A multi-echelon supply chain model for municipal solid waste management system

Yimei Zhang\textsuperscript{a,}, Guo He Huang\textsuperscript{b}, Li He\textsuperscript{a}

\textsuperscript{a}Energy and Environmental Research Academy, North China Electric Power University, Beijing 102206, China
\textsuperscript{b}Environmental Systems Engineering Program, Faculty of Engineering and Applied Science, University of Regina, Regina, Saskatchewan S4S 0A2, Canada

\begin{abstract}
In this paper, a multi-echelon multi-period solid waste management system (MSWM) was developed by inoculating with multi-echelon supply chain. Waste managers, suppliers, industries and distributors could be engaged in joint strategic planning and operational execution. The principal of MSWM system is interactive planning of transportation and inventory for each organization in waste collection, delivery and disposal. An efficient inventory management plan for MSWM would lead to optimized productivity levels under available capacities (e.g., transportation and operational capacities). The applicability of the proposed system was illustrated by a case with three cities, one distribution and two waste disposal facilities. Solutions of the decision variable values under different significant levels indicate a consistent trend. With an increased significant level, the total generated waste would be decreased, and the total transported waste through distribution center to waste to energy and landfill would be decreased as well.
\end{abstract}

1. Introduction

Management of municipal solid waste (MSW) is a priority for urban communities throughout the world (Huang and Chang, 2003). An MSW management system involves a number of processes with socio-economic and environmental implications, such as waste generation, transportation, treatment and disposal (Wilson, 1985). A conventional MSW management system often includes multiple waste collection centers and disposal plants with a series of supply-disposal relationships. These involve activities from the collection of waste to the delivery of treated waste to the end disposal facilities. However, the interactions between transport planning and inventory features of all sections are seldom considered in today's solid waste management.

Actually, MSW management can be considered as a strategic supply chain issue (Hicks et al., 2004). It is often subject to various impact factors, such as collection techniques to be used, transportation tools to be implemented, and disposal facilities to be adopted. As planning for sustainable municipal solid waste management has to address several inter-connected issues, it becomes increasingly necessary to understand the dynamic nature of their interactions (Kollikkathara et al., 2010). Therefore, it is desired that the net system cost be optimized through analyses of operation plan of each disposal plant, transportation schedule of each waste distribution center, and inventory level of each enterprise in a supply chain network.

Previously, a number of models and analysis methods were employed for supporting municipal solid waste management (Beigl et al., 2008; Khan and Faisal, 2008; Su et al., 2008). Hicks et al. (2004) proposed a functional model of waste management that represents supply chains in terms of processes, their interconnections, material flows, waste streams and cumulative cost. Focused on locating collection areas for urban waste management, the relationship between the set covering problem and the MAXSAT problem was analyzed in the metropolitan area of Barcelona (Bautista and Pereira, 2006). Optimality of state-dependent echelon base-stock policies was analyzed in uncapacitated serial inventory systems (Muharremoglu and Tsitsiklis, 2008) Rives et al. (2010) used life cycle analysis to compare container systems in planning and design of integrated municipal solid waste management systems. Chen et al. (2011) developed many models of municipal solid waste management in different geographical units and urban systems of China.

Moreover, in MSW management, uncertainties existing in related costs, impact factors and objectives may be presented...
fuzzy, probabilistic and/or interval formats (Zhang et al., 2010); such uncertainties would affect the related optimization processes and the generated decision schemes (Zhang and Huang, 2010). DeCroix (2006) analyzed a multi-echelon inventory system with inventory stages arranged in series, in which used products can be returned to a recovery facility, where they can be stored, disposed, or remanufactured and shipped to one of the stages to re-enter the forward flow of material. Tempelmeier (2007) addressed single-item dynamic lot sizing problems with stochastic period demands and backordering. Seliaman and Ahmad (2008) investigated a three-stage non-serial supply chain system which involves suppliers, manufacturers and retailers. De Sensi et al. (2008) reported a study on a real three-echelon supply chain (MSC) considering dynamic variations and stochastic behaviors of supply chain variables as well as their complex interactions. Lodree and Uzochukwu (2008) concerned inventory control of a deteriorating product with non-negligible procurement lead-time that perishes after a fixed number of periods; demand for fresh products during each period was represented as a stochastic variable with known probability distribution. You and Grossmann (2008) developed mixed-integer nonlinear programming models for large-scale supply chain design for stochastic inventory management. Muharremoglu and Tsitsiklis (2008) proposed a single-unit decomposition approach to multi-echelon inventory systems with optimality of state-dependent echelon base-stock policies in uncapsacitated serial inventory systems.

