Room for the River

A model-based strategy for the Province of Gelderland

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Executive summary

Given its geographical characteristics, the Netherlands is subject to flood risk from rivers. This report zooms in on flood protection along the IJssel river in the provinces of Gelderland and Overijssel, using a mix of traditional dike-heightening measures and new Room for the River projects. The report is focussed on the safety of the Province of Gelderland, for whom a policy advice has been developed, using a python model based on the XLRM modelling framework

To come to this advice, a Multi-Objective Robust Decision Making method is used. This starts by defining a problem formulation, which consists of minimizing expected annual damage and number of deaths, total investment costs and expected evacuation costs in both Gelderland and Overijssel. For this problem, 16 candidate solutions were found, which were then filtered on Gelderland's specific interests. Next the residual policies were tested for robustness, resulting in a final policy advice.

This policy entails the heightening of the dikes at the first possible moment with 3, 2, 5, 8 and 2 dm for dike rings 1 to 5, respectively. None of the Room for the River projects should be implemented and the early warning signal should be two days ahead. This policy would cost Gelderland € 113 million and would at least halve the expected number of deaths and damage in all dike rings compared to the base case, i.e. implementing no measures. Finally, most deaths are expected to occur in Dike Ring 1, for which the most important uncertain factor is the dike failure probability.

Some limitations to this advice are the lack of certain variables in the model, as well as the unclarity of objectives of all actors in the political arena. Furthermore, in the set problem formulation, expected damage and deaths are valued equally as investment and evacuation costs, which a decision-maker might wish to consider. Finally, the used optimisation method (MORDM) does not include different scenarios in its optimisation. Other methods could have been used to take this into account as well and as such result in, possibly, more robust policies.

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1 - Problem framing

1.1 Introduction problem

The Dutch mainland includes large amounts of surface water, as seventeen percent of it is covered by water (The Netherlands Bureau for Tourism and Congresses, n.d.). As a result of this, water flood risk management has always been a priority on the political agenda. The Netherlands has experienced two major floods in a short period of time, one in 1993 and another one in 1995 (Schut et al, 2010). In 1996 a policy guideline was made, which stated that it was required to explore the possibilities of lowering flood levels by providing Room for the River, before automatically heightening dikes (Klijn et al, 2013). Room for the River measures can be implemented in multiple ways for example, widening the river bed, excavating floodplains, building flood retention zones and digging shortcuts that enable water to quickly be drained to the sea (De Bruijn et al, 2015). The overall Room for the River project was started in 2007 and it consists of giving more room to the rivers IJssel, Rhine, Lek and Waal in 34 different locations (Rijkswaterstaat Room for the River, 2013).

This report zooms in on the Room for the River projects concerning the IJssel in the provinces Gelderland and Overijssel. A policy should be developed to minimize flood risks within this region. Options to achieve this goal are to either heighten dikes or to create more Room for the River. Five Room for the River projects are considered in the case. These are visible in Figure 1 and are referred to as Olbergen, Havikerwaard, Tichelbeeksewaard, obstakelverwijdering and Welsummer buitenwaarden.

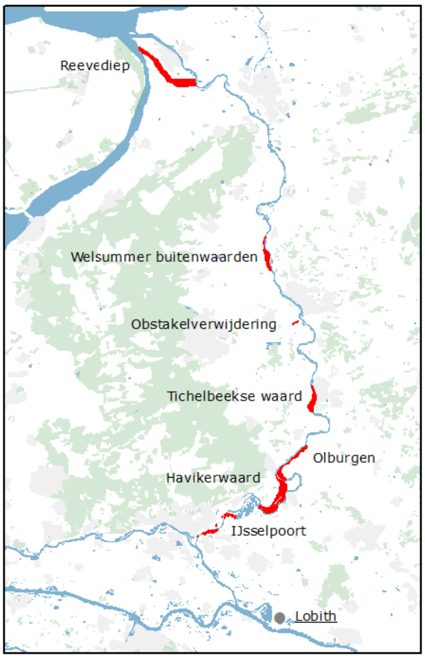

Figure 1 - Room for the River projects

The actors involved in the development of a new policy are Rijkswaterstaat, the Delta Commission, Environmental interest groups, Transport companies and the provinces of Gelderland and Overijssel. All these actors have their own objectives concerning the project, which could cause political tension.

Within this report, policy recommendations are provided for the Province of Gelderland based on state-of-the-art modelling techniques. These techniques analyse different policies under deep uncertainty, as described in section 1.4.

1.2 Stakeholder analysis

This section reviews the important stakeholders which are involved, their concerns and their objectives concerning the Room for the River project. All these stakeholders are highly affected by the implementation of a possible policy; however the dike rings are not directly involved in the decision process.

Rijkswaterstaat

Rijkswaterstaat is the executive organisation of the Ministry of Infrastructure and Water Management. Their goal is to protect the country against floods, protect the environment, to ensure good infrastructure and to secure enough clean drinking water (Rijkswaterstaat, n.d.). Rijkswaterstaat considers the effects of land usage on the environment, economy and pleasure of living.

Delta Commission

The Delta Commission desires to ensure a safe future for the Dutch Delta (Deltacommissie, 2020). In 2008 the Delta Commission has provided the Dutch government with advice on how the country should cope with the consequences of climate change (Deltacommissie, 2008). Safety and durability are the two most important pillars of this advice.

Environmental interest groups

The environmental interest groups are concerned with biodiversity and ecological integrity. They would like to see a Room for the River project in an area that is upstream on the IJssel as they stated: “We would like to see minimal impacts on biodiversity upstream and create an environment wherein species can quickly recover and thrive” (EPA Environmental interest group, personal communication, June 8, 2020)[1]. According to the environmentalist groups, dike heightening will negatively impact biodiversity, whereas Room for the River has a positive impact on it. They prefer a Room for the River project in upstream locations, as these locations are most biodiverse and need to stay intact as much as possible.

Transport companies

The transport companies use the IJssel to transport goods. To do this, the water level should be high enough. Room for the River projects will cause lower water levels (see Appendix B), which will negatively affect transport business. In case of low water levels, ships can handle less load and in cases with extremely low water levels, it will not be possible at all to use waterways for transportation. Therefore they want to preclude a Room for the River project (EPA Transport company, personal communication, May 27, 2020).

Province of Gelderland

Gelderland is the largest province of the Netherlands. In 2020, the Province of Gelderland consists of more than 1.1 million inhabitants and it covers a land surface of 5136 square kilometre (CBS, 2020). Within this case, Gelderland represents the views of dike rings 1, 2 and 3.

Dike ring 1&2 - Ijsselland and Oost-Veluwe

Dike ring 1 and 2 are officially known as dike rings 49 and 52. Dike ring 1 is located east of the IJssel, it covers a surface of 8.700 ha and consists of 20.000 inhabitants. The dike ring consists of three municipalities: Doetinchem, Doesburg and Bronckhorst. No floods have

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[1] This information has been retrieved through a meeting with the Environmental interest group, as part of a serious game debate exercise in the course. The same is true for other EPA actors mentioned in the citations

happened in dike ring 1 in the last 100 years (Rijkswaterstaat Waterdienst, 2014). A map of dike ring 1 and other dike rings mentioned below, can be found in Appendix B.

Dike ring 2 is located west of the IJssel, it covers a surface of 31.100 ha and consists of seven municipalities: Apeldoorn, Deventer, Zutphen, Rheden, Epe, Voorst, Brummen, Heerde and Olst-Wijhe. Most of the land in this dike ring is used for cattle and nature. The last flood happened in 1926, when the dikes broke at Brummen and Voorst (Rijkswaterstaat Waterdienst, 2010).

Within the Room for the River case dike ring 1 and 2 are merged into one actor, as they are situated in the same province and have the same objectives. The goal of these dike rings is to minimize flood risks in their area. They believe that their farmers deserve a similar level of protection, as people living in cities. Furthermore, loss of land caused by Room for the River projects as well as dike heightening is undesirable. If a project does affect the land in dike ring one and/or two, the dike rings would prefer to receive a good compensation for this, as it affects their ability to generate revenue (EPA dike ring 1&2, personal communication, May 25, 2020).

Dike ring 3 - Zutphen

Dike ring 3 is officially called dike ring 50. Dike ring 3 is located east of the IJssel, it covers a surface of 5.200 ha and consists of 4.000 inhabitants. The three biggest residential centres are Zutphen, Vierakker and Warnsveld. The northern part of this dike ring consists mainly of industries (Rijkswaterstaat Waterdienst, 2011a). No floods have recently occurred in this dike ring, the last flooding took place in 1926.

The objective of dike ring 3 is like the objectives of dike rings 1 and 2. Dike ring 3 wants to protect its citizens against floods, and they do not want to give away land. A land loss in dike ring three would mean that citizens of Zutphen would have to leave their houses and move elsewhere. A compensation for this movement is demanded if it is deemed necessary (EPA dike ring 3, personal communication, May 26, 2020).

Province of Overijssel

In 2020, the Province of Gelderland consists of more than 2 million inhabitants and it covers a land surface of 1.156 square kilometre (CBS, 2020). Within this case, Overijssel represents the views of dike rings 4 and 5.

Dike ring 4 - Gorssel

Dike ring 4, also known as dike ring 51, is located east of the IJssel, it covers a surface of 7700 ha land and consists of 12.000 inhabitants. The three biggest residential centres are Gorssel, Eefde and Epse. About 80% of its land is used for nature and agricultural practices (Rijkswaterstaat Waterdienst, 2011b). No floods have recently occurred in this dike ring, the last flooding took place in 1926. The objectives of dike ring 4 are the same as the objectives of dike ring one and two (EPA Overijssel, personal communication, June 5, 2020).

Dike ring 5 - Salland

Dike ring 5, also known as dike ring 53, is located east of the IJssel, it covers a surface of 41.000 ha and consists of 250.000 inhabitants. The dike ring consists of 6 municipalities: Zwolle, Deventer, Raalte, Ommen, Dalfsen and Olst-Wijhe (Rijkswaterstaat Waterdienst, 2013). No information is available on recent floodings in this area. The objectives of dike ring 5 are the same as the objectives of dike ring three (EPA Overijssel, personal communication, June 5, 2020).

1.3 Political arena

As has been described within the stakeholder analysis, the involved stakeholders have different goals. This results in tension amongst all who are involved. Rijkswaterstaat and the Delta Committee can be seen as being neutral towards a solution. They do want a solution which is robust and sustainable, and which considers the wishes of all stakeholders. However, these two actors do not prefer a specific solution to minimize flood risks.

