and can even result in casualties. Appendix A.1 shows the pairplots of the KPIs by location for the base case results.

The figure below shows the two indicators that are not equal to zero in the base case; number of deaths and total costs (meaning the costs for dike heightening and damage). For both criteria points, the figure shows that dike ring 4 has the lowest score. On the other hand, the values for dike ring 1 are high on both variables, which is negative because it is desired to cause as little damage as possible in both damage and casualties. Dike ring 3 takes about the same value as dike ring 1 regarding the number of deaths. The graph of total costs shows that dike ring 3 takes a lower value here than dike ring 1. Furthermore, dike ring 2 and 4 take considerably lower values than dike ring 1, with dike ring 2 having slightly higher numbers than dike ring 4. In conclusion, dike ring 1 has the most damage and dike ring 4 the least.

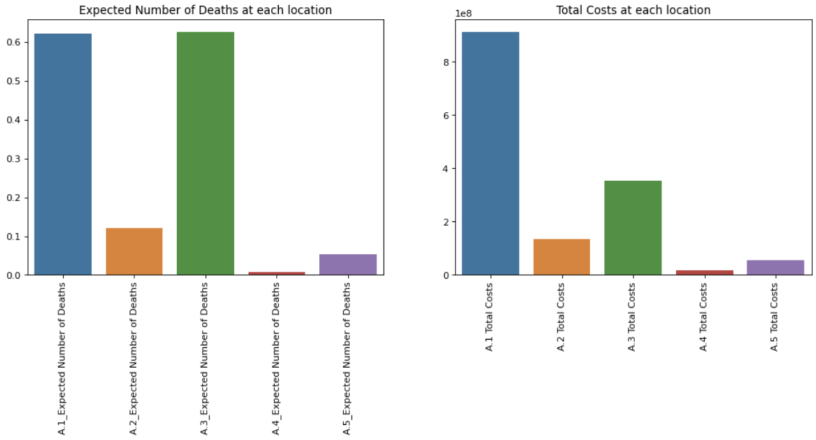


Figure 3 - Expected Number of Deaths and Total Costs per location in base case

3.1.2 Open Exploration with Policy scenarios

To analyse the performance of the system after implementing the policy options, a large range of scenarios is used. As mentioned before, using problem formulation 3, the open exploration analysis is executed by running the model with 100 policies and in 400 scenarios. This resulted in 40.000 different outcomes. From these results, interesting patterns can be extracted. The outcomes are aggregated by location and by KPIs. Appendix A.2 shows the pairplots of the KPIs by location for the results of the scenarios with policy.

The figure below shows per location the values of the number of deaths and the total costs (investment costs of dike heightening and damage). It is striking that locations score differently per KPI, there is not one dike ring that scores the highest on both variables. Dyke ring 3 has by far the most deaths and dyke ring 4 the least. Regarding the total costs, dyke ring 1 and 2 have the highest values and again dyke ring 4 the lowest. On the other hand, dyke ring 3 does not have the highest costs. In both KPIs, dike ring 5 is in the middle.

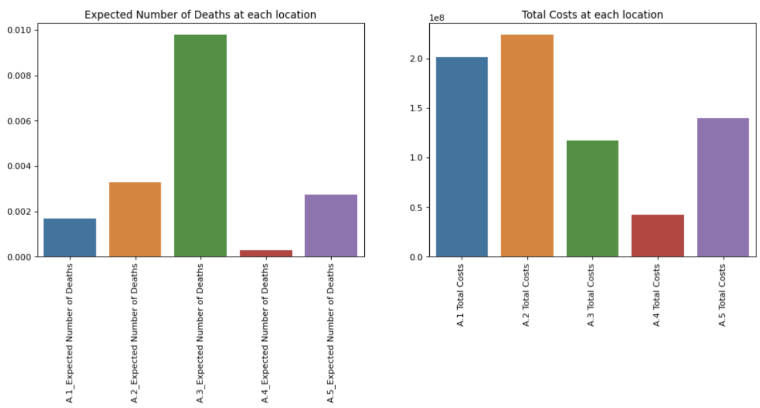


Figure 4 - Expected Number of Deaths and Total Costs per location with policy scenarios

Figure 5 shows the density graph of the total cost for the Room for the River. What is striking about the graph is that the distribution is skewed, most frequent costs take on a value below 1.25. A substantial amount of outcomes have a value higher than 1.4 (third peak in the graph).

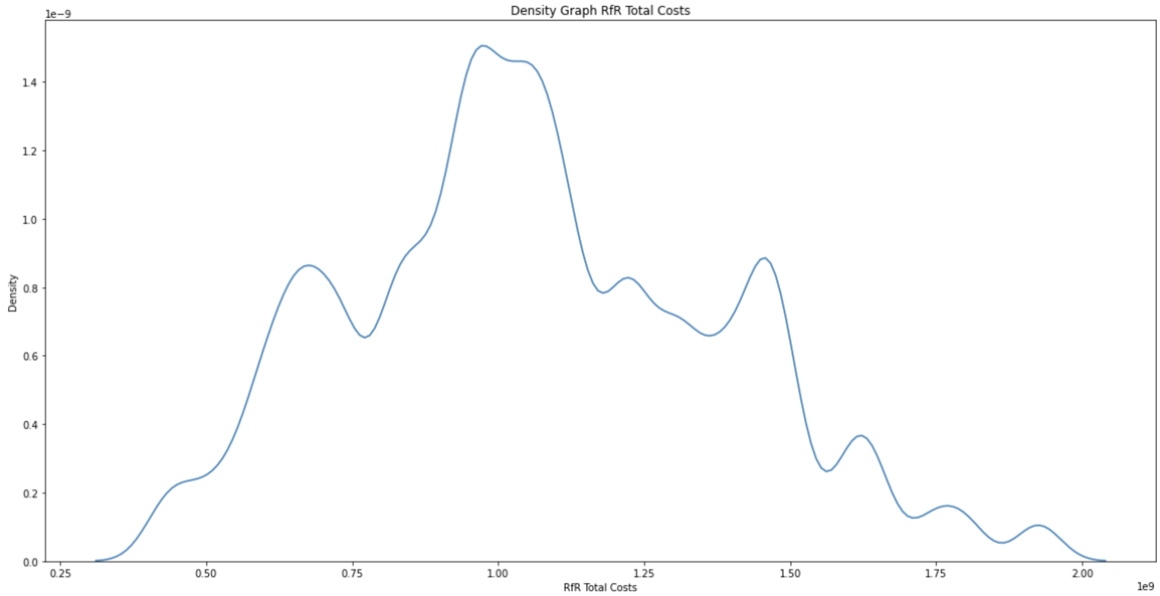


Figure 5 - Density graph RfR costs

The boxplot below shows the evacuation costs. From the figure it can be concluded that there are outliers present which makes it difficult to validate the results. At point 0 of the x-axis, the values are extremely high compared to the other values.

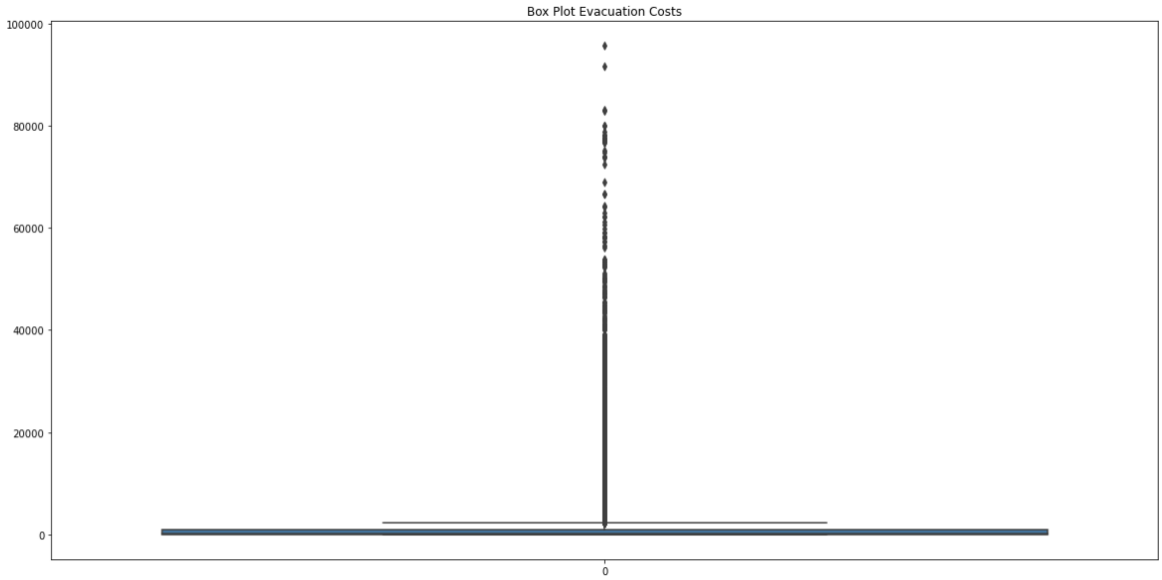


Figure 6 - Box plot evacuation costs

3.1.3 Open Exploration Differences

The two sections above explain the results of the open exploration analyses for both the baseline scenario and the policy options. One of the major differences between the open exploration results for the base case and the policy scenarios is the values of the KPIs evacuation costs and RfR costs. Figure 6 and 7 clearly show the difference, Figure 6 shows that in the base case the cost of evacuation and RfR is zero, while in the policy scenarios it is not.

