EPA 1361
Model Based Decision Making

Flood Risk Management Plan
for Dike Ring 5 Deventer and the IJssel River Area

Final Assignment

(Flooded IJssel river. Retrieved from https://www.deltares.nl/en/projects/governance-smart-combinations-rules-collaboration-flood-risk-mitigation/)

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Executive Summary

This report analyses flood risk management along the IJssel river under deep uncertainty. Exploratory Modelling and Analysis (EMA) is used in this analysis to study deep uncertainty in this decision-making arena. The deep uncertainty stems from the different unpredictable future scenarios possible in this arena. Using EMA, the model approach involves open exploration, sensitivity analysis, scenario discovery and MORO. By utilizing these techniques on a pre-defined model of flood risk in the IJssel river, various uncertainties and policy levers that influence the outcomes of interest are identified. Lastly, best policy recommendations are identified for the key stakeholders in the study in order to minimize the risk of conflict in the decision-making arena.

Based on applying Exploratory Modeling and Analysis on the model, it is evident for Deventer, the solution would be combination of “Room for the River” project in Zutphen in the Province of Gelderland and dike heightening of 2 and 7 decimetres in Doesburg and Zutphen in the Province of Gelderland respectively. Based on the analysis of the model, while keeping in mind the utmost importance of protecting life, dike heightening will be done in Gorssel and Deventer as well. It has to be noted that this preferred policy is not static over time. These policies evolve with the dynamic changes in the environment due to external factors like climate change and changing characteristics of flow in the IJssel river. Furthermore research for the development of a flood management plan that integrates Dynamic Adaptive Policy Pathways (DAPP) approach with the results from the model needs to be adopted to incorporate these dynamic external factors into decision-making.

The policy has been proposed based on the results of the modelling approach. However, the model did not take into account the aspects such as costs, environmental impact or possible measures implemented by other countries upstream. As the model is a microcosm of reality and does not represent every part of the real world, decision makers should not have a blind faith in the results of the model but use it as the reference of decision-making process. Considering that the proposed policy did not apply the cost constraints such as the budget of Deventer of the Ijssel river area. Therefore, further analysis with environmental impact and cost-benefit analysis to monitor the environmental and financial side of impact of the model would be useful.

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1. Problem Framing

1.1 Context

The flood risk in the Netherlands is steadily growing because of climate change (PBL Netherlands Environmental Assessment Agency, n.d.). The sea levels are rising, parts of the Netherlands that are now below sea level are sinking to even lower levels (a phenomenon known as 'settlement'), the floodplains of rivers are shrinking, and water levels are rising as a result of more frequent and heavier rainfall. Now, more than ever, flood risk management is a topic that is often in the agenda of decision-makers.

In the past, flood protection policies in the Netherlands were focused on strengthening and heightening the flood defenses. However, by doing so the riverbeds between the dykes are subjected to extreme water levels which lead to unprecedented volumes of water to flow onto the land in case of a dyke breach (De Bruijn et al., 2015). Therefore, in order to lower the water level in the rivers and reduce overall flood risk, current flood protection policies are heading towards an integrated river basin management (Rijke et al., 2012).

In order to mitigate the flood threat in the Netherlands the government started the Room for the River project (Schasfoort, et al., 2013). In the case of the flood prone areas along the Ijssel river - which include Doesburg, Cortenoever, Zutphen, Gorssel and Deventer - three flood protection measures are being considered for each location in the Room for the River project. The first measure entails *heightening and strengthening the existing dykes*, the second measure requires *making Room for the River* and the third option is an *early warning system* which will alert the population in the flood risk areas about a possible flood before it takes place. The different mitigation measures may be implemented complementary to one another, they can differ per location and they can be implemented at different times.

1.2 Problem description

The city of Deventer, which is situated along the Ijssel river, one of the major rivers in the Netherlands, has experienced high water levels and high risk of flooding into the surrounding urban area. The increased flood risk is partly due to more rainwater and melting water being discharged from the Rhine into the Ijssel river as a result of climate change (Rijkswaterstaat, n.d.). When floods happen, people are often forced to leave their houses. Floods often incur in material (and sometimes physical) losses. For this reason, the city of Deventer would like to reduce the chances of flooding and manage the anticipated high water levels (Nature Based Solutions, n.d.).

The city of Deventer can implement one of the three mitigation measures mentioned earlier in order to make the city more flood resilient. However, flood management strategies should take into account that actions taken in the upstream of the river could influence the water levels downstream, which adds to the complexity of flood risk management. Given that Deventer is located in the downstream area of the Ijssel river as shown in figure 1, the effectiveness of its chosen strategy will depend on the actions of the other stakeholders located along the Ijssel river. It is assumed that, when implementing or discussing strategies, the city of Deventer values overall safety of the region citizens more than anything else. For this reason, the research is conducted aiming to minimize deaths. The table 1 details the uncertainties and the outcomes of interest in the model.

Table 1: Uncertainties and Outcomes of Interests

Uncertainties	**Outcomes of Interest**
'Bmax': maximum breach in meters (location specific)	Expected annual damage (location specific)
'pfail': probability of failure (location specific)	Dike investment costs (location specific)
'Brate': breach growing rate in meters per day (location specific)	Expected number of deaths (location specific)
'discount rate': discount rate to calculate the expected annual damage	'Room for the River' costs (in total)
'A.0_ID flood wave shape': the type of flood wave shape upstream	Expected evacuation costs (in total)

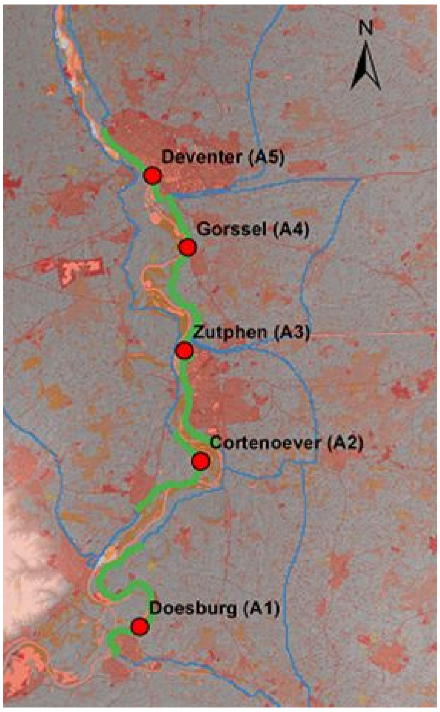


Figure 1. The overview of the Ijssel river area

1.3 Multi-actor nature

There are several different actors with an interest in the IJssel river. These range from cities that the river goes through, companies that use the river to make profit or farmers that farm the land near the riverbed, amongst others. When it comes to river management, the variety of stakeholders that are interested can bring some challenges. By having different goals and different visions on how the river should be managed, the multi-actor nature of this river management can be a quite complex problem. Furthermore, there is another important characteristic of decision-making over a shared river: any action performed by upstream actors will influence the flow of the river downstream. Taking these two points into account, action along the river needs to be coordinated and the political arena in which this decision-making takes place should be considered. In order to have a better overview of these actors and their interests, an actor analysis was conducted (see Appendix A).

In order to achieve a solution that is beneficial for all the actors, the problem should be looked at as a multi-issue game. However, due to time and computational power limitations, the following analysis focuses on the perspective of the city of Deventer and Overijssel at large. Possible solutions and strategies to turn the problem into a multi-issue game are discussed in chapter 4.

1.4 Problem Formulation

Furthermore, the city of Deventer and the various stakeholders involved do not know or cannot agree on the relative importance of the different outcomes of interest, how the system works and how likely possible future states of the world are due to climate change and uncertainty of different factors. For this reason, it can be said that the decision-making process will take place under deep uncertainty (Kwakkel & Haasnoot, 2019).

Overall, finding a flood risk management strategy for the city of Deventer is complex because water safety issues interact with environmental and socio-economic concerns of the different stakeholders involved (Zevenbergen et al., 2013). With this in mind, this paper aims to answer the following research question:

"What flood risk management strategies can the city of Deventer implement in order to guarantee the safety of the region, taking into account the conflicting objectives of the stakeholders involved and the deep uncertainty inherent to the future development of the system?"

1.5 Methodology

In order to analyze the impact of different strategies in flood management, this study will be conducted using a model built by Alessio Ciullo (Ciullo, de Bruijn, Kwakkel & Klijn, 2019). This model simulates the hydrography of the IJssel river and the measures that can be applied to manage flood risk. Then, aiming to provide the decision-maker with a strategy that is successful considering the deep uncertainty of the problem, Exploratory Modeling will be used. This will be executed using the Exploratory Modeling and Analysis (EMA) Workbench, an open source toolkit for exploratory modeling (Kwakkel, 2017a).

1.6 Report structure

In Chapter 2 the chosen methodology will be discussed in more details as well as a motivation for the associated analytical methods used. Afterwards, chapter 3 will present the results from the Exploratory Modeling analysis followed by a critical discussion in chapter 4, including limitations and suggestions for further research. Lastly, chapter 5 will draw conclusions from the result and provide recommendations for a political decision-making discussion.

2. Approach

As mentioned before, decision-making over flood risk management in the IJssel river is characterized by deep uncertainty. To account for this, we propose a combination of techniques. In the first step of the modeling approach will be to find the worst-case scenario. By going with this maximum approach, we make sure our policy interventions perform well in every possible scenario. We use PRIM to find the scenarios that are assumed to be worst-case. This approach is explained from subsections 2.1.1 to 2.1.4.

Based on the worst case scenarios found, multiple policies that can mitigate and prevent the effects of the worst scenarios can be found. Multi-Objective Robust Optimization (MORO) will be used to find the most robust policy interventions that can deal with the worst-case scenarios. MORO searches for policies that are not sensitive to changes in the scenarios. The worst-case scenarios without any policy interventions will be utilized by MORO to run its optimization. MORO will be used to find robust policies since the uncertainty space is large with some unpredictable external factors. MORO finds the most robust solution by running multiple times to attain convergence. The converged solution space will contain the most robust policy interventions that may not work for all the scenarios under study but will help in pinpointing policies that the stakeholder can apply. This could be applying either room for river or heightening of dikes or both.

2.1 Exploratory modeling

Introduced by Bankes(1993), exploratory modeling uses 'computational experiments to assist in reasoning about systems where there is significant uncertainty' . In order to provide decision-makers with an analysis that takes into account the uncertainty of the future development of the system, an exploratory modeling approach is taken for this assignment. To conduct this, the Exploratory Modelling and Analysis (EMA) Workbench (Kwakkel, 2017a) is used. This workbench is built around the concept of a XLRM framework, in which X, L, R and M refer to the four types of factors that are used in the analysis. The key idea is that both external factors (X, over which the decision-maker has no power in and are the source of uncertainty in the system) and policy levers (L, actions that decision-makers can consider or adjust) influence a system and the relationships in it (R), resulting in outcomes (or performance metrics, M) (Kwakkel, 2017a). Figure 2 shows an overview of the framework and its conceptualization, while Appendix B has extensive explanation over these factors on the specific case being studied.

