Abstract

Providing safe transportation for Hazardous Materials (Hazmat) is a concern that attracts a wide range of researchers. Different types of problems have been defined in the literature in order to cope as much as possible with real situations. Most of existing studies consider the transportation between two points, while few of them considered resolving the Vehicle Routing Problem (VRP) in the context of Hazmat transportation. This paper surveys the recent state of the art related to point-to-point Hazmat transportation and the use of VRP to resolve Hazmat transportation problems.

Introduction

Research is more and more concerned with providing environment respecting solutions for industrial problems and secure processes for sensitive fields such as Hazardous materials (Hazmat) transportation. Nowadays, it is no more sufficient to opt for practical and cost-saving techniques. Optimized solutions have to be also safe and risk-free.

The urban traffic of Hazmat transportation knows an increasing development due to the chemical industry rapid growth. This enlargement of the transportation density causes an increase of hazmat accidents probability, with potential harm on population and environment. Hazmat include explosives, gases, flammable liquids and solids, oxidizing substances, poisonous and infections substances, corrosive substances, radioactive materials and hazardous wastes. Despite the danger they represent, they are essential in today’s industry and are inevitably transported on long distances between production points and exploiting industrial sites.

Even though the occurrence of accidents involving Hazmat is rather of low probability, the huge impact of such accidents implies the consideration of serious measures to limit their devastating consequences. These facts prove the importance of hazmat transportation and justify the increasing focus on this topic in operations research. Hazmat routing decisions can be grouped into two major categories: (1) origin to destination routing (point to point) of full truckload shipments, (2) Hazmat routing and scheduling of a fleet of vehicles.

Most of research effort has been focused on the former type of routing decision: List et al. [68] gave an overview on research studies on Hazmat logistics since 1980; whereas Erkut et al. [44] presented an extensive bibliography of the researches on the topic classifying all of them into four different classes: risk assessment, routing, combined facility location and routing and network design. They presented a detailed overview of hazmat logistics research.

The Vehicle Routing Problem (VRP) is one of the most studied combinatorial problems. The first studies on the subject appeared in the 50’s (Dantzig and Ramser [33]) and it is still attracting an intensive interest in the operations research academic sphere. It generalizes the Travelling Salesman problem (TSP) and is applied to model several real-life transportation problems.

In this paper, the recent state of the art related to Hazmat transportation is addressed. Interest is given to emergent problems that attracted the researchers’ attention in the last decade. A specific attention is given to solving a VRP in a context of Hazmat transportation. Section 1 is dedicated to the presentation of the VRP. In Section 2, the point to point Hazmat transportation problem is presented whereas Section 3 is relevant for VRP variants related to Hazmat transportation. Finally, a discussion and perspectives are addressed in Section 4.
1 Vehicle Routing Problem

The VRP consists in using a fleet of identical vehicles to service a given number of customers under the following constraints:
(a) each customer is visited only once by one vehicle,
(b) each vehicle’s route starts from a special location called depot and finishes at the same depot
(c) the total demand assigned to one vehicle does not exceed its capacity.

The aim is to minimize the total travelling cost. The values associated to these costs can be monetary values as it could be distances or time, etc. The most widespread variant of the vehicle routing problem is the VRP with Time Windows (VRPTW) where each customer needs to be serviced within a given time window. Other variants may be encountered in the literature such as: VRP with Pickup and Delivery, VRP with Backhauls, VRP with stochastic demand, dynamic VRP, VRP with heterogeneous fleet of vehicles, Open VRP, Periodic VRP, VRP with multi-depots, VRP with multi-trips, etc.

2 Point to point Hazmat routing

In Point to point Hazmat routing problems, we distinguish different sub-problems:
1) The local routing problem, which consists in selecting the route(s) between a given origin-destination pair for a given hazmat, transport mode, and vehicle type.
2) The global routing problem, where a network of routes is designed to limit the circulation of Hazmat trucks in urban areas.
3) The combined location-routing problem, which consists in locating given facilities then routing vehicles from and/or these facilities to customers.

2.1 Hazmat Local Routing

The local routing of hazmat has been deeply studied since the first works of the sixties. Several surveys were published and the last ones are those of Erkut et al. [44] and Centrone et al. [27]. In Table 1, the papers related to this field since 2007 are enumerated.

The available literature includes static models (Machuca et al. [74], Aslan et al. [8] and Liu et al. [69]), dynamic models (Bonvicini et al. [18], Febbraro et al. [36], Toumazis et al. [99]), multiobjective models (Das et al. [34], Huang et al. [52], Jassbi [54]) and multimodal models (Verma et al. [101], [102], [104]). The routing and scheduling problem has been also studied (Bersani et al. [14], Shen et al. [93]). Game theory methods appeared in the works of Aslan et al. [8] and Bersani et al. [14]. The consideration of weather factor is found in Akgun et al. [2] and El-Basyouny et al. [37]. Desai et al. [35] and Lim et al. [66] considered stochastic parameters. Kwon et al. [63], Toumazis and Kwon [100] and Kang et al. [57] used the Value-at-Risk model. Changxi et al. [28] used the N-shortest path algorithm and the entropy model to solve the problem. Mahmoudabadi et al. ([75], [76]) used the chaos theory and dynamic routing. Mi et al. [80] used combined features of TransCAD traffic forecasts to set a database for path planning of hazmat transportation. Nune et al. [85] considered the threat of a terrorist attack. The hazmat reverse logistic problem was studied by Sheu et al. [94]. The fuzzy logistic and the lane reservation appeared in the work of Zhou et al. [113].