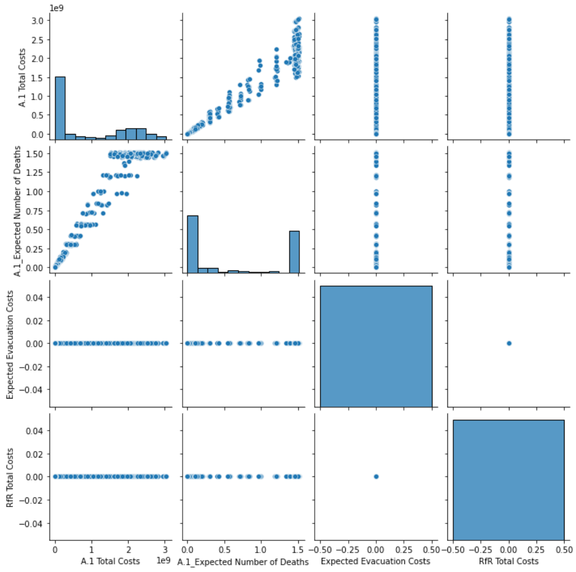


Figure 6 - A1 pairplots base case

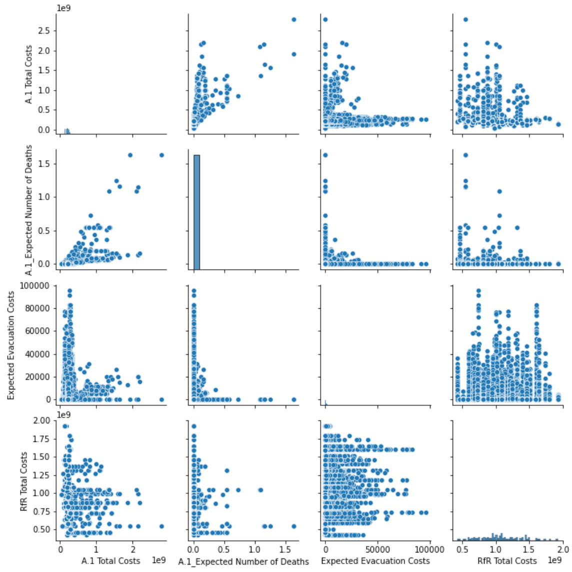


Figure 7 - A1 pairplots policy scenarios

Table 4 shows the values of death and total costs in the base case and in the policy scenarios. In each diked area, policy results in less damage. Overall, when policies are implemented, both deaths and total costs are effectively reduced. Appendix A shows a part of the Python results of the open exploration.

Table 4 - overview differences in deaths and total costs

	A1	**A2**	**A3**	**A4**	**A5**
Mean Total Costs Base Case	9.128055e+08	1.333758e+08	3.531835e+08	1.625533e+07	5.624633e+07
Mean Total Costs Policy	2.014180e+08	2.243187e+08	1.174301e+08	4.261769e+07	1.395959e+08
Mean Number of Deaths Base Case	0,62127	0,120308	0,626465	0,00742	0,052261
Mean Number of Deaths Policy	0,001696	0,003284	0,0098	0,000299	0,002754

In addition, in the base case, dike ring 1 has significantly the highest values for the KPIs number of deaths and total costs (see Figure 3). However, in the policy scenarios, the distribution is completely different (see Figure 4). Dike ring 3 has the most deaths and dike ring 2 incurs the most costs for dike heightening and damage. The similarity in both cases is that dike ring 4 has the fewest deaths and incurs the lowest costs.

3.2 Scenario discovery

3.2.1 Scenario discovery Base Case

Since there are no policies, evacuation costs and RfR costs are 0 in every scenario. These variables will be disregarded. Expected deaths will also be disregarded as apparently 0 results note expected deaths under 0.005 if no policies are being introduced. Therefore only the effects of the scenarios on the total costs, which consists of the damage costs and dike heightening costs, will be inspected.

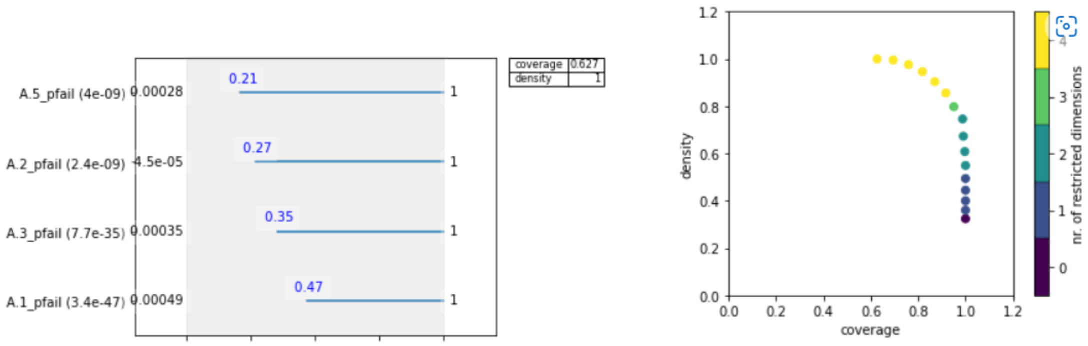


Figure 8 - scenario discovery base case total costs

The figures above show that the failure of dike 1 has the most significant influence on the total costs. The failure of dike 2 and 3 also have an impact on the results, but this impact is less significant. The failure of dike 5 has the smallest impact on the total costs.

3.2.2 Scenario discovery Policy options

For the impact of the failure of the dike rings on the results with policies, the expected number of deaths and the expected total costs, which consists of the damage costs and dike heightening costs, will be investigated. The expected RFR costs and the expected evacuation costs will be visible in Appendix B.

3.2.2.1 Total costs

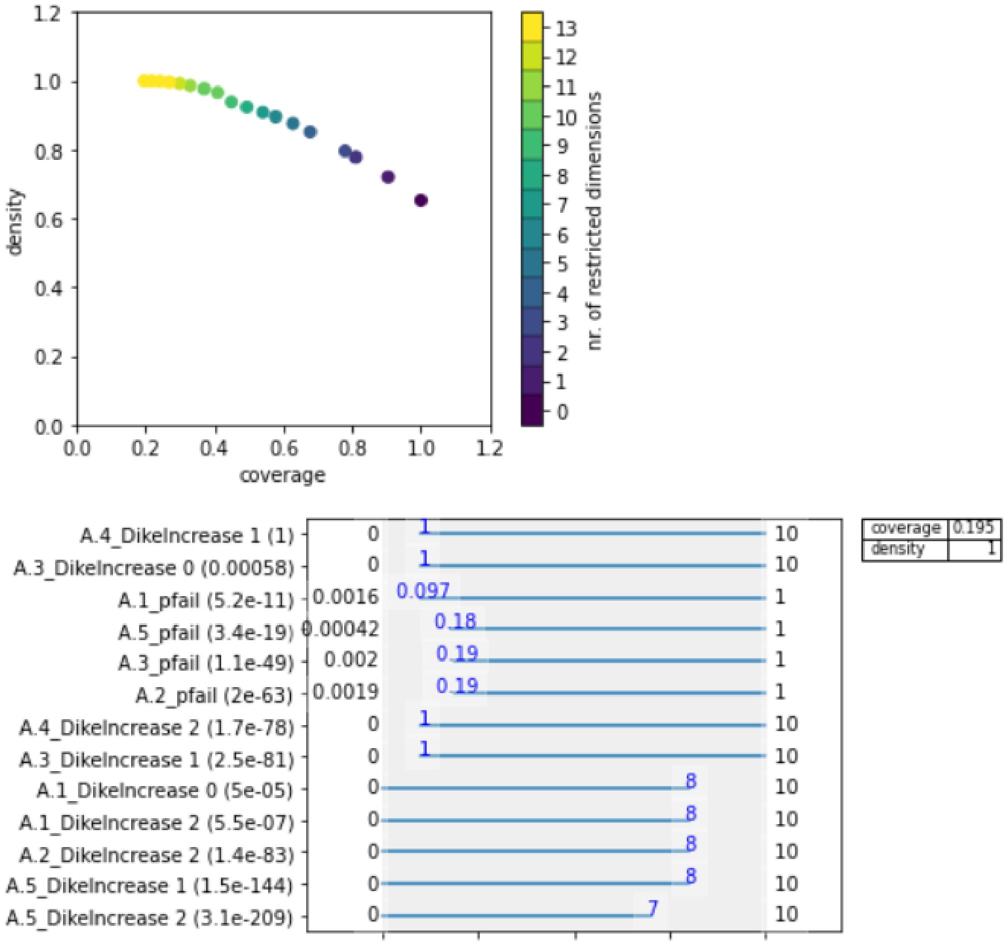


Figure 9 - scenario discovery with policies total costs

Figure 9 shows that increasing dike ring 5 in stage 2 has the least significant impact on the total costs compared to increasing other dike rings. So the dike heightening costs for this dike ring might be high but the damage costs will decrease severely if the dike is heightened. Increasing dike 4 in stage1 or 2, or dike 3 in stage 0 or 1 would not be beneficial to the total costs. Possibly the costs of heightening the dike are not covered by the costs that are being saved by having less damage. The failure of dike 5, 3 and 2 have the most significant impact on the total costs, compared to the failure of other dikes.

