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A Three-Stage Approach for Solving Location-Routing Problem in Hazardous Materials Transportation

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Abstract

In the case of hazardous materials management, selected routes for carrying hazardous materials (Hazmat for short) have significant effects on locating Hazmat distribution centers. Since, transport risk and cost are usually considered as two main attributes to determine the best routes, optimized locations are sequentially outlined depending on selected routes. In the present paper, a three-stage procedure has been developed to determine the routes and Hazmat quantities should be carried from each origin (distribution center) to demand points (destinations). An experimental road network consists of eighty-nine nodes and one hundred and one links has been used as case study for analytical process and model validation. Results revealed that, this approach can be utilized for solving routing-locating problem.

Keywords: Hazardous Materials Transportation, Location-Routing Problem, Risk-Cost Trade-off, Optimization

1. Introduction

In the Islamic Republic of Iran, more than ninety percent of freight transportation is done via inter-city roads (Road Maintenance and Transport Organization, 2013). Due to the nature of hazardous material, Hazmat transportation is a major concern in the field of fright transportation and it is getting a challenging subject over the recent years. Hazmat accidents are potential to become human catastrophes (Azar, et al., 2011) together with another problem of road safety which is an important issue for decision makers in terms of the number of fatalities and injuries (World Health Organisation, 2013). Route determination for hazardous materials is a double-sided consideration of risk and cost attributes in which the aim of local authorities is to find the safest path but transport companies try to reduce time, distance and cost. It is a common technique to propose a trade-off methodology to consider safety and risk from the one side and time, cost and risk from the other side, simultaneously (Mahmoudabadi, et al., 2012).

While Erkut et al. (Erkut, et al., 2007) classified the Hazmat transport considerations into four categories including risk assessment, network design, routing and combined facility location and routing, Jie et al. (Jie, et al., 2010) used a statistical analysis approach to study the road accidents of hazardous materials transportation in China from 2000 to 2008, in terms of locations, times, types of materials and causes of the accidents. There are also several approaches to quantify risk in the literature. Zhang et al. used the expected consequence approach (Zhang, et al.,

2000) to estimate the risk in each link of the network using GIS and mapped the potential concentrations of air pollution by using Gaussian plume model. They defined risk as the production of the probability of an undesirable consequence and the population affected. Presenting models to minimize the risk of Hazmat shipment routes regarding to risk equity constraint is also observed in the literature (Carotenuto, et al., 2005) in which two heuristic algorithms have been proposed for solving the Hazmat routing problem considering risk extended equitably among regions under study.

In principle, risk mitigation for hazardous materials transportation can be achieved by changing the route or transportation mode. Bubbico et al. studied land transportation in three modes of road, rail and inter-modal transportation (combined road and rail) to minimize risk (Bubbico, et al., 2005). To give more estimations on the above concerns, determining an optimal assignment in terms of risk and cost for all O-D pairs and various types of Hazmat in a transportation network (Shariat Mohaymany, et al., 2008), presenting a bi-criteria model considering risk and cost to determine best routes for transporting fuel from a distribution center to some demand nodes (Tavakkoli-Moghaddam, et al., 2013) are also observed in the literature. In the above studies, both in Iran, assessing vulnerable population and environment as the measure of risk and travel time and defining risk based on fuzzy linguistic variables according to the experts opinions and converting to quantitative values are the main focal points of studies.

Hazmat shipments often originate from facilities that themselves are potentially harmful to public and environmental safety such as petroleum refineries. Destinations of Hazmat shipments can also be noxious facilities, such as gas stations or hazardous waste treatment centers. The location decisions pertaining to such facilities have a considerable effect on the routing process of Hazmat shipments. Therefore, integration of facility location and routing decisions can be an effective means to mitigate the total risk in a region where Hazmat is processed and transported (Erkut, et al., 2007). Nagy et al. classified Hazmat transportation in the field of transportation-location problem (TLP) justifying that Hazmat transportation often does not involve tour planning, so it would be better not to classify it in the field of location-routing problem (LRP) (Nagy, et al., 2006). A bi-objective model has also been developed to help decision makers to choose the best possible locations for solid waste facilities (Eiselt, et al., 2014) while objectives are to minimize cost and pollution, simultaneously.

