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Mathematical Modeling for Identifying Cost-Effective Policy of Municipal Solid Waste Management under Uncertainty

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ABSTRACT. In municipal solid waste (MSW) management, many impact factors, such as waste generation rate, treatment capacity, diversion goal, and disposal cost appear uncertain. These uncertainties can result in difficulties in the long-term planning of MSW management activities. A critical issue that decision makers should mitigate is how to address these uncertainties due to a lack of knowledge founded on an incomplete characterization, understanding or measurement of MSW systems. In this study, an inexact two-stage waste management (ITWM) model is developed for planning long-term MSW management in the City of Changchun, China. The ITWM model incorporates the techniques of interval-parameter programming (IPP) and two-stage stochastic programming (TSP) within an integer programming framework, such that uncertainties expressed as both intervals and probabilities can be reflected; it can also analyze different policy scenarios that are associated with different economic penalty levels. Two cases related to different waste management policies are examined, generating varied levels of waste-management cost and system-failure risk. The results obtained are valuable for addressing issues of waste diversion and capacity expansion with a minimized system cost. They also suggest that the developed model be meaningful for real-world planning problems and the practicality of this approach can be extended to other environmental planning applications containing significant sources of uncertainty.

Keywords: MSW management, optimization, planning, policy analysis, uncertainty

1. Introduction

With the booming economy and increasing population, the accumulation of municipal solid waste (MSW) has become an increasingly arduous issue and has aroused the attention from solid-waste managers in public and private sectors (Lee et al., 2016). Global waste generation rate has nearly doubled since 1960, from 2.7 to 4.4 pounds per capita per day, while more than 70% of MSW generated is disposed of at landfills (Li and Huang, 2010). Due to the potential for groundwater contamination, the scarcity of land near urban centers, and the growing opposition from the public with regard to landfill disposal, many cities and nations are making efforts on waste diversion through an integrated solid waste management (ISWM) approach to change the current practice of relying solely on a landfill for the MSW disposal of. However, ISWM activities are often complicated with a number of economic, technical, environmental, legislational, and political factors (Huang et al., 2017). In MSW management systems, one of important issues that decision makers should figure out is how to (i) distribute the MSW among different facilities, and (ii) increase the reliability of infrastructure systems. Difficulties in planning for waste processing can be further compounded by significant stochastic uncertainties attributable to variations in waste density, humidity, temperature, waste packing methods, and estimations of specific cost and revenue components. For MSW management problems, results are often subject to uncertainty due to the combined effects of data variability, erroneous measurements, wrong estimations, unrepresentative or missing data and modeling assumptions (Clavreul et al., 2012; Luz et al., 2015).

Systems analysis approaches have proven useful in supporting policy decisions by providing a comprehensive representation of MSW problems, considering the interactions between their main elements and their evolutions over time (Di Nola et al., 2018). Previously, mathematical models were advanced for supporting decisions of MSW management, evaluating relevant operation and investment policies, and reflecting various uncertainties in waste generation and disposal activities (Erkut et al., 2008; Earnhart and Segerson, 2012; Telle, 2013; Paul et al., 2018; Carvalho et al., 2018). Davila et al. (2005) proposed a grey integer programming-based game theory (GIP-based game theory) for system optimization and cost-benefit analysis at two competing landfills in the Lower Rio Grande Valley (the United States). Ezeah and Roberts (2012) investigated the barriers as well as success factors which affect solid waste management in Nigeria. Soltani et al. (2017) employed

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uncertainty assessment methods (such as sensitivity analysis, fuzzy Analytical Hierarchy Process, and Bayesian games) to assess the MSW management policies in Vancouver (Canada). Di Nola et al. (2018) proposed a dynamic model to analyze the interactions between the main elements of the waste system in Campania (Italy) and their evolution over the critical time horizon. Um et al. (2018) examined the new policy framework that included effective environmental assessment procedure to manage waste in Korea; important strategies toward reduction of waste, preservation of landfill area, stabilization and removal of hazardous substance in wastes, as well as optimal treament for energy and material recovery from wastes were achieved.

There are also a number of studies that consider systems analysis techniques for planning MSW management in China (Cui et al., 2011; Dai et al., 2011; Lee et al., 2016). These research works are valuable for generating alternatives and can help decision makers to identify desired waste management policies with cost minimization and environmental-impact abatement. China has experienced a very rapid increase in its economy during the last three decades. However, in the absence of a comprehensively sustainable development scheme, this increase has brought severe environmental issues, such as water resources depletion and pollution, soil erosion, desertification, acid rain, sandstorms, forest depletion, and solid waste pollution. Among them, MSW is becoming a critical issue, not only in terms of the impacts being created but also in terms of resources being consumed. No country has ever experienced as large or as fast an increase in solid waste amounts that China is now facing. China already produces 29% of the world's solid waste each year, and with the economy continuing to grow rapidly, it is clear that China bears what may be the heaviest solid waste management burden in the world. It has been estimated that the amounts of industrial waste increased by 10% while at the same time MSW has increased by 15% per year in China (Li et al., 2015). Waste management has enormous domestic and international implications. As a result, the Chinese government and many local authorities are devoting more attention to waste management issues. However, such a planning/ management effort is complicated with a variety of uncertain factors as well as their interactions (Zulueta et al., 2017). Precise data is hard to be obtained due to temporal and spatial variations in MSW system conditions; instead, various uncertainties exist in MSW management activities, which can affect the optimization processes and the decision schemes generated.

Therefore, the objective of this study is to develop an inexact two-stage waste management (ITWM) model for supporting municipal solid waste (MSW) management in the City of Changchun, China. The ITWM model will incorporate the techniques of interval-parameter programming (IPP) and two-stage stochastic programming (TSP) within an integer programming framework for better accounting for different uncertainties, the relevant economic penalties, as well as capacity-expansion decision issues. This paper will be organized as follows: Section 2 describes the method for such an ITWM model; Section 3 formulates the ITWM model for supporting MSW management of the study city; Section 4 provides the result analysis, based on different waste diversion policies; Section 5 draws some conclusions.

2. Methodology

Two-stage stochastic programming (TSP) is effective for problems where an analysis of policy scenarios is desired and the related data are mostly uncertain. In TSP, decision variables are divided into two subsets: those that must be determined before the realizations of random variables are known, and those (recourse variables) that are determined after the realized values of the random variables are available. A general TSP model is formulated as (Birge and Louveaux, 1988; Ahmed et al., 2004):

$$z = \min C^T X + \mathrm{E}_{\omega \in \Omega}\left[Q\left(X,\ \omega\right)\right]$$

subject to:

$$x \in X \tag{1a}$$

with

$$Q\left(x,\ \omega\right) = \min\ f\left(\omega\right)^T y$$

subject to:

$$D\left(\omega\right) y \geq h\left(\omega\right) + T\left(\omega\right) x \tag{1b}$$

$$y \in Y$$

where $X \subseteq \mathbb{R}^{n_1}$, $C \in \mathbb{R}^{n_1}$, and $Y \subseteq \mathbb{R}^{n_2}$. The ω is a random variable from space (Ω, F, P) with $\Omega \subseteq \mathbb{R}^k$, $f : \Omega \to \mathbb{R}^{n_2}$, $h : \Omega \to \mathbb{R}^{m_2}$, $D : \Omega \to \mathbb{R}^{m_2 \times n_2}$, and $T : \Omega \to \mathbb{R}^{m_2 \times n_1}$. By letting random var-iables (i.e., ω) take discrete values w_h with probability levels p_h (h = 1, 2, …, v and $\sum p_h = 1$), the above TSP can be equivalently formulated as a linear programming model as follows:

$$\min f = C_{T_1} X + \sum_{h=1}^{v} p_h D_{T_2} Y \tag{2a}$$

subject to:

$$A_r X \leq B_r,\ r = 1,\ 2,\ ...,\ m_1 \tag{2b}$$

$$A_t X + A_t' Y \geq w_h,\ t = 1,\ 2,\ ...,\ m_2;\ h = 1,\ 2,\ ...,\ v \tag{2c}$$

$$x_j \geq 0,\ x_j \in X,\ j = 1,\ 2,\ ...,\ n_1 \tag{2d}$$

$$y_{jh} \geq 0,\ y_{jh} \in Y,\ j = 1,\ 2,\ ...,\ n_2;\ h = 1,\ 2,\ ...,\ v \tag{2e}$$