Generally, the previous study did not systematically consider waste collection, transportation, and disposal process with inventory control. Developing a multi-echelon supply chain model for solid waste management systems is desired. The objective of this study is to develop a multi-echelon multi-period solid waste management system (MSWM) by inoculating with multi-echelon supply chain and to minimize the system cost with cost-effective allocation of waste flows and disposal rates at waste management facilities. Different types of waste transportation vehicles will leave from the origin collection center to destination disposal industries, possibly visiting intermediate pretreatment plants. MSWM comprises of three levels of organizations: solid waste collection stations, waste distribution centers, waste disposal/treatment facilities. For each organization, waste flow rate over the network depends on waste generation rate, transportation capacity, inventory capacity (organizations), and waste disposal/treatment capability. The output of each organization (waste transported or disposed) will be defined as a function of its inputs (waste received).

In this paper, a MSWM system will be proposed. The characteristic of the MSWM system will be introduced. A MSWM case will be used to illustrate the applicability of the system, wherein an environmental manager is responsible for allocating waste from three cities to two disposal facilities through one distribution center. With stochastic forecasting waste generation rate, the results from different scenarios will be analyzed and compared. The practical applicability and implication of the MSWM have been concluded.

2. Materials and methods

2.1. Multi-echelon solid waste disposal supply chain model

2.1.1. Assumptions and constraints

In this study, a multi-echelon network for municipal solid waste management can help decision maker determine the disposal plan of each disposal plant, the transportation plan of each distribution center (DC), the inventory level of each enterprise. The main focus is the operational and transportation planning of municipal solid waste: recycle/reuse waste flow to remanufacturers would be considered in future study. The following assumptions have been made:

- Waste generation rate is the operational and transportation planning of municipal solid waste management (MSWM) by inoculating with multi-echelon supply chain and to minimize the system cost with cost-effective allocation of waste flows and disposal rates at waste management facilities.
1. The waste generation rates of cities are independent to each other.

2. Waste generation rates with known probabilities are forecasted over the entire scheduling periods.

3. Waste generated in each period must be collected by city collection stations.

4. Total waste collection, transportation, and operational cost are assumed to be linear functions.

5. Each period (e.g., month, season) is composed of several time intervals that have the same waste generation rates (e.g., in spring, every week has the same waste generation rate).

6. Each enterprise has its own safe inventory quantity to reduce the influence of fluctuating generated waste. The waste comes to each enterprise would obey first come and first go rule. This means that, for any time intervals in one period, only the waste arrived in this time intervals can be stored.

7. The maximum inventory level for each enterprise is the maximum average inventory level in each time interval in one period. For example, if there are 4 time intervals in a period, for a waste distribution center having capacity of 200 t, the maximum average inventory level would be 50 t. In each time interval of a period, the disposal and transportation processor are exactly the same, but the stored waste in each enterprises is accumulated with equal differences.

With given information of (i) Disposal data, such as quantity of waste disposal per time interval; (ii) Transportation data, such as lead-time and transport capacity; (iii) Inventory data, such as inventory capacity and safe inventory quantity; (iv) Each cost parameter, such as operation and inventory (v) Several scenarios of forecasted product demands with known probabilities, the multi-echelon solid waste disposal supply chain model is developed as follows:

2.1.1. Constraints. For each city, the inventory level of waste storage station at each period equals the amounts at the previous period plus the waste collected less the total amount transported to distribution centers (Eq. (1)). The inventory level of the waste storage station in city $i$ cannot exceed its maximal inventory capacity.

$$I_i = I_i^{t-1} + WQG_{it} - \sum_{d=1}^{n} WQ_{idt}, \forall i, t$$

$$I_i \leq M_{ici}, \forall i, t$$

$d$ is waste distribution center; $i$ is city waste collection center; $t$ is planning time period; $I_i$ is waste inventory level of $i$; $M_{ici}$ is maximum inventory capacity of $i$; $WQG_{it}$ is random waste generation rate of $i$; $WQ_{idt}$ is total waste transport from city to DC.