Optimized locating decisions have gained considerable importance in order to ensure minimum damage to the various environmental components together with stigma reduction associated with the residents living in its vicinity, thereby enhancing the overall sustainability associated with the life cycle of a landfill. (Sumathi, et al., 2007) studied the locating of a new landfill using a multi-criteria decision analysis. (Lahdelma, et al., 2001) applied an ordinal multi-criteria method to locate a waste treatment facility. (Alumur, et al., 2005) proposed a multi-objective location-routing model to determine the optimized location of treatment centers, disposal centers and also the routes to transport different types of hazardous waste to compatible treatment technologies and the route to transport waste residues to disposal centers. (Samanlioglu, 2012) developed a multi-objective location-routing model to help decision makers decide on locations of industrial hazardous waste between these centers minimizing total transportation cost, fixed cost of establishing these centers and site risk or total risk for the population around the locations.

(Caballero, et al., 2005) studied the location of incineration plants for disposal of solid animal waste from some slaughterhouses minimizing startup, maintenance and transport cost considering the social rejection by towns on the truck routes and equity criterion of risks. (Zhang, et al., 2005) proposed a multi-objective heuristic algorithm to assist decision makers for analyzing combined Hazmat location-routing decisions. Considering cost minimization, potential risk minimization and risk equity maximization. (Mahmoudabadi, et al., 2013) proposed a bi-level objective function to determine the best locations for distribution centers and at the second level the safest paths are obtained. They solved the problem several times with different priorities of risk and cost. Results show these priorities have significant role on locating distribution centers and the number of distribution centers have significant role on total combination of risk and cost.

In the following sections the proposed methodology is stated. After that an example with a small hypothetical network is illustrated followed by using an experimental network consists of eighty-nine nodes and one hundred and one links has been used as case study for analytical process and model validation and then the computational results are represented.

2. Problem Definition

As mentioned in the previous section, the aim of this research work is to develop and solve a mathematical model in the cases of simultaneous location-routing for petrol distribution depots located within the study area in which minimizing the combination of risk and cost attributes for transporting Hazmat and minimizing total cost of transport and construction of distribution centers are the objective function components. The following assumptions help readers to understand the definition of the problem.

- Transportation cost is proportional to the distance between origin and destination.
- Demands for all nodes are deterministic.
- Risks associated to network links are pre-determined.
- Costs of construction and capacities of distribution centers in different locations are available.
- Constructing a distribution center is possible in all nominated nodes.

A network which consists of nodes and links is supposed to be used for checking the experimental results. Nodes are divided into three categories including nominated distribution nodes, demand nodes and eventually intermediary nodes. Some of nominated distribution nodes are selected as distribution centers with the specific variables represented the cost of construction and routing.

3. Methodology Definition

Network N(i,j) is supposed, i and j are the supply and demand nodes respectively. K_{ij} in equation (1) represents the combination of risk and cost of the link i-j.

$$K_{ij} = (P_l \times L_{ij}) + (P_r \times R_{ij}) \qquad (1)$$

L_{ij} and R_{ij} are defined as the cost and risk values of link ij, respectively. P_l and P_r are priority importance factors for cost and risk which are usually considered by decision makers. For example P_l=0.5 and P_r=0.5 means that both risk and cost have equal importance priority. As another example, P_l=0.8 and P_r=0.2 means that decision makers give 80% of importance priority to cost and 20% of that to risk attributes. Since traveling distance is getting to be longer, costs of fuel consumption and depreciation of vehicles are increased. Therefore, traveling distance can be considered as transport cost. Risk of each link depends on local expert's points of view. Because of the existing difference between risk and cost dimensions, they should be defined in a uniform pattern (Mahmouabadi, et al., 2014). Equation (2) changes the dimensions of different variables to a close interval [0.05, 0.95].

