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Computers & Operations Research 34 (2007) 1442–1462

computers &
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A coordinated reverse logistics system for regional management of multi-source hazardous wastes

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Available online 10 August 2005

Abstract

This paper presents a coordinated reverse logistics (CRL) management system for the treatment of multi-source hazardous wastes in a given region, in this case, a specific high-technology manufacturing zone. A linear multi-objective analytical model is formulated that systematically minimizes both the total reverse logistics operating costs and corresponding risks. In addition to inter-organizational logistics operating factors, environmental concerns are considered and formulated as corresponding risk-related constraints. Using the proposed model, results of numerical studies indicate that when the aspect of risk-induced penalties is not considered, the operational costs of regional hazardous-waste management can be efficiently reduced by 58%, compared to the existing operational costs at the study site. In addition, it is also observed that the corresponding weight associated with the risk-induced objective function embedded in the proposed model seems to have a significant effect on the CRL costs.

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Keywords: Coordinated reverse logistics management; Hazardous wastes treatment; Risk management; Environmental protection

1. Introduction

With the progressive increase of environmental concerns, the efficiency of coordinated reverse logistics (CRL) has drawn increasing attention for regional hazardous-waste management. As noted in Stock [1], since multiple organizations must be involved in reverse logistics, partnerships or alliances are needed to achieve optimal results. Here, coordinated hazardous-waste reverse logistics refers to a process that

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systematically manages the flows of multi-source hazardous wastes from high-technology product manufacturing in a given region. Compared to traditional strategies of reverse logistics, the defined CRL may exhibit three distinctive features. First, CRL aims to achieve system optimization of regional multi-source waste treatment, rather than individual optimization for a given enterprise. As a consequence, regional environmental protection becomes a significant issue in formulating the corresponding reverse logistics operational problems. Second, because of the geographical concentration of waste sources, a CRL system may readily coordinate the waste collection plans associated with the target manufacturers in the given region. Accordingly, it may facilitate the formation of a centralized reverse logistics system that regulates and integrates the corresponding activities, including waste storage, treatment, transportation, and final disposal for regional waste management. Third, the variety of material characteristics of hazardous wastes coupled with specific environmental regulations can make regional hazardous-waste treatment problems more complex. Therefore, the trade-off relationship between the reduction of aggregated reverse logistics operational costs and the alleviation of induced environmental impacts must be considered in seeking optimum solutions.

Despite the significance of CRL for regional hazardous waste management, there are a limited number of related studies in previous literature. Previous studies of reverse logistics mainly aim at the optimization of corresponding facility network planning and transportation routing for private purposes of business operations. Related issues include using mathematical models to determine the type, location, and size of treatment and disposal facilities, and transportation routes from waste sources to specified facilities. To a certain extent, minimization of private business operational costs is the major concern in previous literature. Some existing models are discussed below.

An early example is the study by Peirce and Davidson [2], which utilizes a linear programming method to formulate the optimization problem of transportation routing among transfer stations, disposal facilities, and long-term storage impoundments. However, their model may be limited to the determination of cost-effective waste transportation routes. Similarly, Jennings and Scholars [3] formulated 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. Nevertheless, the issues of multi-type waste collection and transportation are not considered in their study. In contrast, Zografos and Samara [4] deal only with the problem of a single type of waste to achieve the objectives of minimizing transportation risk, travel time, and disposal risk. Furthermore, in Hu et al. [5], a mathematical linear programming method is utilized to investigate the cost reduction of a decision-making support system used for managing multi-source hazardous-waste reverse flows.

More recently, the use of sophisticated hybrid methods for multiple purposes has drawn increasing attention in early research. ReVelle et al. [6] proposed a synthesized linear programming method for managing the reverse logistics flows of spent nuclear fuel. They synthesized both the 0-1 integer and multi-objective programming models to simultaneously identify waste storage facilities and to determine the shortest paths for shipping. Koo et al. [7] used hybrid techniques, including fuzzy theories and multi-objective programming models to search for hazardous waste treatment centers in South Korea. Similar attempts can also be found in Stowers and Palekar [8] and Nema and Gupta [9]. Nevertheless, the scope of this research is still limited to only certain areas of hazardous-waste reverse logistics.

Although there have been remarkable advances made in the prior literature, coordinated hazardous-waste reverse logistics deserves more investigation, due to the lack of both pertinent literature and knowledge about its potential to reduce environmental pollution. Currently, there are a growing number of researchers advocating system optimum solutions to address issues of reverse logistics. In a study of the

plastics reverse logistics process, Pohlen and Farris [10] have identified a number of fundamental functions, including collection, separation, transitional processing, delivery and integration, within a typical reverse logistics channel. Similar viewpoints can be found in Fleischmann et al. [11], where the interface between reverse logistics activities, e.g., inventory control of returned flows and reverse distribution, is particularly emphasized. Carter and Ellram [12] further points out the significance of specifying a well-grounded conceptual framework for reverse logistics management. In addition, the concept of reverse supply chain, referring to the extension of reverse logistics, is further highlighted in Tsouflias et al. [13], where a case study regarding the reuse of starting, lighting and ignition (SLI) batteries is used as an example.

Accordingly, we attempt to propose a CRL system formulated as a multi-objective linear programming model for regional hazardous waste management. In addition to minimizing the aggregate reverse logistics costs, the proposed method aims to minimize the risk-induced penalties resulting from activities in the reverse logistics operational process. More specifically, the time-varying waste collection amount associated with each given waste source (i.e., any target manufacturer in the region) is regulated by the proposed reverse logistics system and coordinated with other activities, including storage, processing, distribution and final treatment. As such, the proposed model searches for a system-wide optimization condition, which considers both the reverse logistics operational costs and induced environmental impacts measured by corresponding risk functions.

The rest of this paper is organized as follows. In Section 2, we introduce a conceptual framework that describes the process of multi-source hazardous-waste return flows in the proposed CRL system and formulate it as a multi-objective optimization problem. In Section 3, the tasks for input data acquisition, including parameter estimation, are presented. Section 4 describes the numerical studies, including the test scenarios and corresponding numerical results. In addition, findings observed from these numerical results are summarized and discussed to demonstrate the potential advantages and applicability of the proposed method. Concluding remarks, together with suggestions for future research, are summarized in Section 5.

2. Model

The conceptual framework of the model is presented in Fig. 1, which shows its six primary process components: (1) collection, (2) storage, (3) transitional treatment, (4) distribution, (5) final disposal, and (6) recycling. The functionality of this system focuses on systematically managing the reverse physical flows through the entire process, and here, the major waste sources refer to given types of hazardous wastes produced by given manufacturers located in a given industrial region.

