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Greenhouse gas emissions control in integrated municipal solid waste management through mixed integer bilevel decision-making

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ABSTRACT

Recent studies indicated that municipal solid waste (MSW) is a major contributor to global warming due to extensive emissions of greenhouse gases (GHGs). However, most of them focused on investigating impacts of MSW on GHG emission amounts. This study presents two mixed integer bilevel decision-making models for integrated municipal solid waste management and GHG emissions control: MGU-MCL and MCU-MGL. The MGU-MCL model represents a top-down decision process, with the environmental sectors at the national level dominating the upper-level objective and the waste management sectors at the municipal level providing the lower-level objective. The MCU-MGL model implies a bottom-up decision process where municipality plays a leading role. Results from the models indicate that: the top-down decisions would reduce metric tonne carbon emissions (MTCEs) by about 59% yet increase about 8% of the total management cost; the bottom-up decisions would reduce MTCE emissions by about 13% but increase the total management cost very slightly; on-site monitoring and downscaled laboratory experiments are still required for reducing uncertainty in GHG emission rate from the landfill facility.

1. Introduction

Recent studies indicated that municipal solid waste (MSW) has been an important contributor to greenhouse gas (GHG) emissions [1–12]. Carbon dioxide, methane and nitrous oxide emitted in MSW transportation and operation processes were considered the principal components contributing to global warming. Among various waste treatment and disposal processes, landfilling is the largest anthropogenic sources of methane gas. In 2004 the methane emission in the United States was estimated to be 140.9 teragrams of carbon dioxide equivalent, accounting for approximately 25% of the United States' annual methane emissions [12]. Therefore integrated MSW management has received much attention to not only handle the growing amount of MSW but also mitigate GHG emissions.

Many efforts have been made for investigating the relationships between MSW management and GHG emissions and exploring potential waste management polices contributable for GHG emissions reduction. For example, Thorneloe et al. [4] used a life cycle methodology to track changes in GHG emissions during the past 25 years from the management of MSW in the United States. Results showed that GHG emissions were 36 million metric tonnes carbon equivalent (MMTCE) in 1974 but decreased to 8 MMTCE in 1997 through integrated MSW management; however, if the MSW had not been effectively managed since 1974, GHG emissions would be increased to about 60 MMTCE. This revealed that integrated management of MSW would be helpful in considerably mitigating GHG emissions. A report from USEPA [12] showed that integrated solid waste management could help reduce GHGs by affecting: energy consumption in collection, transportation, treatment and disposal processes; nonenergy-related manufacturing emissions; methane emissions from landfills; carbon dioxide and nitrous oxide emissions from waste combustion; natural or manmade processes for carbon sequestration.

Lu et al. [13] presented a single-objective programming model to investigate the potential of GHG emissions mitigation through integrated MSW management. In the model, linear assumptions were provided for the relationships between GHG emissions and the amounts of waste in collection, transportation, and disposal/treatment processes. Another assumption was the negligence of temporal and spatial variations of GHG emissions during the planning horizon. The model was applied to a hypothetical case where three municipalities, two waste-to-energy facilities and one landfill were included. The waste generation rates in the municipalities were assumed to range between 200 and 450 tonnes per day. Results from the case study showed that over 4 million tonnes of GHG emissions would be reduced over a 15-year planning horizon. This provided evidence that integrated MSW management could

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be beneficial to GHG emissions mitigation; however, more efforts would be needed to demonstrate its potential in real-world cases.

Despite the abovementioned efforts, many questions have not yet been resolved like "How to meet the goals of both waste diversion and GHG-emissions reduction?"; "What is the most cost-effective way to manage the (1) delivery of MSW to facilities and (2) timing, sizing and siting for facility expansion (or development)"; and "how many tonnes of emitted GHGs can be avoided through integrated MSW management?". These questions can be answered by the use of decision-making methods with factors like waste flow and facility expansion/development being represented as decision variables, taking GHG-emission factors into account. Another major concern associated with these problems is raised by decision makers at different levels (e.g., waste management sectors at the municipal level and environmental sectors at the national level), who often have inconsistent decision goals. For example, the waste management sectors are interested in minimization of total management cost, while the environmental sectors may focus much on maximization of GHG emissions reduction. It is thus desired that a suitable approach be used to facilitate identifying waste management policies capable of comprehensively attaining the goals from different decision makers.

Nevertheless, neither single-objective nor single-level programs can address the above issues. Multi-objective programs can hardly reflect the dominant–subordinate relationships between objectives at the leader and follower levels. Recently, bilevel decision-making has received much attention, due to its capability of representing a special case with non-compromised decision makers at two different levels; this is entirely different from multi-objective decision-making which requires a compromise among various objectives (raised by the same decision makers). In the decision-making process, the lower-level decision must follow the upper-level one, which should in turn satisfy the lower-level one. Based on it, MSW management policies can be identified by establishing two non-compromised objectives (e.g., management cost minimization and GHG emissions control) which represent the requirements of national and municipal levels, respectively.

Therefore, this study aims to propose a bilevel decision-making approach to supporting identification of policies for integrated MSW management and GHG emissions control (GHG emissions control means mitigation of GHG emissions through integrated MSW management). The approach is expected to address both concerns of economic cost as compulsory at the municipal level and environmental benefit as required at the national level. The city of Regina in Canada is selected as the case study to illustrate the performance of the approach. Moreover, solutions obtained through the bilevel and conventional single-level approaches are compared to examine the pros and cons of the decisions. In consideration of the uncertainty in GHG emission rate, sensitivity analysis is also conducted to investigate its impact on the decisions identified through bilevel decision making.