The dike rings want safety for their community; however, they prefer to not give away their valuable land. The Province of Gelderland and the Province of Overijssel follow the objectives of their dike rings. Within this case, both provinces will have roughly the same goals. Tension could arise between the actors, as they both do not want a Room for the River project to take place on their land.

The environmental interest groups and transport companies have a strong and clear preference concerning the implementation of Room for the River projects. The environmental interest group prefers Room for the River projects over dike heightening and the transport company prefers dike heightening. This causes opposing stand points within the political arena.

1.4 Model setup

The model that has been used in this research is a flood risk model which has been developed in Python. The model is an extended version of the model by Ciullo et al. (2019) and it is based on the XLRM framework by Lempert et al. (2003). This framework is illustrated in Figure 2. Within the XLRM framework, X stands for external factors. These include uncertainties within the environment of the model on which the policy maker has no to little control. These include the flood wave shape, dike failure probability, final breach width, breach width model and the discount rate. The L stands for (policy) levers, the decision variables within the model. These are Dike heightening, Early warning and Room for the River. Through the relationships within the system (R), the measures (M) will be computed. The measures include Expected annual damage, Expected number of deaths, Dike investment costs, Evacuation costs and Room for the River costs. Appendix D provides more information on X, L and M and it includes ranges for the values of the external factors and levers.

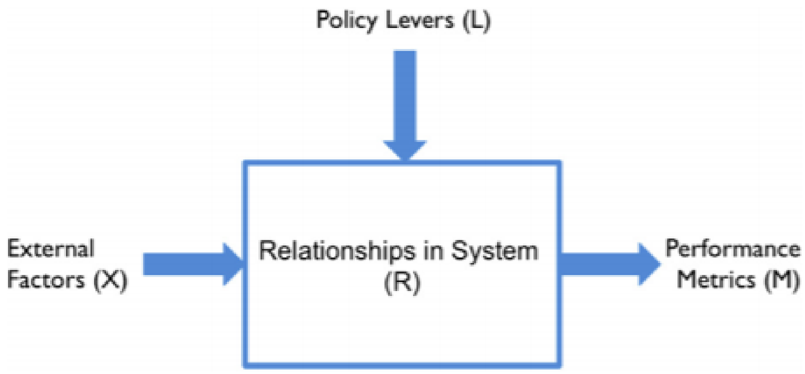

Figure 2 - XLRM framework (Lempert et al., 2003)

1.5 Problem formulation

The recommendations written in this report are made to support Gelderland. To get a policy accepted, the majority of involved actors must support the policy. Therefore, an analysis has been conducted which results in possible policies with overall best outcomes. No constraints have been imposed within the problem formulation. The obtained optimal policies are further filtered based on the preferences of the dike rings within Gelderland. This is further explained in the next chapter.

The problem formulation that has been used in the model to find the overall best policies, consists of the following measures:

- Total investment costs (€), this should be minimised
- Expected evacuation costs (€/year), this should be minimised
- Total damage, aggregated over all dike rings (€/year), this should be minimised
- Total deaths, aggregated over all dike rings (Person/year), this should be minimised

2 - Approach

In the previous chapter, the background to the problem and the different political objectives were described, leading up to a problem formulation, and model specification, that includes as many actors' preferences as possible. In this chapter, the approach from that problem formulation towards a policy advice is illustrated. Firstly, the search for a policy is placed within a wider context of model-based decision-making. Secondly, the search for candidate solutions is detailed, and, finally, the candidate policy solutions are tested across uncertainties, allowing to select a robust policy as an advice to the Province of Gelderland.

Many public policy problems are characterised by deep uncertainty, where the participants to a policy process cannot agree on how a system works, what plausible future states of the world are, and how important different outcomes are (Lempert et al., 2003). Traditionally, human decision-makers have used mental models to catch deep uncertainty, but these are incapable of grasping the complexities of many systems (Sterman, 1994). Therefore, over the last decades, various methods of computational modelling have tried to aid decision-makers facing deep uncertainty (Kwakkel & Haasnoot, 2019), with the goal of developing robust policies, which perform well for many uncertain futures. A key idea of these methods is exploratory modelling, exploring the consequences of various uncertainties instead of predicting a specific future (Kwakkel & Haasnoot, 2019).

In the IJssel River case as well, deep uncertainty persists, as actors do not agree on the functioning of the system, future states, and desired effects. This analysis uses exploratory modelling to generate a robust policy for the Province of Gelderland. For this, the EMA workbench was used, an open source Python library that allows users to carry out computational experiments and visualise the results (Kwakkel, 2017).

2.1 Preliminary exploration of the model

Before searching for a policy, the model workings were explored by testing the effects of some specific policies over a small set of scenarios. This way, some coarse policy effects were visible before starting the analysis in detail. Furthermore, it was decided to conduct the analyses for a planning horizon of 80 years, with 3 planning steps. The default value of 200 years was deemed impractical for policy design, and planning steps around 2-3 decades a reasonable suggestion.

2.2 Searching for candidate solutions

To come to a policy advice, the first step was to find several candidate solutions which could then be reviewed in more detail. Several methods exist for finding such policies, varying in the level of robustness that can be achieved, the likely level of performance of a policy, and its computational costs.

Overview policy search methods

Bartholomew & Kwakkel (2020) outlined various approaches to support decision making under deep uncertainty, as shown in Figure 3. The first of these was developed in 2002 by Lempert et al., and is called Robust Decision Making (RDM), which tests predefined candidate policies against a large range of scenarios. Multi-Objective Robust Decision Making (MORDM), takes it one step further and, instead of using a set of predefined policies, optimises policies under a reference scenario (Kasprzyk et al., 2013). Multi-scenario MORDM is another extension, which expands the reference scenario under which MORDM is run to a set of selected scenarios (Watson and Kasprzyk, 2017). Many Objective Robust Optimization (MORO) finally, optimises under a set of scenarios, and considers these simultaneously (Bartholomew & Kwakkel, 2020). Each method here described increases the robustness of policies found, but at the same time the optimal performance becomes harder to find (Bartholomew & Kwakkel, 2020). Additionally, every increase in robustness described here carries with it an increase in computational costs, because at each consequent method, a wider array of policies is considered.

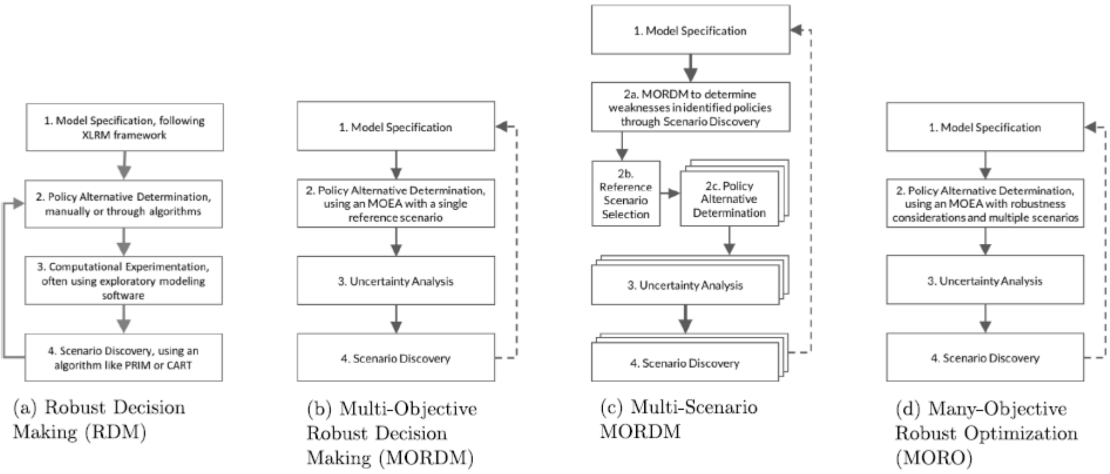

Figure 3 - Robust policy search methods (Bartholomew & Kwakkel, 2020)

In this model study, MORDM was used to strike a balance between optimality and robustness, as well as being the method best fitted to the time constraints present in the preparation of both the debate and the model.

The first step in MORDM is model specification. This is detailed in Appendix D, where the uncertainties, policy levers and the outcomes of interest have been defined. Afterwards, several policies were found by optimising for this model specification, which were then filtered for the best policies for Gelderland by running experiments for the KPI's of Gelderland in specific.

2.2.1 Optimise under general KPI's

The first computational aspect in MORDM is to find the optimal solutions for the KPI's identified in section 1.5. This has been done with an optimisation using a Many-Objective Evolutionary Algorithm (MOEA), as explained below.

Some policies dominate others in their performance. A much-used way to identify these is Pareto dominance. Solutions that score worse on all KPI's than another are discarded. What remains, are the solutions that for some KPI are better than another but score worse in another KPI. This is said to be the Pareto front. In optimisation, traditional approaches often sum over the KPI's to reduce the objectives to one aggregate objective to be able to compare solutions. However, in MORDM algorithms (MOEAs) are used that can circumvent this problem. The algorithm compares policies and drops policies that are Pareto dominated by another. Thus, by repeating this process, the algorithm comes very close to optimal policies, resulting in a better fit than traditional, single-objective optimisation. Next to that, because a MOEA can consider multiple objectives simultaneously, information about trade-offs resulting from the optimal solutions can be preserved (Maier et al., 2019).

To arrive at that optimisation, to approximate the Pareto front, or, to converge, the algorithm should repeat this process very often. In other words, it should have a high number of function evaluations (nfe). This analysis used a value of nfe = 15,000. To check whether the algorithm converged, specific metrics were used: hypervolume and epsilon progress. These are commonly employed metrics to check whether the solutions found approximate to the Pareto front (Reed et al., 2013).

2.2.2: Filtering solutions under KPI's specific for Gelderland

Having acquired a set of candidate policies which maximise desired effects across all dike rings, the policies which were most beneficial for Gelderland were selected. This was done by first selecting a different set of KPI's, which accounted for the interests of Dike Rings 1&2, and 3, specifically. The KPI's of Dike Ring 1&2 and Dike Ring 3 were separated to better understand the effect on the individual dike rings, which could provide a better picture of Gelderland's demands in the political arena.