Waste distribution centers are stocked with waste to be redistributed to waste disposal facilities. Each waste distribution center has its maximum input and out waste due to the transportation limits. For every distribution center in every period, the total transported waste from each city to distribution center cannot exceed its maximal input transport capacity (Eq. (3)). For every distribution center in every period, the total transported waste from distribution center to each waste facility cannot exceed its maximal output transport capacity (Eq. (4)). For each distribution center, the waste inventory level at each period equals the amounts at previous period plus the amounts total waste transported from city less the amounts transported to waste disposal facilities (Eq. (5)). It also has its maximum inventory capacity (Eq. (6)). Delayed transport quantity of waste transported waste from city to DC due to transport lead time is also considered.

$$\sum_{i=1}^{p} WQ_{idt} \leq M_{icdi}, \forall d, t$$

$$\sum_{p=1}^{p} WQ_{dpy} \leq M_{otdp}, \forall d, t$$

$$ID_{di} = ID_{di-1} + \sum_{i=1}^{p} WQ_{id(t-1)} - \sum_{p=1}^{p} WQ_{dpy}, \forall p, t$$

$$ID_{di} \leq M_{icdi}, \forall p, t$$

$p$ is waste disposal plant ($p = 1$, waste to energy plant WTE; $p = 2$, landfill); $WQ_{dpy}$ is total waste transport from $d$ to $p$; $WQ_{dpy}$ is total waste transport from $p$ to $d$; $ID_{di}$ is waste inventory level of $d$; $M_{icdi}$ is maximum inventory capacity of $d$; $M_{otdp}$ is maximum output transport capacity of distribution center $d$; $M_{otdp}$ is maximum output transport capacity of distribution center $d$.

Two types of waste management facilities are considered: landfilling and WTE plant. In WTE plant, the pending disposal waste is the sum of all the inbound waste and waste residue from last period. All the treated waste would be shipped to the landfill. Moreover, if all the pending waste cannot be treated thoroughly; the redundant waste would remain in the inventory of WTE and wait to be disposed in the next period. The pending waste inventory at each period equals its amounts in the previous period plus the amounts of total waste transported from distribution centers, less those of treated waste.

$$IP_{1i} = IP_{1i-1} + \sum_{d=1}^{n} WQ_{id(t-1)} - W_{1i} \leq M_{icp1}, \forall t$$

$$W_{1i} \leq M_{wpq}, \forall t$$

$$IP_{2i} = IP_{2i-1} + \sum_{d=1}^{n} WQ_{i2t} - W_{2i} \leq M_{icp2}, \forall t$$

$$W_{2i} \leq M_{wpq}, \forall t$$

$$IP_{2i} \leq M_{icp2}$$

2.1.2. Objective Function

The total system cost is associated with waste disposal and treatment at management plants, materials handling at waste storage stations and distribution centers, and waste transportations on the highways. The total operational cost of waste disposal plants can be expressed as follows:

$$\sum_{p=1}^{p} T_{Cp} = \sum_{t=1}^{T} (W_{1t} \times U_{oc1t}) + \sum_{t=1}^{T} (W_{2t} \times U_{oc2t})$$

$T_{Cp}$ is total operational cost of $p$; $U_{oc3}$ is unit operational cost of $p$. 

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The total waste collection cost can be obtained using the expectation value of the waste generation rate in each period:

\[ Tcic = \sum_{i=1}^{l} \sum_{t=1}^{T} Uhti \times E[WQGi] \]  

(13)

\( Thci \) is total collection cost of \( i \); \( Uhti \) is unit collection cost of \( i \).