3.2.2.2 Deaths

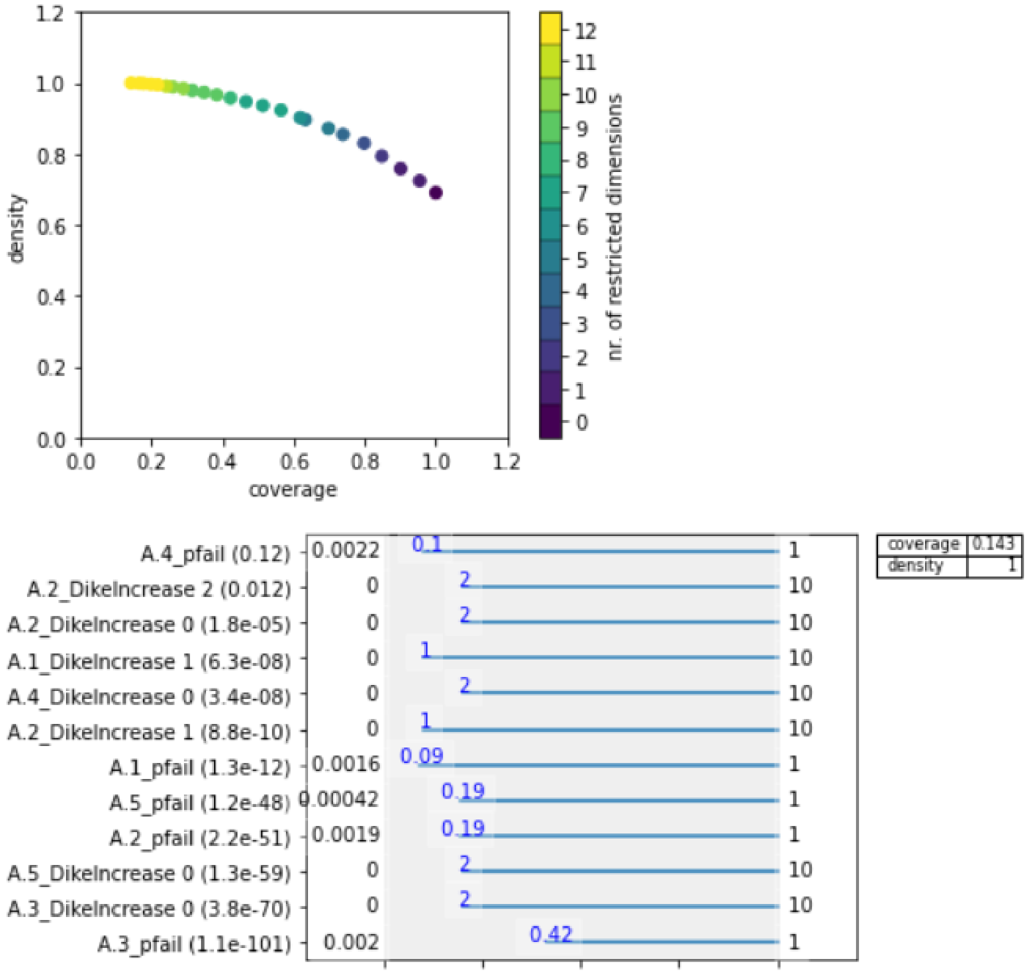


Figure 10 - scenario discovery with policies expected deaths

Figure 10 shows that the failure of dike 3 has the most significant effect on the expected number of deaths. It also shows that dike increasing overall results in an increase of the expected number of deaths. The dikes that are less likely to result in an increase in the expected number of deaths when failing, are dikes 1 and 4.

3.2.3 Scenario discovery differences

The scenario discovery with the base case can be compared to the scenario discovery with the policy based on the total costs, which consists of dike heightening costs and damage costs, and the expected number of deaths. The latter is always greater than 0,005 when no policies are being introduced. This means that in order to achieve the preferred value of 0,005 deaths per year (per 1000 inhabitants) over all dikes combined it is crucial to implement policies. The total costs are in both the base case and in the case with policies, significantly impacted by the failure of dike 3. This means that in order to keep the total costs low, dike 3 has to stay functional. When policies are being implemented the failure of all other dikes has less impact on the total costs than when no policies are implemented.

3.2.4 Worst case scenario

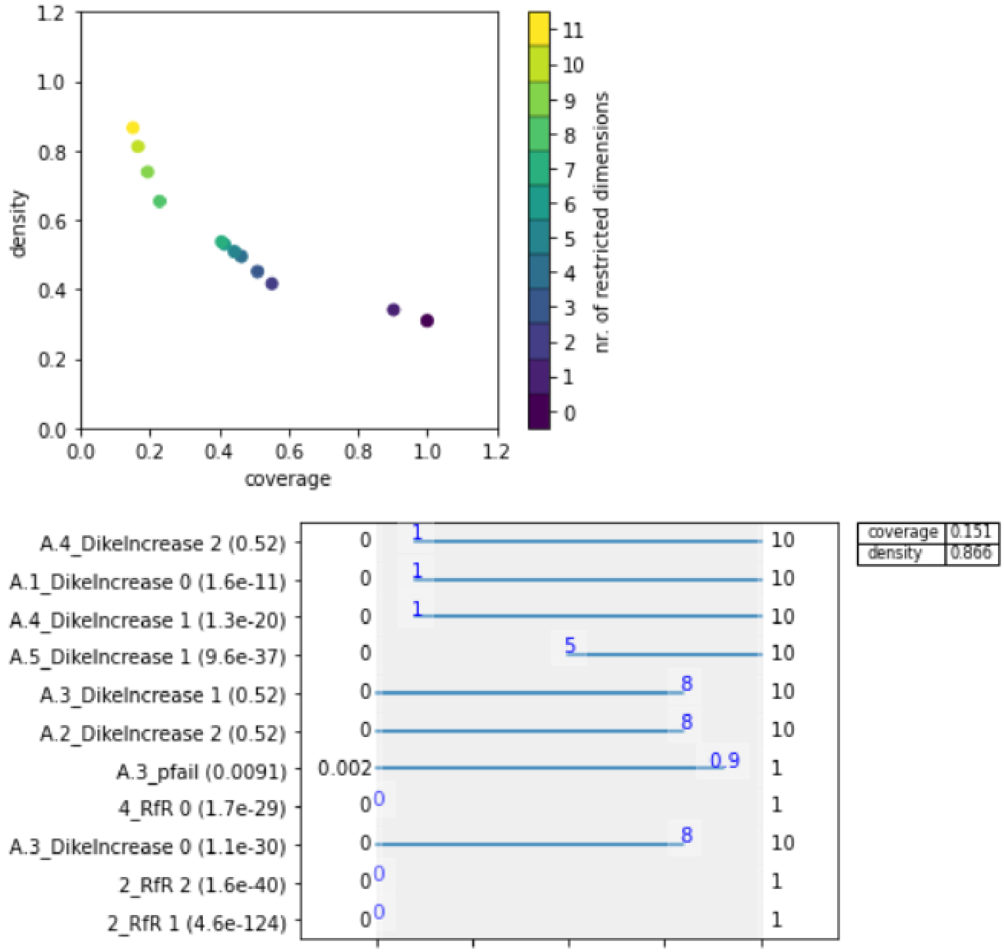


Figure 11 - scenario discovery worst case scenario deaths

Remarkably, figure 11 shows that for the scenarios that fall outside of our thresholds and are considered worst case scenarios, room for rivers in area 2 and 4 result in almost no deaths. This is the biggest difference between the worst case scenarios and the 'best case' scenarios based on deaths and total costs.
The other worst case analysis can be seen in Appendix B.

3.3 Sensitivity Analysis

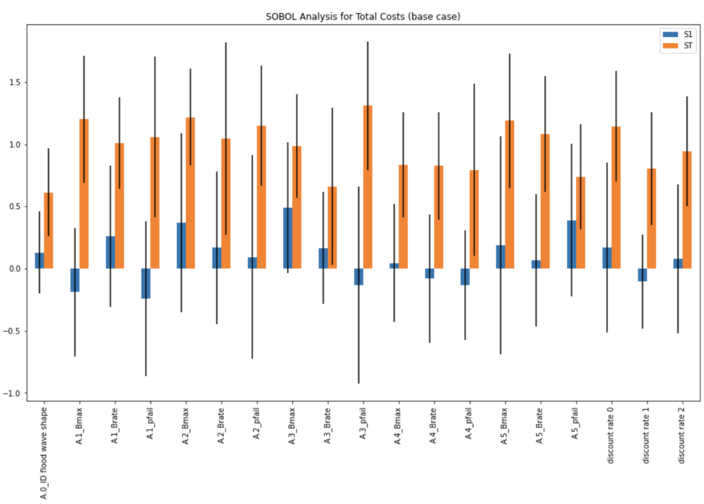
As explained in the approach section, the sensitivity analysis is part of the vulnerability analysis and used to evaluate how input variables contribute to the uncertainty of the output values and how changes in the input variables will affect the outcomes. Feature scoring and SOBOL sensitivity analysis are conducted. The feature scoring is a global sensitivity analysis which shows clearly the uncertainties that have an impact on specific outcomes. The correlation between uncertainties and policy interventions and the outcomes of interest. The results of the SOBOL sensitivity analysis show both the individual influence of a variable and the interaction between variables, total effects on the outcomes.

3.3.1 Sensitivity Analysis Base Case

The figure below shows the SOBOL results for the KPI's total costs and the total expected number of deaths for the base case. The two other KPIs are not included in this analysis as in the base case there is no investment in policy so the values of the RfR costs and the costs of the evacuation are zero. In the figure, the blue line, S1, represents the individual effect of each factor on the outcomes, whereas the orange line, ST, represents the overall effects including the various interactions between variables.

For both KPIs in Figure 11, some of the variables take on negative values at S1. For the total costs, the values vary between -0.2 and +0.5 where A3_Bmax takes the highest value and thus has the largest individual impact on the total costs. Also for the number of deaths graph, the variable A3_Bmax has the largest impact. The S1 values of the variables on the KPI vary between -0.2 and +0.6.

For ST, in both cases, none of the values is negative. In the analysis of the total costs, ST for all variables takes on a value between 0.5 and 1.4, with A3_pfail taking on the highest value. For the expected number of deaths, all variables take a value between 0.5 and 1.1, in this case, there is no specific variable that stands out, and several are around the value 1.0-1.1. In this analysis, the discount rate 0 is the lowest-scoring factor in ST.



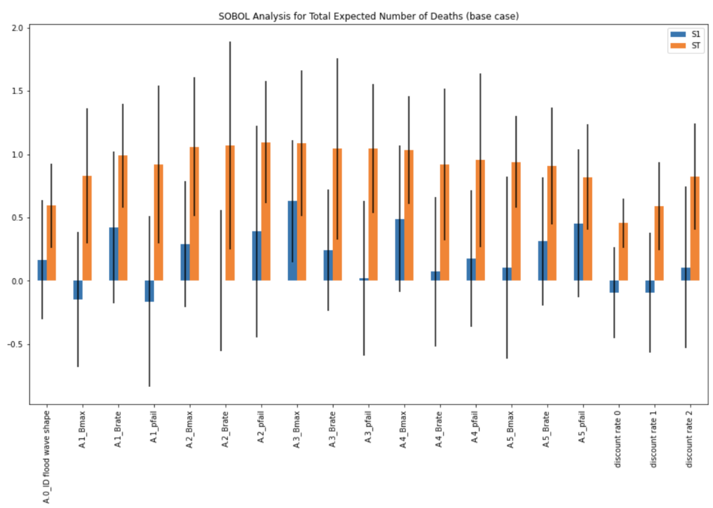


Figure 11- SOBOL Total Costs & Number of Deaths Base Case

Figure 12 shows the feature scoring for the base case. From the figure it can be seen that for RfR total costs and expected evacuation costs all values are equal to 0, the reason being that the base case does not implement a policy and therefore does not invest in RfR and evacuation plans. In addition, it is striking but logical that the total costs and the number of deaths per dike ring are influenced the most by the dike failure probabilities of that particular dike ring. The total costs and the number of deaths for A1 for example are strongly influenced by the dike failure probabilities of A1, idem ditto for the other dike rings. The last two columns of the figure show the total costs and the total number of deaths. It can be seen that A1 and A3 have a significant impact on these values.

