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Optimization of environmental management strategies through a dynamic stochastic possibilistic multiobjective program

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HIGHLIGHTS

- A dynamic stochastic possibilistic multiobjective programming model is developed.
- Greenhouse gas emission control is considered.
- Three planning scenarios are analyzed and compared.
- Optimal decision schemes under three scenarios and different p_i levels are obtained.
- Tradeoffs between economics and environment are reflected.

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ABSTRACT

Greenhouse gas (GHG) emissions from municipal solid waste (MSW) management facilities have become a serious environmental issue. In MSW management, not only economic objectives but also environmental objectives should be considered simultaneously. In this study, a dynamic stochastic possibilistic multiobjective programming (DSPMP) model is developed for supporting MSW management and associated GHG emission control. The DSPMP model improves upon the existing waste management optimization methods through incorporation of fuzzy possibilistic programming and chance-constrained programming into a general mixed-integer multiobjective linear programming (MOP) framework where various uncertainties expressed as fuzzy possibility distributions and probability distributions can be effectively reflected. Two conflicting objectives are integrally considered, including minimization of total system cost and minimization of total GHG emissions from waste management facilities. Three planning scenarios are analyzed and compared, representing different preferences of the decision makers for economic development and environmental-impact (i.e. GHG-emission) issues in integrated MSW management. Optimal decision schemes under three scenarios and different p_i levels (representing the probability that the constraints would be violated) are generated for planning waste flow allocation and facility capacity expansions as well as GHG emission control. The results indicate that economic and environmental tradeoffs can be effectively reflected through the proposed DSPMP model. The generated decision variables can help the decision makers justify and/or adjust their waste management strategies based on their implicit knowledge and preferences.

1. Introduction

Greenhouse gas (GHG) emissions from municipal solid waste (MSW) management facilities have become a serious issue due to their significant contributions to global climate change [1–3]. In the United States, 2.3% of total GHG emissions in 2008 were contributed by waste activities; landfills were the second largest anthropogenic sources for methane emissions, accounting for 22% of total methane emissions [4]. In Canada, 25 Mton CO_2 equivalent (CO_2e) emissions were emanated from solid waste sectors in 2001, among which 23 Mton CO_2e emissions were from landfills [5]. In MSW management, waste collection, allocation, transportation, treatment and disposal activities can impact the emissions of GHGs including CH_4, CO_2 and N_2O [6,7]. In order to mitigate GHG emissions, sound decision alternatives for integrated MSW management are desired. The integrated MSW management planning generally involves numerous factors with multiobjective, multi-period and dynamic characteristics [8]. There are tradeoffs among various management objectives such as economic and environmental considerations which are generally conflicting. How to generate

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optimal management strategies involving multiple conflicting objectives has become a challenge for the decision makers and/or waste managers.

Multiobjective programming (MOP) approaches can aid in the aforementioned decision making processes through simultaneous consideration of multiple objectives for addressing tradeoffs or compromises among them. Meantime, uncertainties inherently exist in a variety of system parameters, objectives, factors and behaviors, consequently affecting the generated decision alternatives for waste management. Previously, a number of MOP methods under uncertainty have been developed and applied in MSW management planning [8–14]. For examples, Chang and Wang [9] advanced a multiobjective mixed integer programming model to generate sustainable waste management strategies in a metropolitan in Taiwan, where four optimization objectives including economics, noise control, air pollution control and traffic congestion were considered. Minciardi et al. [15] presented a nonlinear multiobjective optimization model for waste flow allocation; four minimization objectives were related to economic costs, unrecycled wastes, sanitary landfill disposal and incinerator emissions. Galante et al. [16] addressed economic and environmental issues in MSW management including total annual cost and air pollution caused by vehicles through a multiobjective programming model. He et al. [17] proposed a mixed-integer bilevel programming model for MSW management and GHG emission control. However, most of the previous studies emphasized more on economic and technical objectives in the decision analyses [18]. Few of them incorporated GHG emission control within a multiobjective management framework, especially under complex uncertainties involving multiple forms of uncertainties.

