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A reverse logistics cost minimization model for the treatment of hazardous wastes

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Abstract

This study presents a cost-minimization model for a multi-time-step, multi-type hazardous-waste reverse logistics system. A discrete-time linear analytical model is formulated that minimizes total reverse logistics operating costs subject to constraints that take into account such internal and external factors as business operating strategies and governmental regulations. Application cases are presented to demonstrate the feasibility of the proposed approach. By using the proposed model coupled with operational strategies, it is shown that the total reverse logistics costs for the applications cases can be reduced by more than 49%.

Keywords: Reverse logistics; Hazardous wastes management; Discrete-time; Cost minimization

1. Introduction

Hazardous-waste reverse logistics may be useful for solving waste-induced environmental pollution problems that accompany high-technology industrial development. Here reverse logistics is referred to as the process of logistics management involved in planning, managing, and controlling the flow of wastes for either reuse or final disposal of wastes. The traditional measures, i.e., waste processing technologies, used for the treatment of hazardous wastes are inadequate for

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integrating waste management, collection, storage, distribution and transportation activities into comprehensive, reverse logistics operating strategies. Consequently, it is difficult to coordinate these activities in a hazardous-waste reverse logistics system for reducing environmental pollution. For example, 1.47 million metric tons of hazardous wastes are reportedly produced every year in Taiwan. However, only 40% of them can be efficiently disposed of, due to the limited capacity of Taiwanese hazardous-waste processing facilities (Wei and Huang, 2001).

Although there is an increasing amount of research on reverse logistics (Stock, 1992; Cairncross, 1992; Pohlen and Farris II, 1992; Jahre, 1995; Kroon and Vrijens, 1995; Stock, 1998; Shih, 2001), studies specifically addressing hazardous wastes problems (Peirce and Davidson, 1982; Jennings and Scholar, 1984; Zografos and Samara, 1990; Koo et al., 1991; Stowers and Palekar, 1993; Nema and Gupta, 1999) are rare. It is noteworthy that previous literature appears to be devoted mainly to the optimization of reverse network configurations, including transportation routes, as well as the size and location of disposal facilities for hazardous waste management. An early example is the study by Peirce and Davidson (1982), which utilizes a linear programming model to formulate the optimization problem of transportation routing among transfer stations, disposal facilities, and long-term storage impoundments. Herein, their study may be limited to the identification of the optimal waste distribution routes under the condition that waste treatment facilities as well as specific waste processing technologies are given. The issue of transporting multiple types of wastes is investigated in Jennings and Scholar (1984), which formulates the regional hazardous waste management system (RHWMS) as simply a vehicle routing problem in an attempt to accomplish the goal of either minimum cost or minimum risk. In contrast, the study by Zografos and Samara (1990) deals only with the problem of a single type of waste; however, their method serves three objectives, including the minimizations of transportation risk, travel time, and disposal risk. In addition to vehicle routing, issues with respect to locating waste storage and treatment facilities are investigated in Koo et al. (1991) where fuzzy theories together with multi-objective optimization techniques are utilized for the facility planning of hazardous waste treatment centers in South Korea. Similar attempts can also be found in Stowers and Palekar (1993) and Nema and Gupta (1999). However, the scope of the aforementioned research is still limited to some specific areas of hazardous-waste reverse logistics.

Despite the advances made in the prior literature, hazardous-waste reverse logistics warrants more research. Similar viewpoints can also be found in Fleischmann et al. (1997) in which the field of reverse logistics is classified into three main areas: (1) reverse distribution planning (Pohlen and Farris II, 1992; Jahre, 1995), (2) inventory control of return flows (Schrady, 1967; Barros et al., 1998), and (3) production planning with reuse of parts and materials (Johnson and Wang, 1995; Penev and de Ron, 1996; Richter, 1996; Spengler et al., 1997). In Fleischmann et al. (1997), the interface between reverse logistics activities is particularly emphasized. Carter and Ellram (1998) further point out that in most of previous literature, there is a lack of well-grounded, conceptual frameworks for reverse logistics. Moreover, the variety of material characteristics of hazardous wastes coupled with diverse environmental regulations has made hazardous-waste treatment problems more complex, thus requiring specific solution measures such as control and management of reverse logistics.

In view of the lack of in-depth investigation with respect to hazardous-waste reverse logistics operations in the literature, herein we formulate a hazardous-waste reverse logistics cost model using a multi-time-step, multi-type operations process that minimizes the logistics costs. More specifically, the critical activities executed in a multi-type hazardous-waste reverse logistics system (HWRLS), including waste collection, storage, processing and distribution, together with the relevant logistics operating requirements, are integrated in the proposed model.