$$X_{new} = \left[\left(\frac{X_{old} - X_{min}}{X_{max} - X_{min}}\right) \times 0.9\right] + 0.05 \qquad (2)$$

where, X_{old} in equation (2) is the available amount of risk or cost of each link. X_{min} is the minimum amount of risk or cost among all links and X_{max} is the maximum amount of variable X. X_{new} is the uniform format of risk or cost. According to the above formulations combination of risk and cost for each link (K_{ij}) is calculated. Y_{ij} is the amount of transported materials from node i to node j. For each demand node, parameter D_j is supposed which denotes its demand and two parameters are considered for each nominated distribution center. $C0_i$ which is the estimated cost of constructing distribution center in node i and C_i is the capacity of distribution center. Binary variable X_i represents the decision of selecting node i as a supply center. If node i is selected, X_i will be assigned by 1, otherwise it will be assigned by 0. If X_i=1, $C0_i$ will be added to calculate objective function.

The proposed mathematical model should be able to select the best path for transporting Hazmat together with determining the best locations for distribution centers. In addition, to determine the best paths and the amount of Hazmat for each origin destination pairs, three stages have been proposed as follow:

Stage 1: Equation (3) is the objective function which gives the total cost of establishing distribution centers and transportation costs.

$$\text{Min } Z = \sum_i (C0_i \times X_i) + \sum_i \sum_j (Y_{ij} \times K_{ij}) \qquad (3)$$

Some constraints should be developed following the concept in which locating and routing problems are simultaneously solved. In this way, the amount of shipment departed from and sent to each node should be balanced. Constraint (4), which proposes balancing amounts of shipment in terms of type of nodes, denotes the sum of materials transported from node i to the other nodes and the sum of materials transported from the other nodes to the node i should be balanced in terms of demands or supplies.

$$\sum_{j} Y_{ij} - \sum_{i} Y_{ij} = T(i) = \begin{cases} -D(j) \text{ For all demand nodes} \\ C(i) \text{ For all distribution nodes } \forall\, i \in N \\ 0 \quad \text{For all intermediary nodes} \end{cases} \tag{4}$$

T(i) is defined according to the problem definition. For demand nodes, T(i) is equal to the amount of demand but in negative form. It means that the amount of materials sent to the corresponding nodes should be more than those materials transmitted from and the extent of this inequality should be equal to demand amount of the node. On the contrast, in supply nodes the difference between received and transmitted materials should be positive and less than nodes production capacities. For intermediary nodes, T(i) is equal to zero. They are only virtually assumed, so in order to balance consideration, the sum of materials received by intermediary nodes should be equal to the sum of materials transmitted by them.

Constraint (5) guarantees that node i will be selected as a distribution center (X_i=1), if its output is more than input.

$$\sum_{j} Y_{ij} - \sum_{i} Y_{ij} \leq M \times X(i) \quad \forall\, i \in N \tag{5}$$

Constraint (6) also guarantees that if the amount of input is greater than or equal to the amount of output, then X(i) should be equal to zero.

$$\sum_{j} Y_{ij} - \sum_{i} Y_{ij} - 1 \geq M \times (X(i) - 1) \quad \forall\, i \in N \tag{6}$$

According to the above explanations, mathematical model of simultaneous location-routing problems would consist of both risk and cost and can be summarized as follows:

$$\text{Min } Z = \sum_{i} (C0_i \times X_i) + \sum_{i} \sum_{j} \left(Y_{ij} \times K_{ij}\right) \tag{3}$$

Subject to:

$$\sum_{j} Y_{ij} - \sum_{i} Y_{ij} = T(i) = \begin{cases} -D(j) \text{ For demand nodes} \\ C(i) \text{ For distribution nodes } \forall\, i \in N \\ 0 \quad \text{For intermediary nodes} \end{cases} \tag{4}$$

$$\sum_{j} Y_{ij} - \sum_{i} Y_{ij} \leq MX(i) \quad \forall\, i \in N \tag{5}$$

$$\sum_{j} Y_{ij} - \sum_{i} Y_{ij} - 1 \geq M(X(i) - 1) \quad \forall\, i \in N \tag{6}$$