Model (2) can deal with uncertainties in the right-hand sides presented as probability distributions when coefficients in the left-hand sides and in the objective function are deterministic. However, in the real-world optimization problems, uncertainties may exist in both left- and right-hand sides (of constraints) as well as objective-function coefficients; moreover, the quality of information that can be obtained is mostly not satisfactory enough to be presented as probabilities. Such complexities cannot be solved through model (2). Therefore, one potential approach for better accounting for such complexities is to introduce interval parameters into the TSP framework. Thus, we have:

$$\min f^{\pm} = C_{T_1}^{\pm} X^{\pm} + \sum_{h=1}^{v} p_h D_{T_2}^{\pm} Y^{\pm} \tag{3a}$$

subject to:

$$A_r^{\pm} X^{\pm} \le B_r^{\pm},\ r = 1,\ 2,\ ...,\ m_1 \tag{3b}$$

$$A_t^{\pm} X^{\pm} + A_t'^{\pm} Y^{\pm} \ge w_h^{\pm},\ t = 1,\ 2,\ ...,\ m_2;\ h = 1,\ 2,\ ...,\ v \tag{3c}$$

$$x_j^{\pm} \ge 0,\ x_j^{\pm} \in X^{\pm};\ j = 1,\ 2,\ ...,\ n_1 \tag{3d}$$

$$y_{jh}^{\pm} \ge 0,\ y_{jh}^{\pm} \in Y^{\pm};\ j = 1,\ 2,\ ...,\ n_2;\ h = 1,\ 2,\ ...,\ v \tag{3e}$$

where superscripts '−' and '+' represent lower and upper bounds of one interval, respectively, an interval can be defined as a number with known lower and upper bounds but unknown distribution information (Fan and Huang, 2012).

In model (3), decision variables can be sorted into two categories: continuous and binary. Model (3) can be transformed into two deterministic submodels that correspond to the lower and upper bounds of the desired objective. Interval solutions associated with varying levels of constraint-violation risk can then be obtained by solving the two submodels sequentially. The submodel corresponding to the lower-bound objective function value (f^-) can be firstly formulated as follows (assume that $B^{\pm} > 0$, and $f^{\pm} > 0$):

$$\min f^{-} = \sum_{j=1}^{k_1} c_j^- x_j^- + \sum_{j=k_1+1}^{n_1} c_j^- x_j^+ + \sum_{j=1}^{k_2}\sum_{h=1}^{v} p_{jh} d_j^- y_{jh}^- + \sum_{j=k_2+1}^{n_2}\sum_{h=1}^{v} p_{jh} d_j^- y_{jh}^+ \tag{4a}$$

subject to:

$$\sum_{j=1}^{k_1} |a_{rj}|^+ \operatorname{sign}(a_{rj}^+) x_j^- + \sum_{j=k_2+1}^{n_1} |a_{rj}|^- \operatorname{sign}(a_{rj}^-) x_j^+ \le b_r^+,\ \forall r \tag{4b}$$

$$\sum_{j=1}^{k_1} |a_{tj}|^+ \operatorname{sign}(a_{tj}^+) x_j^- + \sum_{j=k_2+1}^{n_1} |a_{tj}|^- \operatorname{sign}(a_{tj}^-) x_j^+ + \sum_{j=1}^{k_2} |a_{tj}'|^+ \operatorname{sign}(a_{tj}'^+) y_{jh}^- + \sum_{j=k_2+1}^{n_2} |a_{tj}'|^- \operatorname{sign}(a_{tj}'^-) y_{jh}^+ \le w_h^-,\ \forall t, h \tag{4c}$$

$$x_j^- \ge 0,\ j = 1,\ 2,\ ...,\ k_1 \tag{4d}$$

$$x_j^+ \ge 0,\ j = k_1+1,\ k_1+2,\ ...,\ n_1 \tag{4e}$$

$$y_{jh}^- \ge 0,\ \forall h;\ j = 1,\ 2,\ ...,\ k_2 \tag{4f}$$

$$y_{jh}^+ \ge 0,\ \forall h;\ j = k_2+1,\ k_2+2,\ ...,\ n_2 \tag{4g}$$

where $x_j^{\pm}$, j = 1, 2, ..., k_1, are interval variables with positive coefficients in the objective function; $x_j^{\pm}$, $j = k_1 + 1$, $k_1 + 2$, ..., n_1, are interval variables with negative coefficients; $y_{jh}^{\pm}$, j = 1, 2, ..., k_2 and h = 1, 2, …, v are random variables with positive coef-ficients in the objective function; $y_{jh}^{\pm}$, $j = k_1 + 1$, $k_1 + 2$, ..., n_2 and h = 1, 2, …, v, are random variables with negative coefficients. Solutions of $x_{j,opt}^-$ (j = 1, 2, ..., k_1), $x_{j,opt}^+$ ($j = k_1 + 1$, $k_1 + 2$, ..., n_1), $y_{jh,opt}^-$ (j = 1, 2, ..., k_2), and $y_{jh,opt}^+$ ($j = k_1 + 1$, $k_1 + 2$, ..., n_2) can be obtained through submodel (4). Based on the above solutions, the second submodel can be formulated as follows:

$$\min f^{+} = \sum_{j=1}^{k_1} c_j^+ x_j^+ + \sum_{j=k_1+1}^{n_1} c_j^+ x_j^- + \sum_{j=1}^{k_2}\sum_{h=1}^{v} p_{jh} d_j^+ y_{jh}^+ + \sum_{j=k_2+1}^{n_2}\sum_{h=1}^{v} p_{jh} d_j^+ y_{jh}^- \tag{5a}$$

subject to:

$$\sum_{j=1}^{k_1} |a_{rj}|^- \operatorname{sign}(a_{rj}^-) x_j^+ + \sum_{j=k_2+1}^{n_1} |a_{rj}|^+ \operatorname{sign}(a_{rj}^+) x_j^- \le b_r^-,\ \forall r \tag{5b}$$

$$\sum_{j=1}^{k_1} |a_{tj}|^- \operatorname{sign}(a_{tj}^-) x_j^+ + \sum_{j=k_2+1}^{n_1} |a_{tj}|^+ \operatorname{sign}(a_{tj}^+) x_j^- + \sum_{j=1}^{k_2} |a_{tj}'|^- \operatorname{sign}(a_{tj}'^-) y_{jh}^+ + \sum_{j=k_2+1}^{n_2} |a_{tj}'|^+ \operatorname{sign}(a_{tj}'^+) y_{jh}^- \le w_h^+,\ \forall t, h \tag{5c}$$

$$x_j^+ \ge x_{j,opt}^-,\ j = 1,\ 2,\ ...,\ k_1 \tag{5d}$$

$$0 \le x_j^- \le x_{j,opt}^+,\ j = k_1+1,\ k_1+2,\ ...,\ n_1 \tag{5e}$$

$$y_{jh}^+ \ge y_{jh,opt}^-,\ \forall h;\ j = 1,\ 2,\ ...,\ k_2 \tag{5f}$$

$$0 \le y_{jh}^- \le y_{jh,opt}^+,\ \forall h;\ j = k_2+1,\ k_2+2,\ ...,\ n_2 \tag{5g}$$

Solutions of $x_{j,opt}^+$ (j = 1, 2, ..., k_1), $x_{j,opt}^-$ ($j = k_1 + 1$, $k_1 + 2$, ..., n_1), $y_{jh,opt}^+$ (j = 1, 2, ..., k_2), and $y_{jh,opt}^-$ ($j = k_1 + 1$, $k_1 + 2$, ..., n_2) can be obtained by solving submodel (5). Through integrating solutions of submodels (4) and (5), the interval solution for model (3) can be obtained.

