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Cuckoo Optimization Algorithm for a Reliable Location-Allocation of Hubs among the Clients

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KEYWORDS

Hub location,
Allocation,
Reliable Path,
Fully Interconnection,
COA.

ABSTRACT

Hubs are critical elements of transportation networks. Location of hubs and allocation of demands to them are of high importance in the network design. The most important purpose of these models is to minimize the cost, but path reliability is also another important factor which can influence the location of hubs. In this paper, we propose a P-center hub location model with full interconnection among hubs, while there are different paths between origins and destinations. The purpose of the model is to determine the reliable path with lower cost. Unlike the prior studies, the number of hubs in the path is not limited to two hubs. This paper presents a bi-objective model which includes cost and reliability to determine the best locations for hubs, the finest allocation of the demands to hubs, and the most efficient path. In order to illustrate the proposed model, a numerical example is presented and solved using the Cuckoo Optimization Algorithm.

1. Introduction

Public transportation is a very challenging problem in many developed and developing countries. In addition, hubs are critical elements of telecommunication and transportation networks because they play an important role in controlling the traffic. Hubs are special facilities in many-to-many distribution systems, and they are used to connect the origins and destinations in a network. Therefore, instead of connecting each pair of origin-destinations directly, hubs are located between them to consolidate, route, and distribute the traffic in order to take advantage of economies of scale on inter-hub connections. Hub location problems arise in most of the network design problems. The hub location problem is concerned with locating hub facilities and allocating demand nodes to hubs in order to route the traffic between origin-destination pairs. This area is rich and includes many models most of which are aimed to minimize the costs and just differ in their constraints. Capacity constraints, service level constraints, delivery time, single or multiple allocation, etc. are the main constraints in the models. However, the importance of considering the reliability of the networks is often neglected and few papers discuss it. In hub and spoke networks, any malfunction at the path may cause degradation of the whole network's ability to transfer flows; moreover, due to the fact that the current networks are quite vulnerable, designing more reliable networks in hub-and-spoke systems is a critical issue.

Campbell [1] classified hub location problems according to the optimization criteria: (i) minimization of the total transportation cost in the p-hub median problem (which is the original

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model proposed in [2]); (ii) minimization of the total transportation cost and the fixed cost of establishing hubs (un-capacitated/capacitated hub location problem); (iii) minimization of the maximum transportation cost (p-hub center problem); (iv) minimization of the number of hubs while serving each pair within a predetermined bound (hub covering problem).

Alumur, Nickel [3] introduced a multimodal hub location and network design with different possible transportation modes. They jointly considered transportation costs and travel times which are studied separately in different hub location problems. They also considered different service levels for different types of customers. Contreras, Fernández [4] presented a model for hub location problem, where the hubs are connected by means of a tree. The model combines several aspects of location, network design, and routing problems.

Oktal and Ozger [5] developed the traditional model of un-capacitated multiple allocation hub location problem. The new constraints are considering the value and components of cost including direct operating cost, total operating cost, fixed and variable costs for aircrafts. Alumur and Kara [6] reviewed the network hub location problems. Since hubs are special facilities that serve as switching, transshipment and sorting points in many-to-many distribution systems, they classified and surveyed network hub location models. They categorized the hub location models as follows: p-hub median problem, hub location problem with fixed cost, p-hub center problem, and hub covering problem.

Kim and O'Kelly [7] discussed reliable p-hub location problems in telecommunication networks. They presented a new hub location problem which focuses on maximizing network performance in terms of reliability by locating hubs for delivering flows among city nodes. Zhou and Liu [8] formulated a capacitated location-allocation problem with stochastic demands expected value model, chance-constrained programming, and dependent-chance programming according to different criteria. Their objective is to minimize the transportation cost. Melkote and Daskin [9] combined facility location/network design problem. In this model, the capacity of facilities is limited to the amount of demand they can serve. Klose and Drexl [10] designed a distribution network which is a strategic issue. In this model, they developed continuous location models and network location models. Daskin, Snyder [11] presented facility location decisions in a supply chain design. They reviewed classical models including the traditional fixed charge facility location problem and the context of facility location decisions to incorporate additional features of a supply chain.

Bashiri, Mirzaei [12] discussed the qualitative parameters which have critical roles to locate the hubs in the best places. They considered parameters, such as quality of service, zone traffic, environmental issues, and capability for development, in the future, in addition to cost and time. Alumur, Yaman [13] proposed a hierarchical multimodal hub location problem in which two types of hubs and hub links are to be established. In this model, they considered the timer-definite deliveries. de Camargo, de Miranda [14] worked on the MMHLRP and combined two models: the vehicle routing problem and the single-hub location problem to develop a new formulation for the problem of freight industry in a parcel delivery network design. In this problem, several facilities are responsible for assembling flows from origins, re-routing, disassembling, and delivering them to the final destinations. Gelareh and Nickel [15] presented a MIP hub location model for public transport. In their model, several levels of decisions are made simultaneously: (1) locating hub nodes; (2) choosing the connecting hub edges to have a connected hub-level graph; (3) routing the flows through the cheapest paths.