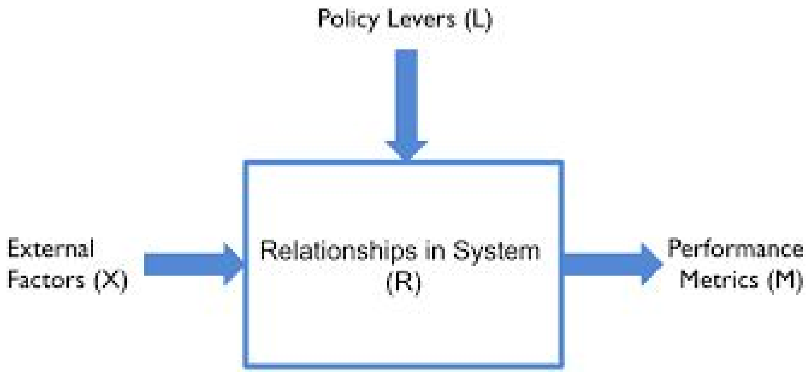


Figure 2: XLRM framework (Kwakkel, 2017a)

2.1.1 Open Exploration

Open exploration is an exploratory modeling systematic sampling method that helps mapping uncertainty in uncertainty space or levers in decision space to outcome space (Kwakkel, 2017b). More specifically, the scenarios are points in uncertainty space and policy levers are points in decision space, and when both of these are combined they form an experiment (Kwakkel, 2017b). Both uncertainties and levers can be continuous, integer or categorical parameters, whereas outcomes are scalar, array or time series (Kwakkel, 2020a). Open exploration heavily relies on sampling to understand the behavior of a modelled system across the entire space or every assumption (Kwakkel, 2020a). By default the workbench uses Latin hypercube sampling which samples over uncertainties and levers using uniform distribution and as a result gives much complete sampled space when compared to Monte-Carlo sampling (Kwakkel, 2017b; 2020a). Equally spaced/complete sample space (uniform distribution) is much preferred over sample points accumulated at one area (normal distribution), because it helps us develop better confidence and reasoning for each part of space rather than having varying confidence and reasoning for a normally distributed space (Kwakkel, 2020a). Open exploration helps in identifying every outcome in outcome space and selecting most favorable outcomes of interest using scenario discovery or sensitivity analysis.

2.1.2 Sensitivity Analysis

Sensitivity analysis is defined as "the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" (Saltelli, 2002; Saltelli et al., 2019). In other words, it locates the source of uncertainty in model input given the model output. Moreover, it contributes to a "plural and conditional approach" in assessing uncertainty, ultimately making it easier for decision-makers to interpret and communicate the results and assigning credibility to the model (Jaxa-Rozen & Kwakkel, 2018; Stirling, 2010). It not only helps us understand which particular parameter(uncertainty and policy lever) has a greater influence on a particular outcome of interest but also gives an insight into the cause behind the behavior of the model as a whole.

Sensitivity analysis is of three types : global, regional and one-at-a-time (OAT). While OAT sensitivity is suitable for linear models and samples only one input at a time, leading to inaccurate results , we perform global sensitivity technique which is based on sampling uncertain inputs simultaneously

(Saltelli et al., 2019). Another alternative to global sensitivity technique can be feature scoring to perform factor prioritisation (Kwakkel, 2017a).
There are three ways in which global sensitivity analysis can be performed: linear regression, Sobol indices and Extra-trees/Random forests. As our model is based on non-linearity, linear regression method is opted out and either Sobol indices or Extra-trees/Random forests methods are suitable for our model. Although, Sobol method is considered computationally expensive, it produces accurate results and is user-friendly (Kwakkel, 2020b). On the other hand, Extra-trees/Random forests is also fast, but considering it is a machine-learning technique and its limits are still unknown (Kwakkel, 2020b), it not only hinders our perception of its underlying working but also retracts our trust in it. Hence, we choose the Sobol method for performing global sensitivity analysis.

2.1.3 Scenario Discovery

Scenarios are common ways to clearly communicate and describe uncertainties in decision-making efforts. These scenario based decision making do not gather collaborative support among stakeholders with diverse interests and values. This necessitates a model-driven, computer assisted, participatory approach to scenario development called scenario discovery (Bryant & Lempert, 2010). Scenario discovery can be done by utilizing two algorithms namely Patient Rule Induction Method (PRIM) and Classification and Regression Tree (CART). PRIM is a “bump-hunter” or “activity region-finding” algorithm that iterates to create a series of hyper-rectangular boxes called “peeling trajectory”. These series of boxes become increasingly smaller and denser as the mean of the output within these regions becomes significantly higher than the overall mean of the dataset. The “Patience” part of PRIM is that it peels away only a small amount of data during each iteration(Lempert, Bryant & Bankes, 2008). CART provides outputs in the form of a decision tree, where the branches of the tree develop based on a hierarchical set of splitting rules to determine output depending on the combinations of input(Breiman, 1984).CART can work without user input while PRIM needs the input space to iterate over. PRIM has better user interactivity and interpretability than CART(Lempert, Bryant & Bankes, 2008). PRIM will be used for analysis since it is more favourable.

2.1.4 Robust optimization

As the future developments of the scenarios are uncertain, successful policies are the ones that not only help actors achieve their goals but also strategies that manage to achieve this in a wide range of different scenarios. In other words, optimal solutions for problems characterized by uncertainty should be robust (Maier et al., 2016). In order to find policies that fit under this description, different techniques can be used. Recent approaches to tackle this include Many-Objective Robust Decision Making (MORDM), Multi-Scenario Many-Objective Robust Decision Making (Multi-Scenario MORDM) and Many-Objective Robust Optimization (MORO) (Bartholomew & Kwakkel, 2020). All these techniques use a process in which previously identified policy solutions are compared and analyzed on how uncertain factors affect their performance. Then, with this information, the policies used initially are fine-tuned to result in more robust alternatives (Bartholomew & Kwakkel, 2020). This is done iteratively. In order to start this analysis, any of the techniques need a list of promising alternatives.

For this analysis, MORDM uses one reference scenario. This can lead to policies performing poorly in scenarios that differ from the reference scenario used during the search. To overcome this, multi-scenario MORDM repeats the search for different scenarios that represent conditions that are difficult to address with reference scenario solutions. Instead of considering a single scenario, MORO considers a set of scenarios and optimizes robustness of the strategies over this set. By considering robustness in the search phase, MORO gives a higher guarantee that the solution reached through the method is robust (Bartholomew & Kwakkel, 2020). As the goal of the actor we represent is to minimize deaths in the entire region, we are aiming to achieve a solution as robust as possible - it is not acceptable for our actor to propose a policy that might perform poorly in any scenario and possibly resulting in deaths. For this reason, MORO is the chosen method for this assignment.

One of the advantages of MORO is that it uses scenarios sampled from the deep uncertainty space instead of previously selected regions, leading to results that are less dependent on the choice of scenarios. However, this also entails some limitations. As MORO uses scenarios sampled from the complete deep uncertainty space, it is necessary to make these samples representative of the entire space. For this reason, more samples are necessary than when using multi-scenario MORDM, leading to higher computational power. Considering that there is a time constraint for the project and the team has a limited computational power available, this might result in less flexibility in the number of analyses performed. Another limitation of this method is related to the price of robustness - as we are looking for the most robust solutions possible, it is likely that these might not be optimal in any of the scenarios (Sniedovich, 2016). However, due to the goal of the actor we are representing, we believe that MORO is, nonetheless, the best method to use.

Finally, during this search for robustness, it is necessary to establish what robustness metric is being used. This and other considerations will be covered in Chapter 3.

3. Results

In this section, the results from the model analysis using approaches discussed in the previous section will be presented. The predefined dike model has 17 outcomes with 5 categories, expected annual damage, expected annual deaths, dike investment cost, evacuation costs and Room for the River costs. As this plan aims to not only reduce Deventer's damage and casualties, but also reduce the total damage and casualties, the priority has been set as to minimise total expected annual deaths and damage.
The model specification used in the dike model can be found in Appendix B. The analysis is conducted with the EMA workbench (Kwakkel, 2017a). The five locations of the Ijssel river area are assigned tags to distinguish them in results. Five tags are described in Table 2.

Table 2: Tags for the Ijssel river area locations

Tag	A.1	A.2	A.3	A.4	A.5
Location	Doesburg	Cortenoever	Zutphen	Gorssel	Deventer

3.1 Open Exploration without Policy (Base Case)[1]

A base case was defined as a situation in which no policy has been introduced, therefore, levers in the dike model are zero. This base case was used for the open exploration, and sensitivity analysis and scenario discovery. Considering that the base case can be a good reference scenario of policy implemented scenarios, the outcomes of base case were not aggregated and remained as 17 objectives. It can be aggregated depending on the further analysis. The relevant ipython notebook file is saved as '3.1 Open Exploration with Base Case.ipynb'.

3.1.1 Open Exploration

First, an open exploration with a base case is conducted with 1000 scenarios. This base case is the current situation and its future development when no policy is applied. Since there is only one scenario, 1000 experiments were computed with 17 objectives. Figure 3 describes the overview of expected annual damage of each dike ring over time steps, under the circumstance that no policy has been implemented in the Ijssel river area. It is clear that A.1 has a significant amount of damage. Figure 4 indicates the average values of expected damage per dike rings. A1 has the most of damage and A3 also has relatively high damage compared to other locations.