The total transportation cost from waste storage stations to distribution centers, from distribution centers to waste disposal plants, and from incineration plants to the landfilling is:

\[ Tcci = \sum_{i=1}^{l} \sum_{d=1}^{D} Tcidd + Tcppp = \sum_{i=1}^{l} \sum_{t=1}^{T} Utcp12 \times WQPi12t \]

\[ + \sum_{p=1}^{P} \sum_{t=1}^{T} \sum_{d=1}^{D} WQDipt \times Utcpdp \]

\[ + \sum_{p=1}^{P} \sum_{t=1}^{T} WQipt \times Uctiap \]  

(14)

\( Tcidd \) is total transportation cost from \( d \) to \( p \); \( Tcidd \) is total transportation cost from WTE to landfill; \( Utcpdp \) is unit transportation cost from \( d \) to \( p \); \( Uctiap \) is unit transportation cost from \( i \) to \( d \); \( Utcp12 \) is unit transportation cost from WTE to landfill.

The inventory costs are proportional to the levels of inventories. The corresponding terms in the objective function are:

\[ Tici = \sum_{i=1}^{l} \sum_{t=1}^{T} Uti \times Ii \]

\[ + \sum_{t=1}^{T} Utdat \times IDat \]

\[ + \sum_{p=1}^{P} \sum_{t=1}^{T} Utcp1t \times IP1t \]  

(15)

\( Tici \) is total inventory cost of \( i \); \( Tcidd \) is total inventory cost of \( d \); \( Tcppp \) is total inventory cost of \( p \); \( Uti \) is unit inventory cost of \( i \); \( Utcpdp \) is unit inventory cost of \( p \). The total system cost to be minimized can be summarized as follows:

\[ MIN TC = \sum_{t=1}^{T} \sum_{p=1}^{P} Wpt \times Uocpt + \sum_{d=1}^{D} \sum_{i=1}^{l} Uhti \times E[WQGi] \]

\[ + \sum_{d=1}^{D} \sum_{l=1}^{l} \sum_{t=1}^{T} WQlidt \times Utcii + \sum_{p=1}^{P} \sum_{t=1}^{T} \sum_{d=1}^{D} WQDpdt \times Utcpdp \]

\[ \times Utcdpt \sum_{t=1}^{T} Utcp12 \times WQPi12t + \sum_{p=1}^{P} \sum_{t=1}^{T} Utcp1t \times IP1t \]

\[ + \sum_{d=1}^{D} \sum_{l=1}^{l} Uti \times IDat \sum_{t=1}^{T} \sum_{i=1}^{l} Uticidt \times Ii \]  

(16)

2.1.3. Chance constrained programming

Since the waste generation rate is a stochastic number, a stochastic programming method is needed to solve the constraints with stochastic parameters. As a stochastic programming method, the chance-constrained programming was an effective method of handling uncertainties by specifying confidence levels at which it is desired that the constraints or goal should hold. The linear chance-constrained programming model can be presented as follows:

\[ \text{Min } CX \]  

(17a)

Subject to:

\[ A_i X \geq b_i, \forall i \]  

(17b)

\[ x_j \geq 0, \forall j \]  

(17c)

The definitions of sets, parameters and variables are listed in nomenclature. The basic technique to solve the chance-constrained programming in a stochastic environment is to convert the stochastic constraints to their respective deterministic equivalents according to the predetermined confidence level. It can be implemented through: (i) fixing a certain level of probability \( p_i \in [0,1] \) for each uncertain constraint \( i \), and (ii) imposing the condition that the constraint is satisfied with at least a probability of \( 1 - p_i \). This maximum value is the deterministic equivalent value that converts the stochastic programming problem into a deterministic programming problem and allows the constraint to be transformed in the parametric form:

\[ A_i X \geq b_i(t)^{p_i} = \mu _{b_i} + zp \sigma _{b_i}, \forall i \]  

(18)

The higher the \( 1 - p_i \) percentage, the greater the downside safety margin adjustment to mean resource supply. When waste supply is certain, the decision maker could develop a deterministic waste disposal plan by linear programming. In contrast, when waste supply is stochastic, the decision maker wishes to satisfy the constraints with a high degree of confidence (say 95% of the time) will set the critical \( zp \) value to 1.645.