Therefore, the objective of this study is to develop a dynamic stochastic possibilistic multiobjective programming (DSPMP) model for supporting waste flow allocation, facility capacity expansion planning, and associated GHG emission control within an integrated MSW management system. The DSPMP model improves upon the existing optimization methods for waste management through incorporation of fuzzy possibilistic programming (FPP) and chance-constrained programming (CCP) into a general mixed-integer MOP framework where various uncertainties expressed as fuzzy possibility distributions and probability distributions can be effectively reflected. It has been applied to a hypothetical case study to generate optimal management strategies for waste flow allocation and facility capacity expansion, where multiple objectives including minimization of total system cost and minimization of total amounts of GHGs emitted from waste management facilities have been simultaneously considered. The generated decision variables can help the decision makers justify and/or adjust waste management strategies through incorporation of their implicit knowledge and preferences. Three scenarios are analyzed corresponding to different economic and environmental tradeoffs:

(a) Scenario 1: two objectives including minimization of total system cost and total GHG emissions from waste management facilities are simultaneously considered. It represents a balanced situation where economic development and environmental impacts are harmonized and an overall satisfaction degree for both objectives is achieved. The proposed DSPMP model has been applied to deal with this scenario.
(b) Scenario 2: only a single objective of total system cost is minimized with consideration of GHG emission control for each waste management facility in the model's constraints. Although there are no requirements for total GHG emissions from a whole system's viewpoint, GHG emissions from each facility are still limited to pre-given emission permits. This scenario represents a commonly used means for integrated municipal solid waste management involving GHG emission control where economic objective is exclusively considered.
(c) Scenario 3: only a single objective of minimizing total system cost is considered without any consideration of GHG emission limits for waste management facilities. This scenario reflects a worst extreme where the sole emphasis of the decision makers is cost.

2. Methodology development

2.1. Multiobjective linear programming

A general mixed-integer multiobjective linear programming (MOP) model can be formulated as follows:

$$\min \; f_h = C_h X, \quad h = 1, 2, \ldots, m \tag{1a}$$

Subject to:

$$AX \le B \tag{1b}$$

$$X \ge 0, \text{ or integers} \tag{1c}$$

where f_h is the multiple and generally conflicting objectives, $A \in \{R\}^{p\times n}, B \in \{R\}^{p\times 1}, C_h \in \{R\}^{1\times n}, X \in \{R\}^{n\times 1}$ (R denotes a set of real numbers).

Many approaches have been proposed to solve the above MOP problems, such as weighting methods, e-constrained approaches, goal programming, and fuzzy programming methods [19]. Among them, fuzzy programming method by Zimmermann [20] is used in this study and model (1) can thus be transformed into the following formulations [19]:

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

Subject to:

$$\lambda \le \mu_{f_h}, \quad h = 1, 2, \ldots, m \tag{2b}$$

$$0 \le \lambda \le 1 \tag{2c}$$

and the constraints (1b) and (1c).

where λ is the overall satisfaction degree of m objective functions, and μ_{f_h} is fuzzy membership function for the objective function f_n which can be determined as follows:

$$\mu_{f_h} = \begin{cases} 1 & \text{if} f_h < f_h^*, \\ \dfrac{f_h^U - f_h}{f_h^U - f_h^*} & \text{if} f_h^* \le f_h \le f_h^U, \\ 0 & \text{if} f_h > f_h^U. \end{cases} \tag{3}$$

where f_h^* is the aspiration level of the hth objective function, and f_h^U represents allowable upper bound of the hth objective function. By setting the aspiration level and allowable upper bound of each objective, the original MOP problem can be converted into a single-objective linear programming one which can easily solved.

2.2. Fuzzy possibilistic programming

When the coefficients of the objective are imprecise and expressed as possibility distributions limited by fuzzy sets, a fuzzy possibilistic programming (FPP) model with imprecise coefficients only in the objective function can be formulated as follows:

$$\max \tilde{Z} = \sum_{j=1}^{n} \tilde{c}_j x_j \tag{4a}$$