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Real options, multi-objective optimization and the development of dynamically robust adaptive pathways

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ABSTRACT

In cases, which are characterized by deep uncertainty it is appropriate to develop dynamic and adaptable plans. This paper presents an approach that uses multi-objective genetic algorithms to automate the development of dynamic adaptation pathways for stormwater management for a tropical urban catchment located in Singapore. Pathways spanning a range of climate and landuse scenarios are developed. Three objectives, namely the economic value of flexibility or the real options value, the traditional net present value and flood robustness are balanced to develop the pareto optimal pathways. Given that the pathways are developed under a blanket of uncertainty it is certain that results will have to be re-computed at different time steps in the future. The assessment performed in this manner offers the ability to recompute results easily when adaptation becomes necessary. Comparison of the results obtained for the different landuse scenarios show that if done right, landuse planning can serve as a solution rather than a problem to cater to a changing climate. This notion coupled with the individual adaptation pathways enables the development of an adaptation strategy that helps outline short and long-term policies necessary to cater to an uncertain future.

1. Introduction

Any long-term environmental policy analysis must confront the fundamental challenge that the long-term future remains fundamentally unpredictable. While long-term forecasts generated by statistical extrapolations, causal models, or future narratives do provide valuable insights, savvy policy-makers cannot confidently rely on a projection of events decades into the future to inform their decisions (Lempert et al., 2009). Adaptive approaches enable decision makers to overcome the limit of predictability of the future. This ideology draws motivation from the need to develop plans that are not restricted to the outlined futures but instead can be adapted to cater to the future as it unfolds. A Central notion of this paradigm is the idea of replacing the traditional static optimal plan with a dynamically robust plan. A static optimal plan aims to reduce vulnerability under the largest range of plausible conditions (Walker et al., 2013) while a dynamically robust plan aims to be successful in a wide variety of plausible futures, through the ability to adapt the plan dynamically in response to how the future unfolds (Kwakkel et al., 2014). Given the irreversibility of built infrastructure and their long lifespans, planning infrastructure investments by means of dynamic robustness is more beneficial than doing so by that of static optimality. The notion of developing dynamically robust plans has been increasingly gaining traction over the past few years. This ideology has been followed in a handful of case studies across disciplines. Dynamically robust plans have been developed for coastal adaptation (Rosenzweig et al., 2011), climate risk adaptation (Lawrence and Manning, 2012; Ranger et al., 2010; Wilby and Dessai, 2010; Dessai and van der Sluijs, 2007; Willows et al., 2003) infrastructure planning (Ranger et al., 2013), river basin management (Groves et al., 2013; Jeuken and Reeder, 2011; Middelkoop et al., 2012), flood management (Haasnoot et al., 2013) and water supply resiliency (Beh et al., 2015; Groves et al., 2008).

Among the multiple adaptive approaches presented in literature, this study employs and further extends the adaptation tipping point and the adaptation pathway approaches. These approaches were chosen due to their ability to develop dynamically adaptable plans and their gaining popularity in the field of water resources development. Further, the adaptation pathways approach is not only robust to climate change but to all other sources of risk and uncertainty, including broader scenario uncertainties (e.g. socioeconomic) and uncertainties resulting from a lack of data (Ranger et al., 2013).

The Adaptation Pathway approach (Haasnoot et al., 2013) was specifically developed to support policymakers in making decisions in view of climate change adaptation. This approach entails developing an adaptable plan that can be modified in response to how the future unfolds. Individual adaptation actions are first identified and their

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Table 1
Portfolio of Adaptation Actions.

Configuration	Notation	Description
Current Drainage Configuration	A	The current configuration is maintained
Drainage Increase C1	B	15% increase from baseline drainage capacity
Drainage Increase C2	C	20% increase from baseline drainage capacity
Drainage Increase C3	D	30% increase from baseline drainage capacity
Drainage Increase C4	E	50% increase from baseline drainage capacity
Porous Pavements C1	F	50% of all available pavements covered
Porous Pavements C2	G	60% of all available pavements covered
Porous Pavements C3	H	80% of all available pavements covered
Green Roofs C1	I	20% of all available roof space covered
Green Roofs C2	J	35% of all available roof space covered
Green Roofs C3	K	50% of all available roof space covered
Combination 1	L	Green Roofs C1 and Porous Pavements C1
Combination 2	M	Green Roofs C2 and Porous Pavements C1
Combination 3	N	Green Roofs C3 and Porous Pavements C1
Combination 4	O	Green Roofs C1 and Porous Pavements C2
Combination 5	P	Green Roofs C2 and Porous Pavements C2
Combination 6	Q	Green Roofs C3 and Porous Pavements C2
Combination 7	R	Green Roofs C1 and Porous Pavements C3
Combination 8	S	Green Roofs C2 and Porous Pavements C3
Combination 9	T	Green Roofs C3 and Porous Pavements C3