Therefore, in this model, with the stochastic waste generation rate \( WQGi \), constraint can be transformed to:

\[ WQGi \leq Mici + \sum_{d=1}^{D} WQDidt - I_{1t-1}, \forall i, t \]  

(19)

According to Eq. (18), with the confidence level \( 1 - p_i \), Eq. (19) can be transformed

\[ \mu _{WQGi} + zp \sigma _{WQGi} \leq Mici + \sum_{d=1}^{D} WQDidt - I_{1t-1}, \forall i, t \]  

(20)

2.2. Characteristics of studied area

In an MSWM system, there are two main processes: (1) waste disposal planning and inventory control which are integrated tightly with each other; (2) the distribution process, which determines how the collected waste is transported from city collection station to waste disposal facilities or remanufacturers through the distribution centers. Inventory control is a key aspect in the network, which represents a main improvement upon the conventional approaches for supporting solid waste management.

There are many differences and similarities between the proposed MSWM and the conventional multi-echelon supply chain management (SCM). With respect to stochastic information, the demand of a product in SCM and the waste generation rate in the MSWM are stochastic variables. In SCM, people buy products at the final store, while in MSWM the government collects waste from households. In SCM, the plants stock raw materials and produce mid or final goods, while in MSWM, the waste disposal facilities stock/dispose waste or recycle/reuse it. The differences and similarities have been summarized in Table 1. The flow chains of product (SCM) and waste (MSWM) are listed as well.

3. Application of the model

Consider a MSW management system wherein an environmental manager is responsible for allocating waste from three cities to two disposal facilities through one distribution center (Fig. 1). The first echelon includes waste collection stations in the cities, with responsibilities of collecting and transporting MSW to waste storage centers. It is assumed that all of the generated waste is collected soon after its generation. The second echelon is a waste
transport lead-time is assumed to be 0. The WTE facility generates residues of 0.36 on a mass basis of the inbound waste streams. Values of the cost parameters and capacity-related parameters are provided in Table 3. Most of the parameters are expressed as deterministic numbers.

The corresponding multi-echelon supply chain model can be formulated as follows:

\[
MIN \ TC = \sum_{t=1}^{T} \sum_{p=1}^{P} W_{pt} \times U_{ocpt} + \sum_{t=1}^{T} \sum_{i=1}^{I} U_{ici} \times E[W_{Qci}] \\
+ \sum_{d=1}^{D} \sum_{t=1}^{T} W_{QD_{dt}} \times U_{tcp} + \sum_{t=1}^{T} \sum_{d=1}^{D} W_{QD_{dt}} \\
\times Utcd_{dp} + \sum_{i=1}^{I} \sum_{t=1}^{T} U_{icp} \times W_{QP_{12it}} + \sum_{t=1}^{T} \sum_{i=1}^{I} U_{icp} \times I_{it} \\
+ \sum_{t=1}^{T} \sum_{i=1}^{I} U_{tcp} \times I_{TP_{it}}
\]

Subject to:

Incineration plant:

\[
I_{P_{t1}} = I_{P_{t1-1}} + \sum_{d=1}^{D} W_{QD_{dt}} - W_{1t} \leq M_{wq1}, t = 1, 2, \ldots, 6
\]

Landfilling:

\[
I_{P_{t2}} = I_{P_{t2-1}} + \sum_{d=1}^{D} W_{QD_{dt}} + W_{QP_{12t}} - W_{2t} \leq M_{wq2}, t = 1, 2, \ldots, 6
\]

City waste collection center:

\[
I_{t} = I_{t-1} + W_{QGt} - \sum_{d=1}^{D} W_{QD_{dt}}, i = 1, 2, 3, \quad t = 1, 2, \ldots, 6
\]

