Developing a Bi-level Objective Model of Risk-Cost Trade-off for Solving Locating-Routing Problem in Transportation of Hazardous Material

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Abstract

Allocating and routing problems in the field of transportation engineering are generally solved using the objective function of minimizing transport cost. Transport risk is a main concern in hazardous material transportation, mainly dependent on the vision of decision makers (national and/or local authorities). In this research work, a trade-off approach has been proposed to determine the safest paths and the best locations of distribution centers for carrying the third type of hazardous materials categorized as flammable liquids. Trade-off has been defined between risk and cost, whereas a bi-level objective function has been developed to determine the best routes for hazardous material transportation and also to determine the best locations for establishing the main distribution centers. At the first level, obtaining the best locations for distribution centers are obtained then determining the safest paths of origin-destination is developed at the second level. Experimental data in the second largest Iranian province of Fars which consists of fifty-nine nodes and eighty edges has been used for applying analytical process. Results show that decision makers should be aware in the process of allocating and routing problems as well as influencing attributes before to make decisions, because the priorities of risk and time and the number of distribution centers play significant roles in routing and allocating hazardous materials.

Keywords: Hazardous materials transportation, location-routing problem, risk-cost trade-off, Risk analysis

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1. Introduction

1.1 Hazmat Routing Problem

Hazardous materials (Hazmat for short) are classified into nine classes of explosives, gases, flammable liquids, flammable solids, oxidizing substances, toxic substances, radioactive materials, corrosive substances, and miscellaneous dangerous goods [Environmental Health & Safety, 2011]. Transportation of hazardous materials covers a large part of economic activities in industrialized countries [Zografos and Androutsopoulos, 2004], therefore management of hazardous material is an extremely complex issue involving a multitude of environmental, engineering, economic, social and political concerns [Dıaz-Banez et al. 2005]. One of the most important issues in management of hazardous material is finding the best path for transportation. Determining the route for carrying hazardous materials, known as Hazmat Routing Problem, is usually a double-sided consideration problem, in which the local authorities are interested in minimizing public risk and carriers are concerned about minimizing transport cost [Erkuta and Alpb, 2007]. Therefore, the combination of risk and cost is usually observed in mathematical models to find the best path. Obviously, the best path outlined using the above consideration is not necessarily as the shortest path. Different combination of risk and cost leads researchers to use different methods of problem solving [Bonvicini and Spadoni, 2008] and [Shariat and Khodadadian, 2008].

1.2 Location Allocation Problem

Location allocation problem, firstly proposed in 1963 by Cooper [Cooper, 1963], is a well-known problem in the field of industrial engineering. The problem is to locate a set of new facilities such that the transportation cost from facilities to customers is minimized [Zhou and Liu, 2003]. The main concept is to find the best locations in terms of effective attributes defined by decision makers. Identification of effective attributes as well as developing mathematical models or proposing proper methodologies are often observed as the main points in the literature, accordingly. Capacitated and interval parameters [Shavandi, 2009] and [Escobar et al. 2013], stochastic parameters [Zhou and Liu, 2003], zone definition [Fotheringham et al. 1995], or congesting situations within stochastic queuing frameworks [Ghambari et al., 2011] are considered as effective attributes in the problem formulation. Uncertainty is also observed in the process of modeling developed for location allocation problems. Probabilistic variables are also utilized in developing location problems mainly solved by heuristic methods [Amiri-Aref et al. 2013]. Using fuzzy variables [Mousavi and Akhavan Niaki, 2013], defining fuzzy demands under the Hurwicz criterion [Wen and Iwamura, 2008], and random fuzzy demands [Wen and Kang, 2011] are studied in this field and observed in the literature.

1.3 Locating-Routing Problem

If routing and location allocation problems are combined, a locating routing problem should be formulated. The locating-routing problem (LRP) includes two types of fundamental problems of supply chain management and vehicle routing problem. In supply chain management, the location of facilities are obtained, and in the vehicle routing problem, the best path for carrying materials are outlined [Escobar et al. 2013]. In general, it is explained that the location problem is a strategic decision which is made for a long time frame, while the routing problem is an operational aspect which can be considered in a short time frame. The locating depots for materials or freights are strongly influenced by transport cost [Rand, 1976]. On the contrary, the term of locating-routing problem is used for introducing a problem in which location and routing are both considered simultaneously to minimize cost in logistic systems [Jarboui, et al., 2013]. It has been recently developed considering cross-docking concept and new solution techniques such as hybrid simulated annealing [Mousavi and Tavakkoli-Moghaddam, 2013]. In addition, more attributes have been considered to satisfy decision makers in order to define locating-routing problem under dynamic vision [Gebennini, et al. 2009] in which the locations of facilities are dynamically changed based on production flow and environmental concerns.