Selected nodes to establish distribution centers and also the net output values (sum of materials transmitted to minus sum of materials received from) of each distribution center are obtained. In this research work, two networks (one in small size and the other in large scale with experimental data) are used to represent results in the following sections

In brief, at the first stage, the best locations for constructing distribution centers are obtained, and at the second stage it is necessary to run the routing model for the second time, from the specified origins to all destinations. Moreover the exact amount of materials shipped from each origin to each destination, is not clearly specified so in the third stage, a transportation model is planning to run. Because, detecting the exact path for each origin-destination pair (O-D pair for short), is not possible, in particular in large size networks, following the proposed three stage procedure, helps decision makers to obtain the route and the exact amount of shipment from each origin to corresponding destinations in combined location-routing problem.

Stage 2: After determining the best locations for constructing distribution centers in the first stage, a routing model should be run from the determined origins to all destinations specified in the previous stage. An origin-destination matrix which also includes the costs of routes is achieved as the result of running this model. As a result of solving this model, the path with lowest value of K(ij) (Refer to section 2-1. is selected for each O-D pair.

Stage 3: As it previously discussed, a transportation model should be run to determine the exact amounts of shipments for each O-D pair. In this model, the sum of transportation costs is minimized considering the capacity and demand constraints. In other words, the amounts of shipments are determined in order to minimize transportation costs. Equations (7) to (9) represent the transportation model.

$$\text{Min } Z = \sum_i \sum_j \left(Y_{ij} \times K_{ij}\right) \quad (7)$$

Subject to:

$$\sum_j Y_{ij} \leq C_i \quad \forall i \quad (8)$$

$$\sum_i Y_{ij} \geq D_j \quad \forall j \quad (9)$$

The above mentioned models following the proposed methodology have been solved and results have been discussed in the next sections.

4. Illustrative Example

To give an estimate on how the proposed methodology is applied in this research work, an illustrative example is discussed at this section. A network consists of 10 nodes and 18 links is supposed. Table 1 shows the amount of demands for demand nodes and construction costs of distribution nodes. To illustrate how to consider parameter T(i), please refer to discussion at section 3-1.

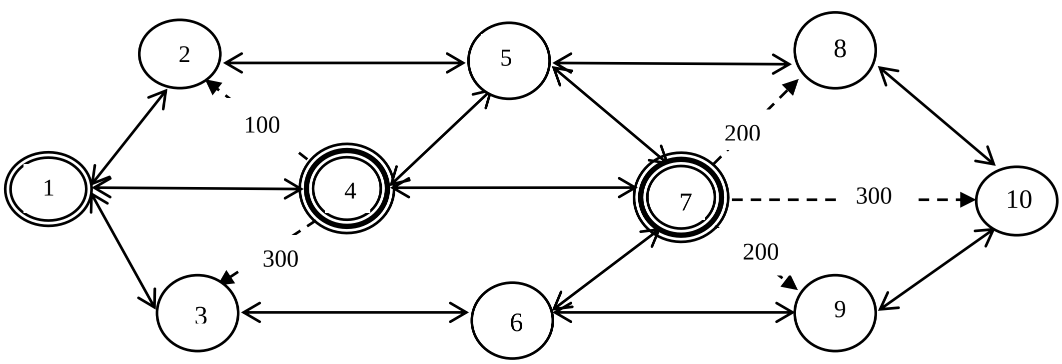

Figure 1- Proposed network

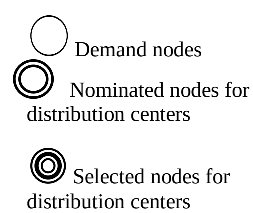

Table 1 – Production capacities and demands

i/j	1	2	3	4	5	6	7	8	9	10
C(i)	700	0	0	700	0	0	700	0	0	0
D(j)	0	100	300	0	0	0	0	200	300	200
T(i)	700	-100	-300	700	0	0	700	-200	-300	-200

Table 2 shows the combination of cost and risk for each O-D pair (total cost of link for short). As it was previously discussed, the first stage is to solve simultaneous location-routing model to determine the best locations for establishing distribution centers and also the net values of output from each selected site. In the illustrative example, locations 4 and 7 (among nodes 1, 4 and 7) are selected as distribution centers and net values of outputs for each of these nodes are also obtained. (O_4=400 and O_7=700)

At the next stage, the routing model is run for the second time, from the selected origins to all reminded destinations. Table 2 shows the combination of cost and risk for each link. Results of this stage are tabulated in table 3. The best path between each distribution center to each corresponding destination and the combination of cost and risk related to each path are also calculated and represented in the above mentioned table.