- Minimising the total damage of Dike Ring 1 and 2
- Minimising the total amount of deaths Dike Ring 1 and 2
- Minimising the total damage Dike Ring 3
- Minimising the total amount of deaths Dike Ring 3
- Minimising the total investment costs for Dike Ring 1,2, and 3
- Minimising the total expected evacuation costs for all locations

The policies found in section 2.2.1 were run on 200 scenarios, with the above-mentioned factors as KPI's. The goal of this step was not to find the optimal solution for the Dike Rings, but rather to discard those policies that were not beneficial for Dike Ring 1,2, and 3. The policies that could be discarded, would not be tested further and this way the uncertainty analysis was less computationally expensive. The scenarios were sampled with Latin HyperCube Sampling, the standard sampling method in the perform_experiments function, providing a "convenient experimental design for scenario discovery" (Bryant & Lempert, 2010). According to them, it is the sampling method best fitting for scenario discovery, because it can efficiently cover the scenario space.

With a parallel axes plot, the effects of the policies on the KPI's and a trade-off between damage and deaths and investment costs could be seen. Considering the importance that the dike rings attach to safety, the number of deaths was chosen as the most important KPI to consider policies. The policies were then filtered as the 50% best scoring policies on this particular KPI. The remaining policies were tested for robustness in the next step.

2.3 Re-evaluate candidate solutions under uncertainty

The remaining policies have been optimised for a certain reference scenario in previous steps, and tested for their effect on Gelderland's KPI's in the same scenario, but how do they perform in other scenarios? In other words, how robust are they? To find out, each policy was run for 2000 scenarios, globally sampled with, again, Latin HyperCube Sampling.

Having acquired the experiment results of the run over the uncertainties, the policies were tested for robustness. To evaluate this, two metrics were used. As this is a search for an optimal policy, these were no metrics for satisfactory performance, but only for actual performance, a distinction made by McPhail et al. in their robustness metrics framework (2018). For each policy, the maximum regret and signal-to-noise ratio were calculated for the KPI's. Maximum regret calculates the difference between the worst score of that policy on that particular KPI and the optimal score of all policies and all scenarios on that KPI (Eker & Kwakkel, 2018). In other words, it measures policy performance in a worst-case scenario. Secondly, the signal-to-noise ratio was used to assess the result, which represents the policy's mean and the dispersion of outcomes around it, measured by the standard deviation (Eker & Kwakkel, 2018). The implementation of the signal-to-noise-ratio depends on the direction of the optimisation. In this case, all KPI's were to be minimised. Thus, the ratio was constructed as the product of the mean and standard deviation, and the goal is to have a low value.

Finally, to distinguish between the policies that scored similarly on the robustness metrics, the remaining policies were compared on their means, which resulted in a single preferred policy.

2.4 Exploring the preferred alternative

As a last step, the preferred alternative has been explored to gain insight in how the policy effects are shaped by uncertainties. For this, an extensive ensemble of scenarios was generated by sampling across the uncertainty space with 40.000 scenarios. Additionally, all problem formulations used in this analysis, the general KPI's, the Gelderland KPI's, and the predefined formulation 'disaggregated over locations'. were combined, so that all possible outcomes in our analysis could result from the scenarios. This scenario space was analysed with a Patient Rule Induction Algorithm (PRIM). PRIM can identify the effects of uncertainties on KPI's. It identifies the region in the scenario space that results in the region of interest in the outcome space by peeling away slices of the scenario space that have few results in the outcome region of interest (Bryan & Lempert, 2010).

After this initial analysis of the uncertainty space of the preferred alternative, several other exploratory modelling techniques were used (dimensional stacking, feature scoring and regional sensitivity analysis), depending on the results of the previous analysis, to delve deeper into uncertainty effects on the KPI's.

At the end of the analysis, a preferred policy could be presented, with insights on how it is affected by the underlying uncertainties.

3 - Results

All coming results follow from analysis using the provided python files. These files are called from Jupyter Notebook files where the analysis code is run. All used files in the analysis could be found in the GitHub repository[2]. Only two adaptations have been made to the originally provided python files, the first being the changes to planning steps and horizon to dike_model_function.py as described in 1.4. The second is the addition of the specified problem formulation to problem_formulations.py, as explained in section 2.2.2.

3.1 Preliminary exploration of the model[3]

The first step in the analysis is creating insight in the model's capabilities and connections. This is needed to fully understand the model and being able to use the model correctly. Therefore, several runs were performed calculating dike heightening cost and their impact on the expected annual damage and number of deaths. Heightening is most expensive for dike ring 2 closely followed by ring 1 (see Figure 4). All dike heightening costs increase exponentially, the more the dikes are heightened. The costs vary from 6 million for 1 dm in ring 4 up to 90 million for 9 dm in ring 2. This is on average cheaper than the Room for the River projects, ranging from 30 to 250 million euro. A full overview of all investment costs of dike heightening and Room for the River projects can be found in Tables 3 and 4 in Appendix E.

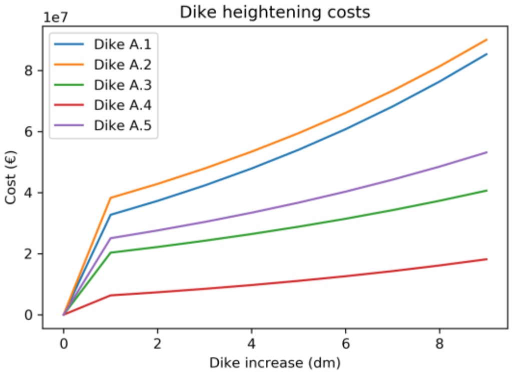

Figure 4 - Dike heightening costs

Next, for the expected annual damage and number of deaths some insights could clearly be based on the graphs in Figure 5. These are constructed by running multiple policies, each with an increasing dike heightening of 1dm per dike. These policies are run over 100 scenarios to calculate the average impact on Expected annual damage and number of deaths. Dike heightening around dikes 1 and 3 have the most impact on reducing these numbers. Another noteworthy insight is that when all dikes are heightened, the damage as well as the number of deaths approach zero. The effect of implementing all Room for the River projects is similar to dike heightening of 0,25 meters in all places. Note that these graphs do not show at which place the damage occurs, but the impact of a dike heightening at a certain dike on the total damage.

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[2] https://github.com/oli4oli4/Model-based-decision-making/tree/master/Final%20assignment%20deliverables

[3] Preliminary exploration is found in preliminary_exploration.ipynb

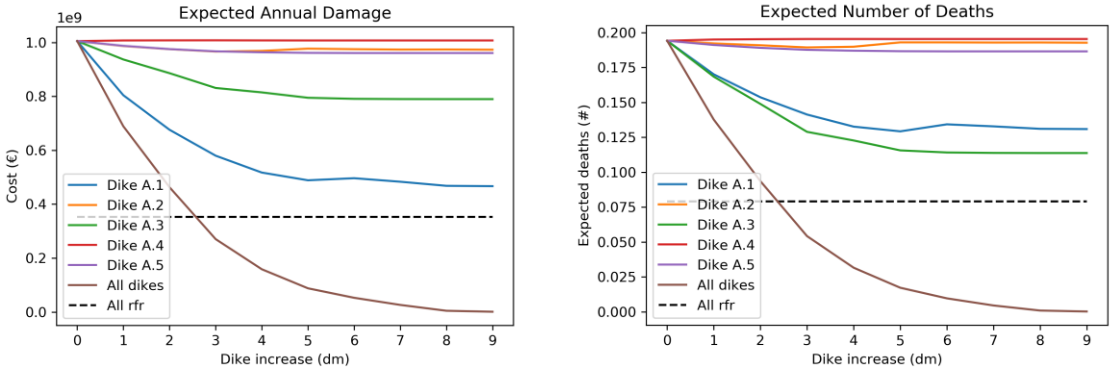

Figure 5 - Effect dike heightening on total expected annual damage (left) and number of deaths (right)

3.2 Searching for and evaluating candidate solutions[4]

After setting the problem formulation, the search for candidate solutions was carried out. For this the optimise parameters are set according to a test run and the number of functional evaluations was set to 15000. Both the hypervolume and epsilon progress starts to converge, see Figure 6 (large size in Appendix E). Based on the epsilon convergence, more iterations could be performed to create more reliable results. Yet it was decided the convergence was good enough and continued with the 16 policies which came out of the optimisation. Of these 16 policies, most of them indicate dike heightening in all dikes 1, 3 and 4 varying from 2 to 7dm. Two policies indicate a Room for the River project in Tichelbeeksewaard. A full overview of the resulting policies from the optimisation is shown in Table 5 in Appendix F.

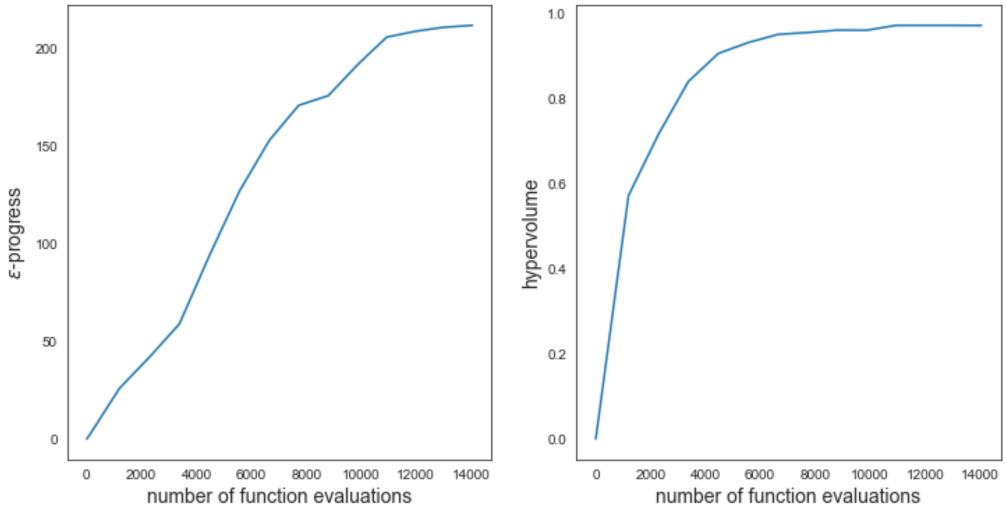

Figure 6 - Optimise convergence graphs: epsilon progress (left) and hypervolume (right)

These 16 policies need to be filtered based on the KPI's for Gelderland. Therefore, experiments are run for all policies over 200 scenarios. A parallel coordinates graph is plotted to determine which trade-offs need to be made, see Figure 7. In this graph, each line represents the mean of the 200 scenarios for a policy. This line is plotted for each KPI on a vertical line ranging from 0 to the maximum occurring value. The goal is to minimize all KPI's, so a line at the bottom of the plot would be ideal. In general, it could be observed that a trade-

[4] Executed in searching_and_evaluating_for_candidate_solutions.ipynb

off must be made between damage/deaths and investment costs. Furthermore, based on a visual inspection, policies seem to rank similar on expected damage and number of deaths.

