Computers & Operations Research 62 (2015) 157–168

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

A bi-objective model for the used oil location-routing problem

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ARTICLE INFO

Available online 4 November 2014

Keywords:
Used oil
Location-routing
Capacity acquisition
Environmental risk
Bi-objective
Dispersion model

ABSTRACT

A staggering amount of used oils (e.g., 1.4 billion gallons in the U.S.) are generated annually as part of our industrial lifestyle. These are harmful to the population and environment in the vicinity of the transport routes as well as the storage, treatment and disposal facilities. In this paper, we provide an analytical framework to simultaneously answer the following questions: Where should the used oil storage, treatment and disposal facilities be located? What are the most appropriate capacity levels for these facilities? Which routes should be used among the different echelons of facilities in the used oil collection network? Focusing on the hazardous ingredients of used oils that are airborne on release, we propose an environmental risk measure by incorporating the Gaussian plume model in the box model. We present a bi-objective model for the location-routing problem so as to minimize the total environmental risk and the total cost. We use a modified weighted goal programming approach, which proved to be computationally efficient through a wide range of tests. The application of the proposed analytical framework in Chongqing of Southwest China provided interesting managerial insights.

1. Introduction

Due to the heightened awareness for environmental preservation, hazardous waste management has become a popular concern in recent years. In this paper, we focus on a particular type of waste i.e., *used oil*, which encompasses any contaminated oil that has been through its intended use cycle. Used oil needs to be handled as a hazardous waste, particularly when it is mixed with certain other wastes and displays any of the following four characteristics: ignitability, corrosiveness, reactivity or toxicity [1]. Over 350,000 t of used oil is produced annually in the U.K. [2] whereas nearly 1.4 billion gallons of used oil is generated in the U.S. [3] each year. Even though most of this waste can be recycled (or cleaned), large quantities of used oil continue to be improperly disposed. In China, for example, about 782,100 t of used oil was emptied into the river system in 2007 [4]. Note that this volume qualifies used oils as the third most important pollution source in China. Evidently, there is a pressing need for the design and development of integrated used oil collection, storage and processing systems. We aim at filling this gap from the network design perspective.

We define the *used oil location-routing problem* as the simultaneous optimization of facility location, capacity acquisition and vehicle-routing decisions so as to minimize the associated total cost and environmental risk. Similar to other hazardous wastes, the management of used oil comprises the processes of transportation, storage, treatment and disposal [5]. Each of the latter three processes can be performed at a different facility. It is also possible to co-locate the storage, treatment and disposal of used oil in which case, the site would be an *integrated facility* [6]. In this paper, we assume that a central decision-maker is required to locate multiple facilities with proper capacity levels, and design vehicle routes visiting all the used oil generation and processing sites.

The optimization of the used oil location-routing problem has bearings on the economy and the environment. The economic impact, measured as cost, is primarily due to the expenditure on facility location, capacity acquisition, and transportation. The impact on the environment, however, can be quantified as the risk to the population and the environment due to a release incident—en route or at a facility. Therefore, the integrated development of a facility and transport network configuration that considers both cost and risk is necessary.

Used oil is an ignitable liquid that contains high levels of heavy metals posing a significant threat to the environment. Petrochemical industries, manufacturing companies, mining and smelter operations, in general, are the major generation points for used oil. The concentration of heavy metals in the used oil increases because of the friction in a metallic cylinder. As reported in Table 1, Pb, Zn, Ba, Cr and Al are the top five heavy metals contained in the used oil, where lead (Pb) constitutes the major concern [7]. When used oils are released from their container, e.g., due to a fire accident, these toxic contaminants and their compounds represent a direct hazard to the environment.

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http://dx.doi.org/10.1016/j.cor.2014.10.016
0305-0548/

A used oil release accident, however, is an extremely low probability event, albeit it can cause serious damage. For this reason, in assessing the environmental risk, we focus on the consequence evaluation. Specifically, we study the "off-specification used oil" which exhibits the toxicity characteristic for lead (D008) [1].

We conceive the used oil collection and processing problem as a three-layer framework, where the generation node, the storage facility and the integrated facility are in different echelons. We assume that the treatment and the safe disposal of used oils are both done at the integrated facility site. As illustrated in Fig. 1, the vehicles originating from the storage facilities perform a tour to collect the available waste at the generation nodes, where used oils are produced as a by-product of the industrial activity. The material collected at the storage facilities is often directly transported to integrated facilities by larger vehicles.

In this paper, we propose a model with two objectives—to minimize the total environmental risk and to minimize the total cost—for the used oil location-routing problem so as to determine:

- Where to open storage facilities and their capacity levels,
- Where to open integrated facilities and their capacity levels,
- The number and routes of the vehicles to collect used oil at the generation nodes, and
- How to ship the used oil from the storage facilities to the integrated facilities.

A main contribution of our paper is the incorporation of vehicle routing problem (VRP) as one of the key components of the proposed model. We represent VRP by adopting a two-commodity flow formulation. Our second key contribution is the proposed integration of the Box Model and the Gaussian Plume Model for the assessment of environmental risk. This enables us to pay close attention to the heavy metals contained in the used oil that are airborne upon an accidental release. We measure the environmental risk around each road segment, or facility, as the size of a "box" that contains a given threshold level of contaminants. The impact radius that determines the box size is obtained using GPM. We also developed a solution approach by adapting the weighted goal programming method for solving the arising bi-objective problem. Through a case study and the related test instances, we demonstrate that the proposed analytical approach is amenable to practical implementation in practice.

Table 1
Contaminants of potential environmental concern occurring in the used oil.

Hazardous component	Approximate concentration range (mg/kg)
Lead (Pb)	3700–14,000
Zinc (Zn)	630–2500
Barium (Ba)	60–690
Aluminum (Al)	4–40
Chromium (Cr)	5–24

The remainder of this paper is organized as follows: Section 2 presents an overview of the relevant literature. The bi-objective location-routing model is presented in Section 3, where the proposed environmental risk assessment model is also described. Section 4 presents the solution procedure developed on the basis of the weighted goal programming method through the percentage normalization technique. In Section 5, we outline the application of the proposed analytical approach in studying a realistic case study based on Chongqing, China. In Section 6, we evaluate the proposed model's scalability. Finally, Section 7 provides some concluding comments and future research directions.

2. Literature review

To the best of our knowledge there is no academic literature pertaining to the design of used oil collection and processing facility networks, although this waste type accounts for a large portion of the total hazardous waste generated. We start this section by a comprehensive review of the state of the art on the generic hazardous waste location-routing problem, and position our work in this context in terms of its contributions. Then, we provide exceedingly brief overviews of the vast literatures on VRP and environmental risk assessment. The main message of this section is that the prevailing studies neglected the tour planning issues pertaining to the collection of hazardous wastes. Moreover, they overwhelmingly focus on improving public safety, while the mitigation of environmental risk has not been well studied in this context.

2.1. Hazardous waste location-routing

Starting from early 1990s, a number of researchers have attempted to address the hazardous waste location-routing problem [8,22]. In Table 2, we provide taxonomy of the existing literature. Evidently, the hazardous waste location-routing problem was first studied by

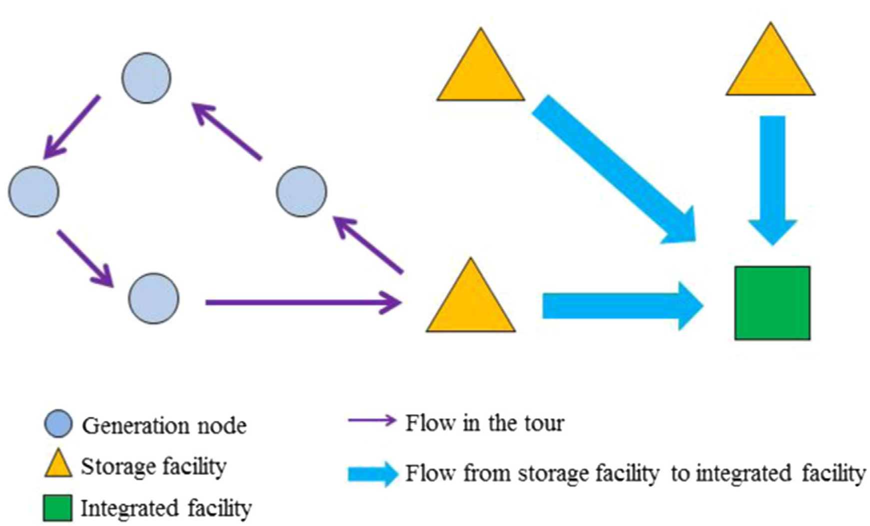

Fig. 1. The used oil management framework.

Table 2
Taxonomy of the most relevant literature.