2. Model

The model of the proposed reverse logistics system is shown in Fig. 1, consisting of four critical activities: (1) collection, (2) storage, (3) treatment, and (4) distribution. The functionality of the hazardous-waste reverse logistics system investigated in this study focuses mainly on integrating the system-wide inter-activity physical flows.

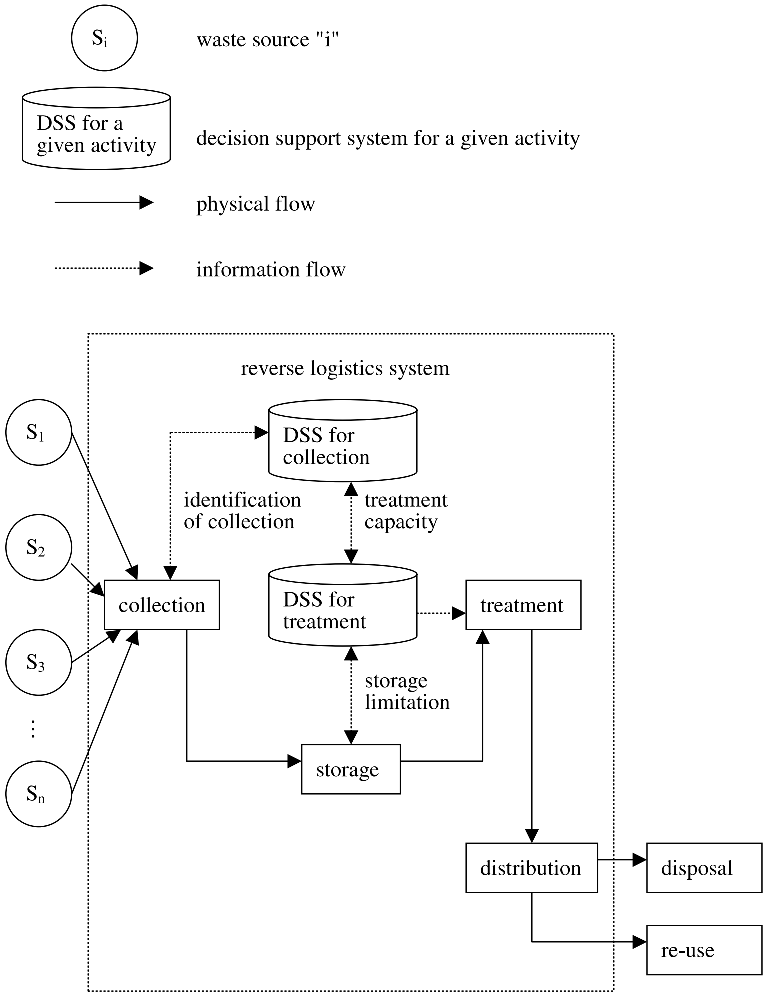

Fig. 1. Conceptual model of the proposed reverse logistics system.

To facilitate model formulation, four assumptions are postulated:

(1) The network configurations of the reverse logistics system are given. These include primarily geographical characteristics associated with the aforementioned related activities, and their capacities in terms of the specific functions they provide in the reverse logistics system.
(2) The time-varying demands for the hazardous waste treatment are known. The time-varying demand corresponds to the amount of a given type of hazardous waste that is produced by a given waste source at a given time step, and herein the waste source can be regarded as a group of contracted manufacturers demanding to treat the same type of hazardous waste. In practice, these time-varying demands can be measured readily from order entries of the waste-treatment company.
(3) The cost for internal distribution is ignored. Correspondingly, only the inbound transportation cost for collection of raw hazardous wastes, and the outbound transportation cost for the activities of reuse and final disposal are taken into account in model formulation, and both of which are herein assumed to be directly proportional to the pre-determined inter-activity spatial distance. In general, the intra-facility waste distribution cost is relatively insignificant in comparison with the other cost items in the reverse logistics system, and thus, it is removed from the proposed cost objective function to facilitate the model formulation.
(4) The storage function is provided specifically for the un-processed hazardous wastes collected from these waste sources, excluding processed wastes. Correspondingly, this may induce an operational policy that the hazardous wastes processed at a given time step should be distributed at the same time for outbound processed-waste distribution.