GIS technologies and DSS have been used in several studies to provide adequate tools to final users (Bonvicini et al. [18], El-Basyouny et al. [37], Luè et al. [72], [71]). Networks with time-variant attributes, that shows the parameters dependence of time windows, are encountered in the works of Bersani et al. [14] and Desai et al. [35]. Case studies have been proposed, for instance, in The State of Texas (Akgun et al. [2]), Honk Kong (Li et al. [65]), Iran provinces (Mohaymany et al. [82]) and city of Milan (Luè et al. [72], [71]).

2.2 Road Hazmat Global Routing

Whereas local routing problem concern the determination of a safe path between a single origin-destination pair, global routing focuses on mapping different origins and destinations in a region’s network. Global route planning belongs generally to a government agency in charge of hazmat shipments management inside its territory, due to the associated public and environmental risks. Recently, Bianco et al. [17] proposed
Table 1: Hazmat Local Routing References

<table>
<thead>
<tr>
<th>Mode</th>
<th>Articles</th>
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<tbody>
<tr>
<td>Road</td>
<td>Toumazis and Kwon [100], Kang et al. [57], Mahmoudabadi et al. [76], Desai et al. [35]\textsuperscript{TV}, Shen et al. [95]\textsuperscript{M,TV}, Toumazis et al. [99]\textsuperscript{TV}, Zhou et al. [113]\textsuperscript{M}, Febbraro et al. [36]\textsuperscript{M}, Das et al. [34]\textsuperscript{DSS,M}, Mahmoudabadi et al. [75], Mi et al. [80], Machuca et al. [74]\textsuperscript{M}, Ma et al. [28]\textsuperscript{DSS}, Kwon et al. [63], Li et al. [65]\textsuperscript{GIS,M}, Liu et al. [69], Bersani et al. [14]\textsuperscript{TV}, Jassbi [54]\textsuperscript{M}, Lim et al. [66]\textsuperscript{DSS,M}, Luè et al. [71]\textsuperscript{GIS,DSS,M}, El-Basyouny et al. [37]\textsuperscript{GIS,DSS,TV}, Bonvicini et al. [18]\textsuperscript{GIS,DSS}, Aslan et al. [8], LuÀ† et al. [72]\textsuperscript{GIS,DSS,M}, Centrone et al. [27]\textsuperscript{S}, Mohaymany et al. [82], Monprapousson et al. [83]\textsuperscript{GIS,DSS,M}, Akgun et al. [2], Nune et al. [85], Sheu et al. [94]\textsuperscript{M}, Erkut et al. [44]\textsuperscript{S}</td>
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<td>Rail</td>
<td>Verma et al. [103]\textsuperscript{GIS,M,CS}, Lai et al. [64], Krawpasert et al. [60], Barkan et al. [9], Gilckman et al. [47]</td>
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<tr>
<td>Rail + Road</td>
<td>Verma et al. [101], [104]\textsuperscript{GIS,M,CS}, Junior et al. [56]\textsuperscript{DSS,M,CS}, Verma et al. [102]\textsuperscript{M,CS}</td>
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\textit{DSS} Decision Support System.  
\textit{GIS} Geographical Information System.  
\textit{TV} Time-Varying.  
\textit{S} Survey.  
\textit{M} Multiobjective.

an overview of the global hazmat routing literature. They divided the existing works into three categories: Generic models addressing equity, Hazmat transportation Network Design and Toll setting policies.

### 2.2.1 Generic models addressing equity

The models presented in this section are related to finding minimum risk routes while distributing the risk uniformly over all the parts of the geographical crossed region. Equity consideration in the spatial distribution of risk is important from different points of view. For the population, inequity in risk exposure may result in a public opposition to the routing of hazmat shipments through the considered zone. More important, the overuse of certain links of the network by hazmat carriers may lead to an increase in the incident probabilities and therefore in the severity of consequences.

Different concepts have been introduced in the literature to build equity models (Table 2):

1. The iterative penalty method which consists of computing iteratively a shortest path and penalize its arcs by increasing their weights for discouraging the selection of the same arc set in the generated paths set in the next iteration (Johnson et al. [55]).
2. The Gateway Shortest Path method which is based on the generation of the shortest paths, between an origin and a destination, constrained to go through defined nodes called "gateways". A set of dissimilar paths can be obtained by imposing different gateways. However, the quality of the paths depends heavily on the selected gateways (Lombard and Church [70]).
3. The Min-Max method that selects a subset of dissimilar paths, starting from a set of \( k \) assigned paths, taking into account both their lengths and dissimilarities (Kuby et al. [62]).
4. The \( p \)-dispersion method that is based on modeling the problem as a \( p \)-dispersion location problem, which consists in selecting \( p \) points in some space, so as to maximize the minimum distance between any couple of selected points. The distance between two points represents the dissimilarity between the two relative paths (Erkut [39]).