Waste distribution center

Table 1

<table>
<thead>
<tr>
<th>SCM</th>
<th>MSWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand of a product</td>
<td>Waste generation rate</td>
</tr>
<tr>
<td>People buy products</td>
<td>Government collects waste</td>
</tr>
<tr>
<td>Raw materials and goods</td>
<td>Pending disposed waste</td>
</tr>
<tr>
<td>Plants–Goods</td>
<td>(1) Households–Waste</td>
</tr>
<tr>
<td>Plants</td>
<td>(2) Waste collection center</td>
</tr>
<tr>
<td>Distribution centers</td>
<td>(3) Distribution centers</td>
</tr>
<tr>
<td>(4) Purchased by people</td>
<td>(4) Waste disposal facilities</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>City</th>
<th>t/period</th>
<th>t = 1</th>
<th>t = 2</th>
<th>t = 3</th>
<th>t = 4</th>
<th>t = 5</th>
<th>t = 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>City 1</td>
<td>(245, 74)</td>
<td>(165, 39)</td>
<td>(168, 74)</td>
<td>(189, 71)</td>
<td>(217, 60)</td>
<td>(203, 52)</td>
<td></td>
</tr>
<tr>
<td>City 2</td>
<td>(195, 56)</td>
<td>(257, 48)</td>
<td>(176, 67)</td>
<td>(262, 60)</td>
<td>(163, 45)</td>
<td>(220, 49)</td>
<td></td>
</tr>
<tr>
<td>City 3</td>
<td>(225, 55)</td>
<td>(238, 51)</td>
<td>(213, 43)</td>
<td>(243, 48)</td>
<td>(238, 66)</td>
<td>(177, 54)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3

| Unit: $/t | i | d | p | Unit: $/t |
| --- | --- | --- | --- | --- | --- |
| MOTCt | 1 | 930 | MICI | 1 | 30 |
| MITCt | 1 | 960 | 2 | 30 |
| MWQp | 1 | 300 | MIP | 2 | 30 |
| MWQp | 2 | 750 | MIP | 2 | 28 |
| MICD | 1 | 34 | 2 | 28 |
| Unit: $/t | i | d | p | Unit: $/t |
| --- | --- | --- | --- | --- | --- |
| UTCd | 1 | 1 | 6 | UICI | 1 | 4 |
| 2 | 2 | 5 | 4 |
| 3 | 1 | 6.5 | 3 | 4 |
| UTCd | 1 | 1 | 5 | UICI | 1 | 5 |
| 2 | 2 | 7 | 1.23 |
| 3 | 1 | 2.5 | 1 | 35 |
| UHCl | 1 | 4 | UOCp | 1 | 15 |
| 2 | 4 | 2 | 35 |
| 3 | 4 |

distribution center, with responsibilities for receiving waste from the three cities, sorting and transporting it to facilities of the third echelon. The third echelon includes a landfilling facility and a WTE plant. The existing landfilling and WTE facilities are available to serve needs of waste disposal. The landfilling is used directly to satisfy waste disposal demand or alternatively to provide capacity for the residue disposal of the other facilities. The problem is how to effectively allocate the waste flows under a number of inventory, transportation and treatment/disposal constraints in order to minimize the overall system costs in six time elapses. The whole scheduling horizon is six periods. The waste generation rate in each period is shown in Table 2. The waste generation rates of three cities in a disposal period are stochastic numbers. The
\[ \begin{align*}
ID_{dt} &= ID_{d_{t-1}} + \sum_{j=1}^{I} WQI_{idt} - \sum_{p=1}^{P} WQD_{dpt}, \quad d = 1, \\
I_{dt} &= 0, \quad t = 1, 2, \ldots, 6 \\
ID_{dt} &\leq Mic_{dd}, \quad d = 1, \quad t = 1, 2, \ldots, 6 \\
\sum_{j=1}^{I} WQI_{idt} &\leq Mitc_{d}, \quad d = 1, \quad t = 1, 2, \ldots, 6 \\
\sum_{p=1}^{P} WQD_{dpt} &\leq Motc_{d}, \quad d = 1, \quad t = 1, 2, \ldots, 6 \\
\end{align*} \]

4. Result analysis

In this model, the initial inventory levels of city storage stations, distribution center and disposal plants are setting to be 0. It is also required that the ending inventory must be 0. Two scenarios according to different significant levels are analyzed.