Accordingly, a discrete-time linear analytical model is formulated to minimize the total operational cost of a multi-time-step, multi-type hazardous-waste reverse logistics system. The proposed model is composed of a discrete-time linear objective function (see Eq. (1)) coupled with several constraints (see Eqs. (2)–(7)) representing the operational conditions of the reverse logistics system needed for the search of feasible solutions in terms of the decision variables. The mathematical formulation of the proposed model is detailed below, and the notations of variables shown in the proposed model are summarized in Appendix A.

The objective of the proposed model is to minimize the total reverse logistics cost for a given multi-time-step period. The total reverse logistics cost involved in the objective function includes five major time-varying cost items: (1) total collection cost, (2) total storage cost, (3) total treatment cost, (4) total transportation cost for reusing processed wastes, and (5) total transportation cost for disposing processed wastes, as shown in sequence in Eq. (1).

$$\begin{aligned}\text{Min} \sum_{k=1}^{K} \sum_{i=1}^{I} t_i^{\mathrm{c}} \times l_i^{\mathrm{c}} \times C_i(k) + \sum_{i=1}^{I} a_i \times \left\{ S_i(0) + \sum_{k=0}^{K-1} [C_i(k+1) - T_i(k+1)] \right\} \\ + \sum_{k=1}^{K} \sum_{i=1}^{I} b_i \times T_i(k) \sum_{k=1}^{K} \sum_{i=1}^{I_\gamma} t_i^{\mathrm{r}} \times l_i^{\mathrm{r}} \times \omega_i^{\mathrm{r}} \times T_i(k) + \sum_{k=1}^{K} \sum_{i=I_\gamma+1}^{I} (t_i^{\mathrm{d}} \times l_i^{\mathrm{d}} + d_i) \times [\omega_i^{\mathrm{d}} \times T_i(k)]\end{aligned} \tag{1}$$

Herein, $C_i(k)$ and $T_i(k)$ represent two types of time-varying decision variables, which are determined in each time step according to the goal of minimizing the total reverse logistics cost. Note that, as can be seen in the first cost item of Eq. (1), the time-varying storage amount associated with the type i of hazardous waste is determined primarily by the time-varying storage increment. And this increment is represented by the difference between the time-varying material amount of collecting the type i of hazardous waste ($C_i(k+1)$) and the associated waste-treating amount ($T_i(k+1)$).

Considering the required conditions of the time-varying decision variables $C_i(k)$ and $T_i(k)$, either compelled by governmental regulations or limited by operating capacities, six groups of constraints are involved in the proposed model, and their mathematical forms are given respectively by

$$\sum_{i=1}^{I} C_i(k) \geqslant \max\{M_{\text{gov}}^{C}, M_{\text{com}}^{C}, 0\}, \quad \forall i, k \tag{2}$$

$$C_i(k) \leqslant \min\{R_i(k), T_i^{\text{Cap}}\}, \quad \forall i, k \tag{3}$$

$$\sum_{i=1}^{I} T_i(k) \geqslant \max\{M_{\text{gov}}^{T}, M_{\text{com}}^{T}, 0\}, \quad \forall k \tag{4}$$

$$T_i(k) \leqslant T_i^{\text{Cap}}, \quad \forall i, k \tag{5}$$

$$S_i(k-1) + [C_i(k) - T_i(k)] \leqslant S_i^{\text{Cap}}, \quad \forall i, k \tag{6}$$

$$\sum_{i=1}^{I} S_i(k) \leqslant S_{\text{safe}}, \quad \forall k \tag{7}$$

Eq. (2) represents the lower-bound constraint in terms of hazardous-waste collection which is specified in consideration of two potential factors: (1) governmental regulations in terms of the minimal hazardous-waste collection amount, and (2) basic requirements for normal business operations. With the growing concern for environmental protection, there is a tendency for governments to compel hazardous-waste treatment companies to commit themselves to improvements in either local or global environmental protection, not merely operating for profit. Therefore, the regulation of minimum collection amount can be issued by the government as a basic requirement for the operations of hazardous-waste treatment companies. Moreover, hazardous-waste treatment companies may have their own waste collection strategies to maintain routine business operations. For the above reasons, the lower-bound waste collection constraint is formulated as expressed by Eq. (2).

Eq. (3) is set in consideration of the upper bound for time-varying hazardous waste collection. In contrast with Eq. (2), the upper-bound collection constraint serves to limit the collection amount associated with a given type i of hazardous waste to be less than either its real time-varying demand ($R_i(k)$) or the associated treatment capacity (T_i^{Cap}).