Zografos and Davis [116] were probably the pioneer in terms of incorporating equity considerations in global routing of hazmat shipments. They proposed a multi-objective model where the total risk, the risk imposed on special population categories, travel time, and property damage are minimized. Equity is achieved
by the limitation of road links’ capacity.

In recent years, Carotenuto et al. [25] gave attention to the Min-Max problem where two selected paths are highly dissimilar with regards to the number of common links but are geographically very close to each other, in a way that the intersection of the two exposure zones around the paths is not negligible, implying a low degree of risk equity. The considered objectives are to minimize the total risk and bound the maximum risk on each link of the network. The considered societal risk measure is an extension of the concept of buffer zone around a link introduced by Batta and Chiu [10]. To overcome this situation, a bounding of the maximum risk sustained by the population living in the proximity of each link of the network is studied. Carotenuto et al. [26] considered in another paper the equitable spread of risk in both space and time. For each hazmat shipment, a set of minimum and equitable risk alternative routes from origin to destination points and a preferred departure time are determined with a two stage approach. In the first stage, dissimilar paths are obtained with the same approach used by Carotenuto et al. [25]. Then the hazmat shipment scheduling problem is modeled as a job-shop scheduling problem with alternative routes. Bell et al. [11] formulated a Min-Max problem that minimizes the maximum link risk to determine the safest set of routes and the safest share of traffic between these routes.

Marti et al. [78] reviewed all previous methods of the literature about the path dissimilarity problem and adapted them to the bi-objective routing problem where a set of paths from an origin to a destination have to be generated with minimum cost and maximum dissimilarity. Their new GRASP was proved to be able to provide better approximations of efficient frontiers than existing methods. Dadkar et al. [31] studied also the Min-Max problem where distance is minimized and dissimilarity maximized. In their problem, the performance of each highway facility, with respect to each objective, can be stochastic and can vary over time.

They formulated a mixed integer program to identify a subset of paths, which represents an acceptable trade-off between geographic diversity and performance. Caramia and Giordani [23] proposed a clustering-based approach that aims to select k efficient paths for hazmat shipments with respect to different measures (length, cost and risk). The selected paths are representative of the whole efficient path set and have high spatial dissimilarity. Later Caramia et al. [24] solved the same problem with a different selection approach based on combining the k-means algorithm with a heuristic method that maximizes the total spatial dissimilarity.

Touati-Moungla et al. [98] studied a multi-criteria variant of hazardous material routing on a geographical area subdivided in regions. The two objective functions are to minimize the cost and the maximum risk perceived within a region. Very recently, Cappanera and Nonato [21] solved the gateway location problem in order to determine paths that diverts vehicles from their shortest (and risky) path from origin to destination, by forcing each vehicle to pass through an intermediate check point. The problem consists in selecting the location of a given number of gateways among a larger number of potential locations and assigning a gateway to each vehicle such that the total risk is minimized. An efficient Pareto frontier is then computed with respect to total risk and total cost on realistic instances taken from the literature.

From their side, Kang et al. [58] proposed an approach in which the Value-at-Risk (VaR) framework is applied to determine routes that minimize the global VaR value while satisfying equity constraints. The model aims to embed the algorithm for the single hazmat trip problem into a Lagrangian relaxation framework to obtain an efficient solution method for this general case.

A new problem defined by Bronfman et al. [20] proposes to maximize the distance between the route and its closest vulnerable centre, weighted by the centre’s population. A vulnerable centre is a school, hospital, senior citizens’ residence or the like, concentrating a high population or one that is particularly vulnerable or difficult to evacuate in a short time. The potential consequences on the most exposed centre are thus minimized. The developed integer programming formulation and heuristic are tested in a real-world case study set in the
2.2.2 Hazmat Transportation Network Design

In the literature, two approaches were introduced to model the bi-level hazmat transportation network design (HTND) problem: a combinatorial approach, and a toll-setting approach. In the combinatorial bi-level formulation, the risk is minimized at the first level and the cost at the second level. According to Kara and Verter [59], the problem is defined as follows: "given an existing road network, the HTND problem involves selecting the road segments that should be closed to hazmat transport so as to minimize the total risk”. Whereas the toll setting bi-level model imposes tolls on certain road segments instead of closing road segments altogether. In this section, attention will be given to the combinatorial approach. Toll setting approach is discussed in the next section.

In Kara and Verter [59], the first work that poses the HTND problem was developed. In the bi-level formulation, two actors are involved: the local government and the carriers. The local government designs the network with the objective of minimizing the risk and the carriers choose the routes with the aim of minimizing the cost. They considered the population exposure measure of risk. Once the government decides on the network, the carriers will take least-cost routes between the origins and destinations on this network. The behaviour of the carriers should be taken into account by the government when designing the network, since it cannot impose to carriers to stay on minimum risk routes.

For the resolution, the bi-level problem is transformed into a single-level one. However, the model presents some disadvantages that limit its use. The network design does not consider the interactions between different materials groups, because the optimization problem is independent for each material group. Additionally, the bi-level optimization model presents problems in the optimum stability and multiple solutions are produced over the network. A feasible solution of HTND problem is called stable if the sub-network does not admit multiple minimum cost paths with different risk values.

