Environmental Modelling & Software 83 (2016) 326–343

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Robust discrimination between uncertain management alternatives by iterative reflection on crossover point scenarios: Principles, design and implementations[☆]

Joseph H.A. Guillaume[a, b, *], Muhammad Arshad[b], Anthony J. Jakeman[b], Mika Jalava[a], Matti Kummu[a]

[a] Water & Development Research Group (WDRG), Aalto University, Tietotie 1E, 02150 Espoo, Finland
[b] National Centre for Groundwater Research and Training, Integrated Catchment Assessment and Management Centre, The Fenner School of Environment and Society, The Australian National University, Building 48A, Linnaeus Way, Canberra, ACT 0200, Australia

A R T I C L E I N F O

Article history:
Received 29 May 2015
Received in revised form
1 March 2016
Accepted 4 April 2016

Keywords:
Uncertainty
Crossover points
Robustness
Scenario analysis
Fuzzy set theory
Vulnerability analysis

A B S T R A C T

When comparing environmental management alternatives, there is a need to assess the effect of uncertainty in the underlying model(s) and future conditions on robustness of recommendations. At times, it may be difficult or undesirable to specify the uncertainty in inputs and parameters *a priori*. An alternative approach instead generates *crossover points*, describing scenarios where the preferred alternative will change (i.e. alternatives are of equal value), and prompts the analyst to assess their plausibility *a posteriori*. This paper extends previous work by introducing principles, design and implementation of a new method to analyse crossover points. It reduces the complexity of dealing with many variables by identifying single crossover points of greatest concern, and progressively building understanding through three stages of analysis. We present three implementations using R, Excel and a web interface. They use two examples involving cost-benefit analysis of managed aquifer recharge and the water footprint impact of changing diets.

Software availability

This article presents three prototype open source implementations of the proposed process for iterative analysis of crossover point scenarios.

Name of Software	Breakdown and crossover analysis
Contact	Joseph Guillaume
Software Requirements	To use software, Web browser, e.g. Google Chrome. Web interface available thanks to the OpenCPU service (Ooms, 2014). To host, opencpu web server, or R and opencpu package
Availability and Cost	Free access to web interface at http://josephguillaume.ocpu.io/breakdown/www/. Open source code, under GPLv3 License, available at https://github.com/josephguillaume/breakdown
Programming language	R, JavaScript
Size	1.08 MB, including examples

Name of Software	CrossoverAddon
Contact	Joseph Guillaume
Software Requirements	Microsoft Excel 2013
Availability and Cost	Open source, under MIT License, either in archived form (Guillaume, 2015), or latest version from http://josephguillaume.github.io/crossover/
Programming language	Visual Basic for Applications
Size	1.5 MB, including example and how-to guide

Name of Software	mar-under-uncertainty
Contact	Joseph Guillaume
Software Requirements & Programming language	R, in order to run scripts

[☆] This article is part of a thematic issue on “Innovative Techniques for Quantitative Scenarios in Energy and Environmental Research”.

* Corresponding author.
E-mail address: joseph.guillaume@aalto.fi (J.H.A. Guillaume).

http://dx.doi.org/10.1016/j.envsoft.2016.04.005
1364-8152/

Availability and Cost	Open source, under GPLv3 License, in archived form (Guillaume and Arshad, 2014)
Size	18.8 kB, including example documented in Arshad et al. (2014)

1. Introduction

A key purpose of environmental modelling and decision support is to help compare management alternatives. Models help to structure understanding of a system and hence reach a reasoned recommendation regarding the best management alternative to pursue for a given goal. Uncertainty is however pervasive in environmental management problems, both as a result of imperfect knowledge of the current system (in model structure, parameters and data) and the potential for future changes (system inputs but also other aspects of the system that evolve). It is therefore crucial to test the related robustness of a recommended management alternative to these two types of uncertainties, i.e. to determine whether there are scenarios (either with different representations of the system or future changes) in which a different management alternative would be recommended.

Typical approaches to test robustness of a recommendation however still rely on knowing what scenarios are considered plausible *a priori*, before creating them. Scenarios are then constructed and used to evaluate alternative strategies (Durbach and Stewart, 2012). This is also the approach used by uncertainty quantification techniques (Matott et al., 2009; O'Hagan, 2006; Refsgaard et al., 2007; Roy and Oberkampf, 2011). Probabilities of model inputs and parameters are propagated through a model in order to quantify the uncertainty associated with a recommended management alternative. However, this requires agreement on the probabilities, or at least bounds on those probabilities (e.g. Rinderknecht et al., 2012), and there are known issues with eliciting and communicating them (Anderson, 1998; Garthwaite et al., 2005; O'Hagan and Oakley, 2004).