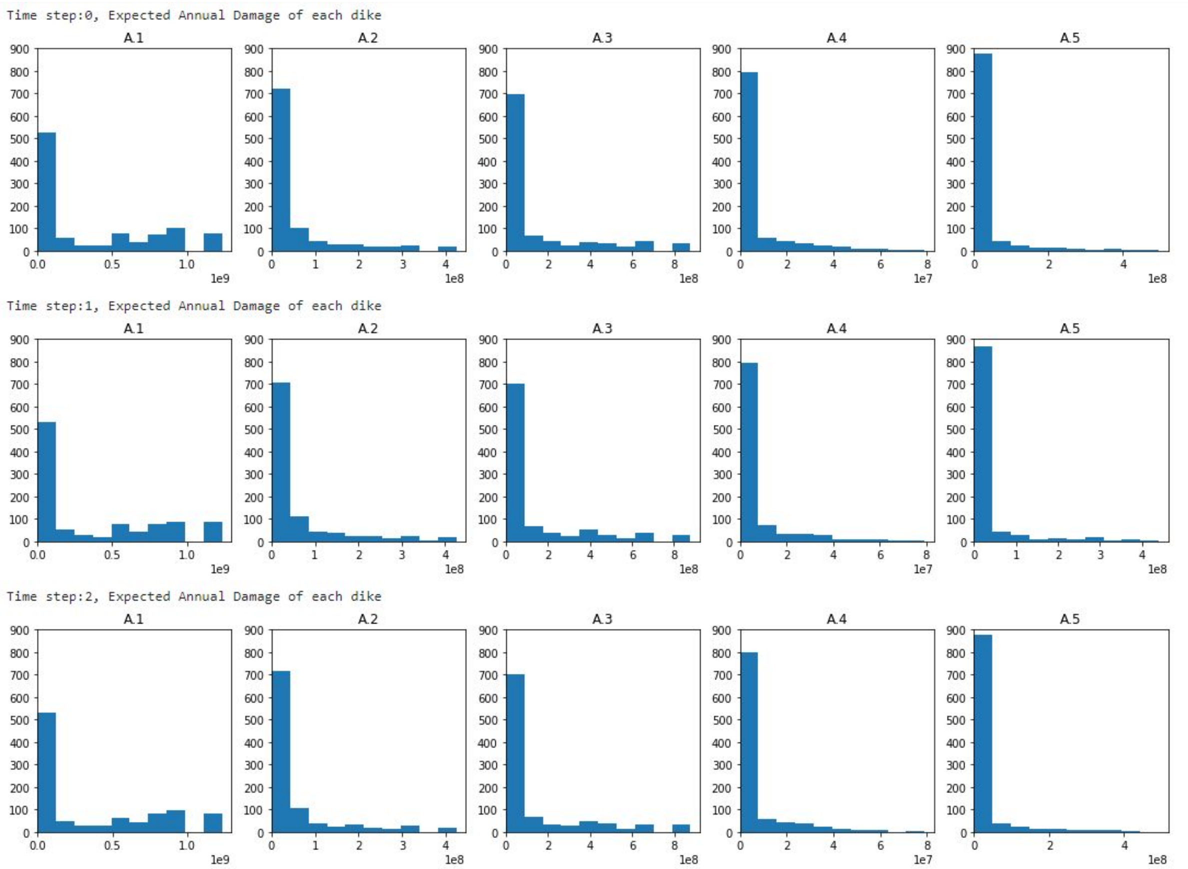


Figure 3. Expected Annual Damage of each dike over 3 time steps

[1] Python notebook '3.1 Open Exploration without Policy'

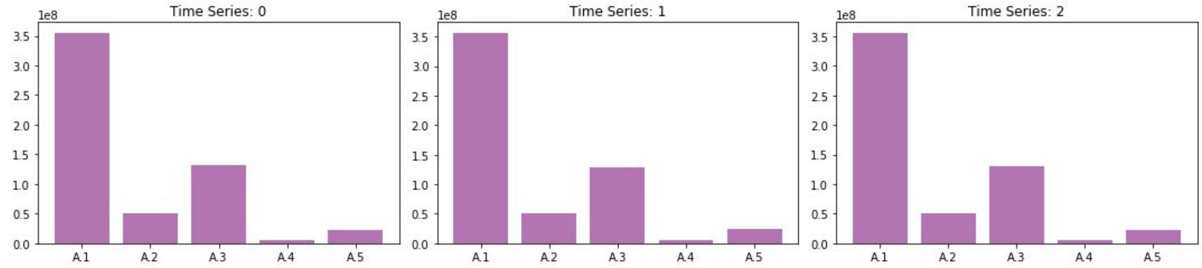


Figure 4. The average of Expected Annual Damage of dike rings

Figure 5 and 6 show the results of expected annual deaths of each dike ring in the same format with figure 2 and 3. As the mean of expected annual damage did, A1 is expected to have the most casualties. However, the results of A3 are worth notice, expected casualties of A3 is as high as dike ring 1 unlike the difference between A1 and A5 of expected damage.

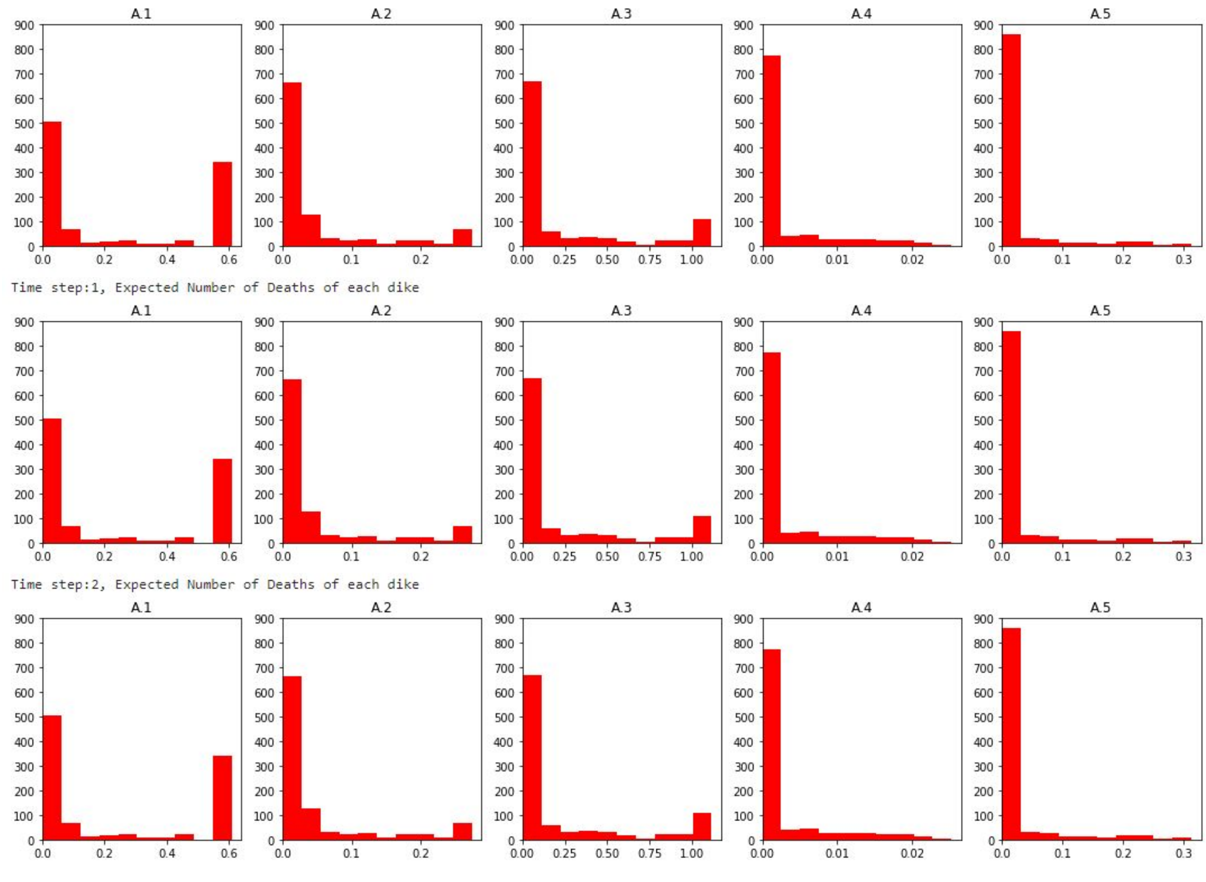


Figure 5. Expected Number of Deaths of each dike over 3 time steps

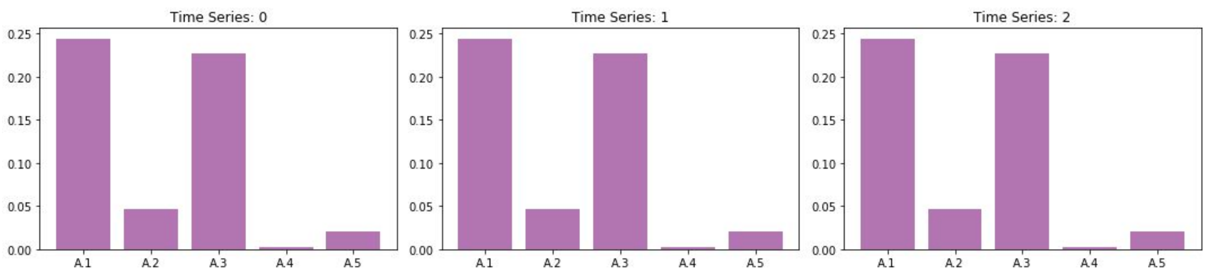


Figure 6. The average of Expected Number of Deaths

3.1.2 Sensitivity Analysis

For the sensitivity analysis, feature scoring and sobol sensitivity analysis using SALib were conducted. First, feature scoring is a simple global sensitivity analysis, and one can have a quick grasp of uncertainties which have an impact on the selected or interesting outcomes. In addition, feature scoring requires relatively low computational power and gives a visual overview.
Among 17 objectives, only an expected number of deaths and expected annual damage were taken into account. These two categories are the priority of the flood management plan, thus, each category was aggregated to the sum of all dikes and time steps. Figure 6 shows the feature scoring results over two aggregated outcomes. Total expected annual damage is highly depending on the probability of failure in A1, Doesburg. The probability of failure in A3 affects the total number of deaths.