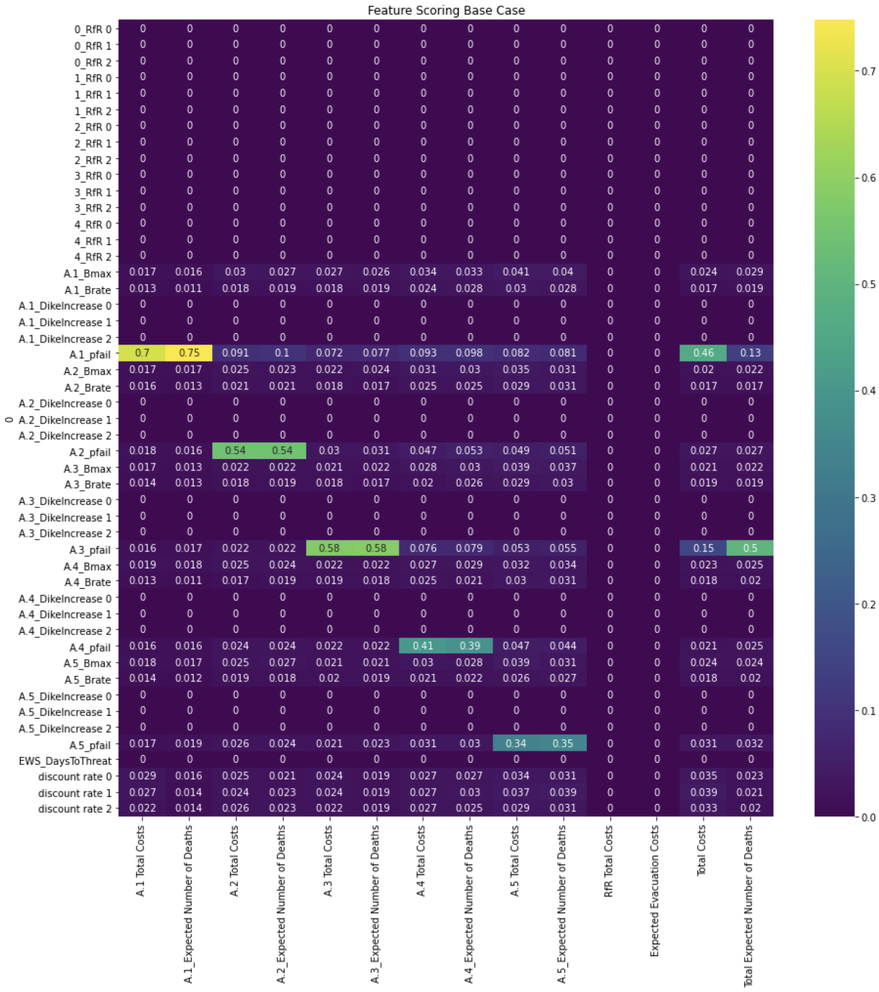


Figure 12 - Feature Scoring Base Case

3.3.2 Sensitivity Analysis Policy Options

The figure below shows the SOBOL results for the total cost of the KPIs and the total expected number of deaths for scenarios in which the policy options are implemented.

For both KPIs in Figure 13, some variables take negative values at S1. For the total cost, the values vary between -0.1 and +0.3, with A0_ID_floodwaveshape taking the highest value and thus having the largest individual impact on the total cost. For the KPI number of deaths, the variables A2_Brate and discount rate_1 have the greatest impact. The S1 values of the variables on the KPI vary between -0.4 and +1.3.

For ST, none of the values are negative in both cases. In the analysis of total cost, ST takes a value between 0 and 1.6 for all variables, with A5_Bmax overwhelmingly having the highest value. For the expected number of deaths, all variables take a value between 0.3 and 6.5, with A5_Bmax again being the variable with the highest overall effect on the expected number of deaths. The vast majority of these variables have values of 2.5 or lower. In contrast, 4 variables have a total effect of 5.0 or higher.

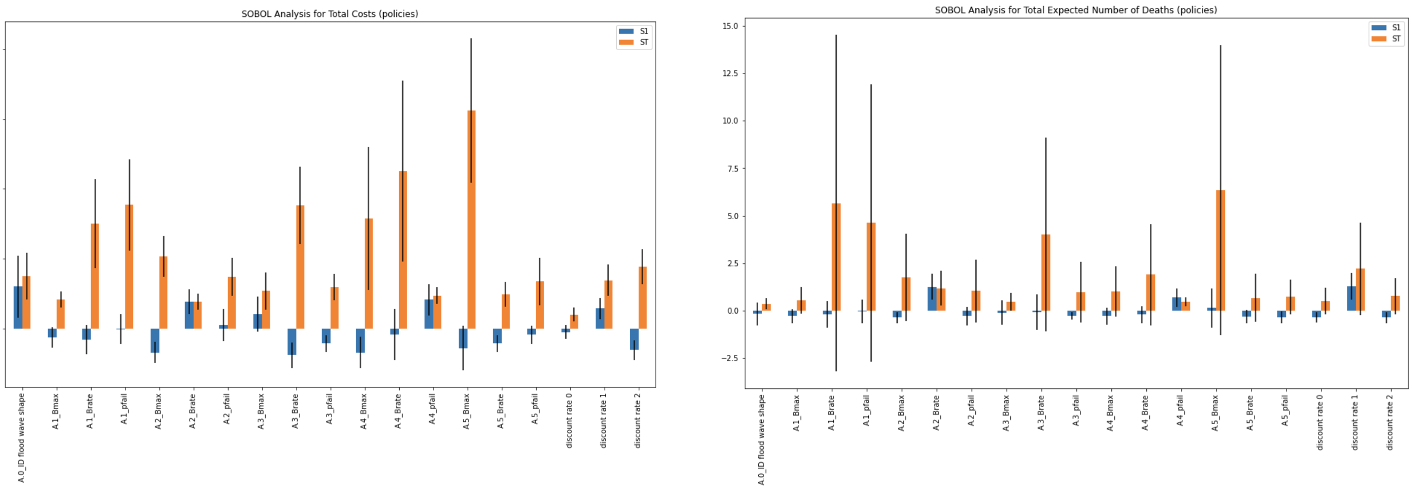


Figure 13 - SOBOL Total Costs & Number of Deaths Policy scenarios

Figure 14 shows the feature scoring for the policies. It is striking but logical that the total costs and the number of deaths per dike ring are influenced the most by the dike failure probabilities of that particular dike ring. The total costs and the number of deaths for A3 for example are strongly influenced by the dike failure probabilities of A3, idem ditto for the other dike rings. The last three columns of the figure show the evacuation costs, the total costs and the total number of deaths. It can be seen that A3 has a significant impact on these values. This can be explained by the high population density of A3 (Zutphen). The 1_RfR1 (policy 1 at location A1 and A2) and 4_RfR2 (policy 4 at location A4 and A5) influence the total costs of RfR the most.

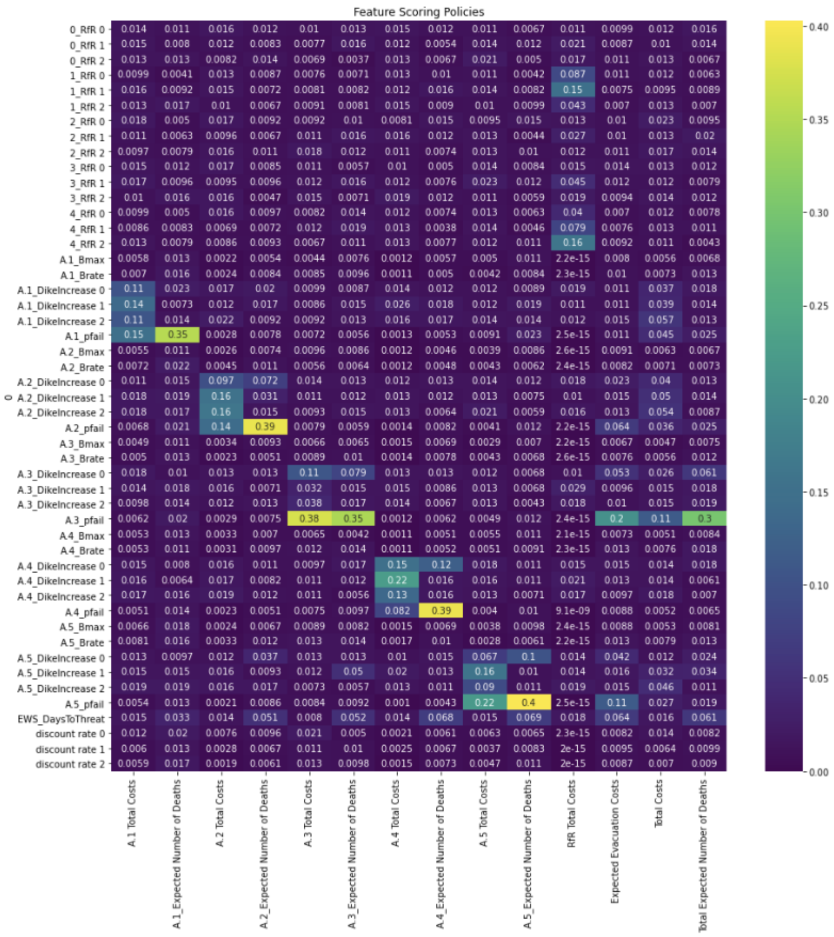


Figure 14 - Feature Scoring Policy Scenarios

3.3.3 Sensitivity Analysis Differences

The biggest difference in the sensitivity analysis for the base case and the scenarios with policy options are the values of the evacuation costs and the costs for RfR in the feature scoring. The reason for this is, as mentioned earlier, that the base case does not implement a policy which means that the values are equal to 0. The similarity in the feature scoring is that the number of deaths in both cases has the largest impact of A3 probability failure. Whereas the probability failure of A1 in the base case causes the largest impact on the total costs, this is the case for A3 with the number of deaths in the policy scenarios. In addition, the values of the total expected number of deaths with policies are considerably higher than in the base case. The ST curve in the base case is around 1.0 and with policies this value increases in 4 cases to around 5.0 or higher.