2. Methodology

2.1. Site overview

The city of Regina, the capital of the province of Saskatchewan, has an area of 118.4 km^2. It is located in south-central Saskatchewan, Canada, and the north of the borders with Montana and North Dakota, USA. The city has a population of approximately 187,441, generating about 69,000 tonnes of residential waste annually [14,15]. The current MSW management system in the city comprises garbage transportation trucks, a landfilling, a centralized composting, and a set of recycling facilities. With the growth of waste generation rates, the city initiates a serious of waste diversion programs, mainly including development of two new landfills in the north and south areas, and expansion of the existing landfilling, composting and recycling facilities.

The existing landfilling site, located in the northeast part of the city, is the only available waste disposal facility in Regina. Currently, the capacity of the site is 60 ha, among which 28.5 ha is reserved for residential waste disposal while the remaining is for industrial, commercial, institutional and rural wastes. The landfill is estimated to be able to serve till 2011 or 2012 [14,15], thus generating a requirement of developing new landfills before it is filled. The existing centralized composting facility is operating to contain part of MSW for prolonging the life of the landfill. The available capacity for treating MSW is 270 tonnes per week. The recycling system includes a big blue bin paper recycling, a used oil recycling, a paint-recycled, a white goods recycling, and a backyard composting program [15]. Through these programs, the capacity reserved for treating the MSW is approximately 140 tonnes per week.

In April 1995, the city of Regina established the Regina Round Table on Solid Waste Management to obtain community input on a long-range MSW management plan. An integrated MSW management decision was desired to be made based on discussion from a committee composed of mayors, county executives, city and county councils, waste managers, stakeholders, and environmental engineers. In the discussion, the committee showed strong interest in mitigation of local GHG emissions (i.e., GHG emitted within the urban area) through integrated MSW management. Development of the most cost-effective MSW management policies to attain this objective was thus suggested by the committee members.

To comprehensively account for the goals of decision makers from different sectors, a bilevel decision-making approach was proposed for supporting GHG emissions control and MSW management for the city. The management system included five major components: waste generation, waste collection and transportation, waste treatment and disposal, waste facility expansion, and GHG emissions control. In the waste generation component, weekly waste generation rate was estimated according to local populations. While the waste generation rate would vary from week to week (and even day to day), it was assumed to take an average within each planning period. For waste collection and transportation, the purpose was to collect the waste from the generation sources and then send to the existing landfill, composting or recycling facility. In the waste treatment and disposal component, the waste was treated or disposed of through landfilling, composting, or recycling. In the component of GHG emissions control, specific GHG emission control techniques were not considered due to the lack of implementation of such techniques in the existing facilities.

2.2. Modeling formulation

The planning horizon for the waste management was determined to be 30 years (2011–2040), which was classified into six periods with each one having a time interval of 5 years. Over the horizon, one landfill, one composting and one recycling facilities have been available to serve the waste disposal needs. Table S1 of the Supplementary Material shows the estimated weekly waste generation rate of the city. The collection and transportation cost, operating cost are provided in Tables S2 to S3 of the Supplementary Material. The composting and recycling facilities would generate approximate residues of 10% and 8% (on a mass basis) of the incoming waste stream, respectively. In terms of the requirement of the decision makers, onsite disposal of such residues could be allowable, avoiding the shipment of residues to the landfill (Table S4 of the Supplementary Material shows the operating cost for the onsite disposal). However, revenues can be generated from the composting and recycling facilities which would in part offset the increased operation cost. Table S5 of the Supplementary Material exhibits the revenues from the two facilities. Since the capacities of facilities could be insufficient to deal with the incoming waste flow, expansion for existing facilities and development for one new landfill can be allowable.

According to the region's environmental policy, the exiting (or new) landfill can be expanded (or developed) only once during the entire planning horizon; the capacity increments for the existing, the intended north and south sites are 28.5, 42.8, and 42.8 ha, respectively. In comparison, the composting and recycling facilities can be expanded no more than once in each period. Three options would be available for the composting and recycling facilities, respectively, with each of them corresponding to a specific capacity increment. Tables S6 to S8 of the Supplementary Material present the expansion costs and capacity increments for the landfilling, composting and recycling facilities. Table S9 of the Supplementary Material exhibits the GHG emission rates.