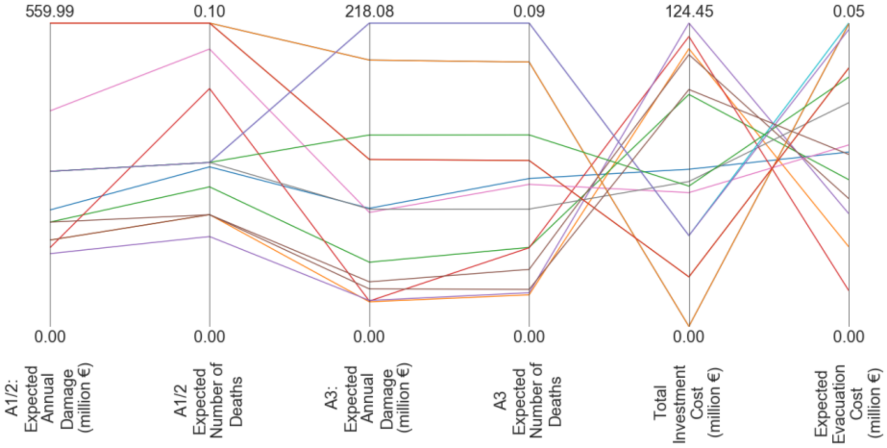

Figure 7 - Parallel coordinates plot: mean all optimisation policies

Based on these observations and the common mandates of both dike rings 1 - 3 which states that they should be kept safe, the policies are filtered on the number of deaths in both dike rings. The 8 policies where the expected number of deaths exceeds the median, being 0,4 for ring 1&2 and 0,2 for ring 3, are discarded. The remaining 8 policies will be checked on robustness.

The first robustness metric which will be maximum regret, see the parallel coordinates plot in Figure 8. As could be seen, for most policies, the regret is similar. The only one standing out is policy 3 (green), where the regret of number of deaths rises far above the others. Therefore this policy will not be taken into account.

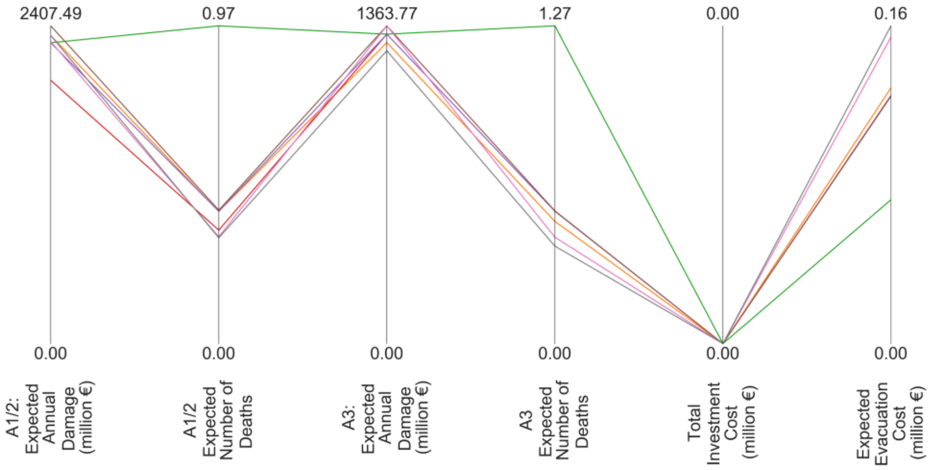

Figure 8 - Parallel coordinates plot: Robustness metric maximum regret

The next robustness is signal-to-noise, this checks the deviation as a product to the mean to determine the quality of the policy. On this metric, the results vary more. Policies 6, 7 and 2 (brown, pink and orange) score worst on the signal-to-noise for damage and deaths and are therefore discarded as well. See Figure 9 for the plot.

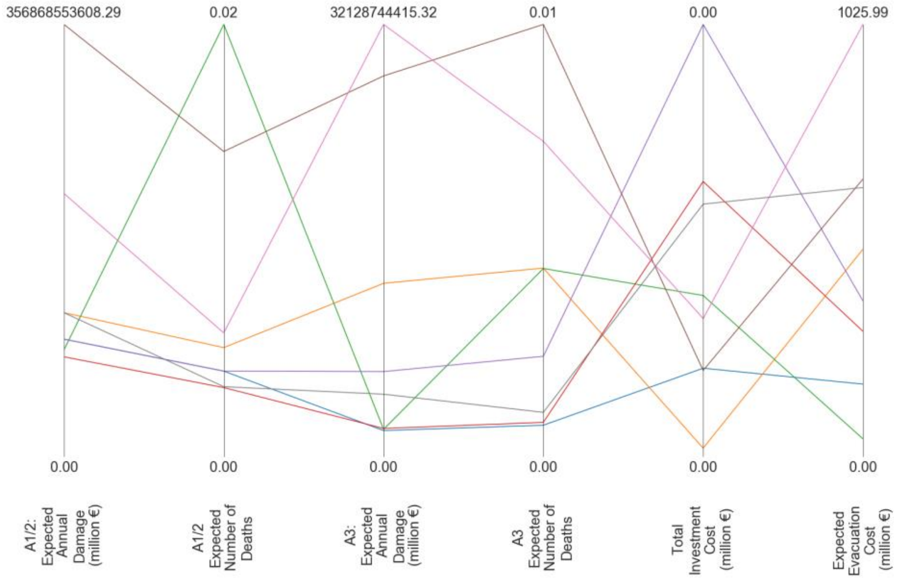

Figure 9 - Parallel coordinates plot: Robustness metric signal to noise

The four remaining policies (1, 4, 5, 15) score equally well on robustness metrics and so the final policy will be chosen based on the mean outcomes, since this should be the most likely outcome for the policy. These means are again plotted in a parallel coordinates plot, shown in Figure 10. In this figure, blue is policy 1, policy 4 is orange, 5 is green and the red line represents policy 15. Policy 1 scores well on the means of expected deaths and damage while keeping the investment and evacuation costs relatively low. Therefore this will be the recommended alternative.

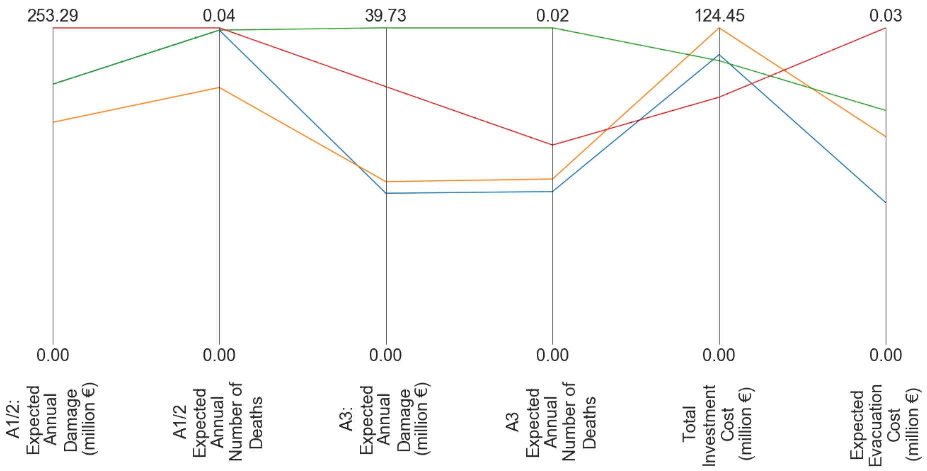

Figure 10 - Parallel coordinates plot: means remaining four policies

This policy means heightening the dikes with 3, 2, 5, 8 and 2 dm for respectively dike rings 1 to 5, all in the first planning step. No Room for the River projects will be implemented, and the early warning signal should be two days ahead, see Table 1 for the lever overview of this policy.

Table 1 - Levers for advised policy

Lever	**Level**
Heightening ring 1	3dm
Heightening ring 2	2dm
Heightening ring 3	5dm
Heightening ring 4	8dm
Heightening ring 5	2dm
Room for the river	no
Early warning signal	2 days

3.3 Exploring the preferred alternative[5]

The advised policy as mentioned above will now be evaluated under uncertainty. At first, experiments are run over 40.000 scenarios, which are sampled using sobol sampling techniques to create a reliable uncertainty space. These experiments are run for a combination of problem formulation outcomes to be able to evaluate on different KPI's.

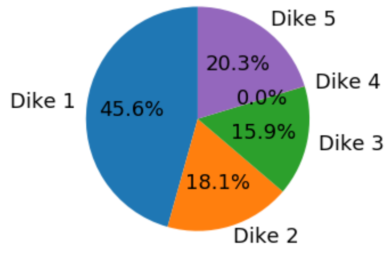

Figure 11 - Expected deaths distribution

At first, the outcomes of the policy are shown using some statistics. The mean, standard deviation, minimum, maximum and 90th percentile is calculated. On average, the expected number of deaths is 0,05 with a standard deviation of 0,08. In the worst case, 0,6 deaths are expected and the 90th percentile is at 0,17. The spread of mean deaths over the dike rings could be seen in Figure 11.
The expected annual damage has a mean of 263 million euros and a standard deviation of 420 million. The spread is comparable to the pie charts of the expected deaths except for dike ring 4, which has a share of 4% in the expected damage.
The total investment costs of this policy are 158 million euros of which 113 million accounts for Gelderland. Finally, the expected evacuation costs range from 0 to 80.000 with a mean of 11.500 euros.

3.3.1 Base case comparison

Next, the means are compared to the mean outcomes when no measures are being taken. This is shown in the parallel coordinates plot in Figure 12. The orange line represents the base case where the blue line represents the advised policy. It could be seen that the advised policy at least halves the outcome value of the base case and in dike ring 3, the new outcomes are at a tenth compared to the base case. Of course, in the advised policy, the investment costs are higher compared to the base case (where the costs are 0).