Razmi, Zahedi-Anaraki [16] proposed a model for reliable warehouse network design. They presented a bi-objective stochastic mixed-integer linear programing model to minimize average costs of production, transportation, relocation, and capacity extension and to maximize the coverage percent of customer demand delivered within preferred delivery lead time. Eghbali, Abedzadeh [17] proposed a multi-objective model which consists of cost minimization and minimization of the total number of intermediate links (between all origins and destinations). Although they considered a constraint which assured that the reliability of a route is not less than a specified value. A mathematical model for the dynamic single allocation hub covering problem was proposed by Zare Mehrjerdi and Hosseininasab [18], which considered the covering radius of hub nodes as one of the decision variables in order to save the costs of establishing additional hub nodes. Davari, Zarandi [19] presented an HLP which aims to maximize the reliability of the routes. They considered the reliability of each arc in the network of hub-and-spoke as fuzzy variables.

Kim [20] discussed a model to design a reliable and survivable hub network. Kim [19] considered the substantial aspects of the current network systems such as locations demanding service, their interactions, the role of hubs, and inter-hub links. Karimi, Eydi [21] presented a model for the capacitated single allocation hub location problem with a hierarchical approch. Mohammadi, Tavakkoli-Moghaddam [22] presented a mixed-integer programming model and two improved meta-heuristic algorithms to solve a capacitated single allocation hub covering location problem. Ghodratnama, Tavakkoli-Moghaddam [23] compared three proposed meta-heuristics to solve a new p-hub location-allocation problem. Yahyaei, Bashiri [24] used multi-criteria decision making methods under criteria weights uncertainty to solve logistic hub location. Tavakkoli-Moghaddam, Gholipour-Kanani [25] proposed a multi-objective imperialist competitive algorithm for solving the capacitated single-allocation hub location problem. Zarei, Mahdavi [26] presented the multi-level capacity approach to specify the appropriate link types to be installed on the network edges leading to deteminination of the correct optimum hub location and spoke allocation. Tavakkoli-Moghaddam, Baboli [27] proposed a new robust mathematical model for a p-hub covering problem, which coped with the intrinsic uncertainty of some parameters.

Cuckoo search (CS) is an optimization algorithm developed by Yang and Deb [28]. A multi-objective cuckoo search (MOCS) method was formulated to deal with multi-criteria optimization problems. This approach uses random weights to combine multiple objectives to become a single objective. As the weights vary randomly, Pareto fronts can be found, so the points can be distributed diversely over the fronts.

The significant shortcoming of the papers in this scope is that the researchers consider one or two hubs between the origins and destinations, while there may be more than two hubs in the path. The situation arises when the cost of using three hubs in a path is less than using two hubs, such as the non-Euclidean TSP. Therefore, in this paper, we propose a *P*-center hub location model with full interconnection among hubs, and there are different paths between origins and destinations. In this model, we consider the cost to be minimized and the reliability to be maximized. The model finds the best path for flows between origins and destinations.

The remainder of the paper is organized as follows. We would have the notations and assumptions of the model in Section 2. The main body and formulation of the problem is presented in Section 3. Section 4 discusses a short description of COA. Numerical example is discussed in Section 5 to illustrate the model. Finally, Section 6 concludes the paper and presents the potential area for further studies.

2. Notations and Assumptions

This section introduces the notations and formulations of our model. Here, we state decision variables, input parameters, and assumptions underlying our models.

2-1. Input parameters and decision variables

In this paper, we introduce two different sets of potential hubs. One of them is a subset of demand nodes potential for constituting a hub. The other one is a subset of non-demand nodes. Therefore, we define the following sets:

N: Set of Clients; This set includes all of the customers in the problem.

N_P: Set of potential hub locations within demand nodes ($N_P \subseteq N$)

N'_P: Set of potential hub locations within non-demand nodes ($N'_P \cap N = \emptyset$)

In this model, we consider different costs, including fixed cost of establishing hubs, cost of allocating the customers to the hubs, and cost of transportation. The notations of different costs are as follows:

$\tilde{C}_i$: Fixed cost of installing hub at node $i \in N_P$

$\check{C}_i$: Fixed cost of installing hub at node $i \in N'_P$

$\underline{C}_{ij}$: The cost of allocating node i to hub j.