3. Case Study

Changchun is the capital city of Jilin province, located in the northeast of China. The region covers an area of approximately 379.9 square kilometers, including five main districts. Each district is responsible for the collection of its own solid waste, whilst all the collected solid wastes are delivered to transfer stations and waste processing facilities (i.e., landfill and incinerator) via a number of routes. With population growth, economic development and urbanization, an increase in the city's MSW is verified. The results of waste-yield prediction study indicate that the city generates waste at an average rate of approximately 1.09 kg/capita/day, and a waste-generation rate of 1.30 kg/capita/day is predicted in 2020 (Cui et al., 2011). The city's solid waste management system includes source reduction, curbside recycling, material recovery, transfer station, incinerator and landfilling.

The wastes reduced and recycled are achieved from the following two aspects. Firstly, the wastes generated from residents are collected into the litter bins, and some useful wastes are picked by some trash pickers to sell on market to obtain benefit. This means the waste flows can be reduced and recycled by trash pickers before they are shipped to transfer stations and/or disposal facilities. Secondly, the transfer stations provide an inspection area where wastes are viewed and many useful materials are recycled; this can further reduce the amount of waste final disposed of at incinerator and landfill sites. Therefore, trash pickers and transfer stations provide two useful options for waste reduction and recycling. Due to the potential of the scarcity of land near urban centers and the growing public opposition from landfill sites, the city's incinerator was operated in 2004. Although the construction of waste incineration is very adventurous, the dioxin emission from incinerator can be effectively reduced for avoiding human health hazards through the advanced technology and strict control of furnace temperature.

A variety of complexities drive decision makers to seek effective and forward-looking solutions to address waste-management issues such as (i) what is the least-cost means for achieving the waste-diversion goal to lengthen landfill life, (ii) how select an optimal facility-expansion scheme with a cost-effective manner, and (iii) what is the optimal regional coordination of solid waste routing among districts, transfer stations and disposal facilities. Therefore, based on the methodology advanced in Section 2, an inexact two-stage waste management (ITWM) model can be formulated for supporting the city's long-term planning of MSW management as follows:

$$\min f^{\pm} = (1) + (2) + (3) + (4) + (5) + (6) + (7) + (8)$$

(1) Cost for regular waste collection and transportation:

$$\sum_{k=1}^{3} L_k \left(\sum_{i=1}^{3}\sum_{j=1}^{5} T_{ijk}^{\pm} TR_{ijk}^{\pm} + \sum_{j=1}^{5}\sum_{r=1}^{6} T_{jrk}^{\pm} TR_{jrk}^{\pm} + \sum_{i=1}^{3}\sum_{r=1}^{6} T_{irk}^{\pm} TR_{irk}^{\pm} \right) \quad (6a)$$

(2) Cost for regular waste disposal:

$$\begin{aligned} & L_1 \left(\sum_{j=1}^{5} T_{1j1}^{\pm} OP_{11}^{\pm} + \sum_{r=1}^{6} T_{1r1}^{\pm} OP_{11}^{\pm} \right) \\ & + \sum_{k=1}^{3} L_k \left[\sum_{j=1}^{5} \left(T_{3jk}^{\pm} + T_{2jk}^{\pm} FE^{\pm} \right) OP_{3k}^{\pm} \right. \\ & + \sum_{r=1}^{6} \left(T_{3rk}^{\pm} + T_{2rk}^{\pm} FE^{\pm} \right) OP_{3k}^{\pm} + \sum_{j=1}^{5} T_{2jk}^{\pm} OP_{2k}^{\pm} \\ & \left. + \sum_{r=1}^{6} T_{2rk}^{\pm} OP_{2k}^{\pm} + \sum_{j=1}^{5}\sum_{r=1}^{6} T_{jrk}^{\pm} OP_{rk}^{\pm} \right] \end{aligned} \quad (6b)$$

(3) Cost for regular residual disposal of incinerator and transfer stations:

$$\sum_{k=1}^{3} L_k \left(\sum_{j=1}^{5} T_{2jk}^{\pm} FE^{\pm} FT_k^{\pm} + \sum_{r=1}^{6} T_{2rk}^{\pm} FE^{\pm} FT_k^{\pm} \right) \quad (6c)$$

(4) Cost for excess waste collection and transportation:

$$\begin{aligned} & \sum_{k=1}^{3}\sum_{h=1}^{3} L_k p_{jh} \left(\sum_{i=1}^{3}\sum_{j=1}^{5} M_{ijkh}^{\pm} MR_{ijk}^{\pm} + \sum_{j=1}^{5}\sum_{r=1}^{6} M_{jrkh}^{\pm} MR_{jrk}^{\pm} \right. \\ & \left. + \sum_{i=1}^{3}\sum_{r=1}^{6} M_{irkh}^{\pm} MR_{irk}^{\pm} \right) \end{aligned} \quad (6d)$$

(5) Cost for excess waste disposal:

$$\begin{aligned} & \sum_{h=1}^{3} L_1 p_{jh} \left(\sum_{j=1}^{5} M_{1j1h}^{\pm} MP_{11}^{\pm} + \sum_{r=1}^{6} M_{1r1h}^{\pm} MP_{11}^{\pm} \right) \\ & + \sum_{k=1}^{3}\sum_{h=1}^{3} L_k p_{jh} \left[\sum_{j=1}^{5} \left(M_{3jkh}^{\pm} + M_{2jkh}^{\pm} FE^{\pm} \right) MP_{3k}^{\pm} \right. \\ & + \sum_{r=1}^{6} \left(M_{3rkh}^{\pm} + M_{2rkh}^{\pm} FE^{\pm} \right) MP_{3k}^{\pm} + \sum_{j=1}^{5} M_{2jkh}^{\pm} MP_{2k}^{\pm} \\ & \left. + \sum_{r=1}^{6} M_{2rkh}^{\pm} MP_{2k}^{\pm} + \sum_{j=1}^{5}\sum_{r=1}^{6} M_{jrkh}^{\pm} MP_{rk}^{\pm} \right] \end{aligned} \quad (6e)$$

Table 1. Shipping and Disposal Costs

	k = 1	k = 2	k = 3
Cost for treating regular waste ($/t)			
Landfill	[0.8, 1.0]	[1.2, 1.4]	[1.6, 1.8]
Incinerator	[15.0, 18.0]	[16.0, 19.0]	[17.0, 20.0]
Transfer station	[2.2, 2.6]	[2.3, 2.8]	[2.5, 2.9]
Cost for treating excess waste ($/t)			
Landfill	[1.2, 1.5]	[1.8, 2.1]	[2.4, 2.7]
Incinerator	[22.5, 27.0]	[24.0, 28.5]	[25.5, 30.0]
Transfer station	[3.3, 3.9]	[3.5, 4.2]	[3.7, 4.4]
Cost for shipping regular residue ($/t)	[14.0, 14.5]	[14.5, 15.0]	[15.0, 15.5]
Cost for shipping excess residue ($/t)	[21.0, 21.9]	[21.9, 22.5]	[22.5, 23.4]