1.4 Vision

Following the above mentioned issues, in addition to finding routes for transportation of hazardous material where a trade-off between effective attributes play significant role, locating the best places for establishing distribution centers should also been highlighted in hazmat transportation. Therefore, the main concern of decision makers in hazmat transportation may lie on finding specific routes and locating distribution centers, simultaneously. This concern is leading to be more serious when a huge portion of goods categorized as hazmat are carried annually in I.R Iran. Therefore, the vision followed in this paper is to achieve a solution in which a combination of risk and cost should be minimized while finding the routes and locating distribution centers are simultaneously considered in defining the problem. The first and main consideration or focal point of this research work lies in answering the question that whether the locations of distribution centers for hazmat are affected by the strategies imposed by national/local authorities in terms of considering risk and cost of hazmat transportation or not. To achieve this aim, a bi-level objective function is required and mathematical model should be developed in two levels. The first level is regarding the minimizing of the total amount of transportation cost and risk over the network, while the second level is corresponded to minimizing of the above criterion for finding the best path for each origin-destination pair. The second consideration of this research work is to apply a way to solve a bi-level objective function, therefore a two-stage procedure has been introduced to solve a bi-level objective function which is solved by several methods, observed in the literature [Bianco, 2009].

2. Problem Definition

Fuel, the third type of hazardous materials recognized as flammable liquids, is one of the most important substances which is carried to fulfill the purposes of home-warming, industries, private cars and agricultural activities. The usual way of transportation is to carry fuels from refineries to the main distribution centers through pipelines, then carry them from distribution centers to demand points by trucks. According to whatever is mentioned in our introduction, the main concern of local or national authorities is to determine suitable paths in terms of risk and cost for transportation of hazardous material. In the case of pre-defined points of demands, which are identified according to population and geographical characteristics of inhabited points, location of distribution centers should be determined to minimize the transport risk and cost, simultaneously. On the other hand, decision makers have different viewpoints on priorities of transport risk and cost. Transportation risk of hazardous materials is mainly associated with accidents in road networks as well as the population inhabited near the roads. It also includes the environmental concerns, represents effects on natural resources such as rivers, lakes, trees, …, and heavy damages to vital infrastructures of tunnels and bridges [Mahmoudabadi and Seyedhosseini, 2013].

Following the above mentioned issues, the main question is “which points should be selected as distribution centers for hazardous material to the pre-defined demands points while risk and cost are minimized simultaneously”? In this case, the main distribution centers will be located regarding to combined priorities of risk and cost which are dictated by national or local authorities. Decision makers are able to check a wide range of priorities and sensitivity analysis utilizing the proposed methodology to ensure making a proper decision in terms of locating distribution centers and routing for transportation of hazardous material.

3. Defining Methodology

According to the problem definition, the proposed methodology is a two-stage procedure based on the developing mathematical model for routing and allocating risk-cost trade-off approach. At the first level of objective function in mathematical model, the total combination of risk and cost should be minimized, while in the second level, the best path for each origin-destination pairs is determined regarding to risk and cost priorities imposed by decision makers. In other words, the best locations for distribution centers are identified in the first level and the safest routes are identified for hazmat transportation at the second level. The procedure is being run until the whole different priorities of risk and cost checked. As figure 1 including the below steps shows the overall view of proposed procedure, it is, considering that origin-destination pairs is substituted by (O-D pairs) to use