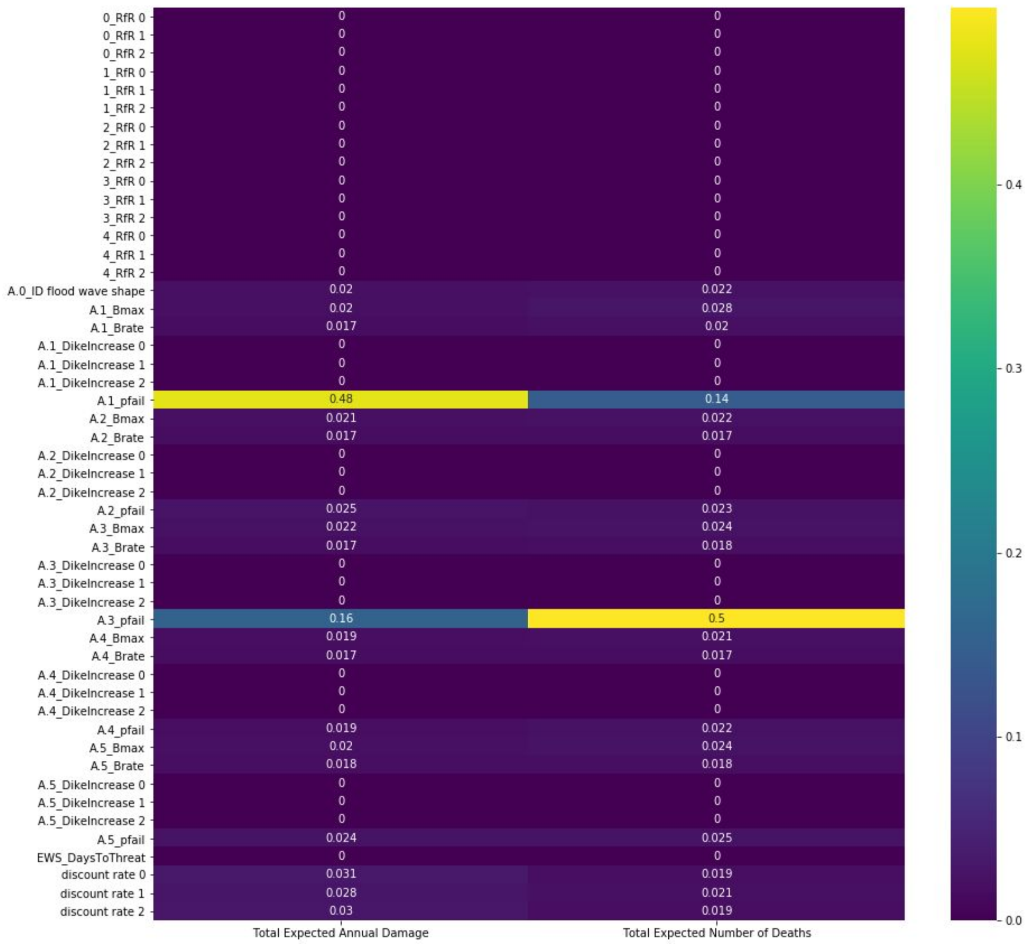


Figure 7. Feature scoring analysis of aggregated outcomes

Following the feature scoring, the global sensitivity analysis method with more advanced sampling techniques, Sobol, was used. 1000 scenarios were passed to ‘perform_experiments’ and by N * (2D + 2) where D is the number of uncertain parameters, it got multiplied by 40. Figure 7 depicts the results of sobol analysis to model uncertainty variables over the total expected number of deaths.

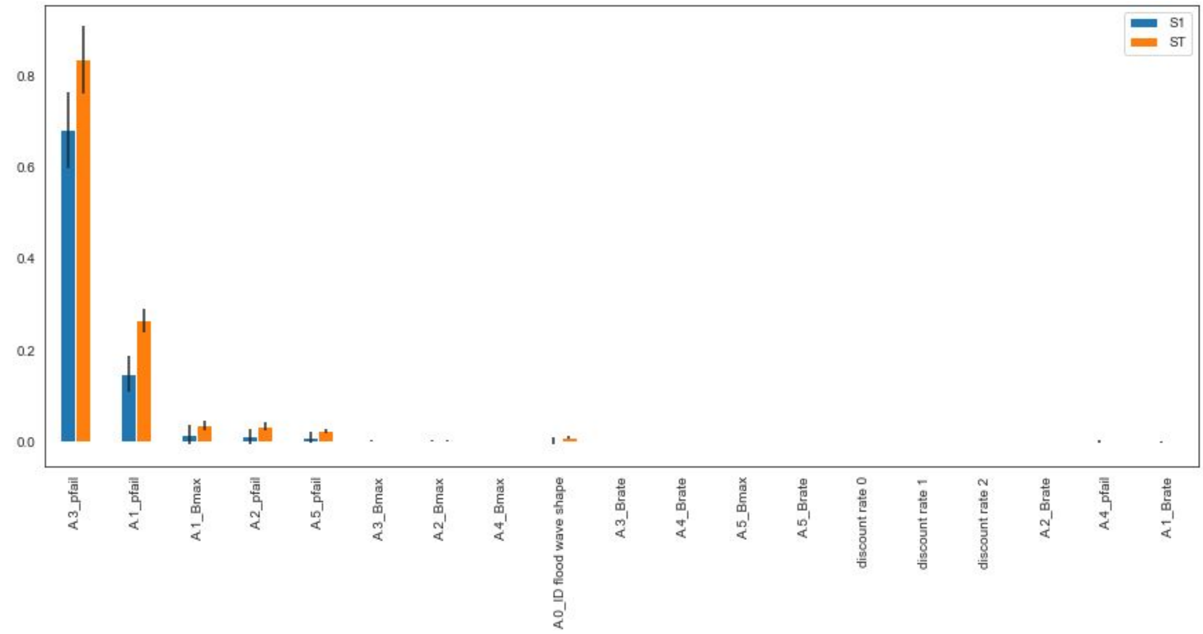


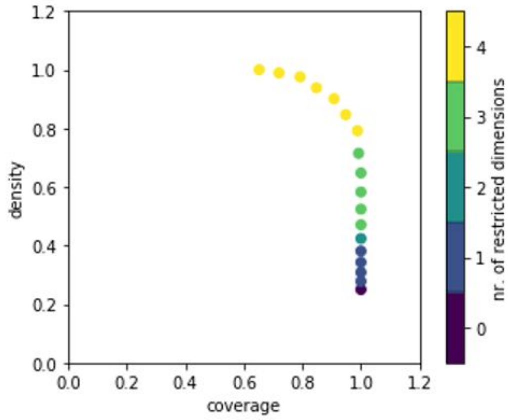
Figure 8. Sensitivity Analysis using SOBOL for uncertainties on Total Expected Number of Deaths

The orange bar represents S1, the first-order effect of input variables on the outcome, and the blue bar represents the total effect impact on the outcome, ST. Compared to A3_pfail and A1_pfail, other uncertainties have a neglectable impact on the total expected number of deaths. In figure 6, the graph implies the current situation will lead to high casualties in dike 3. Through two sensitivity analysis, we can deem that the probability of failure in A3 has a significant impact not only to dike 3, but also to the total number of deaths.

3.1.3 Scenario Discovery

To conduct the scenario discovery, the original results with 17 objectives were aggregated into two outcomes of interest. As reducing the total losses is a priority, total expected annual damage and total expected number of deaths were selected as the new outcomes data. Total outcomes were calculated by adding all damage or deaths over the dike rings and time steps. First, scenario discovery using PRIM is executed with total expected deaths - the first priority. To do that, the outcome was specified to a certain range of interest by setting the threshold. This threshold was chosen to accept only the lowest 25% of outcomes to meet the aforementioned priority.

	coverage	density	id	mass	mean	res_dim
0	1.000	0.250000	0	1.000	0.250000	0
1	1.000	0.277778	1	0.900	0.277778	1
2	1.000	0.308642	2	0.810	0.308642	1
3	1.000	0.342936	3	0.729	0.342936	1
4	1.000	0.381098	4	0.656	0.381098	1
5	1.000	0.423729	5	0.590	0.423729	2
6	1.000	0.470810	6	0.531	0.470810	3
7	1.000	0.524109	7	0.477	0.524109	3
8	1.000	0.582751	8	0.429	0.582751	3
9	1.000	0.647668	9	0.386	0.647668	3
10	0.992	0.714697	10	0.347	0.714697	3
11	0.988	0.791667	11	0.312	0.791667	4
12	0.948	0.846429	12	0.280	0.846429	4
13	0.908	0.900794	13	0.252	0.900794	4
14	0.848	0.938053	14	0.226	0.938053	4
15	0.792	0.975369	15	0.203	0.975369	4
16	0.720	0.989011	16	0.182	0.989011	4
17	0.652	1.000000	17	0.163	1.000000	4



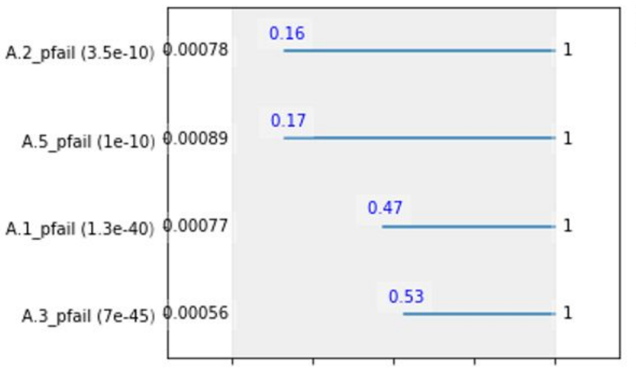


Figure 9. The PRIM results using total expected number of deaths and the 14th box

The 14th box was used to analyse as it had more than 80% of coverage and density. From figure 9, it is visible that A.3_pfail, the probability of failure of dike 3, has the most significant influence on the results, the total expected number of deaths. Alongside that, the probability of failure of dike 1 also has an impact on the results. Not as much as A3_pfail and A1_pfail, but the failure of dike 5 and 2 also have some amount of impact. It can be also verified by the dimensional stacking of figure 10.

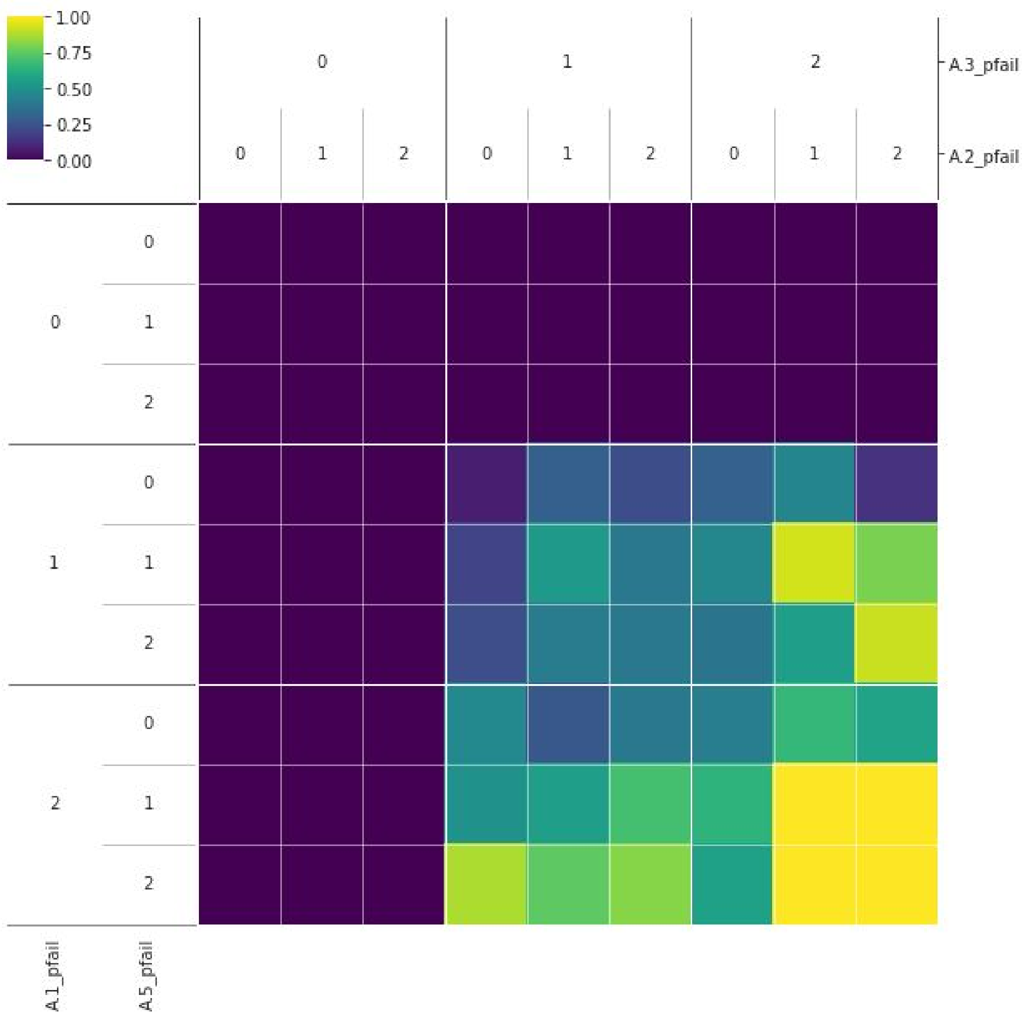


Figure 10. Dimensional Stacking for the outcome - Total Expected Number of Deaths

Figure 7 already explained that A.1_pfail has an impact on the total expected annual damage whereas A.3_pfail has an impact on the total expected number of deaths. By figure 10, it is clear that when the probability of failure at A1 and A3 have a high probability, the desired outcome will be drawn by it.