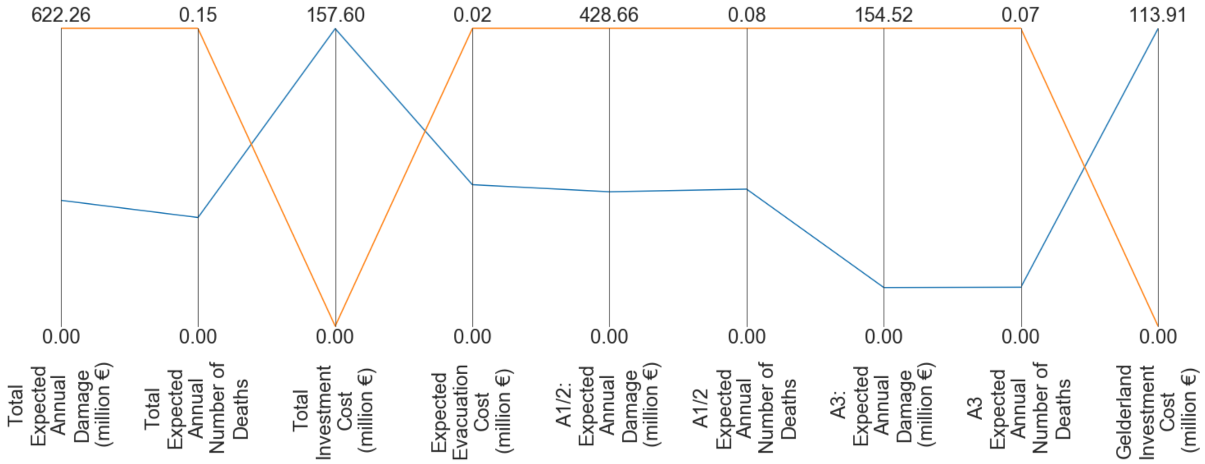

Figure 12 - Parallel coordinates plot base case against advised policy

[5] Preferred alternative exploration performed in exploring_preferred_alternative.ipynb

3.3.2 Uncertainty exploration

The first analysis of the uncertainty exploration is to inspect under which scenarios certain outcomes occur. There are a few outcomes of interest for this. To begin with a high expected number of deaths and damage for all dike rings combined, calculated by the top 90th percentile. This is tested using the PRIM algorithm with a threshold of 0,7. For both outcomes of interest, the cases of interest occur only with a low dike failure probability (pfail) on dike ring 1. Following the PRIM results, a box could be found where A.1_Pfail lies between 0 and 0,084 with density of 1 and a coverage of 0,84 for expected annual damage and 0,75 for expected number of deaths. This means all cases in this box have a high expected damage and number of deaths. The coverage means of all cases with a high expected damage, 84% occurs in this box, which is 75% for the cases with high expected deaths. In Figure 13, the significance of the results could be observed. In this density plot, the orange surface represents the cases of interest and blue means no cases of interest. The high orange peak at the beginning shows the density of a high number of deaths with a low A.1_pfail.

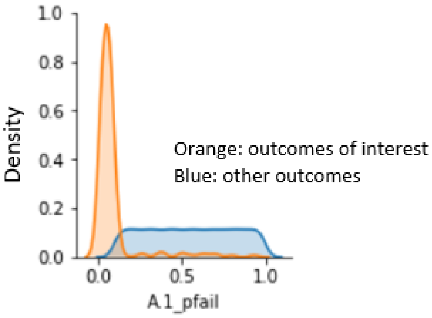

Figure 13 - Density plot expected deaths, differentiated on A.1_pfail box

Next, to inspect where the number of deaths occur, some more density graphs are plotted. Figure 14 shows the density of the expected number of deaths per dike ring. It could be seen that all dike rings have their peak at 0 deaths, yet dike ring 1 has another small peak at 0.25. This is in line with the PRIM results above; because the number of deaths is mostly caused by deaths around dike ring 1, the fail chance of this dike could dominate over the other dikes.

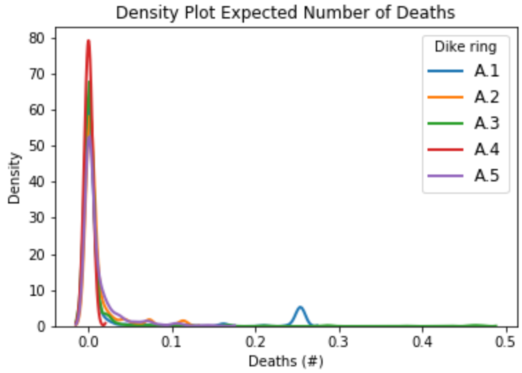

Figure 14 - Expected number of deaths per dike ring

However, these results do not confirm that a low dike failure probability in ring 1 also leads to deaths in the same area. To confirm this thought, a correlation should be found between the dike failure probability and number of deaths. This could be visually found using a feature scoring plot as shown in Figure 15. Here the feature scoring is run to inspect correlation between all uncertainties and the outcomes of interest per dike. Here, the thoughts above are confirmed by observing that a dike failure probability in a dike ring correlates with the damage and number of deaths in the same dike.

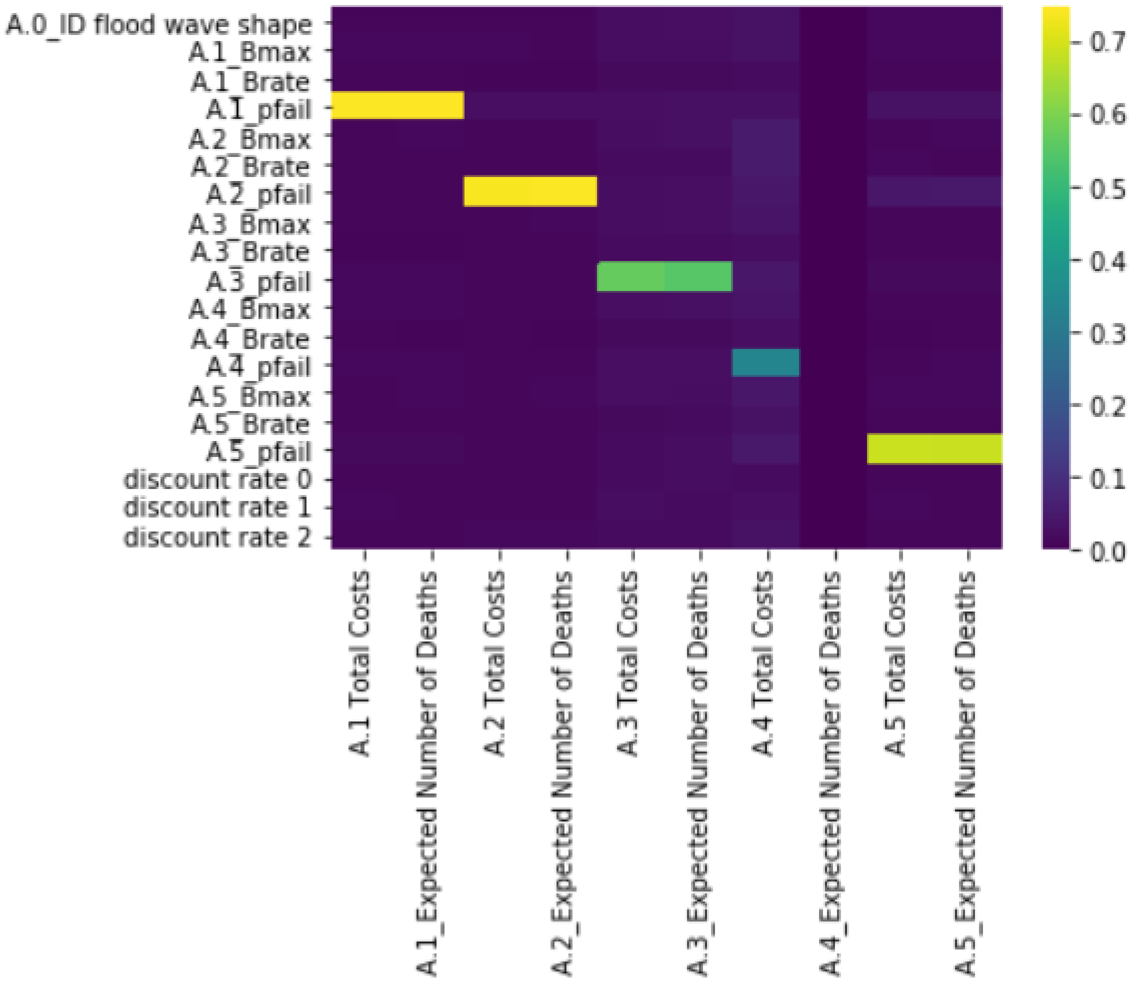

Figure 15 - Feature scoring card

Based on these results, it could be said that the expected number of deaths is mostly caused by the deaths in dike ring 1. Furthermore, the cases of high number of deaths could be explained by the uncertainty dike failure probability for dike ring 1.

Besides the dike failure probability, other uncertainties could have an impact on the outcomes, which is faded because of the dominance of dike failure probability. Therefore, a PRIM and future scoring are run again with a filtered uncertainty set discarding the dike failure probability. These analyses show there is no other clear correlation between the uncertainties and outcomes, see appendix G for these results.

4 - Discussion

The research executed in this report, leaves room for improvement for both the methodological and political aspects.

Starting with the political arena, within the stakeholder analysis, objectives of the involved actors are described. The exact objectives of the actors are however unclear. All actors are part of a political game, in which behaving strategically is extremely attractive (de Bruijn, 2018). A lot of this strategic behaviour is unseen, as it usually does not take place in public. This could mean that actors have different objectives and are part of different alliances, than can be seen by the public eye. Examples of this might be a province pushing for a safety solution somewhere else, claiming it is the best for overall safety, while their real goal is not hurting the people within their jurisdiction. It is hard to openly justify a position of NIMBYism, saying you want to get a solution as long as someone else pays the price for it, but NIMBYism definitely a part of resistance in the Room for the River planning (Warner, Edelenbos & van Buuren, 2012) and by extend will be taken into account by policymakers.

