Journal of Cleaner Production 141 (2017) 909–919

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Hazardous materials collection with multiple-product loading

Germán Paredes-Belmar [a, c], Andrés Bronfman [a, c], Vladimir Marianov [b, *], Guillermo Latorre-Núñez [a]

[a] Graduate Program, Department of Electrical Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile
[b] Department of Electrical Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile
[c] Engineering Sciences Department, Universidad Andres Bello, Santiago, Chile

ARTICLE INFO

Article history:
Received 3 December 2015
Received in revised form
4 June 2016
Accepted 20 September 2016
Available online 21 September 2016

Keywords:
HAZMAT collection
Multiple hazardous materials
Exposed population
Minimum risk and cost

ABSTRACT

We present a new hazardous material (HAZMAT) collection problem in which various industrial HAZMAT are transported using a homogeneous capacitated truck fleet. Different materials have different risk levels in terms of the size of exposed population. A truck can simultaneously carry different materials. The size of the population exposed to a loaded truck increases if a higher risk material is added to the load. We minimize the total exposed population and the total transportation cost. We present a case study in the City of Santiago in Chile to show practical application of our proposed approach.

1. Introduction

Some industries located in urban or semi-urban areas require large amounts of hazardous materials (HAZMAT) as supplies on a daily basis, which must be transported from their production sites. In turn, multiple hazardous wastes produced by industries must be transported to their final treatment and disposal sites. A few years ago, four billion tons of HAZMAT were estimated to have been annually transported worldwide (Zografos and Androutsopoulos, 2004).

The main risk of transporting HAZMAT or wastes comes from the possibility of accidents (fire, explosion, chemical leak, radiation, etc.) with significant consequences for human life and environment. Although the number of accidents may be low compared with the number of shipments of these materials, the danger to which the population is exposed can be very significant. This fact causes society to be particularly sensitive to HAZMAT transport and to clearly differentiate it from the shipment of other goods (Tarantilis and Kiranoudis, 2001; Leal Junior and D'Agosto, 2011; Bianco et al., 2013). The general concern about the consequences of an accident involving HAZMAT has motivated researchers to develop multiple mathematical models to identify low-risk routes (Erkut et al., 2007; Zografos and Androutsopoulos, 2008).

Generally, using low-risk routes tends to result in a high transportation cost. In contrast, low-cost routes can be riskier in terms of the potential consequences of an accident. Therefore, most of the literature on HAZMAT transportation considers the joint minimization of cost and risk, aimed at offering a set of efficient alternatives to decision makers (Giannikos, 1998; Zografos and Androutsopoulos, 2004; Das et al., 2012; Bronfman et al., 2015; Kremer et al., 2016).

We propose a new approach to multi-product HAZMAT transportation that reduces cost and risk, which involves loading different types of HAZMAT or wastes in the same truck. This approach has been used in practice. In fact, standards exist that deal with compatibility of different HAZMAT for transportation (e.g., GPO, 2016). However, to the best of our knowledge, our approach has never been presented in the literature. Although some authors deal with the transportation of different types of HAZMAT (e.g., Nema and Gupta, 1999, 2003), they did not consider loading them on the same truck.

Some definitions are required to properly describe the advantages of our approach. Different authors use the term *risk* to express different indicators. We follow Tarantilis and Kiranoudis (2001), who defined risk as the *number of people exposed* to a certain

* Corresponding author.
E-mail addresses: german.paredes@unab.cl (G. Paredes-Belmar), abronfman@unab.cl (A. Bronfman), marianov@ing.puc.cl (V. Marianov), golatorre@uc.cl (G. Latorre-Núñez).

http://dx.doi.org/10.1016/j.jclepro.2016.09.163

danger or hazard (*population exposure risk*). We consider the fact that the distance that can potentially be reached by the negative effects of an accident involving HAZMAT depends on the material being carried, and this distance has been estimated (U.S. Department of Transportation, 2012). As a consequence, the exposed population also depends on the material, and it is defined as the population within the area that can be reached by a HAZMAT accident for a certain material. The population exposed to negative consequences by specific material *A* is associated to what we denote here as *material A risk*. A ranking can be made of all materials according to their risk and reachable area. We note that the population exposed to a riskier material also includes the population exposed to a less risky material.

By using our approach, both cost and risk decrease compared with the standard approach, which uses multiple trucks to carry a single material. The cost reduction comes from the economies of scope (different materials sharing the same trip), and the risk reduction is due to the fact that a truck loaded with multiple products exposes the same population that would similarly be exposed by the riskiest material being carried, in contrast to the condition when each material is separately transported, in which, the total exposed population is the sum of all the populations exposed to each material. In other words, the *truck risk* involves the riskiest material being carried by the truck irrespective of how many less risky materials are being simultaneously carried.

In our approach, a single truck risk varies along the route, and it is a function of the products transported by the truck on each section or link of the route. We assume that each customer or HAZMAT generator node produces HAZMAT with a single type of risk and that incompatible wastes or HAZMAT cannot be transported together. Because we deal with collection, the population exposed to a truck risk in successive sections of the route either remains the same or increases, depending on the risk associated with the last collected waste.

We also design a methodology to optimize the application of the proposed approach to real-size instances. Given an available capacitated truck fleet, the solution prescribes the least number of trucks to perform the collection as well as the routes that each truck must follow to collect the HAZMAT at the minimum weighted sum of costs and risks. The method includes constructing an auxiliary graph of the network and formulating an integer programming (IP) model that is solved using commercially available software (CPLEX). To determine an approximate set of non-dominated solutions, we use the weighting method where both objectives are normalized. Finally, a real HAZMAT collection case in a transportation network in the City of Santiago, Chile, is solved.

The remainder of the paper is organized as follows. Section 2 contains the literature review. Section 3 provides more details on the approach, whereas Section 4 describes the methodology. Section 5 presents the application to a real case in Santiago, Chile. Section 5 presents the conclusions and future work.

2. Literature review

In the specialized literature, most of the articles address the problem of transporting a single HAZMAT or product. Jacobs and Warmerdam (1994) simultaneously considered the routing and location of dumping sites. Giannikos (1998) located treatment or final disposal facilities and defined the transportation of hazardous wastes, thus minimizing operational cost, risk, difference in risk between population centers, and difference in disutility caused by placement of facilities. Leonelli et al. (2000) selected HAZMAT transportation routes that minimize costs and risk. The arcs had limited capacity. Tarantilis and Kiranoudis (2001) mitigated population exposure by designing the HAZMAT distribution routes. Zografos and Androutsopoulos (2002) presented two heuristics to solve the routing problem using time windows for HAZMAT distribution and studied the optimum deployment of emergency facilities for an adequate response in case of an accident. Shih and Lin (1999, 2003) studied the problem of infectious medical wastes in Taiwan. Zografos and Androutsopoulos (2004) defined the HAZMAT distribution problem as the vehicle routing and sequencing problem using time windows. Pradhananga et al. (2010) presented an ant colony algorithm to solve the HAZMAT transportation problem using time windows. Androutsopoulos and Zografos (2012) studied the HAZMAT distribution problem as a bi-objective vehicle routing and sequencing problem using time windows. Siddiqui and Verma (2015) proposed a linear IP model to route and sequence a heterogeneous fleet of ships for transportation of oil, thereby minimizing the cost and risk. Bronfman et al. (2015) proposed a new HAZMAT routing problem using a single type of product in an urban area between pre-selected origin and destination points.

