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An interval-based possibilistic programming method for waste management with cost minimization and environmental-impact abatement under uncertainty

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ABSTRACT

Considerable public concerns have been raised in the past decades since a large amount of pollutant emissions from municipal solid waste (MSW) disposal of processes pose risks on surrounding environment and human health. Moreover, in MSW management, various uncertainties exist in the related costs, impact factors and objectives, which can affect the optimization processes and the decision schemes generated. In this study, an interval-based possibilistic programming (IBPP) method is developed for planning the MSW management with minimized system cost and environmental impact under uncertainty. The developed method can deal with uncertainties expressed as interval values and fuzzy sets in the left- and right-hand sides of constraints and objective function. An interactive algorithm is provided for solving the IBPP problem, which does not lead to more complicated intermediate submodels and has a relatively low computational requirement. The developed model is applied to a case study of planning a MSW management system, where mixed integer linear programming (MILP) technique is introduced into the IBPP framework to facilitate dynamic analysis for decisions of timing, sizing and siting in terms of capacity expansion for waste-management facilities. Three cases based on different waste-management policies are examined. The results obtained indicate that inclusion of environmental impacts in the optimization model can change the traditional waste-allocation pattern merely based on the economic-oriented planning approach. The results obtained can help identify desired alternatives for managing MSW, which has advantages in providing compromised schemes under an integrated consideration of economic efficiency and environmental impact under uncertainty.

1. Introduction

Globally, waste-generation rate has nearly doubled since 1960, from 2.7 to 4.4 pounds per capital per day, while more than 70% of municipal solid waste (MSW) generated is disposed of at landfills (Zacarias-Farah and Geyer-Allely, 2003; USEPA, 2007). Since Anderson (1968) first proposed economic optimization for the planning of municipal solid waste (MSW) management systems, most of the waste-related planning models have been focused on the cost minimization through using systems analysis techniques (Wilson, 1985; Kirca and Erkip, 1988; Baetz, 1990; Thomas et al., 1990; Chang et al., 2005). However, uncertainties exist in the related parameters, impact factors, and waste disposal of processes, creating complexities which are beyond the capabilities of deterministic programming approaches. Such uncertainties may be further multiplied by the complex features of the system components, as well as by their associations with economic implications and environmental concerns being examined.

As a result, a large number of inexact mathematical models have been developed for dealing with various uncertainties in the planning of MSW management problems (Wilson and Baetz, 2001; Davila et al., 2005; Huang et al., 2005a, b; Li and Huang, 2006a, b; Chang and Davila, 2007; Xu et al., 2009; Wulder et al., 2010). Among them, stochastic mathematical programming (SMP) can deal with various probabilistic uncertainties; however, the increased data requirements for specifying the parameters' probability distributions can affect their practical applicability. For example, a planner may know that the daily waste-generation rate fluctuates within a certain interval, but he/she may find it difficult to state a reliable probability distribution for this variation. Fuzzy mathematical programming (FMP), derived from the fuzzy set theory, is effective in reflecting ambiguity and vagueness in decision-making problems (Huang et al., 1993; Chang et al., 2008). There are two major FMP approaches: possibilistic programming and flexibility programming (abbreviated as FFP and FPP) (Inuiguchi and Sakawa, 1994). In FFP, the flexibility in the constraints and fuzziness in the objective (which are represented by fuzzy sets and denoted as "fuzzy constraints" and "fuzzy goal", respectively), can be expressed as membership grades; however, FFP could hardly tackle uncertainties

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expressed as ambiguous coefficients in the objective function and constraints (Inuiguchi and Tanino, 2000). In FPP, fuzzy parameters can be introduced into the modeling framework, which represent fuzzy regions where the parameters are regarded as possibility distributions; however, when many uncertain parameters are expressed as fuzzy sets, interactions among these uncertainties may lead to serious complexities, particularly for large-scale practical problems (Huang et al., 1993). Interval-parameter programming (IPP) is an alternative for handling uncertainties in the model's left- and/or right-hand sides and in the objective function as well as those that cannot be quantified as membership or distribution functions, since interval numbers are acceptable as its uncertain inputs (Huang et al., 1992; Li et al., 2008). However, IPP may become infeasible when the model's right-hand-side coefficients have large intervals; moreover, it has difficulties in reflecting uncertainties expressed as fuzzy sets.

Previously, combining advantages of FFP and IPP, Huang et al. (1993) proposed a grey fuzzy flexible programming method and applied it to MSW management systems to tackle uncertainties that presented in fuzzy and interval forms. Chang et al. (1997) proposed a fuzzy interval multiobjective mixed integer programming model for evaluating strategies of solid waste management; it demonstrated how uncertain message could be quantified by specific membership functions and combined through the use of interval numbers in a multiobjective analytical framework. Wilson and Baetz (2001) developed a derived probability model for curbside waste collection activities that allowed for analyzing stochastic information in the MSW management. Solano et al. (2002) developed an integrated solid waste-management model to assist in identifying desired solid waste-management strategies that could satisfy cost, energy and environmental emission objectives. Li et al. (2009) developed an inexact fuzzy-stochastic constraint-softened programming method for planning waste-management systems under uncertainty through introducing FFP into an inexact multistage stochastic programming framework, where a number of violation variables for the constraints are introduced, allowing in-depth analyses of tradeoffs among economic objective, satisfaction degree, and constraint-violation risk. However, few applications of FPP to MSW management were reported. Therefore, as an extension of previous efforts, an interval-based possibilistic programming method (IBPP) could be advanced by introducing IPP techniques into FPP framework to reflect uncertain parameters expressed as intervals and fuzzy sets existing in MSW management systems.