3.2 Open Exploration with 17 Objectives with Policy [2]

After analysing a base case of no policy implementation, 75 random policies with 1000 scenarios were compared to the base case. The comparison can be used to see the consequences of implementing policies.

3.2.1 Comparison with Base Case

Among the five categories of 75 policies outcomes, two of them were chosen as criteria to compare with a base case. Expected annual damage and expected number of deaths of each dike and time step were selected and used to produce the average values. Figure 11 and 12 implies that policy implementation will have better consequences than the future development of the current situation.

[2] Python notebook '3.2 Open Exploration with 17 Objectives with Policy.ipynb'

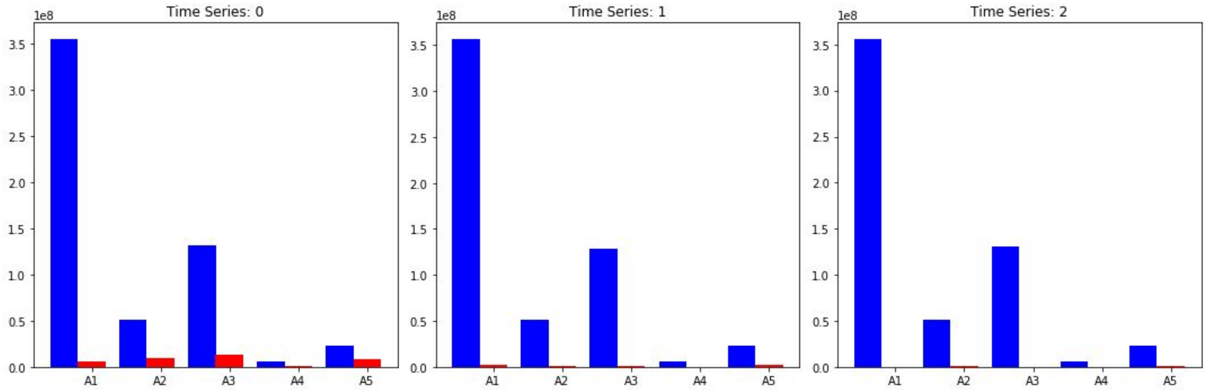


Figure 11. Comparison between the Base Case and 75 Policies of the average expected annual damage of dikes

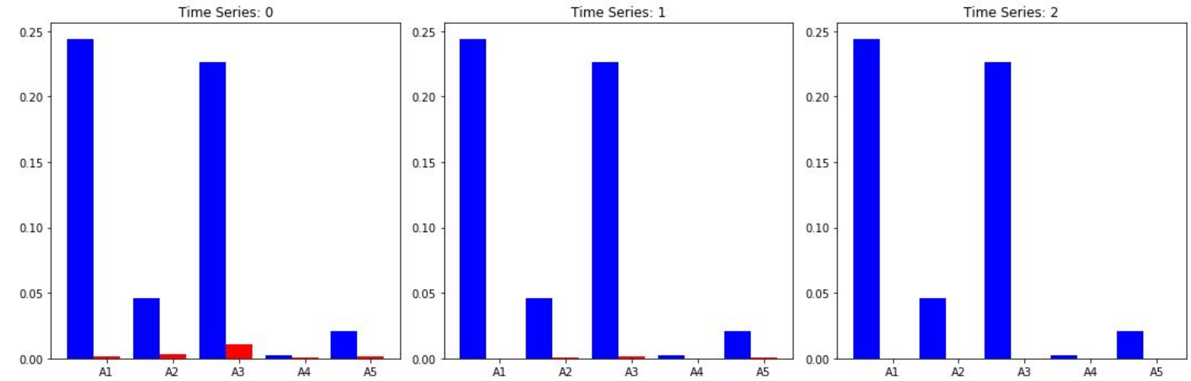


Figure 12. Comparison between the Base Case and 75 Policies of the average expected annual damage of dikes

However, as figure 11 and 12 have a limitation to give specific information of each policy as the figures only show the mean values of the overall policies. Figure 13, 14 and 15 are the scatter plots showing the results of expected damage and casualties over the three time steps. One plot represents the one dike, and a dot represents the result of one policy implementation. Vertical lines are the corresponding expected annual damage of respective dikes and time steps whereas horizontal lines are the expected number of deaths of respective dikes and time steps. The x-axis, y-axis, a vertical line and a horizontal line will form a box, thus, if the dot is located inside of the box, it means it has a better result than the current situation. Therefore one can easily distinguish whether the results of policy implementation are better with clear visuals.

At the time step 0, some policies are located outside of the box, and 3 policies have worse results than the base case at both damage and deaths. However, over the time steps, it is obvious that these policies will have better results than a base case and eventually at the last time steps, every policy has a better result than the current situation.

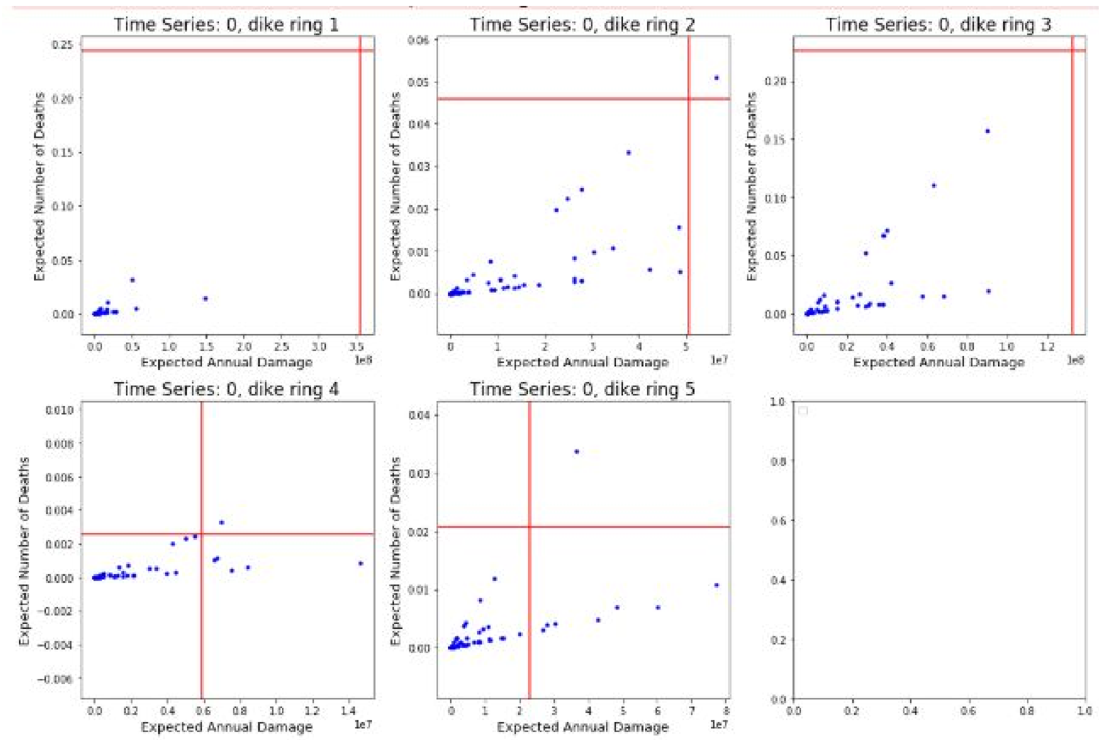


Figure 13. The Scatter Plots of expected damage and casualties at dikes in time step 0

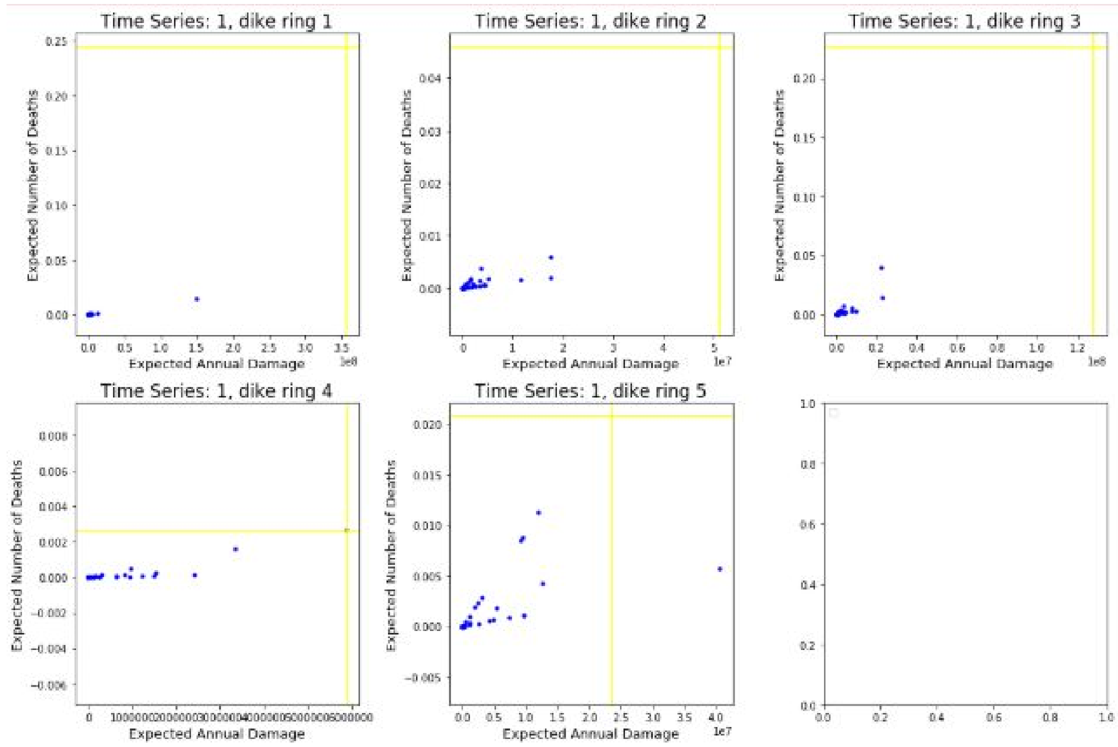


Figure 14. The Scatter Plots of expected damage and casualties at dikes in time step 1