Author	Model features				Objectives			Risk model
	Year	Waste	Technology	Tour	Cost	Risk	Equity	
Zografos and Samara [9]	1989	Single	Single	No	No	Yes	No	Edge weight
Revelle et al. [10]	1991	Single	Single	No	Yes	Yes	No	Population exposure
Stowers and Palekar [11]	1993	Single	Single	No	No	Yes	No	Population exposure
Jacobs, Warmerdam [12]	1994	Single	Single	No	Yes	Yes	No	Incident probability
Current and Ratick [13]	1885	Single	Single	No	Yes	Yes	Yes	Population exposure
Wyman and Kuby [14]	1995	Single	Multiple	No	Yes	Yes	Yes	Population exposure
Giannikos [15]	1998	Single	Single	No	Yes	Yes	Yes	Population exposure
List, Mirchandani [16]	1991	Multiple	Multiple	No	Yes	Yes	Yes	Impact area
Nema and Gupta [17]	1999	Multiple	Multiple	No	Yes	Yes	No	Pop. exposure × waste amount × incident prob.
Nema and Gupta [18]	2003	Multiple	Multiple	No	Yes	Yes	Yes	Pop. exposure × waste amount × incident prob.
Alumur and Kara [5]	2007	Multiple	Multiple	No	Yes	Yes	No	Population exposure × waste amount
Zhao and Zhao [19]	2010	Multiple	Multiple	No	Yes	Yes	No	Population exposure × waste amount
Shuai and Zhao [20]	2011	Multiple	Multiple	No	Yes	Yes	No	Population exposure × waste amount
Funda [21]	2012	Multiple	Multiple	No	Yes	Yes	No	Population exposure × waste amount

Zografos and Samara [9], who suggested a multi-objective model, minimizing travel time, transportation risk and disposal risk, to determine the location of disposal facilities and the transportation route. The risk in their model was represented as the known weight of edges in the network. However, their model is restricted to only one type of hazardous waste, and the vehicle route is designed as a trip that starts at waste generation node and ends at the selected disposal facility. Stowers and Palekar [11] developed a single objective model that minimizes the risk due to location and transportation decisions. They quantified the risk as the exposed population i.e., the number of people exposed to hazardous wastes. In accordance with this assessment, highly populated regions can be avoided.

Minimizing the economic impact is another common objective when making location-routing decisions. Revelle et al. [10] developed a model for the minimization of a convex combination of cost and risk for the route selection and storage facility location. This combination is formulated through the weighting method of multi-objective programming. The risk in their study is measured as the exposed population. The minimization of cost can also be found in the model presented by Jacobs and Warmerdam [12]. The locations of storage and disposal facilities, and the related routes from generation nodes to the facility sites are simultaneously determined in their model. They estimated the risk as the total probability of a release-causing accident en route and at a site. Using the constraint method to define the trade-off between cost and risk, their multi-objective linear programming model is amenable to solution by commercial software packages. Current and Ratick [13] and Wyman and Kuby[14] studied risk equity maximization in this context. Risk in these two models is estimated by population exposure. The difference between these two multi-objective models is that Wyman and Kuby [14] make an additional decision that involves technology selection. Moreover, to deal with the convex objectives, Current and Ratick [13] adopted the weight method, while Wyman and Kuby [14] performed several sensitivity analyses based on different sub-objectives to indicate the robustness of the results, which provided various plans for decision-makers. Giannikos [15] formulated a location-routing model with four objectives: to minimize cost, to minimize perceived risk, to maximize risk distribution equity, and to maximize the facility operation disutility distribution. Goal programming was used to preprocess this multi-objective model.

The papers cited until now assume the presence of a single type of hazardous waste, ignoring the possibility of having to deal with multiple types of commodities. List and Mirchandani [16] presented a location-routing model that incorporates multiple types of hazardous wastes. The risk in their model is inversely proportional to the square of distance. In order to represent the efficiency of technology options, Nema and Gupta [17,18] formulated waste–waste and waste–technology compatibility constraints in a comprehensive model. A waste–waste compatibility constraint states that the two types of waste can be transported and/or treated together since they would not have a chemical reaction. Similarly, a constraint for waste–technology compatibility indicates that a technology alternative is capable to treat the specified waste type.

More recent papers in this field are [5,19–21]. Alumur and Kara [5] proposed a multi-objective model with the purpose of optimizing technology acquisition, treatment center and disposal center locations, routes for multiple waste types from generation nodes to treatment centers with compatible technologies, and routes for waste residues from treatment centers to disposal centers. It is noteworthy that each route in their model is a direct trip, with a different origin and destination. To obtain efficient solutions, they aggregated the multiple objectives into a weighted sum of the individual objective functions. Zhao and Zhao [19] developed a bi-objective model, minimizing the total cost and risk, to additionally decide how to route waste residues from generation nodes to disposal centers. In contrast with [5], the model in [19] incorporates the risk associated with fixed facilities. In a more comprehensive location-routing model Shuai and Zhao [20], focused on the societal risk associated with the management of multiple types of hazardous wastes, while they have assumed direct shipments for waste collection. Most recently, Funda [21] utilized three criteria: total cost, transportation risk, and site risk.

Among the prevailing studies, the work that is most relevant to ours is by Alumur and Kara [5]. Hence, we complete this subsection by highlighting the differentiating features of our model from theirs. In addition to focusing on a specific waste type i.e., used oil, we aim at determining the capacity of each facility that was not modeled in [5]. In addition, the waste collection routes in our model are tours, each of which starting and ending at the same storage facility. Also in contrast with Alumur and Kara [5], we focus on mitigating the environmental risk due to both transportation and siting decisions, and incorporate the variable costs of the facilities in the total cost function.

2.2. Other streams of relevant research

The traditional two-index (and three-index) vehicle flow formulation [23,24], the set partitioning formulation [25], and the two-commodity flow formulation [26] are the three main forms for representing VRP. The first formulation requires a special set of constraints to eliminate sub-tours, such as the ones proposed by Dantzig et al. [27] and Miller et al. [28]. The set partitioning formulation is deemed impractical due to the large number of variables [29]. In this paper we resort to the two-commodity flow formulation, since it is known to achieve lower gaps with shorter computational times [30].

The environmental and societal health risks associated with hazardous wastes have been known for three decades [31]. A variety of air dispersion models, which are applicable for the environmental impact assessment, have been proposed. The Box Model and Gaussian Plume Model (GPM) are by far the most popular air quality models recommended for the air pollution analysis and official regulatory guidelines [32–35]. The basic box model is based on mass balance [36], which only predicts the volume-averaged concentration for the emissions near the surface. The impact area is represented as a box, and it is assumed that the air mass inside the box is well mixed. It is well known, however, that the hazardous material concentration generally decreases with distance from the release site. Verma and Verter [37] is a good example that demonstrates the use of GPM to estimate the spatial distribution of toxic concentration level for ground-level emissions during rail transportation.

3. Mathematical formulation

In this section we first describe two important building blocks of our analytical framework: the environmental risk assessment model and the two-commodity VRP formulation. Then, we present the proposed model for the hazardous waste location-routing problem. The formulations in this section capture the characteristics of the collection and processing networks that deal with hazardous wastes that are airborne upon accidental release. The generic model is then calibrated to represent the differentiating features of used oils in Section 5. We start by stating the following assumptions: (i) the environment is stable and does not present major changes over time; (ii) the total amount of hazardous waste on the truck (or the facility) constitutes the potential release source; and (iii) the vehicles and facilities satisfy the security requirements of transporting and processing hazardous wastes.

3.1. Environmental risk assessment

We focus on the hazardous ingredients of used oils that are airborne upon accidental release into the environment. The box model is a rather practical approach to assess the environmental risk in this context [33]. The risk is measured as the size of the box within which a pre-determined threshold level of contamination will be reached after an accidental release of the hazmat contained in used oils en route and at site. Thus, each segment of a transport corridor could be surrounded by a number of boxes with different sizes. The size of each box represents the potential impact volume of the used oil being shipped, stored or processed.