The problem under consideration was formulated as the following MGU-MCL model, suggesting that minimization of GHG emissions occur at the upper level while minimization of total management cost do at the lower level:

[Upper-level objective:]

$$\min_{\forall X_{it}} \mathrm{TMTCE} = \sum_{i=1}^{5}\sum_{t=1}^{6} L_t \cdot X_{it} \cdot \mathrm{MTCE}_{it} \tag{1a}$$

s.t.:

[Upper-level constraints:]

- ○ Binary constraints:

$$Y_{it} = \begin{cases} 1 & \text{if expansion or development is required} \\ 0 & \text{if not required} \end{cases} \quad (i=1,2,3;\quad t=1,2,3,4,5,6) \tag{1b}$$

- ○ Expansion/development constraint for the landfills (i.e., landfill expansion/development can only be performed once during the entire planning horizon):

$$\sum_{i=1}^{3}\sum_{t=1}^{6} Y_{it} \le 1 \tag{1c}$$

- ○ Expansion/development constraints for composting and recycling facilities (i.e., expansion/development can only be performed once in each time period):

$$Z_{imt} = \begin{cases} 1 & \text{if expansion or development is required} \\ 0 & \text{if not required} \end{cases} \quad (i=4,5;\quad m=1,2,3;\quad t=1,2,3,4,5,6) \tag{1d}$$

$$\sum_{m=1}^{3} Z_{imt} \le 1 (i=4,5;\quad t=1,2,3,4,5,6) \tag{1e}$$

where X_{it} solves

[Lower-level objective:]

$$\begin{aligned} \min_{\forall Y_{it}, Z_{imt}} \mathrm{TCOST} = & \sum_{i=1}^{5}\sum_{t=1}^{6} L_t \cdot X_{it} \cdot (\alpha_t \cdot \mathrm{CCT}_{it} + \alpha_t \cdot \mathrm{OP}_{it}) \\ & + \sum_{i=4}^{5}\sum_{t=1}^{6} L_t \cdot X_{it} \cdot \mathrm{RES}_{it} \cdot (\alpha_t \cdot \mathrm{OPR}_{it}) \\ & - \sum_{i=4}^{5}\sum_{t=1}^{6} L_t \cdot X_{it} \cdot (\alpha_t \cdot \mathrm{REV}_{it}) + \sum_{i=1}^{3}\sum_{t=1}^{6} Y_{it} \\ & \cdot (\beta_t \cdot \mathrm{FLC}_{it}) + \sum_{i=4}^{5}\sum_{m=1}^{3}\sum_{t=1}^{6} Z_{imt} \cdot (\beta_t \cdot \mathrm{FTC}_{imt}) \end{aligned} \tag{1f}$$

s.t.

[Lower level constraints:]

- ○ Landfill capacity constraints:

$$\sum_{t'=1}^{t} L_t x_{it'} \le LC_i + \Delta LC_i \cdot Y_{it'} (i=1,2,3;\quad t=1,2,3,4,5,6) \tag{1g}$$

- ○ Composting capacity constraints:

$$\begin{aligned} x_{4t} \le \mathrm{CC} + & \sum_{m=1}^{3}\sum_{t'=1}^{t} \Delta \mathrm{CC}_{mt'} \\ & \cdot Z_{4mt'} (m=1,2,3;\quad t=1,2,3,4,5,6) \end{aligned} \tag{1h}$$

- ○ Recycling capacity constraints:

$$\begin{aligned} x_{5t} \le \mathrm{CC} + & \sum_{m=1}^{3}\sum_{t'=1}^{t} \Delta \mathrm{RC}_{mt'} \\ & \cdot Z_{5mt'} \quad (m=1,2,3;\quad t=1,2,3,4,5,6) \end{aligned} \tag{1i}$$

- ○ Waste disposal demand constraints:

$$\sum_{i=1}^{5} x_{it} \ge \mathrm{WWG}_t (t=1,2,3,4,5,6) \tag{1j}$$

$$\sum_{i=1}^{3} x_{it} \ge \mathrm{WWG}_t \cdot \eta \quad (t=1,2,3,4,5,6) \tag{1k}$$

$$x_{5t} \ge \mathrm{WWG}_t \cdot \xi \quad (t=1,2,3,4,5,6) \tag{1l}$$

- ○ Nonnegative constraints:

$$x_{it} \ge 0 \quad (i=1,2,3;\quad t=1,2,3,4,5,6) \tag{1m}$$

where TMTCE = total emission of metric tonne carbon equivalent (MTCE), the objective to be minimized at the upper level; L_t = length of time period (week); X_{it} = solid waste flow to the facility i in period k ($/tonne), the decision variables at the lower level; MTCE_{it} = unit emission of metric tonne carbon equivalent in facility i (MTCE/tonne); Y_{it} = binary variable for landfill expansion/development at the start of period t (i = 1, 2, 3), the decision variables at the upper level; Z_{imt} = binary variable for expansion of composting and recycling facilities with option m at the start of period t (i = 4, 5), the decision variables at the upper level; *TCOST* = present value of the total management cost ($), the objective to be minimized at the lower level; α_t = discount factor for the costs and revenues in period t, where $\alpha_t = 1/[1-(i-g)]^t$ with i and g being interest and inflation rates, respectively; β_t is discount factor for facility expansion cost in period t; CCT_{it} = cost for waste collection and transportation for facility i in period t ($/tonne); OP_{it} = operating cost for facility i in period t ($/tonne); RES_{it} = residue generation rate in composting and recycling facilities in period t (%) (i = 4, 5); OPR_{it} = operating cost for disposing of residues in period t ($/tonne) ($i$ = 4, 5); REV_{it} = revenue generated from composting and recycling facilities in period t ($/tonne) ($i$ = 4, 5); FLC_{it} = capacity expansion cost for landfill i in period t ($) ($i$ = 1, 2, 3); FTC_{imt} = capacity expansion cost for composting/recycling facility i with option m in period t ($) ($i$ = 4, 5); LC_i = available capacity of the landfill (ha) (i = 1, 2, 3); ΔLC_i = expanded/developed capacity of the landfill (tonne) ($i = 1, 2, 3$); CC = available capacity of the composting facility (tonne/week) ($i = 4$); $\Delta CC_{mt'}$ = expanded capacity of the composting facility with option m in period t' (tonne/week); RC = available capacity of the composting facility (tonne/week) ($i = 4$); $\Delta RC_{mt'}$ = expanded capacity of the composting facility with option m in period t' (tonne/week); WWG_t = weekly waste generation rate in period t (tonne/week); η = ratio of MSW that should be sent to the landfill (%); ξ = ratio of MSW that should be sent to the recycling facility (%); i = index for facilities, where $i = 1, 2, 3, 4, 5$ indicates the indicates the existing landfilling, north landfilling, south landfilling, composting, and recycling facility, respectively; t = index for periods ($t = 1, 2, 3, 4, 5, 6$); t' = index for periods ($t' = 1, 2, 3, 4, 5, 6$); m = index for facility capacity expansion type ($m = 1, 2, 3$).