To specify the study scope and to facilitate model formulation, several assumptions are postulated

- (1) The facility network configurations of the proposed reverse logistics system are given. These primarily include geographical characteristics of the corresponding facilities and their functional capacities.
- (2) The CRL distribution center is set within the given region to facilitate the activities of collection, storage, transitional treatment, and outbound distribution.
- (3) The time-varying demands (i.e., $D_i(k)$) for the hazardous waste treatment are known. Here, the time-varying demand ($D_i(k)$) refers to the amount of a given type i of hazardous waste that is produced

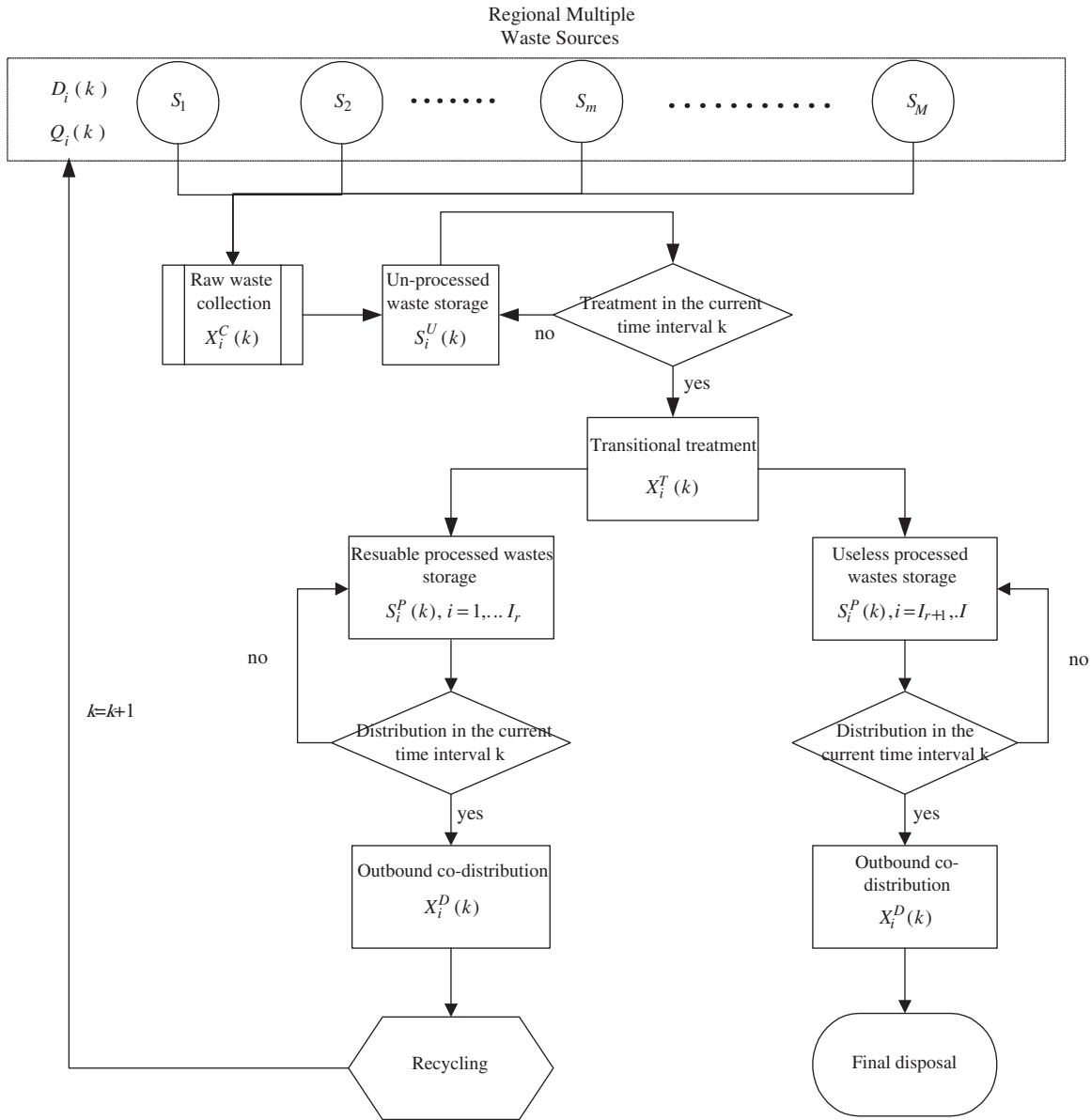


Fig. 1. Conceptual framework of the proposed coordinated reverse logistics system.

by a given waste source at a given time step k . In practice, these time-varying demands can be easily predetermined according to the plans of the corresponding manufacturers.

- (4) The storage functions provided for both unprocessed and processed wastes are separate, due to their different inventory costs and corresponding operational risks.

Given these assumptions, a multi-objective optimization model is formulated to seek optimal solutions with the goal of minimizing both the total operational costs and the corresponding risk-induced penalties

of the reverse logistics system. However, it is almost certain that these two goals will conflict with each other in the corresponding reverse logistics operational process. A typical example is the trade-off between minimizing transitional treatment costs and corresponding risks caused by unprocessed wastes. And thus, the proposed CRL system is formulated as a discrete-time, multi-objective optimization problem.

The model is composed mainly of two objective functions, i.e., cost-minimization (Min C) and risk-minimization (Min R), and 10 sets of constraints. In the proposed model, three types of decision variables, $X_i^C(k)$, $X_i^D(k)$, and $X_i^T(k)$, are specified to determine the time-varying amounts of physical flows associated with a given waste type i in the process of three corresponding CRL activities. These activities are raw-waste collection (superscript C), outbound logistics distribution (superscript D), and transitional treatment (superscript T), at a given time step k . In addition, 10 sets of constraints are included to consider the effects on the domains of feasible optimal solutions, due to logistics requirements, either implemented by governmental regulations or limited by operating capacities. Accordingly, given the total number of types of hazardous wastes I and that of time intervals involved in a given multi-interval time horizon K , we then have $(3 \cdot I \cdot K)$ decision variables coupled with $[(9I + 3) \cdot K]$ constraints involved in the proposed model. The mathematical formulation of the model is detailed below.

According to the proposed CRL conceptual framework (see Fig. 1), the proposed objective function with respect to aggregate reverse logistics costs (C) includes six corresponding items: (1) total collection cost (C_C), (2) total storage cost (C_S), (3) total transitional treatment cost (C_T), (4) total distribution cost (C_D), (5) total final disposal cost (C_F), and (6) potential revenue resulting from the reuse of recycled materials through the reverse logistics process (\tilde{C}_R). Therefore, the corresponding mathematical form is given by

$$\begin{aligned} \text{Min C} &= \text{Min}\{C_C + C_S + C_T + C_D + C_F - \tilde{C}_R\} \\ &= \text{Min} \sum_{k=1}^K \sum_{i=1}^I [c_i^C \times X_i^C(k)] + \left\{ \sum_{i=1}^I \left[c_i^U \times \sum_{k=1}^K S_i^U(k) + c_i^P \times \sum_{k=1}^K S_i^P(k) \right] \right\} \\ &\quad + \sum_{k=1}^K \sum_{i=1}^I [c_i^T \times X_i^T(k)] + \sum_{k=1}^K \sum_{i=1}^{I_H} (c_i^D \times l_i^H) \times X_i^D(k) \\ &\quad + \sum_{k=1}^K \sum_{i=I_H+1}^I (c_i^D \times l_i^F + c_i^F) \times X_i^D(k) - \sum_{k=1}^K \sum_{i=1}^{I_G} b_i \times X_i^D(k), \end{aligned} \tag{1}$$

$$\begin{aligned} \Rightarrow \text{Min C} &= \text{Min} \sum_{k=1}^K \sum_{i=1}^I \{ [c_i^C \times X_i^C(k)] + [c_i^U \times S_i^U(k) + c_i^P \times S_i^P(k)] + [c_i^T \times X_i^T(k)] \} \\ &\quad + \sum_{k=1}^K \sum_{i=1}^{I_H} [c_i^D \times l_i^H - b_i] \times X_i^D(k) + \sum_{k=1}^K \sum_{i=I_H+1}^I (c_i^D \times l_i^F + c_i^F) \times X_i^D(k), \end{aligned} \tag{2}$$