Multiple products have been considered by many authors. Abkowitz and Cheng (1988) minimized risk and cost in HAZMAT transportation, and they focused on risk estimation. The levels of risk depended on the type of material, and each material was separately transported. Alternate routes to transport products between origin–destination pairs were established. Hu et al. (2002) presented a model to minimize costs for a reverse logistics system for several hazardous wastes. The model considered operational and governmental limitations in the design of an efficient and safe system. Ahluwalia and Nema (2006) developed a model for a multi-objective reverse logistics problem for the collection of several types of computational wastes. The costs and risks were minimized. Waste quantities varied with time, and these quantities were estimated using Monte Carlo simulation. Sheu (2007) developed a management system for the treatment of three types of hazardous wastes from multiple sources as a reverse logistics problem. The logistical costs and risk were minimized. The risk depended on the quantity of products being transported. The volume of wastes varied with time. Verter and Kara (2008) solved a network design for HAZMAT distribution by choosing among previously known paths. They considered various types of HAZMAT (gasoline, oil, petroleum, tar, and alcohol) that carried different levels of risk. Similar to our model, the risk imposed by a link of the route was estimated by the number of exposed people and depended on the type of material. No HAZMAT combinations were allowed in a truck. Samanlioglu (2013) determined the location of different technology treatment centers, recycling facilities, and disposal centers. The model was strategic and prescribed the total flow of waste between HAZMAT generators and the different types of facilities. The routes between generators and facilities and among facilities were preset, rather than designed for minimum risk and cost. Different types of wastes were transported in separate trucks. Nema and Gupta (1999) proposed a multi-objective integer model to optimally solve the problem of collection, treatment, and disposal of several hazardous wastes. Truck capacities were not considered. The risk imposed by each material depended on the volume of waste being transported, the hazard associated with it, the probability of an accident, and the exposed population. The model minimized costs and risk. Interactions among materials or the predominance of material risks was not considered. The authors applied the model to a test instance with 16 nodes and 20 arcs. Nema and Gupta (2003) improved the model proposed by Nema and Gupta (1999) using a goal programming model. Hamdi et al. (2010) studied the problem of routing and sequencing by transporting different compatible materials in a single truck but without considering the risk; only the transportation cost was minimized. They proposed a local search heuristic to solve the problem. Hamdi-Dhaoui et al. (2011) continued the work of Hamdi et al. (2010) by incorporating two heuristics: Iterated Local Search and greedy randomized adaptive search procedure—Evolutionary Local Search.

In contrast to the described models, the approach presented in the present paper allows loading different materials in the same vehicle, which considers the vehicle capacity, costs, and population exposure that varies with the truck risk. The inclusion of capacity adds additional complexity because more than one vehicle is needed to satisfy all the customer demands. For each truck, the methodology determines the customers to be visited and the sequence to be followed in such a manner that all the products are collected. We note that the problem is NP-hard because for a single type of waste, the problem is reduced to a vehicle routing problem (VRP), which is NP-hard (Toth and Vigo, 2001).

3. HAZMAT collection problem with multiple-product loading

Different hazardous wastes must be collected from a set of customers located in an urban area and transported to a single depot site. All wastes must be collected, and a customer must have all its wastes collected by one truck in one visit. The transportation network of the urban area is modeled as graph $G(N, A)$. The set N of nodes includes the depot, customers, and street intersection nodes. Set A of arcs represents the streets. Each customer generates a single type of hazardous waste. However, if a customer produces more than one type of waste, replicas of the node can be created: one for each type of waste. All replicas are co-located.

A fleet of trucks with equal capacities collects all the wastes, starting and ending their trips at the depot. The objective of the problem is to minimize both the exposed population and the transportation cost. The risk model is based on the population exposure (Giannikos, 1998; Wyman and Kuby, 1995). Each hazardous waste has an associated risk that corresponds to a maximum radius of reach in case of an accident, which is defined by the Emergency Response Guidebook (U.S. Department of Transportation, 2012). The population within reach of an accident that could happen on an arc in the route is considered as exposed, and its size depends on the risk of the waste being carried over that arc. Fig. 1 shows this concept of arc (i, j).

The polygons shown in Fig. 1a) represent census blocks with uniform population densities, as indicated by the gray shades. Fig. 1b) shows the exposure zone ("stadium") around arc (i, j) based on a material with a known risk and its corresponding radius of reach. The total population inside the stadium is exposed if arc (i, j) is in the route of a truck. The size of the stadium depends on the risk of the material transported over the arc; for a riskier material, the size of the stadium increases and so does the exposed population. We note that the total exposed population is overestimated as the stadiums of successive arcs in the route intersect with one another. However, because this is not the focus of this study, we do not consider this error, which can be easily corrected as described in Kara et al. (2003).

Because the truck risk consists of the collected product with the highest risk, as the truck collects the wastes from a series of customers, its risk after each collection either remains the same or increases in discrete steps. Fig. 2 shows an example of an instance and its solution for a single truck in which only the population exposure objective is minimized (and not the transportation cost). Fig. 2a) shows the transportation network. The square (node 0) represents the depot, the circles represent the customers, and the framed letters show the risk of the material requiring collection at every customer node. The trucks can travel only over the arcs (streets). Three compatible materials are considered, namely, A, B, and C, with risk A < risk B < risk C. Because the truck risk represents the riskiest product in the truck, A + B = B, A + C = C, B + C = C, and A + B + C = C.

Fig. 2b) shows the sequence in which the customer wastes must be collected for minimum population exposure, and Fig. 2c) shows the route over the actual transportation network that a truck must follow to collect the HAZMAT following the sequence shown in Fig. 2b). The continuous arrows in Fig. 2b) show the collection sequence, and the arcs in Fig. 2c) represent the actual truck routes. Their thickness and the italics letters show the risk in which the population is exposed to in that particular step in the sequence or arc of the network. Each link (i, j) of the sequence in Fig. 2b) must be implemented as the "best" path between successive customer nodes i and j shown in Fig. 2c). By "best," we mean the path over the actual network that, among all possible paths between nodes i and j, contributes the most to minimize the objective, as will be explained in the next section.

We note that, to follow the optimal sequence shown in Fig. 2b), the path over the actual transportation network [Fig. 2c)] must visit some nodes twice without necessarily collecting waste, e.g., nodes 9 and 15. The hazardous waste in node 9 is collected on the first visit, whereas the reason for the second visit is that, among all

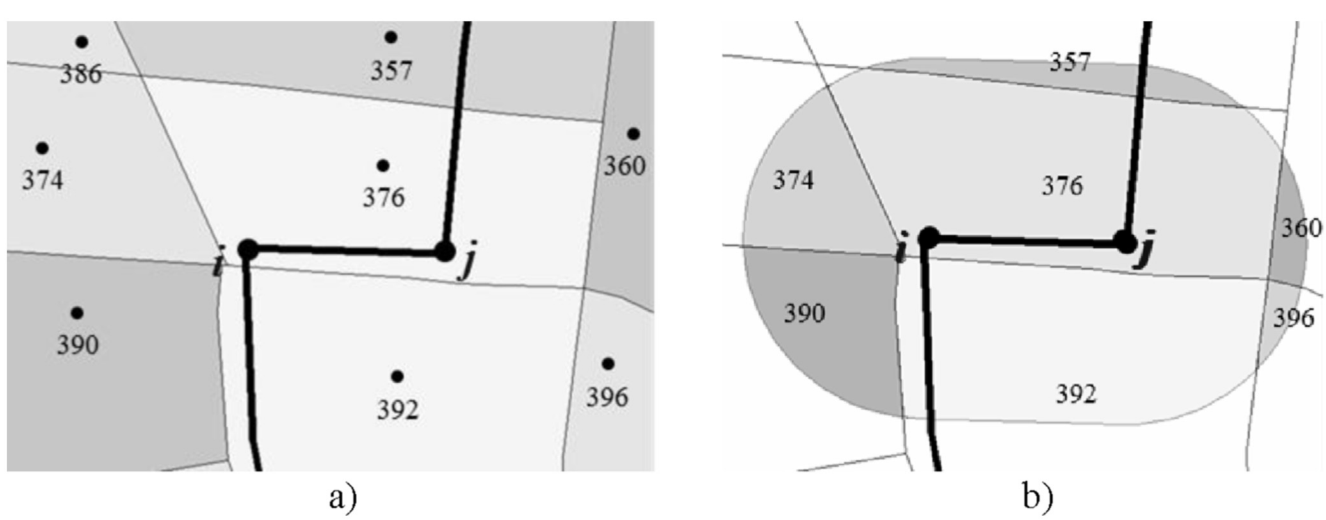


Fig. 1. Computation of exposed population within each arc of the transportation network.

