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A dual-uncertainty-based chance-constrained model for municipal solid waste management

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ABSTRACT

A double-sided dual-uncertainty-based chance-constrained programming (DDCCP) model was developed for supporting municipal solid waste management under uncertainty. The model was capable of tackling left-hand- and right-hand-side variables in constraints where those variables were affected by dual uncertainties (i.e. e.g. both fuzziness and randomness); and they were expressed as fuzzy random variables (FRVs). In this study, DDCCP model were formulated and solved based on stochastic and fuzzy chance-constrained programming techniques, leading to optimal solutions under different levels of constraints violation and satisfaction reliabilities. A long-term solid waste management problem was used to demonstrate the feasibility and applicability of DDCCP model. The obtained results indicated that DDCCP was effective in handling constraints with FRVs through satisfying them at a series of allowable levels, generating various solutions that facilitated evaluation of trade-offs between system economy and reliability. The proposed model could help decision makers establish cost-effective waste-flow allocation patterns under complex uncertainties, and gain in-depth insights into the municipal solid waste management system.

1. Introduction

Municipal solid waste (MSW) management continues to be a major challenge for urban managers over the world. This is mainly due to the elevated complexities that are associated with rapid increase of waste-generation rates and irrational waste-flow allocation patterns. In addition to controlling the population size and increasing the facility capacities, there is an urgent need to develop effective management tools to help improve the waste-management efficiency and generate cost-effective waste-flow allocation strategies for waste managers.

However, a typical MSW management system involves extensive uncertainties that could be associated waste generation, transport and treatment. The problem is further exacerbated by multi-period and multi-layer features that are embedded with many system parameters. For example, the waste-generation rates are affected by both subjective and objective factors, such as population size, economic status of local region, and environmental regulations; the treatment capacities of various facilities are influenced by waste property, facility's service time and transportation condition, and they may exhibit random and vague properties. In order to effectively reflect uncertain features of above components, an effective uncertainty-analysis

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technique that is capable of describing and reflecting multiple types of uncertain information (i.e. objective and subjective information) is desired.

Previously, many inexact optimization techniques were proposed to describe and tackle uncertain elements comprised by solid waste management system. The majority of these methods focused on fuzzy, stochastic and interval programming approaches, as well as their combinations [1–8]. Besides, many researchers from all over the world have successfully applied many solid waste management models in real world problems, such as Beijing, Foshan, and Regina [9–14]. For example, Huang et al. [1] proposed a grey linear programming model for supporting MSW management under uncertainty, where interval-format solutions were obtained through an interactive two-step algorithm. Xu et al. [5] proposed a stochastic robust interval linear programming model for helping waste managers to identify desired policies that under various environmental, economic, system-feasibility and system-reliability constraints. Li et al. [7] developed a scenario-based fuzzy-stochastic quadratic programming (SFQP) model for identifying optimal MSW management policies. Qin et al. [14] developed a trapezoidal-shaped fuzzy chance-constrained mixed-integer programming (TFCMP) model for supporting municipal solid waste management in Foshan city, China, where the solutions of waste allocation patterns and expansion options were obtained. From these studies, it is clear that the proposed methods could be used for tackling uncertain parameters in management system and generating optimal management alternatives. Nevertheless, in some real-world applications, a parameter may be associated with both fuzziness and randomness. For example, the waste generation rate in an urban community has a random feature due to population fluctuation and economic development; meanwhile, the statistical information of such a random parameter is also affected by data error (or shortage) and human judgment which could be better described by fuzzy sets. Similar situation also occur in many fields, including production problem, water resource management and financial portfolio planning. It is thus desired that a novel approach which is capable of tackling multiple uncertainties associated with one parameter be advanced.

Fuzzy stochastic linear programming (FSLP) method is suitable in handling special variable containing information which is both fuzzily imprecise and probabilistically uncertain, which has been called the fuzzy random variable (FRV). Recently, many definitions, notions and explanations of FRV have appeared, such as probability of a fuzzy event, probabilistic set, fuzzy random variable and linguistic probabilities [15–17]. Moreover, a variety of solution methods were carried out and used in many real-world applications, including linear programming with random variables and fuzzy numbers, flexible stochastic linear programming with fuzzy random variables coefficients and inequality-constrained linear programming with fuzzy random variables coefficients [18–27]. However, few FSLP methods are applied in solid waste management field. Moreover, many FSLP methods are incapable of solving large-scale management problems due to the extensive computational burden caused by large numbers of variables and equations, and iterative searching for optimal solutions.

In this study, a new FSLP method, entitled double-sided dual-uncertainty-based chance-constrained programming (DDCCP), is to be developed. DDCCP is useful in tackling FRVs included in both sides of the model constraints, generating optimal solutions under allowable constraints-violation and constraints-satisfaction levels, and evaluating the balance between system economy and reliability, where the concept of "system economy" is mainly used to reflect the solution performance in economical aspect. Generally, a high "system economy" means that the obtained solutions lead to a low system cost or a high system benefit. A solid waste management system will be used to demonstrate the feasibility and applicability of the proposed method. This study aims to apply the developed model to a solid waste management system under complex uncertainties. The objective entails: (i) formulate and solve DDCCP model in the "Methodology" section; (ii) introduce system components, structure and operation procedures of solid waste management system in "Case study" section; (iii) demonstrate and analyze the characteristics and variation trends of the obtained solutions from DDCCP model in the "Result analysis" section; (iv) a short summary is given in the "Conclusion" section.

2. Methodology

Previously, many types of definitions of FRV were proposed. Generally, the defined formats and properties of FRVs will determine the algorithm of model solutions. In this study, it is assumed that a random variable ξ has a normal distribution, i.e. $\xi \sim N(m, \delta^2)$, where m and δ denotes the mean value and standard deviation, respectively; due to subjective and objective influencing factors, m and δ are also considered as uncertain and will be described by fuzzy possibilistic distributions, i.e. $\tilde{m}$ and $\tilde{\delta}$. The definition of FRV is listed as follows:

$$f(x) = \frac{1}{\sqrt{2\pi}\tilde{\delta}} \exp\left(-\frac{(x-\tilde{m})^2}{2\tilde{\delta}^2}\right), \tag{1a}$$

$$\tilde{m} = \left\{(x, \mu_{\tilde{m}}(x)) \mid x \in X\right\}, \tag{1b}$$

$$\mu_{\tilde{m}}(x) = \sup\{\alpha \mid \alpha \in [0,1], x \in m_\alpha\}, \tag{1c}$$

$$\tilde{m}_\alpha = \left\{x \mid \mu_{\tilde{m}}(x) \geq \alpha,\ x \in X\right\}, \tag{1d}$$

$$\tilde{\delta} = \left\{(x, \mu_{\tilde{\delta}}(x)) \mid x \in X\right\}, \tag{1e}$$