where b_i represents the unit benefit for selling a given type i of reusable wastes after the transitional treatment process; the parameters c_i^C , c_i^D , c_i^F , and c_i^T represent the unit costs associated with a given waste type i in the process of the corresponding CRL activities of raw-waste collection (superscript C), outbound logistics distribution (superscript D), final disposal (superscript F), and transitional treatment (superscript T), respectively; similarly, c_i^P and c_i^U represent the corresponding unit costs of storage associated with

a given processed (superscript P) and unprocessed (superscript U) waste type i , respectively; I_H represents the total number of types of reusable (subscript H) wastes after the process of transitional treatment; l_i^F and l_i^H represent the specific distribution lengths associated with a given type i of processed wastes for the activities of final disposal and reuse (superscript H), respectively; $S_i^P(k)$ and $S_i^U(k)$ represent the time-varying storage amounts associated with a given type i of processed and unprocessed wastes at a given time step k , respectively. Here $S_i^P(k)$ and $S_i^U(k)$ can be further expressed as

$$S_i^P(k) = a_i X_i^T(k) + S_i^P(k - 1) - X_i^D(k), \tag{3}$$

$$S_i^U(k) = X_i^C(k) + S_i^U(k - 1) - X_i^T(k), \tag{4}$$

where a_i represents the material transition rate associated with a given type i of hazardous waste through transitional treatment. Note that here, $X_i^T(k)$ is referred to as the time-varying amount of a given unprocessed hazardous waste i input to the transitional treatment process. In (3), considering the change of the corresponding waste amount after the process of transitional treatment, the corresponding time-varying transitional treatment amount $X_i^T(k)$ is multiplied by a_i , forming the new material amount to update the corresponding processed-waste storage amount $S_i^P(k)$. In contrast, there is no need for physical transformation during unprocessed waste storage, and thus, the value of $X_i^T(k)$ is directly used to update the corresponding unprocessed waste storage amount $S_i^U(k)$.

The objective function with respect to risk-minimization (Min **R**) aims to alleviate, to the greatest extent, the aggregate operational risks potentially existing in the proposed CRL process. Four corresponding items are involved: (1) uncollected raw-material exposure risks (R_E), (2) storage risks (R_S), (3) treatment risks (R_T), and (4) vehicle-based distribution risks (R_D). Accordingly, the mathematical form of Min **R** is given by

$$\begin{aligned} \text{Min R} &= \text{Min}\{R_E + R_S + R_T + R_D\} \\ &= \text{Min} \sum_{k=1}^K \sum_{i=1}^I \{g_i^E \times [D_i(k) - X_i^C(k) + Q_i(k)]\} \\ &\quad + \sum_{k=1}^K \sum_{i=1}^I \{g_i^U \times [X_i^C(k) + S_i^U(k - 1) - X_i^T(k)]\} \\ &\quad + \sum_{k=1}^K \sum_{i=1}^I [g_i^T \times X_i^T(k)] + \sum_{k=1}^K \sum_{i=1}^I \left\{ \left[g_i^C \times \frac{X_i^C(k) \times l_i^C}{\bar{v}_C} \right] + \left[g_i^D \times \frac{X_i^D(k) \times l_i^D}{\bar{v}_D} \right] \right\}, \end{aligned} \tag{5}$$

where g_i^C and g_i^D represent the respective vehicle-based unit increments of risk-induced penalties associated with a given type i of wastes in the process of collection and of outbound distribution, respectively. Similarly g_i^E , g_i^T , and g_i^U represent the unit increments of risk-induced penalties associated with a given type i of wastes in the status of exposure (superscript E) in any given waste source and in the activities of transitional treatment and unprocessed waste storage, respectively. The parameters l_i^C and l_i^D represent the distribution lengths associated with a given type of waste i in the activities of raw-waste collection and outbound logistics distribution, respectively; in contrast, \bar{v}_C and \bar{v}_D represent the corresponding loading limit of a unit transportation vehicle associated with the activities of raw-waste collection and outbound logistics distribution, respectively; and $Q_i(k)$ represents the remaining waste amount associated with

hazardous waste i , which has not be collected at the beginning of a given time step k . Accordingly, $Q_i(k)$ is given by

$$Q_i(k) = D_i(k-1) + Q_i(k-1) - X_i^C(k-1). \quad (6)$$

The aforementioned risk assessment involves identification of the corresponding CRL activities that may contribute to undesirable events (e.g., accidents, environmental and ecological impacts) and monetary quantification of the induced risks. Although there are numerous analytical methods that have been proposed to quantify risks [14–19], it is generally agreed that risk estimation should reflect the nature of occurrence probabilities of undesirable events and the corresponding penalties for these events, namely, the costs of potential risks. Accordingly, in this study we introduce the idea of incremental risk-induced penalty costs to deal with risk quantification. Here, a unit increment represented by g_i^* , as shown in (5), refers to the monetary value of a risk-induced penalty that is caused by a given unit of physical amount associated with a given CRL-related activity. Correspondingly, each disaggregate risk item shown in (5) is assumed to have a linear relationship with the corresponding waste quantity, and thus, is formulated as a deterministic penalty cost function with a specific incremental penalty cost parameter. Briefly, the greater the amount of waste materials that are held, the greater the corresponding penalty should be paid, due to the higher probability of event occurrence.

Note that the above concept is similar to the idea of marginal external costs, which has been widely utilized in previous literature to estimate the marginal social costs, for which respective users should pay, in addition to normal out-of-pocket payment [17,20–28]. This similarity is our main reason for applying this concept to quantify the respective risk-related objective function in our proposed model.

Considering the diverse potential effects of the aforementioned two goals (i.e., cost and risk minimizations) on the corresponding CRL decision process, two positive weights (i.e., w_C and w_R) are introduced. In addition, the difference of measurement scales associated with costs and risks may influence the determination of optimal solutions. Therefore, the proposed multi-objective functions are rewritten as a composite form (\mathbf{U}) given by

$$\mathbf{U} = w_C \tilde{\mathbf{C}} + w_R \tilde{\mathbf{R}}, \quad (7)$$

where the sum of the weights given to the cost and risk terms, i.e., w_C and w_R , should be equal to 1; and the respective values of w_C and w_R depend on the decision makers of the CRL system; $\tilde{\mathbf{C}}$ and $\tilde{\mathbf{R}}$ represent the normalized forms of the corresponding aggregate operational costs and risks, respectively, and are given by

$$\tilde{\mathbf{C}} = \frac{\mathbf{C} - C_{\min}}{C_{\max} - C_{\min}}, \quad (8)$$

$$\tilde{\mathbf{R}} = \frac{\mathbf{R} - R_{\min}}{R_{\max} - R_{\min}}. \quad (9)$$

In (8) and (9), C_{\min} and R_{\max} represent the estimates of aggregate operational costs and risks measured, in the case that only the cost minimization problem is considered (i.e., w_C is set to be 1); and, in contrast, C_{\max} and R_{\min} represent the corresponding estimates measured, in the case that only the risk minimization problem is involved (i.e., w_R is set to be 1).