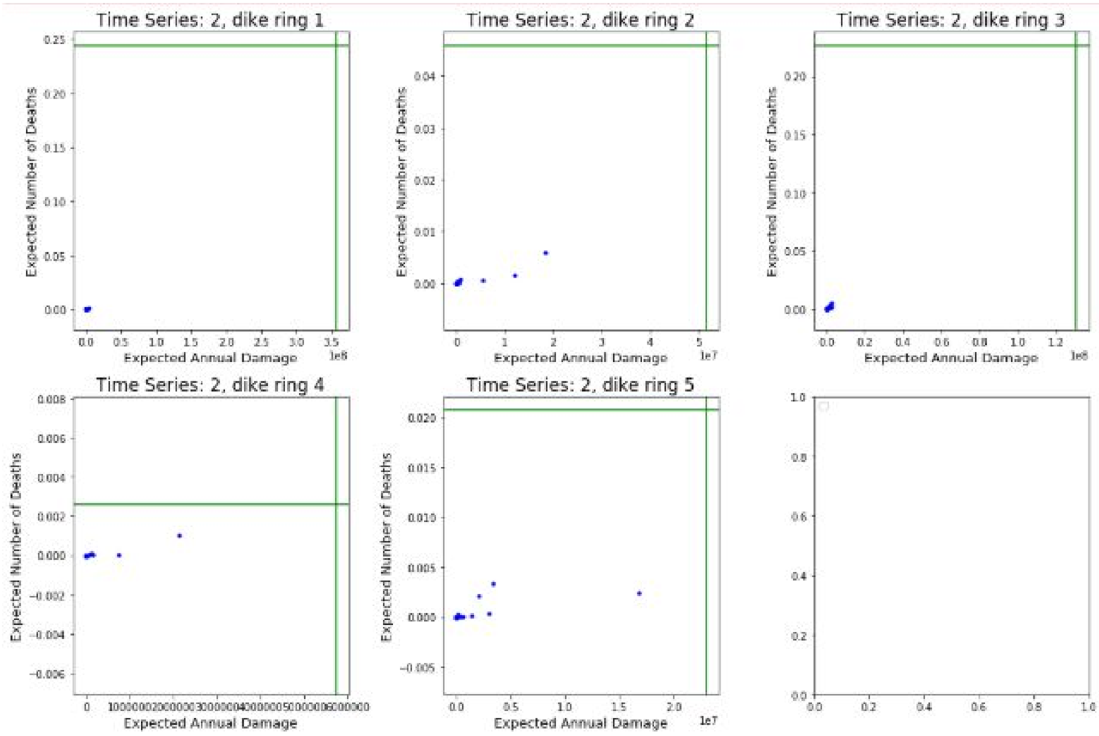


Figure 15. The Scatter Plots of expected damage and casualties at dikes in time step 2

3.3 Open Exploration with 5 Objectives

3.3.1 Open Exploration

Firstly, this open exploration is done to explore the implications of uncertainties and policy levers on the various costs while the above exploration is explored on the damages and deaths. This computation is done for 25.000 experiments with 1000 scenarios with 25 policies. Due to the computational limitations and compute cost concerns, the experimentation has been limited to 25.000 in this case. Since the possible combination of policy levers forming policies are less than the combinations of uncertainties that form the scenarios, the number of scenarios is fixed larger than the number of policies. The policy levers are integer parameters while the uncertainties are real parameters. The policy formulation chosen for this open exploration case gives five outcomes of interest: 1) Expected Annual Damage 2) Expected Number of Death 3) Dike Investment Costs 4) RfR Investment Costs 5) Evacuation Costs. The 'Expected Number of Deaths' is a combination of expected deaths over all locations while the three different cost components are combinations of costs over all locations as well. These three different cost components were considered for experimentation to better understand and advise stakeholders regarding the costs related to the three policy interventions. The results of the experiments are saved and further used for visual analysis and intrepretation. The obtained results were aggregated by policy to find the mean for each outcome of interests[3].

[3] Refer notebook 3.3 Open Exploration - 5 obj.ipynb

The mean, maximum, minimum of the outcomes of interest are tabulated in Table 3. The maximum number of expected annual deaths due to reach 1.7 while it can be closer to zero, which is a better outcome.

Table 3 : Mean, Maximum, Minimum of the outcomes of interest

	Total Dike costs(Millions Euros.)	Total RfR Investments costs (Millions Euros.)	Total Evacuation Costs (Millions Euros.)	Expected Death
Mean	682	108	142	0.02
Maximum	994	168	816	1.7
Minimum	418	321	0.0	0.0

Figure 16 gives the dike model behaviour for 25.000 runs. From the open exploration of the model we could see that in most cases the expected number of deaths are low with an increase in costs while in few cases it is high. The early warning systems seem to do a better job at reducing deaths with an increase in the evacuation related costs. Also, the damages don't reduce with an increase in evacuation cost which is logical as evacuation is purely a mitigation measure rather than preventive. Both dike heightening and room for river levers reduce the expected damage with an increase in costs.

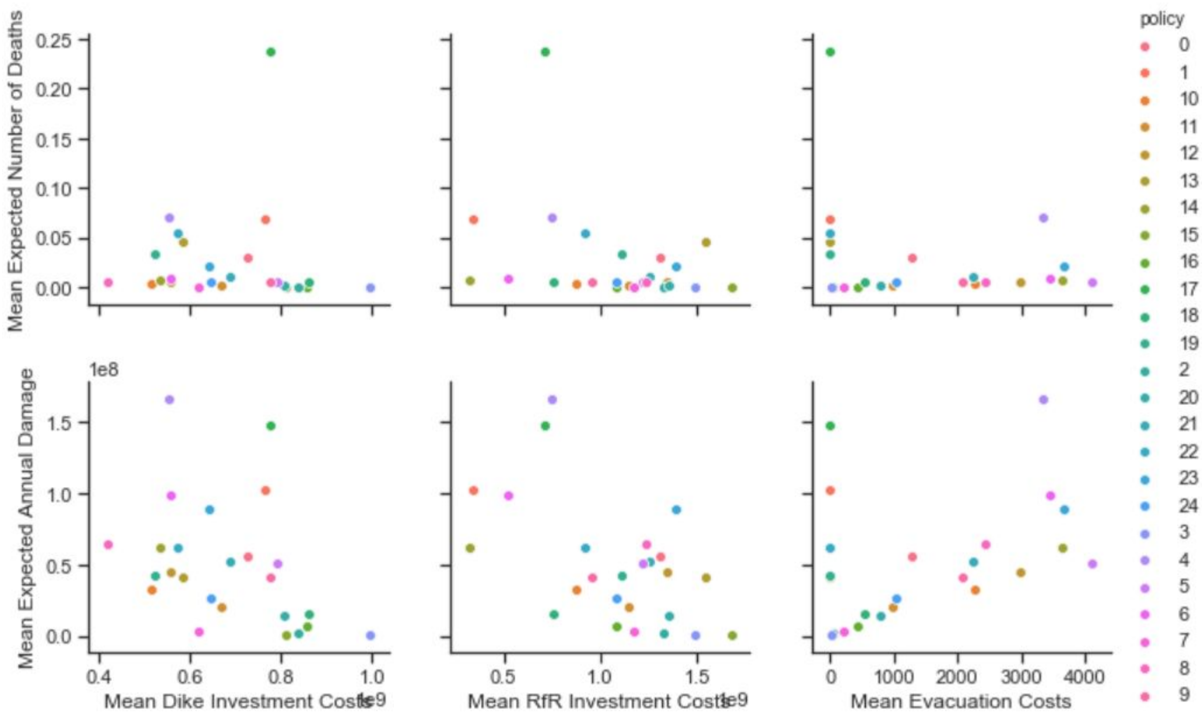


Figure 16. Mean of outcomes of interests for 1000 scenarios and 25 policies

3.3.2 Sensitivity Analysis

As a first stage of sensitivity analysis, featuring scoring is done and visualized in figure 17. This gives the correlation between uncertainties and policy interventions and the outcomes of interest. Four outcomes of interest such as “Expected Annual Damage”, “Dike Investment Costs”, “RfR Investment Costs”, “Evacuation Costs”, “Expected Number of Deaths” from 25.000 experiments consisting of 1000 scenarios and 25 policy levers are used for this analysis. RfR investment costs are strongly influenced by “Room for River” policy 4 (4_RfR_1) at location A3 and A4. This can be explained since the costs are higher due to the need for removing obstacles between A3 and A4. Also, the expected number of deaths are strongly influenced by the uncertainty A3_pfail which implies a higher probability to dike failure at A3. This could be because A3 (Zutphen) is a high population density area with a high chance of people living very close to the water bodies. The expected annual damage is influenced by A3_pfail and A1_pfail, where A3 and A1 are in Gelderland[4].