3.4 Optimization

In this section the results of the optimization using multi-objective robustness optimization (MORO) are presented. Here the KPI's selected in the scenario discovery are linked to the selected policy levers.

3.4.1 MORO

In Figure 15, the number of experiments or nfe's required for a flat curve are presented which are to be plugged into the MultiprocessingEvaluator. The conclusion of this analysis is that the number required comes to 200 experiments.

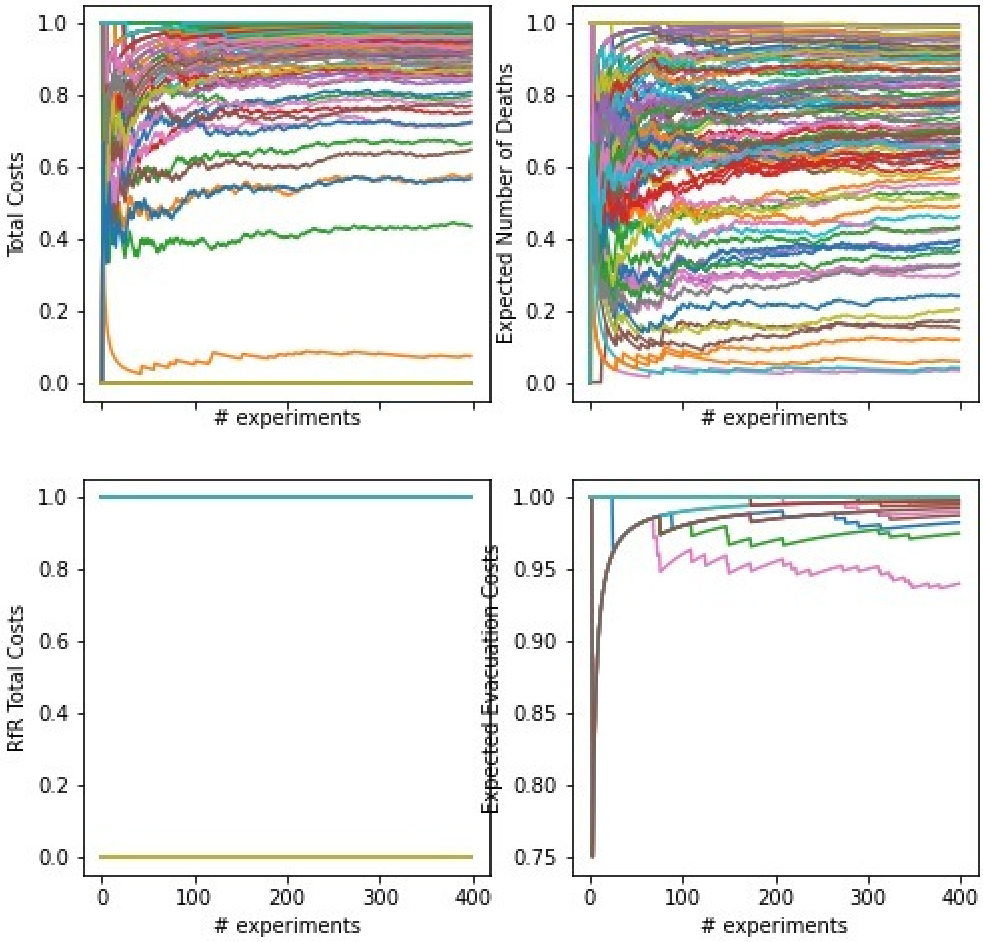


Figure 15 - Number of experiments for a flat curve.

As for the epsilon convergence and hypervolume curves which would have been calculated using the MultiprocessingEvaluator, this was extensively modelled and run. However we didn't manage to clear the errors called up after multiple instances of multithreaded, long run cycles.. This resulted in not being able to finish the MORO and extract meaningful results out of this part. In the attached code the setup and preparation for results extraction has been finished, but the actual running of the code didn't finalise.

3.4.1 Robustness Analysis

For the robustness analysis, the robustness function defined in Kwakkel et al (2015) was used in the attached code. This optimises robustness using the outcomes of interest (linked to KPI's) multiplied by the interquartile distance plus one and displayed in a paracoords graph. These have been completed using 200 experiments. The outcomes of this analysis would have been displayed below, but didn't manage to materialise as error codes kept us from completing this step. As the KPI's specified, the low number of deaths in combination with low-risk strategies and policies would have been preferential to the expected outcome of the robustness analysis.

4. Discussion

It is important to mention that the results generated by the model might not fully represent the actual situation, since the model has several limitations. Therefore indicating these limitations is crucial to measure the validity of the suggested flood management plan. In this chapter, the results of the project will be reflected on. The discussion will address the modelling approach, policy selection and solutions to the model limitations. Additionally, points for further research will be suggested.

4.1 Limitations and solutions

4.1.1 Model

When performing exploratory research using the modelling perspective, it is hard to define the optimal number of scenarios that would produce valid results. One might argue that the more scenarios are used the better, however, we shouldn't forget about computational memory limitations of the equipment and time at our disposal.

Usually, experiments with 1000 scenarios have been performed in this project, however, no technique has been used to determine that this is an optimal number of scenarios to use. As a solution we would suggest being transparent with this number, and simply exclaim it when we report the results. Similar limitation is applied to the number of experiments (nfe) in MORO analysis. However, for the MORO analysis we have indicated that the required number of experiments is 10,000, but this is clearly the absolute minimum and should be increased. The recommended number of nfe couldn't be defined, but we would suggest a range of 20,000 - 100,000. Before finalising the proposal for the flood management plan of the Ijssel, it is recommended to run a complete MORO analysis.

4.1.2 Thresholds

The maximum threshold for death KPI has been set to 0,005. Which is probably not the most intuitive way to express the positive impact of any policy. As it was suggested in the political reflection, all these KPIs could be converted to the percentile improvement compared to the base case scenario, where no policy is applied. In that case, the total costs and number of deaths would drastically increase when compared to the impacts of proposed policy in the flood management plan. Additionally, there was a disucssion about which value from the model to use to reflect on the KPI, the average or maximum value. To stay on the safe side, Rijkswaterstaat decided to report the maximum value for the number of deaths. However, when analysing the results, we encountered that often maximum values represent outliers from the dataset of total values. Therefore we consider using a median instead of a mean, or assign the probability factor to the maximum values.

4.1.3 Ethical implications

In the course of this study the value of a human life has been discussed, in the context of how it could be expressed in financial units. From the technical point of view, that would make the process of result interpretation much easier, since every KPI would be expressed in monetary values. However, we have faced certain ethical barriers when assessing this possibility. For instance, if a human life could be converted into a monetary variable, can it be used to substitute for higher costs for other measures? Finally we have decided to stick to the assigned treshold and operate in the existing categories.

5. Conclusion

In this report, the main objective is to formulate a concise and grounded policy advice to the customer: Rijkswaterstaat. Based on the analysis and discussions completed, a policy advice has been formulated to be perceived as most optimal. In order to be able to provide well-based advice to this objective, the political arena of the multi-actor arena was integrated into the decision making. Out of the political reflection and debates the actors agreed that the policy should be robust and economically viable. A more extensive outlook onto these actors can be found in the political reflection of the debate, also the role as analysts will be played out in more detail. As for the advised policy, this is displayed in table 5.

Table 5 - policy advice

Policy 1	
RfR	Dikes 1,2 and 4
Dike heightening	Area 5
Early Warning system	4 days
Problem formulation	3

Formulated together with Rijkswaterstaat with input of all actors and considerations. Implemented immediately, this policy advice is based on the principle of minimum risk with arguably quite drastic measures. The RfR implemented in the upstream areas is the most effective measure, but some changes have to be implemented also downstream. As dike heightening increases flood risks in downstream areas, these have to be protected in an equal way regarding the giving up of landmass. The interests of the transport company and the environmental group are to be satisfied as both need to be able to operate and fulfil their goals. To ensure the goals of the transport company are taken into account, river navigation needs to be ensured with regards to floodplain excavation. Also the port to be developed by dike ring 3 will not be affected in these measures. In the case of the environmental group, RfR is given a high priority in this advice to ensure compliance on their part.

Maximum death ratios are complied with and the average of these values is well below the threshold of 0,005. But as discussed with Rijkswaterstaat, also the total maximum costs of 750.000.000 euros, the Room for river costs with a maximum of 1.250.000.000 euros and the evacuation costs with a maximum of 50.000 will be met with the advised policy.

The policy recommendations given in this section should give Rijkswaterstaat the position to implement a RfR plan with the considerations of the other stakeholders. A more resilient IJssel river delta as the result of water combating measures.

To safeguard the safety of population centres in the IJssel delta and catchment areas, further research with continuously updated data sets should be conducted to model the effectiveness of measures taken. Further research can also look into the usage of Many-Objective Robust

Decision Making (MORDM) instead of Many-Objective Robust Optimization, to generate more useful insights about the robustness of the chosen policy.
Combatting water is an ever changing battle, so the updated data sets should include the impacts of increased erratic behaviour regarding climate and sea level.

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Appendix

Appendix A: Open Exploration

This appendix shows the multiple results of the open exploration analysis.

Appendix A.1: Base Case

These plots show the relations between the different outcomes for each location separately in the open exploration analysis with the base case.