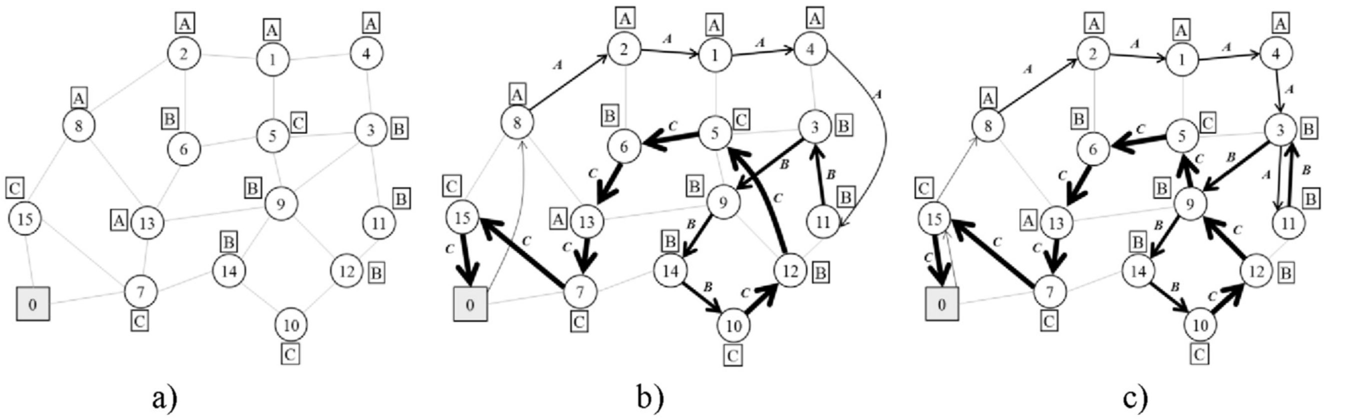


Fig. 2. a) Transportation network. b) Sequence of customer node visits. c) Actual truck path.

possible paths between nodes 12 and 5 over the transportation network, the best one includes node 9. The same reason applies for node 15, whose HAZMAT is loaded on the second visit because if they were loaded on the first visit, the total exposed population would be much bigger. We note also that the truck travels along arcs (3, 11) and (11, 3). We consider risk A when the truck travels over arc (3, 11) and risk B when it travels over arc (11, 3) because the truck passes through these arcs at different times in its journey and causes exposure to different population sizes during each pass (some population is exposed twice).

To expose a smaller number of people to risk, the truck is loaded first with the least hazardous products (A) and later with the most hazardous ones (C) whenever possible. However, in some cases, loading the less dangerous products later in the route is convenient (such as in the case of node 13).

4. Proposed methodology

4.1. Description of the method

We initially assume that the least cost collection route is sought and that the travel cost over an arc is not necessarily proportional to its length. Such route could be found by solving a traveling salesman problem (TSP). The usual method consists of first constructing an auxiliary fully connected graph $G'(N', A')$ whose node set N' contains the depot and the customers. For each and every pair of nodes $i, j \in N'$, arc $(i, j)' \in A'$ exists with the same cost as the least cost path between i and j over the original graph $G(N, A)$. TSP is applied to this auxiliary graph, and the collection sequence is determined. This sequence is then transformed to a route over the original network by following the same collection sequence and replacing each arc $(i, j)' \in A'$ by the corresponding least cost path between i and j.

We now assume that the population exposure is minimized, instead of the cost, and that all materials have the same risk. In this case, the truck risk remains the same along the route after the first customer waste has been collected. Again, TSP can find the solution, and the procedure will be the same except that in this case, instead of the cost, each arc $(i, j)' \in A'$ will have the same population exposure as the least population exposure path between i and j over the original graph $G(N, A)$.

By now assuming that the materials have different risks, the population exposure of each arc is not known beforehand compared with the preceding case, and it depends on the materials that have been collected by the truck up to the time it reaches the arc. Consequently, it depends on the route between the depot and the node through which the arc is entered. The TSP cannot be applied, unlike that in the previous condition, and we propose a different procedure. By considering the same example shown in Fig. 2, each arc has three possible population exposures corresponding to material risks A, B, and C. To solve this problem, we construct auxiliary graph $\overline{G}(\overline{N}, \overline{A})$ in the same manner as that in the preceding case (least population exposure paths) except that for each pair of nodes i and j, three "least exposure" arcs $\overline{(i,j)}^m$ that connect them are now possible, one for each material risk m. Once the auxiliary graph is constructed, an IP model will find the route, where arc $\overline{(i,j)}^m$ that corresponds to the risk m of the truck that travels from node i to j is chosen for each pair of nodes i, j. This auxiliary graph can be constructed for any number of material risks.

Finally, if the population exposure and cost are minimized, the procedure is similar except that the least exposure paths between node pairs now become the "least contribution to the objective" paths. Computing these paths is possible only if the full expression of the objective is known. Because the problem is bi-objective (cost and exposure objectives), the objective is known only if the problem is solved using the weighting method, i.e., minimizing a linear combination of population exposure and cost, with known weighting factors α and $(1 - \alpha)$ respectively. The objective would then be expressed as,

$$Z = \alpha EP + (1 - \alpha)C \tag{1}$$

where EP is the total exposed population, C is the total cost, and $0 \le \alpha \le 1$ is the weight of the population exposure objective.

4.2. Steps of the method

We now formally define the following sets, parameters, and variables.

4.2.1. Sets and parameters

4.2.2. Decision variables

$$x_{ij}^k = \begin{cases} 1 & \text{If truck } k \in K \text{ goes from node } i \text{ to node } j : i, j \in \overline{N} \\ 0 & \text{otherwise} \end{cases}$$

$$y_i^k = \begin{cases} 1 & \text{If truck } k \in K \text{ loads product from customer } i \in V \\ 0 & \text{otherwise} \end{cases}$$

R	Set of risks or waste types
K	Set of trucks
$N, \overline{N}$	Sets of nodes of the original and auxiliary graphs
$\overline{N}_C$	$\overline{N}_C = \overline{N}\backslash\{0\}$, i.e., the set of nodes including customers only
$A, \overline{A}$	Set of arcs of the original and auxiliary graphs
IR	Set of ordered pairs (i, m), meaning that customer i generates a material with risk m
D^m	Set of risks r such that the mixture of r and m is equal to r. It includes $r = m$
COM	Set of pairs (m, r) such that products with risks m and r are compatible
0	Depot node
α	Weight of the population exposure objective
EP^m_{lh}	Exposed population by a truck with risk m traveling over arc $(l, h) \in A$
c_{lh}	Travel cost over arc $(l, h) \in A$
c^m_{lh}	Contribution of arc $(l, h) \in A$ to the objective; $c^m_{lh} = \alpha EP^m_{lh} + (1-\alpha)c_{lh}$
$P^m(i, j)$	Least objective value path between i and $j \in A$ for a truck with risk m
$\overline{(i,j)}^m$	Arc of the auxiliary graph between i and j used for the route when the truck risk is m
a^m_{ij}	Attribute (weight) of arc $\overline{(i,j)}^m$
q_i	Amount of hazardous waste generated by customer $I \in V$. Note that $q_0 = 0$
Q	Capacity of a truck

$$w^{km}_{ij} = \begin{cases} 1 & \text{If truck } k \in K \text{ transports material with maximum} \\ & \quad \text{risk } m \in R \text{ between nodes } i, j \in \overline{N} \\ 0 & \text{otherwise} \end{cases}$$

C^k_i:Amount of waste transported by truck $k \in K$ before visiting node $i \in \overline{N}$. $C^k_0 = 0$

4.2.2.1. *First step.* The first step of the solution approach consists in constructing auxiliary graph $\overline{G}(\overline{N}, \overline{A})$ as follows:

Initialization. $\overline{N} = \{$customers, depot node 0$\}$. $\overline{A} = \phi$, the empty set. Pick a value for α.

i. For every possible risk m, compute the contribution of each arc $(l, h) \in A$ to the objective; $c^m_{lh} = \alpha EP^m_{lh} + (1-\alpha)c_{lh}$.
ii. For every pair of nodes $(i \in \overline{N}, j \in \overline{N})$ and every risk m
   a. Find path $P^m(i, j) \in G(N, A)$ between i and j that contributes the least to the objective value for a truck with risk m. Use any shortest path algorithm with c^m_{lh} as the attribute of arc $(l, h) \in A$.
   b. Add arc $\overline{(i,j)}^m$ to the set of arcs $\overline{A}$ whose attribute z^m_{ij} is the contribution of path $P^m(i, j)$ to the objective $a^m_{ij} = \sum_{(l,h) \in P^m(i,j)} c^m_{lh}$.