Secondly, the flood risk model lacks certain variables which are of high importance to the stakeholders. Algorithms, and models by extension, can favour political orientation due to what they do and don't take into account (Janssen & Kuk, 2016). As the model does not take some variables into account, it is arguable whether the model is able to find objective optimal results. One of those missing variables is the amount of land that is used for implementing Room for the River projects or heightening dikes. All dike rings have objectives related to the amount of land that is possibly lost with the implementation of a new policy. Furthermore, costs are not taken into account which are concerned with loss of land. These costs could include the costs for yield that is lost and moving costs in case urban areas are replaced with Room for the River projects. Another set of variables that is missing, are variables connected to the ecological impact of policies. The policies will undoubtedly influence biodiversity within the area; however, the exact impacts are not accounted for in the model and taking them into account will require a large-scale survey (Lawrence, 1979). The model does not include the impact of policies on transport possibilities. Transport companies are highly interested in this variable, as it influences their firms. By excluding this variable from the model, it is unsure how a policy will exactly influence this actor.

A third limitation to the model has to do with the problem formulation, over which has been optimised. Within this problem formulation, no weights have been given to the different KPI's and therefore all facts are considered as being equally important. Two out of four KPI's in the problem formulation are focussed on costs. Costs are considered to be equally important as the amount of deaths expected because of floods. This might lead to a frugal policy, as it does not fully represent reality. In reality, it is probably of more importance to consider the number of casualties than to consider the exact costs of the project.

Next, there are some limitations which are related to the methodology. At first, the computing power was limited. The complexity of the model causes highly computational model runs. Therefore, the optimisation was performed where the results did not fully converge. Preferably, the number of functional evaluations was set higher and the epsilons smaller to create more reliable results. As a consequence, to the current convergence, the evaluated policies might not be optimal.

Next, the optimisation is based on a Multi Objective Evolutionary Algorithm (MOEA), which, to generate policies, uses random values, which are generated on basis of a seed. The optimisation will come to the same results as long as the seed is not changed. By running the optimisation with multiple seeds, and comparing whether the optimal policies, one can build more trust in the optimisation and the model results.

Furthermore, the policies out of the optimisation were filtered and rated using signal-to-noise, maximum regret and finally the mean. These rating metrics are arguably chosen, and other metrics could have led to other considered policies. Another arguable choice which could affect the results are the chosen time horizon of 80 years and the three planning steps.

Finally, while MORDM can optimise across multiple objectives, it does so in only one scenario, possibly discarding policies that are optimal in other scenarios. By performing an optimisation in different scenarios (Multi-Scenario MORDM), these could come to light.

Future research

Based on the mentioned limitations, some further research is recommended. First, the optimisation runs could be done using different problem formulations where the ratio of deaths/damage and deaths is variated to change the weights to different factors in the model and thus change focus. Especially since the analysis of the advised policy shows a high expected number of deaths in dike ring 1, an adapted formulation could be made adding the number of deaths in this area as KPI.
Research could also be done on the uncertainty leading to this high number of deaths; the dike failure probability. If dikes are able to handle more hydraulic loads or the uncertainty becomes known, the number of deaths could be prevented.

Furthermore, the model could be extended by including missing variables for the transport companies, environmentalists and dike rings. Adding these variables, a more mature consideration could be made.

On a final note, performing Multi-Scenario MORDM could bring additional optimal policies to light. These can then be used to either boost the robustness of the current optimal policies, if they are comparable, or to warrant further exploration of new policies.

5 - Conclusion

The objective of this report is to advise the Province of Gelderland on a policy concerning a flood risk management plan for the IJssel. This advice has been created while considering the multi-actor context of the problem. All involved stakeholders and their objectives have been discussed within the report, together with tensions that could arise among these actors. The divergent interests of different stakeholders, results in a highly complex political arena.

Based on a flood risk model by Ciullo et al. (2019), an analysis was carried out to find the optimal policy. The model has been used to choose between doing nothing, heightening dikes and making Room for the River in five locations. Four outcomes (KPI's) have been considered as being most important in finding a solution based on preferences of all stakeholders. These are the total investment costs, expect evacuation costs per year, total damage per year and total deaths per year.

To optimise over these KPI's and to find a set of candidate solutions, the Multi Objective Robust Decision Making (MORDM) method was used. The candidate solutions were filtered, based on KPI's which are especially of interest for the Province of Gelderland. KPI's of interest to the Province of Gelderland are expected damage and deaths in each of their dike rings, total investment costs for dike rings in Gelderland and the expected evacuation costs. This resulted in a set of optimal policy solutions, which have been re-evaluated under uncertainty. Based on robustness tests, one single preferred policy has been found:

- No implementation of Room for the River projects
- 3 dm dike heightening in dike ring 1
- 2 dm dike heightening in dike ring 2
- 5 dm dike heightening in dike ring 3
- 8 dm dike heightening in dike ring 4
- 2 dm dike heightening in dike ring 2
- An early warning signal of 2 days ahead of possible floods

This policy would result in an expected annual damage of 263 million Euro, an expected number of deaths of 0.056, total investment costs of 158 million Euro and expected evacuation costs of 11,500 Euro. These numbers are the aggregates over all five dike rings.

It would be advised to the Province of Gelderland to go into policy negotiations with somewhat higher values for dike heightening than the ones of the preferred policy. This is based on the possibility that the province will have to give in on its proposed policy in order to reach a final policy accepted by all actors.

There are some limitations to the conclusions made in this report. As not all factors of interest have been included in the model (e.g. land loss, ecological effects) and there are some points of improvement in the methodology. These points are further discussed within the discussion chapter, and further research should be done to resolve these issues and improve policy recommendations for the Province of Gelderland.

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Appendix A: Political reflection

In the political process of this research project our group came across several challenges posed when models are used in a decision-making process.

A.1 Identified challenges

The first challenge identified was a tension between an optimal solution and the interest of different individual actors. Political relations between actors can make overall optimal solutions undesirable. This was seen in our personal Room for the River project experience, where provinces tried to push solutions outside their own territory: The dike rings wanted safety, but not at the cost of their own land. It also showed in the real life Room for the River project where tension between civil engineers and planners on the one hand, and citizens and local stakeholders on the other hand lead to tension and frustration about the lack of consultation (Warner, Edelenbos & van Buuren, 2012; Warner & Van Buuren, 2011). Warner, Edelenbos & van Buuren also mentioned that NIMBYism, the desire for a solution as long as it's 'not in my back yard', undoubtedly played a part in this response. Gilroy (1991) says that a community can accept measures as part of their fair share in the public's interest, as long as the compensation is fair and they don't feel like they're being exploited.

Another part of this challenge is the relation of the model to the real world it is trying to represent. There is a threat of a disconnect between the numbers of the model and real-world considerations. The political decision-making arena is the place where, in the end, the agreement must be made. According to Kwakkel and Haasnoot (2019) uncertainty decision-making support should, under deep uncertainty, move away from trying to define what is the right choice instead of aim at enabling deliberation and joint sense making among the various parties to a decision. This means that models should have a supportive role in decision-making, instead of being an optimisation tool for the future.

The second identified challenge is on how to deal with factors outside the scope of a model. During the debates it became clear that certain values or parameters were not included in the model but valued by some actors. Examples of these parameters are things like biodiversity, soil degradation and land lost due to taken measures. Janssen and Kuk (2016) mention that algorithms, and models by extension, can favour a political orientation or reinforce undesired practices. The values outputted by the model are based on the data that was inputted, which is subject to the way data is collected. The output parameters, over which a model is optimised, are also chosen when the model is designed. Reflecting on our case, this model was probably designed for flood risk, while neglecting certain societal and environmental interests that matter when developing policy.

The third identified challenge is the subjectivity of the modeller. In our Room for the River project debates it became quickly apparent that, even though everyone uses the same model, different results were found based on the input of the modeller. These models, and the algorithms within them, are very complex and to most people very opaque. In the case of this project, the model did not have a clear explanation that went with it. This creates a black box between input and output, where the inner workings of a model are hard to grasp. Janssen and Kuk (2016) call out this problem, saying that models are not free from human interference and biases. This means that the construction of the model and the specification of both in- and output are inherently biased, since a human created them.

A.2 Dealing with these challenges

A.2.1 In the analysis

In order to mitigate these challenges, we decided to take a broad approach in the decision-making process, especially since our actor had the option to propose a policy. By adapting the problem formulation to include the key performance indicators of other actors as well, we allowed a broader look at the problem. This was done by splitting generalised indicators into their original parts. While retooling the model to include some missing indicators, like biodiversity, was outside the scope of this research, this did allow us to take into account some of the factors that were valued by other actors. This would help us mitigate part of the third challenge, as we get a slightly more generalised outcome. There, of course, is still bias within the underlying black-box flood risk model, but in this way, we are trying to prevent a skew to our actor. This would also help with the first raised challenge, as we get to understand the trade-offs between optimal results and how much each individual actor must give in.

In the decision-making process the first identified challenge, the interest of each individual actor versus the interest of the larger population, really showed. Different actors are all lobbying and framing the problem in their own interest. Almost every actor acknowledges that a compromise needs to be made to get to a decision through but giving in is something an actor who carries responsibility cannot necessarily do. Due to the nature of the voting, 7 out of 9 actors are needed to pass a policy, and our modelling outcomes, we decided to propose a policy with the least expected resistance: all dike-heightening. This was thought to be a relatively undisputed policy, because almost no actor, except the environmentalist interest groups, must really give in for this policy to be realized.

In preliminary meetings for the project, it became clear that some things needed to be realized in the policy to obtain a majority vote. One of these was that there had to be at least one Room for the River project. This led to the re-evaluation of the model and proposition of a policy which had a project in dike ring 4. In this way, the analysis was changed to the apparent political restrictions.

A.2.2 In the political arena

The second challenge, values not being incorporated within the model, was also a point that was raised in the decision-making process. In this case it was about possible biodiversity gains and the cost of lost land. In order to deal with this, we prepared arguments that supported our policy. As an example, we used information on the water level reduction due to Room for the River projects in order to form an alliance with the transport companies. Lawrence (1979) mentions that, in the case of biodiversity, qualitative data can be used in a generally quantitative approach. To do this, they suggest a sampling framework with standardised data collection could be made, or a similar assessment method involving different stakeholders can be put in place. This would be a way to, if you have the means to do this, deal with missing data. It also shows interest in the standpoints of different actors, which could help from alliances.