In addition, considering the logistics requirements either compelled by governmental regulations or limited by operating capacities, 10 sets of constraints, shown as follows, are involved in the proposed model.

$$\sum_{i=1}^I X_i^C(k) \geq \max \{ \mathbf{M}_G^C, \mathbf{M}_B^C, 0 \} \quad \forall k, \tag{10}$$

$$X_i^C(k) \geq \underline{M}_i^C \quad \forall i, k, \tag{11}$$

$$X_i^C(k) \leq D_i(k) + Q_i(k) \quad \forall i, k, \tag{12}$$

$$\sum_{i=1}^I X_i^T(k) \geq \max \{ \mathbf{M}_G^T, \mathbf{M}_B^T, 0 \} \quad \forall k, \tag{13}$$

$$X_i^T(k) \leq \bar{M}_i^T \quad \forall i, k, \tag{14}$$

$$S_i^U(k) \leq \bar{M}_i^U \quad \forall i, k, \tag{15}$$

$$S_i^P(k) \leq \bar{M}_i^P \quad \forall i, k, \tag{16}$$

$$\sum_{i=1}^I S_i^U(k) \leq \mathbf{M}^U \quad \forall k, \tag{17}$$

$$X_i^D(k) \leq \bar{M}_i^D \quad \forall i, k, \tag{18}$$

$$X_i^*(k) \geq 0 \quad \forall i, k, * \tag{19}$$

where \underline{M}_i^C represents the minimal requirement for the collection amount of unprocessed hazardous waste i at any given time step; \bar{M}_i^D , \bar{M}_i^P , \bar{M}_i^T , and \bar{M}_i^U represent the corresponding facility capacities for the activities of outbound distribution, processed waste storage, waste transitional treatment, and unprocessed waste storage, respectively; \mathbf{M}_G^C and \mathbf{M}_G^T represent the mandatory minimum amounts required by governmental regulations (subscript G) for the CRL activities of corresponding waste collection and transitional treatment at any given time step k (which are set to be zero, if the related regulations do not exist at the study site). In contrast, \mathbf{M}_B^C and \mathbf{M}_B^T represent the minimal amounts associated with the activities of hazardous-waste collection and transitional treatment that are predetermined by decision makers of the CRL system in consideration of economy of scale for business operations (subscript B), respectively; and \mathbf{M}^U represents the maximal aggregate amount allowable for storing the unprocessed hazardous wastes at the study site due to regional safety concerns.

Eqs. (10) and (11), respectively, denote the aggregate and disaggregate lower-bound constraints of unprocessed hazardous-waste collection, considering two potential factors: (1) governmental regulations for the minimal hazardous-waste collection amount, and (2) basic requirements for normal CRL operations. With the increased concern about environmental issues, 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 to operate merely for profit. Therefore, the government may issue regulations to regulate the minimum collection amount of CRL operations for regional hazardous-waste management. In addition, any given CRL organization may have their own waste collection strategies to maintain routine business operations. For these reasons, the lower-bound waste collection constraints are formulated as given by (10) and (11).

In contrast, (12) is set to specify the upper bound for time-varying hazardous waste collection. For each given type of waste i , the time-varying collection amount should not exceed the corresponding cumulative waste amount, i.e., the sum of the new waste demand ($D_i(k)$) and the corresponding remaining demand ($Q_i(k)$) at any given time step k .

Similar to (10)–(12), the lower- and upper-bound constraints associated with the activity of hazardous-waste transitional treatment are specified, as (13) and (14), respectively. 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, the corresponding governmental regulations are used as normative criteria to assess if any given waste treatment organization can meet its commitment to waste transitional treatment, at any given time step. In addition, companies may have their own waste treatment strategies to maintain routine business operations. Accordingly, the related parameters \mathbf{M}_G^T and \mathbf{M}_B^T are involved with (13). In contrast with (13), the upper-bound treatment constraint (14) is readily determined by the respective transitional treatment capacity (\bar{M}_i^T).

Eqs. (15) and (16) correspond to the restrictions of disaggregated storage amounts associated, respectively, with given unprocessed and processed wastes. From a disaggregated point of view, the time-varying waste storage amount should be subject to the corresponding facility capacity in storage, and thus is formulated as shown in (15) and (16).

In addition, considering the potential risk caused by the incompatibility of different types of unprocessed hazardous wastes that are gathered in a given space or facility, in some cases, a governmental administration, e.g., the environmental protection administration (EPA), may issue regulations to restrict the aggregated storage amount of these wastes, as presented in (17), for regional risk management. If such regulations do not exist in practice, the corresponding upper bound \mathbf{M}^U can be set to be approximately infinity.

Eq. (18) is set by considering the outbound logistical distribution capacity, due to the limitation of the corresponding available fleet size and of scheduling.

It is noteworthy that all the estimates of time-varying decision variables should be subject to the non-negative domain, as shown in (19), to meet the basic requirement of a feasible solution.

3. Input data acquisition

To apply the proposed model, two groups of input data are generated: (1) waste demand data, referring to the time-varying amount associated with each type of hazardous waste at a given time step; and (2) model parameters, e.g., the unit costs and increments of monetary risks associated with the corresponding CRL activities (shown in the objective functions) and the corresponding upper and lower bounds (shown in the specified constraints). In the following numerical studies, we specify 1 month as the unit length of a time step and 12 time steps (i.e., 1 year) as the time horizon for planning.

To estimate the input data of the model, we selected the Hsinchu Science-based Industrial Park (HSIP) of Taiwan as the study site. This site is regarded as the center of Taiwanese high-technology manufacturing industries, and also as the major source of industrial hazardous wastes in northern Taiwan. Out of 312 high-tech manufacturers, 123 have integrated circuit (IC) manufacturing as the major industry (accounting for 40%). Among the remaining manufacturers are 57 in telecommunications (18%), 51 in personal computers and peripherals (16%), 51 in optoelectronics (16%), 19 in biotechnology (6%), and 11 in precision machinery (4%).

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	11	12
F1	609	627	625	613	640	620	588	632	628	615	640	627
F2	386	402	377	422	367	353	355	407	425	401	393	392
F3	263	269	306	283	251	278	290	301	274	264	298	266

According to statistics of the HSIP administration [29], isopropanol, (coded as F1), waste sulfuric acid (coded as F2), and waste photoresist (coded as F3) are the major types of hazardous wastes in the park, produced mainly by the IC and optoelectronics manufacturing industries. Out of 1360 tons of hazardous industrial wastes produced monthly, these three wastes make up approximately 1300 tons (96% of the total). Of these, processed wastes F1 and F2 are reusable; however F3 is not reusable and needs to be incinerated for final disposal. The other wastes (4%) include miscellaneous hazardous wastes that vary with the type of high-technology industry and are difficult to appropriately classify. Because these wastes are regarded as minor by HSIP, they are not involved in our proposed CRL system. To overcome the growing waste management inefficiency problem resulting from waste overproduction, the park administration and the corresponding manufacturers considered CRL, which involves the waste sources of F1, F2, and F3. Thus, the aforementioned HSIP hazardous waste management case is explored in this study using the proposed method.

Due to the lack of details in the monthly statistics, the following two phases were undertaken to generate the time-varying monthly waste demand data associated with F1, F2 and F3. First, we estimated the respective monthly mean values of waste production using the aforementioned aggregate waste amount (i.e., 1300 tons/month) multiplied by the corresponding waste production percentages (i.e., 48%, 30% and 22%). Second, following respective Poisson processes with the aforementioned monthly mean values, time-varying demand data associated with these wastes were simulated. Each simulation covered 12 time steps, comprising 1 year. After 10 simulations, the time-varying waste demand data were averaged to generate a 12-time-step demand database. Table 1 summarizes these data, which were the input of the proposed model in this study.