As shown in model (1), the objective of the upper level (also the national or leader level), TMTCE, can only be attained subject to the constraints at both the upper and lower levels, as well as the realization of the lower-level (also the municipal or follower level) objective; TMTCE can be estimated in terms of the previous findings that (1) the compounds can emit nitrous oxide (N_2O) and carbon dioxide (CO_2) from the composting process, methane (CH_4) from the landfilling process, and CO_2 from the transportation process [2]; (2) GHG emission amount can be estimated by the product of waste generation amount (by weight) and GHG emission rate [13,14]. The lower-level objective was introduced to minimize the total waste management cost, as calculated by the sum of costs for waste collection and transportation, waste diposal, existing facilities expansion, and new facilities development, deducted revenues from the composting and recycling facilities.

The constraints at the upper level included a set of binary, development and expansion restrictions. The lower level includes: (1) landfill capacity constraints: For the landfills, the total waste flow to each landfill should not exceed the sum of its total capacity of both new and existing landfills; (2) composting capacity constraints: the weekly waste flow to the composting facility should not exceed the sum of its weekly capacity; (3) recycling capacity constraints: the weekly waste flow to the recycling facility should not be higher than its weekly capacity; (4) waste disposal demand constraints: the total amount of the waste sent to the five facilities should not be less than the waste generation rate in each week; (5) landfill diversion constraints: as suggested by the decision makers, at least 30% of the waste should be sent to the landfill every week (such constraints aim to mitigate the workload of the composting and recycling facilities); (6) recycling diversion constraints: at least 12.5% of the waste should be recycled every week and (7) nonnegative constraints: the decision variables should be larger than or equal to zero.

The decision variables were classified into 2 categories, representing the decisions at the lower and upper levels, respectively. All the binary integer decision variables (Y and Z) were placed at the upper level to indicate whether the existing facility should be expanded or a new landfill should be established. The remaining continuous variables (X) indicated weekly waste flow from the city to the facility in each period. They were placed at the lower level since they were the major concern of waste managers. Located at this level, variables X should be optimized (say, X^*) at first under all possible realizations of Y and Z values (say, Y^0 and Z^0) to guarantee the minimization of total management cost. Subsequently the best decisions should be selected (at the upper level) from decision sets composed of all potential decision sets (X^*, Y^0 and Z^0).

Since this decision-making problem was multi-period, discount factors were introduced in each planning period to obtain the present value of the total management cost. For the present value of transportation and operation costs, an average discount factor was chosen for each time period. For the present value of facility development and expansion costs, it was assumed that development or expansion would be completed by the end of the previous period, if additional capacity was required at the beginning of a particular time period.

3. Results

3.1. Modeling solution

We also proposed an MCU-MGL model (Section S1 of the Supplementary Material) which is similar to the MGU-MCL except that the levels of the two objectives were switched. Note that while the objectives and constraints in the models are linear, they are nonlinear-programming (NP) hard problems as each of the decision variables at the upper level is nonlinearly associated with those at the lower level. Therefore it is desired that a solution algorithm be selected to solve the NP-hard problems. A number of algorithms can be used, including the Karush–Kuhn–Tucker (KKT), exact penalty function, and branch-and-bound algorithms. This study selected the KKT algorithm [16] as it does not (1) depend on the iterative computation to approximate the actual solutions and (2) need to check the convergence of the decision-making problem. This algorithm has thus been widely applied to many engineering problems. In terms of the algorithm, the bilevel decision-making problem can be transformed into its equivalent single-level problem by replacing the inner decision-making problem with a set of equations that define its KKT optimality conditions. Then this single-level problem can be solved by a global optimization solver like GAMS and Lingo. More details with regard to modeling description, solution method and parameters input to the models are shown in section S2 of the Supplementary Material.

Since the decision was made within the future 30 years, there was difficulty in comparing our theoretical values to practical ones. Therefore, two conventional single-level decision-making approaches were used (MCS and MGS, section S1 of the Supplementary Material) to compare the theoretical values achieved through the bilevel decision-making approaches to those achieved through conventional single-level schemes.