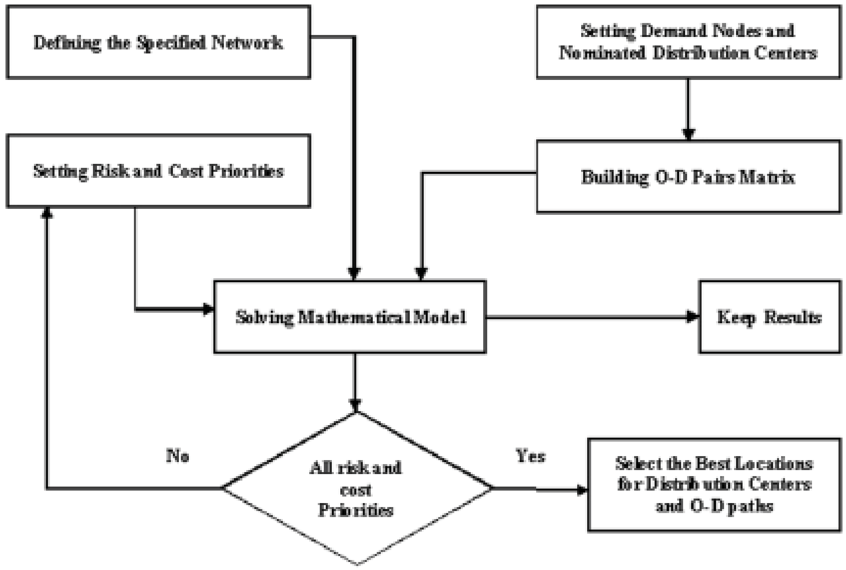

Figure 1. An overall view of developed methodology for routing and locating problem in hazmat transportation

short sentences :

1- Defining the specified network, nodes, edges and their attributes.

2- Setting demand nodes and nominated distribution centers to build the matrix of O-D pairs.

3- Setting risk and cost priorities imposed by national or local authorities.

4- Solving the proposed mathematical model to determine risk-cost combination factors of the best path for O-D pairs and to determine the locations of distribution centers.

5- Keep results regarding to the total combination of risk and cost for each priority set.

6- If all amounts of priorities for risk and cost are checked go to step 7, otherwise go back to step 3.

7- Analyze results and select the best locations for establishing distribution centers.

4. Developing Mathematical Model

Assume that the road network is defined by graph G (n, e) including pre-defined nodes and edges. Nodes are categorized into three main sets corresponding to demand nodes, origin nodes nominated as distribution centers, and connecting nodes. Demand and distribution centers are known as connecting nodes and distribution centers may be known as demand nodes but not vice versa. Following the concept defined in the previous section, mathematical model should be able to minimize the total combination of risk and cost over the network. It would be obtained by determining the best path in terms of combined risk and cost priorities followed by determining the amount of hazmat should be carried from each distribution center to demand points (destinations). Therefore, a bi-level objective function is required to satisfy the above mentioned purposes.

The first level of model objective function is to minimize the total prioritized combination of risk and cost for hazmat transportation. It is calculated by sum product risk-cost combination and the amount of hazmat transported from all origins to predefined destinations. According to the above mentioned, objective function at the first level is defined by equation (1).

$$Min\ Z_1 = \sum_{OD} CR_{od} \times Q_{od} \qquad (1)$$

Where:

CRod is the best combination factor of risk and cost obtained by running the second objective function will be discussed later. Qod is the amount of hazmat thath should be transported from origin node “o” to destination node “d”, which are represented by origin set “O”, and destination set “D”, respectively.

Satisfying demands and supplies can be formulated as constraints in the first level of mathematical model.

Equations (2) and (3) define constraints to meet supplies and demands corresponding to origin nodes and destinations, respectively.

$$\sum_{D} Q_{od} \leq U_o \quad \forall o \in O \tag{2}$$

$$\sum_{O} Q_{od} \geq F_D \quad \forall d \in D \tag{3}$$

U_o is the upper bound of hazmat which can be satisfied by origin "o", and Fd is the required amount of hazmat should be transported to destination "d". The other constraint of the first level is the number of stations mainly restricted by budget limitation, defined by equation (4). It should be mentioned that the upper bound for supply is calculated based on the number of stations because demand of destinations should be met.

$$\sum_{O} Y_o \leq n(Number\ of\ stations) \tag{4}$$

where:

Y_o is assigned by 1 if distribution center is established in origin "o", otherwise it is assigned by 0. Because Y_o is a binary variable depends on the amount of hazmat transported from "o", two equations (5) and (6) are necessary to formulate the binary variable Y_o. The well-known technique of big M is utilized to apply this approach. It is obvious that, fixing distribution centers would be possible, if variable Y_o is pre-assigned 1 by decision makers.

$$MY_O \geq \sum_{D} Q_{od} \ \forall o \in O \tag{5}$$

$$M(Y_o\text{-}1) < \sum_{D} Q_{od} \ \forall o \in O \tag{6}$$

As mentioned before, CRod is the best combination of risk and cost obtained by determining the safest path between origin node "o" and destination node "d" while the total combination of risk and cost for selected path is considered as criterion. Therefore, the second level of objective function should be developed to find the best path in which the combination of risk and cost will be minimized simultaneously. In this case, the second level of objective function is defined by equation (7).