C_{kla}: Unit cost of transportation among clients k and l via path a

Each demand node has a flow to another node and the amount of this flow is an input parameter.

w_{kl}: Demand flow between nodes k and l

The capacity of each hub is distinctive and the amount of demand cannot be more than this capacity.

cap_i: Capacity of hub i

Since a P-center hub location problem is supposed, it is necessary to locate P hubs in the network and allocate the customers to these hubs.

P: Number of hubs

In this model, there are different paths between origins and destinations, and also each path has different reliability as follows:

R_{kla}: Reliability of path *a* among client *k* and *l*
We consider that it is possible to have more than one hub in a path between two demand nodes.
F_{kla}: Set of hubs in path *a* between clients *k* and *l*
In addition, the decision variables are defined as follows.

$$x_{kla} = \begin{cases} 1 & \text{if path } a \text{ is selected between nodes } k \text{ and } l \\ 0 & \text{otherwise} \end{cases}$$

$$y_i = \begin{cases} 1 & \text{if node } i \text{ is selected as a hub} \\ 0 & \text{otherwise} \end{cases}$$

$$z_{ij} = \begin{cases} 1 & \text{if node } j \text{ is assigned to hub } i \\ 0 & \text{otherwise} \end{cases}$$

2-2. Assumptions

The proposed model in this paper is based on the following assumptions:

1. There are P hubs to be located.
2. Each client is just allocated to one hub (single allocation).
3. The hubs are fully interconnected.
4. There are different paths between two clients based on the number of hubs in the determined path. The total number of paths is as follows:

$$TNP = \binom{|N_p| + |N'_p|}{P} \sum_{i=1}^{P} i! \quad (1)$$

and then, we would have: $a = \{1, 2, \ldots, TNP\}$.

5. The number of hubs in each path is less than the total number of hubs.

$$F_{kla} = \{j \mid j \in a, \text{and it is a hub between nodes } k \text{ and } l\}, \quad (2)$$

where $|F_{kla}| < P$.

3. The Proposed Model

There are many papers, including hub location-allocation models. The main shortcoming of these models is that they determine a specific number of hubs in each path, and they just consider the cost, but as in reality, maximizing the reliability of the path is as important as minimizing the cost of establishing hubs and the cost of transportation between two clients.
Here, we have a bi-objective function which consists of minimizing the cost and maximizing the reliability.

$$Min\ OB1 = \sum_{i \in N_p} \tilde{C}_i y_i + \sum_{i \in N'_p} \breve{C}_i y_i + \sum_i \sum_j \underline{C}_{ij} z_{ij} + \sum_k \sum_l \sum_a C_{kla} w \quad (3)$$

$$Max\ OB2 = \sum_k \sum_l \sum_a R_{kla} x_{kla} \quad (4)$$

$$\sum_{i \in N_p \cup N'_p} y_i = P \quad (5)$$

$$\sum_{i \in N_p \cup N'_p} z_{ij} = 1, \ \forall j \in N \quad (6)$$

$$z_{ij} - y_i \le 0, \ \forall i \in N_p \cup N'_p, \ \forall j \in N \quad (7)$$

$$x_{kla} - y_i \le 0, \ \forall i \in F_{kla} \quad (8)$$

$$x_{kla} - \sum_{k \in N - N_p \cup N'_p} z_{ik} \le 0, \ \forall i \in F_{kla} \quad (9)$$

$$w_{kl} x_{kla} \le cap_i, \ \forall i \in F_{kla} \quad (10)$$

$$x_{kla}, y_i, z_{ij} \in \{0,1\} \quad (11)$$

The first objective function minimizes the cost of installing hubs in demand nodes and non-demand nodes, the cost of allocating a node to a hub, and the cost of flow between origin and destination. The second one maximizes the reliability of the path, which is selected to transport the flows. Constraint (1) shows the number of hubs in the model. We have a single allocation in this model, i.e., each demand node should be allocated to only one hub. This concept is shown by constraint (2). Constraints (3) allow a node to be allocated to a hub only if that hub is installed. Constraints (4) guarantee that the path between *k* and *l* includes hub *i* if that hub is established. Constraints (5) show that the path between *k* and *l* can exist if *k* and *l* are assigned to the existing hubs in that path. Since each hub has a limited capacity, the amount of flow cannot be more than its capacity. This constraint is shown in (6).

4. Cuckoo Optimization Algorithm

The model is solved by the cuckoo optimization algorithm (COA) which is suitable for continuous nonlinear optimization problems. COA has some advantages in comparison to other metaheuristic methods such as rapid convergence, higher accuracy, and ability of local search in addition to global search. Applying MOCS, we use random weights to combine two objectives to a single objective. In this algorithm, cuckoos with their eggs are initialized and located in different places as the initial solution. Some of the initial solutions (eggs) are detected as infeasible solutions, and thus removed. Then, a new generation of cuckoos is produced and the profit values and infeasible solutions are detected. At last, the best places for the cuckoos are determined as the optimum solution. The flowchart of this algorithm is as in Fig. 1 [29].