Once the first step is finished, a fully connected auxiliary graph is obtained.

4.2.2.2. *Second step.* Solve the IP problem over $\overline{G}(\overline{N}, \overline{A})$.

$$Min\ Z = \sum_{i \in \overline{N}_C, j \in \overline{N}} \sum_{m \in R} \sum_{k \in K} a^m_{ij} w^{km}_{ij} + \sum_{j \in \overline{N}_C} \sum_{m \in R} \sum_{k \in K} a^m_{0j} w^{km}_{0j} \tag{2}$$

$$\sum_{i \in \overline{N}_C} y^k_i q_i \le Q \quad \forall k \in K \tag{3}$$

$$\sum_{k \in K} y^k_i = 1 \quad \forall i \in \overline{N}_C : (i, m) \in IR \tag{4}$$

$$\sum_{j \in \overline{N}_C} x^k_{0j} \le 1 \quad \forall k \in K \tag{5}$$

$$\sum_{i \in \overline{N}} x^k_{ij} = \sum_{h \in \overline{N}} x^k_{jh} \quad \forall k \in K, j \in \overline{N} \tag{6}$$

$$\sum_{h \in \overline{N}} x^k_{hi} = y^k_i \quad \forall k \in K, i \in \overline{N}_C : (i, m) \in IR \tag{7}$$

$$\sum_{j \in \overline{N} \backslash i} w^{km}_{ij} \le 1 - \sum_{h \in \overline{N}_C \backslash i} w^{kr}_{hi} \quad \forall k \in K, i \in \overline{N}_C, m, r \in R : r \in D^m \backslash m \tag{8}$$

$$\sum_{j \in \overline{N} \backslash i} w^{km}_{ij} \le 1 - y^k_i \quad \forall k \in K, i \in \overline{N}_C, m, r \in R : r \in D^m \backslash m, (i, r) \in IR \tag{9}$$

$$\sum_{m \in R} w^{km}_{ij} \ge x^k_{ij} \quad \forall k \in K, i, j \in \overline{N} \tag{10}$$

$$\sum_{m \in R} w^{km}_{ij} \le 1 \quad \forall k \in K, i, j \in \overline{N} \tag{11}$$

$$y^k_i + y^k_j \le 1 \quad \forall k \in K, i, j \in \overline{N}_C, (i, m), (j, r) \in IR, (m, r) \in COM \tag{12}$$

$$C^k_j \ge C^k_i + q_i - Q\left(1 - x^k_{ij}\right) \quad \forall k \in K, j \in \overline{N}_C, i \in \overline{N} \tag{13}$$

$$x^k_{ij}, y^k_i, w^{km}_{ij} \in \{0, 1\} \quad \forall k \in K, i, j \in \overline{N}, m \in R \tag{14}$$

$$C^k_j \ge 0 \quad \forall k \in K, j \in \overline{N} \tag{15}$$

Objective function (2) minimizes the exposed population and the total transport cost, weighted by α and $(1 - \alpha)$, respectively. Constraints (3)–(7) and (13) are capacitated VRP constraints. Constraint (3) limits the capacity of each truck. Constraint (4) indicates that each customer is attended to using a single truck. Constraint (5) indicates that each active truck only leaves the depot once. We note that the equality in constraint (5) would force all trucks being used even if not needed. The forced use of all trucks in any situation could result in a sub-optimal solution in terms of population exposure and cost. Constraint (6) establishes the flow balance in all nodes and all trucks. Constraint (7) indicates that if truck k travels from node h to node i, then a load is added to the truck, which comes from customer i.

Constraints (8)–(11) allow following and updating the risk associated with the trucks along the arcs and nodes in their route over $\overline{G}(\overline{N},\overline{A})$. Because the truck risk can only increase when collecting HAZMAT, if truck k exits node i with risk m, constraint (8) indicates that the same truck could not have entered node i with a risk higher than m. We note that none of the constraints preclude a truck from loading a product with lower risk m at node j if the truck goes from i to j with higher risk r. Constraint (9) guarantees that if a truck loads a product with a type r risk from a customer, then the risk of the next arc cannot be lower than risk m, i.e., the truck cannot leave node i with a risk lower than r. Constraints (10) and (11) indicate that if truck k goes from node i to node j, its load will only have one type of risk. Constraint (12) avoids incompatible material combinations. Constraint (13), also known as the Miller–Tucker–Zemlin constraint (Miller et al., 1960), records the volume of products after each customer collection of the truck and avoids the appearance of sub-tours; Constraints (14) and (15) define the nature of the decision variables.

If p is the number of hazardous wastes, n is the number of nodes (including the depot), and k is the number of trucks, then the model has $(n^2k(1+p)-nkp+n)$, i.e., $O(n^3kp)$ decision variables and $(k+np+2kn+kp^2(2(n-1)+(n^2-1))+3k(n^2-n))=O(n^3k^2)$ constraints, excluding domain constraints (14) and (15).

Instead of using the absolute values of the exposure and cost objectives f_E and f_C, respectively, we normalize them so that they become comparable. We use the normalization in Bronfman et al. (2015).

$$Z_i=\left[\frac{f_i-I_i}{AI_i-I_i}\right] \tag{16}$$

where Z_i is the normalized objective (cost or population exposure), f_i is the objective function before normalization, I_i is best value of f_i, and AI_i is its worst value.

We use the following *ad hoc* cuts to tighten the model and accelerate the problem solution.

$$y_i^m=\sum_{j\in\overline{N},r\in D^m} w_{ij}^r \quad \forall k\in K, i\in\overline{N}_C,(i,m)\in IR \tag{17}$$

Constraint (17) indicates that if truck k collects a type m product from customer i, the outgoing arc can only have a risk that is the same or higher than that from customer i.

4.2.2.3. Third step. The solution of the IP formulation is a sequence of arcs $\overline{(i,j)}^m$ for each truck k (described by variables $w_{ij}^{km}=1$) that prescribes the order in which the customer waste must be collected to minimize the objective. The third step consists of finding the route over the actual transportation network, represented by graph $G(N,A)$, which is found by replacing each arc $\overline{(i,j)}^m$ with its corresponding path $P^m(i,j)\in G(N,A)$.

Fig. 2b) and 2c) show this concept. Fig. 2b) shows the visit sequence of a truck (arcs $\overline{(i,j)}^m$), whereas Fig. 2c) shows the corresponding route over the original transportation network.

Finally, the total transportation cost is the sum of the costs of all arcs in the routes, and the total exposed population is the sum of all exposed populations in all routes.

