Omega 000 (2018) 1–13

Contents lists available at ScienceDirect

Omega

journal homepage: www.elsevier.com/locate/omega

Adjustable robust strategies for flood protection

Krzysztof Postek[a,*], Dick den Hertog[b], Jarl Kind[c], Chris Pustjens[d]

[a] Department of Econometrics, Erasmus University Rotterdam, The Netherlands
[b] Data Science Center Tilburg, Tilburg University, The Netherlands
[c] Deltares, The Netherlands
[d] Ortec, The Netherlands

ARTICLE INFO

Article history:
Received 25 September 2016
Accepted 20 December 2017
Available online xxx

JEL classification:
C61
Q54

Keywords:
Robust optimization
Flood protection
Adjustability
Adaptivity

ABSTRACT

Flood protection is of major importance to many flood-prone regions and involves substantial investment and maintenance costs. Modern flood risk management often requires determining a cost-efficient protection strategy, i.e., one which has the lowest possible long run cost and which satisfies flood protection standards imposed by the regulator throughout the entire planning horizon. There are two challenges that complicate the modeling: (i) *uncertainty* - many of the important parameters on which the strategies are based (e.g. the sea level rise) are uncertain, and will be known only in the future, and (ii) *adjustability* - decisions implemented at later time stages need to adapt to the realized uncertainty values. We develop a new mathematical model addressing both issues, based on recent advances in integer robust optimization, and we apply it to the Rhine Estuary - Drechtsteden area in the Netherlands. Our approach shows, among others, that (i) considering 40% uncertainty about the sea level rise leads to a solution with less than 10% increase in the total cost, (ii) solutions taking the uncertainty into account are cheaper in the long run if the ‘bad scenarios’ for the uncertainty materialize, even if the ‘optimistic solutions’ are allowed to be repaired later on, and (iii) the optimal here-and-now investment decisions change when uncertainty and adjustability are included in the model.

1. Introduction

Managing flood risks is of vital importance for the Netherlands, as two-thirds of the country is flood prone. The areas at risk are protected by a large flood protection system, with dike rings consisting of dikes, dams, dunes, high grounds, and other water defense structures. Each year, about 1 billion euro is spent to maintain and improve this system.

Improving the flood defenses is necessary when flood protection standards are no longer met. This can be caused, for example, by a general deterioration of the flood defense, climate change, or a change of protection standards. In recent years, and within the context of the Dutch Delta Program, the Netherlands has been in the process of revising all of its legal flood protection standards [26], since parts of the old standards were still based on the advice of the first Delta Commission, installed after the last great flood disaster in the Netherlands of 1953 [27].

In the Delta program, a novel, optimizing cost-benefit analysis (CBA) using operations research techniques was used to derive economically efficient (‘optimal’) flood protection standards, in which the discounted total cost of expected long-run investment and flood damages was minimized [10,14,15,21]. This CBA assumed dike reinforcements as a flood protection measure and determined the optimal timing and size of the reinforcements, from which optimal flood protection standards were subsequently derived. It proved to be the case that although the optimal timing and size of the reinforcements were dependent on the climate scenario assumed, the optimal standards were not. The optimal standards, however, are very sensitive to assumptions about the economic scenario, discount rate, investment cost, and flood damages [17].

The updated standards, accepted by the Dutch government on July 5, 2016, are based on considerations of equality (a maximum tolerable probability for all individuals to lose his/her life because of flooding), efficiency (CBA) and social disruption [28]. After the new flood protection standards become legally binding in 2017, regional delta programs will have the task of developing more detailed flood risk management strategies to meet those new flood protection standards. Those strategies are not necessarily restricted to dike reinforcements, but may consider other measures.

In the lower reaches of the Rhine and Meuse rivers, the regional Delta Program *Rhine Estuary - Drechtsteden* studies alternatives to dike reinforcements, such as water storage, channel deep-

---

[*] Corresponding author.
E-mail address: postek@ese.eur.nl (K. Postek).

https://doi.org/10.1016/j.omega.2017.12.009
0305-0483/© 2018 Elsevier Ltd. All rights reserved.

ening, storm surge barriers, and ‘room for the river’ measures - alternatives which lower water levels and hence reduce the need to reinforce and heighten the dikes [20]. To aid the regional program in developing and evaluating combined strategies, including proposals for the timing of investments, a ‘planning kit’ was developed [23]. In this kit, there were many possible strategies, and it was practically infeasible to find an optimal strategy by trial and error, even if uncertainties in climate scenarios were not considered.

There are two important challenges remaining in designing optimal flood risk management strategies. First, it is important to incorporate climate change related uncertainties in the analysis explicitly. In the previous approaches, sensitivity analysis was used to show robustness, that is, the performance of the given solution was tested against different realizations of the uncertainty. Such an approach (i) may require a lot of computation time, in particular for a detailed specification of the parameter evolution for each scenario, and (ii) may already be infeasible at the implementation stage – because parameter values different from the assumed ones are revealed between decision-making and implementation. This raises the challenge of *robustness to parameter uncertainty*. Second, it is important that the solutions are *adjustable* to the revealed values of uncertainties, as opposed to *static* solutions. In static solutions, one may not base later-stage decisions on the true values of uncertain variables, such as, the sea level rise in the first 30 years. Static solutions may therefore prove to be over-conservative and expensive. This raises the challenge of *adjustability to revealed uncertainties*.