Similar to Eqs. (2) and (3), the lower- and upper-bound constraints associated with the activity of hazardous-waste treatment are involved in the proposed model, as expressed respectively by Eqs. (4) and (5). Herein, the lower-bound treatment constraint is determined by either one of the following two factors: (1) related governmental regulations and (2) basic requirements of normal business operations. In general, governmental regulations with respect to the minimal hazardous-waste treatment amount are used as normative criteria to assess if hazardous-waste treatment companies can meet their commitment in terms of hazardous-waste treatment. In addition, waste treatment companies may have their own waste treatment strategies to maintain routine business operations. Accordingly, the related parameters M_{gov}^{T} and M_{com}^{T} are involved with Eq. (4). In contrast with Eq. (4), the upper-bound treatment constraint (Eq. (5)) is readily determined by the treatment capacity (T_i^{Cap}).

Eqs. (6) and (7) correspond to the restrictions of disaggregated and aggregated storage amounts, respectively. From a disaggregated point of view, the time-varying storage amount of any given type of hazardous waste should be subject to the associated storage capacity, as shown in Eq. (6). In addition, considering the risk caused by the incompatibility among different types of hazardous wastes, the aggregated storage constraint (Eq. (7)) is set to ensure that the aforementioned safety requirement is satisfied in the proposed hazardous-waste reverse logistics system. Note that in Eq. (7), $S_i(k)$ can be further denoted by

$$S_i(k) = S_i(k-1) + [C_i(k) - T_i(k)] \tag{8}$$

It is noteworthy that, in addition to the aforementioned constraints, all the estimates of time-varying decision variables should be subject to the non-negative domain in order to meet the basic requirement of feasible solution.

3. Parameter estimates

For application of the proposed model, its input data are classified into two groups: (1) demand data which include the types of hazardous wastes, and the time-varying amount associated with each type of hazardous waste, and (2) supply-related parameters including the unit costs of storage, treatment, and transportation, related capacities as well as basic requirements, and so forth.

To generate the input data of the model, we selected the Nan-Tzi Industrial Processing Zone (Nan-Tzi IPZ) of Taiwan as the study site, aiming at five international high-technology manufacturers located there which are regarded as the major hazardous-waste resources in this special industrial zone. The Nan-Tzi IPZ of Taiwan is a special industrial zone which is located in the city of Kaohsiung, Taiwan, and administered by the government of Taiwan to facilitate the value-added procedures of import/export (I/E) goods, as well as transit goods. To overcome the existing intra-zone hazardous-waste treatment problem, the five manufacturers plan to form a specific organization to treat and distribute their hazardous wastes. Therefore, the aforementioned waste treatment case is explored in this study. For this study, historical demand data of hazardous wastes as well as interview data regarding the performance and basic requirements of business operations associated with these five manufacturers were collected.

The demand data are the un-processed hazardous wastes which were produced periodically by the aforementioned five high-technology enterprises in the Nan-Tzi IPZ of Taiwan. Conveniently, the historical waste demand data collected from each targeted enterprise were aggregated, and then classified, by their distinctive characteristics, into five groups coded, A1 to A5. Herein, wastes A1 and A2 are reusable; the others are not reusable, and need specific treatment technologies such as chemical-fixation, solidification, and incineration for final disposal. Then, the multi-type waste demand data were processed to generate a 10-time-step demand database. Table 1 presents the definitions of the five types of wastes and the processed demand-related data. Note that herein, a given 10-time-step period lasts five months, and each time step is correspondingly set to be half a month.

Table 1
Time-varying demands of hazardous wastes (unit: ton/time step)

Type of waste	Time step									
	1	2	3	4	5	6	7	8	9	10
A1	200	220	215	220	195	205	200	210	190	220
A2	250	230	250	235	270	250	240	260	255	230
A3	270	310	290	250	270	300	285	275	280	260
A4	240	200	210	230	225	245	220	205	200	235
A5	190	215	180	165	200	180	165	160	170	190

A1: metal waste reusable, A2: petrochemical waste reusable, A3: metal waste not reusable, A4: petrochemical waste not reusable, A5: waste residues not reusable.