4.3. Other mixing rules

Some particular cases exist in which combining the transport of different types of hazardous wastes can generate risks that are different from that associated with the most hazardous waste. Usually, these combinations are prohibited by incompatibility restriction (12). However, our model can also solve this special situation by adding new constraints. For example, if the mixture of a risk A material with a risk B material results in a type C risk (which may have a higher or lower risk level than type B), the constraints take the following form:

$$\sum_{j\in\overline{N}\backslash i} w_{ij}^{kB}\le 1-\sum_{h\in\overline{N}_C\backslash i} w_{hi}^{kA} \quad \forall k\in K, i\in\overline{N}_C \tag{18}$$

$$\sum_{j\in\overline{N}\backslash i} w_{ij}^{kB}\le 1-y_i^k \quad \forall k\in K, i\in\overline{N}_C,(i,A)\in IR \tag{19}$$

$$\sum_{j\in\overline{N}\backslash i} w_{ij}^{kC}\ge \sum_{h\in\overline{N}\backslash i} w_{hi}^{kB}+y_i^k-1 \quad \forall k\in K, i\in\overline{N}_C,(i,A)\in IR \tag{20}$$

$$\sum_{j\in\overline{N}_C\backslash i} w_{ij}^{kC}\ge \sum_{h\in\overline{N}_C\backslash i} w_{hi}^{kA}+y_i^k-1 \quad \forall k\in K, i\in\overline{N},(i,B)\in IR \tag{21}$$

Constraint (18) indicates that if a truck travels along arc (h,i) carrying risk A wastes, then the same truck cannot leave node i with risk B because although it loads a type B material at node i, the combination of A and B does not result in risk B. Constraint (19) states that a truck that loads a type A material at node i cannot exit that node carrying a type B material because if the truck has entered node i carrying a type A material, the output risk would be A; if it has entered i carrying a type B material, the output risk would be C. Constraint (20) establishes that if a truck travels along arc (h,i) with risk B and collects a risk A material at node i, then the truck will leave that node with a type C risk. The same idea is replicated in constraint (21).

5. Case study

5.1. Description

We applied the proposed methodology to a hypothetical case based on a network of streets, roads, and industrial areas in Santiago, Chile. The city has an area of 641 km^2. The transportation network has 6231 arcs and 2205 nodes; in other words, this is a very large network. We must mention that the city has a high population density, reaching 446.9 inhabitants per square kilometer (INE, 2010). Without losing generality, we assumed that cost c_{ij} of using arc $(i,j)\in A$ is proportional to its length. Of the sample 3500 industries in the Metropolitan Region of Santiago, as reported by Cisternas-Véliz (2003), we selected 167 factories whose industrial activities correspond to manufacturing of chemical substances and products. The factories are distributed throughout the city. Five types of wastes with risk notations A, B, C, D, and E were considered based on the production activity in the sample of selected industries. The types and quantities of wastes generated from each factory were randomly assigned.

Article 87 of the Chilean legislation concerning the handling of hazardous wastes (MINSAL, 2004) stipulates that certain wastes cannot be transported in a single vehicle because they may produce violent reactions such as explosions or fire. We defined 14 groups of hazardous wastes, designated *A*-1 to *A*-7 and *B*-1 to *B*-7. The wastes included in these groups were corrosive liquids, explosives,

Table 1
Initial isolation and protective action (U.S. Department of Transportation, 2012).

Id.	Compatibility group	ERG number	Hazard radius (m)
A	*A*-4	129	50
B	*B*-4	137	100
C	*B*-7	131	200
D	*A*-7	156	300
E	*B*-4	156	400

Table 2
Waste–waste compatibility rules and risk dominance.

Id	Id				
	A	B	C	D	E
A	A	–	C	D	–
B	–	B	C	D	E
C	C	C	C	–	E
D	D	D	–	D	E
E	–	E	E	E	E

pesticides, alcohols, and other chemicals.

Table 1 lists the detailed information of the five types of hazardous wastes. It was created based on information from the following sources: Chilean Code 382 Hazardous Substances—Terminology and General Classification (INN, 1998), Decree 298 on the Regulation of Hazardous Shipments through Streets and Roads in Chile (MINTRATEL, 1995), Decree 148 on the Regulation of Safe Handling of Hazardous Wastes in Chile (MINSAL, 2004), and the Emergency Response Guidebook (ERG) (U.S. Department of Transportation, 2012). The first column in the table lists the identifier for HAZMAT types. A is an aqueous waste, B is a hydride, C is a mineral acid, D is a waste derived from chloride, and E is a metallic waste. The second column determines the compatibility group of the wastes for transportation and storage. The third column indicates the number of emergency response guide (ERG number) for each material. The information in the ERG considers inherent potential risks of the material in terms of fire, explosion, and health effects and information about immediate isolation of the incident location and evacuation distances for small and large spills, as well as emergency response actions, including first-aid activities. Finally, the fourth column shows the isolation distances (hazard radius) established in case of spill incidents involving small quantities of the materials during daytime.

For this case study, we considered that the five waste classes are transported during a single day. Table 2 lists the risk dominance and compatibility of the five types of waste being studied when these were transported by a single truck. To determine the risk when two or more different risk levels were transported together in a same truck, we used both Tables 1 and 2.

The region was divided into eight collection zones (see Fig. 3). Zone 8 is a residential area with no factories. This regional division is frequently used to distribute products in the City of Santiago because the neighborhoods grouped in Fig. 3 have similar

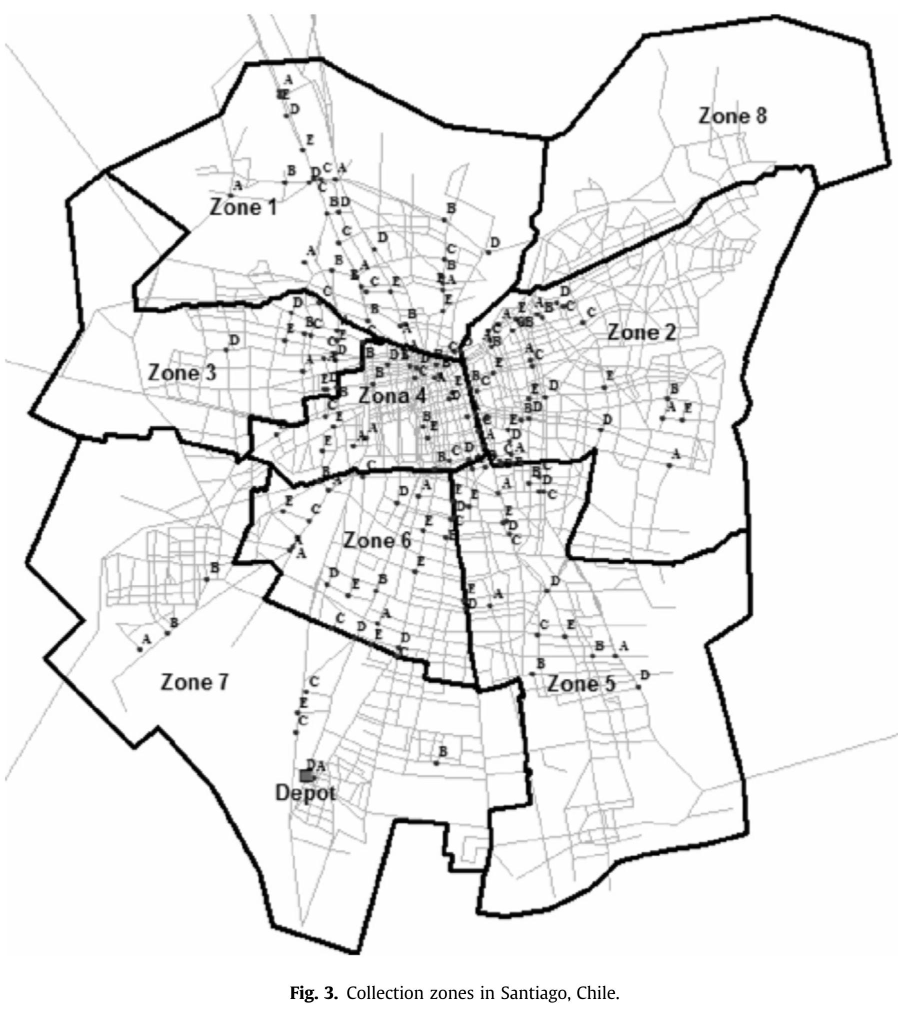


Fig. 3. Collection zones in Santiago, Chile.

Table 3
Detailed information on the study zones.

	#H	q_A	q_B	q_C	q_D	q_E
Zone 1	32	7640	6680	3040	4260	5720
Zone 2	36	5440	10,890	14,420	20,540	11,740
Zone 3	16	8040	2170	4170	4120	1970
Zone 4	30	12,440	1840	3560	5940	3390
Zone 5	21	1560	4370	1820	2760	2810
Zone 6	21	5600	3270	6060	2310	3770
Zone 7	11	3840	2490	2170	4980	2230

municipal regulations. Table 3 lists the regional information. #H is the number of factories in each zone, and q_A, q_B, q_C, q_D, and q_E are the quantities of waste types A, B, C, D, and E, respectively, generated in each of the zones. Each zone has two trucks with sufficient capacity to carry the wastes from each subdivision. The problem is independently solved for each zone.

