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A factorial dual-objective rural environmental management model

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ABSTRACT

In this study, a factorial dual-objective rural environmental management (FDREM) model is proposed for supporting regional sustainable development under uncertainty. The FDREM model can coordinate the conflicting relationship between economic growth and resources consumption and provide more sustainable decision alternatives on the basis of the optimal ratio of the two conflicting objectives, i.e., optimal economic efficiency. The factorial analysis (FA) technique is integrated within the framework of the FDREM model to deal with uncertain modeling parameters. This technique can quantify the effect of uncertain parameters, reveal the hidden interrelationships and thereby provide decision makers with a comprehensive understanding in regard to the effect of the variation of uncertain parameters on the responses of the model. The comprehensive understanding can help decision makers gain more robust decision alternatives in the related systems analysis. The FDREM model was applied to an international collaborative project launched by the Chinese government and the United Nations Development Programme (UNDP) in Makit County, China. The results indicate that the FDREM model is a practical model for planning regional sustainable development under uncertainty. Efficiency-based decision alternatives can reduce the risk of overexploitation and make economic activities more efficient. The embedded FA technique can reveal the interrelationships of uncertain parameters and provide robust decision support to deal with any variation of these parameters.

1. Introduction

Sustainable development is a concept that has been gaining growing recognition in recent years all around the world. It is about meeting the needs of present without compromising the needs of future generations (OECD, 2001; UNDP, 2012; WCED, 1987). Specifically, it is interpreted as improving the quality of life, conserving the environment, using natural resources efficiently and advancing long-term economic prosperity (EC, 2010; FATDC, 2015). To reach sustainable goals, it requires the integration of economic, environmental and social considerations into policies and implementations. Meanwhile, it requires a careful balance of the interrelationships between economic growth, environmental conservation and social development. Thus, it is important to develop integrated approaches that can encompass the multiple needs and objectives of different interest groups so that sustainable development can be steadily propelled at all levels—citizens, agriculture, industry and governments.

Previously, a number of multi-objective optimization approaches were developed to address the conflicting relationships between economic development and environmental issues (Costi et al., 2004; Kanzian et al., 2013; Marques et al., 2015; Roozbahani et al., 2015; Rosén et al., 2015; Su et al., 2008; Tu et al., 2015; Xevi and Khan, 2005). For instance, Costi et al. (2004) considered environmental issues in a cost optimization model by translating environmental issues into constraints, whereas the objective function was driven exclusively by economic costs; Su et al. (2008) suggested that environmental impacts could be estimated as system costs and thus they converted environmental issues into economic objectives; Xevi and Khan (2005) specified priority levels to economic and environmental goals and weighted them within a combined objective function. These methods have general limitations in the following two aspects (Zhu and Huang, 2011): (1) they convert objectives of different aspects into a uniform magnitude on the basis of subjective assumptions and none could compare the objectives of multiple aspects directly within

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the original magnitudes of objectives, and (2) they focus on system inputs and outputs so that none could measure the efficiency of a system in terms of its output/input ratio. Linear fractional programming (LFP) is a distinctive method with advantages in the two aforementioned aspects. Recently, the LFP method was introduced into a variety of management studies that require a comparison of two magnitudes (e.g., economic growth/resources consumption) (Claassen, 2014; Gómez et al., 2006; Zhou et al., 2014, 2015a; Zhu and Huang, 2011, 2013; Zhu et al., 2014). It is particularly useful in evaluating the efficiency of a system. However, this method also has limitations to deal with the intrinsic nature of real-world problems—uncertainty. Due to various complexities of uncertainties in real world, only a few authors could consider uncertainty issues in studies of the LFP method (Zhou et al., 2014, 2015a; Zhu and Huang, 2011, 2013; Zhu et al., 2014). Interval mathematical programming, fuzzy mathematical programming and stochastic mathematical programming are the most common techniques that were applied to deal with uncertain parameters of a modeling system (Ahmadi et al., 2015; Armbruster and Delage, 2015; Chen et al. 2013; Claassen, 2014; Li et al., 2013; Miao et al., 2014; Xu et al., 2014; Yang and Yang, 2014; Zhang et al., 2014; Zhou et al. 2013, 2014). However, these techniques can only provide an effective way to characterize the uncertainty encountered in real-world problems, but are incapable of providing decision makers with a reliable instruction on how to deal with the variation in uncertain parameters. Accordingly, the modeling results may become less meaningful to decision makers and the related result analysis may become unsound for supporting the decision-making process under uncertainty. Therefore, it is essential to develop a sound approach that can not only characterize the uncertainty within system parameters but also provide decision makers with a comprehensive analysis regarding the effect of the variation of uncertain parameters on the responses of the system. Factorial analysis (FA) is a powerful statistical tool that has been widely used by scientists to understand the effect of two or more independent variables upon a single dependent variable. Its outstanding capability has established a decent reputation for the process improvement in industrial and laboratory experiments. Recently, this technique was introduced into water resources management studies under uncertainty (Wang and Huang, 2015; Zhou et al., 2013, 2015b, 2016; Zhou and Huang, 2011). It was used to explore the interrelationships of uncertain parameters within water resource systems and assist water managers in enhancing their knowledge in systems analysis under uncertainty. These applications indicate that this technique can be introduced into the study of the LFP method to address its limitation in uncertainty analysis. A more robust approach can be developed through integrating the FA technique with the LFP method.