3.2. Waste diversion analysis

Results were obtained by solving the MCU-MGL and MGU-MCL models; moreover, they were compared to those from two single-level models (MCS and MGS). The description of the models is provided in Table 1 and section S1 of the Supplementary Material. Fig. 1(a) shows the optimized waste flow schemes obtained from the MGU-MCL model. It is indicated that most of the waste would be transported to the recycling facility in each period; the amount would be increased from 478 tonnes per week in period 1–948 tonnes per week in period 6. Over the entire planning horizon, the recycling facility would treat approximate 46.33% of the total waste. With the increase of waste generation, more and more waste would be delivered to the recycling facility due to its low GHG emissions. The north landfill would play the second important role in waste disposal. Nevertheless, the amount would be decreased from 809 tonnes per week in period 1–641 tonnes per week in period 4, and finally to zero. In comparison, the existing landfill would dispose of 15.11% of the waste, and the south landfill would not be used over the entire planning horizon. While the cost for collection, transportation and operation were low compared to recycling, they would not be preferred due to high expansion cost and GHG emissions. Composting would be the last choice compared to landfilling and recycling due to the uncompetitive treatment cost and the capacity of GHG emissions reduction; only 270 tonnes of waste would be suggested in each period, mainly for alleviating the workload of the landfilling and recycling facilities.

Table 1
Four models for results comparison.

Features	MGU-MCL	MCU-MGL	MCS	MGS
Number of levels	2	2	1	1
Objective of the upper level	Minimization of total GHG emissions	Minimization of total management cost	–	–
Objective of the lower level	Minimization of total management cost	Minimization of total GHG emissions	–	–
Objective of the single level	–	–	Minimization of total management cost	Minimization of total GHG emissions

Fig. 1(b)–(d) present the optimized waste flow schemes from the other three models. For the MCS results, composting would play the most important role in diverting waste; particularly in the last five periods; it would treat over 800 tonnes of waste per week. This shows that if GHG emissions were not considered, composting would be strongly recommended due to its rather low costs for collecting, shipping and treating waste. Most of the other part of waste would be shipped to the existing and north landfills. Different from the MGU-MCL scheme, the MCS model suggested dealing with only a small portion of waste (about 200 tonnes per week) by recycling due to its high collection, transportation and operation costs. Fig. 1(d) shows an environmentally-aggressive waste diversion scheme because its single target is to mitigate GHG emissions. Under this consideration, those facilities with less GHG emissions would be preferred (e.g., composting and recycling). Due to high GHG emission rate, landfilling would play a minor role in waste disposal. In comparison, the MCU-MGL solutions provided a compromised waste diversion scheme (Fig. 1b) as both of economic cost and environmental benefit were emphasized. Therefore, those facilities with low cost would be attached more importance (e.g., composting and landfilling). It was found that the MGU-MCL and MCU-MGL solutions provided much reasonable policies, since the two objectives (i.e., management cost minimization and GHG emissions control) were simultaneously considered. In comparison, the two single-objective models generated either too environmentally-aggressive (MGS, only focused on GHG emissions control) or economically-aggressive (MCS, only focused on management cost minimization) policies.

3.3. Facility expansion analysis

Facility expansion schemes were also determined by analyzing optimized binary decision variables (Table 2). The MGU-MCL solutions indicated that the north landfill should be developed at the beginning of the planning horizon (in period 1). Since the landfill was allowed to be expanded only once in the entire period, the capacity could not satisfy the increased requirements for waste disposal. Thus, the recycling facility would be expanded in periods 1, 2 and 5, with an incremental of 350, 350, and 140 tonnes of capacities available to be used. Expansion schemes were also compared using results from the other three models. The MGS model would require the composting and recycling facilities to be expanded in each period. This means that the majority of the waste would be sent to them for mitigating GHG emissions. In terms of the MCS model, the composting facility would be expanded only in periods 1 to 3; recycling would not be favorable, with only once of expansion being suggested in period 1 (the incremental is 140 tonnes/week). The MCU-MGL model also generated similar expansion schemes to the MCS model, suggesting that economic cost would be more emphasized than environmental benefit.