5.2. Results

The case study was solved using the commercial solver CPLEX Version 12.6 and coded with AMPL version 20130109 on a PC with Intel processor i7-2600, 3.4 GHz, 16-GB RAM, and an Ubuntu Server 12.04 LTS.

Fig. 4 shows the solutions for minimum cost and minimum exposed population when the wastes from the 36 customers in Zone 2 are collected. The route of each truck is separately shown. The population density is indicated by shades; darker shades indicate higher population density. Fig. 4a) and 4b) show the routes that result in minimum exposed population for the two trucks used (disregarding transportation costs).

Fig. 4a) shows that the truck begins its route unloaded at the depot until it loads hazardous product A (indicated by the thinnest line). The truck then collects type A wastes from several customers (indicated by segmented line sections). Finally, it loads type D wastes, indicated by changes in the type and thickness of the line (continuous double lines). The truck risk remains at D until it reaches the depot. We note that in the last section, the truck also collects type A wastes, with the dominance between A and D being maintained. Fig. 4b) shows that the truck begins its route at the depot. It then loads risk B products followed by C products, changing the truck risk from risk B to risk C. The truck risk remains constant (indicated by segmented lines) until it loads risk E products. The truck risk remains at E on the return trip to the depot (indicated by continuous double lines). Fig. 4c) and 4d) show the

Fig. 4. (a) and (b) Minimum risk solutions and (c) and (d) minimum cost solutions in Zone 2.

Table 4
Non-inferior solutions: Zones 1 to 4.

α	Zone 1			Zone 2			Zone 3			Zone 4		
	Z_1	Z_2	T	Z_1	Z_2	T	Z_1	Z_2	T	Z_1	Z_2	T
0.0	903,547	155,629	306	1,402,070	126,354	14	623,614	89,565	1	1,061,540	98,155	14
0.1	833,642	157,974	23,973	1,241,740	127,333	16	494,322	89,919	2	1,047,880	98,184	7
0.2	801,631	160,202	8737	1,188,350	129,013	31	442,571	91,277	2	997,973	99,136	17
0.3	599,435	177,142	50,875	1,113,960	130,272	38	388,960	93,681	2	932,783	101,475	34
0.4	529,482	189,183	6514	1,039,610	134,074	50	352,480	96,819	7	810,527	111,129	43
0.5	527,862	190,300	3875	995,684	138,140	411	352,480	96,819	4	807,328	112,124	43
0.6	527,861	190,300	1545	985,787	140,171	288	330,726	98,466	7	805,208	112,602	33
0.7	521,715	197,604	13,601	940,303	151,982	14,656	330,726	98,466	8	805,208	112,602	23
0.8	518,628	201,312	9481	939,033	154,250	2239	330,726	98,466	9	805,208	112,602	100
0.9	491,501	239,727	3767	931,954	165,060	23,456	330,726	98,466	7	804,982	118,679	29
1.0	482,214	307,576	3894	926,804	166,340	24,836	325,137	106,926	15	795,138	129,177	27

Table 5
Non-inferior solutions: Zones 5 to 7.

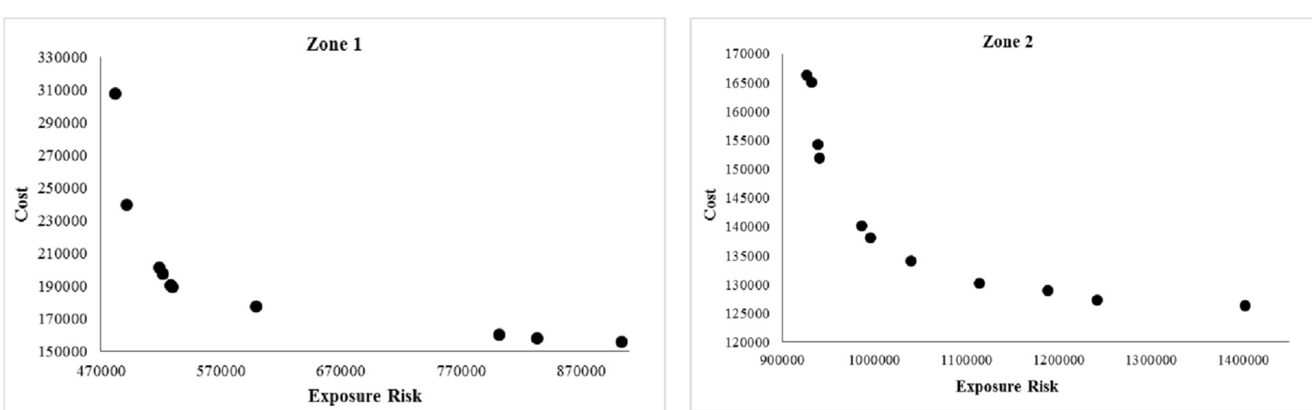
α	Zone 5			Zone 6			Zone 7		
	Z_1	Z_2	T	Z_1	Z_2	T	Z_1	Z_2	T
0.0	1,314,110	91,416	52	506,311	76,038	20	528,548	73,727	1
0.1	750,240	93,549	93	465,917	76,492	14	308,804	74,024	1
0.2	667,934	94,980	57	441,919	77,395	4	177,098	74,747	1
0.3	658,548	95,595	32	441,241	77,461	4	173,410	74,971	1
0.4	637,343	96,600	37	441,241	77,461	4	160,615	76,052	1
0.5	618,596	97,714	18	440,194	77,574	5	160,615	76,052	1
0.6	618,596	97,714	26	432,915	79,370	4	154,897	77,119	1
0.7	618,596	97,714	16	432,915	79,370	4	150,658	79,311	1
0.8	604,930	104,584	31	428,229	82,316	5	127,131	84,378	1
0.9	603,127	107,253	19	426,224	89,092	11	127,131	84,378	1
1.0	580,803	148,435	16	425,712	98,510	13	125,158	90,324	1

minimum cost routes for both trucks. In these two figures, the line thickness is the same for all routes given that there is no interest in counting the exposed population or the change in risk of the trucks. Fig. 4 shows that the solutions for the minimum exposed population tend to be longer and therefore costlier. These routes avoid transit through areas with high population densities. On the other hand, the routes with the minimum cost are shorter but expose a larger population. In both sample cases (cost and exposed population), incompatibility conditions are observed. Fig. 4a) shows how special care is taken regarding the loading of type D risk wastes at the end of the route to avoid exposure of the population to higher risk. Similarly, Fig. 4b) shows that the collection of type E wastes is done at the end of the route.

If transportation cost is the objective, HAZMAT loading order is not a concern, except in not loading incompatible materials on the same truck. Therefore, Fig. 4c) shows that the first truck collects types A and D wastes from 14 customers, and Fig. 4d) shows that the second truck collects types B, C, and E wastes (22 customers), both in any order.

We study the effects of changing the relative weights of both objectives, i.e., changing the value of α, and obtaining an approximation to the Pareto-optimal (or non-inferior) solution set. Tables 4 and 5 list the non-inferior solutions obtained for each in the study zones. In the tables, Z_1 is the value of the exposed population, Z_2 is the transportation cost, and T is the CPU time in seconds. The tables show a conflict between the two objectives. For example, in Zone 1, when the value of total risk Z_1 is optimized, the distance covered by both trucks is 307,576 km, which is 1.96 times the distance covered when Z_2 is minimized. In addition, the exposed population measured in terms of the total number of people exposed by the routes is 482,214, which is approximately half of the extreme solution that minimizes cost. This effect is observed in all the study zones.

We can also see that the computation times are higher in Zones 1 and 2 because the associated graphs are highly asymmetrical and there are many solutions with the same objective value. In these two zones, a wider spectrum of efficient solutions is present given the large differences in the magnitude of their extreme solutions. We note that the model is particularly sensitive to the number of nodes in each zone.



a) b)

Fig. 5. Trade-off curve of the first two zones.