$$CR_{od} = Min\ Z_2 = \sum_{G} [P_r \times R_{ij} + P_C \times C_{ij}] \times X_{ij} \tag{7}$$

P_r and P_c are the priorities of risk and cost, respectively. R_{ij} is the uniformed risk for edge (i, j) and C_{ij} is uniformed transportation cost for edge (i, j). X_{ij} is a binary variable which will be set as 1 if edge (i, j) is located in determined path, otherwise it will be assigned by 0. The uniformed amount of variables corresponding to risk and cost are used due to the existing different dimensions for risk and cost [Seyedhosseini and Mahmoudabadi, 2012] and they are converted into close interval [0 1]. In order to keep continuous path, equation (8) is inserted in the model [Erkuta and Alpb, 2007].

$$\sum_{G} X_{ij} - \sum_{G} X_{ji} = \begin{cases} -1 & if\ j=origin \\ 1 & if\ j=destination \\ 0 & otherwise \end{cases} \tag{8}$$

In inter-city transportation mode, two-way edges are usually available, so equation (9) is inserted in mathematical model to provide the above characteristics.

$$(i,j),(j,i) \in G \tag{9}$$

To summarize the above descriptions, mathematical model is formulated as follow:

First Level of Objective Function

$$Min\ Z_1 = \sum_{OD} CR_{od} \times Q_{od} \tag{10}$$

$$S.T. \quad \sum_{D} Q_{od} \leq U_o \quad \forall o \in O \tag{11}$$

$$\sum_{O} Q_{od} \geq F_D \quad \forall d \in D \tag{12}$$

$$\sum_{O} Y_o \leq n\ (Number\ of\ stations) \tag{13}$$

$$MY_o \geq \sum Q_{od} \ \forall o \in O \tag{14}$$

$$M(Y_o\text{-}1) < \sum_{D} Q_{od} \ \forall o \in O \tag{15}$$

Second Level of Objective Function

$$CR_{od} = Min\ Z_2 \sum_{G} [P_r \times R_{ij} + P_c \times C_{ij}] \times X_{ij} = \tag{16}$$

$$S.T. \sum_{G} X_{ij} - \sum_{G} X_{ji} = \begin{cases} -1 & if\ j = origin \\ 1 & if\ j = destination \\ 0 & otherwise \end{cases} \tag{17}$$

$$(i,j),(j,i) \in G \tag{18}$$

$$CR_{od}, Q_{od} \geq 0, \quad X_{ij}, Y_o \quad Binary\ variables \tag{19}$$

5. Case Study

Fars, the second largest province in Iran, is selected as case study. Figure 2 shows an overall view of Fars road network. It consists of 59 main nodes and 80 two-way edges. Some of nodes are border nodes, which connect research area to other provinces [Mahmoudabadi and Seyedhosseini, 2013].

It is also assumed that fuels, carried from refineries to distribution centers, are not within the scope of this research work, but transporting fuels from distribution centers to destinations should be determined. Therefore, some of nominated points will be determined as distribution centers utilizing the proposed model. For each link, risk has been calculated based on four components of accident, environment, population and infrastructure issues [Mahmoudabadi and Seyedhosseini, 2013]. Cost is corresponding to length and travel time obtained by conducting a library study using geographical maps.

6. Running Model and Discussion

6.1 Details on Problem Definition

A number of sets of origins and destinations have been selected to solve the proposed model. Distribution centers will be constructed by three different capacities. The sum of demands and supplies should not necessarily be equal, but demands must be fully satisfied. It is also assumed that transporting hazmat from an origin node to itself is not considered as inter-city transportation, so combination of cost and risk will be set as 0 when a destination node is a distribution center. According to the case study, 12 nodes are identified as destination nodes, shown in table (1), whose names are explained in appendix I. In addition, there are eight origin nodes nominated as distribution centers. Some of them are destination nodes shown in table 1. Upper bounds for origin capacities depend on the number of distribution centers may be set as 3000, 2000 and 1500 thousands M3 per year.

6.2 Scenarios

According to the problem definition and proposed mathematical model, two factors have significant influences on solving problem and consequent results. The first is the priority of risk and cost and the second is the limitation of the number of distribution centers. Assuming three different sets of risk and cost priorities together with three different distribution centers nine scenarios would be made and shown in table 2. Due to establishing some pre-defined centers, upper bounds for their capacities are also set in the last row of table 2.