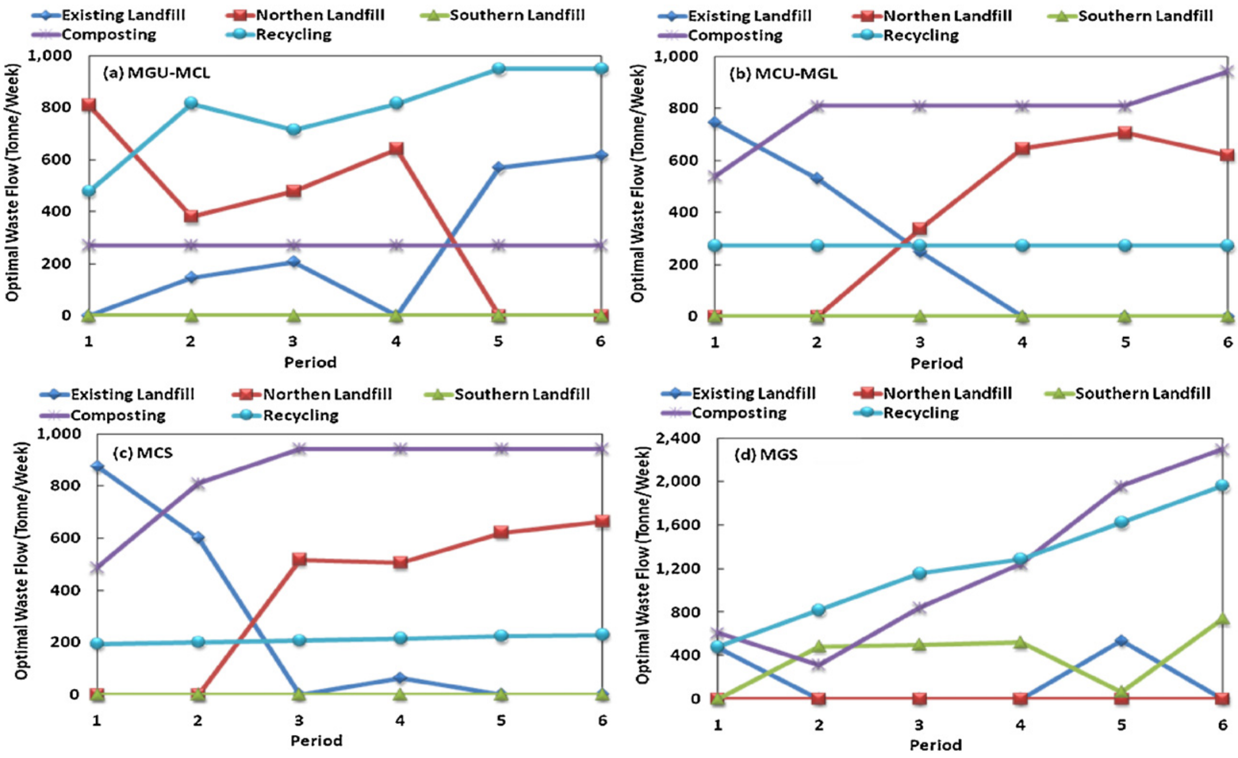

Fig. 1. Optimized waste flow to the facilities.

Table 2
Expansion schemes identified through the four models.

Model	Facility	Expansion periods	Expansion option	Available capacity after expansion
MGU-MCL	Landfill	1	Develop the north one	28.5 ha
	Recycling	1, 2	Expansion with option 3	350 tonnes
	Recycling	5	Expansion with option 1	140 tonnes
MCU-MGL	Landfill	2	Develop the north one	28.5 ha
	Composting	1, 2	Expansion with option 2	270 tonnes
	Composting	3	Expansion with option 1	132 tonnes
	Recycling	1	Expansion with option 1	140 tonnes
MCS	Landfill	3	Develop the north one	28.5 ha
	Composting	1, 2	Expansion with option 2	270 tonnes
	Composting	6	Expansion with option 1	132 tonnes
	Recycling	1	Expansion with option 1	140 tonnes
MGS	Landfill	2	Develop the south one	28.5 ha
	Composting	1–6	Expansion with option 3	338 tonnes
	Recycling	1, 2, 3, 5, 6	Expansion with option 3	350 tonnes
	Recycling	4	Expansion with option 1	140 tonnes

3.4. *Economic cost and environmental benefit analysis*

Fig. 2 shows the minimized total MTCE amount and the total management cost. It can be known that the MGU-MCL scheme would emit approximate 1.51×10^5 MTCE, about 59.13% lower than the emission under the MCS scheme. However, such mitigation would lead to an increase of 7.55% of the total management cost. The increased management cost may be acceptable due to high marginal cost, i.e., reducing each percent of GHG emission amount would correspond to an increase 0.13 percent of the total management cost in average. In comparison, the MCU-MGL scheme would emit approximate 3.21×10^5 MTCE (13.14% lower than the emission under the MCS scheme); it would slightly increase the total management cost by 0.74%. It seems that such a scheme would be of little help in GHG emissions control due to the low difference from the MCS scheme. The MGS scheme would contribute the highest GHG emissions reduction; it would reduce by 89.90% of MTCE compared to the MCS scheme. However, the total management cost would have to be doubled. This environmentally-aggressive scheme was not suggested due to lower the marginal cost than that achieved through the bilevel models; also the lack of considering economic cost in decision making could hardly be preferred by the decision makers.

3.5. *Sensitivity analysis*

GHG emission rate (GHGE) was mainly estimated in terms of the suggested values by USEPA [11,12] and the composition of the city's MSW [14,15]. However, intensive uncertainty may exist in GHGE due to the complex characteristics of MSW (e.g., waste composition), site conditions, and operating status. Sensitivity analysis was useful in observing variations of model solutions to those of model inputs. Therefore it was conducted to examine the sensitivity of the model solutions to the change of GHGE in the landfilling, composting and recycling processes. In the analysis, we assumed GHGE was changed by −40% to 40%, respectively. With the variation of GHGEs, the variation rate of the total MTCE and management cost (compared to the MCS solutions) were analyzed. It was conducted to investigate how much difference in economic cost and environmental benefit would occur between decisions through bilevel and single-level decision-making analyses approaches.