Table 2- Combinations of Risk and Cost for Network Links

Path number	Origin	Destination	Combination of cost and risk	Path number	Origin	Destination	Combination of cost and risk
1	1	2	0.5	19	5	8	0.9
2	2	1	0.5	20	8	5	0.9
3	1	4	0.6	21	5	7	0.7
4	4	1	0.6	22	7	5	0.7
5	1	3	0.4	23	6	7	0.7
6	3	1	0.4	24	7	6	0.7
7	2	4	0.1	25	7	8	0.4
8	4	2	0.1	26	8	7	0.4
9	3	4	0.2	27	8	10	0.3
10	4	3	0.2	28	10	8	0.3
11	2	5	0.2	29	7	10	0.7
12	5	2	0.2	30	10	7	0.7
13	4	5	0.1	31	7	9	0.5
14	5	4	0.1	32	9	7	0.5
15	4	7	0.6	33	6	9	0.9
16	7	4	0.6	34	9	6	0.9
17	3	6	0.3	35	9	10	0.2
18	6	3	0.3	36	10	9	0.2

Table 3- Selected paths and cost resulting of routing model

Origin	Destination	Path	Cost of path
4	2	4_2	0.1
7	2	7_4_2	0.6+0.1=0.7
4	3	4_3	0.2
7	3	7_4_3	0.6+0.2=0.8
4	8	4_7_8	0.6+0.4=1
7	8	7_8	0.
4	9	4_7_9	0.6+0.5=1.1
7	9	7_9	0.5
4	10	4_7_8_10	0.6+0.4+0.3=1.3
7	10	7_10	0.7

In the third stage, considering the selected distribution centers net values of output for each distribution center and costs of paths are obtained in the previous stage and transportation model is run to determine the exact amounts of materials transported between each O-D pair. Table 4 represents final solution.

Table 4- Amounts of transported material between O-D pairs

i \ j	2	3	8	9	10
4	100	300			
7			200	300	200

2. Case Study and Numerical Analysis

Five provinces in the northwest area of Iran including West-Azerbaijan, East-Azerbaijan, Ardabil, Zanjan and Kurdistan are selected as case study. Figure 2 shows an overall view of the road network corresponding to case study. This network, which is an experimental network, consists of eighty-nine nodes and one hundred and one links.

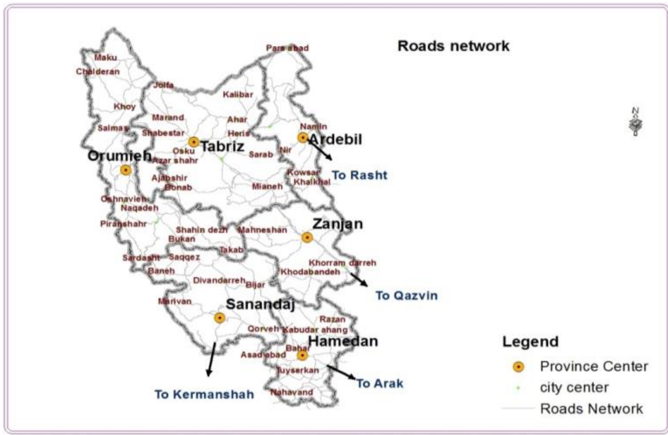

Figure 2- Map of study area

As it discussed in the previous sections, simultaneous locating and routing approach contains three stages. In the first stage, the mathematical model which solves location routing problems is run. In the second stage, routing O-D pairs for selected distribution centers is run followed by the third stage running a common transport model to obtain exact amounts of shipments for O-D pairs. Table 7 shows candidate nodes for constructing distribution centers and costs together with their production capacities of fuels. As the result of running this model, selected nodes for establishing distribution centers and net value of output from each node are obtained and represented in table 8.

