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Multi-criteria group decision making under uncertainty: Application in reservoir flood control operation

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ABSTRACT

This paper proposes an innovative framework for solving stochastic multi-criteria decision making (MCDM) problems when uncertainties exist in criteria performance values (PVs) and criteria weights (CWs) simultaneously. Methods for quantifying uncertainties in criteria PVs and CWs are presented. We establish the SMAA-TOPSIS model by combining stochastic multicriteria acceptability analysis (SMAA) and technique for order preference by similarity to ideal solution (TOPSIS). The risk of decision making errors is proposed to assess the impact of uncertainties on MCDM. We develop the LHS-based Monte Carlo simulation algorithm and corresponding computer program for solving the SMAA-TOPSIS model. We also suggest a three-stage MCDM procedure for stochastic MCDM problems. We apply the proposed methodology to a flood control operation case study to demonstrate its applicability. Our results indicate that the proposed methods can provide valuable risk information and enable risk-informed decisions to be made with higher reliabilities.

Software availability

Name of software: SMAA-TOPSIS for stochastic MCDM
Developer: Feilin Zhu
Email: zhufeilin@hhu.edu.cn
Software required: Visual Basic 6.0, Visual Basic for Applications, R project
Availability: The software is freely available for noncommercial use upon request from the first author

1. Introduction

Multi-criteria decision making (MCDM) is a methodology which has been extensively employed to assist water resources and environmental decision making (Fowler et al., 2015; Ganji et al., 2016; Hyde and Maier, 2006; Romañach et al., 2014; Su and Tung, 2014), since it facilitates multi-stakeholder participation and allows the consideration of multiple criteria measured in incommensurable units. Reservoir flood control operation requires concurrent optimization of several conflicting objectives, such as hydropower generation, flood control, water supply, irrigation and etc. It is difficult to determine an optimal solution that optimizes all objectives simultaneously (Luo et al., 2015; Qin et al., 2010). Instead, MCDM methods are typically employed to evaluate and select the non-inferior alternatives generated by multi-objective optimization models so as to obtain the most preferred alternative and put it into practice. Hajkowicz and Collins (2007) reviewed applications of MCDM methods for a diverse range of water resources problems, and classified these methods into six categories: (1) multi-criteria value functions; (2) outranking approaches; (3) distance to ideal point methods; (4) pairwise comparisons; (5) fuzzy set analysis; and (6) tailored methods.

In reservoir flood control operation, uncertainties mainly come from two aspects, including the uncertainty of criteria performance values (PVs) and criteria weights (CWs). On one hand, numerous uncertainty factors (e.g., inflow forecasting errors, reservoir capacity curve errors, river flood routing errors and etc.) lead to the randomness of flood control target factors, which usually serve as criteria to evaluate the performance of alternatives. When

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considering uncertainties, these target factors are no longer constants but random variables with certain probability distributions. Since the 1980s, hydrologists have paid much attention to the risk analysis of flood control operation (Bogner and Pappenberger, 2011; Chen et al., 2015; Yan et al., 2014). However, little research attempted to combine risk analysis with MCDM models. On the other hand, CWs, used to measure criteria's relative importance and coordinate multiple operation objectives, have been found to be a potential source of uncertainty in MCDM (Ganji et al., 2016). The CWs can be either subjective or objective. In the context of group decision making, all decision makers need to express subjective preferences to incorporate their knowledge and experience into MCDM models. It is difficult for multiple decision makers with conflicting interests to reach consensus over CWs (de Brito and Evers, 2016; Madani and Lund, 2011). Moreover, the weighting process usually contains fuzziness and subjectivity of human judgments, which will lead to imprecise or uncertain CWs. Objective CWs are determined based on the information of decision matrices, and it has been found that different CWs elicitation methods may elicit diverse CWs (Hajkowicz and Collins, 2007; Hyde and Maier, 2006; Zhu et al., 2017). Furthermore, considerable information loss will occur and the real uncertainty of CWs will be concealed if CWs obtained from multiple decision makers or diverse methods are aggregated or averaged as a deterministic CW (Cai et al., 2004). Therefore, uncertainties exist in criteria PVs and CWs simultaneously during the MCDM modelling process.