Table 6
Comparison between the single- and multiple-product loading.

	Zone 1 (min EP)		Zone 1 (min cost)		Zone 2 (min EP)		Zone 2 (min cost)	
	Single	Multiple	Single	Multiple	Single	Multiple	Single	Multiple
#Trucks	5	2	5	2	5	2	5	2
EP	**616045**	**482214**	1237880	903547	**1069150**	**926804**	1587930	1402070
Cost	511759	307576	**312198**	**155629**	333838	166340	**263279**	**126354**

	Zone 3 (min EP)		Zone 3 (min cost)		Zone 4 (min EP)		Zone 4 (min cost)	
	Single	Multiple	Single	Multiple	Single	Multiple	Single	Multiple
#Trucks	5	2	5	2	5	3	5	2
EP	**460922**	**325137**	790990	623614	**1074320**	**790773**	1479860	1061540
Cost	227717	106926	**202895**	**89565**	245761	162004	**210350**	**98155**

	Zone 5 (min EP)		Zone 5 (min cost)		Zone 6 (min EP)		Zone 6 (min cost)	
	Single	Multiple	Single	Multiple	Single	Multiple	Single	Multiple
#Trucks	5	3	5	2	5	3	5	2
EP	**754824**	**575217**	1170300	1314110	**509814**	**405792**	671858	506311
Cost	232946	173088	**194901**	**91416**	197635	125485	**159891**	**76038**

	Zone 7 (min EP)		Zone 7 (min cost)	
	Single	Multiple	Single	Multiple
#Trucks	5	4	5	2
EP	**153917**	**114281**	183309	174312
Cost	110789	92182	**103743**	**73727**

Fig. 5 shows the efficient boundary (Pareto optimal solutions) for each of the first two zones. In each case, we see the same conflict of objectives. Each point in the figures represents a different combination of weights of the objectives and a different route configuration.

Because this is the first time that a problem of multi-product collection with mixed load on the same truck is dealt with, no other method is available for comparison with our works. Any comparison would mean simplifying the problem in such a manner that our approach would not make sense anymore. However, the results can be compared with those using separate trucks for each material, which is the problem solved in the literature. Using five available trucks in all cases, Table 6 list the comparison of a single product with multiple-product loading in two extreme cases: minimization of exposed population only and minimization of cost only.

The results are shown in terms of the number of required trucks, exposed population objective (EP), and cost objective (Cost). The results listed in Table 6 show how the solutions with multi-product loading completely dominate those of the separate loading in the sense that both objectives are better (by far, in most cases) when multiple-product loading is used, irrespective of what objective is being minimized. The only exception is Zone 5 where, when the cost is minimized, the exposed population increases compared with that of the single-product loading. However, by slightly changing the weights of the objectives, a solution that dominates the single-product solution is found with a cost of 96,732 and an exposed population of 732,601. Further, the number of trucks is always smaller: at most four in one case, three in three cases, and two in three cases.

6. Conclusions and future work

We have proposed a new approach to solve the problem of hazardous waste collection in a transportation network. The proposed work minimizes the risk of exposure of the population, expressed quantitatively as the total population affected by the route in case of an accident, and minimizes transportation costs.

In contrast to other contributions in the literature, we propose loading multiple products in the same trucks, which reduces both the cost and the exposed population. We design a methodology to appropriately use the multi-product loading, which includes precomputation of the best paths among all relevant nodes in the network for different waste risks and the formulation of an IP model that monitors risks along the route followed by the capacitated trucks, keeping track of the changes in the risk that each truck exposes the population to as new waste is added. The risk associated with each truck tends to increase when products with higher risk are loaded. We suggest an extension of the model that considers other mixing conditions.

The model is applied to HAZMAT collection over the transportation network in Santiago, Chile. The results indicate significant differences between the extreme minimum cost and minimum risk solutions. Therefore, determining a set of intermediate non-dominated solutions that allow decision makers to select the best alternative becomes necessary.

This study can be extended to several directions. From the multi-objective perspective, we could incorporate criteria such as exposure time, total hazard, expected consequence, and other factors. Although a distribution model can be trivially formulated as a variant of the collection model, a model of pickup and delivery would be an interesting extension in which the risk associated with the trucks may increase or decrease when the customers supply or require HAZMAT. Preliminary tests with such a model indicate that designing an efficient heuristic would be necessary to solve large instances in short times.

Acknowledgements

Marianov and Latorre-Núñez gratefully acknowledge partial support by FONDECYT Grant 1130265 and the Complex Engineering Systems Institute through Grants ICM-MIDEPLAN P-05-004-F and CONICYT FB0816. The works of Paredes-Belmar and Bronfman were supported in part by the National Research Center for Integrated Risk Disaster Management CONICYT/FONDAP 15110017.

References

Abkowitz, M., Cheng, P.D.-M., 1988. Developing a risk/cost framework for routing truck movements of hazardous materials. Accid. Anal. Prev. 20 (1), 39–51.

Available at: http://www.sciencedirect.com/science/article/pii/0001457588900139 [Accessed 13 December 2014].

Ahluwalia, P.K., Nema, A.K., 2006. Multi-objective reverse logistics model for integrated computer waste management. Waste Manag. Res. J. Int. Solid Wastes Public Clean. Assoc. ISWA 24 (6), 514–527. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17252998 [Accessed 16 May 2016].

Androutsopoulos, K., Zografos, K., 2012. A bi-objective time-dependent vehicle routing and scheduling problem for hazardous materials distribution. EURO J. Transp. Logist. 1 (1–2), 157–183. Available at: http://dx.doi.org/10.1007/s13676-012-0004-y [Accessed 16 May 2016].

Bianco, L., Caramia, M., Giordani, S., Piccialli, V., 2013. Operations Research models for global route planning in hazardous material transportation. In: Batta, R., Kwon, C. (Eds.), Handbook of OR/MS Models in Hazardous Materials Transportation SE-3. International Series in Operations Research & Management Science. Springer, New York, pp. 49–101. Available at: http://dx.doi.org/10.1007/978-1-4614-6794-6_3 [Accessed 16 May 2016].

Bronfman, A., Marianov, V., Paredes-Belmar, G., Lüer-Villagra, A., 2015. The maximin HAZMAT routing problem. Eur. J. Oper. Res. 241 (1), 15–27. Available at: http://www.sciencedirect.com/science/article/pii/S0377221714006213 [Accessed 16 May 2016].

Cisternas-Véliz, M., 2003. Modelación del transporte de carga en la Región Metropolitana: Generación y distribución. Master of Science Thesis. Pontificia Universidad Católica de Chile.

Das, A., Mazumder, T.N., Gupta, A.K., 2012. Pareto frontier analyses based decision making tool for transportation of hazardous waste. J. Hazard. Mater. 227–228, 341–352. Available at: http://www.sciencedirect.com/science/article/pii/S0304389412005717 [Accessed 16 May 2016].

Erkut, E., Tjandra, S.A., Verter, V., 2007. Transportation. Elsevier. Available at: http://www.sciencedirect.com/science/article/pii/S0927050706140098 [Accessed 16 May 2016].

Giannikos, I., 1998. A multiobjective programming model for locating treatment sites and routing hazardous wastes. Eur. J. Oper. Res. 104 (2), 333–342. Available at: http://www.sciencedirect.com/science/article/pii/S0377221797001884 [Accessed 16 May 2016].

GPO, 2016. U.S. Government Publishing Office, Electronic Code of Federal Regulations e-CFR 177.848—Carriage by Public Highway. Available at: http://www.ecfr.gov/cgi-bin/text-idx?node=pt49.2.177&rgn=div5 [Accessed on 17 May 2016].

Hamdi, K., Labadi, N., Yalaoui, A., 2010. An iterated local search for the vehicle routing problem with conflicts. In: 8th International Conference of Modeling and Simulation—MOSIM 2010. Available at: www.enim.fr/mosim2010/articles/185.pdf [Accessed 16 May 2016].