Estimation of supply-related parameters was completed using interview data. In general, it is difficult to estimate supply-related parameters such as the unit operational costs directly from reported statistical data because of business confidentiality. With the aid of the administration of Nan-Tzi IPZ of Taiwan, interviews with high-level decision makers of the aforementioned five intra-zone high-technology manufacturers were conducted. The interviews included both open- and closed-ended questions. The responses were then used to analyze the potential operating performance and limitations of the planned waste-treatment co-organization in dealing with the zonal multi-type hazardous-waste problem. The analytical results of the interview data were then aggregated to identify the unit operational costs and the boundaries, appearing respectively in the objective function and constraints of the proposed model. Tables 2 and 3 present the estimated supply-related parameters.

Table 2
Estimated parameters used in the objective function

Type of waste	Parameter								
	$S_i(0)$ (ton)	a_i (\$/ton)	b_i (\$/ton)	d_i (\$/ton)	ω_i^{r} or ω_i^{d}	t_i^{r} or t_i^{d} (\$/ton)	t_i^{r} or t_i^{d} (\$/ton)	l_i^{c} (km)	l_i^{r} or l_i^{d} (km)
A1	500	500	1000	0	0.6	130	100	0.5	15
A2	870	600	780	0	0.5	130	105	0.6	15
A3	600	750	900	400	0.7	120	120	0.6	17
A4	780	900	1100	500	0.6	140	110	0.4	17
A5	650	670	850	550	0.8	140	115	0.8	17

Table 3
Estimated parameters used in the constraints

Type of waste	Parameter				
	M_{gov}^{C} or M_{com}^{C} (ton/time step)	M_{gov}^{T} or M_{com}^{T} (ton/time step)	T_i^{Cap} (ton/time step)	S_i^{cap} (ton)	S_{safe} (ton)
A1	1000	1000	240	2200	8500
A2	1000	1000	270	2000	8500
A3	1000	1000	320	1700	8500
A4	1000	1000	250	2100	8500
A5	1000	1000	220	2000	8500

4. Optimization results

In this section, numerical results for four cases demonstrate the potential of the proposed model for business strategic planning of hazardous-waste treatment enterprises. Given the 10-time-step time-varying demand data shown in Table 1, four cases associated with different sets of supply-related parameters (i.e., Cases 1–4) were investigated. The Lindo [1] software package (linear, interactive and discrete optimizer) 6.0 was used to search for the optimal solutions, i.e., the minimum total operational costs of the hazardous-waste reverse logistics system, in the cases studied. The following summarizes the operating conditions as well as numerical results associated with the four cases studied.

Case 1 herein serves as the contrast case in which all the predetermined parameters as well as presumed operating conditions remain the same as shown in Tables 2 and 3. With the case background mentioned previously, we attempted to search for the optimal solution for the issue of multi-type hazardous-waste treatment in EPS of Nan-Tzi IPZ, Taiwan. The numerical results obtained in this scenario are summarized in Table 4.

Table 4 indicates the applicability of the proposed method for Case 1. As can be seen in Table 4, utilizing the proposed model, the time-varying treatment amount associated with any given type i of hazardous waste tends to reach to its upper bound (T_i^{Cap}) under the condition that the time-varying demand exceeds the supply-side treatment capacity at each time step. However, considering the impact of storage cost, such a collection strategy as the time-varying collection amount being less than the associated real demand can be implemented at some time steps to minimize the total reverse logistics cost. This is particularly true for the hazardous wastes A3, A4, and A5, as illustrated by the shadowed regions shown in Table 4. Nevertheless, the aforementioned specific collection strategy may be ignored by traditional hazardous-waste treatment enterprises, resulting in the phenomenon that both the time-varying waste collection and treatment amounts reach the associated operational capacities at each time step.

In the following scenario, we explored three different cases (i.e., Cases 2–4) by strategically loosening the basic operational requirements, including the minimal amount associated with the activities of waste collection and treatment. The purpose of this scenario is to investigate the relative performance of the proposed method under diverse operational conditions, as compared with the results obtained in Case 1. In contrast with Case 1, the parameters of Case 2 remain the same except for the minimal collection requirements, namely M_{gov}^C and M_{com}^C shown in Eq. (2), i.e., the parameters M_{gov}^C and M_{com}^C are both reduced from the preset value of 1000–500, representing an adjusted waste collection strategy in response to a looser governmental regulation with respect to the minimal collection amount. Compared to Cases 1 and 2, Case 3 presents another specific operating condition under which not only the minimal collection requirements (i.e., M_{gov}^C and M_{com}^C),

[1] Lindo 6.0 is a commercial optimization package, which has been broadly used for formulating and solving diverse optimization problems. The fundamentals of Lindo were proposed by Schrange, and its commercial distribution began in 1979. Citing a survey of business schools, OR/MS Today magazine reported, “The use of operations research and management science software is dominated by LINDO”. Therefore, the Lindo 6.0 is conveniently employed in this study for solving the cost-minimization problem of the hazardous-waste reverse logistics operations.