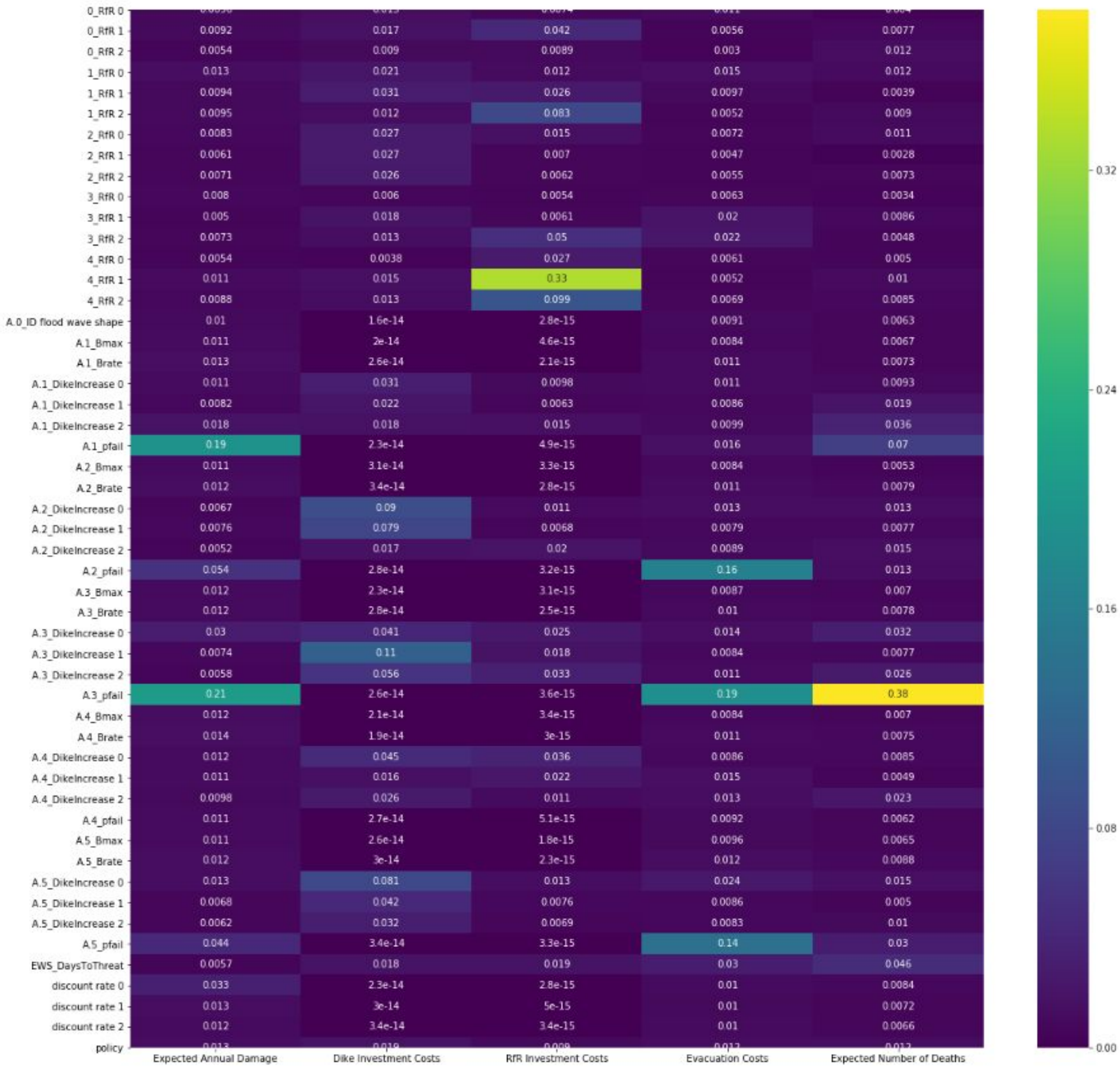


Figure 17. Feature scoring results, with the sensitivity of outcomes to experiments

[4] Refer 3.3.2 in 3.3 Open Exploration - 5 obj.ipynb

3.4 Multi-Objective Robust Optimization[5]

As the project aims to reduce total expected damage and casualties in all regions, the proposed policies cannot afford high-yield high risks strategies. Therefore multi-objective robust optimization is conducted to optimize the robustness of proposed policies. This chapter will start with preparing the MORO analysis and end with the robustness score of the outcomes of interest as a result of the analysis.

3.4.1 Setting Up the Experiments

To run the MORO experiments, a few steps should be preceded before performing the experiments that will be used in the analysis. The equation of robustness will be discussed in 3.4.3 Robustness part. From 3.2 Open exploration with 75 policies, we obtained 75000 results, which can be used to generate a test set of scenarios to calculate the robustness of candidate solutions. Candidate solutions are evaluated for each scenario. After that, the calculated robustness range of each outcome of interest was used to set epsilons and hypervolume. MORO was performed over the 50 scenarios and 5000 nfe's. Epsilon convergence and hypervolume indicator are shown at Figure 18.

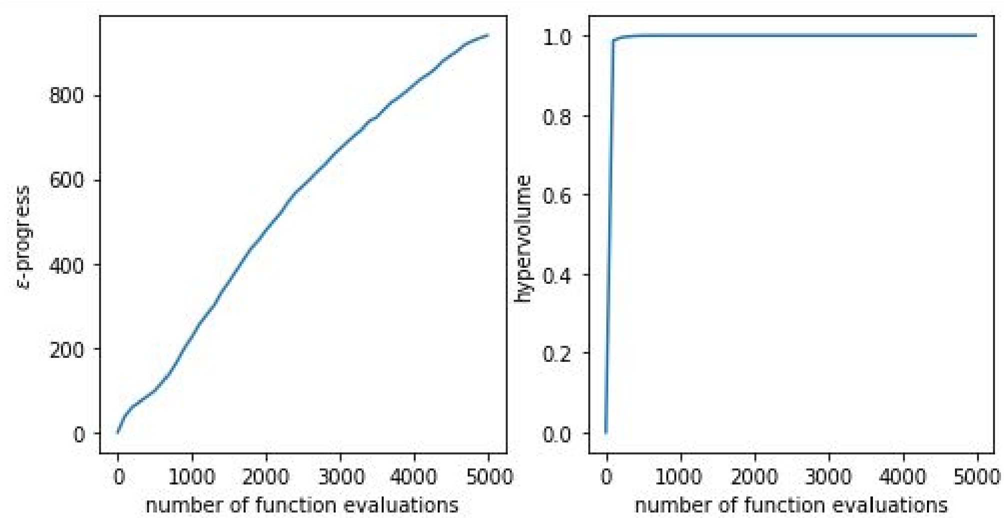


Figure 18. Epsilon convergence and hypervolume over nfes

The hypervolume indicator went 0.00 to near 1 at the beginning of the graph, and it stayed at 1. This behaviour might be happening because of the maximum value of hypervolume, which is the only 3 times greater than maximum value of robustness score. The epsilon values were calculated by robustness score * 0.05 and the values are shown at Table 4.

[5] Python notebook 'Multi-Objective Robust Optimization.ipynb'

Table 4. Epsilon values of the outcomes of interest

Outcome of Interest	**Epsilon Value**
Total Expected Annual Damage	3.916887e+13
Total Expected Number of Deaths	1.169892e-04
Total Dike Investment Costs	1.699652e+07
Total RfR Total Costs	1.475000e+07
Total Expected Evacuation Costs	1.592965e+0

3.4.2 Robustness Analysis

The robustness function was defined using Kwakkel et al (2015). To optimize robustness, the median values of the outcomes of interest are multiplied by the interquartile distance plus one. The solutions from performing 'robust_optimize' were evaluated with 200 scenarios each. The outcomes of interest were calculated their robustness score by robustness function, and figure 19 shows the trade-offs of outcomes.

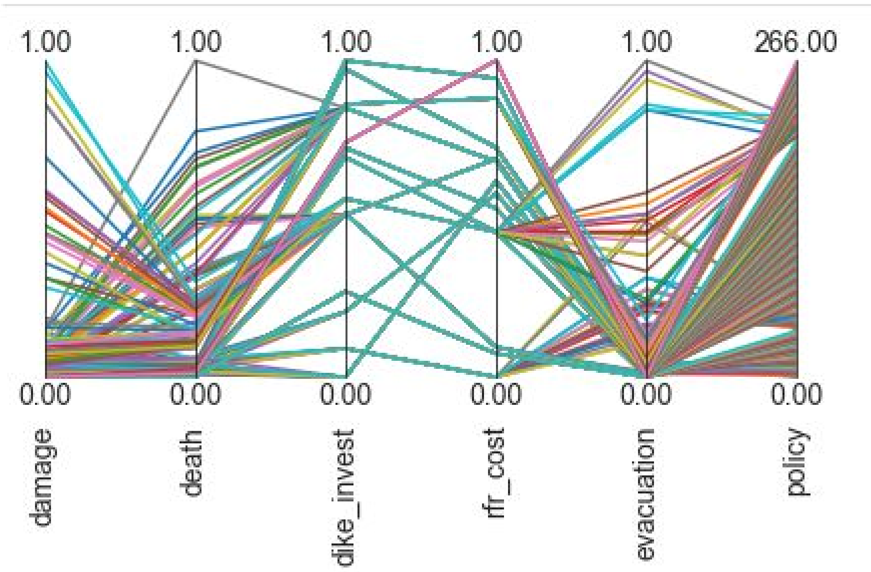


Figure 19. The trade-offs of the robustness score among outcomes of interest

The robustness score in figure 19 got normalised into 0 - 1. Remarkably, there are trade-offs between damage and deaths when the scores go higher. Since the project's best interest is to minimize the deaths and optimize the robustness of total expected number of deaths, a policy with maximum robustness score on total expected number of deaths has been proposed.

4. Discussion

The approach and results using the model have a few flaws and limitations. It is important to discuss these before using the results, as they can potentially be a threat to validity of the flood management plan suggested. In this chapter, the reflection of the project will be discussed in the modelling approach and policy arena perspectives and solutions to these limitations are addressed. Lastly, further research based upon this project will be discussed.

Limitations and solutions

In the modelling perspective, it is difficult to know the exact amount of scenarios to produce that can lead to the most valid results when performing the direct search. The number of scenarios is important to analyse the consequences of policy implementation. Usually, experiments with 1000 scenarios had been performed in this project, however, we cannot determine that 1000 scenarios are the ideal amount to perform the experiments. The ideal procedure is to adjust through several trials that introduce different amounts of scenarios, but it has not been executed in this project due to time constraints. The same limitation is applied in the number of nfe in MORO analysis. Even though we executed several experiments with different nfe, they were all relatively small numbers. Due to the computational power constraints, the maximum nfe was 5000. The initial plan was to use the results of a run with 10 000 nfe. However, due to time constraints, the analysis was not finalized on time. More nfes would have meant more (and possibly better) solutions. Before making policy proposals for the flood management plan of the IJssel, it is recommended to run MORO with a higher value for nfe.

When backing up decision-making with a modeling analysis, it is important to be aware of the approach's limitations. One of the most important things to take into consideration are the boundaries of the model. As it is impossible (and not useful) to model the world in a perfect replica, analysts need to make decisions regarding the boundaries of the system they want to model. These boundaries need to be clear and understood by the actors in order to allow for informed decision-making. The model used for the analysis of the IJssel river has several points of focus that are interesting to reflect upon:

- Geographical boundaries - the model focuses on the IJssel river in Gelderland and Overijssel. However, this river is a branch of a bigger one - the Rhine, that crosses several other countries before reaching the Netherlands. As all these countries are located upstream, the flood management strategies implemented in these countries will influence the volume of water that flows in the IJssel. An interesting further study could be the integration of the IJssel model in a bigger overview of the Rhine, allowing to use insights of the consequences of flood risk management in Germany, for instance, in the dutch downstream;
- Outcomes of interest - while the model uses number of deaths, damage and costs as metrics to evaluate how the different strategies perform, it is important to be aware that these are not the only metrics of interest for the actors involved. For instance, when making large-scale decisions such as making room for the river or heightening the dikes, there will be environmental and social consequences that are not included in the model. However, these consequences are valued by some of the stakeholders (for example the environmental

interest group is concerned about the biodiversity consequences of the implementations) and will be brought up in the decision-making process. Future research could include adding more performance metrics that are valued by actors in the model;

- Cost constraints - another interesting feature of the model is that there is no cost constraint. This assumes that any measure that is beneficial will never not be implemented for budgetary reasons. However, this might not be realistic as often ministries of governments have budgetary plans for the coming years. Future research could include adding cost constraints in the model;

Further Research

Taking into account the multi-actor nature of the problem, it would be interesting to explore stakeholder's interests a bit deeper before making a policy proposal. Although we try to take it into account in the way the policy is framed and presented, the techniques used are based on what we think the other actors value. However, these are mere assumptions based on the actors' attitudes and statements during the decision-making debate or limited research. In order to have a clearer overview of the stakeholders' interests and goals, a more extensive stakeholder analysis should have been conducted. This could have included interviews and more extensive research. Then, by knowing the outcomes of interest of each actor, the model could have been used with their perspective and understand their preferred policies. By having these results before a debate, this would have allowed Deventer to prepare a policy that could integrate other stakeholder's interests, leading to possible formation of coalitions or deals. Further research in this direction is suggested.

