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scale infrastructural projects in a highly urbanized environment are increasingly subject to political and societal pressure to add costly additional features.

64. Optimization of flood risk reduction through multiple lines of defence

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INTRODUCTION

Floods can have a huge impact on the regions they affect. The impact of these disasters can be reduced with a flood risk management system. Flood-prone regions often require a combination of interventions to reduce the risk to an acceptable level. The amount of risk reduction provided by various interventions can be quantified using probabilistic risk analysis.

The interdependence between multiple lines of flood defences within the same flood risk management system can have a large effect on the flood risk in a region. For example, the height and strength of a coastal levee greatly affects the impact of any inland flood risk reduction measures, like vegetation for wave attenuation. This can be investigated with the use of probabilistic risk assessment. However, assessing such flood defence systems can be computationally very intensive, as well as time-consuming. Although methods have been developed to optimize a single type of intervention (e.g. defences (Kind, 2014; Duipuits and Schweckendiek, 2015)), there are no generic approaches that address combinations of interventions.

In this paper, a new model is presented that is able to (1) simulate combinations of flood risk reduction measures and (2) optimize these based on costs, economic risk reduction, and environmental impact. A key feature of the model is the capability to incorporate different types of interventions, including barriers, dikes, wetlands, non-structural interventions, modifications of structures, and buyouts. This is kept computationally workable by using simple, yet realistic representations of the system elements in the form of fragility curves, cost curves, and damage curves. This form of modelling follows earlier explored concepts described in (Haasnoot, 2014) and (Kwakkel, 2013). Other aspects such as societal and environmental impacts will be discussed qualitatively and ranked with other indicators.

SIMULATION MODEL

The model is built up out of three parts: the *Damage Model*, the *Risk calculation* and the *Optimization Model*. Figure 1 shows how the different parts interact and which actions are included.

The *Damage Model* calculates the construction cost, environmental impact and estimated damage

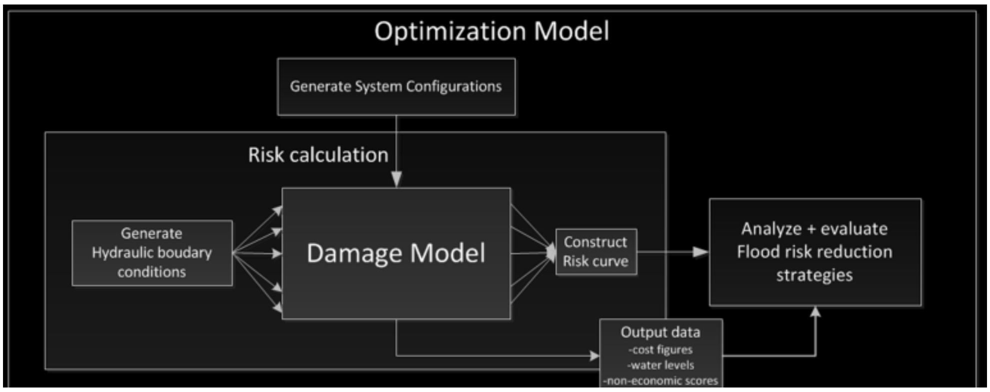


Figure 1 - Schematization of the interaction between the Damage Model, the Risk Calculation – which cycles through the Hydraulic Boundary conditions – and the Optimization Model, which cycles through the Flood risk reduction strategies.

cost for a single storm. This is done by combining three layers of information for the region: the Region lay-out, the Flood risk reduction strategy – consisting of the chosen combination of flood risk reduction measures – and the Hydraulic boundary conditions. This is illustrated in Figure 2. The impact of a storm on the region and the flood risk reduction strategy is calculated using simplified hydraulic formulas (Jonkman & Schweckendiek, 2015; Van der Meer et al., 2016).

The *Risk calculation* uses this combination to calculate the estimated value of damage. It repeats the calculations from the Damage Model for storms with different return periods. With this information, it is possible to construct a risk curve. The basis is a set of (flood) scenarios with their probablities and consequences (cf. Kaplan and Garrick, 1981)

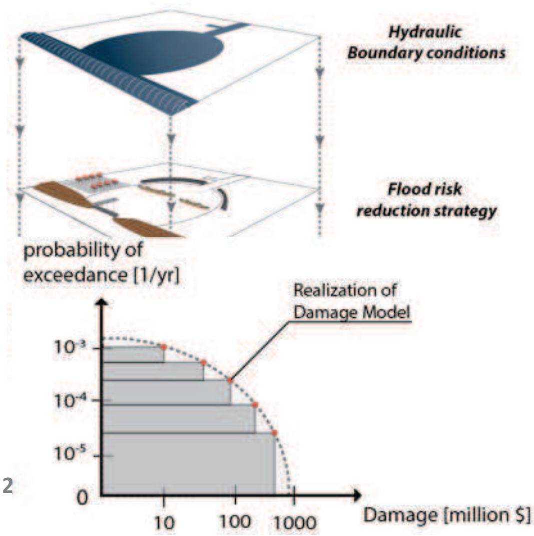


Figure 2

The graph shows the probability of exceedance of an event with a certain damage level. The expected damage can also be computed from this information. How this risk curve is constructed by combining the Damage Model with the Risk calculation, can be seen in figure 2.