The model parameters were estimated for two different scenarios: (1) cost-related parameters using interview data, and (2) risk-related parameters using the corresponding statistics. The details are described below.

In general, it is difficult to estimate cost-related parameters, such as unit operational costs, directly from reported statistical data, because of business confidentiality. Therefore, with the aid of the HSIP administration, interviews were conducted with high-level decision makers, e.g., managers of the logistics-related sectors of three contracted waste treatment companies. The sample size of the survey was 28. The interviews included both open- and closed-ended questions about the potential operating performance and limitations in dealing with the present HSIP multi-source hazardous-waste problem. The questionnaire was designed mainly on the basis of the need to estimate the cost-related parameters of the model. For instance, given a certain cost item, each respondent was requested to propose an acceptable range for the unit cost, in the case that the proposed CRL system at the study site were operated by the corresponding waste treatment company.

In addition, considering the reliability of the survey data, information about respondents' familiarity with hazardous-waste reverse logistics was collected to make the survey results more convincing. To obtain this information, survey respondents were asked to evaluate their familiarity with hazardous-waste reverse logistics on a 5-point scale, ranging from 1 "not aware at all" to 5 "very familiar." Furthermore, they were asked to propose key functions of hazardous-waste reverse logistics without hints from the surveyors. Among the 28 respondents, 25 (i.e., 89% of the total sample size) were identified as being familiar to a certain extent with hazardous-waste reverse logistics, and thus, were regarded as valid samples in this survey.

The analytical results of the interview data were then aggregated to identify the unit operational costs and the boundaries, appearing, respectively, in the cost-minimization objective function and in the corresponding constraints.

Risk-related parameters estimated in this scenario aim at these unit increments of monetary risks (i.e., g_i^* shown in the risk-minimization objective function). They are classified into four groups associated with the following activities: (1) uncollected remaining waste exposure (i.e., g_i^E), (2) unprocessed waste storage (i.e., g_i^U), (3) transitional treatment (i.e., g_i^T), and (4) inbound and outbound distribution (i.e., g_i^C and g_i^D). As mentioned previously, although there are a variety of measures that can be used to estimate risks, we introduce the idea of incremental risk-induced penalties to deal with risk quantification in this study. Here, a unit increment of risk-induced penalty refers to the monetary value of a respective penalty that is caused by a unit of given physical amount associated with a given CRL-related activity.

Here, we estimated both g_i^E and g_i^U with the following procedures. First, using historical data provided by the Taiwan EPA for the aggregate external costs of Taiwan's manufacturing-induced environmental pollution in recent years, we measured the corresponding averaged value of the aforementioned external costs (\bar{R}). Second, we estimated the unit external costs (\bar{r}), by dividing \bar{R} by the yearly aggregate amount of manufacturing-induced wastes, which can be readily collected from the annual report of the Taiwan EPA. Third, the unit risk-induced penalties, i.e., g_i^E and g_i^U , associated with a given waste i were estimated by multiplying \bar{r} by the ratio of the regional accumulated unprocessed amount to the corresponding yearly production amount associated with the given type of hazardous waste at the study site. The Taiwan EPA annually updates the aggregate external costs of the domestic manufacturing-induced environmental pollution following the concept of Green Gross Domestic Product (Green GDP), as was promoted by the World Commission on Environment and Development in 1987. It is noteworthy that the basic idea of Green GDP is that domestic ecological and environmental damage should be regarded as a type of negative gross domestic cost and thus, involved in the estimation of the net GDP. The concept of Green GDP has been extensively used in several related fields, e.g., environmental economics, environmental management, and ecological economics.

In contrast, waste distribution risks may mostly depend on the accident frequency of the transportation. Similar to the concept of the external accident costs of urban transportation proposed in previous literature [17,30], we estimated the parameters g_i^C and g_i^D by approximating the marginal truck accident costs under off-peak traffic conditions. Here, according to the method proposed by Mayeres et al. [17], the truck accident risk can be expressed by the number of accidents divided by the number of kilometers. In our studied cases, statistics of traffic accidents from the National Police Agency of the Ministry of Interior [31] are used to estimate the corresponding truck accident risk. It is noteworthy that the activity of transporting hazardous wastes, particularly using large freight vehicles such as trucks and trailers, is not permitted at the study site during peak hours, according to governmental regulations. Therefore, only off-peak conditions are considered in this study.

In addition, we would like to clarify our reasons for employing the concept of marginal accident costs to estimate the corresponding unit risk-induced penalties g_i^C and g_i^D with the following reasons:

- (1) The materials transported in the proposed outbound distribution procedure consist mainly of processed wastes for transitional treatment, and thus may not be as dangerous as unprocessed hazardous wastes, which is the main type of waste studied in hazardous waste management problems in previous literature. Correspondingly, the risk induced by an accident of vehicles transporting those processed wastes may not be as high as in traditional hazardous waste management problems. Accordingly, we employ the concept of marginal accident costs to estimate the corresponding risk-related parameter in this study.
- (2) Although the materials transported in the waste collection procedure are unprocessed hazardous wastes, in this study the region of this activity is limited to the HSIP, under the condition of CRL operations. Thus, the impact area of waste collection is quite limited and is controllable in the proposed CRL system. Therefore, we think that the risk induced by waste collection in the proposed system may not be as high as in a traditional hazardous waste management problem. Thus, it is convenient to use the marginal accident cost for the risk-induced penalty estimation.
- (3) Despite several sophisticated models that have been proposed for the estimation of hazmat transportation risks [32–34], risk-related parameter estimation problems may still remain, since there are a greater number of parameters in these sophisticated models, e.g., the probability of an accident per unit distance movement) on each given road segment and the probability of an incident from an accident on a given road segment during transport of a given material, which should be accurately estimated before risk assessment.

Here, our attempt is not to challenge risk estimation models of previous researchers, but to employ alternatives to solve the coordinated hazardous waste reverse logistics problem efficiently and effectively.

Transitional waste treatment risks mainly result from either the malfunction of facilities or the carelessness of handling in facility operations, which may damage the internal facility and workers and create external environmental pollution. Accordingly, we considered insurance for facilities and workers in the estimation of g_i^T . In this study, g_i^T was estimated from insurance expenses; we obtained identical g_i^T values associated with the three types of wastes. To a certain extent, the consistent insurance expenses used in this study imply that any waste-treatment company should cover the same unit risk or induced penalty for hazardous-waste transitional treatment in the proposed CRL system. It should be noted that the parameter g_i^T may vary with the type of hazardous waste, and ideally, the features of different types of wastes should be appropriately identified and considered in the estimation of corresponding risk-related parameters. However, such sophisticated procedures may need further research, and thus, are not considered in our current study scope.

Tables 2 and 3 summarize the primary estimated parameters shown in the composite objective function and in the corresponding constraints, respectively.