Conventional MCDM methods for reservoir flood control operation are mainly developed and applied under deterministic or fuzzy environments (Chen and Hou, 2004; Cheng and Chau, 2002; Fu, 2008; Wang et al., 2011; Zhu et al., 2016). In deterministic or fuzzy cases, an absolutely fixed ranking of alternatives is obtained. However, when considering uncertainties in input parameters (i.e. criteria PVs and CWs), any alternative is likely to get better or worse ranks, and a reversal of the fixed ranking will occur, which further lead to the risk of decision making errors. Xiong and Qi (2010) presented a method for stochastic MCDM problems with incomplete weight information. In this method, a stochastic MCDM problem was converted into an interval MCDM problem by interval estimation. Qin (2011) introduced a relative dominance based MCDM method when criteria PVs are normal random variables. Qin's study is meaningful since it first combines risk analysis with MCDM models, but they disregard the uncertainty in CWs and limit criteria PVs as normal random variables. In addition, Madani and Lund (2011) proposed a Monte-Carlo Game Theory (MCGT) approach for dealing with uncertainty in the performance of alternatives, which mapped the stochastic MCDM problem into many deterministic strategic games and solved them using non-cooperative stability definitions. However, little attention has been paid to consider uncertainties in criteria PVs and CWs simultaneously. The subject of multi-criteria group decision making under uncertainty has not yet been addressed thoroughly in a unified framework.

Stochastic multicriteria acceptability analysis (SMAA) is a family of methods for assisting mulita-criteria group decision making in situations where criteria PVs and CWs are uncertain (Lahdelma et al., 1998). Plenty of SMAA variants have been developed, such as SMAA-2 (Lahdelma and Salminen, 2001), SMAA-AHP (Durbach et al., 2014), SMAA-PROMETHEE (Corrente et al., 2014) and so on. SMAA-2 forms the basis of other SMAA variants, and is regarded as the most representative one. In SMAA-2, an additive utility function is used to represent decision makers' preference and map different alternatives to real values. In reality, any type of utility function can be used in SMAA-2, namely, SMAA-2 can be applied in combination with other MCDM methods. The technique for order preference by similarity to ideal solution (TOPSIS), first introduced by Hwang and Yoon (1981), has been extensively applied to water resources and environmental problems (Zagonari and Rossi, 2013). Based on the concepts of ideal and anti-ideal points, the best alternative determined by TOPSIS should be the one which is simultaneously closest to the ideal alternative and farthest from the anti-ideal alternative. TOPSIS is recommended by the United Nation Environmental Program (UNEP) to evaluate water resources development projects. Moreover, some fuzzy versions of TOPSIS have also been developed (Triantaphyllou and Lin, 1996; Torfi et al., 2010). Okul et al. (2014) presented the idea of integrating the SMAA theory and TOPSIS method, and they applied the combined method to the problem of light machine gun selection. The main purpose of their study was to improve the basic TOPSIS method and allow TOPSIS to handle imprecise data. However, the issue of how to deal with related uncertainties was ignored. In addition, the superiority of SMAA-TOPSIS was not well-evaluated.

This paper proposes an innovative framework for solving stochastic MCDM problems when uncertainties exist in criteria PVs and CWs simultaneously. This helps to allow all expected uncertainties to be incorporated into the MCDM modelling process and make risk-informed decisions with higher reliabilities. First, we define the formulation of MCDM problems. Methods for quantifying uncertainties in criteria PVs are discussed. We introduce the feasible weight space (FWS) in combination with fuzzy analytic hierarchy process (FAHP) to quantify the weight uncertainties. We then establish the SMAA-TOPSIS model by integrating TOPSIS and SMAA-2. Moreover, we propose the concept of the risk of decision making errors and its quantitative calculation method to assess the effect of existing uncertainties on MCDM results. The Monte Carlo simulation algorithm based on Latin Hypercube Sampling (LHS) and corresponding computer program are developed for solving the SMAA-TOPSIS model. In addition, we suggest a three-stage MCDM procedure for stochastic MCDM problems. We summarize the difference between SMAA-TOPSIS and deterministic MCDM models. The proposed methodology is applied to a flood control operation case study to demonstrate its applicability and insights it can provide beyond traditional methods.

The remainder of this paper is organized as follows. The proposed methodology is presented in Section 2, followed by results and discussion of the case study in Section 3. Section 4 contains summary and conclusions.

2. Methodology

Fig. 1 shows the flowchart of the proposed methodology. Details of each step are presented in the following subsections.

2.1. Formulation of MCDM problems

There are many terminologies used to refer to MCDM. Some other terms include multi-criteria decision analysis (MCDA), multi-attribute decision making (MADM), and multi-objective decision support (MODS). All these terms share the same theoretical basis and are jointly referred to in this paper as MCDM. Generally, an MCDM problem comprises: (1) a set of alternatives which need to be evaluated, ranked and selected; (2) a set of criteria, measured in incommensurable units; and (3) an MCDM model. The set of alternatives can be either implicitly defined by constraints in multi-objective optimization models or explicitly defined and discrete in number (Durbach and Stewart, 2012). Each criterion should be associated with a measurable attribute which provides a qualitative or quantitative scale for assessing performances of alternatives. This can be done via mathematical models