Table 4
Optimal solutions associated with Case 1

Step	C_{A1} (k)	T_{A1} (k)	S_{A1} $(k-1)$	C_{A2} (k)	T_{A2} (k)	S_{A2} $(k-1)$	C_{A3} (k)	T_{A3} (k)	S_{A3} $(k-1)$	C_{A4} (k)	T_{A4} (k)	S_{A4} $(k-1)$	C_{A5} (k)	T_{A5} (k)	S_{A5} $(k-1)$
1	200	240	500	250	270	870	185	320	600	0	250	780	190	220	650
2	220	240	460	230	270	850	310	320	465	200	250	530	215	220	620
3	215	240	440	250	270	810	255	320	455	0	250	480	180	220	615
4	180	240	415	220	270	790	235	320	390	230	250	230	165	220	575
5	195	240	395	270	270	755	110	320	320	75	250	210	170	220	520
6	205	240	350	250	270	755	300	320	110	245	250	35	180	220	470
7	200	240	315	240	270	735	230	320	90	220	250	30	0	220	430
8	210	240	275	260	270	705	275	320	0	205	250	0	160	220	210
9	190	240	245	255	270	695	80	320	240	200	250	50	140	220	370
10	220	240	195	230	270	680	260	320	0	235	250	0	190	220	290

Total reverse logistics cost for 10 time steps: US$1,080,110.

but also the minimal treatment requirements (i.e., M^T_{gov} and M^T_{com} shown in Eq. (4)), are reduced to the value of 500 tons per time step. By contrast, Case 4 represents an extreme deregulation case in which the lower-bound constraints associated with the activities of waste collection and treatment (i.e., Eqs. (2) and (4)) are dropped. Moreover, the time-varying hazardous-waste collection amount $(C_i(k))$ is set to be the same as the associated time-varying real demand $(R_i(k))$ without considering the treatment capacity.

The results associated with Cases 2–4 are presented in Tables 5–7, respectively. In addition, Table 8 summarizes the reductions in the total reverse logistics costs associated with these cases when compared with Case 1. The following provides several generalizations obtained in these study cases.

(1) A looser requirement in terms of the minimal collection and treatment amount helps to improve the performance of the proposed hazardous-waste reverse logistics system as compared with the results of Case 1. As can be seen in Tables 5 and 6, the total reverse logistics costs have been reduced by 31.2%, and 49.1%, respectively, in comparison with those in Table 4 of Case 1. Such a result seems supportive of governmental deregulation of hazardous-waste treatment companies.
(2) Without violating the basic operating requirements, the hazardous-waste treatment alliance tends to eliminate some time-step activities in minimizing the total reverse logistics operating costs. As can be observed in Table 6, the hazardous wastes A3 and A5 are not processed beyond step 4. Another interesting example is that the collection activity associated with the hazardous waste A4 starts from time step 4, and then, is discontinued twice during the 10-time-step period.
(3) The extreme deregulation condition postulated in Case 4 cannot ensure improved operating performance of the proposed reverse logistics system relative to the other loose regulation cases. As can be observed by comparing the results of Tables 6 and 7, the total reverse logistics cost increased under deregulation. Such a generalization also implies the importance of appropriately determining the basic operational requirements of a hazardous-waste reverse logistics system in response to governmental deregulation.

In addition, it is induced from these numerical results that the trade-off relationship between the commitment of a hazardous-waste treatment company to the improvement in environmental protection and its unique benefits from professional business operations is worth noting, both by the government and to the related business entity. Correspondingly, both the public and private sides must appropriately identify the relationship between the marginal cost and benefit of a hazardous-waste reverse logistics system before making any decisions relevant to system operations. Further research is also warranted for analysis that elaborately compares the estimated reductions in the total reverse logistics cost with any potential deregulation-induced negative effects on environmental protection. Using the proposed method together with any measurement tool for environmental impacts, the government can evaluate the alternatives of deregulation policies with respect to the minimal waste collection amount committed to the hazardous-waste treatment enterprises. As for the private side, a hazardous-waste treatment company can use the proposed method to adjust their waste collection strategies in response to any related requirements made by the government.

