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Development of an optimization model for water resources systems planning

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ABSTRACT

A number of inexact fuzzy programming methods have been developed for the planning of water-resources-management systems under uncertainty. However, most of them do not allow the parameters in the objective and constraints of a programming problem to be functional intervals (i.e., the lower and upper bounds of the intervals are functions of impact factors). In this study, an interval fuzzy bi-infinite De Novo programming (IFBDP) method is developed in response to the above concern. A case study is also conducted; the solutions are then compared with those obtained from inexact De Novo programming (IDNP) and interval-fuzzy De Novo programming (IFDNP) that takes no account of bi-infinite programming. It is indicated that the IFBDP method can generate more reliable solutions with a lower risk of system failure due to the possible constraints violation and provide a more flexible management planning since the budgets availability can be adjusted with the variations in water price. These solutions are more flexible than those identified through IFDNP since the tolerance intervals are introduced to measure the level of constraints satisfaction. Moreover, it can be used for analyzing various scenarios that are associated with different levels of economic consequences under uncertainty.

1. Introduction

In recent decades, environmental systems analysis and design have become important managerial and operational issues confronting many countries and regions in the world (He et al., 2009). It is an active process that seeks a portfolio of resource levels and optimizes the objective function by allocating a budget according to a resource price, where resource levels are considered as decision variables (Zeleny, 1990). However, such planning efforts are complicated with a variety of uncertain parameters as well as their interactions. In fact, in water resources management and planning problems, many system parameters and their interrelationships are often associated with uncertainties presented in terms of multiple formats (Li et al., 2006). Moreover, these uncertainties may be multiplied by limited budget and resources with a maximized system benefit. Therefore, it is necessary to develop effective optimization methods for supporting water resources management under such complexities and uncertainties.

1.1. Literature review

A number of methods, such as fuzzy, stochastic and interval mathematical programming were developed for dealing with the uncertainties in water resources management problems. For example, Slowinski (1986) proposed an interactive fuzzy multiobjective linear programming method and applied it to water supply planning. Wu et al. (1997) proposed an interactive inexact-fuzzy multiobjective programming model for planning water resources systems, where IPP and fuzzy programming (FP) were incorporated within a multiobjective framework to handle uncertainties presented in terms of discrete intervals and fuzzy sets. Jairaj and Vedula (2000) optimized a multi-reservoir system using fuzzy mathematical programming method, where the uncertainties existing in reservoir inflows were treated as fuzzy sets. Bender and Simonovic (2000) proposed a fuzzy compromise approach to water resources planning under imprecision uncertainty. Lee and Chang (2005) proposed an interactive fuzzy approach for planning a stream water resources management system that involved vague and imprecise information. Li et al. (2009) advanced a multistage fuzzy-stochastic programming model for water-resources allocation and management, where uncertainties expressed as probability distributions and fuzzy sets could be reflected. Lu et al. (2010) developed an interval-valued fuzzy linear programming method based on infinite α-cuts for water resource management. These methods have been applied to various hypothetical and real cases and presented effectiveness in

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accounting for uncertainty in interval parameter program and fuzzy program. However, in real world problems, the constraint resources have imprecise features, which are difficult to or cannot be determined precisely.

Compared with the traditional fuzzy programming methods, De Novo programming was effective for dealing with optimal design problems with unknown resource availability and seeking a portfolio of resource availability level to optimize multiple objective functions by allocating a budget according to the resource price (Zeleny, 1981, 1986, 1990). Previously, a number of research works based on the De Novo programming were applied to various system design cases. For example, Zeleny (1990) proposed a basic method to construct the optimal system design for solving a De Novo problem via an ideal system design; one of the important issues in multicriteria De Novo programming was to determine an optimum-path ratio for enforcing a particular budget level of resources so as to establish the optimal system design. Li and Lee (1990) extended Zeleny's basic method to identify fuzzy system designs for De Novo problems by considering the fuzziness in coefficients, and further treated fuzzy goals and fuzzy coefficients simultaneously, depending on a numerical approach which could be solved as either linear or nonlinear problems (Li and Lee, 1993). Shi (1995) introduced several optimum-path ratios for enforcing different budget levels of resources to identify alternative optimal system designs for solving multicriteria De Novo programming problems. Kotula (1997) used the De Novo programming for control and adjustment of reservoir design and operation characteristics which resulted in optimal or near optimal system performance throughout the life of the reservoir. Zeleny (2005) investigated the evolution of optimality of single and multiobjective programming, where a number of major optimality concepts according to a dual classification were discussed. Chen and Hsieh (2006) presented a fuzzy multistage De Novo programming, where random distribution of budget was analyzed.