Erkut and Gzara [41] considered a bi-level bi-objective HTND problem that minimizes both cost and risk similar to that discussed by Kara and Verter [59]. They proposed a heuristic algorithm that exploits the network flow structure at both levels, instead of transforming the bi-level problem to a single-level formulation. Later Erkut and Gzara [40] generalized their model to the undirected case. They consider the possible lack of stability of the solution of the bi-level model obtained by solving the single-level mixed integer linear model, and propose a heuristic method that solves a set of network flow models iteratively and breaks cycles heuristically until a stable solution is obtained.

Amaldi et al. [4] consider the same network design problem as Kara and Verter [59] and prove that the version of the HTND problem where a subset of arcs can be forbidden is NP-hard even when a single commodity has to be shipped. They propose a bi-level integer programming formulation that guarantees solution stability and derive a (single-level) mixed integer linear programming formulation that can be solved in reasonable time with a state-of-the-art solver. Gzara [48] formulated the problem as a multi-commodity bi-level network flow problem. They proposed a family of valid cuts and an exact cutting plane and showed that their method is faster than other methods in the literature on the same formulation (Marcotte et al. [77], western Ontario instance) but the toll-setting approach still gives better results for both cost and risk (see next section).

Erkut and Alp [42] formulated the HTND problem as a tree selection problem. The authors proposed to design the network in such a way that there is only one route between any given origin and destination. This sparse hazmat network allows numerous benefits: giving the local authority full control over the routing of hazmat shipments, minimizing the costs of road conditions improvements, simplifying the network control and emergency interventions. While there are some benefits of a tree design, this topology takes away the carriers’ freedom in route selection and simplifies the bi-level problem to a single level. However, it also results in circuitous and expensive routes.

All the previous papers adopt a link-based formulation for the carriers’ problem, while Verter and Kara [105] provided a path-based formulation. The solution of the considered model is a set of alternative paths for each hazmat shipment. Each set of paths corresponds to a certain compromise between the regulator and the carriers in terms of the associated transport risks and costs. This facilitates the incorporation of carriers’ cost concerns in regulator’s risk reduction decision, and allow to formulate the problem with a single-level integer programming formulation, that assure that the cheapest path among the available ones is used by each carrier.

Berman et al. [13] considers the problem of selecting obnoxious routes on a transportation network using an extreme measure assuming that population centers on or outside the network within a certain distance from
the selected routes can be expropriated at a given price. The objective is to select the routes so as to minimize the total weighted transportation and expropriation costs.

Bianco et al. [15] formulated a linear bi-level programming problem in which the regional authority aims to minimize the total transport risk, while local authorities want the risk over their local jurisdictions to be the lowest possible, forcing the regional authority to assure also risk equity. The authors then transform the bi-level model into a single-level mixed integer linear program.

Figure 1 shows an adapted and completed version of the figure proposed by Bianco et al. [15] to explain different bi-level models.

2.2.2.1 Terrorist Attack: Paying attention to the growth of terrorism threat, Dadkar et al. [32] and Reilly et al. [91] proposed new perspectives that incorporate terrorists' activities into the routing model. Dadkar et al. [32] developed a game theory modeling the interaction between government agencies, carriers and terrorists. Government agencies can determine which specific facilities to restrict for each class of material and for which times of the day and/or week. The interactions between the carrier and the terrorist is modeled as a non-cooperative two-person non-zero sum game with the carrier wishing to maximize the value of the routes used when there is a known probability of an attack and the terrorist wanting to inflict as much damage as possible in an attack. This work assumes only one hazmat shipment and a single origin-destination pair. Reilly et al. [91] extended the approach to multiple origin-destination pairs and applied the solution on a realistic case study based on the freight rail network in the continental United States.

2.2.2.2 Uncertainty: The previous studies can only solve hazmat transportation network design problem with certain and crisp parameters. In order to model the reality, Gao et al. [45] consider the problem of network design for hazmat transportation in an uncertain environment, assuming that the parameters such as transport risks of road sections are uncertain and can be represented by fuzzy numbers. The authors adopted the strategy of Erkut and Alp [42] in which a tree network model is developed in such a way that there exists one and only one route between any given origin and destination in the tree network. The authors assume that the local government and the carriers determine together the Hazmat flows in the network. To solve the tree network model with fuzzy parameters, a fuzzy chance-constrained programming model is provided, then converted to its crisp equivalent before being solved using a commercial solver.

Ghatee et al. [46] studied the minimal cost flow problem (MCFP) with fuzzy link costs to understand the effect of uncertain factors in applied shipment problems. With respect to the most possible case, the worst case and the best case, the fuzzy MCFP can be converted into a 3-objective MCFP. In the shipment of Hazmat, the decision maker may not be interested in a short path in order to achieve a low cost transportation and may consider the worst case or the most possible case with high priorities. In such cases, applying a lexicographical ordering may help to find a preemptive priority based optimal solution, by taking high priority for pessimistic concept of problem and low priority for optimistic concept of problem, a reasonable solution can be concluded.

Xin et al. [108] used maximum regret criterion robust optimization to model the HTND problem as a bi-level integer programming problem under edge risk uncertainty where an interval of possible risk values is associated with each arc. The authors used a heuristic approach inspired from Erkut and Gzara [40] that always finds a robust and stable hazmat network.