Table 5
Optimal solutions associated with Case 2

Step	C_{A1} (k)	T_{A1} (k)	S_{A1} $(k-1)$	C_{A2} (k)	T_{A2} (k)	S_{A2} $(k-1)$	C_{A3} (k)	T_{A3} (k)	S_{A3} $(k-1)$	C_{A4} (k)	T_{A4} (k)	S_{A4} $(k-1)$	C_{A5} (k)	T_{A5} (k)	S_{A5} $(k-1)$
1	200	240	500	30	270	870	0	320	600	0	250	780	0	220	650
2	220	220	240	230	270	850	310	320	465	200	250	530	215	220	620
3	215	65	240	250	270	810	255	320	455	0	250	480	180	220	615
4	220	220	240	220	270	790	235	320	390	230	250	230	165	220	575
5	195	70	240	270	270	755	110	320	320	75	250	210	170	220	520
6	205	205	240	250	270	755	300	320	110	245	250	35	180	220	470
7	200	200	240	240	270	735	230	320	90	220	250	30	0	220	430
8	210	210	240	260	270	705	275	320	0	205	250	0	160	220	210
9	190	190	190	255	270	695	80	320	240	200	250	50	140	220	370
10	220	220	220	230	270	680	260	320	0	235	250	0	190	220	290

Total reverse logistics cost for 10 time steps: US$702,933.

Table 6
Optimal solutions associated with Case 3

Step	C_{A1} (k)	T_{A1} (k)	S_{A1} $(k-1)$	C_{A2} (k)	T_{A2} (k)	S_{A2} $(k-1)$	C_{A3} (k)	T_{A3} (k)	S_{A3} $(k-1)$	C_{A4} (k)	T_{A4} (k)	S_{A4} $(k-1)$	C_{A5} (k)	T_{A5} (k)	S_{A5} $(k-1)$
1	140	240	500	0	270	870	0	320	600	0	250	780	0	220	650
2	220	240	400	230	270	600	310	320	280	0	250	530	100	220	430
3	0	240	380	0	270	560	50	320	270	0	250	280	0	220	310
4	220	240	140	130	270	290	250	250	0	220	250	30	130	220	90
5	195	240	120	170	270	150	0	0	0	180	180	0	0	0	0
6	205	240	75	250	270	50	0	0	0	0	0	0	0	0	0
7	200	240	40	240	270	30	0	0	0	0	0	0	0	0	0
8	210	155	0	260	245	0	0	0	0	90	90	0	0	0	0
9	185	240	55	255	270	15	0	0	0	0	0	0	0	0	0
10	220	220	0	230	230	0	0	0	0	40	40	0	0	0	0

Total reverse logistics cost for 10 time steps: US$550,000.

Table 7
Optimal solutions associated with Case 4

Step	$C_{A1}(k)$	$T_{A1}(k)$	$S_{A1}(k-1)$	$C_{A2}(k)$	$T_{A2}(k)$	$S_{A2}(k-1)$	$C_{A3}(k)$	$T_{A3}(k)$	$S_{A3}(k-1)$	$C_{A4}(k)$	$T_{A4}(k)$	$S_{A4}(k-1)$	$C_{A5}(k)$	$T_{A5}(k)$	$S_{A5}(k-1)$
1	200	240	500	250	270	870	270	320	600	240	250	780	190	220	650
2	220	240	460	230	270	850	310	320	550	200	250	770	215	220	620
3	215	240	440	250	270	810	290	320	540	210	250	720	180	220	615
4	220	240	415	235	270	790	250	320	510	230	250	680	165	220	575
5	195	240	395	270	270	755	270	320	440	225	250	660	200	220	520
6	205	240	350	250	270	755	300	320	390	245	250	635	180	220	500
7	200	240	315	240	270	735	285	320	370	220	250	630	165	220	460
8	210	0	275	260	270	705	275	320	335	205	250	600	160	220	405
9	190	0	485	255	0	695	280	320	290	200	250	555	170	220	345
10	220	0	675	230	0	950	260	0	250	235	0	505	110	0	295

Total reverse logistics cost for 10 time steps: US$702,933.

Table 8
Relative improvement in the total reverse logistics cost (compared to Case 1)

Comparison measure	Case			
	Case 1	Case 2	Case 3	Case 4
Total cost (US$)	1,080,110	702,933	550,000	991,494
Cost reduction (compared to Case 1)		377,117	530,110	88,616
Relative improvement (%)		31.2	49.1	8.2

5. Conclusion

This paper has presented a cost-minimization model for minimizing the total operating costs of a multi-time-step, multi-type hazardous-waste reverse logistics system. By identifying the critical activities and related basic requirements involved in the process of hazardous-waste reverse logistics operations, a discrete-time linear objective function coupled with six groups of constraints are formulated.