As mentioned before, flood risk management in the IJssel river is characterized by deep uncertainty. An important uncertainty in this problem is climate change and the way it will influence the water flow in the river. In this study we suggest a strategy for the next 75 years and use several different scenarios of how the future develops to find a robust one. However, as the future comes, these scenarios will become less uncertain and the strategy should be adapted to how the future actually unfolds (Maier et al., 2016). An interesting method to take into account the actual development of scenarios is by using 'Adaptation Pathways'. While all the possible steps are defined anyway, they will only be executed when a certain event happens. By defining tipping points, strategies can be implemented in response to actual events. As models often do not offer direct guidance to the policy maker, complementing its results with an Dynamic Adaptive Policy Pathway approach (DAPP) is recommended when deciding under deep uncertainty (Kwakkel, Haasnoot & Walker, 2016). Further research for the development of a flood management plan for the IJssel river can be the integration of a DAPP approach with the results from the model.

While models provide a good starting point for analysis of possible policies and guiding decision-making, it is key to stress that it should never be used for policy-making on its own. Taking into account the limitations highlighted above, it is important for a decision-maker to be able to use these results and complement it with other methods in order to adapt to the decision-making arena the discussion is placed in.

5. Conclusions

This report was conducted to answer the following research question: *"What flood risk management strategies can the city of Deventer implement in order to guarantee the safety of the region, taking into account the conflicting objectives of the stakeholders involved and the deep uncertainty inherent to the future development of the system?".* In order to answer this question, a robust decision making approach was conducted, using scenario discovery and Multi Objective Robustness Optimization (MORO).

Based on the model outcomes, several suitable policies can be proposed considering the robustness and outcomes. However, as Deventer has minimizing deaths as the most important objective, one strategy stands out. In order to achieve its objectives, Deventer should aim for a policy that combines both making room for the river and dike increase at different locations. The preferred solution in order to achieve minimum death possible across most of the scenarios (the most robust strategy) is divided into three action times. First, in the first 25 years, dike 1, 3 and 4 should invest in dike heightening. Then, the same measure should be applied in dike 4 and 5. Finally, at the last time step, dike 4 and 5 should increase dike heightening again, while dike 3 should make room for the river. This policy is further detailed in Table 5, where the amount (in dm) of dike heightening is included.

Table 5. Detail of the proposed policy

	Time Step	**A1**	**A2**	**A3**	**A4**	**A5**
Room for the River	0	No	No	No	No	No
	1	No	No	No	No	No
	2	No	No	Yes	No	No
Dike Increase (dm)	0	2	0	7	1	0
	1	0	0	0	2	1
	2	0	0	0	4	1

It is important to note that this strategy is the result of the model and is hence restrained by the limitations outlined in Chapter 4. For this reason, our advice for Deventer is that, before deciding on policies to be implemented, further research is necessary into understanding the possible implications of this strategy. For instance, a cost and benefit analysis can be performed to understand the impact of the strategy proposed by the model and evaluate if it is better than its alternatives, taking into account financial, environmental and social aspects. Then, as most of the actions that compose the solution found in the exploratory analysis are to be implemented in later times than now, it is highly recommended that the analysis is conducted later on and takes into account the actual developments of the future.

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Appendices

Appendix A. Actor Scan

When making decisions about the flow of the IJssel and what measures to implement, a variety of actors show an interest in the discussion. These range from areas around the river who directly benefit from it, provinces that represent these areas, interest groups or companies. First, there is a brief explanation of each one of these actors and their interests. The information gathered about each actor's preference comes from the debates and meetings hosted between the 4th and 11th of June 2020.

Note that this analysis is based on the situation before Rijkswaterstaat abandoned the decision-arena as this is closer to the real world situation.

Province of Gelderland
In the province of Gelderland there are both rural and urban areas that are placed around the IJssel. Although they recognize the need to have an intervention on the river and hence do not support the 'do-nothing' approach, these areas seem to value their land very highly. With this in mind, the preferred solution of Gelderland is to increase dike heightening in both its provinces in order to reduce flood risk but also avoid losing land. However, as this province is upstream, dike heightening will mean that a bigger volume of water can be kept along the river, increasing consequences if a flood occurs. The province of Overijssel is therefore not supportive of dike heightening in Gelderland.

Province of Overijssel
Overijssel is a province around the IJssel river but downstream from Gelderland. As a both urban and rural area, Overijssel aims at protecting both their land, their businesses and citizens. For this reason, they want to minimize flood risk. As they are downstream from Gelderland, any measure that the latter implements will influence the Overijssel province. Ideally, their proposed solution is that Gelderland makes Room for the River so that the volume of water flowing to the downstream province is reduced, consequently reducing the flood risk.

Transport Company
As the Netherlands has an extensive network of rivers, water became one of the most important means of transportation of goods in the country. Inland shipping contributes around 30% of the total transport of goods (Visser, 2009). To guarantee that this is continuously possible, it is necessary to assure that a constant water level is maintained in each river (or increase, which would give the possibility to operate bigger boats and transport more cargo). Due to climate change and rising temperature, the water level has been threatened in recent years - in summer 2018, one of the driest summers on record in the Netherlands, water levels reached such a low value that ships could only take half to a third of their normal loads (Meijer, 2018). This constraint led to a range of consequences from good shortages to factories closing down because they couldn't operate their transport systems anymore.

With this economical aspect in mind, the transport company will be in favour of any measure that does not reduce water levels. In other words, they will strongly oppose any 'Room for the River' implementation anywhere along the IJssel.

Rijkswaterstaat

With a mandate to design, construct, manage and maintain the main infrastructure facilities in the Netherlands (Rijkswaterstaat, n.d.), Rijkswaterstaat is part of the Dutch Ministry of Infrastructure and Water Management and is the administrative actor in this decision-arena. Rijkswaterstaat is responsible for formulating a policy recommendation for the IJssel river, which the other actors will vote upon and approve (or not). In other words, in order for the policy to be successful, Rijkswaterstaat should take into account safety, economic and environmental concerns. Rijkswaterstaat also funds all the necessary infrastructural interventions.

Delta Commission

Another body of the Dutch Government, the Delta Commission is responsible for giving recommendations on how to manage the water resources of The Netherlands. Their main goal is to protect the country from flooding while ensuring a sufficient supply of fresh water (Ministry of Infrastructure and Water Management, 2019). Delta Commission should also guarantee that the interests of every actor in the arena is considered when making a decision. For this reason, they have a veto power that they can use in case they believe that the proposed policy does not take stakeholders' interests into account.

Environmental Groups

As big infrastructural changes often lead to environmental consequences, environmental interest groups are frequently interested and active in the decision-making process of these projects. This group will have as main interest protecting nature around the IJssel. As the *Room for the River* project resorts to making more room for nature, this will be the actors preferred policy. Policies that involve dike heightening will not be supported by this actor as it reduces soil fertility, killing biodiversity in the long run and reducing the ecological quality of the surroundings.

Appendix B. Model Specifications

B.1 Outcomes

In the predefined model, 17 outcomes of interest can be found. The outcomes concern the damage or casualties of each dike or the investment costs for implementing policies for each dike. While three of them are specified to the area located near the Ijssel river, evacuation costs and Room for the River costs do not divide by location. The predefined model has six outcome options by the level of aggregation, aggregated by the locations or costs. All outcomes will be derived for each time step and aim to minimise the values.

Table B.1. Model specifications - outcomes

Outcome		Description	Unit
Expected Annual Damage	A1 Doesburg	Expect annual economic damage by a flood at each location. **The outcome should be minimised.**	€
	A2 Cortenoever		
	A3 Zutphen		
	A4 Gorssel		
	A5 Deventer		
Expected Annual Casualties	A1 Doesburg	Expected annual casualties by a flood at each location. The outcome should be minimised. **To minimise casualties is chosen as the priority of this project.**	
	A2 Cortenoever		
	A3 Zutphen		
	A4 Gorssel		
	A5 Deventer		
Dike Investment costs	A1 Doesburg	Investment costs for increasing dikes.	€
	A2 Cortenoever		
	A3 Zutphen		
	A4 Gorssel		
	A5 Deventer		
Evacuation costs			€
Room for the River costs		Total investment costs for Room for the River project.	€

B.2 Uncertainties

Table B.2. Model specification - uncertainties

Variable name		Description	Range	Unit
pfail	A1 Doesburg	Probability of failure for each dike ring	0 - 1	
	A2 Cortenoever			
	A3 Zutphen			
	A4 Gorssel			
	A5 Deventer			
Bmax	A1 Doesburg	Maximum bridge width	30 - 350	m
	A2 Cortenoever			
	A3 Zutphen			

	A4 Gorssel			
	A5 Deventer			
Brate	A1 Doesburg	Growth rate of bridge	(1., 1.5, 10)	1/day
	A2 Cortenoever			
	A3 Zutphen			
	A4 Gorssel			
	A5 Deventer			
Discount rate			(1.5, 2.5, 3.5, 4.5)	
Flood wave shape			0 - 132	

B.3 Levers

Table B.3. Model specifications - levers

Factor		**Description**	**Range**	**Unit**
Dike Increase	A1 Doesburg	Amount of increased dike height.	0,1	m
	A2 Cortenoever			
	A3 Zutphen			
	A4 Gorssel			
	A5 Deventer			
RfR	A1 Doesburg	Implement Room for the River project or not (binary)	0-4	
	A2 Cortenoever			
	A3 Zutphen			
	A4 Gorssel			
	A5 Deventer			
EWS Days Threat		Early warning system. Early warning systems are designed to help the effective response by anticipating a threat of the flood. It will be useful to reduce the damage and deaths from the flood, however, because of deep uncertainty, early warning systems can be triggered by a false alarm. While early warnings can help residents, frequent fake warnings can lower people’s alertness.	0, 1	days