(6) Cost for excess residual disposal of incinerator and transfer stations:

$$\sum_{k=1}^{3}\sum_{h=1}^{3}L_k p_{jh}\left(\sum_{j=1}^{5}M_{2jkh}^{\pm}FE^{\pm}MT_k^{\pm}+\sum_{r=1}^{6}M_{2rkh}^{\pm}FE^{\pm}MT_k^{\pm}\right) \quad (6f)$$

(7) Capital cost for facilities' expansions:

$$\sum_{m=1}^{3}\sum_{k=1}^{3}FLK_{3k}^{\pm}Y_{3mk}^{\pm}+\sum_{m=4}^{6}\sum_{k=1}^{3}FLK_{2k}^{\pm}Y_{2mk}^{\pm} \quad (6g)$$

(8) Revenue from selling energy and recycling materials:

$$\begin{aligned}&-\sum_{j=1}^{5}\sum_{k=1}^{3}\sum_{h=1}^{3}L_k\left(T_{2jk}^{\pm}RE_{2k}^{\pm}+p_{jh}M_{2jkh}^{\pm}ME_{2k}^{\pm}\right)\\&-\sum_{r=1}^{6}\sum_{k=1}^{3}\sum_{h=1}^{3}L_k\left(T_{2rk}^{\pm}RE_{2k}^{\pm}+p_{jh}M_{2rkh}^{\pm}ME_{2k}^{\pm}\right)\\&-\sum_{j=1}^{5}\sum_{r=1}^{6}\sum_{h=1}^{3}L_k\eta^{\pm}\left(T_{jrk}^{\pm}RE_{r}^{\pm}+p_{jh}M_{jrkh}^{\pm}ME_{r}^{\pm}\right)\end{aligned} \quad (6h)$$

The detailed nomenclatures for the variables and parameters are provided in the Appendix. The study time horizon is 15 years, which is further divided into three planning periods. The objective (i.e., formulae 6a ~ 6h) is to minimize the total cost with desired plans for facility expansion/development and waste-flow allocation over the planning horizon. The total cost will cover expenses for handling regular and excess waste flows, costs for developing and/or expanding facilities, and revenues from the waste-management facilities. Complexities in waste characteristics and geographical conditions may result in uncertainties in estimating the costs for waste collection, transportation, diversion and disposal of (Li and Huang, 2010). Table 1 provides costs for handling regular and excess wastes. The cost parameters present in terms of interval values. Costs for waste collection and transportation are estimated based on the existing conditions in the collection areas; the average container size, collection frequency, collection mode (automatic and manual), and collection time (per load). Operating costs could be functions related to energy price, labor fee, and management expenses. Penalty costs for the excess wastes (associated with infeasibilities for the relevant constraints) are significantly higher than the regular ones for the allowable wastes. The incomes from selling energy (generated by incinerator) and recycling materials (generated at transfer stations) are [11.8, 12.6] $/t (i.e., US$/tonne) and [17.8, 18.3] $/t, respectively.

The constraints define the interrelationships among the decision variables and the waste generation/management conditions. They include:

(i) Constraint for waste disposal demand:

$$\sum_{i=1}^{3}\left(T_{ijk}^{\pm}+M_{ijkh}^{\pm}\right)+\sum_{r=1}^{6}\left(T_{jrk}^{\pm}+M_{jrkh}^{\pm}\right)\geq W_{jkh}^{\pm},\ \forall j,\ k,\ h \quad (6i)$$

This constraint represents that, for each district in each period, the wastes to landfill, incinerator and transfer station must be not less than the amount of waste generation. This constraint also assumes that all solid wastes have to be shipped to a disposal site within a certain period after its generation, and no mass loss is incurred in the transportation process. Table 2 presents the waste generation rates (levels) and the associated occurrence probabilities. Since waste generation amounts are uncertain (presented by intervals and probabilities) and vary among different periods, a regular waste level for each district is predefined. If this level is not exceeded, it will result in a regular (normal) cost; however, if it is exceeded, the surplus waste

Table 2. Waste-Generation Rates and the Associated Probabilities

District	Level of waste generation	Probability	Waste generation amount (t/d)		
			Period 1	Period 2	Period 3
	low	0.2	[570, 610]	[593, 634]	[617, 660]
1	medium	0.6	[610, 650]	[634, 676]	[660, 703]
	high	0.2	[650, 690]	[676, 718]	[703, 746]
	low	0.2	[740, 792]	[770, 824]	[800, 857]
2	medium	0.6	[792, 844]	[824, 878]	[857, 913]
	high	0.2	[844, 896]	[878, 932]	[913, 969]
	low	0.2	[610, 653]	[634, 679]	[660, 706]
3	medium	0.6	[653, 696]	[679, 724]	[706, 753]
	high	0.2	[696, 739]	[724, 769]	[753, 799]
	low	0.2	[470, 503]	[499, 523]	[508, 544]
4	medium	0.6	[503, 536]	[523, 557]	[544, 580]
	high	0.2	[536, 569]	[557, 592]	[580, 615]
	low	0.2	[390, 417]	[406, 434]	[422, 451]
5	medium	0.6	[417, 444]	[434, 462]	[451, 480]
	high	0.2	[444, 471]	[462, 490]	[480, 509]

will be disposed of expensively, resulting in an excess cost (e.g., penalty that implies in terms of raised transportation and operation costs). Under such a situation, the total waste is the sum of both fixed allowable and probabilistic surplus flows.

(ii) Constraints of landfill and incinerator capacities:

$$\sum_{j=1}^{5} L_1\left(T_{1j1}^{\pm}+M_{1j1h}^{\pm}\right)+\sum_{r=1}^{6} L_1\left(T_{1r1}^{\pm}+M_{1r1h}^{\pm}\right)\le TL_1^{\pm},\ \forall h \qquad (6j)$$

$$\begin{aligned}&\sum_{j=1}^{5}\sum_{k=1}^{k'} L_k\left[\left(T_{3jk}^{\pm}+M_{3jkh}^{\pm}\right)+\left(T_{2jk}^{\pm}+M_{2jkh}^{\pm}\right)FE^{\pm}\right]\\ &+\sum_{r=1}^{6}\sum_{k=1}^{k'} L_k\left[\left(T_{3rk}^{\pm}+M_{3rkh}^{\pm}\right)+\left(T_{2rk}^{\pm}+M_{2rkh}^{\pm}\right)FE^{\pm}\right]\\ &\le\sum_{m=1}^{3}\sum_{k=1}^{k'} EC_{mk}^{\pm}Y_{3mk}^{\pm},\ \forall h,\ k'=1,2,3\end{aligned} \qquad (6k)$$

$$\begin{aligned}&\sum_{j=1}^{5}\left(T_{2jk}^{\pm}+M_{2jkh}^{\pm}\right)+\sum_{r=1}^{6}\left(T_{2rk}^{\pm}+M_{2rkh}^{\pm}\right)\\ &\le TE^{\pm}+\sum_{m=4}^{6} EC_{mk}^{\pm}Y_{2mk}^{\pm},\ \forall h\end{aligned} \qquad (6l)$$

The city relies mostly on landfill for disposing of its MSW. It also operates an incinerator to reduce the amounts of waste that ends up at the landfill. The incinerator generates residues of [20, 35] % on a mass basis of the incoming waste. These residues should all be hauled to landfill. The above constraints specify that wastes to landfill and incinerator must not exceed their existing and expanded capacities.