Results of sensitivity analysis for the MGU-MCL model are shown in Fig. 3(a) and (b), where the horizontal axis represents the variation rate of GHGEs from the landfill, composting and recycling facilities. In term of Fig. 3(a), the landfill emission rate would have a significant impact on optimized total MTCE, with each percent variation leading to about 2.5 percent of minimized total MTCE. This means that each increase of 1% landfill emission rate would lead to the growth of the total amount of GHG emissions by about 2.5%. Conversely, each percent reduction in the GHG emission rate from the landfill would reduce 2.5% of the total amount over the entire planning horizon. This reduction would be meaningful particularly where stringent GHG-emissions regulations should be implemented. In comparison, the change of recycling emission rate would have a moderate impact on total MTCE emissions, with the ratio of variation of minimize total MTCE to variation of GHG emission rate varying from −1.6 to −0.8. This implies that reduction of emission rate in the recycling process would also play a positive part in mitigating GHG emissions. Composting would have a minor impact on GHG emission rate, showing that new GHG collection technologies would not be prerequisite in the composting facility.

Fig. 3(b) shows that the total management cost is not sensitive to the variation of GHG emission rate, as any change of emission rate (within a range of −40 to 40%) does not lead to an 3% of the resulting variation in the minimized total cost. Fig. 3(c) and (d) presents the sensitivity analysis results from the MCU-MGL model, which shows that the model results are extremely insensitive to the variation of GHG emission rate.

In general, the sensitively analysis results revealed that the uncertainty in GHGE would not significantly change the optimized waste management policies identified through bilevel decision-making analysis. The only caution that should be taken is the variation of GHGE from the landfill, as demonstrated to have rather high impact on model solutions. To improve the reliability of decisions, much work would be undertaken to reduce the uncertainty in such factors as GHGE through onsite monitoring and uncertainty analysis. The complex characteristics (e.g., the composition) of MSW should be particularly considered when measuring GHGE.

4. Discussion and conclusions

This study presents two mixed integer bilevel decision-making models with two objectives that should be minimized sequentially: one is the total GHG emissions as required at the national level, and the other is the total management cost as required at the municipal level. The MGU-MCL model represents a top-down decision strategy, with the environmental sectors at the national level dominating the upper-level objective (leader's one) and the waste management sectors at the municipal level providing the lower-level objective (follower's one). Such a decision emphasizes the importance of GHG emissions control, but the environmental goal can only be guaranteed prior to the satisfaction of the follower's economic objective. The MCU-MGL model implies a bottom-up decision strategy where municipality plays the leading role;

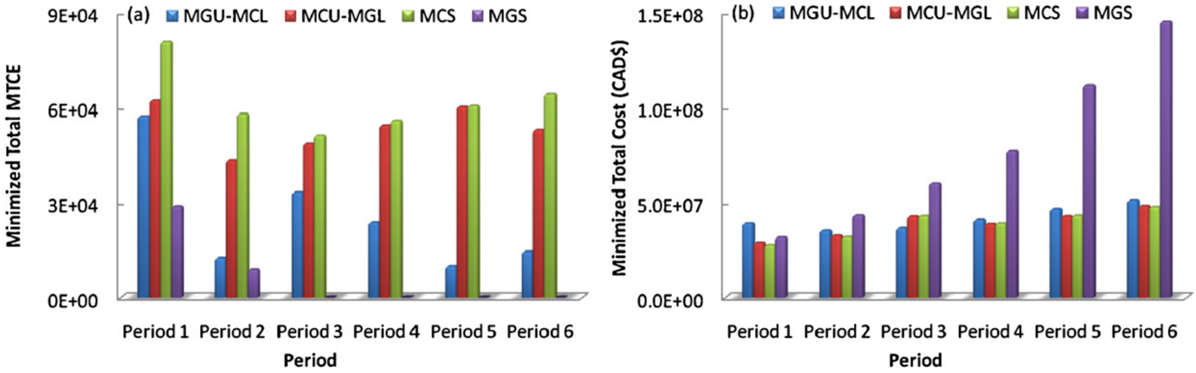

Fig. 2. Minimized total MTCE and total management cost.

similarly, the minimization of the economic objective can hardly be guaranteed unless the environmental goal can be realized.

This is the first attempt to treat both GHG emissions and waste management cost as the long-term MSW management goals established by different decision makers. Results from the bilevel decision-making can facilitate (a) identifying allocation schemes for waste flows, (b) timing, sizing, and siting for facility expansions, and (c) estimating minimized total management cost and GHG emissions during the entire planning horizon. While the decision-making was applied to the city of Regina, they could be extended to other environmental decision-making problems where GHG emission is strictly controlled and/or the environmental credit prices are high. The approach would be useful in addressing a special case with non-compromised (or non-cooperative) decision makers with dissimilar decision goals at various municipal, provincial, national and international levels.

The implicit in the model solutions included: the top-down decisions would reduce MTCE emissions by about 59% yet increase about 8% of the total management cost; the bottom-up decisions would reduce MTCE emissions by approximate 13% but increase the total management cost very slightly (by about 0.74%); this would be more attractive than the bottom-up and the MGS decisions because of the commensurate capacity in reducing MTCE emission amount and total management cost; while there was large uncertainty in GHGEs, they would not have a significant impact on the bilevel decisions; nonetheless, onsite monitoring and downscaled laboratory experiments would be conducted to observe GHG emission rate (GHGE) from the landfill, due to high sensitivity of model results to GHGE in the top-down decision-making strategy.