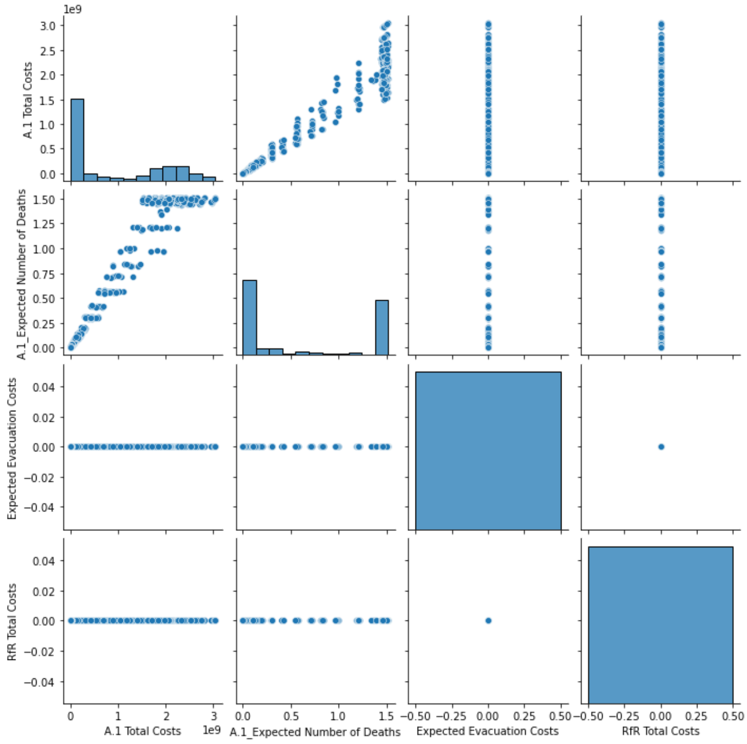

Figure A.1.1 - Doesburg pairplots

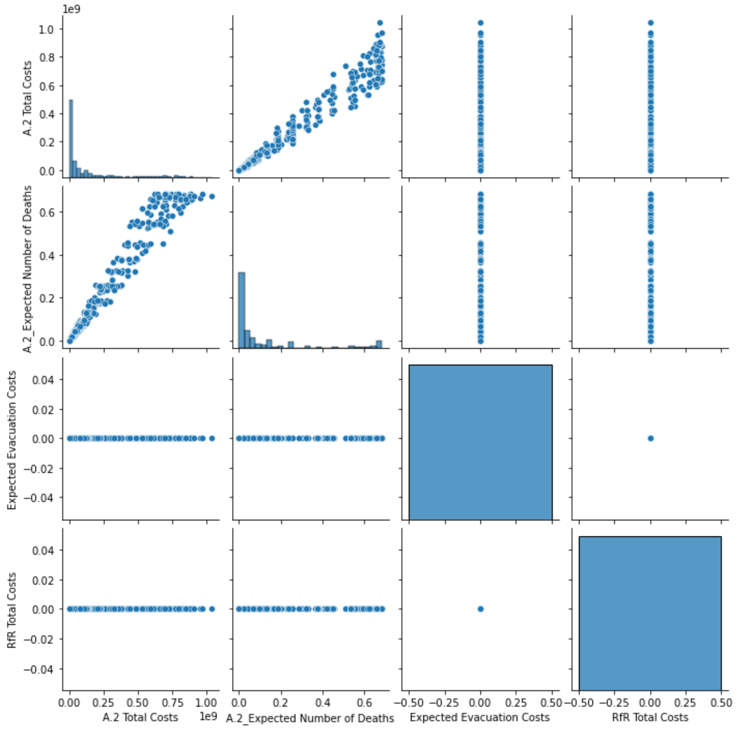

Figure A.1.2 - Cortenoever pairplots

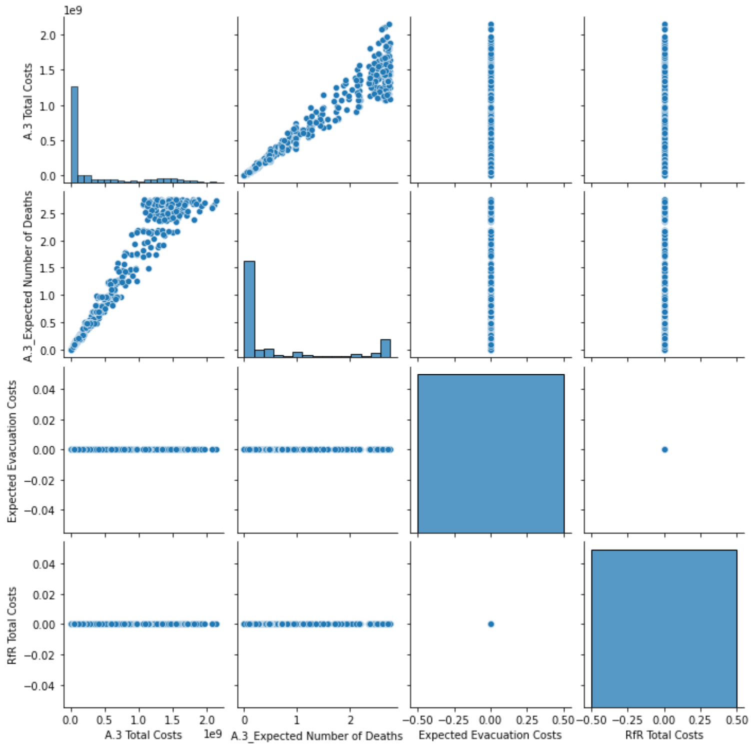

Figure A.1.3 - Zutphen pairplots

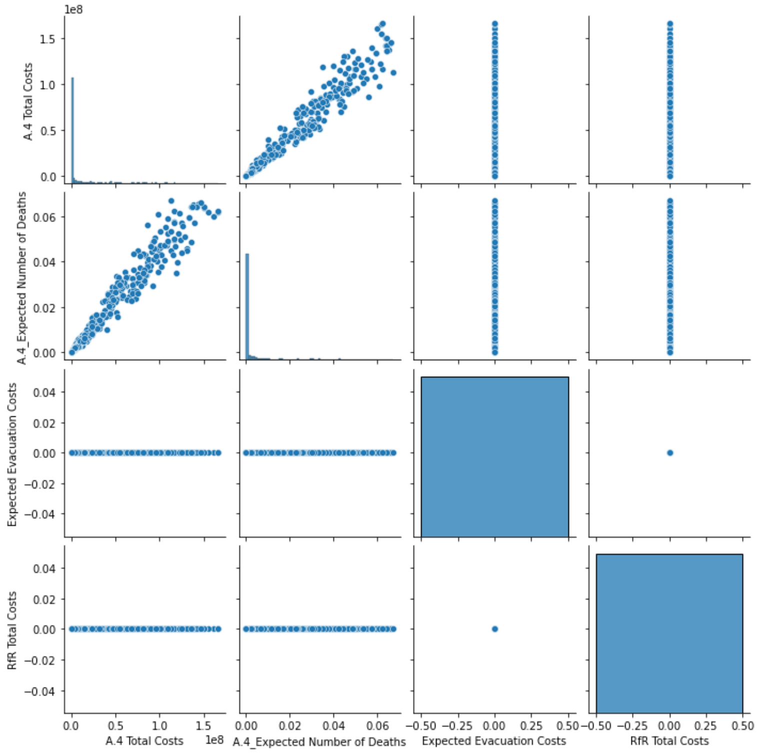

Figure A.1.4 - Gorssel pairplots

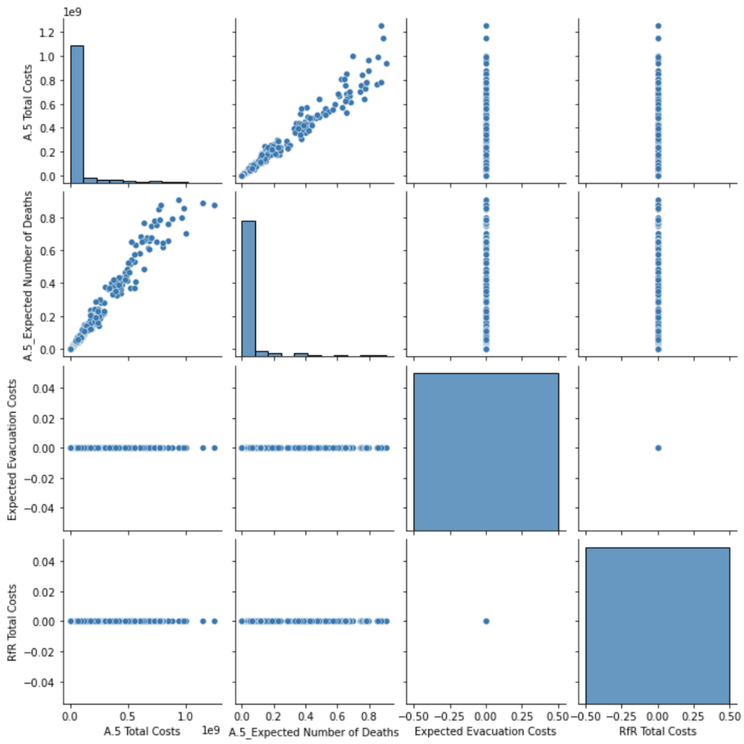

Figure A.1.5 - Deventer pairplots

	A.1_Expected Number of Deaths	A.2_Expected Number of Deaths	A.3_Expected Number of Deaths	A.4_Expected Number of Deaths	A.5_Expected Number of Deaths
mean	0.62127	0.120308	0.626465	0.00742	0.052261

Figure A.1.6 - Mean number of death per location in the base case

	A.1 Total Costs	A.2 Total Costs	A.3 Total Costs	A.4 Total Costs	A.5 Total Costs
mean	9.128055e+08	1.333758e+08	3.531835e+08	1.625533e+07	5.624633e+07

Figure A.1.7 - Mean total costs per locatio in the base case

Appendix A.2: Policy scenarios

These plots show the relations between the different outcomes for each location separately in the open exploration analysis with policy levers implemented.