(iii) Constraints of transfer stations:

$$\sum_{j=1}^{5}\left(T_{jrk}^{\pm}+M_{jrkh}^{\pm}\right)\left(1-\eta^{\pm}\right)=\sum_{i=1}^{3}\left(T_{irk}^{\pm}+M_{irkh}^{\pm}\right),\ \forall r,\ k,\ h \qquad (6m)$$

$$\sum_{j=1}^{5}\left(T_{jrk}^{\pm}+M_{jrkh}^{\pm}\right)\le TT_r^{\pm},\ \forall r,\ k,\ h \qquad (6n)$$

In the study system, there are big six transfer stations that have a total capacity of 2,280 tonnes per day. Transfer stations have a number of advantages in waste transportation and treatment such as (i) decreasing vehicle traffic going to and from landfill and incinerator and thus reducing transportation cost, (ii) recycling various useful wastes, (iii) providing an inspection area where wastes can be viewed and unacceptable materials be removed, (iv) providing an effective control on dumping site at the landfill, (v) reducing the volume of wastes buried at the landfill, and (vi) raising the efficiency of incinerating wastes and reducing air pollutants. Besides, transfer stations are also more convenient for both MSW collectors and individual users since they are closer and easier to access than landfill and incinerator sites.

(iv) Constraints for waste diversion:

$$\sum_{j=1}^{5}\left(T_{1j1}^{\pm}+M_{1j1h}^{\pm}\right)+\sum_{r=1}^{6}\left(T_{1r1}^{\pm}+M_{1r1h}^{\pm}\right)\le LC_1^{\pm},\ \forall h \qquad (6p)$$

$$\begin{aligned}&\sum_{j=1}^{5}\left[\left(T_{3jk}^{\pm}+M_{3jkh}^{\pm}\right)+\left(T_{2jk}^{\pm}+M_{2jkh}^{\pm}\right)FE^{\pm}\right]\\ &+\sum_{r=1}^{6}\left[\left(T_{3rk}^{\pm}+M_{3rkh}^{\pm}\right)+\left(T_{2rk}^{\pm}+M_{2rkh}^{\pm}\right)FE^{\pm}\right]\le LC_3^{\pm},\ \forall k,\ h\end{aligned} \qquad (6q)$$

Two cases are examined based on different waste-management policies. In case 1, the city's waste-management practices are based on a cost-minimization policy over the planning horizon; in the current practice, landfill is the main waste-disposal facility; thus a high allowable waste-flow level is regulated to the landfill, while incinerator is an accessorial treatment facility. Case 2 is based on an aggressive policy for waste minimization and diversion, where 50% diversion of waste to landfill should be achieved at the end of planning horizon; this case will correspond to decisions with significant efforts for capacity development/expansion to reduce the waste shipped to the landfill and thus to mitigate the environmental pollution caused by the landfill.

Table 3. Capacity Expansion Options and the Related Costs

Expansion option	Capacity expanded	Capital for expansion (million $)		
		Period 1	Period 2	Period 3
Landfill (million tonne)				
Option 1	[5, 7]	[5.5, 7.7]	[4.6, 6.8]	[3.7, 5.9]
Option 2	[10, 14]	[11.0, 15.4]	[10.1, 14.5]	[9.2, 13.6]
Option 3	[15, 21]	[16.5, 23.1]	[15.6, 22.2]	[14.7, 21.3]
Incinerator (t/d)				
Option 1	[300, 320]	[12.8, 15.8]	[12.6, 15.6]	[12.4, 15.4]
Option 2	[500, 520]	[23.4, 26.4]	[22.5, 26.2]	[21.7, 26.0]
Option 3	[1000, 1040]	[46.8, 52.8]	[46.0, 52.4]	[45.1, 52.0]

(v) Constraints for facility-capacity expansions:

$$Y_{imk}^{\pm}\begin{cases} = 1, \text{ if expansion of facility } i \text{ is undertaken} \\ = 0, \text{ if otherwise} \end{cases} \quad (6r)$$

$$\sum_{k=1}^{3}\sum_{m=1}^{3} Y_{3mk}^{\pm} \le 1 \quad (6s)$$

$$\sum_{m=4}^{6} Y_{2mk}^{\pm} \le 1, \forall k \quad (6t)$$

With population increase and economic growth, the existing waste management facilities would encounter difficulties in meeting the requirements of handling rapidly increased waste amounts. Facility capacity expansions have to be considered. According to the city's MSW management policy, the landfill can be expanded once during the entire planning horizon. The incinerator can be expanded once in each period. For each facility expansion, three options are available, which are associated different expansion costs and capacity increments. Table 3 shows the capacity-expansion options and the relevant capital costs. In the ITWM model, all of decision variables must be non-negative. Solutions are generated through solving the two submodels (as provided in Section 2); binary-variable solutions represent the decisions of facility expansion, where several alternatives are generated; the continuous-variable solutions are related to decisions of waste-flow allocation.

4. Result and Discussion

The results indicate that, under cases 1 and 2, landfill would be expanded with a capacity of [15, 21] million tonnes at the start of period 1. However, the results indicate that the expansion schemes for the incinerator would be different from each other under the two cases. There are two options for the incinerator expansion, where the zero expansion option corre-

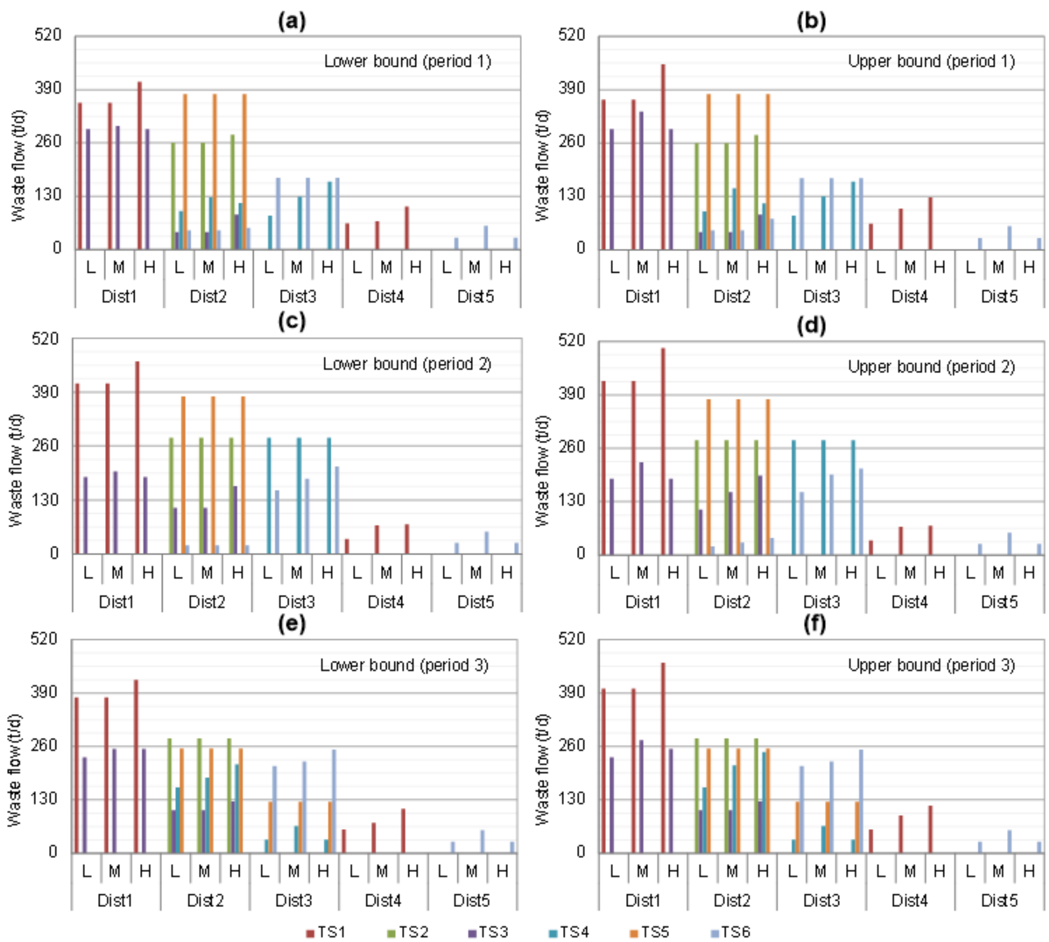

Figure 1. Wastes shipped to transfer stations under case 1. (Symbols of "L, M and H" denote "low, medium and high waste-generation levels", respectively; "Dist" and "TS" are abbreviations of "district" and "transfer station", respectively)