respective adaptation tipping points are calculated under multiple outlined climate scenarios. Adaptation Tipping Points are the physical boundary conditions where acceptable technical, environmental, societal or economic standards may be compromised (Haasnoot et al., 2011). Once an Adaptation Tipping Point is encountered, the system cannot continue to perform as expected and requires the implementation of another adaptation action. Simulation models are used to establish tipping points for predefined adaptation actions, under various scenarios. This enables the sequencing of adaptation actions to form adaptation pathways. The adaptation pathways are then combined to develop an adaptation pathways map.

Building dynamically robust plans by means of an adaptive pathway approach thus entail the consideration of multiple plausible futures, a large number of adaptation actions that can be implemented in response to these futures and the multiple ways these actions can be applied in isolation and combination to meet objectives all along the planning horizon. In addition to this, there are also socio-economic factors and different planning perspectives of decision makers that can impact the outlining and selection of these plans. Only when we understand the interplay of factors can we outline a map that can cater to any reality i.e. that is truly dynamically robust. Analysing a problem in this manner results in the 'curse of dimensionality' and is severely limited in practice by the necessary computational burden (Webster et al., 2012; Heer and Maussner, 2018). Once built, the adaptation pathways map provides an overview of sequences of possible actions that can be implemented under an uncertain climate. While having the entire solution space available has its own benefits in terms of visualizing all possible available solutions, it still leaves decision makers in an impossible position to choose among the multiple available pathways. This creates a need for further assessment of the developed adaptation map to trim down the large number of developed solutions into a more manageable subset. In addition, as every plan must be reassessed at specific intervals, the assessment must be repeated periodically. As the adaptation pathway map is currently drawn manually (Manocha and Babovic, 2017; Haasnoot et al., 2013) it makes the future re-assessment of the plan equally computationally intensive.

This paper aims to address two main objectives. The first objective is to show how the dynamic adaptive pathways approach developed for flood management in the Kent Ridge Catchment (Manocha and Babovic, 2017) can be supported computationally. The second objective is to extend the adaptive pathway approach by automating the identification of a sub-set of dynamically robust pathways that meet multiple objectives offering a trade-off between maximizing the flexibility of adapting to changing climate scenarios, maximizing robustness to a range of climate scenarios while being also cost effective. This is done by means of multi-objective evolutionary algorithms.

The rest of the paper is organized as follows: Section 2 offers in an introduction to the Kent Ridge case study. The application of the approach and the manner in which the optimization problem has been formulated is described in the Methodology section (Section 3). Results and discussions are presented in Section 4, followed by a conclusion in Section 5.

2. Introduction to the case study

The approach presented in this paper is illustrated by means of the Kent Ridge Case Study. The Kent Ridge Catchment is 85,000 square meters in size and is located in the south of Singapore, within the campus of the National University of Singapore. This catchment contains all the main land use types of Singapore and hence can be considered as reasonably representative from a hydrological point of view.

Singapore's Second National Climate Change Study determines that annual rainfall totals show a statistically significant upward trend over the last 30 years (CCRS, 2015). Singapore has become hotter and more prone to heavier storms (PUB, 2016). Thus there is a need to introduce measures to significantly reduce and manage the flood risks that may be increased due to a changing climate. In accordance with this notion, the adaptation tipping point and the adaptation pathway approach was employed in a previous study (Manocha and Babovic, 2017) to develop adaptive plans for flood management in the Kent Ridge Catchment. This paper employs this case study as a starting point. The adaptation actions and assessment scenarios employed in the study are presented here for brevity. For details, please refer to the original study.

The portfolio of adaptation actions considered in this study includes both traditional grey and innovative green infrastructure solutions, namely: expansion of drainage canals, implementation of green roofs and the implementation of porous pavements. These, in varied configurations, make up the set of adaptive actions assessed in this study. They are summarized in Table 1. The notations specified, are used to address the actions in the subsequent sections of the paper. The configurations of adaptive actions are selected in alignment with the broad national objectives (Manocha and Babovic, 2017).

Scenarios developed for this study cover a range of possible climatic and land-use futures. This is done to study the individual and coupled impact of climatic and anthropogenic influences on the timing of reaching an adaptation tipping point. The climate scenarios were