2.2.3 Toll setting policies

In order to control traffic congestion, different regulation methods are used including toll pricing. When increasing network roads capacity induces huge costs, imposing tolls on certain road segments may resolve the problem. Tolls can motivate drivers to detour or travel during less congested time periods, hence reduce traffic congestion. In the case of hazmat shipments, discouraging carriers from using crowded portions of the network reduces the risk of population exposure. Hazmat shipments are then channeled on less populated areas according to the carriers’ own choice rather than by authorities’ prohibition. Marcotte et al. [77] were the first to propose the use of tolls to deter the hazmat carriers from using certain road segments. The authors state that toll setting policy is more flexible and effective than the popular network design policies, and network design policy may be infeasible in certain cases. The proposed toll problem is solved by inverse optimization when the only objective is to minimize hazmat transport risk.

The model proposed by Marcotte et al. [77] does not take into consideration risk equity. It may happen that a given segment of the network is chosen by many carriers, inducing an unacceptable risk level on that segment.
even though the total risk on the network remains relatively low. This drawback is overcome by Wang et al. [106] and Bianco et al. [16], who propose toll setting models that do not only limit the hazmat risk, but also equitably spread it in the zone where the transportation network is embedded. Wang et al. [106] propose a dual toll pricing method in which regular and hazmat vehicles are both controlled to reduce the risk. The authors incorporate a new risk measure to consider duration-population-frequency of hazmat exposure.

Bianco et al. [16] assume that the toll paid by a carrier on a network link depends on the usage of that link by all carriers. The tolls dissuade the carriers from using links with high total risk, i.e. links that has been chosen by several other carriers.

### 2.3 Hazmat Location-Routing

For an extensive discussion on undesirable facility location one can refer to Erkut and Neuman [43] and Tang et al. [96], which is the most recent review published in this area. An extensive survey of location-routing models along with exact and heuristic solution methods is given in Nagy and Salhi [84].

Combined location-routing problems involve two different types of decision: strategic (location) and operational (routing). In the context of Hazmat transportation, the presence of risk represented a coupling factor of these two decisions. Two types of risk are considered: facility risk and transport risk. The obnoxious facilities could be dump sites, chemical industrial plants, electric power supplier networks, or nuclear reactors. The location-routing problem (LRP) involves determining the optimal number, capacity, and location of facilities as well as the associated optimal set of routes (and shipping schedules) to be used in serving customers (Erkut et al. [44]). The LRP is NP-hard and offers a variety of challenges since the formulation of its first model by Christofides and Elon [29].

According to existing studies, we classified the proposed models into four categories represented in the Figure 2.
2.3.1 First Model: Locate one type of center

In this model, routing is considered between only two types of nodes: from generation to treatment or disposal nodes. The first effort to model the location-routing problem simultaneously for hazmat was by Zografos and Samara [117]. They proposed a goal-programming model for one type of hazardous waste, which minimizes travel time, transportation risk, and disposal risk. The studied model contains two main limitations: each population center is affected only by its nearest treatment facility, and each source node is assigned to only one treatment facility. Cappanera et al. [22] studied a single commodity hazmat LRP with the objective to minimize the cost of facilities’ opening.

Zhang et al. [110] developed a location-routing model in order to locate treatment centers and route hazmat from generation points to treatment centers, taking into consideration population centers that are on the route. Their model had three criteria: cost minimization, potential risk minimization and risk equity maximization.

Aboutahoun [1] proposed a hybrid path metric designation model that simultaneously locates multiple disposal or treatment facilities and determines the hazmat routing. The objective is to minimize the distance traversed and population at risk. The used measure is path reliability that gives the expected number of accidents over a given planning horizon which is significantly different from the minimum distance path.

Berglund and Kwon [12] considered a robust facility location problem for hazmat transportation under uncertainty. Given a network and a known set of nodes from which hazmat originate, locations of hazmat processing sites are computed in order to minimize total cost and exposure risk. The authors made an interesting assumption that the hazmat carriers select the shortest-path based on distances only. This modeling approach is common in HTND literature. Therefore the proposed model in this paper has a similar model structure including bi-level mixed integer programming.

2.3.2 Second Model: Locate two types of centers

In this model, routing is performed through treatment or recycling node before to finish in disposal nodes, or directly to disposal nodes. Alumur and Kara [3] proposed a multi-objective location-routing model that aims to minimize the total cost and the transportation risk. Facilities to locate include treatment and disposal centers. The model can manage different types of hazardous waste and different treatment technologies and also allows that recycling can either be done at a generation node or at a treatment center.

Emek and Kara [38] define the hazardous waste management problem as the combined decisions of selecting the disposal method, siting the disposal plants and deciding on the waste flow structure from factories, recycling centers, and hospitals to incinerators and from factories to recycling centers.

Zhao and Zhao [111] presented a bi-objective mixed integer model to decide for the openings of treatment and disposal centers, the routing of different types of hazardous waste and waste residue (1) from generation nodes to treatment or disposal centers and (2) from treatment centers to disposal centers. The routing process takes into consideration different waste types, treatment technologies, waste-technology compatibility and the capacity of the considered centers.