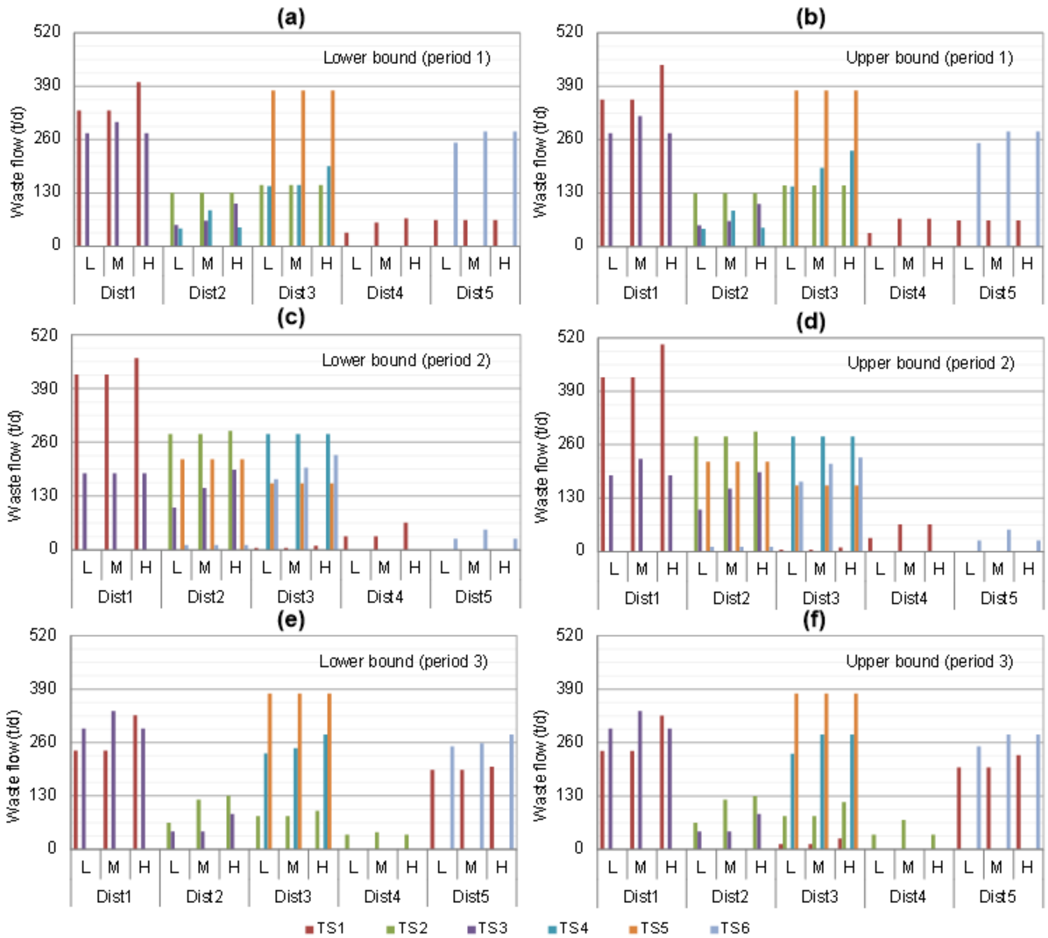

Figure 2. Wastes shipped to transfer stations under case 2.

sponds to f^- (under advantageous condition), and [300, 320] t/d (i.e., tonne/day) expansion option corresponds to f^+ (under demanding condition). Under case 1, when the decision scheme tends towards f^- under advantageous conditions, the existing facilities can treat the generated waste; when the scheme tends toward f^+ under more demanding conditions, it should be suitable to expand by [300, 320] t/d in period 3. The results indicate that, under case 1 due to no consideration of increasing waste diversion rate, the landfill would be the main waste disposal option while incinerator would only be expanded once. Under case 2, incinerator would be expanded by the increment of [500, 520] t/d in period 1 and followed by another increment of [500, 520] t/d in period 2. Case 2 is based on an aggressive policy for waste diversion (i.e., 50% diversion of waste to landfill is required to be achieved at the end of planning horizon), leading to more incineration capacities to reduce waste shipped to landfill in future.

Figures 1 and 2 present the results of wastes from five districts to six transfer stations under the two cases. Results indicate that wastes to transfer stations would fluctuate along with time and waste-generation level. Under case 1, district 1 would ship all of its waste to transfer stations 1 and 3; for district 2, transfer stations 2, 3, and 5 would be the constant choice for its waste first treatment and while transfer stations 4 and 6 would play different roles in different periods; district 2 is far from facilities than districts 3, 4 and 5, leading to more wastes being shipped to facilities via transfer stations; transfer stations 4 and 6 would be the main choices for district 3; for districts 4 and 5, only one transfer station to pick up their wastes. Under case 2, for district 2, transfer station 5 would not be the constant choice for its waste rough handling; district 2 would ship less waste to transfer stations, and more wastes would be shipped to incinerator (as compared to case 1); for district 3, transfer stations 4 and 5 would be the main choice for disposal of its waste (instead of transfer station 6); district 4 would ship its wastes to transfer station 1 in periods 1 and 2 and to transfer station 2 in period 3; for district 5, transfer station 1 would be the new choice for its waste preliminary disposal in periods 1 and 3.

Figures 3 and 4 show the solutions of wastes from districts and transfer stations shipped to the landfill under the two cases. Generally, different policies for waste management would result in varied waste-allocation patterns. For example, under case 1 (in period 1), the wastes from district 3 directly shipped to the landfill would be [393, 448] t/d under a low waste-genera-

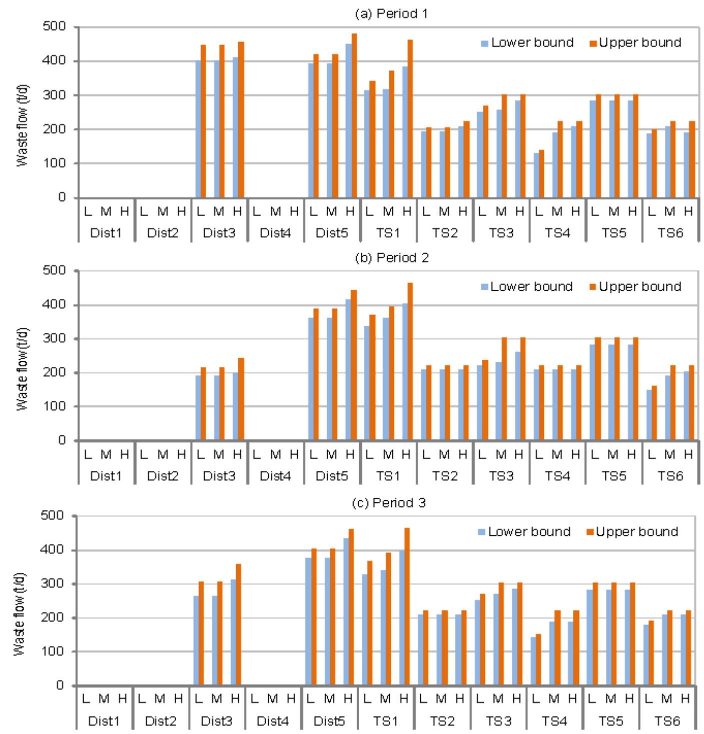

Figure 3. Wastes shipped to landfill (case 1).