4. Numerical results

In this section, numerical studies are illustrated to demonstrate the applicability of the model for regional hazardous waste CRL operations, given the predetermined 12-time-step, time-varying waste demand data

Table 2
Primary parameters estimated in the composite objective function

Parameters										
Type of waste	a_i	$S_i^*(0)$ (ton)	c_i^C (\$/ton)	c_i^U (\$/ton)	c_i^P (\$/ton)	c_i^T (\$/ton)	c_i^D (\$/ton/km)	c_i^F (\$/ton)	b_i (\$/ton)	l_i^T or l_i^F (km)
<i>Cost minimization</i>										
F1	0.5	150	10	3	4	90	3	0	260	15
F2	0.8	60	10	5	6	30	3	0	140	15
F3	0.3	30	12	6	6	100	4	58	0	17
Type of waste	$Q_i(0)$ (ton)	g_i^E (\$/ton)	g_i^U (\$/ton)	g_i^T (\$/ton)	g_i^C (\$/veh/km)	g_i^D (\$/veh/km)	l_i^C (km)	\bar{v}_C (ton/veh)	\bar{v}_D (ton/veh)	
<i>Risk minimization</i>										
F1	20	60	64	67	0.18	0.18	2	6	6	
F2	15	60	64	67	0.18	0.18	2	6	6	
F3	10	60	64	67	0.18	0.18	2	6	6	

\$: US dollars

Table 3
Primary parameters estimated in the constraints

Type of waste	Parameters								
	M_G^C or M_B^C (ton/month)	M_G^T or M_B^T (ton/month)	\underline{M}_i^C (ton/month)	\bar{M}_i^T (ton/month)	\bar{M}_i^U (ton)	\bar{M}_i^P (ton)	M^U (ton)	\bar{M}_i^D (ton/month)	
F1	400	400	250	650	2000	1800	3000	600	
F2			100	400	1200	1200		600	
F3			50	100	1000	500		600	

from three types of hazardous wastes, as shown in Table 1. We then have one composite objective function, coupled with 360 respective constraints, in the proposed model, to search for the optimal solutions of 108 time-varying decision variables. The numerical studies were conducted in three different scenarios for two different purposes. In the first scenario, the purpose is to evaluate the performance of the CRL operational system as compared to the HSIP waste operational system (i.e., the case without coordination). In the second scenario, we investigate the effects of environmental pollution risks on the performance of the system. The third scenario summarizes the numerical results obtained from the sensitivity analyses of several target parameters, shown in boundary constraints. Note that all the preset parameters shown in Tables 2 and 3 remain the same in the first two scenarios, whereas some of them may change in the third scenario for the sensitivity analyses.

In these numerical studies, the Lindo software package (Linear, Interactive and Discrete Optimizer) 6.0, a commercial optimization package broadly used for formulating and solving diverse optimization problems, was employed to search for the final solutions. Note that in our numerical studies, it takes less than 30 s overall to search for the optimal solutions.

The following discussion summarizes the numerical results and corresponding procedures conducted in these three scenarios.

The case studied in the first scenario serves as a contrast to the other scenario, in which we attempted to assess the performance of the proposed CRL system by comparing it to the HSIP hazardous waste management strategy (i.e., non-coordination). Currently, following regional waste treatment regulations, the manufacturers of HSIP are in charge of their own industrial wastes without coordination. However, most of the HSIP high-technology manufacturers handle their industrial wastes with outsourcing strategies, i.e., by employing professional waste treatment companies. Consequently, risk-related factors affecting the regional environmental pollution may not be considered by either these private waste treatment companies or these high-technology manufacturers. In this scenario, only the operational cost function is involved for system evaluation. Our purpose in the first scenario is to compare the reverse logistics strategy and the present waste management strategy based on the operational costs for regional hazardous-waste reverse logistics.

Therefore, by setting the corresponding cost-assessment weight of the composite objective function to 1, our model becomes a specific single-objective optimization model. Accordingly, using the proposed CRL model, the optimal reverse logistics cost was estimated and then compared to the reported annual expenses in the HSIP zonal waste treatment. The numerical results obtained in this scenario are summarized in Table 4. The change patterns of the optimal solutions of the specified decision variables associated with these three types of wastes are graphically presented in Fig. 2.

Table 4 indicates that there are relatively significant advantages of our method for the HSIP hazardous waste management. As can be seen in Table 4, the relative reduction of total reverse logistics costs reaches as high as 58%, compared to the existing HSIP waste management performance. According to our observations, such a result is mainly caused by reusing wastes F1 and F2. Their unit benefits of recycling are significantly greater than the unit costs of reverse logistics, thus contributing to the aggregate cost reduction in the case of CRL operations.

Furthermore, the above comparison results also imply an urgent need to improve the HSIP waste management measure, because the present HSIP waste treatment strategy is to use outsourcing without coordination. Thus, the corresponding manufacturers may not be able to benefit from recycling wastes F1 and F2 in the reverse logistics operational procedure. Furthermore, they should pay for the reverse logistics costs to their outsourced waste treatment companies.

Fig. 2 provides implications, as summarized below. Similar to the just-in-time (JIT) strategy of business logistics, both the time-varying waste collection and treatment amounts tend to approach their upper bounds in the proposed CRL system. In contrast, the function of storage, for either unprocessed or processed wastes, does not seem to have significant effects on the CRL system performance in the case of the appropriate adjustment of the functions of transitional treatment and outbound distribution. This result can be readily observed in Fig. 2, because the time-varying storage amount of either processed or unprocessed wastes approximates to zero at each time step. Such a JIT strategy may be applicable under the condition where demand exceeds supply. However, the above generalization may reverse when, for example, the waste demands less than the treatment and collection capacities. Thus, the typical trade-off relationship between the functions of storage and distribution may remain an important issue in the proposed CRL system.

The second scenario investigates the effects of the diverse preset values of the weights w_C and w_R , shown in (7), on the performance of the CRL system. Using the proposed model, we can determine the optimal value of aggregate costs including the risk-induced penalties that should be paid by HSIP