Recently, Ardjmand et al. [7] proposed a genetic algorithm that minimizes weighted sum of the cost and risk by answering these questions: (1) where to open the facilities which produce hazmat; (2) where to open disposal sites; (3) to which facilities every customer should be assigned; (4) to which disposal site each facility should be assigned; (5) which route a facility should choose to serve the customers; and (6) which route a facility should choose to reach a disposal site.

2.3.3 Third Model: Locate three types of centers

In this model, three types of facilities are located and routing is organized between them. The first location-routing model to consider multiple hazardous waste types is by List and Mirchandani [67]. The model has three objectives: minimization of risk, minimization of cost, and maximization of equity. The located facilities are: treatment, storage and disposal; and a new risk measure inversely proportional to the square of the distance is proposed. However, this complex risk function was abandoned while applying the model to the capital district of Albany, NY.

Shuai and Zhao [95] extended the problem studied by Zhao and Zhao [111] by considering location and routing to and from recycling centers in addition to treatment and disposal centers. A three-criterion problem is solved where transportation and sites risks are considered separately.
Samanlioglu [92] developed a multi-objective Hazmat LRP. The aim of the model is to help decision-makers decide on (1) locations of treatment centers utilizing different technologies, (2) routing different types of industrial hazardous wastes to compatible treatment centers, (3) locations of recycling centers and routing hazardous waste and waste residues to those centers, and (4) locations of disposal centers and routing waste residues there. Three criteria are considered: minimizing total cost, total transportation risk, and total site risk considering the population exposure measure.

2.3.4 Fourth Model: Locate three types of centers with multiple paths

The last model was designed by Boyer et al. [19]. They developed a bi-objective mixed integer programming model for location-routing industrial hazardous in which total cost and transportation risk are minimized. The considered risk measure is the population exposure within a bandwidth along the routes. This model helps decision makers to locate treatment, recycling, and disposal centers simultaneously and also to route waste between these facilities. Wastes are divided into three groups, receiving a different process each (see Figure 2). First group is recyclable waste; it is transferred to the recycling centers. Second group requires treatment facility, so they are routed to the treatment centers with incineration technology. Third group is non-recyclable and non-treatable waste, therefore it is transported to the disposal centers directly. In the end, residues from treatment and recycling centers are carried to the disposal centers.

Motivated by the lack of research on multimodal Hazmat LRP and the increasing demand for it, Xie et al. [107] proposed a multimodal Hazmat model that simultaneously optimizes the locations of transfer yards and transportation routes. For this multimodal network, highways and railways are connected only at transfer yards, where Hazmat can be transferred from trucks to railcars and vice versa. Transfer yards are usually determined by Hazmat carriers based on safety, security, availability, cost, and accessibility concerns.
3 Vehicle Routing Problem for Hazmat Transportation

The growing interest on environmental issues gave rise to the emergence of new VRP variants concerned with welfare of mankind and sustainable development. In this section, VRP variants that aim to reduce or avoid the risk related to Hazmat transportation are detailed. The use of VRP for Hazmat transportation started attracting interest in the last few years. Literature is less dense on this topic. In this part, we focus on the state of the art related to this specific problem.

3.1 Multi-objective vehicle routing for Hazmat transportation

The most spread approach in combining vehicle routing and Hazmat risk management is to consider a bi-objective or multi-objective problem. The first criterion is obviously the minimization of the transportation cost traditionally considered as in the CVRP goal. The other objectives related to the nature of the transported material and concern the minimization of the risk while choosing arcs constituting the routes.

Tarantilis et al. [97] proposed a pioneer study in which VRP studied in a Hazmat transportation context. The authors considered the risk of population exposure when building their truck-routes. For this purpose they employed a List Based Threshold Accepting (LBTA) metaheuristic algorithm that was applied in a real case study.

Zografos and Androutsopoulos gave a great interest to the topic and dedicated, since 2004, several works to the use of VRP models in Hazmat transportation. Zografos and Androutsopoulos [114] proposed a bi-objective formulation of the problem in which risk, expressed in terms of exposed population, and cost are minimized. But ultimately, they transformed the bi-objective model into a single objective one, using weighting approach. An insertion based heuristic is used for routing and Dijkstra shortest path algorithm for route choice between customers. Zografos and Androutsopoulos [115] developed a GIS based decision support system for integrated Hazmat routing and emergency response decisions. The authors considered the same routing problem as in Zografos and Androutsopoulos [114] and a Lagrangean relaxation heuristic algorithm has been developed in order to solve the emergency response units location problem. The proposed system has been applied on a case study within a heavily industrialized area in Greece. Considering that the population exposure and the accident probability may vary considerably for different parts of a day, Androutsopoulos and Zografos [5] addressed the bi-criteria time-dependent VRPTW. The authors focused on minimizing the perceived risk measure and proposed an alternative algorithm that determines the k-shortest time-dependent paths. The time-dependent VRPTW was also studied by Androutsopoulos and Zografos [6]. In both papers, the traditional risk is used. The vehicle routing and scheduling problem was decomposed into a series of single-objective instances of the problem, where the objective function is expressed as a weighted sum of the criteria under consideration. A route-building heuristic algorithm was presented to resolve each of the sub-problems.