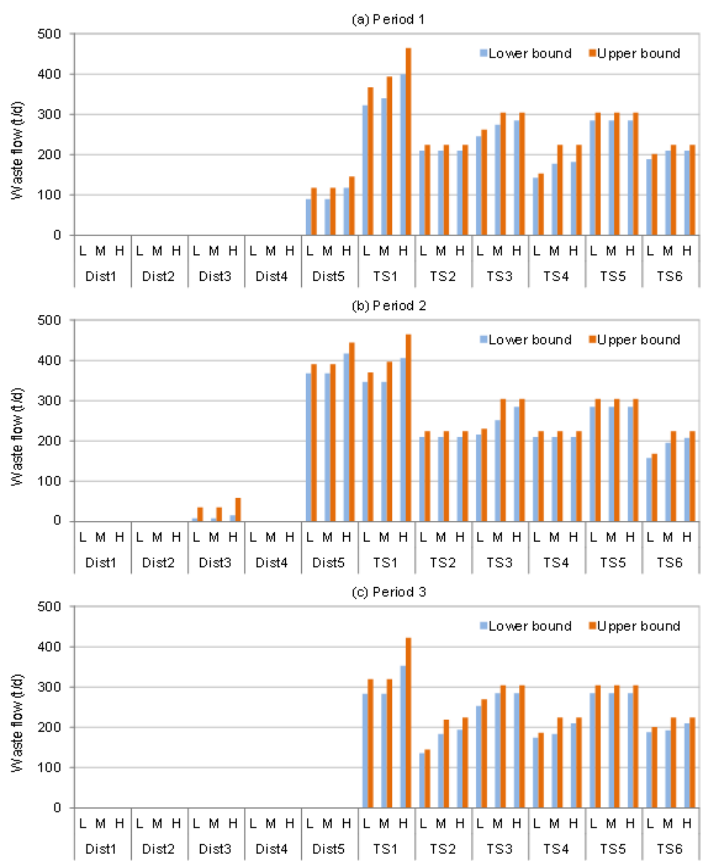

Figure 4. Wastes shipped to landfill (case 2).

tion level (p = 0.2), [393, 448] t/d under a medium waste-generation level (p = 0.6), and [451, 458] t/d under a high waste-generation level; in comparison, no waste would be shipped directly from district 3 to landfill under case 2. Under case 1 (in period 1), the wastes from transfer station 1 to landfill would be [316, 344] t/d (low), [320, 373] t/d (medium), and [385, 464] t/d (high); under case 2, the wastes would be [322, 367] t/d (low), [340, 394] t/d (medium), and [399, 464] t/d (high). The solutions present as interval and probabilistic forms, demonstrating that the related decisions are sensitive to the uncertain modeling inputs.

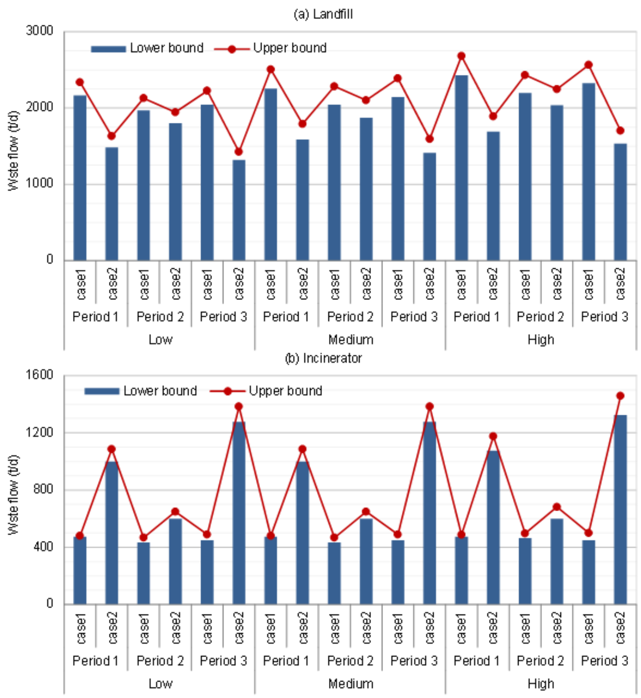

Figure 5. Wastes disposed of at landfill and incinerator.

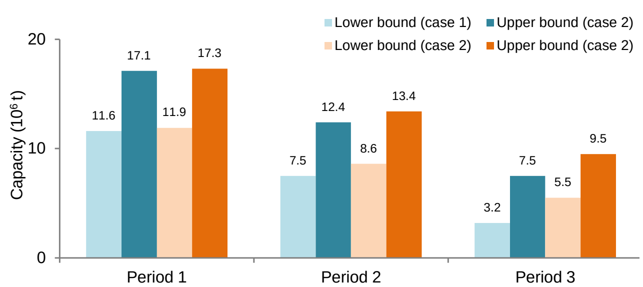

Figure 6. Remaining capacity of landfill (at the end of each period).

Figure 5 summarizes the total wastes disposed of at landfill and incinerator over the planning horizon. Generally, under case 2, wastes disposed of at landfill would be largely reduced due to the waste diversion policy. The waste-allocation patterns (including regular and excess wastes) would vary dynamically due to different levels of waste generation. For example, under case 1, when waste-generation rates are all low in three periods, there would be [11.3, 12.2] × 10^6 tonne of wastes disposed of at landfill; in comparison, when waste-generation rates are all high in three periods, there would be [12.7, 14.0] × 10^6 tonne of wastes handled at landfill; under case 2, the amounts of waste allocated to landfill would decrease to [8.4, 9.1] × 10^6 tonne (low) and [9.6, 10.7] × 10^6 tonne (high). On the contrary, the wastes treated at incinerator would increase under case 2. For instance, when waste-generation levels are low over the planning horizon, wastes treated at incinerator would be [2478.4, 2620.7] × 10^3 tonne (case 1) and [5246.9, 5690.4] × 10^3 tonne (case 2); when waste-generation rates are high over the planning horizon, the wastes treated at incinerator would be [2533.1, 2708.3] × 10^3 tonne (case 1) and [5476.8, 6049.9] × 10^3 tonne (case 2). Figure 6 provides the results of landfill-capacity consumption under the two cases. Case 1 would correspond to higher consumption rate of landfill capacity; the expected mean value for remaining landfill capacity would increase from [3.2, 7.5] × 10^6 tonne (case 1) to [5.5, 9.5] × 10^6 tonne (case 2).

Different policies for waste management are associated with different cost levels, as shown in Figure 7. Under case 1, the total cost is $[121.1, 271.9] million (i.e., million US dollar), which includes expenses for handling fixed regular and probabilistic excess flows as well as expanding/developing landfill and incinerator. The capital for facility expansion is $[16.5, 38.5] million, including $[16.5, 23.1] million for landfill expansion and $[0, 15.4] million for incinerator expansion. Besides, the cost for disposing/diverting regular wastes is $[100.0, 219.4] million, and the penalty for disposal of excess wastes is $[4.6, 14.0] million; the cost for waste landfilling is $[31.2, 42.3] million while the cost for waste incinerating is $[29.2, 66.8] million. The total cost is $[163.5, 315.8] million under case 2, increased by $[42.4, 43.9] million compared to that under case 1. The capital for facility expansion is $[62.4, 75.7] million, including $[16.5, 23.1] million for landfill expansion and $[45.9, 52.6] million for incinerator expansion. Besides, under case 2, the costs for disposing/diverting regular and excess wastes are $[96.1, 225.5] million and $[5.0, 14.6] million, respectively; the costs for waste landfilling and incinerating are $[27.2, 37.3] million and $[133.6, 165.2] million, respectively.