Therefore, the objectives of this paper are to propose a factorial dual-objective programming (FDP) approach and develop a factorial dual-objective rural environmental management (FDREM) model for supporting regional sustainable development under uncertainty. The highly integrated FDP approach will be used to address dual-objective planning problems and provide a comprehensive analysis regarding the effect of the variation of uncertain parameters on system responses. In addition to linear fractional programming and factorial analysis, two-stage stochastic programming (TSP) will also be introduced to enhance the capacity of the FDP approach to deal with stochastic events. An FDREM model will be developed through the FDP approach and it will be applied to an international collaborative project launched by the Chinese government and the United Nations Development Programme (UNDP) in Makit County, China. This project aims at the prevention of desertification in this region and the advancement of local economic development. In this study, the FDREM model will give full and equal consideration to both total net benefit and water consumption in the decision-making process. The model will seek an optimal efficiency ratio between total net benefit and water consumption in the objective function, where a sustainable balance can be reached. A comprehensive analysis regarding the results of the FDREM model will be carried out to provide decision support for future adjustments of the project guideline.

2. Development of the FDREM model

2.1. Factorial dual-objective programming approach

The factorial dual-objective programming (FDP) approach is a highly integrated approach that is capable of dealing with two conflicting objectives optimization problems under uncertainty. This approach integrates factorial analysis, linear fractional programming and two-stage stochastic programming in a general setting. In this section, a brief introduction is given for each of the three techniques first and the FDP approach is illustrated next.

In linear fractional programming (LFP), the objective function is a ratio of two linear functions. A general LFP problem is formulated as follows (Charnes and Cooper, 1962; Zhu and Huang, 2011, 2013; Zhu et al., 2014):

$$\text{Max } f(x_1, x_2, \ldots, x_n) = \frac{\sum_{j=1}^{n} c_j x_j + \alpha}{\sum_{j=1}^{n} d_j x_j + \beta} \tag{1a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij} x_j \le b_i, \forall i \tag{1b}$$

$$x_j \ge 0, \quad \forall j \tag{1c}$$

where a_{ij}, b_j, c_i, $d_i \in R$; α and β are scalar constants. Assume that the solution set of model 1 is nonempty and bounded and that the objective function is continuously differentiable. Charnes and Cooper showed that if the denominator is constant in sign (i.e., $\sum_{j=1}^{n} d_j x_j + \beta > 0$ for all $X = (x_1, x_2, \ldots, x_n)$ on the feasible region), the LFP model can be transformed to the following linear programming problem:

$$\text{Max } g(x_1^*, x_2^*, \ldots, x_n^*, t) = \sum_{j=1}^{n} c_j x_j^* + \alpha \cdot t \tag{2a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij} x_j^* \le b_i \cdot t, \forall i \tag{2b}$$

$$\sum_{j=1}^{n} d_j x_j^* + \beta \cdot t = 1 \tag{2c}$$

$$x_j^* \ge 0, \forall j \tag{2d}$$

$$t \ge 0 \tag{2e}$$

where $x_j^* = t \cdot x_j$. Model 2 is solvable by the simplex algorithm. The optimal solutions of Model 1 can be obtained through a transformation of $x_j = x_j^*/t$.