Meng et al. [79] considered a multi-objective VRPTW for Hazmat transportation subject to three kinds of practical constraints: limited operational time, service time and waiting time window at each node. The authors studied transportation networks with multiple time-varying attributes. A dynamic programming method was developed while considering the traditional risk.

Pradhananga et al. [86] studied a bi-objective VRPTW for Hazmat transportation then extended it to a multi-objective VRPTW in (Pradhananga et al. ([87], [88], [89]) where the number of used vehicles, the total service time including waiting at customer site and travel times are minimized in addition to the risk criterion. The traditional risk was also used in this study. The authors proposed an ant colony metaheuristic to resolve the problem. In their last work so far, Pradhananga et al. [90] defined the Hazmat VRPTW (HVRPTW) in which a bi-objective problem is solved where risk and overall routing distance are minimized simultaneously. In this work also the traditional risk was considered. The authors used one more time the multi-objective ant colony system to determine the Pareto optimal solutions.

Zheng [112] proposed a multi-objective optimization model for VRP in Hazmat transportation that aims to minimize road risk, population affected along the way, and total cost, while using a multi-objective genetic algorithm.

Recently, Dabiri and Tarokh [30] studied the bi-objective Hazmat inventory routing problem (IRP), where Hazmat routing and inventory assignment are integrated together. In this problem, customers do not formulate expressive demands but are resupplied by a central depot that keeps an eye on each customer’s inventory level. The authors proposed a mathematical model for a bi-objective problem were the risk is minimized as well as the inventory holding and routing cost and a multi-objective genetic algorithm was used to resolve it.
Meanwhile, Kokkinos et al. [61] presented a software framework in which several risk and cost models are incorporated. The software can simulate various decision making scenarios for dynamically formed road networks of the so called Hazmat VRP (HVRP) and can be used by the competent authorities. The authors studied the traditional risk model. They proposed a new constraint that focuses on elimination of “hot spots”, or high frequation, on edges with large risk values. Even though the authors called it as VRP, the studied instances are more about finding the shortest path with minimum risk between two points on a graph.

3.2 Single-objective Hazmat routing

Whereas the multi-objective approach considers the risk as an additional objective to minimize, in the single objective version of the problem, the risk is integrated as new constraints that may define new variants of the problem. In this section, two new variants that have been investigated in the last few years are presented: the VRP with link capacity and the VRP with conflicts.

3.2.1 Link capacity constraints

Zhang et al. [109] studied a new VRP variant where a load constraint is imposed on different edges of the route depending on the nature of the crossed area. Ma et al. [73] formally called this variant as the vehicle routing problem with time windows and link capacity constraints (VRPTWLC). Link capacity is imposed on all road segments to restrict vehicle load due to environmental requirements. The study was motivated by a business project of a Hong Kong transportation company that transports Hazmats across the city and between Hong Kong and mainland China. The authors developed a tabu search heuristic with an adaptive penalty mechanism (TSAP) to help managing the company’s vehicle fleet.

3.2.2 Conflict constraints

Starting from a property of Hazmat, a new variant of VRP emerged: VRP with conflicts. In fact, Hazmat are categorized into different classes and some of them are incompatible. Totally incompatible materials have to be stored in separate warehouses and transported in different vehicles. We talk about totally conflicting materials. Whereas partially conflicting materials can be transported in the same vehicle, but have to be separated by a horizontal safety distance. Table 3 shows the Hazmat compatibilities according to the "Regulations for management of hazardous wastes, Government of Canada" (http://www.csc-scc.gc.ca/text/plcy/doc/318-5-gl_e.pdf). The concept of conflict appeared first in the context of bin-packing problem [53] then, the VRP with conflicts (VRPC) has been defined by Hamdi-Dhaoui et al. ([49],[50]). The authors proposed a mathematical model, adapted heuristics and two metaheuristics for the totally conflicting Hazmat transportation: an Iterated Local Search (ILS) and hybrid GRASP-ELS (Greedy Randomized Adaptive Search procedure-Evolutionary Local Search). A lower bound has also been developed.

Table 3 shows the different Hazmat categories and the relation linking them. The letter P means that storing the items together, in the same vehicle or warehouse, is permitted. The symbol X means that the items are incompatible, so they cannot be stored or transported together in the same compartment. The letter A is used for partially incompatible items: they can be stored together, but have to be separated by minimum 1 meter horizontal distance. When DS is mentioned, it means that it depends on the situation, and the Material data sheet has to be consulted.

Recently, Hamdi-Dhaoui et al. [51] studied the two-dimensional loading vehicle routing problem with partial conflicts (2L-CVRPPC). A memetic algorithm was developed to resolve the routing problem and several heuristics were used to pack partially conflicting items while respecting safety distances. An NSGA-II algorithm helped resolving the bi-objective problem, where the load balance was considered as an objective in addition to routing cost minimization in order to distribute equitably conflicting pairs of items among the vehicles.