Figure 2. Road Network Map in Fars Province

Table 1. List of destination nodes (Dimension = Thousands M^3 per year)

Number	1	2	3	4	5	6	7	8	9	10	11	12
Destination Nodes	{2}	{11}	{13}	{15}	{17}	{23}	{32}	{35}	{40}	{42}	{45}	{56}
Demand	300	500	950	500	550	400	300	350	400	450	500	450
Origin Nodes	{3}	{13}	{14}	{26}	{35}	{38}	{49}	{55}				
Capacity	3000, 2000, 1500(Depends on the number of distribution centers)											

Table 2. Proposed scenarios in terms of distribution centers and (risk, cost) priorities

(Risk, Cost) priorities	Number of distribution Centers		
	2	3	4
(0.3, 0.7)	A1	A2	A3
(0.5, 0.5)	B1	B2	B3
(0.7, 0.3)	C1	C2	C3
Upper Bound	3000	2000	1500

Table 3. Amounts of hazmat from selected distribution centers for (risk, cost) priorities (0.3, 0.7)

Scenario	D.C.	Destination nodes													Z_1
		{2}	{11}	{13}	{15}	{17}	{23}	{32}	{35}	{40}	{42}	{45}	{56}	Sum	
A1	{13}	300	500	950	500							300	450	3000	4351
	{38}					550	400	300	350	400	450	200		2650	
A2	{13}	250		950								350	450	2000	3856
	{14 }	50	500		500	550	400							2000	
	{38}							300	350	400	450	150		1650	
A3	{13}		50	950								500		1500	3414
	{14}		50		500	550	400							1500	
	{38}							300	350	400	450			1500	
	{55}	300	400										450	1150	

Table 4. Amounts of hazmat from selected distribution centers for (risk, cost) priorities (0.5, 0.5)

Scenario	D.C.	Destination nodes													Z_1
		{2}	{11}	{13}	{15}	{17}	{23}	{32}	{35}	{40}	{42}	{45}	{56}	Sum	
B1	{13}	300	500	950	500		300						450	3000	5089
	{38}					550	100	300	350	400	450	500		2650	
B2	{13}			950	500	50						500		2000	4422
	{38}					500		300	350	400	450			2000	
	{55}	300	500				400						450	1650	
B3	{13}		50	950								500		1500	3822
	{ 14}		50		500	550	400							1500	
	{38}							300	350	400	450			1500	
	{55}	300	400										450	1150	

Table 5. Amounts of hazmat from selected distribution centers for (risk, cost) priorities (0.7, 0.3)

Scenario	D.C.	Destination nodes													Z_1
		{2}	{11}	{13}	{15}	{17}	{23}	{32}	{35}	{40}	{42}	{45}	{56}	Sum	
C1	{13}	300	500	950	500							300	450	3000	5792
	{38}					550	400	300	350	400	450	200		2650	
C2	{13}			950	500	50						500		2000	4863
	{38}					500		300	350	400	450			2000	
	{55}	300	500				400						450	1650	
C3	{13}		50	950								500		1500	4218
	{14}				500	550	400							1450	
	{38}							300	350	400	450			1500	
	{55}	300	450										450	1200	

6.3 Numerical Results

The proposed mathematical model has been performed using nine different scenarios, discussed in the previous section. Results have been tabulated in tables 3 to 5. The results are categorized in to three tables regarding to different priorities of risk and cost including (0.3, 0.7), (0.5, 0.5) and (0.7, 0.3). For each table, origin and destination nodes presented in bracket i.e. symbol {2} shows the node number 2 referred to appendix I. Three scenarios in each table are different based on the number of distribution centers imposed by budget limitation or decision makers. The second column shows the nodes selected for establishing distribution centers. The amount of hazardous material should be carried from distribution centers to destination points are identified in the above tables. For example in scenario A1 (table 3), 500 thousands M3 are annually required to transport from distribution center 13 to destination node 11. Total combination of risk and cost which has been used as criterion in the first level of mathematical model, identified as Z1, is also presented in the last columns of tables.

The numerical analysis shows that there is no limitation for solving the proposed mathematical model using the network selected as the case study, if the number of nodes getting to be raised, the existing binary variable model may be a NP Hard problem. The above consideration should be checked using another (large) network, but there was no network available to do that.