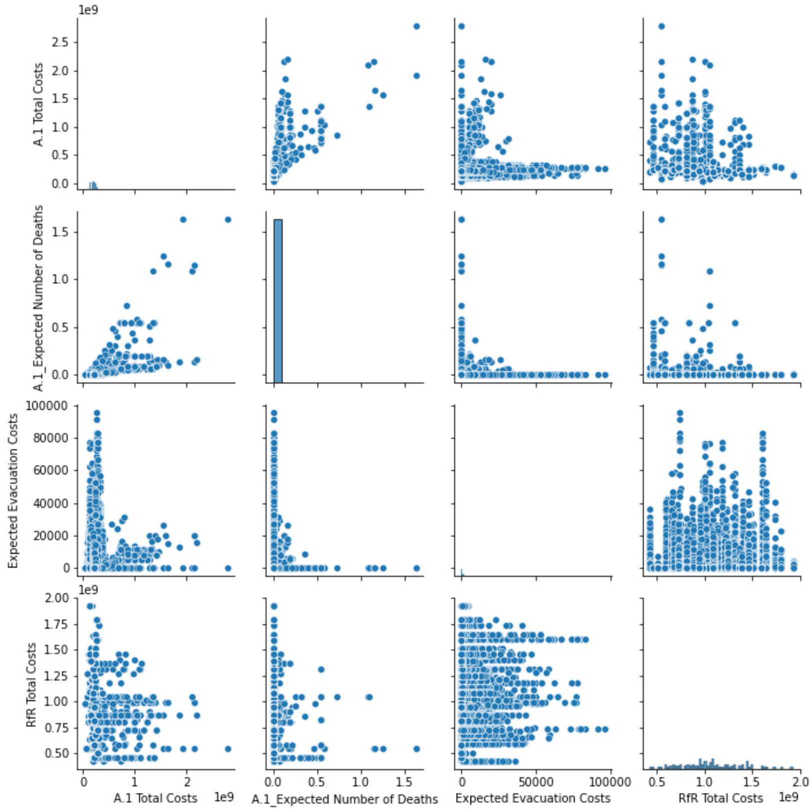

Figure A.2.1 - Doesburg pairplots

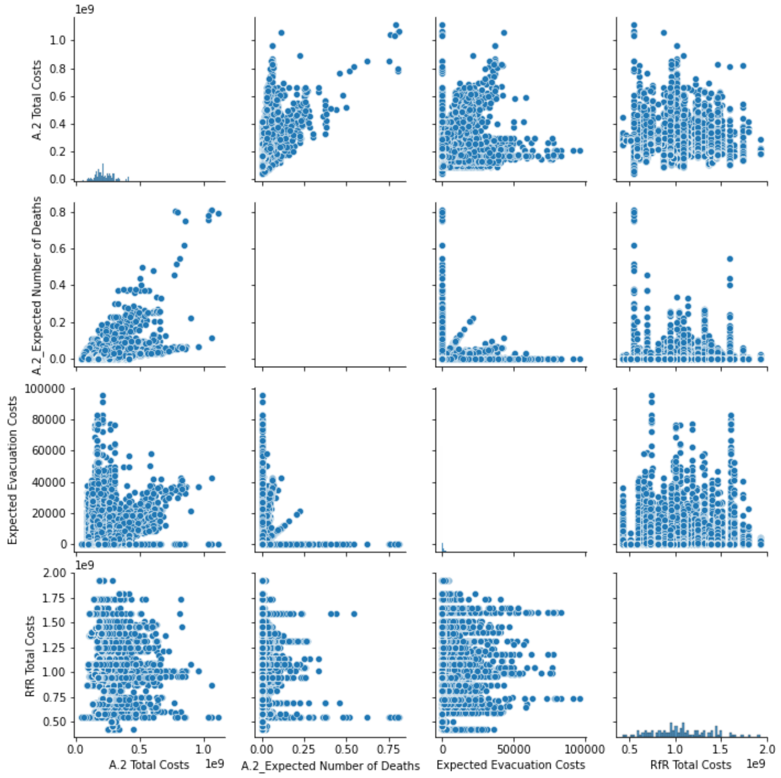

Figure A.2.2 - Cortenoever pairplots

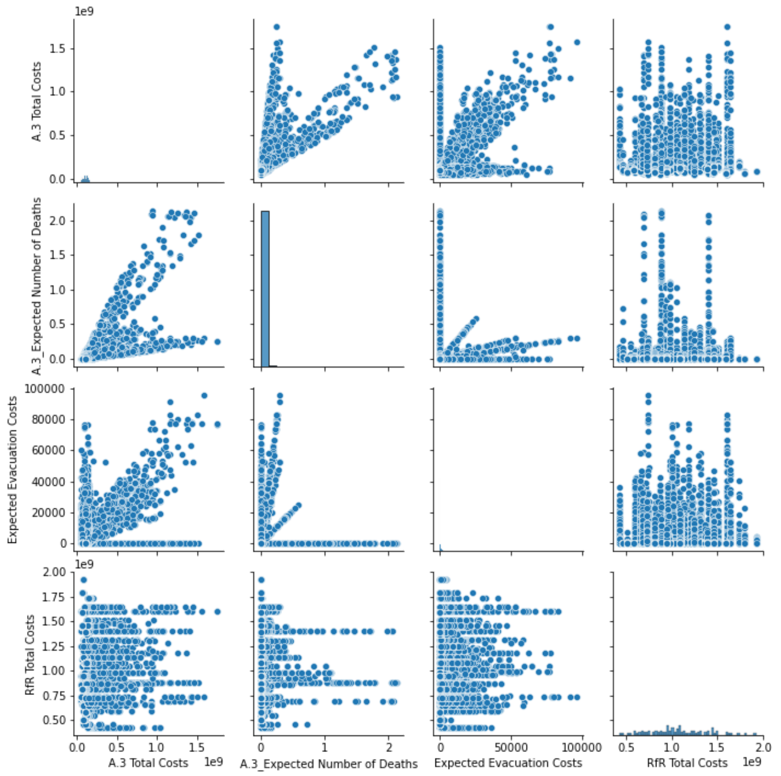

Figure A.2.3 - Zutphen pairplots

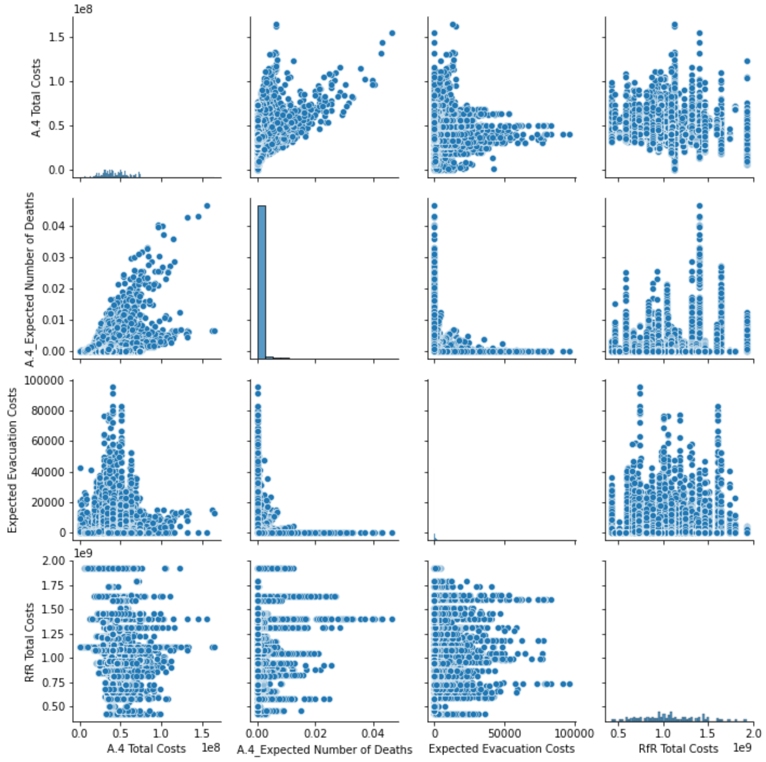

Figure A.2.4 - Gorssel pairplots

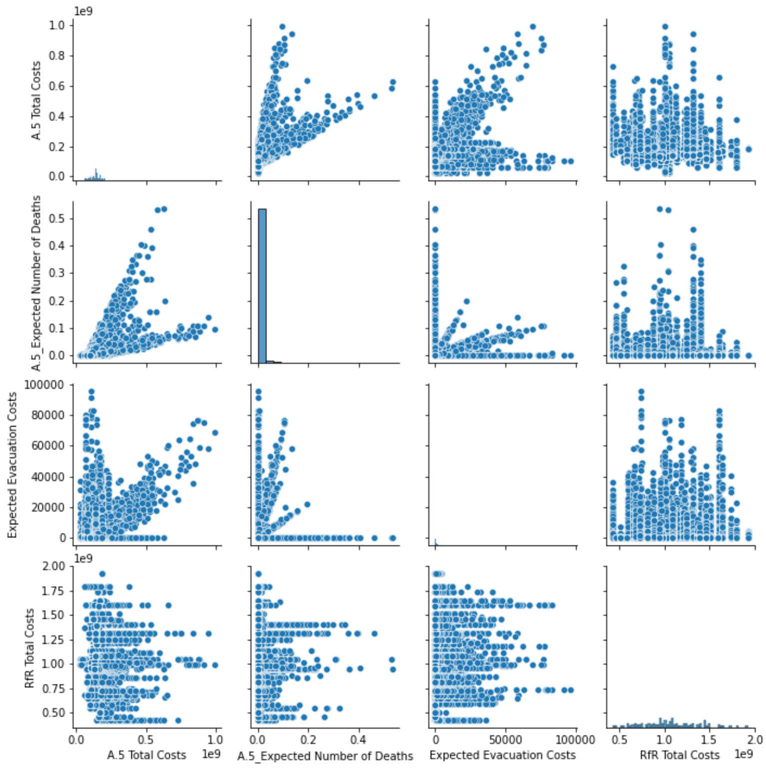

Figure A.2.5 - Deventer pairplots

	A.1_Expected Number of Deaths	A.2_Expected Number of Deaths	A.3_Expected Number of Deaths	A.4_Expected Number of Deaths	A.5_Expected Number of Deaths
mean	0.001696	0.003284	0.0098	0.000299	0.002754

Figure A.2.6 - Mean number of death per location in policy scenarios

	A.1 Total Costs	A.2 Total Costs	A.3 Total Costs	A.4 Total Costs	A.5 Total Costs
mean	2.014180e+08	2.243187e+08	1.174301e+08	4.261769e+07	1.395959e+08