In this study, both the facilities and routes are regarded as release sources, and we refer to them as node source and edge source, respectively. For a node source, the box is as a hemisphere, whereas for an edge source the box is a semi cylinder. Suppose B is the size of box, the environmental risks for node and edge sources can be formulated as follows:

$$B^{node} = \frac{1}{2} \times \frac{4}{3}\pi\left(R^{node}\right)^3 \quad (1)$$

$$B^{edge} = \frac{1}{2} \times \pi R^{edge} D^{edge} \quad (2)$$

where R^{node} and R^{edge} are the impact radius of node and edge sources, respectively, and D^{edge} is the length of the edge. For the materials with similar characteristics to used oil, the impact radius R^{edge} is 800 m in all directions according to the hazmat transportation guidelines from U.S. EPA [38]. Therefore, Function (2) can be modified into:

$$B^{edge} = 400\pi D^{edge} \quad (3)$$

Note that we calculate the impact volumes of the involved box, including the ones generated from each node and edge source, based on the same concentration level. To estimate the impact radius of node sources, we modify the GPM, where the standard GPM is appropriate for representing a single release source that is specially regarded as a node. The steady-state node source can be thereby modeled as

$$C^{node}(x, y, z) = \frac{Q^{node}}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (4)$$

where $C^{node}(x, y, z)$ is the concentration (mg/L, mg/m^3) at downwind point (x, y, z); Q^{node} is the release rate of hazmat (mg/s, m^3/s) from node source; u is the average downwind speed (m/s); x is the downwind distance from node source (m); H is the release source height (m); σ_y and σ_z are the horizontal and vertical dispersion coefficient respectively (m). The dispersion coefficients in Model (4) are determined by the atmospheric stability category and the downwind distance x to node source, where $\sigma_y = ax^c$, $\sigma_z = bx^d$. Pasquill and Smith [39], and Arya [33] provide the values of dispersion parameters a, b, c and d based on atmospheric stability category.

We use $C^{node}(x)$ to present the concentration level at point with the downwind distance x from the node source. At zero elevation of both release sources and impact areas ($H=0$), Eq. (4) can be modified into

$$C^{node}(x) = \frac{Q^{node}}{\pi uab x^{c+d}} \quad (5)$$

As for the edge source with the release rate Q^{edge}, the maximum ground-level concentration $\overline{C}$ can be obtained at the downwind point with the distance 800 m from the edge source:

$$\overline{C} = \frac{Q^{edge}}{\pi uab \times 800^{c+d}} \quad (6)$$

For determining the impact radius of node sources R^{node}, we can use the following function:

$$R^{node} = \sqrt[c+d]{\frac{Q^{node}}{\pi uab\overline{C}}} \quad (7)$$

The release rate at a node depends on the hazmat amount, rupture size, internal pressure and facility capacity [8]. Let CAP denote the facility capacity, and T denote the release duration. We assume that the node capacity is the main determinant of the release rate, and hence use the following simplification:

$$Q^{node} = \frac{CAP}{T} \quad (8)$$

3.2. The two-commodity flow VRP formulation

Each collection tour starts from a storage site, visits a number of generation sites and returns to the same storage facility, which constitutes a VRP. We represent such tours using the two-commodity flow formulation provided by Baldacci et al. [26]. The advantage of this formulation is that the sub-tour elimination constraints, in the traditional sense, are not required. Instead, for each tour, a copy of the origin node is added to the original road network in order to represent the destination of that tour. Accordingly, we extend the original road network by introducing the nodes that present the copies of storage facility candidates.

Note that, there are two types of flows on each vehicle route: First, from the storage facility to its copy, which indicates the load on vehicle; and second, from the copy to the storage facility, which represents the empty space on the same vehicle. Besides the basic flow rules stated in the two-commodity flow formulation, we build the vehicle routes such that: (i) each vehicle route starts at an open storage facility with a selected capacity level, and ends at its copy with the same capacity level; (ii) each vehicle visits at least one generation node; (iii) each generation node is visited exactly once; and (iv) the total amount of used oil transported by each vehicle cannot exceed its capacity.

3.3. A bi-objective location-routing model

The following sets, parameters and decision variables are used in developing the bi-objective used oil location-routing model.

Sets:

- $N(V, E)$ road network with vertices V and edges E, where $V = G \cup S \cup \overline{S} \cup F$.
- $G(1,2,\ldots,g)$ used oil generation nodes.
- $S(1,2,\ldots,s)$ storage facility candidates.
- $\overline{S}(1,2,\ldots,\overline{s})$ the copies of storage facility candidate.
- $F(1,2,\ldots,f)$ integrated facility candidates.
- $L(1,2,\ldots,l)$ capacity level options for facilities.

Parameters:

- FC_{il} fixed cost of opening facility $i \in S \cup F$ with capacity level $l \in L$.
- CAP_{il} capacity level $l \in L$ acquired at facility $i \in S \cup F$.
- VC_i unit variable cost of operating used oil at facility $i \in S \cup F$.
- g_i amount of used oil generated at node $i \in G$.
- VFC fixed cost of collection vehicle.
- $VCAP$ collection vehicle capacity.
- D_{ij} length of edge $(i,j) \in E$.
- TC^{store} vehicle cost of transporting used oil per kilometer among generation nodes, storage facilities and copy storage facilities.
- TC^{treat} unit cost of transporting used oil per kilometer from storage facilities to integrated facilities.
- $\overline{C}$ maximum ground-level concentration of the hazmat contained in used oils.
- T_{il} release time of used oil at facility $i \in S \cup F$ with capacity level $l \in L$.

Decision variables:

- o_{il} 1 if facility with capacity level $l \in L$ is located at node $i \in S \cup F$, 0 otherwise.
- w_{ijml} 1 if edge $(i,j) \in E$ appears in the vehicle route, where this vehicle is destined to the copy storage facility $m \in \overline{S}$ with capacity level $l \in L$, 0 otherwise.
- x_{ijml} amount of used oils loaded in the vehicle on edge $(i,j) \in E$, where this vehicle is destined to the copy storage facility $m \in \overline{S}$ with capacity level $l \in L$.
- x_{jiml} empty space on the vehicle traveling on edge $(i,j) \in E$, where this vehicle is destined to the copy storage facility $m \in \overline{S}$ with capacity level $l \in L$.
- y_{ijl} amount of used oil transported from storage facility $i \in S$ (or, equivalently, copy storage facility) to integrated facility $j \in F$ with capacity level $l \in L$.
- z_{iml} 1 if the used oil generated at node $i \in G$ is finally transported to copy storage facility $m \in \overline{S}$ with capacity level $l \in L$, 0 otherwise.
- s_{ml} amount of used oil stored at facility $m \in \overline{S}$ with capacity level $l \in L$, where

$$s_{ml} = \sum_{i \in G, (i,j) \in E} x_{ijml} \tag{9}$$

f_{il} amount of used oil treated at facility $i \in F$ with capacity level $l \in L$, where

$$f_{il} = \sum_{j \in S} y_{jil} = \sum_{\substack{m \in \overline{S} \\ m-j=|S|}} y_{mil} \tag{10}$$

Note that, $m-i=|S|$ denotes that node $m \in \overline{S}$ is the copy of node $i \in S$

K number of collection vehicles needed.

Using the above notation, Fig. 2 provides an illustrative example for the basic flow rules used in our two-commodity flow formulation.

The proposed location-routing model is as follows:

$$M(A): \ \min h_1 = \sum_{i \in S \cup F}\sum_{l \in L} FC_{il} o_{il} + \sum_{i \in S \cup F}\sum_{l \in L} VC_i (s_{il} + f_{il}) + \sum_{i \in S}\sum_{j \in F}\sum_{l \in L} TC^{treat} D_{ij} y_{ijl} + \sum_{i,j \in G \cup S \cup \overline{S}}\sum_{m \in \overline{S}}\sum_{l \in L} \frac{1}{2} TC^{store} \times D_{ij} w_{ijml} + K \times VFC \tag{11}$$

$$\min h_2 = \sum_{i \in S \cup F}\sum_{l \in L} \frac{2\pi o_{il}}{3}\left(\frac{CAP_{il}}{\pi uab\overline{C}T_{il}}\right)^{3/(c+d)} + \sum_{i,j \in G \cup S \cup \overline{S}}\sum_{m \in \overline{S}}\sum_{l \in L} 200\pi D_{ij} w_{ijml} + \sum_{i \in S}\sum_{j \in F}\sum_{l \in L} \frac{400\pi D_{ij} y_{ijl}}{VCAP} \tag{12}$$

Subject to (9) and (10)

$$\sum_{\substack{j \in G \cup S \cup \overline{S} \\ j \neq i}} (x_{ijml} - x_{jiml}) = 2 \times g_i \times z_{iml}, \quad \forall i \in G, \ \forall m \in \overline{S}, \ \forall l \in L \tag{13}$$

$$\sum_{i \in G}\sum_{m \in \overline{S}}\sum_{l \in L} x_{miml} = K \times VCAP - \sum_{i \in G} g_i \tag{14}$$

$$\sum_{i \in G} x_{imml} = \sum_{i \in G} g_i \times z_{iml}, \quad \forall m \in \overline{S}, \forall l \in L \tag{15}$$

$$\sum_{i \in G}\sum_{j \in S}\sum_{m \in \overline{S}}\sum_{l \in L} x_{ijml} \le K \times VCAP \tag{16}$$

$$x_{ijml} + x_{jiml} = VCAP \times w_{ijml}, \quad \forall i,j \in G \cup S \cup \overline{S}, i \neq j, \forall m \in \overline{S}, \forall l \in L \tag{17}$$

$$\sum_{\substack{i \in G \cup S \cup \overline{S} \\ i \neq j}} w_{ijml} = 2 \times z_{jml}, \quad \forall j \in G, \forall m \in \overline{S}, \forall l \in L \tag{18}$$