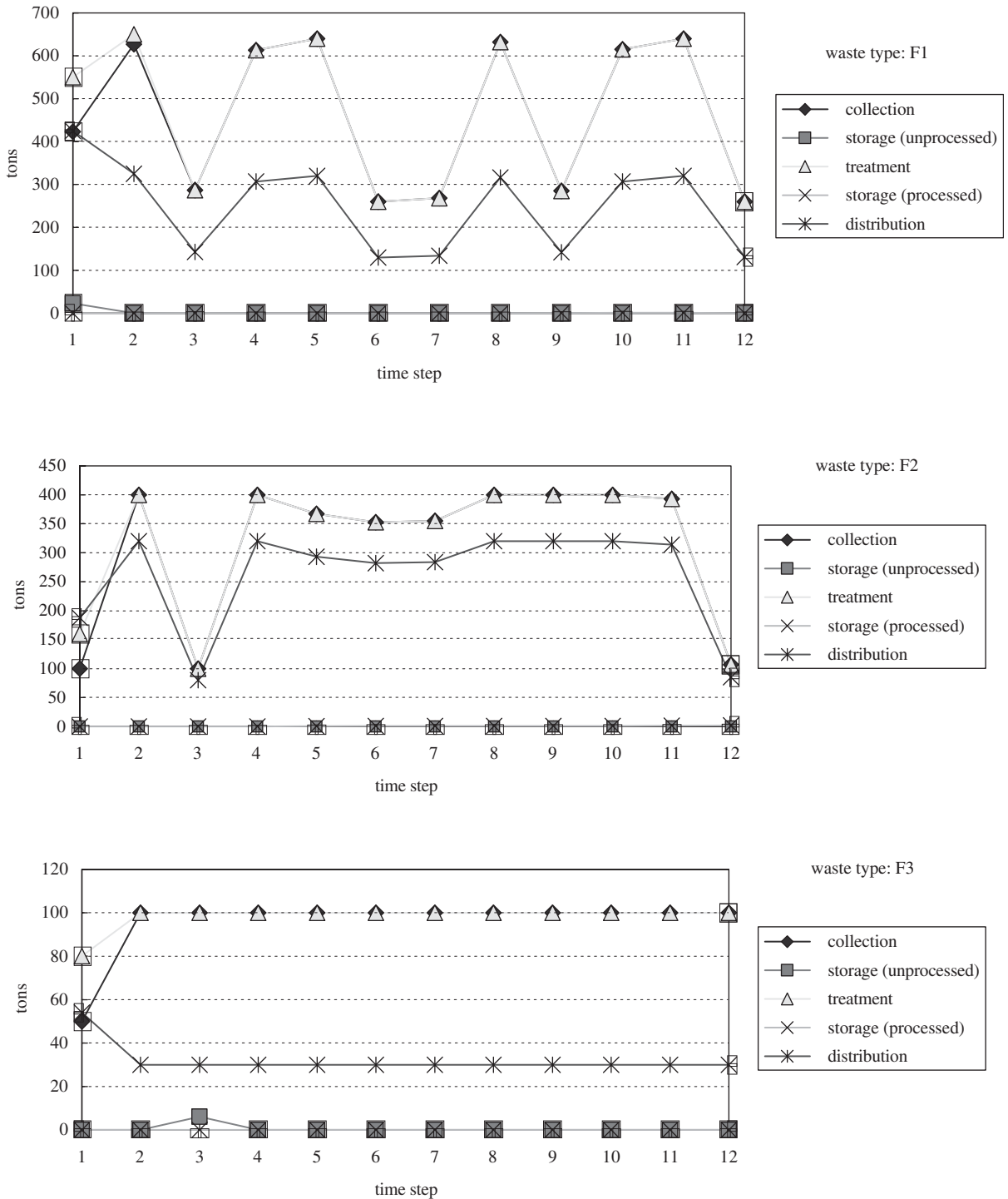


Fig. 2. Optimal solutions of decision variables using the proposed model.

Table 4
Performance evaluation of the proposed CRL system

Solution step	Waste														
	F1					F2					F3				
	Col	Str ^u	Tre	Str ^p	Dis	Col	Str ^u	Tre	Str ^p	Dis	Col	Str ^u	Tre	Str ^p	Dis
1	423	23	550	0	425	100	0	160	0	188	50	0	80	0	54
2	627	0	650	0	325	400	0	400	0	320	100	0	100	0	30
3	287	0	287	0.5	143	100	0	100	0	80	100	6	100	0	30
4	613	0	613	0	307	400	0	400	0	320	100	0	100	0	30
5	640	0	640	0	320	367	0	367	0.6	293	100	0	100	0	30
6	260	0	260	0	130	353	0	353	1	282	100	0	100	0	30
7	268	0	268	0	134	355	0	355	1	284	100	0	100	0	30
8	632	0	632	0	316	400	0	400	1	320	100	0	100	0	30
9	285	0	285	0.5	142	400	0	400	1	320	100	0	100	0	30
10	615	0	615	1	307	400	0	400	1	320	100	0	100	0	30
11	640	0	640	1	320	393	0	393	1.4	314	100	0	100	0	30
12	260	0	260	0	131	107	0	107	2	85	100	0	100	0	30
Total reverse logistics costs (C: US\$/year)															
The proposed CRL system						265,255									
The existing system						631,560									
Relative improvement (%)						58									

Col: collection amount of raw hazardous wastes.
 Str^u: storage amount of unprocessed hazardous wastes.
 Tre: transitional treatment amount of hazardous wastes.
 Str^p: storage amount of processed wastes.
 Dis: outbound logistics distribution amount of processed wastes.

manufacturers for regional environmental protection. The preset value of w_R exhibits the significance of environmental protection in goal setting for the system. Note that in the case studied in the first scenario, risk-induced penalties for corresponding environmental impacts, as applied to existing private business operational conditions at the study site are not considered; and thus, w_R is set to be 0. In contrast, if such a CRL system is operated and supervised mainly by the public sector, e.g., by the EPA, the value of w_R might be greater than 0 and would contribute to a multi-objective optimization problem, such as that presented in (7). As a result, the estimated aggregate risk-induced penalties can be regarded as the extra operational costs charged to real users, i.e., high-technology manufacturers, rather than as the external social costs paid by non-users of society, e.g., the local residents.

Accordingly, considering a variety of potential operational circumstances, in this scenario, different combinations of w_C and w_R were set to investigate the corresponding potential effects on the CRL system performance. The numerical results are summarized in Table 5 and graphically presented in Fig. 3.

The results of Table 5 indicate two important generalizations. First, the aggregate reverse logistics costs including risk-induced penalties (i.e., C plus R) appear to decrease when the risk-related weight w_R is increased. One extreme case is that if environmental impacts are fully considered in setting goals for the HSIP zonal waste management, the total reverse logistics costs will decrease to 2.3 million dollars

Table 5
CRL system performance with different preset weights w_Θ and w_Ω

Case studied	Cost-related weight (w_C)	Risk-related weight (w_R)	Aggregate (cost C)	Aggregate risk (R)	Normalized (cost \tilde{C})	Normalized risk (\tilde{R})	Value of the composite objective function
Case-1	1.0	0	265,255	3,065,277	0	1	0
Case-2	0.9	0.1	298,657	2,941,321	0.23	0.83	0.29
Case-3	0.8	0.2	330,453	2,899,356	0.44	0.78	0.51
Case-4	0.7	0.3	344,777	2,822,455	0.54	0.67	0.58
Case-5	0.6	0.4	355,377	2,772,443	0.61	0.60	0.61
Case-6	0.5	0.5	364,298	2,693,452	0.67	0.50	0.59
Case-7	0.4	0.6	377,654	2,601,789	0.76	0.37	0.53
Case-8	0.3	0.7	388,456	2,554,332	0.83	0.31	0.47
Case-9	0.2	0.8	393,259	2,497,123	0.86	0.23	0.36
Case-10	0.1	0.9	402,127	2,433,659	0.92	0.15	0.23
Case-11	0	1.0	414,029	2,323,948	1	0	0