Table 7- Nominated nodes, costs and capacities

Nominated nodes	Cost of construction	Capacity	Nominated nodes	Cost of construction	Capacity
Poldasht	20,000	1,000	Oskou	10,000	1,000
TazehShahr	10,000	700	QarehAghaj	10,000	1,500
Shabestar	10,000	900	Malekan	10,000	900
HadiShahr	15,000	1,500	Naghadeh	10,000	700
Khajeh	10,000	1,000	Boukan	10,000	1,000
Kalibar	10,000	800	Takab	10,000	900
Razi	20,000	1,000	DivanDarreh	10,000	1,000
Kuraim	20,000	1,500	Dehgolan	15,000	1,000
BostanAbad	15,000	2,000	ZarrinAbad	10,000	900

Table 8- Selected nodes for distribution centers and their optimum productions

Row	Selected nodes	Output value	Row	Selected nodes	Output value
1	Shabestar	900	7	Malekan	900
2	HadiShahr	1,500	8	Boukan	1,000
3	Khajeh	1,000	9	Takab	900
4	BostanAbad	2,000	10	DivanDareh	1,000
5	Oskou	1,000	11	ZarinAbad	900
6	QarehAghaj	1,100			

The objective function value is calculated as 133,520.84. In second stage routing model is repeated considering the selected origins (distribution centers selected in the previous stage) to all destinations in order to determine the combination of cost and risk for each possible O-D pair. In the third stage, a common transportation model should be solved to determine the exact amount of materials which are required to be transported in each O-D pair. Table (10) shows all destinations for each origin and amount of materials transported to each of them. Optimum amounts of hazardous material shipment are represented in parenthesis next to the name of nodes.

Table 10- Optimum amounts of shipments

Supply Node	Demand nodes (Amount of shipment)
Shabestar	Bazargan(50), Makou(100), Showt(100), Firuraq(100), Khoi(300), Salmas(150), Soufian(100)
HadiShahr	Bazargan(50), Chaldoran(200), NaziOlia(150), QareZia'edin(150), marand(300), Jolfa(100), Aslandouz(100), ParsAbad(50), BilehSavar(100), Jafarabad(100), Germi(200)
Khajeh	Tabriz(100), Varzeqan(150), Ahar(100), Heris(100), Soltanali(150), Aslandouz(100), MeshkinShahr(300),
BostanAbad	Namin(200), Astara(100), Ardebil(800), Sarein(300), Khalkhal(400), Nir(100), Sarab(100)
Oskou	Tabriz(600), KhosroShahr(100), Mamaghan(100), AzarShahr(200)
QarehAghaj	Maragheh(100), Hashtrud(200), Mianeh(300), Khodabandeh(100), Abhar(200), Soltanieh(300)
Malekan	Orumieh(300), Ajabshir(50), Bonab(100), Leilan(100), Miandoab(200), Oshnavieh(50), PiranShahr(100)
Boukan	Orumieh(100), Mahabad(300), Saqez(200), Baneh(300), Sardasht(100)
Takab	Orumieh(500), ShahinDezh(100), bijar(100), Qorveh(100)
DivanDareh	Marivan(200), Sanandaj(700), Kamyaran(100)
ZarinAbad	ZarinAbad(900)

6. Summary and Conclusion

This research work is focused to solve the location-routing problem simultaneously. For this purpose, a three stage procedure is proposed and utilized in a real road network in the Iranian northwest provinces. In addition, an illustrative example has been discussed. Moreover the mentioned approach is applied on a network consisted of eighty-nine nodes and one hundred and one links in northwest of Iran. Results show that decision makers who are dealing with Hazmat transportation would be able to utilize this approach to solve routing-location problem.

While amounts of demands are considered deterministic in this research work, researchers who are interested in studying in this field are recommended to focus on real conditions in which demands might be probabilistic. Types of trucks may have significant impacts on transportation cost, so they are also recommended to consider that as a major attribute.

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Biographies

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