4.1. Conservative scenario

In the conservative scenario, the significant level of 0.05 is chosen. Table 4 tabulates final results of the MSWM model. The minimized total operational cost is 1364.8 \times 10^3 dollars. The inventory operation process can be obtained by focusing on the inventory levels of enterprises in each echelon. Fig. 2 shows the whole waste flow of the entire system in period 1. From this figure, the waste transported from three cities to the DC would be 366.7 t, 267.8 t and 315.5 t in each time interval. City 2 would store 19.3 t of waste in the safety inventory center, since the total generated waste is greater than the inbound transportation limit of the DC. 20 t of waste would be stored in inventory of DC because of the outbound transportation limit. The DC would transport 300 t and 630 t to WTE and landfill. WTE would treat all the income waste and transport the residue to the landfill. The landfill would operate at its peak workload and store 14 t of waste which needs to be disposed in the next period.

For the inventory process in the first echelon, all waste from cities 1 and 3 would be shipped to distribution center in the first period, while some waste from city 2 would be deposited in the city waste inventory center. This is due to the inbound waste transportation limit from the distribution center; waste would not be transported to DC. Meanwhile, the inventory cost of distribution center would be higher than that of city storage center. In periods 2, all the generated and stored waste from period 1 would be shipped to DC. In period 3, without any left waste from period 2, all the generated waste would be transported. With high waste generation rate in period 4, both cities 1 and 2 would store 8.5 t and 30.0 t of waste. All these stored waste would be shipped in the period 5 and no waste needs to be storage in city waste stations. As requested, in the last period 6, the inventory should be 0.

![Fig. 2. Waste flow in the period 1 (p' = 0.05).](image-url)
For the inventory process in the second echelon, DC receives from cities and sends the waste to the disposal plants. Fig. 3 shows the waste flow of DC in 6 periods. In period 1, the total inbound waste would be 950 t, and the outbound waste would be 930 t. The difference 20 t would be stored in the inventory of DC. In period 2, the inbound waste would be 922.4 t, 910 t of them with the stored 20 t from period 1 would be shipped out. The left 12.4 t would be stored. In period 3, only 859.7 t of waste transported to DC. Because of the low level of inbound waste, total generated waste in period 3 and stored waste from last period would be shipped out. No waste needs to be stored in this period. In period 4, DC would face exactly the same situation as in period 1. DC would store 20 t of waste. In period 5, the inbound waste still high (937.8 t), the inventory of DC would increase to 30.1 t. In the last period, both inbound waste (855.0 t) and the stored waste (30.1 t) could be transported to WTE and landfill (see Fig. 4).

For the operation of WTE and landfill, depending on the inbound waste from DC in 6 periods, the WTE would store 0.0 t, 28.0 t, 0.0 t, 14.0 t, 28.0 t, 0.0 t of waste respectively. For the landfill, the disposed waste would reach its maximum disposal capacity (730 t) in all of the 6 periods, no matter how much waste is generated. If the less waste is transported, less work of WTE would be required. This is due to the high operational cost of the WTE plant.

4.2. Progressive scenario

In progressive scenario, the chosen significant level is 0.1. The results of the MSWM model under this situation are shown in Table 5. The minimized total operational cost is $1230.4 \times 10^3$ dollars. In period 1, the waste transported from three cities to the DC would be 340.1 t, 267.0 t and 295.7 t in each time interval. The DC would transport 278.6 t and 624.1 t to WTE and landfill. WTE would treat all the income waste and transport the residue to the landfill. The landfill would operate at its peak workload. In the period 2, the waste transported from three cities to the DC would be 215.1 t, 336.0 t and 338.0 t, respectively. In period 3, with lower waste generation rate, all the waste stored in the DC would be transported to WTE and landfill, and then would all be disposed. In the period 4, with the highest waste generation rates, the waste transported from

![Fig. 3. Waste flow of DC in six periods ($p = 0.05$).](image1)

![Fig. 4. Waste flow in the period 4 ($p = 0.1$).](image2)
three cities to the DC would be 280.2 t, 339.1 t and 304.7 t in each time interval. From DC, 308.0 t and 616 t of waste would be transported to WTE and landfill. Because of the maximum load of WTE, WTE would store 8.0 t of waste in the inventory. WTE and landfill would dispose 300 t and 730 t.