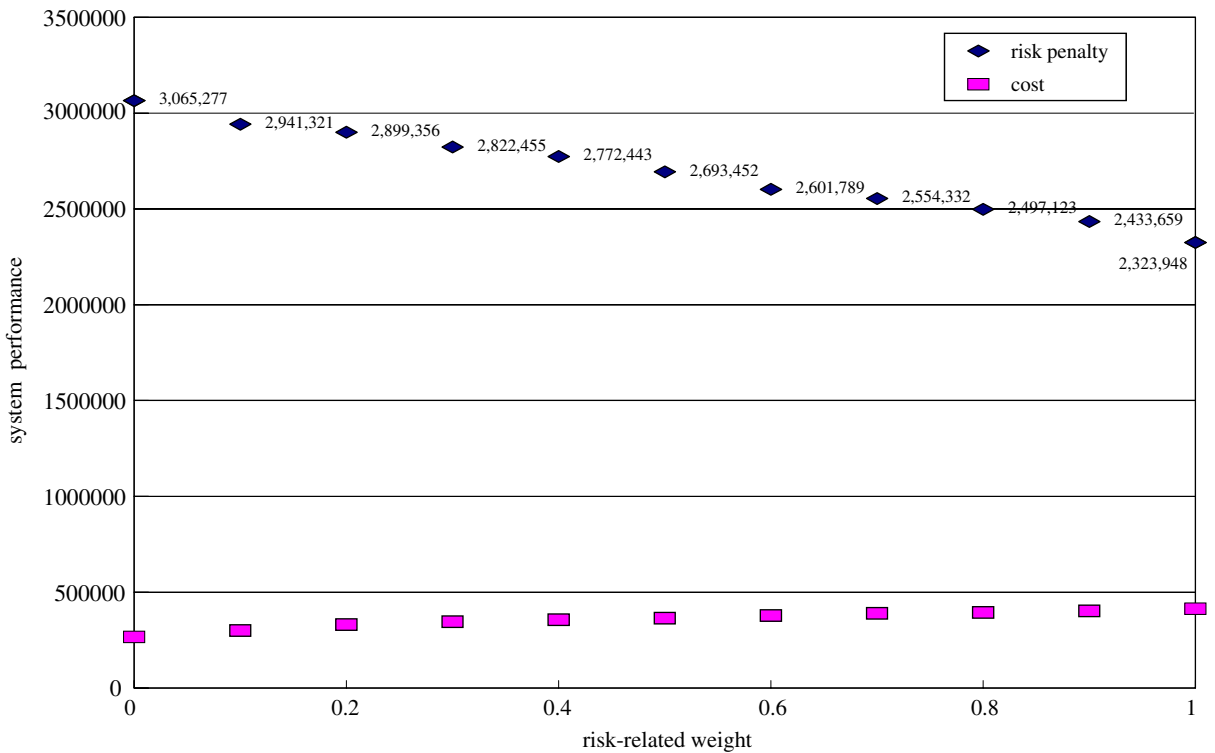


Fig. 3. Effect of the risk-related weight w_R on the CRL system performance.

Table 6
Results of sensitivity analyses with respect to boundaries of constraints

Target parameter	Boundary increment (%)			
	−50	−25	+25	+50
	Variations in aggregate CRL costs (relative to the costs of Case-6)			
M_G^C or M_B^C	−11,496	−5748	32,262	71,704
M_G^T or M_B^T	0	0	20,286	41,238
\bar{M}_i^T	93,449	26,245	−1392	−1392
\bar{M}_i^U	0	0	0	0
\bar{M}_i^P	228,826	113,528	−111,825	−221,938
\bar{M}_i^D	245,860	111,030	−101,293	−200,315

per year, under the optimal condition, about 0.6 million less than the corresponding costs of Case 1 (the original case). This decrease implies that environment-driven, CRL operational strategies may improve the performance of zonal waste management to a certain extent as a result of considerable decreases in risk-induced penalty costs. Second, it seems reasonable that from a paid-by-user point of view, the HSIP high-technology manufacturers should bear the responsibility of zonal environmental protection, and thus, need to share the estimated aggregate CRL costs, including risk-induced penalty costs. Accordingly, the HSIP administration can use the increments of the aggregate CRL costs, shown in Table 5, to specify regulations for HSIP zonal environmental protection fees.

In addition, Fig. 3 implies that the risk-related weight w_R has a significant effect on the performance of the proposed CRL system. As can be seen, as the value of w_R increases from 0 to 1, the corresponding risk-induced penalties decrease by 24%, thus contributing to a decrease in the aggregate CRL costs of 18%.

In the following scenario, we explored several different cases by either strategically loosening or tightening the upper and lower bounds of some critical CRL operational requirements, e.g., the treatment and distribution capacities. The purpose of this scenario is to assess the relative performance of the proposed method under diverse operational requirements. In addition, the results may help both the private and public sectors of HSIP to review current strategies and related regulations of the HSIP reverse logistics requirements. In contrast to Case 6 of Scenario 2 (i.e., the case with $w_C = w_R = 0.5$), the model parameters remain almost the same in this scenario, except for the target boundaries preset in the constraints, which were each tested with the range −50% to +50%, relative to their preset values. The corresponding numerical results are presented in Table 6.

According to the numerical results of Table 6, our generalizations are summarized below.

- (1) Tightening the lower bound of either the time-varying collection amount or the corresponding treatment amount may not be an appropriate strategy for cost reduction of the proposed CRL system. For instance, as illustrated in Table 6, the aggregate CRL costs may increase by 6.4%, if the corresponding minimal collection requirement is raised by 50%. Similarly, there is a trend to increase the aggregate CRL costs in the case of treatment.

- (2) Loosening the lower bound of the time-varying collection requirement may help to reduce aggregate CRL costs. As can be seen in Table 6, the costs have been reduced by 1% in the case where the minimal collection requirement is reduced by 50%, i.e., from 400 to 200 tons per month. In contrast, a looser lower bound for the time-varying treatment amount does not seem to have a significant effect on the corresponding CRL cost reduction.
- (3) Expanding the capacities of processed waste storage and/or outbound distribution significantly improves the operating performance of the proposed CRL system, compared to the aforementioned loose regulation cases, in terms of minimal requirements. As can be observed in Table 6, the aggregate CRL costs have been reduced by 20%, if the corresponding waste storage capacity is increased by 50%. Similar results can be found in the case of outbound waste distribution.

These numerical results imply that the trade-off relationship between the goals of cost minimization and risk minimization in the proposed CRL system is worth considering. Specification of the corresponding weights, w_C and w_R , also appears to be a significant issue. In addition, the expansion of waste storage and distribution capacities seems beneficial for reverse logistics cost reductions. However, this hypothesis may be problematic, if investment costs and expenses for routine facility maintenance are considered. Nevertheless, using the proposed method as a decision-making support tool would allow the government to evaluate diverse strategies for hazardous waste management to protect the regional environment. In the private sector, the proposed system seems to be an efficient measure to satisfy both governmental regulations for environmental protection, and business operational conditions.

5. Conclusions

This paper has presented a CRL system for regional hazardous waste management with the goal of minimizing both the corresponding operating costs and the induced risks. By identifying the critical activities and related operational requirements of the proposed CRL system, a composite multi-objective function and ten groups of constraints are formulated.

Compared to previous literature, the proposed method has two distinctive features. First, by coordinating the critical reverse logistics activities of multi-waste sources in a given region, the classical regional waste management problem can be efficiently solved with a systematic waste management strategy. Second, environmental impacts caused by regional industrial hazardous wastes are considered in the model, which is formulated with a risk-minimization objective function, thus addressing regional environmental protection concerns. Results of numerical studies have indicated that using the proposed CRL method, the aggregate reverse logistics costs can be reduced by 58%, compared to the existing operational costs at the study site in the case where the goal of risk-minimization is not involved.

Nevertheless, it is suggested that the trade-off relationship between the goals of cost minimization and risk minimization warrants more investigation to enhance the applicability of the proposed CRL method. Furthermore, issues of corresponding waste source reduction measures may need to be addressed in future research. Correspondingly, integration of the proposed model with business logistics, forming a green supply chain management (Green-SCM) system may also warrant more research. Due to the limitations of the corresponding data collection, and to facilitate model formulation, extension of the proposed model with more sophisticated risk functions is not considered in this study. Nevertheless, measures of the specification of diverse risk prediction functions, which indicate more complicated operational

conditions, e.g., time-varying road traffic conditions in freight vehicle routing, are also our interests for future research.

Acknowledgements

This research was supported by Grant NSC 93-2416-H-009-006 from the National Science Council of Taiwan. The authors wish to thank the referees for their helpful comments, which have led the authors to consider more deeply the subjects of hazardous waste reverse logistics and corresponding risk management. The valuable suggestions of the Guest Editor Professor Erhan Erkut to improve this paper are also gratefully acknowledged. Any errors or omissions remain the sole responsibility of the authors.

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