In general, case 2 has a higher system cost (total cost) than case 1 due to the following facts: (i) the diversion rate under case 2 is significantly higher than that under case 1; (ii) the cost for waste diversion (to incinerator) is much higher than that for waste disposal of at landfill; (iii) the capital cost (for facility expansion) under case 2 is significantly higher than that under case 1, since the incinerator will be expanded twice under case 2. Although case 1 has a lower system cost than case 2, issues of land resources consumption and groundwater contamination may imply higher environmental penalties than the savings obtained under case 1. Thus, the traditional aim of the local waste managers, i.e., to provide a low-cost waste removal service for residents through operating mainly a landfill, is being required to alter. Therefore, from a long-term planning point of view, case 2 could be much better than case 1 for supporting long-

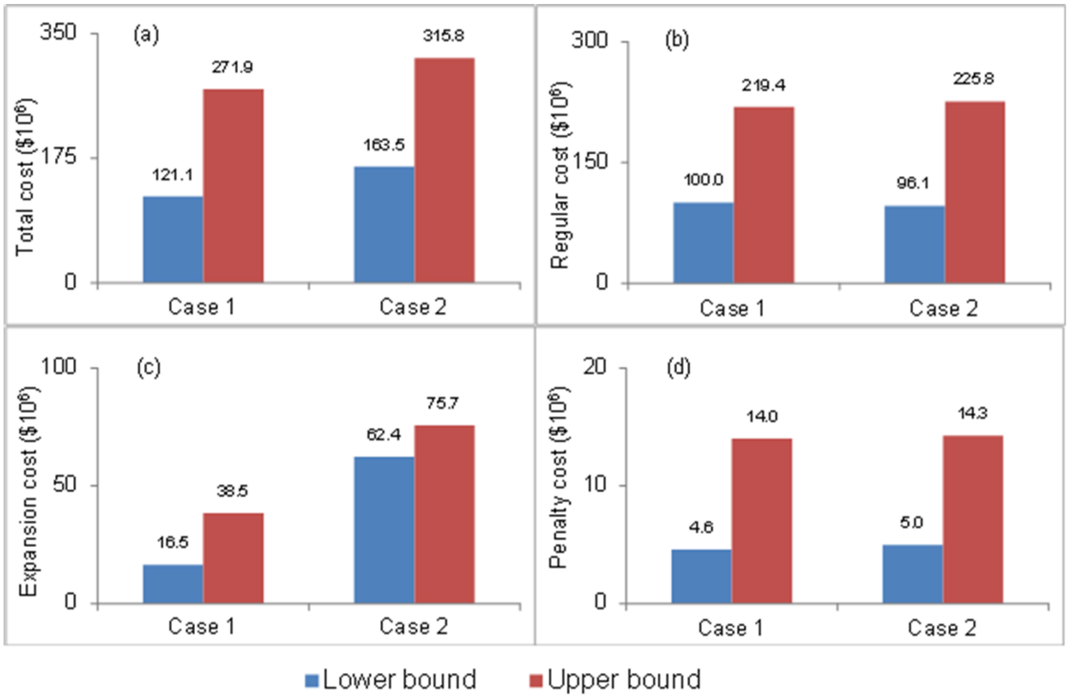

Figure 7. Costs under different waste management policies.

term planning of the city's waste management.

Summarily, the results indicate that the most wastes would be disposed of at landfill due to its relatively low operation cost and low capital for facility development/expansion. However, since the landfill can generate leachate (with a high concentration of organic matter, nutrients, toxic chemicals, and heavy metals) and emit harmful and greenhouse-effect gases (such as ammonia, hydrogen sulfide, nitrous oxide, and methane) to heavily pollute the environment, they usually require 30 years or longer to reach biological stability (Baddi et al., 2013). This can bring about high cost for mitigating its negative environmental impacts (i.e., environmental impacts mean those impacts that have a negative or deleterious effect on air, land or water quality) posed by such sites and their pollutant emissions (Li et al., 2015). Besides, for the city, the serious scarcity of land near urban centers would lead to waste disposed of at landfill more and more noneconomic (i.e., high cost for acquiring land resources). Therefore, issues of land resources consumption, surface water/groundwater contamination, and greenhouse gas (GHG) effect may imply higher environmental penalties than the savings obtained from waste treated by other options. The results also indicate that the city has to expand the incinerator to treat its more and more MSW flows over the planning horizon. However, waste incineration can also generate considerable pollutant emissions (e.g., acid gases, metals and various organic compounds) that can present potential human health hazards. Emissions from incinerator 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; Cheng et al., 2017). Therefore, from a long-term planning point view, policies under an integrated consideration of economic efficiency and environmental effect are desired for managing the solid waste.

5. Conclusions

In this study, an inexact two-stage waste management (ITWM) model has been developed for supporting the long-term planning of waste management in Changchun, China. The ITWM model incorporates approaches of interval-parameter programming (IPP) and two-stage stochastic programming (TSP) within an integer programming framework. It can help tackle the dynamic, interactive and uncertain characteristics of the municipal solid waste (MSW) management system. Three important issues can be addressed by the ITWM model such as (i) how to effectively ship waste to each treatment facility to minimize the system cost, (ii) how to reflect inexact and dynamic changing situation for landfill facility expansion, and (iii) how to analyze penalties under different waste management policies, which are associated with different economic penalties when the pre-defined policy goals are violated. The modeling results are valuable for helping local government more intuitive to know some basic situation under each policy, such as facility-expansion scheme, waste-flow allocation, waste-flow routing, as well as economic implementation. In a sense, the solutions obtained by the ITWM model can be used to generate decisions for supporting long-term planning of

MSW management activities, and thus help managers to identify desired MSW policies in association with cost minimization under uncertainty.

Two cases based on different waste management policies are examined. The results can reflect waste-flow routing under a relatively low diversion rate, when its waste management practices continue to be that the landfill is the main treatment facility over the planning horizon. However, a high waste minimization and diversion rate can be achieved if the city's policy is based on an aggressive capacity-expansion plan for incinerator. Although this policy could bring a high system cost, it can reduce the potential risk for the secondary pollution caused by the landfill. In a long-term perspective, incinerator operating cost will be reduced with the improvement of treatment technology, while environmental penalties and land-resource values could be increased with economic development and population growth. In fact, waste minimization and diversion can be achieved not only by incinerator, but also by composting and other facilities. However, composting facility is difficult to operate in the study city, because the northern cold weather limits the promotion of composting technology. Furthermore, waste sorting collection and selection rate is relatively low in the city. From a long-term planning point view, the results suggest that utilization of source-separated collection is one of the key steps in the city's future integrated MSW management. Source separated collection begins at the sources of MSW and involves the whole process of collection, transportation, disposal and recycling, which enables waste minimization, resource utilization, and hazardous waste disposal of. This also requires the local government to establish standards and regulations for the source separated collection. Besides, all MSW flows should be hauled to transfer stations to be pre-treated when they disposed at landfill and incinerator. A comprehensive MSW management scheme under an integrated consideration of economic efficiency and environmental effect can be achieved.

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