Figure A.2.7 - Mean total costs per location in policy scenarios

Appendix B: Scenario Discovery

Appendix B.1: With policies

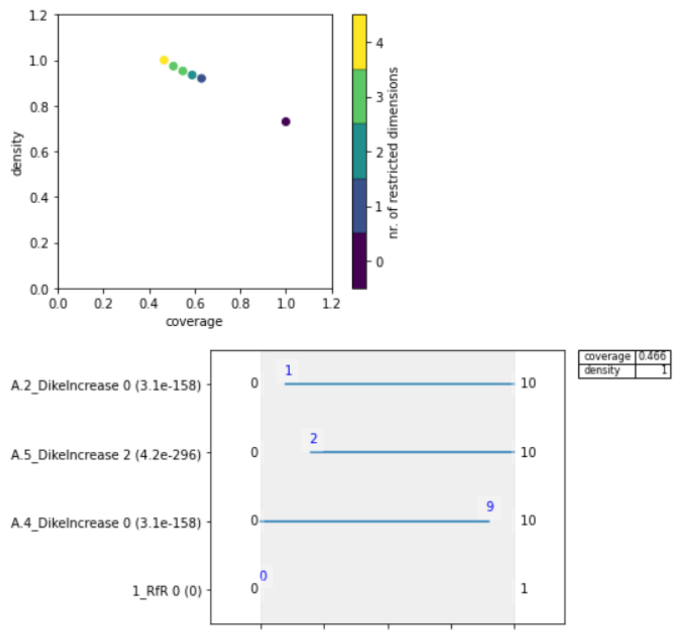

Figure B.1.1 - scenario discovery with policies RFR costs

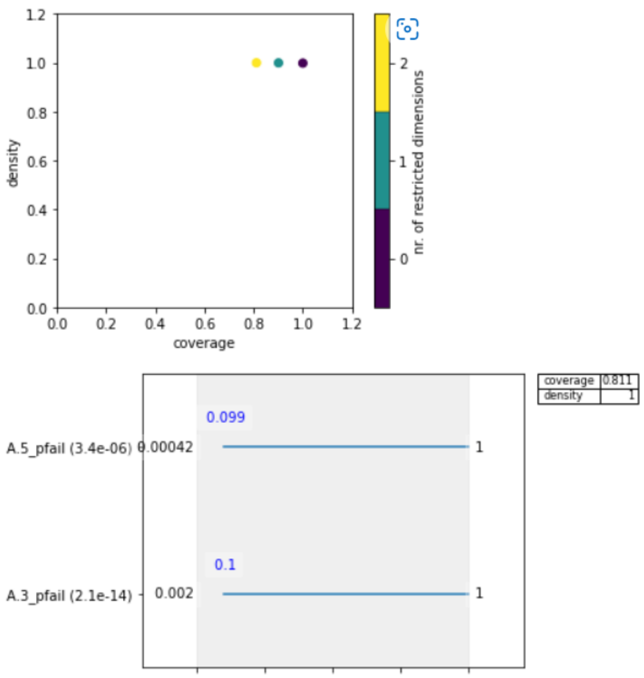

Figure B.1.2 - scenario discovery with policies RFR costs

Appendix B.2: Worst case

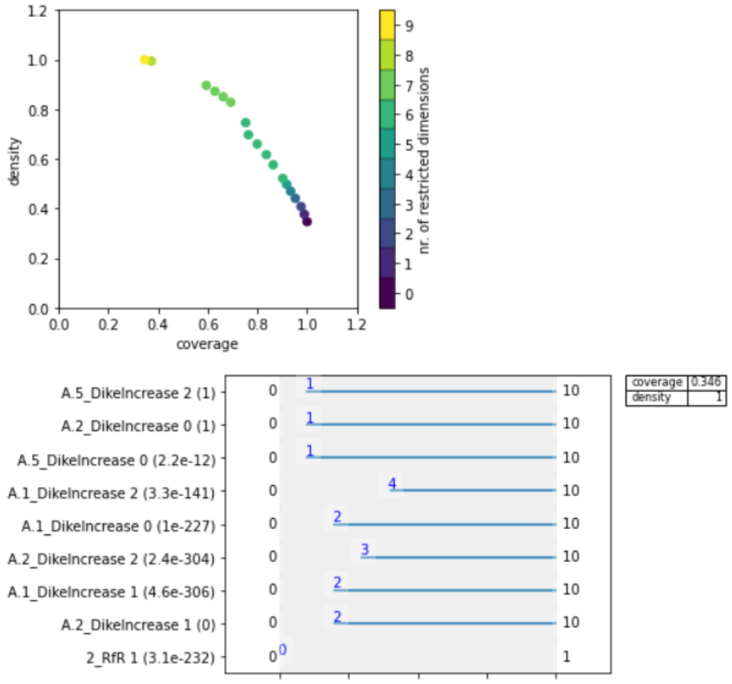

Figure B.2.1 - scenario discovery worst case total costs

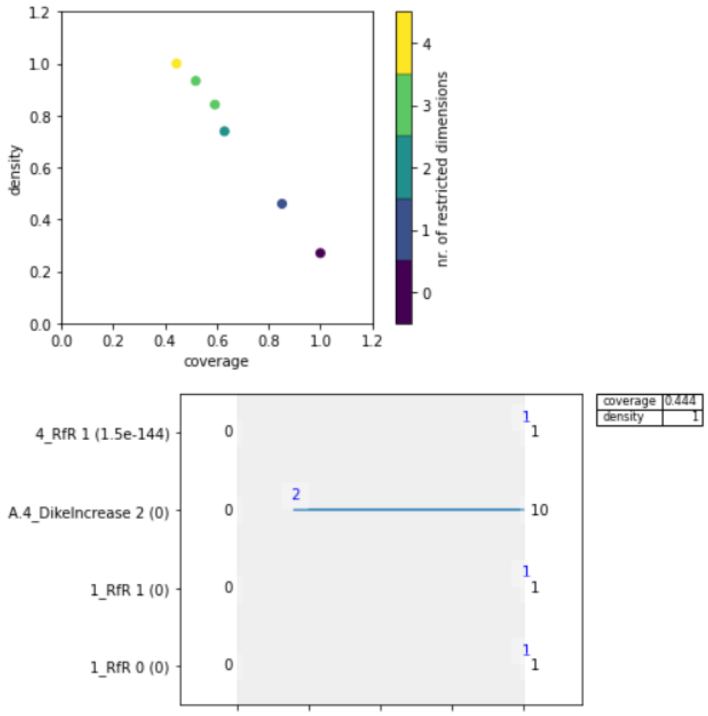

Figure B.2.1 - scenario discovery worst case rfr costs

Appendix C: Sensitivity analysis

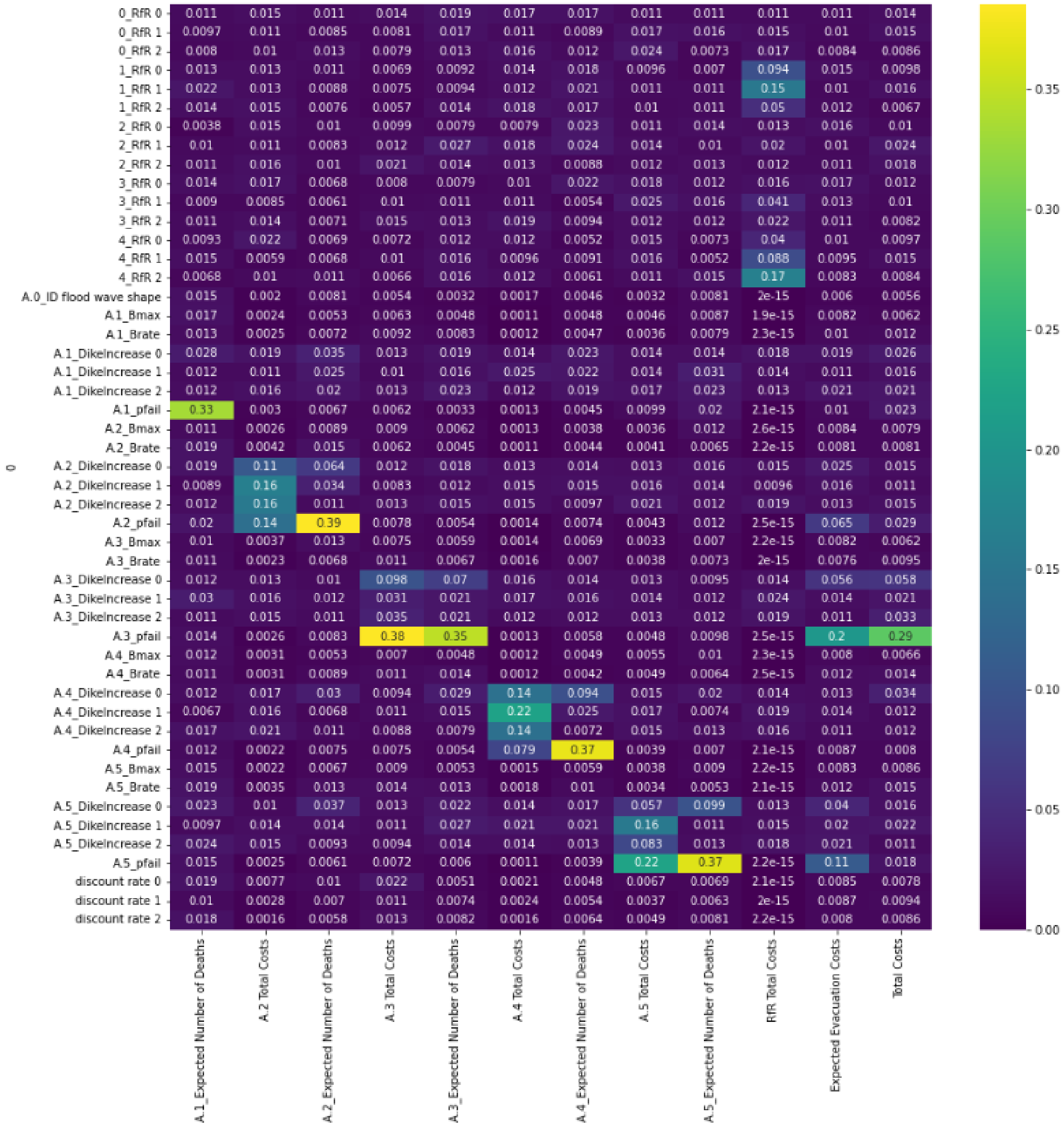

Figure C1 - sensitivity analysis feature scoring