Simulation Modelling Practice and Theory 84 (2018) 232–250

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

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

Model-based multi-objective decision making under deep uncertainty from a multi-method design lens

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ARTICLE INFO

Article history:
Received 15 December 2017
Revised 9 February 2018
Accepted 28 February 2018

Keywords:
Decision analysis
Multi-method
Simulation
Exploratory modelling
Multi-objective optimisation
Adaptation
Uncertainty

ABSTRACT

Several approaches within the exploratory modelling literature—each with strengths and limitations—have been introduced to address the complexity and uncertainty of decision problems. Recent model-based approaches for decision making emphasise the advantage of mixing approaches from different areas in leveraging the strengths of each. This article shows how a multi-method lens to the design of decision-making approaches can better address different characteristics of multi-objective decision problems under deep uncertainty. The article focuses on interactions between two broad areas in model-based decision making: exploratory modelling and multi-objective optimisation. The article reviews this literature using a specific multi-method lens to analyse previous researches and to identify the knowledge gap. The article then addresses this gap by demonstrating a multi-method approach for designing adaptive robust solutions. The suggested approach uses a Pareto optimal search from multi-objective optimisation for enumerating alternative solutions. It also uses Robust Decision Making and Dynamic Adaptive Policy Pathways approaches from exploratory modelling for analysing the robustness of enumerated solutions in the face of many future scenarios. A hypothetical case study is used to illustrate how the approach can be applied. The article concludes that a new lens from a multi-method design perspective is needed on exploratory modelling to provide practical guidance into how to combine exploratory modelling techniques, to shed light on exiting knowledge gaps and to open up a range of potential combinations of exiting approaches for leveraging the strengths of each.

1. Introduction

1.1. Exploratory modelling for coping with complexities and uncertainties in the decision-making process

Modelling is a crucial approach for decision making associated with real-world systems. These systems are featured with complexity and deep uncertainty—a situation where decision makers often do not know and cannot agree upon the values of system variables and their associated probabilities [3,53,87]. The complexity and deep uncertainty challenge the usefulness of model-based decision-making approaches in suggesting robust solutions; solutions that can remain valid under many possible futures [3,55,56]. This challenge highlights the need for decision-support tools, which allow an improved understanding of how solutions may play out under a wide range of plausible future scenarios.

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https://doi.org/10.1016/j.simpat.2018.02.009
1569-190X/

An emerging area of research, known as *exploratory modelling,* aims to address the challenges of complexity and deep uncertainty by analysing the implications of different assumptions using computational experimentation [2,5,59]. The decision-making approaches which adopt exploratory modelling [86]—or as we call them *exploratory decision-making approaches* in this article—argue that decision making cannot rely on only one assumedly superior modelling method, an ultimate model structure, a set of input data, or a fixed definition for outcome's desirability. Instead, a variety of possibilities must be explored under different assumptions to build confidence in recommended decisions. Several exploratory decision-making approaches have been introduced so far, such as Robust Decision Making (RDM) [59,86], Dynamic Adaptive Policy Pathways (DAPP) [29], and Info-Gap Decision Theory [6,37]. See [69,86] for an overview these approaches. Each of these approaches has some advantages in coping with complexity and uncertainty.

1.2. A multi-method design lens to exploratory decision-making approaches

Recent advances in model-based approaches for decision making under deep uncertainty emphasised the benefits of mixing approaches in leveraging the strengths of each [29,34,35,50,63,69,78]. Mixing different approaches has been also encouraged increasingly within the broader community of operations research and modelling and simulation for improving the effectiveness of the decision-making process [74]. Mixing approaches enhances the capability of individual approaches by allowing modellers to overcome the limitations of one approach through the strengths of others [39]. Approaches can be combined based on different mixing designs [9,66,82]. Morgan et al. [71] synthesised six possible mixing designs from the literature. These designs, along with our examples from their implementation in the area of exploratory modelling, are presented as follows:

- *Isolationism* where each approach is used separately (no mixing) for a specific problem. Examples are the isolated use of individual approaches such as RDM in [58] and Adaptive Policymaking in [54].
- *Comparison* where multiple approaches are applied independently to the same problem and conclusions are drawn from their comparison. An example is the comparison of RDM and DAPP in [50] or the comparison of RDM and Epoch-Era Analysis in [69].
- *Sequential* where one approach is informed by the results of another approach in a linear relation while each approach is used within its own original paradigm. An example is the sequential use of uncertainty analysis and global sensitivity analysis in [76].
- *Enrichment* where a variety of approaches (from different paradigms) is used to enrich a primary approach. Examples are the improvement of scenario discovery with statistical machine learning algorithms in [49,51] and informing exploratory analysis with qualitative narratives in [16,38,68].
- *Interaction* where the paradigm restriction of each approach is relaxed and multiple interactive connections between approaches are made. No new approach is presented in this design. An example is the interaction of qualitative narratives from social sciences with quantitative models from systems engineering for the policy analysis of sustainability transitions [67,79,85].
- *Integration* where the elements of each approach are combined in a new approach. One example is DAPP [29] which resulted from the integration of Adaptive Policymaking and Adaption Pathways. Another example is the participatory exploratory modelling approach of Moallemi and Malekpour [70], resulted from the integration of qualitative participatory approach and quantitative exploratory modelling.

1.3. Aim and expected contribution

This article focuses on the application of multi-method design—as an increasingly adopted perspective in modelling and decision analysis—in the exploratory modelling literature. It aims to show how a multi-method lens to the design of exploratory decision-making approaches can better address different characteristics of complex and uncertain decision problems than individual approaches. In particular, the article focuses on interactions between exploratory modelling and optimisation methods as they have been complimentary to each other in several previous studies [33,41,46,88]. The article first reviews the exploratory modelling literature in interaction with optimisation using the multi-method design lens proposed in Section 1.2. This new perspective to exploratory modelling—which has not been discussed extensively before—provides explicit insights into possible research design and areas which require more research. The article selects the *interaction* mixing design as a less-worked area of multi-method design in the exploratory modelling literature. Second, to show the application and advantages of a multi-method design in exploratory modelling, potential interactions between exploratory modelling and multi-objective optimisation are demonstrated by proposing an approach for the development of adaptive robust solutions for multi-objective decision-making problems under deep uncertainty. Adaptive robust solutions are robust as they can fulfil multiple performance objectives while maintaining certain performance thresholds over many future possibilities. They are also adaptive as they can be modified by the emergence of new conditions in the future.

Based on the review of previous studies in the following section, we use computational experimentation and an analytical data-mining technique called scenario discovery [13] from RDM to generate future scenarios and to identify the conditions leading to specific clusters of scenarios. We also use scenario discovery to specify *failure scenarios* where performance thresholds are unlikely to be satisfied under any circumstances. These scenarios provide decision makers with