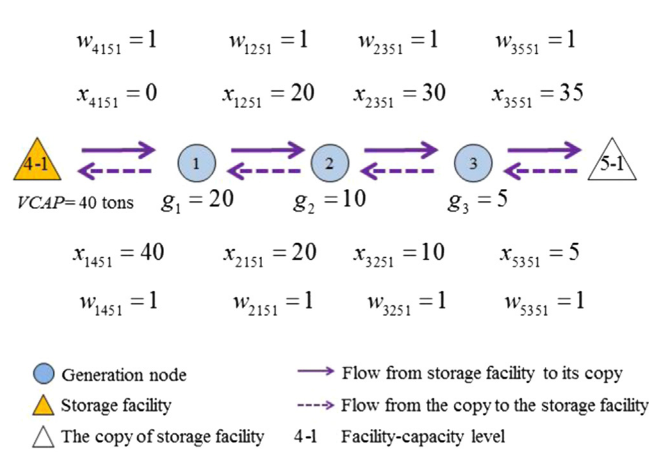

Fig. 2. The illustration of basic flow rules for the two-commodity flow formulation.

$$\sum_{\substack{i \in G \cup S \cup \overline{S} \\ i \neq m}} \sum_{l \in L} (w_{ijml} + w_{jiml}) = 0, \forall j \in S, \forall m \in \overline{S}, m - j \neq |S| \quad (19)$$

$$\sum_{\substack{i \in G \cup S \cup \overline{S} \\ i \neq m}} \sum_{l \in L} (w_{ijml} + w_{jiml}) = 0, \forall j, m \in \overline{S}, j \neq m \quad (20)$$

$$\sum_{m \in \overline{S}} \sum_{l \in L} w_{ijml} = 0, \quad \forall i, j \in G \cup S \cup \overline{S}, i = j \quad (21)$$

$$\sum_{m \in \overline{S}} \sum_{l \in L} z_{iml} = 1, \quad \forall i \in G \quad (22)$$

$$w_{ijml} \le o_{il}, \quad \forall i \in S, \forall j \in G \cup S \cup \overline{S}, \forall m \in \overline{S}, m - i = |S|, \forall l \in L \quad (23)$$

$$\sum_{j \in F} \sum_{l \in L} y_{ijl} = \sum_{l \in L} s_{il}, \quad \forall i \in S \quad (24)$$

$$s_{il} \le o_{il} CAP_{il}, \quad \forall i \in S, \forall l \in L \quad (25)$$

$$f_{il} \le o_{il} CAP_{il}, \quad \forall i \in F, \forall l \in L \quad (26)$$

$$\sum_{l \in L} o_{il} \le 1, \quad \forall i \in S \cup F \quad (27)$$

$$o_{il} = 0, 1, \quad \forall i \in S \cup F, \forall l \in L \quad (28)$$

$$w_{ijml} = 0, 1, \quad \forall (i,j) \in E, \forall m \in \overline{S}, \forall l \in L \quad (29)$$

$$x_{ijml} \ge 0, \quad \forall (i,j) \in E, \forall m \in \overline{S}, \forall l \in L \quad (30)$$

$$x'_{jiml} \ge 0, \quad \forall (i,j) \in E, \forall m \in \overline{S}, \forall l \in L \quad (31)$$

$$y_{ijl} \ge 0, \quad \forall i \in S \cup \overline{S}, \forall j \in F, \forall l \in L \quad (32)$$

$$s_{il} \ge 0, \quad \forall i \in S, \forall l \in L \quad (33)$$

$$f_{il} \ge 0, \quad \forall i \in F, \forall l \in L \quad (34)$$

$$K \text{ Integer} \quad (35)$$

Objective function (11) aims to minimize the total cost, whereas objective function (12) minimizes the total environmental risk. The cost objective function is the sum of the fixed cost of storage and integrated facilities, the variable cost of operating storage and integrated facilities, the total used oil transportation cost on the road network and the vehicle fixed costs. Notable in this objective function is that, each collection route in the planned tour is counted twice since the route is defined by two paths. Once a collection route is selected, its distance traveled will be doubled in the model. To eliminate the cost of the second path, we divide the term of transportation cost in the tour by two. Turning to the risk objective (12), the first term represents the total volume of the boxes around the nodes with a predetermined uniform concentration level. This term is obtained by combining (1), (7) and (8). The second term in (12) corresponds to the total risk associated with the collection tours, whereas the third term represents that of the return trips between the storage and integrated facilities. Note that the impact radius of 800 m is associated with the collection vehicles with capacity *VCAP*, whereas the vehicles used between the storage and integrated facilities typically carry larger amounts of used oil, denoted by y_{ijl}. These terms are based on (3).

The first four constraints (13)–(16) are for conservation of flow during the collection of used oils. Constraint (13) states that the total outflow minus the inflow at each generation node is equal to twice the amount of used oil generated at this node, where this generation node is allocated to a copy storage facility with a selected capacity level. Constraint (14) guarantees that the total outflow of copy storage facilities is equal to the remaining capacity of vehicles. Constraint (15) ensures that the total inflow of a copy storage facility with a selected capacity level is equal to the total generation amount of allocated used oils. Constraint (16) ensures that the total inflow of copy storage facilities is limited by the vehicle capacity. Constraint (17) ensures that the x_{ijml} and x'_{jiml} variables take feasible values, whereas (18) states that each generation node has two incident edges. Note that when $m - j \neq |S|$ the nodes j and m are not copies of each other. Therefore, Constraint (19) ensures that the vehicle cannot visit any of the other copy storage facilities on its way from a storage facility j to its copy m. Constraint (20) guarantees that there are no links connecting copy storage facilities, whereas constraint (21) eliminates the trivial sub-tours, where a link has the same starting and ending node (as noted earlier, these are the only type of sub-tours that are allowed by our formulation). Constraint (22) indicates that the used oils produced at each generation node are finally transported to only one copy storage facility with only one selected capacity level. Meanwhile, constraint (23) guarantees that the vehicle can only start at an open storage facility. The conservation of flow at the storage facilities is guaranteed by constraint (24)–(26) are capacity constraints. Constraint (27) guarantees that each facility can only acquire at most one capacity level. The variable domains are given at Constraints (28)–(35).

The developed used oil location-routing model $M(A)$ is formulated as a bi-objective mixed integer linear programming model including 0-1, integer and continuous decision variables. For problems of realistic size, the resulting model may not be amenable to solution via commercial software. Thus, in the next section,

Table 3
Weekly amounts of the used oil produced at generation nodes.

Generation node	Amount (t)	Generation node	Amount (t)
1	2	11	15
2	4	12	10
3	4	13	10
4	10	14	2
5	5	15	8
6	20	16	10
7	10	17	5
8	7	18	10
9	5	19	10
10	10	20	10

Table 4
Facility candidates.

Storage facility candidate		Integrated facility candidate	
Node	Fixed cost (10^3 yuan)	Node	Fixed cost (10^3 yuan)
21	100; 120; 150; 160	31	200; 220; 250; 250
22	120; 150; 160; 180	32	180; 200; 210; 220
23	150; 160; 180; 200	33	150; 160; 180; 200
24	100; 120; 150; 160	34	120; 150; 160; 180
25	120; 150; 160; 180	35	150; 160; 180; 200
26	150; 160; 180; 200	36	180; 200; 210; 220
27	100; 120; 150; 160	37	120; 150; 160; 180
28	120; 150; 160; 180	38	140; 150; 160; 180
29	150; 160; 180; 200	39	160; 180; 200; 220
30	180; 200; 210; 220	40	120; 150; 160; 180

we present a modified weighted goal programming approach to obtain representative efficient solutions.

4. Solution procedure

When solving the developed bi-objective optimization model, there is usually a Pareto optimal solution set. The solution of single-objective optimization model, in the contrast, can be obtained within reasonable time. For this reason, converting $M(A)$ into a single-objective model is a practical solution approach.

Since the goal programming technique and linear weighting method have been widely used as the efficient conversion approaches to solve the multi-objective problem of hazardous waste management [5,9,10,13–15,19], we implement the weighted goal programming method [40], namely transforming our proposed bi-objective location-routing problem into a weighted single-objective one based on the goal programming technique. Although this method has been successfully applied to the solution procedure designed by Zhao and Zhao [19], the analysis of each weighted sub-objective has been ignored. Similar to Alumur and Kara [5], we pay attention to the weight of each sub-objective, and aim to provide various efficient plans for the used oil location-routing problem through verifying weights. To be specific, we modify the weighted goal programming method [40] and rewrite $M(A)$ as

$M(B)$:

$$\min h_3 = \lambda\alpha_1\beta_1 + (1-\lambda)\alpha_2\beta_2 \quad (36)$$

Table 5
Optimal values for $M(A)-1$ and $M(A)-2$.