Multi-objective programs can hardly solve the problems with multiple decision makers. On the one hand, the multi-objective program assumes that the multiple objectives are located at the

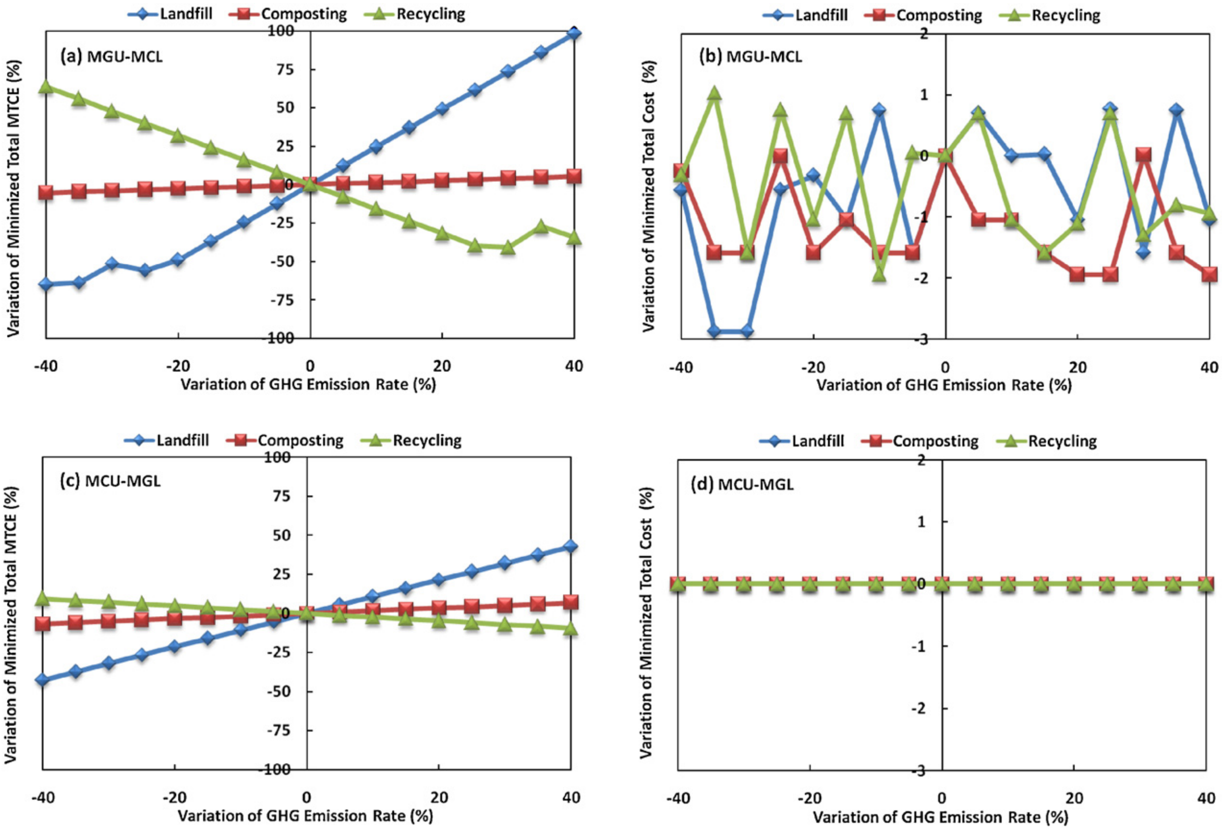

Fig. 3. Variation of minimized total MTCE and total management cost versus variation of GHG emission rate.

same level (i.e., established by the same decision makers). As the objectives have to be optimized simultaneously, a tradeoff needs to be determined for compromising the multiple objectives [17,18]. In contrast, the bilevel decision-making follows a dominant-subordinate (or leader-follower) relationship and attempts to sequentially optimize the objectives according to the levels of decision makers [19–21]. Such decisions are based on decision makers' non-compromised or non-cooperative game; in the game process, the upper-level decision makers have the ability to enforce their decision on the lower-level ones but must satisfy the objective of the lower-level decision makers. On the other hand, the multiobjective decisions depend to a large extent on selected weights, probably leading to subjective discrepancy in judging the priority of each objective. In comparison, the most distinguished advantage of bilevel decision making does not need to determine any weights to assign to each of the objectives.

In terms of the sites survey, most of the residues were temporally sequestrated in some special pits or holes without any additional treatment. Due to the difficulty in estimating GHG emissions from such temporary facilities, an assumption was given that GHG emissions from the onsite disposal facilities were not considered. However, such an assumption may lead to an underestimate in the total amount of GHG emissions mitigation. When extended to other MSW management systems, emissions from the residues may be counted in depending on the residues disposal techniques and site conditions. This study did not take into account the GHG emissions in the process of waste collection, due to the difficulty in obtaining the data associated with it. This could lead to the underestimation of the mitigation in the total GHG emissions. The ongoing study is being conducted to gain such information through on-site monitoring stations.

Two concerns need to be addressed in future studies. One is that the models did not consider GHG collection and technology improvement in the decision-making process. The introduction of these factors would probably lead to lower GHG emissions and management cost, compared to those attained in this study. The other one is regarding the solution method to bilevel problems, as most of them are NP-hard to be solved. This is especially true in large-scale problems with a number of decision variables and decision goals to be addressed. Also, the increased nonlinear complexity in large-scale problems would lead to the enhancement of computational cost. Thus, linearized or heuristic solution algorithms may be used in future studies to improve the computational efficiency.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhazmat.2011.07.036.

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