4.3. Discussion

In terms of the results under different significant levels from two scenarios, obviously, higher \( p_i \) levels correspond to relatively lower operational costs. When \( p_i = 0.05 \), the total operational cost equals to $1364.8; when \( p_i \) increases to 0.1, the costs would decrease to $1230.4 \times 10^4$, respectively. In waste collection constraints, an increased \( p_i \) level would lead to a decreased strictness for the constraints (decreased waste generation), and thus an expanded decision space, which may then result in a decreased system costs. In all, the decrease system costs would be derived from increased risks of violating the constraints. Therefore, the system risk would increase with increased \( p_i \) levels. Solutions of the decision variable values under different \( p_i \) levels also indicate a consistent trend. With an increased \( p_i \) level, the total generated waste would be decreased, and the total transported waste through DC to WTE and landfill would be decreased as well.

In the real case, it can be concluded from the history data that the high waste generation would exist in an exact period, such as festival, national day. Then, the decision maker can determine the inventory level of the enterprise in advance. For example, if in period 6, the waste generation would be extremely high, the decision maker can set the inventory of city and DC in period 5 be 0 to prepare for the high season of waste flow. In all, the decrease system costs would be derived from increased risks of violating the constraints, and thus decreased operational costs.

The practical applicability of the proposed MSWM model is comprehensive. The significant of the model is comprehensively engaging the waste managers, suppliers, industries and distributors in joint strategic planning and operational execution. In most WSM cases, decision makers of transportation, disposal and collection will execute their own operational and inventory plan individually. The proposed MSWM model, systematically considering interactions between transport planning and inventory features, is applicable in many MSW cases.

With respect to its implication to solid waste management, MSWM can provide waste disposal, distribution and inventory control planning for both real time and long time MSW planning, regarding supplies, inventories, production levels, and operational devices. An efficient inventory management plan for MSWM would lead to optimized productivity levels under available capacities. It can provide environmental-friendly supports with minimized the system cost and cost-effective allocation of waste flows and disposal rates at waste management facilities.

5. Conclusions

In this study, a multi-echelon supply model was developed for supporting decisions of solid waste management. Waste managers, suppliers, industries and distributors could be engaged in joint strategic planning and operational execution. The principal of MSWM system is interactive planning of transportation and inventory for each organization in waste collection, delivery and disposal. It is able to provide decision support for both real time and long time MSW planning, which are (1) waste disposal planning and inventory control which are integrated tightly with each other; and (2) the distribution process, which determines how the collected waste is transported from city collection station to waste disposal facilities or remanufacturers through the distribution centers.

The most significant difference between conventional supply chain and MSWM is that the demand of a product in SCM is a stochastic variable which follows a distribution, while that waste generation rate in the MSWM is stochastic. By the assumption of the average inventory level during the period, it is able to provide real time and long time MSW planning for decision makers. The applicability of the proposed system was illustrated by a three city, one distribution and two disposal facility case. Different significant levels are analyzed. In application, the decision maker can determine the inventory level of the enterprise in advance based on the forecasted data, to prepare for high season of waste generation. Future studies will be undertaken to integrate interval programming to deal with uncertain data, or integer programming to plan the capacity expansion problem of disposal facility, transportation load or inventory. In future studies, it is desired to design of multi-waste, multi-echelon, multi-uncertainty supply chain of waste management network. Moreover, the proposed approach would be applicable to other environmental management problems (e.g., water management). It can also be improved by introducing multiply uncertainties in the model parameters and variables.

References