A.3 Reflection on strategy

Reflecting on our strategy, we probably played the political game too safe. We came in with a compromise already, which then got pushed to a new compromise. We started with the previously outlined proposal, all dike-heightening, As de Bruijn, de Bruijne and ten Heuvelhof (2015) mention: “A win-lose dimension will more often than not result in political conflicts, and has consequences for societal acceptance and can impede political decision-making”. In the end of negotiations, the provinces stood on opposite sides of the same argument: If there is going to be a Room for the River project, it will be in the other province. This created that win-lose dimension, as giving in to such demands would indicate you lost that political battle. As our province was pushed into this losing position, we stood our ground and, partially unintentionally, became a disruptive force in some of the negotiations.

In order to make a strategy have the desired consequences, forming alliances is important. If you can find allies within the decision-making process, the power you have in formulating the policy will increase. Within the politics, the common ground between actors is only the shared interests. In the debate exercise, we had hoped that we could convince the Delta committee of our low friction policy. However, Overijssel Province had convinced them that only with a Room for the River project, a sustainable solution could be made and that that could only be at Dike Ring 1. This alliance controlled the narrative, effectively posing their models as objective, while we failed to shape the narrative in a beneficial way for us, putting pressure on Overijssel instead of us.

Appendix B: Water level reduction with Room for the River projects

This appendix contains information about the water level reduction due to Room for the River projects being implemented.

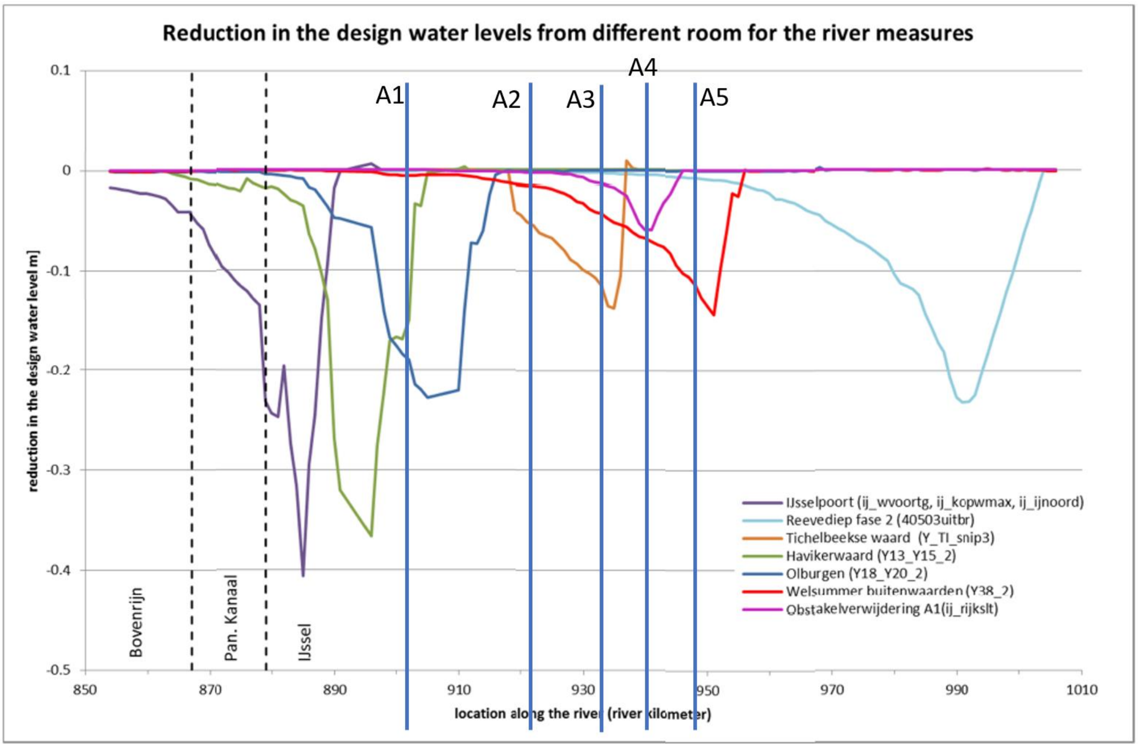

Figure 16 - Water level reduction from different Room for the River measures

The graph above illustrates how ‘obstakelverwijdering’ has the smallest effect on reduction of water levels and IJsselpoort has the largest effect. However, it is notable that all Room for the River projects cause water levels to drop.

Appendix C: Dike rings

This appendix contains figures indicating the geographical locations of different dike rings.

Figure 17 - Geographical location dike ring 49

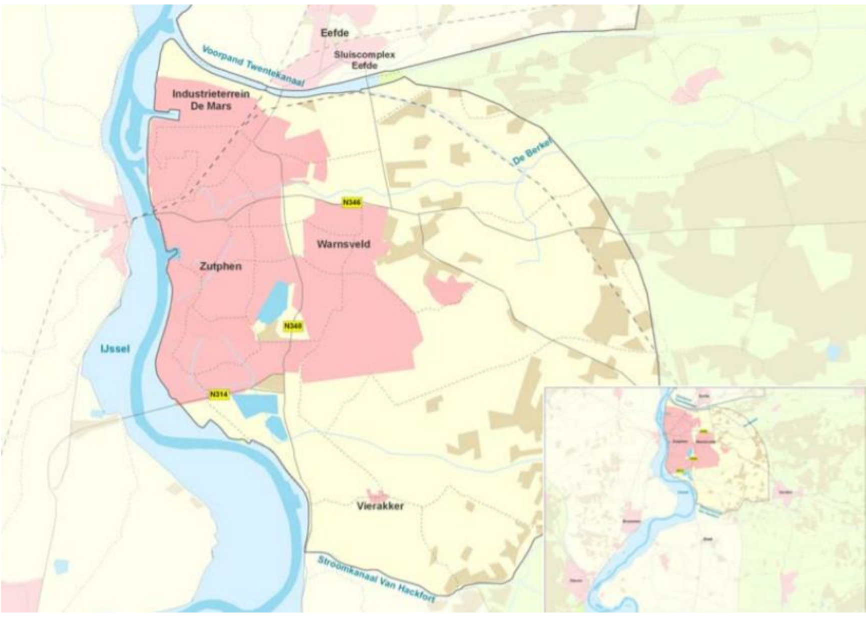

Figure 18 - Geographical location dike ring 50

Figure 19 - Geographical location dike ring 52

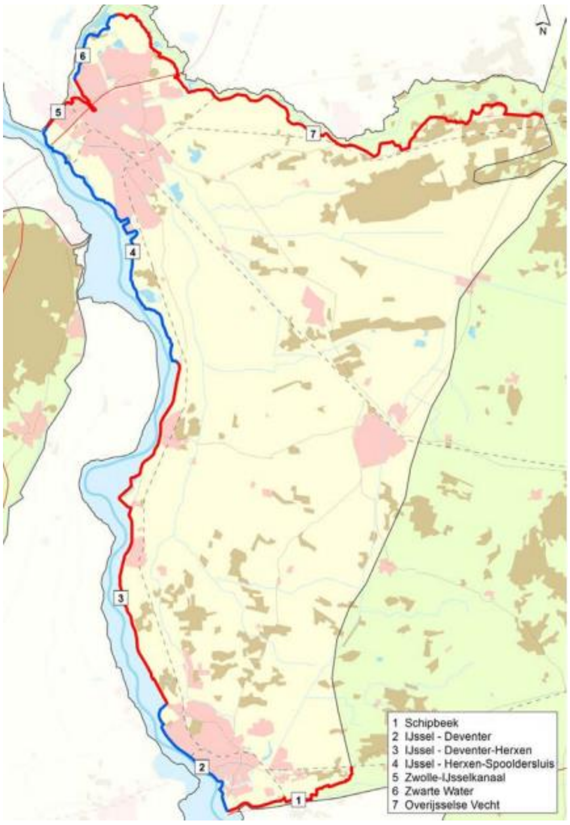

Figure 20 - Geographical location dike ring 53

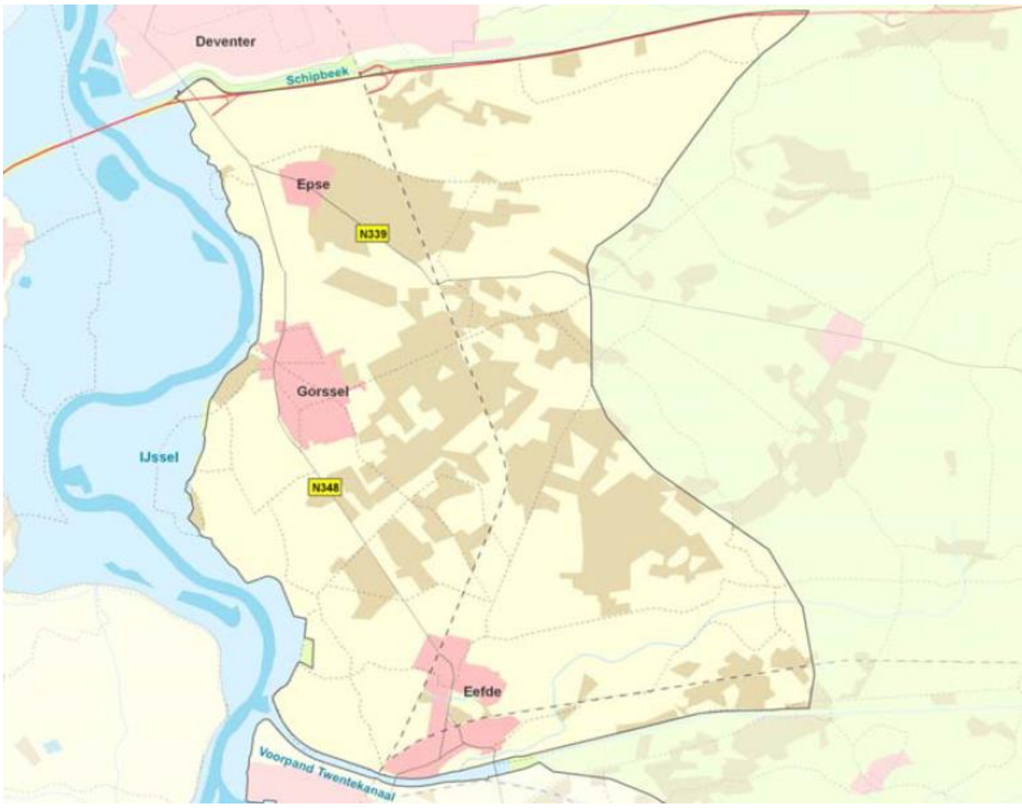

Figure 21 - Geographical location dike ring 51

Appendix D: XLM factors

This appendix contains different parameters from the XLM model.