Model	Objective	Annual cost (yuan)	Environmental risk (km³)	CPU time (s)
M(*A*)-*1*	Min cost	**433,360**	84,222	1614.61
M(*A*)-*2*	Min envir. risk	1,213,400	**22,351**	2414.05

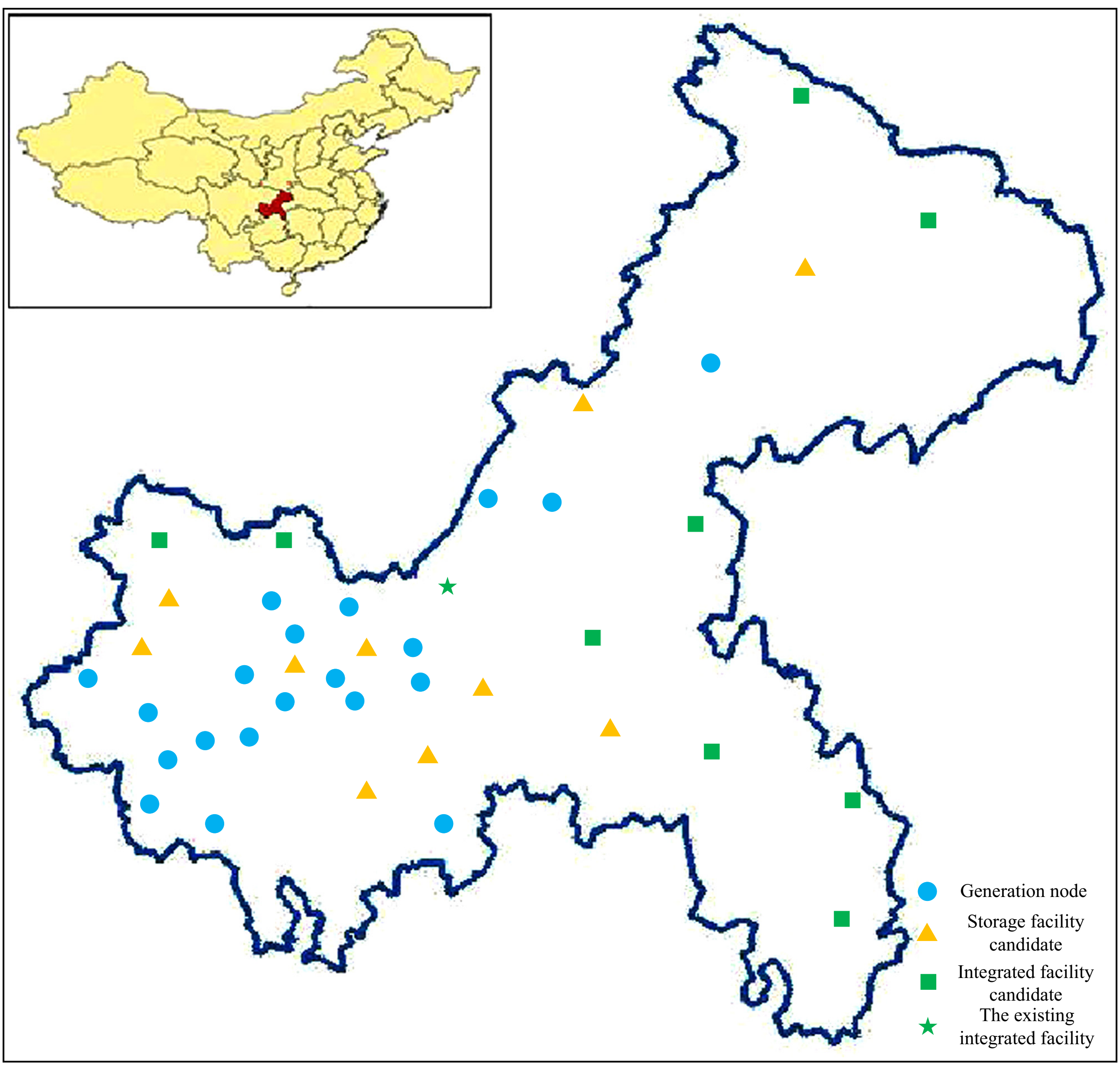

Fig. 3. Used oil generation nodes and alternative facility sites in Chongqing.

Table 6
Optimal solutions for of *M*(*A*)-*1* and *M*(*A*)-*2*.

Model	Storage facility/ capacity level (t yr^{-1})	Integrated facility/ capacity level (t yr^{-1})	# of Collection vehicle	Tour	Route
M(*A*)-*1*	24/6000	34/6000	5	24-4-24; 24-13-11-9-10-24; 24-12-20-15-18-24; 24-1-7-14-6-17-24; 24-8-19-5-2-3-16-24.	24–34
M(*A*)-*2*	21/1500, 26/1500, 27/1500, 28/1500.	31/1500, 36/1500, 37/1500, 38/1500.	7	21-5-21; 21-3-16-10-4-1-2-21; 26-6-26; 26-18-15-20-14-26; 27-7-27; 27-19-11-9-17-27; 28-13-8–12-28.	21–31; 26–36; 27–37; 28–38.

Subject to Constraints (8)–(10), (13)–(35) and

$$h_1 - \beta_1 = h_1^* \tag{37}$$

$$h_2 - \beta_2 = h_2^* \tag{38}$$

Note that parameters h_1 and h_2 are the sub- objective functions presented in Sections 3. λ and $(1-\lambda)$ are the respective positive weights attached to deviations, where $\lambda \in [0,1]$. α_i is the normalization factor of sub-objective, $i=1,2$. β_i is the positive deviation of sub-objective, $i=1,2$. h_i^* is the target value of sub-objective, $i=1,2$.

The objective function (36) is the achievement function of minimum optimization problem. Eqs. (37) and (38) are the regular constraints formulated in the weighted goal programming. They state that the positive deviations are obtained from the target values of sub-objective. Once the target value and normalization factor are given, the *M*(*B*) is easy to solve. For this reason, a solution procedure for *M*(*A*) can be designed as follow, where some key techniques are adopted to decide the related target value and normalization factor:

Step 1: Find h_i^*. Solve *M*(*A*) with the sub-objective of minimizing the total cost and environmental risk separately, and we refer them as *M*(*A*)-*1* and *M*(*A*)-*2*. The optimal value of each sub-objective is set as the target value h_i^*, $i=1,2$.
Step 2: Set α_i. Use percentage normalization technique [40] to decide the normalization factor value α_i, $i=1,2$, where

$$\alpha_i = \frac{100}{h_i^*} \tag{39}$$

Step 3*:* Set λ and $(1-\lambda)$.
Solve *M*(*B*). The final solution of *M*(*B*) is an efficient solution of *M*(*A*).

It can be assessed that the solution of *M(B)* is flexible to the respective positive weight λ, which is set by decision-makers according to their personal preferences. As the value of λ varies, a number of potential optimal solutions are generated. As for the decision-makers who are concerned about the cost and environmental risk in the used oil location-routing optimization, the solution with a proper range of weight λ would be desirable.

In the next section, we test the developed model and approach based on a case study of the used oil management in Chongqing, where the proper range of parameter λ is recommended from the trade-off analysis. Meanwhile, some related comparisons are also provided.

5. A realistic case study: Chongqing, China

A case study, which makes use of the developed model and approach in Chongqing of Southwest China, is presented in this section. First we outline the data set that is derived from the real-life instance. Then, we present our findings through the solution of the case.

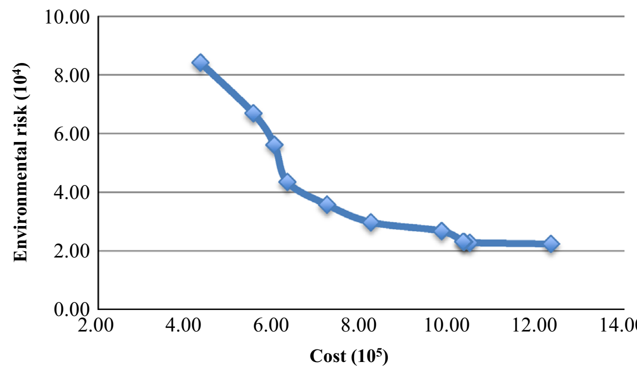

Fig. 4. Trade-off curve with λ increment of 0.1.

