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Inexact two-phase fuzzy programming and its application to municipal solid waste management

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In this study, an inexact two-phase fuzzy programming approach was proposed for municipal solid waste management. Through introducing multiple control variables, objective function and constraints of the management model were relaxed under different levels, and compromised decision schemes with a high satisfactory level can be expected. Compared to the previous studies, it showed sound capability in identifying key factors and/or input conditions that may significantly affect system outputs, and thus facilitating the decision maker adjusting current system status to benefit the future management. A MSW management problem was provided to demonstrate the performance of the approach. Special parameters having significant or no impact on system performance were specified, which were then respectively changed to constitute two scenarios. The scenario analysis proved the accuracy of the model in identifying key factors. It was also found that the average satisfactory level of optimal solutions from the two-phase model was [0.287, 0.829], which was higher than that obtained from the conventional approach (i.e. [0.130, 0.804]), indicating the advantage of the proposed approach in searching for optimal solutions with high satisfactory level.

1. Introduction

Environmental protection and resources conservation continue to be challenges faced by solid waste managers in public and private sectors (Chan and Huang, 2003; Lu et al., 2008; Cheng et al., 2003a; He et al., 2008; He et al., 2011a,2011b). These challenges become more aggravated with the raises of population, arising from which waste generation rates are intensively increased. The multidisciplinary system design of MSW treatment facilities has thus been deemed critical and obtains a number of attentions of the researchers (Luo and Huang, 1997; Cheng et al., 2003b; Xi et al., 2010).

Anderson (1968) first conducted economic optimization for the planning of a solid-waste-management system. Afterwards, a number of mathematical efforts were made to solve various solid waste management problems (Jenkins, 1982; Baetz, 1990; Lund, 1994; Chang and Wang, 1997; Joghataie and Allahverdipur, 2004; Hsu et al., 2005). Recently, uncertainties existing in most of real-world practices have been widely concerned, leading to the development of many inexact programming methods for planning MSW management systems. For example, Chi and Huang (1998) developed an interval-parameter mixed-integer linear programming model for the regional MSW management in the City of Regina. The model can be used to handle the uncertainties existing in the left-hand-side coefficients and the problems of capacity expansion for MSW treatment facilities. Sae-Lim (1999) proposed an inexact fuzzy-stochastic mixed-integer linear programming method for the planning of waste management. This method allowed for system constraints to be violated to a certain extent. He et al. (2008) studied an inexact bi-infinite programming method for sizing, timing, and sitting the facilities' expansion of a MSW management system; the method was then advanced to semi-infinite programming with an application to environmental decision making (He et al., 2011a,2011b). Lu et al. (2009) advanced an inexact dynamic optimization model for supporting solid waste management in association with GHG emission control. He et al. (2009) provided an inexact integer model containing infinite objectives and constraints for regional solid waste management problems.

The above methods have been used in both hypothetical and real cases, and presented effectiveness in reflecting uncertainties. However, when compromised management strategies are acceptable for decision makers, these approaches become inefficient. Fuzzy flexible programming, as an effective means in handling such problems has been introduced into the modeling frameworks in many previous studies (Polit et al., 2002; Adenso-Díaz et al., 2004; Huang et al., 2006; He et al., 2008). Nevertheless, only one control variable was mostly adopted to relax the constraints,

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such that the solutions spaces were curtailed when many constraints may be less relaxed (corresponding to a high satisfactory level) to obtain optimal solutions. In 1999, Guua and Wu first proposed a two-phase fuzzy programming approach which incorporated multiple control variables in the solution procedure. It can be noted as a helpful supplementation to conventional fuzzy programming and was then applied to solve various problems. For example, Arıkan and Güngör (2007) proposed a two-phase approach for multi-objective programming problems with fuzzy coefficients. Kahraman et al. (2007) introduced a two-phase multi-attribute decision-making approach for new product introduction. Doğan et al. (2008) used two-phase possibilistic linear programming methodology for multi-objective supplier evaluation and order allocation problems. Lu et al. (2010) advanced a two-phase flexible optimization model based on inexact air dispersion simulation for regional air quality control. However, no efforts were found to use the two-phase fuzzy programming approach in solving solid waste management problems.

Therefore, this study aims to develop an inexact two-phase fuzzy programming (ITFP) approach for planning MSW management, wherein multiple control variables exist to make different relaxation levels to the objective function and constraints. Mixed-integer programming and interval-parameter programming will also be communicated into the modeling framework to plan expansion engineering and deal with parameter uncertainty. A case study will also be investigated to demonstrate the performance of the approach.