Various types of facilities are available for waste treatment and disposal; however, landfill disposal and incineration in waste-to energy facility (WTE) are two major options for managing MSW flows. For example, in 2007, there were 137.2 million tons of waste buried at landfills and 31.9 million tons of waste treated by WTE in the United States, occupying approximately 67% of MSW generated in the whole nation (USEPA, 2007); the UK can produce around 400 million tons of waste each year, and 80% of them are disposed of at landfills (Koshy et al., 2007); it was estimated that up to 85% of the MSW generated in the South Africa was landfilled (Lumby, 1996). During the last decades, considerable public concerns have been raised since pollutant emissions from both landfill and WTE have negative and/or deleterious effects on air, land or water quality (i.e. environmental impacts) and thus pose a risk on human health. Numerous studies investigating the behaviors of MSW landfills and incinerators and their emissions were conducted (Khalil, 1999; Khalil, 2000; Koshy et al., 2007). For example, in UK, around 80% of the population lives within 2 km of a landfill (Koshy et al., 2007). Pollutant emissions from landfills can take a number of forms: gaseous emissions of volatile organic compounds (VOCs), airborne particulate matter and leachate. The surface water could be polluted by rainwater flowing through solid waste piles. Groundwater could be contaminated by leachate from landfill sites where solid wastes are disposed of. The polluted surface water and groundwater can further affect the drinking water safety; leachate containing hazardous materials can enter soil and further reside in the agricultural products that make our foods poisonous. Typically, landfill gas consists of 50–60 vol.% of methane and 30–40 vol.% of carbon dioxide, and trace amounts of numerous chemical compounds such as aromatics, chlorinated organic compounds and sulfur compounds (Khalil, 1999). Landfills are the first and/or second largest contribution of methane (CH_4) source. Recently, there is an increasing concern for CH_4, as a major greenhouse gas, while its global warming potential is about 23 on a 100-year time horizon (Crutzen, 1991; Mor et al., 2006; Chen et al., 2010). The annual global CH_4 emissions to the atmosphere were approximately 500 Tg in the mid-1990s, with amount of CH_4 emitted from landfills up to 70 Tg per year (Khalil, 2000); in 2006, the amount of CH_4 released from landfills was 5985 Gg, occupying 23% of total US anthropogenic methane emissions (USEPA, 2007, 2008). Therefore, the composition of the waste deposited at the landfill site should be ascertained for the estimation of the gas emission potential of the landfill site.

Waste incineration can also generate considerable pollutant emissions (e.g., acid gases, metals and various organic compounds) that can present potential human health hazards. Waste treated by WTE can pose serious threats on the surrounding environment under high ground-level pollutant concentrations caused by inefficient pollutant control, source configuration, certain meteorological condition, and surrounding terrain. Emissions from WTE contain a large number of pollutants (e.g., heavy metals, polychlorinated dibenzo-pdioxins, dibenzofurans, biphenyls), which are of considerable toxicological interest. Some of these contaminants are alleged to increase the incidence of cancer and contribute to adverse pregnancy outcomes on the basis of laboratory and epidemiologic data (Vinceti et al., 2008). For example, in the United States, over 90,000 tons per year of various air pollutants could be released from the MSW incinerators if control measures were not adopted (USEPA, 2007). The amount of sulfur dioxide (SO_2) emission can range from 20 kg to 78 kg when combusting 1 ton MSW (Glorennec et al., 2005). However, according to the SO_2-loading standard determined by the World Health Organization (WHO, 2000), the SO_2-loading level could not exceed the annual threshold of 50 $\mu g/m^3$. High levels of SO_2 in the air can aggravate various lung problems in people with asthma and can cause breathing difficulties in children and the elderly; in some instances, breathing high levels of SO_2 can even damage lung tissue and cause premature death. Consequently, in the planning of MSW management, reduction of various pollutant emissions to protect human health and clean surrounding environment is desired.

The objective of this study is to develop an interval-based possibilistic programming (IBPP) method for waste management with cost minimization and environmental-impact abatement under uncertainty. In IBPP, approaches of FPP and IPP will be incorporated within a general framework to deal with uncertainties expressed as interval values and fuzzy sets in the objective and constraints. An interactive solution algorithm will be advanced for solving the IBPP model, with a relatively low computational requirement. A municipal solid waste (MSW) management problem will then be provided for demonstrating applicability of the developed method. Mixed integer linear programming (MILP) technique will be introduced into the IBPP to facilitate dynamic analysis for decisions of timing, sizing and siting when expanding waste-management facility capacities. Three cases will be examined based on different waste-management policies. The results obtained will help identify desired alternatives for managing MSW with cost minimization and environmental-impact abatement under uncertainty.

2. Methodology

Interval-parameter linear programming (ILP) method can deal with the uncertain parameters expressed as intervals without any distributional information that is always required in fuzzy and stochastic programming. The ILP allows the interval information to