5.1. The data set

To estimate the parameters related to the environmental risk assessment model presented in Section 3, we first use the threshold impact radius of 800 m in all directions around the edge sources in accordance with the recommendations in [38,41]. Then, according to the report for immediately dangerous to life or health concentrate level of lead and its compounds commissioned by CDC [42,43], we assume the release time as 60 min. The dispersion parameters in GPM, assumed as per the suggestion in [44], are as follows: $a=0.02$, $b=0.05$, $c=0.89$, $d=0.61$ and $u=3$ m/s.

In 2012, the GDP of Chongqing is almost 500 billion yuan (i.e., US$80 billion), majority of which is based on the petrochemical industries. Nearly 300 petrochemical facilities are distributed in 38 regions of this province, and there is only one integrated hazardous waste treatment facility located in Changshou. As the industrial development of Chongqing accelerates, the exiting integrated facility is facing capacity problems in processing all the used oils generated in the province.

The weekly generation of used oil at each facility is less than the truck capacity of 40 t. Also, to comply with the definition of a “large hazardous waste generator” in the Resource Conservation and Recovery Act Subtitle C of EPA,[1] we combined the small generation nodes that are in the vicinity of each other. As a result, thus case includes 20 nodes that generate used oil. The weekly generation amounts of used oil are reported in Table 3. Note that the concentration of Pb in the used oil at each generation node equals to the allowable level of 100 mg/kg [3]. In view of the constituted regulations in China, we also determined 10 alternative sites for the storage facilities (i.e., nodes 21–30) and 10 alternative locations for the integrated facilities (i.e., nodes 31–40). Table 4 reports the fixed costs of facility candidate for four different capacity levels i.e., 1500, 3000, 4500 and 6000 t annually. The spatial distribution of these 40 nodes, including generation nodes, storage facility candidates and integrated facility candidates, are all illustrated in Fig. 3.

[1] See http://www.epa.gov/region02/waste/csummary.htm.

Table 7
Optimal Solution for $M(A)$ with $\lambda = 0.40$.

Storage facility/capacity level (t yr^{-1})	Integrated facility/capacity level (t yr^{-1})	# of Collection vehicle	Tour	Route
21/1500; 24/3000; 27/1500.	34/3000; 37/1500; 40/1500.	6	21-3-16-9-11-21; 24-15-19-8-24; 24-10-17-5-2-13-24; 24-12-20-4-18-24; 27-14-6-27; 27-1-7-27.	21–40; 24–34; 27–37.

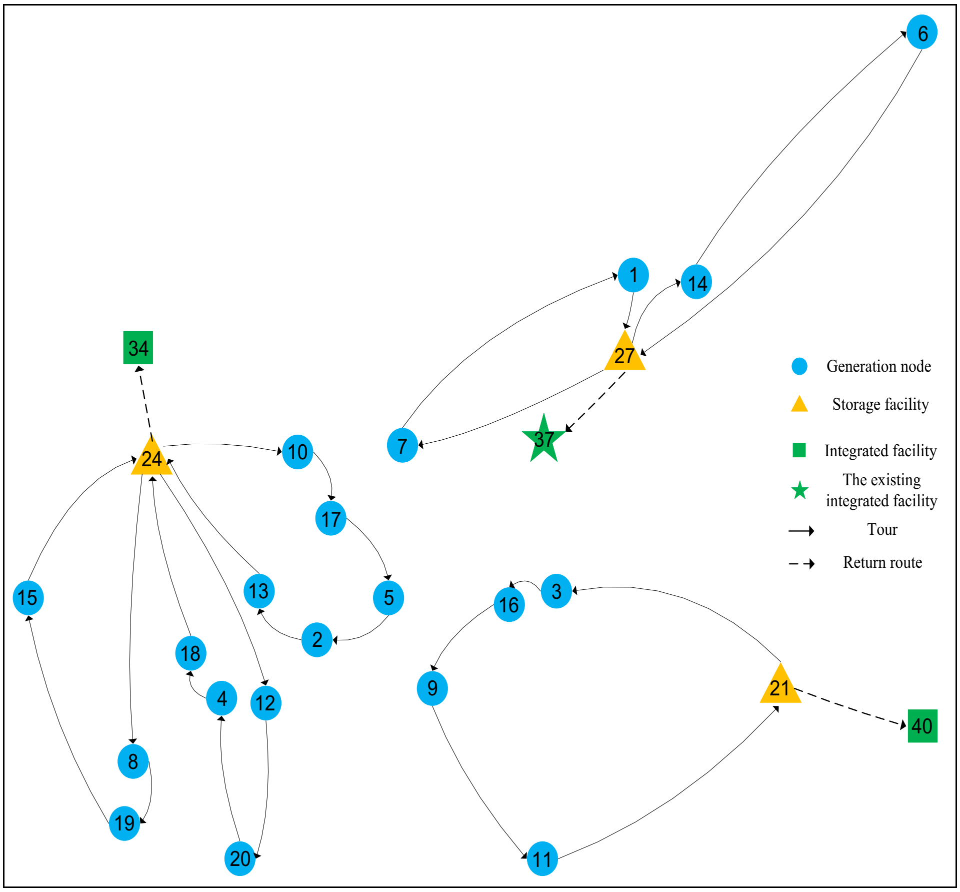

Fig. 5. The optimal solution to the used oil location-routing problem in Chongqing ($\lambda = 0.40$).

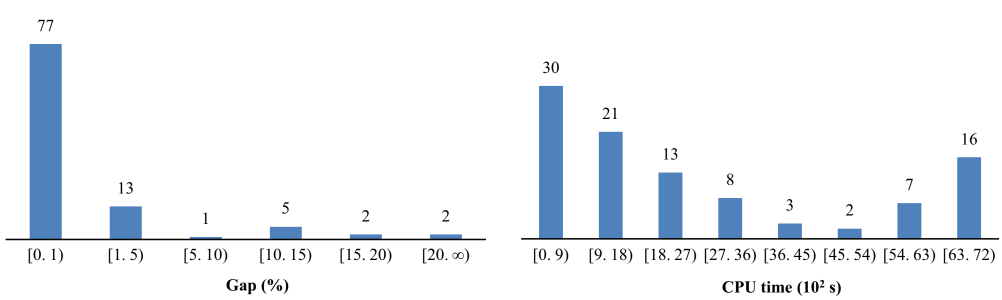

Fig. 6. Results for 100 test instances with different generation amounts of used oil.

The vehicle cost and the unit cost of transporting used oil per kilometer are calculated based on the average cost of fuel as 7.32 yuan km^{-1} and 3.66 yuan t^{-1} km^{-1}, respectively. A vehicle, in this work, is assumed to use on average 0.30 l km^{-1}, and fuel costs about 1.22 yuan l^{-1}.

5.2. Solution of the Chongqing case

The solution procedure is implemented on a computer with a 2.2 GHz Intel processor and 2 GB RAM and by using IBM ILOG CPLEX 12.5 with active standard CPLEX cuts. Table 5 depicts the solutions to $M(A)$-*1* and $M(A)$-*2* i.e., the cost-only and risk-only solutions, respectively. Note that the optimal cost-only solution and the optimal risk-only solution (bold-faced, underlined) are the target values in the developed solution procedure. For these two solutions, Table 6 reports the facility locations, capacity levels, collection tour plans, and routes between storage and integrated facilities.

It is worthwhile to note that the two-commodity flow formulation of the VRP involves about 100 times more continuous variables than the traditional three-index vehicle flow formulation [24]. Nevertheless, we were able to find an optimal solution to *M* (*A*)-*1* in 27 min, whereas the traditional formulation was not able to identify the optimal solution within an hour. The best solution found via the traditional model within an hour has 50% higher costs than the optimal solution. It is also interesting to compare the proposed model with that of Alumur and Kara [5]. As mentioned earlier, the vehicles in [5] make a return trip to each generation node for collecting the used oils, in contrast with the collection tours developed by our model. Therefore, [5] would need 20 vehicles for transporting used oils from the generation nodes to the storage facilities in this case, whereas our model provides a plan with at most 7 vehicles. Arguably, the latter is more desirable from the perspective of both the costs and the environment.

To represent the trade-off between the cost and the environmental risk, we increase λ from 0 to1 in increments of 0.1 and plot Fig. 4. The optimal solution to *M*(*A*)-1 is the right-most point in Fig. 4 where $\lambda=1$ and that of *M*(*A*)-*2* is the left-most point with $\lambda=0$. Note that the points for $\lambda=0.7$, 0.8 and 0.9 overlap in the figure. It seems that the reduction in the environmental risk flattens when $\lambda>0.4$. Thus, Table 7 presents the location-routing plan for $\lambda=0.40$, and Fig. 5 depicts the solution, where directed solid lines refer to collection tours, and dotted ones represent routes between storage and integrated facilities. The cost of this solution is 982,510 yuan, whereas the environmental risk is 26,750 km^3. That is it is possible to achieve an environmental risk within 2200 km^3 of the risk-only solution by incurring about 550,000 yuan. We remark that the location of the existing facility was represented as alternative site 37, and it indeed appears in the optimal solution (i.e., the star in Fig. 5).