2. Modeling formulation

Consider a MSW management system, wherein one landfilling and two waste-to-energy (WTE) facilities exist for serving the disposal need of three MSW generation sources over a 15-year planning horizon (with three 5-year periods). Two options are available for the wastes disposal: (i) directly ship to the landfill, and (ii) ship to WTE facilities for incinerating and then deliver the residues to the landfill for terminal disposal. Within the planning horizon, waste generation rates of the sources will instantly increase, leading to a shortage of facilities' capacity. Thus, how to plan the expansion engineering is another major concern. The decision maker wants to obtain a compromised allocation strategy with satisfactory system cost under an acceptable reliability level. Meanwhile, the key restrictions that significantly affect the system performance need to be specified. Therefore, the problem can be handled through identifying an optimal allocation scheme with a minimum system cost under a number of environmental, mass-balance, and infrastructural constraints:

[Objective function]:

$$\min f^{\pm} = \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\left[(OC_{jk}^{\pm}+TC_{ijk}^{\pm})x_{ijk}^{\pm}\right] + \sum_{i=1}^{3}\sum_{j=2}^{3}\sum_{k=1}^{3} RF^{\pm}(d_{jk}^{\pm}+OC_{1k}^{\pm})x_{ijk}^{\pm} + \sum_{j=1}^{3}\sum_{p=1}^{3}\sum_{k=1}^{3} EC_{jpk}^{\pm}Y_{jpk} - \sum_{i=1}^{3}\sum_{j=2}^{3}\sum_{k=1}^{3} RE_{jk}^{\pm}x_{ijk}^{\pm} \tag{1a}$$

[Constraints]:

Mass-balance constraints: There should be a balance of waste flows from the source location to the destination. We can interpret such constraints by the following formula:

$$\sum_{j=1}^{3} x_{ijk}^{\pm} \geq WG_{ik}^{\pm} \tag{1b}$$

Capacity constraints: For the landfill, the total allocated waste flow cannot exceed the sum of its total capacity of both new and existing landfills. Similarly, the total waste flow to each WTE cannot exceed the sum of its daily capacity of both new and existing facilities. These can be described as follows:

$$\sum_{i=1}^{3}\left(x_{i1k}^{\pm}+RF^{\pm}\sum_{j=2}^{3}x_{ijk}^{\pm}\right) \leq LAN^{\pm}+\sum_{p=1}^{3}\left(\Delta C_{1p}^{\pm}\sum_{k=1}^{k}Y_{1pk}\right) \tag{1c}$$

$$\sum_{i=1}^{3}x_{ijk}^{\pm} \leq WTE_{j}^{\pm}+\sum_{p=1}^{3}\left(\Delta C_{jp}^{\pm}\sum_{k=1}^{k}Y_{jpk}\right) \quad (j=2,3) \tag{1d}$$

Non-negative and integer constraints: These are the constraints on the range of allowable values for the variables in the model. For MSW management problems, the constraints mean all decision variables are positive, and all integer variables equal either 0 or 1:

$$x_{ijk}^{\pm} \geq 0 \tag{1e}$$

$$Y_{jpk} = \begin{cases} 0 \text{ expansion engineering not developed} \\ 1 \text{ expansion engineering developed} \end{cases} \tag{1f}$$

where f=system cost; i=index for waste generation sources; j=index for treatment/disposal facilities (j=1 for landfill, and j=2 and 3 for WTE facilities 1 and 2, respectively); k=index for planning periods; p=index for facility expansion options; OC_{jk}=operation cost of facility j in period k; TC_{jk}=transportation cost of shipping wastes from source i to facility j in period k; x_{ijk}=waste stream from source i to facility j in period k; RF= residual rate of incineration; d_{jk}=transportation cost of shipping residues from WTE j to landfill in period k; EC_{jpk}=expansion cost for facility j with option p in period k; Y_{jpk}=binary variable for expanding facility j with option p in period k; RE=revenue of unit wastes disposed by WTE j in period k; LAN=existing capacity of landfill; WTE_j=existing capacity of WTE j; ΔC_{jp}=expansion capacity for facility j in option p; WG_{ik}=daily waste generation rate of source i in period k; subscript "$\pm$" indicates the corresponding parameter/decision variable is interval-valued with identified lower and upper bounds. In this model, interval parameters are incorporated to present uncertain inputs when the information of many parameters cannot be identified due to practical reasons. Correspondingly, the solutions obtained from this model will also present interval feature according to the solution method for interval programming problems proposed by Huang et al. (1993). Such solutions can offer more conveniences to decision makers with the provision of multiple alternatives. Considering the characteristics of most MSW systems, we identified waste generation rate, facility capacities, and economic-related parameters being intervals in this study.

Apparently, the above model can deal with parameter uncertainty associated with modeling inputs. However, when fuzzy relations also exist between the modeling objective and constraints, enhanced techniques need to be introduced. Therefore, in this study, the above model (model 1) is further converted to an enhanced model based on the two-phase fuzzy programming approach (Guua and Wu, 1999). Through introducing a max–min operator $\lambda^{\pm}$, model (1) is first rewritten to the following phase-I problem:

$$\max \lambda^{\pm} \tag{2a}$$

subject to

$$\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\left[(OC_{jk}^{\pm}+TC_{ijk}^{\pm})x_{ijk}^{\pm}\right] + \sum_{i=1}^{3}\sum_{j=2}^{3}\sum_{k=1}^{3} RF^{\pm}(d_{jk}^{\pm}+OC_{1k}^{\pm})x_{ijk}^{\pm} + \sum_{j=1}^{3}\sum_{p=1}^{3}\sum_{k=1}^{3} EC_{jpk}^{\pm}Y_{jpk} - \sum_{i=1}^{3}\sum_{j=2}^{3}\sum_{k=1}^{3} RE_{jk}^{\pm}x_{ijk}^{\pm}$$