6.4 Discussion

In order to give a good estimate, results shown in tables 3-5 have been summarized and shown in table 6. Results revealed that risk and cost priorities have significant effects on selecting origin nodes as distribution centers. For example, if risk and cost priorities considered by (0.3, 0.7) and the number of distribution centers set by 3, the selected nodes for establishing distribution centers will be {13}, {14} and {38}, but if the risk and cost priorities defined by (0.7, 0.3), the selected points will be obtained as {13}, {38}, {55}. The total combination of risk and cost (the obtained value corresponding to the first level of objective function, Z1) is getting to be decreased when the number of distribution centers moves forward to rise. It means that the investment value for the initial progress should be considered carefully according to economic engineering. Therefore, decision makers should be aware not only the risk and cost priorities but also the number of distribution centers is main criterion in routing and allocating approach for hazardous material transportation. It is very important for decision makers to be aware that a trade-off between total cost of transportation and establishing distribution centers should be considered as a main concern in hazmat transportation. Based on the above issues, it can be concluded that, in the real world, when some concerns such as green transportation may impose limitation or constraint for developing industrial aspects, decision makers should be careful to look at all the aspects influencing on transportation and in this case, hazardous material transportation and locating related industries.

7. Summary and Conclusion

In general, hazmat routing problems are solved regarding to minimizing the risk and cost for specified origins and destinations. It might be a good idea if decision makers locate sources of hazmat, mainly distribution centers, based on minimizing the above factors, simultaneously. In this paper a mathematical model considering risk and cost minimization has been developed, where the total combination of risk and cost is minimized. For this aim, a bi-level objective function in a mathematical model has been developed. At the first level, the amount of hazmat should be carried to destination nodes minimizing the total combination of risk and cost, while risk and cost are prioritized by national or local authorities. Following that the locations for installing distribution centers are obtained. At the second level, the best route for each origin destination pair is outlined to be used in the first level. A two-stage process has also been applied to solve a bi-level objective function model where in the first stage safest paths are obtained and in the second stage the best locations for establishing distribution centers are selected. Fars Province, the second largest province of Iran, has been selected as the case study in this research and experimental results are discussed. Having developed the model, decision makers are able to run model using different priorities of risk and

Table 6. Summarized results for risk-cost routing and allocating model

(Risk, Cost) Priorities	(0.3, 0.7)			(0.5, 0.5)			(0.7, 0.3)		
Number of distribution centers	2	3	4	2	3	4	2	3	4
Selected nodes as distribution	{13}, {38}	{13}, {14}, {38}	{13}, {14}, {38}, {55}	{13}, {38}	{13}, {38}, {55}	{13}, {14}, {38}, {55}	{13}, {38}	{13}, {38}, {55}	{13}, {14}, {38}, {55}
Total combination of risk and cost	4351	3856	3414	5089	4422	3822	5792	4863	4218

cost while there is an ability to set some distribution centers as fixed ones. Results have been discussed and it is concluded that the priorities of risk and cost have significant effects on locating distribution centers. Results also revealed that the number of distribution centers play a significant role on total combination of risk and cost which would be a main concern for those who are dealing with investment and budgeting in real projects.

For further studies, researchers interested in this topic are recommended to focus on the other kinds of hazmat which have influences on routing problems. In addition, considering more real constraints such as installing budget, other transport modes for carrying hazmat from refinery to distribution centers are also recommended for future studies.

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Appendix I: List of nodes and their names corresponding to case study

Code	Name	12	Soltanaabad	24	To Sirjan	36	Chah eyni	48	Konartakhteh
1	Izadkhast	13	Shiraz	25	Ich	37	Khonj	49	Qaemiyeh
2	Abadeh	14	Polefasa	26	Darab	38	Qirokarzin	50	Norabad
3	Sormagh	15	Estahban	27	Dolatabad	39	Simakan	51	Serahi*
4	Safashahr	16	Dorahi **	28	Khosvaieh	40	Jahrom	52	Mosiri
5	Bovanat	17	Fasa	29	Hajiabad	41	Qotbabad	53	Koshk
6	Sarvestan	18	Sahrarood	30	Dorahi Lar Jahrom	42	Firuzabad	54	Asias
7	Saadatshahr	19	Fadshokoieh	31	Mansourabad	43	Esmaeilabad	55	Eqlid
8	Arsanjan	20	Chaliyan	32	Lar	44	Fathabad	56	Sepidan
9	Naghsherostam	21	Dindarlo	33	To Bandarabbas	45	Kazerun	57	To Yasooj
10	Jamalaabad	22	Ghaleh ab barik	34	Evaz	46	Dashteharzhan	58	Forg
11	Marvdasht	23	Neyriz	35	Lamerd	47	Bazernegan	59	Dehno

*: Serahi-Norabad-Sepidan-Shiraz **: Dorahi-Estahban-Fasa