An alternative approach is to generate scenarios that instead represent vulnerabilities of the proposed management interventions, describing possible future failures that might occur due to uncertainty of variables (Brown et al., 2012; Bryant and Lempert, 2010; Guillaume and El Sawah, 2014; Lempert, 2013; Walker et al., 2013a). The analyst evaluates the plausibility of the scenarios *a posteriori*, after they have been generated, without requiring reliable knowledge about uncertainty of variables. The focus is then explicitly on determining how the vulnerability can be avoided or otherwise addressed (Dewar, 2002) rather than whether appropriate probabilities have been specified. More generally, these scenarios can help inform more traditional scenario planning processes consisting of possible future states of the world (Mahmoud et al., 2009). For example, discussion of possible future failures can help determine “sell-by dates” in adaptive policy pathways (Haasnoot et al., 2013). Discussion of vulnerabilities might also help scope specific studies in which probabilistic uncertainty quantification methods would be beneficial.

One type of scenario describing vulnerabilities is the “crossover point”. Crossover point scenarios are combinations of values of variables where cost-benefit or other trade-off analysis frameworks show two alternatives to be of equal value. The set of crossover points therefore demarcates a boundary at which the analysis crosses over from favouring one alternative to the other. If uncertainty in assumptions leads to variables reaching these values, a recommended management alternative may no longer be worthwhile. Scenarios describing crossover points are therefore particularly suitable to help test the robustness of recommendations. The concept of a crossover point is relatively simple but, along with its close relative, the break-even point, has previously been seen as difficult to implement with many variables (Frey and Patil, 2002; Von Winterfeldt and Edwards, 1986).

In this paper, we describe principles, a design, and three implementations to put analysis of crossover points into practice. By design, we mean a plan for the construction of the analysis and its supporting tools. The provision of three implementations recognises that this design can be operationalised in different ways to fit with the interest and skills of the analyst and the characteristics of the model they are using. We provide an illustrative case study to demonstrate how the principles, design and implementation come together.

Specifically, the set of proposed principles extends the idea of crossover points in three ways. Firstly, it helps to reduce the complexity of dealing with many variables by ranking scenarios according to the concern attributed to them by the analyst, using a heuristic measure of *level of concern* introduced in Section 4.1.2, without aiming to objectively quantify the likelihood of a scenario. This allows the use of optimisation to identify single crossover points of greatest concern, and therefore greatest interest, to the analyst. Secondly, the set of principles assists the analyst in building intuition about how crossover points change when more than one variable is varied. Thirdly, it takes an interactive learning approach to the identification of crossover points. Rather than considering a static set of points, the analyst *explores* points using an interactive interface. The points are consequently defined by different numbers of variables and an evolving understanding of the limits within which values of variables may be of concern, even allowing addition of more variables to the model as the exercise progresses. The differences of this work compared to previous publications is further discussed in Section 2.

To summarise the preceding discussion, the proposed approach is intended to apply to a class of problems that involves a need for “reflective stress-testing of a model-based recommendation.” The emphasis is on supporting the analyst's iterative reflection to enable learning about the robustness of recommendations (see also Guillaume and El Sawah, 2014; Sterman, 1994) despite poor *a priori* knowledge about uncertainty. As defined here, the problem class is characterised by:

- An existing analysis, by which management alternatives can be compared according to clearly stated quantitative criteria, based on best available information.
- An existing preferred alternative selected using that model, and known competing alternatives.
- A need to determine robustness of the recommended alternative in the presence of uncertainty.
- Uncertain probability distribution and bounds, that preclude uncertainty quantification.
- The opportunity that reflection on scenarios may be able to help to prompt revision of alternatives, criteria, and understanding of uncertainty, making *a posteriori* use of tacit or previously unconsolidated knowledge.
- Iteration prompted by reflection being possible, notably because the model can be interactively modified and nearly instantaneously re-run. An analyst may however be willing to tolerate short delays between iterations.

This article is structured to emphasise the generality of the method while providing concrete examples. To provide context, Section 2 presents an overview of previous uses of crossover points and Section 3 introduces two example problems, involving cost-