Minh et al. [81] studied the VRPTW and applied it to industrial waste collection, where collected items may be conflicting. A combination of flow and set partitioning formulation is suggested to model a multi-objective version of the problem. To minimize the total traveling time and the number of vehicles, the authors proposed a memetic algorithm (MA) with \( \lambda \)-interchange mechanism.
Table 3: Hazmat Compatibility

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<tr>
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<th>1</th>
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<td>P</td>
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<td>P</td>
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<td>X</td>
<td>A</td>
<td>A</td>
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<td>X</td>
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4 Discussion and perspectives

In this paper, the recent state of the art about Hazmat transportation and related topics is addressed. New problems like the network design raise new challenging issues involving authorities’ strategic decisions while taking into account new factors like terrorist attacks. One can notice that the literature on using the VRP in Hazmat transportation context is rather scarce but it seems to gain interest in recent years. The consideration of risk as a constraint or/and objective function within VRP led to the emergence of new variants of the problem such as VRP with Link Capacity constraints or VRP with Conflicts. A deeper investigation of Hazmat properties may give birth to other variants in the future. The development of exact or hybrid approaches is also a challenging issue for future researches on the subject.

In this section, some possible evolutions and new models involving the resolution of VRP in the context of Hazmat transportation are proposed. The new problems are based on hybridizing the classical point to point Hazmat transportation problems (network design, addressing equity, toll setting, location-routing) with the VRP model. For the multi-objective version of the problem, new objectives that may be considered are expressed, whereas new VRP variants are detailed for the single objective version.

4.1 Multi-objective VRP

In the proposed multi-objective studies, we can notice that the most frequent objectives are to minimize the total risk (traditional risk) or the population exposure. In Table 4, the risk measures associated with Hazmat transportation in VRP models are summarized.

Table 4: Risk Measurement in Multi-objective VRP

<table>
<thead>
<tr>
<th>Risk Measure</th>
<th>VRP variant</th>
<th>References</th>
</tr>
</thead>
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<tr>
<td>Population exposure</td>
<td>CVRP</td>
<td>[97], [114], [115]</td>
</tr>
<tr>
<td>Traditional Risk</td>
<td>time-dependent VRPTW</td>
<td>[5], [6], [79]</td>
</tr>
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<td></td>
<td>VRPTW</td>
<td>[86], [87], [88], [90],</td>
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<td></td>
<td>IRP</td>
<td>[30]</td>
</tr>
<tr>
<td>Traditional risk &amp; Population exposure</td>
<td>CVRP</td>
<td>[112]</td>
</tr>
</tbody>
</table>

4.1.1 Risk Equity:

One other objective that deserves focus is to balance the amount of risk between vehicles (or tours) when assigning the customers to vehicles. If all the vehicles perceive a reasonable amount of risk, the impact of a disaster occurring to any one of them will be reduced. No vehicle will assume a higher level of risk than the
others and be more attractive for terrorist attackers, for instance. For this purpose, a potential risk measurement should be assigned to hazardous items, (according to their nature, quantity, distance for which the item should be carried by the vehicle, etc) and also to the road arcs. The goal could be achieved by minimizing the maximum risk incurred by all the vehicles when building the routes.

4.1.2 Value-at-risk:

As explored for point-to-point Hazmat transportation, this economic indicator could also be used for VRP in Hazmat context. The VaR consists in taking into account uncertainty when estimating the risk associated to a given path since accident probabilities and accident consequences are both subject to many ambiguous factors.

4.2 Single objective VRP

For the single objective VRP, the model constraints may be modified or new constraints can be added in order to obtain a new VRP variant. In the existing literature, some studies added a conflict constraint, while another opted for a link capacity constraint.

4.2.1 VRP with toll setting:

From another point of view, the attribution of demands with relatively high risk to the same vehicle can be restricted. In this case, there is no real conflict between the items (according to the classification and compatibility of Hazmat), but it is not preferable to have the concerned items assigned to the same vehicle. By exploiting the idea of toll setting in the context of vehicle routing, it is possible to impose a high cost to such an assignment without prohibiting it completely, like a penalty. It is also possible to define a new relationship of conflict that will depend on the amount of total risk not on the nature of Hazmat.

4.2.2 Location-Routing VRP:

While considering the problem of location-routing, it is possible to imagine such a problem in which a fleet of vehicle makes tours over a given number of customers to collect their demands before routing them to a location or more (recycling center, disposal center, treatment center...). The location presents the depot in the traditional VRP, but it is not provided initially. It should be determined while solving the VRP in order to reduce the total travel cost. The tours performed by the vehicles can be also open (Open VRP), since the departure may be any of the nodes.

4.2.3 VRP with Gateways:

In order to keep the Hazmat traffic away from urban areas, the authorities may impose on the fleet of vehicles to go through a given number of gateways. The gateways will then be a part of each route and should be considered as a visited point with the customers. They could be either defined beforehand or located during the optimization process, which comes to solve a location-routing VRP.

5 Conclusion

In this paper, the recent state of the art about Hazmat transportation was addressed. A focus was given to the use of VRP in the context of Hazmat transportation. The consideration of risk in the literature was achieved in two ways: either as an additional objective to be minimized, in multi-objective VRP; or as a new constraint that gives raise to new VRP variants, like VRP with conflicts or VRP with link capacity constraints.

Finally, some new propositions have been made to exploit the VRP models in a multitude of real-life situations involving Hazmat transportation. Inheriting from the properties of classical point to point Hazmat routing problems, new VRP variants could be defined, like VRP with toll setting, VRP with location-routing or VRP with Gateways.
Acknowledgment

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