Table 2 - XLM factors (TU Delft, Department of Technology, Policy and management, 2020)

	Factor	Description	Range/set	Unit
X	Flood wave shape	A normalized curve describing the way discharges at the most upstream location change over time. There are 140 possible wave shapes.	0-140	
	Dike failure probability	Probability that the dike will stand the hydraulic load. The higher this number, the 'stronger' the dike.	0-1	
	Final breach width	The final extent of the breach width. The larger the width, the greater the volume of water flowing into the floodplain.	30-350	m
	Breach width model	The way the breach width develops over time, with the uncertainty being the growth rate. The final breach width can be reached within 1,3 or 5 days.	(1, 1.5, 10) for 5,3,1 day respectively	1/day
	Discount rate	It determines the present value of the future expected damage. The lower the value, the more damage to future generations is valued.	(1.5, 2.5, 3.5, 4.5)	
L	Dike heightening	Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand.	0-10	dm
	Early warning	Early warning systems anticipate a threat and help limiting damage and/or avoiding deaths. The earlier the alert, the more effective the response, but also the more uncertain it is that the event will actually happen. False alerts can be costly and undermine people's trust into the authority. Waiting too long is also problematic as the efficacy of late alerts is poor. In the model you can choose how much time in advance to give the alert.	0-4	days
	Room for the River	RfR projects widen the river bed thus lowering the water levels	0-1	

		associated to a given water volume. There are five RfR projects which can be either implemented or not (1 or 0). Each project corresponds to a profile of water level reductions across locations.		
M	Expected annual damage	Expected annual value of flood damage over the planning period. Clearly, for each location, the lower this value, the better.		€
	Expected number of deaths	Same as above but related to amount of deaths and not economic damage.		
	Dike investment costs	Investment costs of raising dikes.		€
	Evacuation costs	Function of the number people evacuated and the number of days they need to be out from home. The estimation is based on the 1995 evacuation in the Netherlands.		€
	Room for the River costs	Investment costs of the implemented Room for the River project.		€

Appendix E: Investment costs overview

This appendix contains an overview of investment costs per dike.

Table 3 - Dike heightening costs per dike per increase

Heightening (dm)	Dike 1	Dike 2	Dike 3	Dike 4	Dike 5
0	0	0	0	0	0
1	32.694.901	38.245.121	20.299.287	6.320.800	25.037.214
2	37.255.203	42.818.415	22.167.818	7.332.080	27.578.229
3	42.291.505	47.842.699	24.198.032	8.453.407	30.351.526
4	47.847.947	53.358.573	26.403.379	9.695.195	33.377.116
5	53.972.506	59.410.102	28.798.397	11.068.771	36.676.675
6	60.717.312	66.045.103	31.398.797	12.586.457	40.273.672
7	68.139.002	73.315.450	34.221.561	14.261.651	44.193.513
8	76.299.088	81.277.411	37.285.037	16.108.916	48.463.701
9	85.264.360	89.992.006	40.609.051	18.144.080	53.114.002

Table 4 - Room for the River project cost

Project name	Olburgen	Havikervaard	Tichelbeekse	Welsummer	Obstakelverwijdering
Cost	84,6	217,8	30,7	121,2	256,1

Appendix F: Visuals results MORDM

This appendix contains the visual results from the Multi-Objective Robust Decision Making (MORDM) analysis.

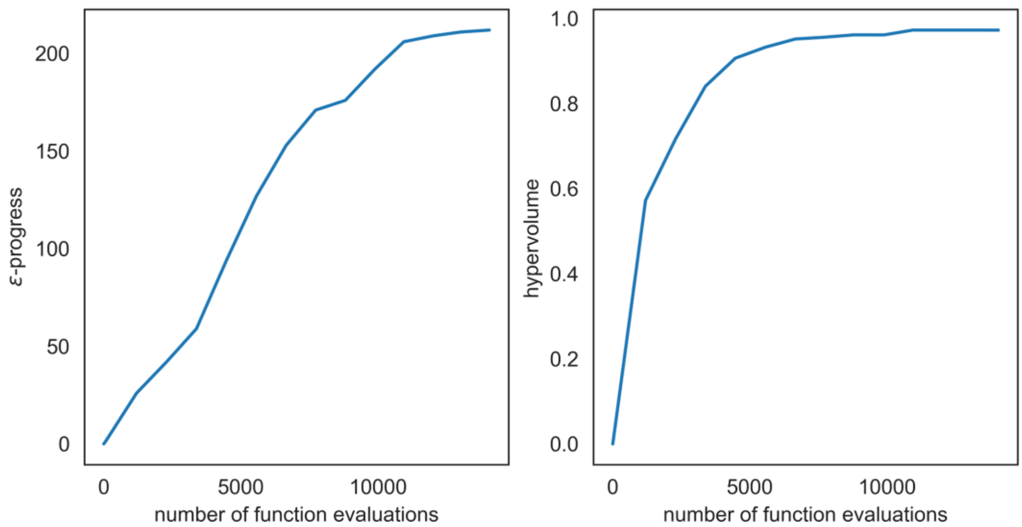

Figure 22 - Convergence graphs optimisation (large)

Table 5 - Policies resulting from optimisation (0 values columns are left out)

Policy	2_RfR 1	2_RfR 2	EWS_Days ToThreat	A.1_Dike Increase 0	A.2_Dike Increase 0	A.3_Dike Increase 0	A.4_Dike Increase 0	A.5_Dike Increase 0
0	0	0	2	3	0	2	7	0
1	0	0	2	3	2	5	8	2
2	1	0	2	3	0	2	7	0
3	0	0	1	3	3	5	9	3
4	0	0	2	3	4	5	6	0
5	0	0	2	3	2	4	6	0
6	0	0	2	1	0	2	7	0
7	0	0	3	2	0	2	0	0
8	0	0	3	0	0	1	7	0
9	0	0	3	2	0	0	0	0
10	0	0	3	0	0	0	4	0
11	0	0	3	0	0	0	7	0

12	0	0	3	2	0	1	5	0
13	0	0	3	0	0	1	4	0
14	0	0	3	2	0	0	6	0
15	0	1	3	3	0	3	7	0

Appendix G: Results advised policy exploration

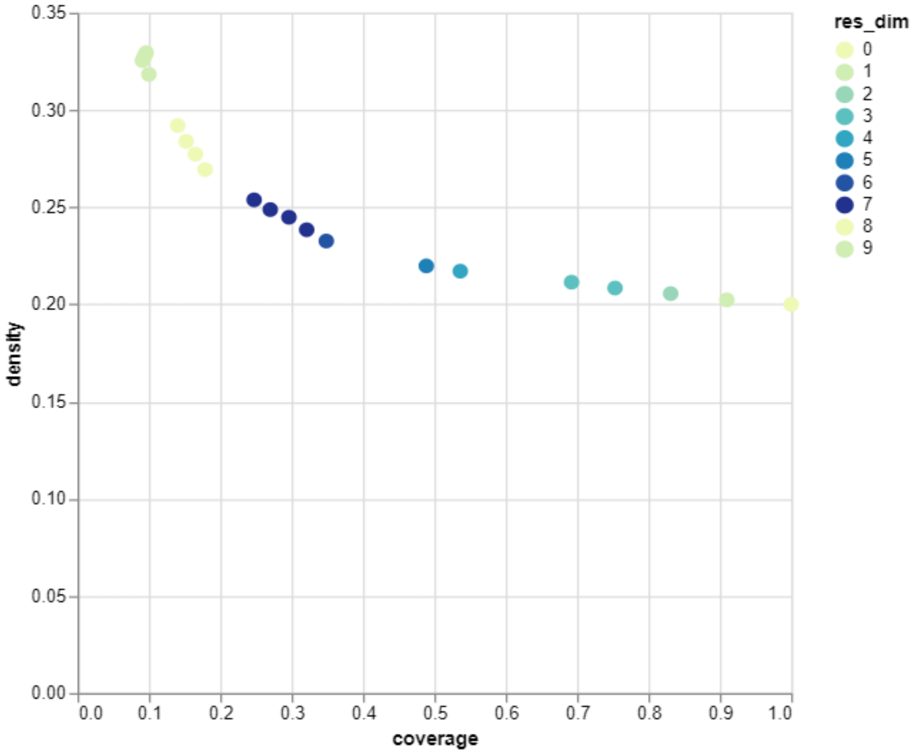

Figure 23 - PRIM trade-off plot without pfail

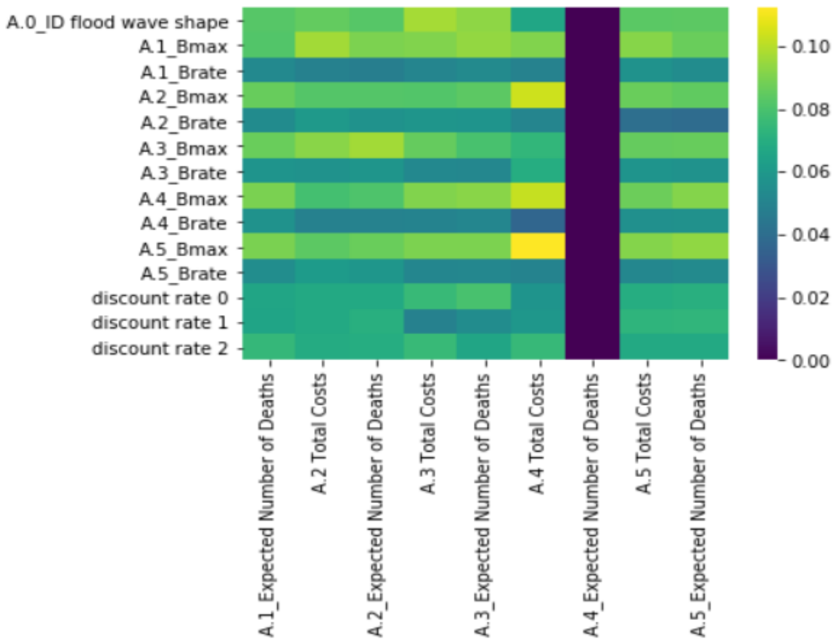

Figure 24 - Feature scoring card without pfail