Compared to early literature on addressing hazardous-waste treatment problems, the model found in this study has two distinctive features. First, by coordinating the critical activities of reverse logistics management, the proposed method addresses the classical hazardous-waste treatment problem with a systematical management strategy rather than with waste-treatment technologies, as conventionally employed. Second, internal and external factors, e.g., basic requirements of business operations and governmental regulations, are taken into account in the model, thereby addressing the performance of a hazardous-waste reverse logistics system. Results from applying the model to several cases suggest that total reverse logistics costs of hazardous-waste treatment systems can be reduced by more than 49% by carefully relaxing the constraints for the minimal collection and treatment requirements (i.e., Eqs. (2) and (4)).

A manager of a hazardous-waste treatment facility can employ the proposed model to strategically determine the time-varying waste collection amounts and treatment amounts in response to the variety of waste demands from multiple waste resources under the goal of minimizing total logistics costs. In future research, cost minimization of hazardous-waste treatment will be modeled in a supply chain management framework.

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Appendix A. Variables specified in the proposed model

The variables and parameters shown in the proposed cost-minimization model are summarized as follows:

- a_i: the unit cost of storage associated with a given type i of hazardous waste.
- b_i: the unit cost of treatment associated with a given type i of hazardous waste.
- $C_i(k)$: the amount of time-varying raw material associated with a given type i of hazardous waste which is scheduled to be collected at time step k.
- $C_i(k+1)$: the amount of time-varying raw material associated with a given type i of hazardous waste which is scheduled to be collected at time step $k+1$.
- d_i: the unit cost of final disposal associated with a given type i of hazardous waste.
- I: the total number of types of raw hazardous wastes.
- I_γ: a subset of I, which represents the total number of types of raw hazardous wastes that are scheduled to be processed directly for reuse coded with 'r'.
- l_i^{c}: the total transportation distance associated with a given type i of hazardous waste for the activity of collection coded with 'c'.
- l_i^{r}: the total transportation distance associated with a given type i of hazardous waste for the activity of reuse coded with 'r'.
- l_i^{d}: the total transportation distance associated with a given type i of hazardous waste for the activity of disposal coded with 'd'.
- M_{com}^C: the minimal hazardous-waste collection amount pre-determined by a given hazardous-waste treatment company in consideration of the basic requirements for business operations.
- M_{gov}^C: the mandatory minimum amount required by related governmental regulations for business operations of hazardous-waste collection at any given time step k, which is set to be zero if the related regulations do not exist at the study site.
- M_{com}^T: the minimal treatment amount pre-determined strategically by a given hazardous-waste treatment company to meet the basic requirements for normal business operations.
- M_{gov}^T: the mandatory minimal treatment amount required by related governmental regulations at any given time step, which is equal to zero if the related regulations do not exist at the study site.
- $R_i(k)$: the time-varying demand from the waste source for the collection of a given type i of hazardous waste at time step k.
- $S_i(0)$: the storage amount associated with a given type i of hazardous waste at the initial time step 0.
- $S_i(k-1)$: the time-varying storage amount associated with a given type i of hazardous waste at time step $k-1$.
- $S_i(k)$: the time-varying storage amount associated with a given type i of hazardous waste at time step k.
- S_i^{Cap}: the storage capacity associated with a given type i of hazardous waste.
- $T_i(k)$: the time-varying raw material amount associated with a given type i of hazardous waste which is scheduled to be treated at time step k.
- $T_i(k+1)$: the time-varying raw material amount associated with a given type i of hazardous waste which is scheduled to be treated at time step $k+1$.
- T_i^{Cap}: the treatment capacity associated with a given type i of hazardous waste.
- t_i^{c}: the unit cost in terms of transporting the given type i of hazardous waste for the activity of raw hazardous-waste collection coded with 'c'.
- t_i^{d}: the unit cost in terms of transporting the given type i of hazardous waste for the activity of final disposal coded with 'd'.

- t_i^{r}: the unit cost in terms of transporting the given type i of hazardous waste for the activity of reuse coded with 'r'.
- ω_i^{d}: the output/input (O/I) ratio parameter associated with the given type i of hazardous waste processed for the activity of final disposal coded with 'd'.
- ω_i^{r}: the output/input (O/I) ratio parameter associated with the given type i of hazardous waste processed for the activity of reuse coded with 'r'.

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