6. Further computational results

In this section, we evaluate the scalability of the proposed model for the used oil location-routing problem. To this end, we use the Chongqing case as a "base case" and develop two sets of hypothetical problem instances. In Problem Set 1, we took the base case location data as given and generated 100 instances, each with different amounts of used oil generated at the 20 sites. Problem Set 2 contains 20 instances, each with an expanded set of location alternatives compared to the base case.

Based on the case study involving 10 storage and 10 integrated facility candidates, an instance in Problem Set 1 corresponds to a realization of the weekly used oil generation at each of the 20 source facilities from a uniform distribution between 1 and 40 t. In solving *M*(*A*)-*1* for each of the 100 instances, we imposed a 2-h CPU time limit. CPLEX found the optimal solution within 2 h for only two instances. For the other instances, we determined the time point at which the best solution was identified (i.e., after which no improvement in the solution was recorded). Fig. 6 provides the frequency distribution of the CPU time for these best-known solutions within two hours and the gap between the lower bound and the best-known solution. Remarkably, the gap is less than 1% for 77 instances and the best-known solution was identified in 72 instances within an hour.

Table 8
Categorization the 100 test instances with different generation amounts of used oil.

Group	Amount of used oil (t)	Average CPU time (s)	Max CPU time (s)	Min CPU time (s)	Average gap (%)	Max. gap (%)	Min. gap (%)
A	[1,10]	1210.12	2330.95	551.94	0.10	0.43	0.01
B	[1,15]	1626.80	7150.33	288.02	0.36	4.52	0.00
C	[1,20]	2356.52	7151.66	288.02	1.07	27.08	0.00
D	[1,30]	2531.78	7151.66	288.02	1.35	27.08	0.00
E	[1,40]	2718.20	7183.89	288.02	2.04	32.28	0.00

We also categorized the same 100 instances into five groups according to the level of variation among the amount of used oil generated at the 20 source facilities. The second column in Table 8 indicates that Group A comprises all the instances where generation amounts are up to 10 t, whereas Group B comprises all the instances where generation amounts are up to 15 t etc. Evidently the problem becomes computationally more challenging as the variation among the generation amounts increases.

In order to test the proposed model for tackling larger networks, each of the 20 instances in Problem Set 2 expands the sets of existing and alternative sites by adding randomly generated nodes. Ranked in ascending order of the total number of nodes, Table 9 depicts the numbers of generation sites and alternative storage and integrated facility locations for these instances. We used a 10 h CPU time limit in solving *M*(*A*)-*1*. The computational results reported in Table 9 indicate that when the total number of generation nodes and storage/integrated facility site alternatives exceeds 50, it becomes more likely to obtain unacceptable gaps with a CPU time of 10 h. As expected, the problem quickly becomes computationally prohibitive as the location sets are expanded. We conducted further computational experiments on the instances with a gap between the lower bound and the

Table 9
Results for the test instances on larger networks.

Instance	# of generation nodes	# of storage facility candidates	# of integrated facility candidates	CPU time (min)	Gap (%)
Network 1 (Case study)	20	10	10	26.92	0.02
Network 2	20	15	10	68.32	2.00
Network 3	20	10	20	29.52	1.11
Network 4	20	20	10	585.62	25.18
Network 5	35	10	10	60.63	2.59
Network 6	20	15	20	85.83	2.00
Network 7	40	10	10	588.40	21.02
Network 8	20	10	30	32.27	1.83
Network 9	20	20	20	586.10	31.35
Network 10	35	10	20	63.65	2.99
Network 11	20	15	30	141.10	3.78
Network 12	20	10	40	33.35	3.62
Network 13	20	20	30	589.68	36.77
Network 14	40	20	10	599.67	38.51
Network 15	35	10	30	66.68	3.33
Network 16	20	15	40	183.12	8.96
Network 17	40	20	20	591.13	45.23
Network 18	20	20	40	596.97	40.25
Network 19	35	10	40	71.25	3.82
Network 20	40	25	20	588.88	56.24

Table 10
Results for the test instances on gaps > 4% with extended CPU time limit.

Instance	CPU (min) < 10 h	Gap (%)	CPU (min) < 20 h	Gap (%)	CPU (min) < 30 h	Gap (%)
Network 4	585.62	25.18	767.15	7.81	1465.27	1.17
Network 7	588.40	21.02	882.60	10.51	1412.17	2.63
Network 9	586.10	31.35	767.78	9.72	1481.83	2.04
Network 13	589.68	36.77	884.53	18.39	1397.55	5.33
Network 14	599.67	38.51	1085.40	23.11	1736.63	6.24
Network 16	183.12	8.96	722.38	5.10	1341.83	1.01
Network 17	591.13	45.23	916.25	29.40	1604.45	9.70
Network 18	596.97	40.25	1074.53	25.36	1762.47	15.51
Network 20	588.88	56.24	865.67	39.37	1532.22	11.81

best-known solution larger than 4%. It is clear from Table 10 that additional computational time is effective in reducing the gap. Note that within a CPU Time of 30 h (which is quire reasonable for this kind of strategic design problems), we were able to reduce the gap under 10% in all, but two, instances.

In concluding this section, we reiterate that the variation among the collection nodes in terms of the amounts of used oil generated seems to be a significant determinant in problem complexity, in addition to the size of the location sets, which is a somewhat more obvious factor. It also seems that the development of a solution algorithm that takes advantage of the structure of the integer formulation at the core of the proposed model may become necessary when the problem instance at hand is significantly larger than the Chongqing case.

7. Conclusion

This paper presents a new bi-objective model for the used oil location-routing problem, in which, the main contribution is threefold. First of all, we propose a new used oil location-routing formulation, where the problem is defined as simultaneous optimization of facility location, capacity acquisition and vehicle routing. Note that, we assume that the vehicles in vehicle-routing sub-problem make two types of trips—tours and routes. Secondly, we propose a new risk measure by focusing on the air pollution resulting from accidental release accidents causing fire. To this end, we integrated the box model and GPM, and formulate the assessment model as a sum of impact volumes in air due to the release and ignition of the used oils. Thirdly, we develop a solution methodology for the proposed bi-objective model. Note that the cost and risk objectives are measured in different units. Moreover, the weights for these two objectives can be different according to decision-makers' preferences. We modify the weighted goal programming method to convert the bi-objective optimization problem into a traditional MILP through the adoption of percentage normalization technique. This allows the decision-makers to obtain various optimal location-routing plans for used oil management through a parametric analysis of the weights associated with each objective.

We also present a case study in Chongqing of Southwest China, and test instances to demonstrate the workability of the developed model and approach. Based on the case study we also prove that our model outperforms the traditional VRP model in this domain i.e., our solution has both lower cost and lower environmental risk, with smaller gap and shorter CPU time. The test instances demonstrate the applicability of our model and evaluate the scalability of our developed model for the used oil location-routing problem, in which, the computational results show that, our model can provide efficient solutions for different size problems with various generation amounts of used oil.

It is important that our model is specifically proposed for the used oil. When managing *multiple hazardous wastes*, some new improvements in the model and approach are required. On the one hand, it may be necessary to consider other relevant objectives and constraints in the model. For instance, balancing the workload on vehicles in the sub-problem of vehicle-routing [45], introducing waste–waste compatibility into the constraint set, namely one must ensure that incompatible wastes are not shipped on the same vehicle. Also, there is a possibility of incorporating the time window limitation on vehicle routes into the modeling process [46,47]. On the other hand, a heuristic technique is essential for solving large-scale problems. For instance, one can divide the combined location-routing problem into several sub-problems. According to the priority of each sub-problem, especially the VRP [47,48], the efficient solutions can be found through multiple heuristic solving stages.

Extension of the proposed environmental risk assessment model can be another research direction. To be specific, the ecology damage before a cleanup and the remains impact after stopping a release or even removing the released material should be considered [49]. In actual, the environment is changing over time. There is thereby a motivation that the downwind speed can be taken into account in combination with risk assessment. The pollution in water and soil can also be explored. Moreover, in an effort to minimize the environmental risk, the proposed routes may pass through highly populated regions, which would increase the total population exposure. The extended model can also incorporate this trade off among multiple risk measures. Another concern lies in the exploration of the choice of λ. Based on the proposed solution procedure, the selection of λ is challenging due to its data sensitive, which may require large amount of sensitivity analysis in each case study to choose a right value.