EVALUATION TOOL

The strength of the model is the ability to compare large numbers of strategies with both structural and non-structural flood risk reduction measures, such as levees, oyster reefs, improving evacuation routes, and steering urban development locations. This evaluation is done in the *Optimization Model*. It provides the input for the Damage Model, analyzes the output, and investigates how the risk profile of the region reacts to different design choices, for example by identifying design trade-offs.

Figure 3 – graphical representation of how the Risk curve (the dotted line) is constructed by combining the results of different damage calculations as part of the Risk calculation. The rectangles illustrate how the total expected value of damage is derived by numerically integrating the risk curve.

By searching for design trade-offs, one could think of trade-offs between project goals (e.g. "High environmental scores are hard to achieve in combination with low barrier heights inland") or trade-offs between design choices (e.g. "Placing a relatively low barrier at the coast significantly diminishes the impact of Nature-based solutions in the first protected area*").*

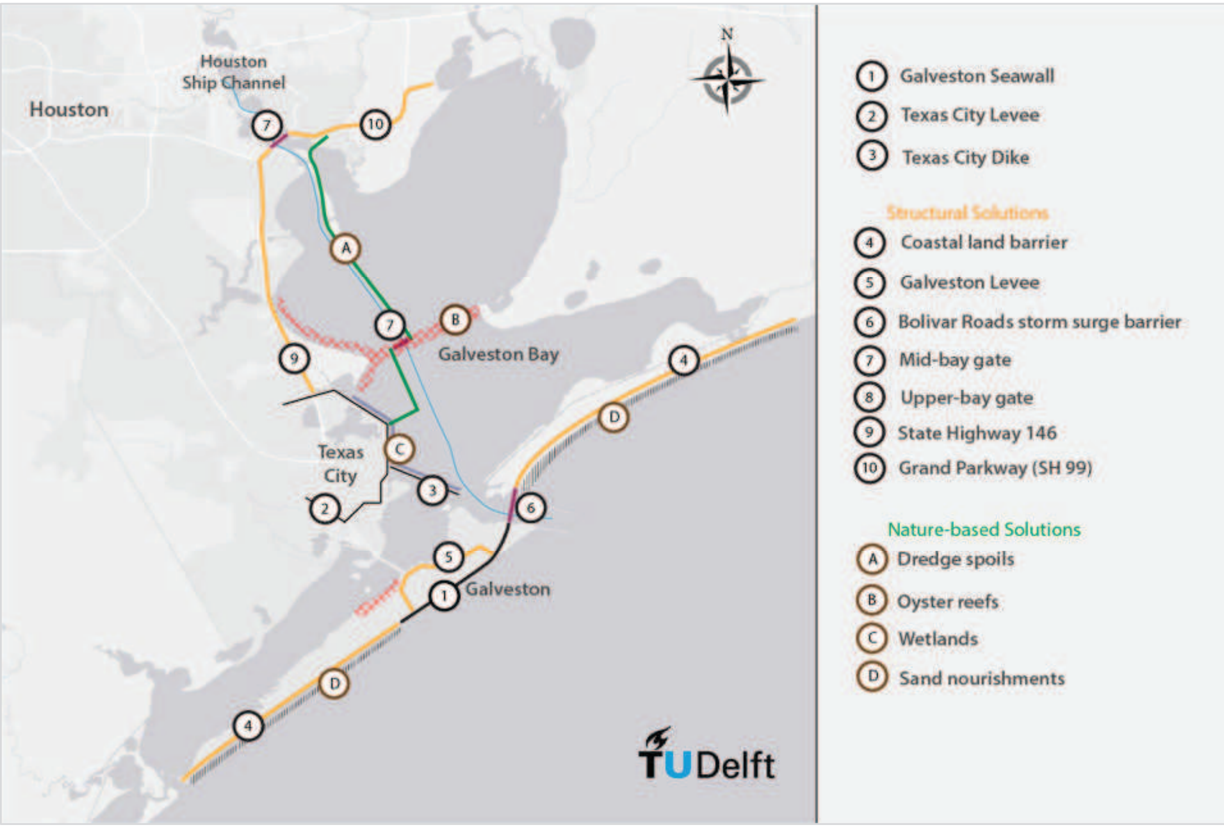
SYSTEM OPTIMIZATION

A stylised case study based on the Houston-Galveston Bay Area in Texas was used to demonstrate the model (van Berchum, 2017). It was able to show how the region reacts to design choices, for example by providing insight into the change of effectiveness of wetlands around the bay depending on the investments in coastal structures. The case study included both structural and non-structural

Figure 3 – map of the Galveston Bay Area with implemented and identified possible flood risk reduction measures.

measures, ranging from levees and storm surge barriers to *Nature-based Solutions* like wetlands, and spatial planning measures like raising insurance premiums.

The model is designed to be used as a decision-making tool during early phases of a design. Especially



during the conceptual design phase, when design choices are impactful and information is scarce, it can provide valuable insights and save precious time and money in finding attractive solutions for reducing risks for high-vulnerability areas threatened by coastal flooding.

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