More recently, Zhang et al. (2009) developed an interval De Novo programming (IDNP) method through introducing interval-parameter programming (IPP) into the De Novo programming framework for the planning of water-resources systems, where uncertainties presented as discrete intervals were addressed. However, the IDNP can only solve the problems containing crisp interval coefficients $[a, b]$, whose lower and upper bounds (i.e., a and b) are both deterministic and definitely known. This is based on the assumption that these interval coefficients are unchanged even if they could be affected by associated impact factors. However, a challenge leads to a need of further improving the aforementioned efforts. It is that traditional crisp intervals in their programs (i.e., the lower and upper bounds are both constants) can hardly address the association of their impact factors and fuzzy programming could be an approach to fill this gap by introducing an intermediate control variable (λ) to measure the level of constraints satisfaction. For example, the unit water supply cost and benefit of water users are important parameters determining optimal water allocation and wastewater treatment schemes, and maximum net system benefits in the process of decision making. However, it will vary with the dynamic fluctuation of its impact factors such as water price. In consideration of such an impact, the lower and upper bounds of the unit water supply cost and benefit of water users can hardly be expressed as simple constants any more. Functional intervals represent a type of highly complex uncertainty in comparison to conventional crisp intervals (He and Huang, 2008). It is an extended interval whose lower and upper bounds are both represented as functions of an independent variable (e.g., water price); thus, it could be used to simultaneously account for the parameters' uncertainty (due to imprecise information) and association (with other impact factors).

Therefore, one approach to potentially address these uncertainties is to introduce interval bi-infinite programming (IBIP) and fuzzy programming (FP) into the De Novo programming framework; this will lead to an interval fuzzy bi-infinite De Novo programming (IFBDP) method. The developed IFBDP can effectively deal with uncertainties expressed as fuzzy sets and functional interval values in single and multiobjective problems. Besides, techniques of post-optimality analysis (e.g., multicriteria decision analysis, analytical hierarchy process technique, dual programming, and parametric programming) could be used for further supporting fine adjustments of the modeling results and thus for enhancing their applicability to practical situations. Furthermore, intelligent decision support system (IDSS) could be developed based on an integration of optimization modeling, scenario development, user interaction, policy analysis and visual display into a general framework (Li et al., 2010). Uncertainties in water resources planning systems could be effectively reflected and addressed through the interval fuzzy bi-infinite De Novo programming approach, improving the stability of the IDSS for real-world applications.

Then the method is applied to a case study of (i) water resources systems planning, which designs an inexact optimal system with budget limit and different weight, and (ii) illustrating its advantages over the previous approach such as inexact De Novo programming (IDNP), and interval-fuzzy De Novo programming (IFDNP) which does not consider bi-infinite programming. A number of scenarios were examined for system uncertainties and decision processes to identify an optimum system design with higher benefits. The results obtained can be used to help decision makers evaluate alternative system designs and to determine which of these designs can most efficiently achieve the desired system objectives.

2. Modeling formulation

2.1. Interval fuzzy bi-infinite De Novo programming

Definitions for the concepts of intervals and functional intervals are given before the formulation of the interval fuzzy bi-infinite De Novo programming problem. An interval can be defined as an interval with known upper and lower bounds but unknown distribution information (Chang and Wang, 1997; He et al., 2009):

$$a^{\pm}=[a^{-},a^{+}]=\{a|a^{-}\leq a\leq a^{+}\} \quad (1)$$

where a^- and a^+ are lower and upper bounds of $a^{\pm}$, respectively. If $a^-=a^+$, then $a^{\pm}$ becomes a deterministic number. As an extension of intervals, the concept of functional intervals is proposed for addressing a kind of more complicated uncertainty. Similar to the definition of intervals, functional interval $a^{\pm}(y)$ can be defined as:

$$a^{\pm}(y)=[a^{-}(y),a^{+}(y)]=\{a(y)|a^{-}(y)\leq a(y)\leq a^{+}(y)\} \quad for \quad y\in[y_l,y_u] \quad (2)$$

where $a^-(y)$ and $a^+(y)$ are lower- and upper-bounds functions, respectively, and y is independent variable ranging from y_l to y_u. With definitions (1) and (2), an interval fuzzy bi-infinite De Novo programming problem can be conceptualized as follows:

$$\text{Max} f^{\pm} \underset{\sim}{=} C^{\pm}(y)X^{\pm} \quad \text{for all} \quad y_0\in[y_{l0},y_{u0}] \quad (3a)$$

subject to:

$$A^{\pm}(y)X^{\pm}-b^{\pm}\leq 0 \quad \text{for all} \quad y\in[y_l,y_u] \quad (3b)$$