Acknowledgments

This study is conducted while the first author was a graduate research trainee at McGill University. She greatly acknowledges the fellowship provided by the China Scholarship Council to support this one-year visit. She was also supported by the Project of Chinese National Natural Science Fund (Serial no. 71173177) and the Southwest Jiaotong University Doctoral Innovation Fund. The second author's work has been funded in part by a grant from the Social Sciences and Humanities Research Council of Canada. The authors are grateful to the two anonymous referees and the guest editor for their comments and suggestions that were helpful in improving the paper.

References

[1] U.S.EPA. Mixtures of used oil and characterristics hazardous waste; 1993. [accessed at: ⟨http://yosemite.epa.gov/osw/rcra.nsf/ea6e50dc6214725285256bf00063269d/b000cb82ff03922f8525670f006bcb84!OpenDocument⟩.
[2] U.K.DEFRA. A strategy of hazardous waste management in England; 2010 [accessed at ⟨http://www.defra.gov.uk⟩.
[3] Pichtel J. Waste management practices: municipal, hazardous, and industrial. Management of used oil. CRC Press; 2010 (chapter 19).
[4] P.R.China MEP. The first national pollution census bulletin; 2010.
[5] Alumur S, Kara BY. A new model for the used oil location-routing problem. Comput Oper Res 2007;34:1406–23.
[6] Michael DL, Phillip LB, Jeffrey CE. Hazardous waste management. Environmental resources management. 2rd ed. 2001.
[7] U.S.EPA. Listing of oil as a hazardous waste pursuant to section(8)(2), public law 96-463, Washington, DC; 1981.
[8] Erkut E, Tjandra SA, Vedat V. Hazardous materials transportation. Handbooks in operations research and management science, vol. 14. Elsevier; 2007; 539–621 (chapter 9).
[9] Zografos KG, Samara S. Combined location-routing model for hazardous waste transportation and disposal. Transp Res Record 1989;1245:52–9.
[10] Revelle C, Cohon J, Shobrys D. Simultaneous siting and routing in the disposal of hazardous wastes. Transp Sci 1991;25(2):138–45.
[11] Stowers CL, Palekar US. Location models with routing considerations for a single obnoxious facility. Transp Sci 1993;27(4):350–62.
[12] Jacobs TL, Warmerdam JM. Simultaneous routing and siting for hazardous-waste operations. J Urban Plan Dev 1994;120(3):115–31.
[13] Current J, Ratick S. A model to assess risk, equity and efficiency in facility location and transportation of hazardous materials. Location Sci 1995; 3(3):187–201.
[14] Wyman MM, Kuby M. Proactive optimization of toxic waste transportation, location and technology. Location Sci 1995;3(3):167–85.
[15] Giannikos I. A multiobjective programming model for locating treatment sites and routing hazardous wastes. Eur J Oper Res 1998;104(2):333–42.
[16] List G, Mirchandani P. An integrated network planar multi-objective model for routing and siting for hazardous materials and wastes. Transp Sci 1991; 25(2):146–56.
[17] Nema AK, Gupta SK. Optimization of regional hazardous waste management systems: an improved formulation. Waste Manag 1999;19(7–8):441–51.
[18] Nema AK, Gupta SK. Multiobjective risk analysis and optimization of regional hazardous waste management system. Pract Period Hazard Toxic Radioact Waste Manag 2003;7(2):69–77.

[19] Zhao J, Zhao J. Model and algorithm for hazardous waste location-routing problem. In: Proceeding of the ICLEM 2010: logistics for sustained economic development, 2010 ASCE; 2010. p. 2846–52.

[20] Shuai B, Zhao J. Multi-objective 0–1 linear programming model for combined location-routing problem in hazardous waste logistics system. J Southwest Jiaotong Univ 2011;46(2):326–32 (in Chinese).

[21] Funda S. A multi-objective mathematical model for the industrial hazardous waste location-routing problem. Eur J Oper Res 2013;226(2):332–40.

[22] Erkut E, Verter V. Hazardous materials logistics. In: Drezner Z, editor. Facility location. New York: Springer; 1995. p. 467–500.

[23] Laporte G, Nobert Y, Desrochers M. Optimal routing under capacity and distance restrictions. Oper Res 1985;33:1058–73.

[24] Golden BL, Magnanti TL, Nguyen HQ. Implementing vehicle routing algorithms. Networks 1977;7:113–48.

[25] Balinski M, Quandt R. On an integer program for a delivery problem. Oper Res 1964;12:300–4.

[26] Baldacci R, Hadjiconstantinou E, Mingozzi A. An exact algorithm for the capacitated vehicle routing problem based on a two-commodity network flow formulation. Oper Res 2004;52:723–38.

[27] Dantzig G, Fulkerson R, Johnson S. Solution of a large-scale traveling-salesman problem. J Oper Res Soc Am 1954;2:393–410.

[28] Miller CE, Tucker AM, Zemlin RA. Integer programming formulation of traveling salesman problems. J ACM 1960;7:326–9.

[29] Laporte G. What you should know about the vehicle routing problem. Nav Res Logist 2007;54(8):811–9.

[30] Ramos T. Tactical and operational planning in reverse logistics systems with multiple depots. (Ph.D. thesis). Instituto Superior Técnico, Universtidade Técnicade Lisboa; 2012.

[31] Wagner T. Hazardous waste: evolution of a national environmental problem. J Policy Hist 2004;16(4):306–31.

[32] Gifford FA. Atmospheric dispersion models for environmental pollution applications. In: Hauger DA, editor. Lectures on air pollution and environmental impact analysis. Boston, MA: American Meteorological Society; 1975 (chapter 2).

[33] Arya SP. Air pollution meteorology and dispersion. Cambridge: Oxford University Press; 1999.

[34] Schere KL, Demerjian KL. A photochemical box model for urban air quality simulation. In: Proceedings of the 4th conference on sensing of environmental pollutants. Washington, DC: American Chemical Society; 1978; 427–33.

[35] Jin S, Demerjian K. A photochemical box model for urban air quality study. Atmos Environ Part B. Urban Atmos 1993;27(4):371–87.

[36] Gurjar BR, Luisa T, Molina C, Shekhar PO. Air pollution: health and environmental impacts. CRC Press, New York; 2010.

[37] Verma M, Verter V. Railroad transportation of dangerous goods: population exposure to airborne toxins. Comput Oper Res 2007;34:1287–303.

[38] Brown DF, Policastro AJ, Dunn WE, Carhard RA, Lazaro MA, Freeman WA. et al. Development of the initial isolation and protective action distances for the 2000 Emergency Response Guidebook. Decision and Information Sciences Division, Argonne National Laboratory, ANL/DIS-00-1.

[39] Pasquill F, Smith FB. Atmospheric diffusion. 3rd ed. Chichester, UK: Ellis Horwood; 1983.

[40] Tamiz M, Jones D, Romero C. Goal programming for decision making: an overview of the current state-of-the-art. Eur J Oper Res 1998;111(3):569–81.

[41] Michel NM, Adrian VG. Quantitative risk assessment of hazardous materials transport systems: rail, road, pipelines and ship. Netherlands: Kluwer Academic publishers; 1996.

[42] Gerarde HW. Toxicology and biochemistry of aromatic hydrocarbons. New York, NY: Elsevier Publishing Company; 1960.

[43] National Institute for Occupational Safety and Health: NTIS Publication No. PB-94-195047. Accessed at 〈http://www.cdc.gov/niosh/idlh/default.html〉.

[44] Briggs GA. Diffusion estimation for small emissions. Preliminary report. Oak Ridge, TN, USA: National Oceanic and Atmospheric Administration, Atmospheric Turbulence and Diffusion Laboratory; 1973.

[45] Sahoo S, Seongbae K, Byung-In K, Bob K, Alexander Jr P. Routing optimization for waste management. Interfaces 2005;35(1):24–36.

[46] Santos AC, Duhamel C, Aloise DJ. Modeling the mobile oil recovery problem as a multiobjective vehicle routing problem. Modelling, computation and optimization in information systems and management sciences. In: Proceedings of the second international conference MCO 2008, Metz, France-Luembourg, September 8–10, 2008, vol. 14; 2008. p. 283–92.

[47] Kim B, Kim S, Sahoo S. Waste collection vehicle routing problem with time windows. Comput Oper Res 2006;33(12):3624–42.

[48] Bianchi-Aguiar T, Carravilla MA, Oliverira JF. Vehicle routing for mixed solid waste collection—comparing alternative hierarchical formulations. In: Proceedings of the ORP3 Meeting, Cadiz, September 2011. p. 13–17.

[49] Suleiman AA, Baaj MH, Pijawka KD, Serhan DS. Environmental impact assessment of transporting hazardous waste generated by maquiladora industry in U.S.–Mexico border region. Transportation Research Record: Journal of the Transportation Research Board, No. 1602. Washington, DC: Transportation Research Board of the National Academies; 1997. p. 84–92.