Hamdi-Dhaoui, K., Labadie, N., Yalaoui, A., 2011. The vehicle routing problem with conflicts. In: Proceedings of the 18th IFAC World Congress. Available at: http://www.sciencedirect.com/science/article/pii/S1474667016451864 [Accessed 16 May 2016].

Hu, T.-L., Sheu, J.-B., Huang, K.-H., 2002. A reverse logistics cost minimization model for the treatment of hazardous wastes. Transp. Res. Part E Logist. Transp. Rev. 38 (6), 457–473. Available at: http://www.sciencedirect.com/science/article/pii/S1366554502000200 [Accessed 14 December 2014].

INE, 2010. Instituto Nacional de Estadísticas. Compendio Estadístico 2010—Estadísticas Demográficas. Available at: http://www.ine.cl/canales/menu/publicaciones/compendio_estadistico/compendio_estadistico2010.php [Accessed 16 May 2016].

INN, 1998. Instituto Nacional de Normalización INN. Norma Chilena NCh382.Of98: Sustancias peligrosas—Terminología y clasificación general. Available at: http://www.vertic.org/media/National%20Legislation/Chile/CL_Norma_Chilena_382_Sustancias_Peligrosas_Terminologia.pdf [Accessed 16 May 2016].

Jacobs, T., Warmerdam, J., 1994. Simultaneous routing and siting for hazardous-waste operations. J. Urban Plan. Dev. 120 (3), 115–131. Available at: http://dx.doi.org/10.1061/(ASCE)0733-9488(1994)120:3(115) [Accessed 16 May 2016].

Kara, B.Y., Erkut, E., Verter, V., 2003. Accurate calculation of hazardous materials transport risks. Oper. Res. Lett. 31 (4), 285–292. Available at: http://www.sciencedirect.com/science/article/pii/S0167637702002389 [Accessed 16 May 2016].

Kremer, G.E., Haapala, K., Murat, A., Chinnam, R.B., Kim, K.Y., Monplaisir, L., Lei, T., 2016. Directions for instilling economic and environmental sustainability across product supply chains. J. Clean. Prod. 112 (3), 2066–2078. Available at: www.sciencedirect.com/science/article/pii/S0959652615010057 [Accessed 16 May 2016].

Leal Junior, I.C., D'Agosto, M. de Almeida, 2011. Modal choice for transportation of hazardous materials: the case of land modes of transport of bio-ethanol in Brazil. J. Clean. Prod. 19 (2–3), 229–240. Available at: www.sciencedirect.com/science/article/pii/S0959652610000442 [Accessed 16 May 2016].

Leonelli, P., Bonvicini, S., Spadoni, G., 2000. Hazardous materials transportation: a risk-analysis-based routing methodology. J. Hazard. Mater. 71 (1–3), 283–300. Available at: http://www.sciencedirect.com/science/article/pii/S0304389499000849 [Accessed 16 May 2016].

Miller, C.E., Tucker, A.W., Zemlin, R.A., 1960. Integer programming formulation of traveling salesman problems. J. ACM 7 (4), 326–329. Available at: http://doi.acm.org/10.1145/321043.321046 [Accessed 16 May 2016].

MINSAL, 2004. Ministerio de Salud. Decreto Supremo N° 148: Reglamento sanitario sobre manejo de residuos peligrosos. Diario Oficial. Available at: http://www.sinia.cl/1292/articles-38293_pdf_respel.pdf [Accessed 16 May 2016].

MINTRATEL, 1995. Decreto Supremo N° 298: Reglamento transporte de cargas peligrosas por calles y caminos. Ministerio de Transporte y Telecomunicaciones. Available at: https://www.leychile.cl/Navegar?idNorma=12087 [Accessed 16 May 2016].

Nema, A., Gupta, S., 2003. Multiobjective risk analysis and optimization of regional hazardous waste management system. Pract. Period. Hazard. Tox., Radioact. Waste Manag. 7 (2), 69–77. Available at: http://dx.doi.org/10.1061/(ASCE)1090-025X(2003)7:2(69) [Accessed 16 May 2016].

Nema, A.K., Gupta, S.K., 1999. Optimization of regional hazardous waste management systems: an improved formulation. Waste Manag. 19 (7–8), 441–451. Available at: http://www.sciencedirect.com/science/article/pii/S0956053X9900241X [Accessed 27 November 2014].

Pradhananga, R., Taniguchi, E., Yamada, T., 2010. Ant colony system based routing and scheduling for hazardous material transportation. Proced. Soc. Behav. Sci. 2 (3), 6097–6108. Available at: http://www.sciencedirect.com/science/article/pii/S187704281001075X [Accessed 29 November 2014].

Samanlioglu, F., 2013. A multi-objective mathematical model for the industrial hazardous waste location-routing problem. Eur. J. Oper. Res. 226 (2), 332–340. Available at: http://www.sciencedirect.com/science/article/pii/S0377221712008624 [Accessed 23 October 2014].

Sheu, J.-B., 2007. A coordinated reverse logistics system for regional management of multi-source hazardous wastes. Comput. Oper. Res. 34 (5), 1442–1462. Available at: http://www.sciencedirect.com/science/article/pii/S0305054805001905 [Accessed 27 March 2015].

Shih, L., Lin, Y., 2003. Multicriteria optimization for infectious medical waste collection system planning. Pract. Period. Hazard. Tox., Radioact. Waste Manag. 7 (2), 78–85. Available at: http://dx.doi.org/10.1061/(ASCE)1090-025X(2003)7:2(78) [Accessed 16 May 2016].

Shih, L., Lin, Y., 1999. Optimal routing for infectious waste collection. J. Environ. Eng. 125 (5), 479–484. Available at: http://dx.doi.org/10.1061/(ASCE)0733-9372(1999)125:5(479) [Accessed 16 May 2016].

Siddiqui, A.W., Verma, M., 2015. A bi-objective approach to routing and scheduling maritime transportation of crude oil. Transp. Sci. Part D Transp. Environ. 37, 65–78. Available at: http://www.sciencedirect.com/science/article/pii/S1361920915000425 [Accessed 16 May 2016].

Tarantilis, C., Kiranoudis, C.T., 2001. Using the vehicle routing problem for the transportation of hazardous materials. Oper. Res. 1 (1), 67–78. Available at: http://link.springer.com/10.1007/BF02936400 [Accessed 13 December 2014].

Toth, P., Vigo, D., 2001. In: Paolo, T., Daniele, V. (Eds.), The Vehicle Routing Problem, p. 363.

U.S. Department of Transportation, 2012. P. and H.M.S.A Emergency Response Guidebook. U.S. Department of Transportation. Available at: http://app.knovel.com/web/toc.v/cid:kpERG00021/viewerType:toc/root_slug:emergency-response-guidebook [Accessed 11 February 2015].

Verter, V., Kara, B.Y., 2008. A path-based approach for Hazmat transport network design. Manag. Sci. 54 (1), 29–40. Available at: http://dx.doi.org/10.1287/mnsc.1070.0763.

Wyman, M.M., Kuby, M., 1995. Proactive optimization of toxic waste transportation, location and technology. Locat. Sci. 3 (3), 167–185. Available at: http://www.sciencedirect.com/science/article/pii/0966834995000143 [Accessed 15 December 2014].

Zografos, K., Androutsopoulos, K., 2002. Heuristic algorithms for solving hazardous materials logistical problems. Transp. Res. Rec. J. Transp. Res. Board 1783 (-1), 158–166. Available at: http://dx.doi.org/10.3141/1783-20 [Accessed 16 May 2016].

Zografos, K.G., Androutsopoulos, K.N., 2008. A decision support system for integrated hazardous materials routing and emergency response decisions. Transp. Res. Part C Emerg. Technol. 16 (6), 684–703. Available at: http://www.sciencedirect.com/science/article/pii/S0968090X08000211 [Accessed 29 November 2014].

Zografos, K.G., Androutsopoulos, K.N., 2004. A heuristic algorithm for solving hazardous materials distribution problems. Eur. J. Oper. Res. 152 (2), 507–519. Available at: http://www.sciencedirect.com/science/article/pii/S0377221703000419 [Accessed 13 December 2014].