In this paper, we develop a mathematical optimization model to determine optimal adaptation strategies that address both of the challenges above. This model is general and applicable in any area, and in our experiment we apply it to the Rhine Estuary area, where it improves upon the planning kit of Kind et al. [23]. The issue of climate change related uncertainties is addressed by using Robust Optimization [RO, see 1]. In this approach, instead of specifying a precise climate change trajectory, an uncertainty set of ‘possible outcomes’ of the unknown parameters is specified. Then, the problem is solved in such a way that the constraints (requirements) are satisfied by the decisions for every outcome of uncertainty within the uncertainty set.

The strict requirement that the decisions are feasible for all allowed outcomes of uncertainty makes RO the preferred methodology for safety-related optimization problems, such as flood prevention. For an introduction and overview of techniques used in RO, we refer the reader to the work by Ben-Tal et al. [1], Bertsimas et al. [3] and Gabrel et al. [16] and references therein.

To make later-stage decisions adapt to the revealed uncertainties from previous stages, we resort to an extension of RO – Adjustable Robust Optimization (ARO). In ARO, the constraints are required to hold for all outcomes of the uncertainty, but later-stage decisions are formulated as functions of the observed uncertainties, and the way these decisions adapt (‘shape of the reaction’) is also optimized.

ARO was initially developed to solve problems with continuous decision variables in Ben-Tal et al. [2], where the concept of using affinely adjustable decision rules was introduced; this was extended by Chen et al. [11], Chen and Zhang [12], Ben-Tal et al. [1] and Bertsimas et al. [9]. In the flood protection problem, however, most of the decisions are binary variables determining whether (and when) a given measure, such as dike heightening, is applied. The first applications of ARO to integer recourse problems were introduced by Bertsimas and Caramanis [4], Bertsimas and Caramanis [5] and Vayanos et al. [29], where the idea was to simply divide the uncertainty set into a dense grid of points and allow a different decision for each of them. Bertsimas and Georghiou [8], Bertsimas and Georghiou [7] and Hanasusanto et al. [19] proposed using specific decision rules for the integer variables whose ‘shape’ is optimized. However, these methodologies do not scale well with the size of the problem, which makes their application to problems like ours impossible.

The approach used in our paper is to construct multi-period adjustable integer decisions by means of multi-stage splitting of the uncertainty set into subsets. This is the approach taken in Postek and Hertog [24] and Bertsimas and Dunning [6] where, after the splits of the uncertainty set are determined, a different constant decision is applied for each part of the uncertainty set. The essence of this approach lies in determining the conditions that a split needs to satisfy in order to improve on the decisions’ adaptivity. Since, however, in the model we consider it is not possible to determine the structure of the splits using the methods proposed by Postek and Hertog [24], our splitting strategy of the uncertainty set is pre-determined.

Our contribution is as follows:

- we provide a mathematical optimization model to the flood protection problem (without uncertainty) whose optimal solution was not known before – as the earlier approaches relied on heuristics;
- we address the very important phenomenon of uncertainty – widespread in the water management community – by illustrating the cost of robustness of the solutions and the value of adjustability;
- we explain how adjustable robustness with integer variables – a notoriously difficult issue for which methods have been developed very recently – is applied to a real-life large-scale problem;
- we describe several findings from the numerical results of our experiments, among them: (i) considering 40% uncertainty about the sea level rise leads to a solution with less than 10% increase in the total cost, (ii) solutions taking the uncertainty into account are cheaper in the long run if the ‘bad scenarios’ for the uncertainty materialize, even if the ‘optimistic solutions’ are allowed to be repaired later on, (iii) the optimal here-and-now investment decisions change when uncertainty and adjustability are included in the model.

The structure of this paper is as follows. Section 2 gives the generic mathematical formulation of our problem without parameter uncertainty and adjustability. Section 3 defines how multi-stage parameter uncertainty is modeled and how the corresponding adaptive decisions are constructed. Section 4 presents the results of numerical experiments for the Rhine - Meuse Estuary - Drechtsteden area. Section 5 concludes the paper with an overview of the results and possible avenues for future research.

2. Deterministic model

We consider the problem of constructing an optimal flood protection strategy that is cost effective, i.e., determining when to implement measures so that the present value of the cost is minimized. Moreover, such a strategy must ensure that at each time period and for each dike segment, the flood protection standard is satisfied.

We assume that the flood protection system consists of N_s dike segments. The flood protection standards can be formulated in terms of *relative dike height* requirements – the height of the dike compared to the water level. The relative dike height can be improved by one of N_h dike heightenings of size $h \in \mathcal{H}$, and N_m large-scale measures, such as changing the discharge distribution of a river (directing it via other river segments in the delta). While a dike heightening affects only the relative dike height at a single segment, the large-scale measures affect more than one segment, and their impact may differ throughout the time horizon

Please cite this article as: K. Postek et al., Adjustable robust strategies for flood protection, Omega (2018), https://doi.org/10.1016/j.omega.2017.12.009