4-1. Solution representation

The random key representation is used for encryption and the smallest position value (SPV) rule is applied to decrypt and calculate the objective functions.

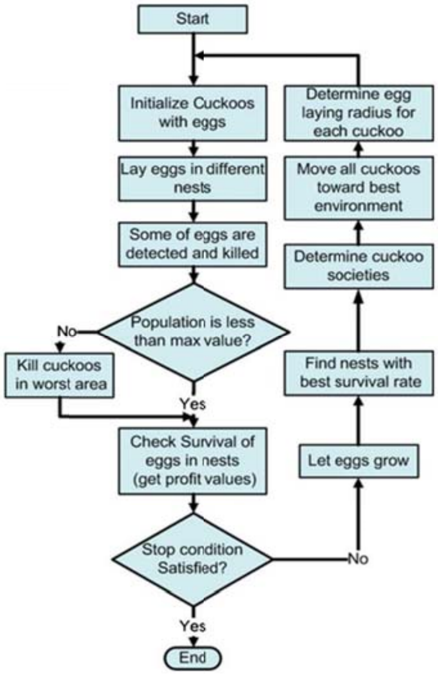

Fig. 1. Flowchart of COA [29]

4-2. Parameter tuning

We design different experiments based on the important factors of COA such as the number of cuckoos, the maximum number of eggs, the maximum number of iterations, the number of clusters, the motion coefficient, and the maximum number of cuckoos. In order to set the parameters, the Taguchi method is used for the design of experiments. The levels of different factors are shown in Table 1, and the results are shown in Fig. 2.

Tab. 1. Levels for different factors of COA

No. of Cuckoos	Max No. of Eggs	Max Iteration	No. of Clusters	Motion Coefficient	Max No. of Cuckoos
10	4	100	1	5	10
20	6	120	2	6	12
	8	140	3	7	14
	10	160	4	8	16

We have also varied population size n and probability P_a. We have used n = 15, 20, 50, 100, 150 and P_a = 0, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35. The simulations show that n = 20 and P_a = 0.25 are sufficient for this optimization problem.

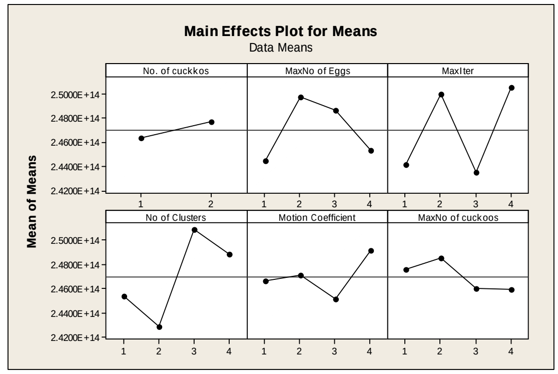

Fig. 2. Result of the Taguchi method

5. Numerical Example

Suppose that a country with 24 cities and all of them are potential locations for hubs among non-demand and demand nodes. Also, suppose that a 5-center hub location-allocation problem. There would be at most 5 hubs in each path between two clients, and the purpose is to determine the location of hubs and allocate the clients to them (see Appendix A). Then, the path between origins and destinations would be determined to maximize the reliability and minimize the cost. The model is solved by the cuckoo optimization algorithm (COA), and the results are as follows:

Tab. 2. Hubs selected by the proposed algorithm

Best locations for hubs
Tehran, Mashhad, Isfahan, Kerman, Tabriz

Tab. 3. Allocation of cities to the selected hubs

Hub	Allocated City
Tehran	Mazandaran, Gilan, Ghazvin, Zanjan, Hamedan, Karaj
Mashhad	Golestan, Semnan, Khorasan_N
Isfahan	Ghom, MarKazi, ChaharMahalVaBakhtiari, Yazd
Kerman	Hormozgan, SistanVaBaluchestan, Khorasan_S
Tabriz	Urmia, Kordestan, Ardabil

By solving the model, the locations of hubs and their allocated cities are determined as in Tables

2 and 3. They show that the cost would be minimized by using these hubs. The reliable paths are determined as well. For example, consider that someone in Yazd wants to travel to Urmia. Using this model leads to the following path:
"Yazd- Isfahan- Tehran- Tabriz- Urmia" with the reliability of 0.9234 which is more reliable than the path *"Yazd- Isfahan- Tabriz- Urmia"* with the reliability of 0.7302.
The paths between the hubs are different, and since we have 20 cities and five hubs, we would have lots of paths which are determined by the model.

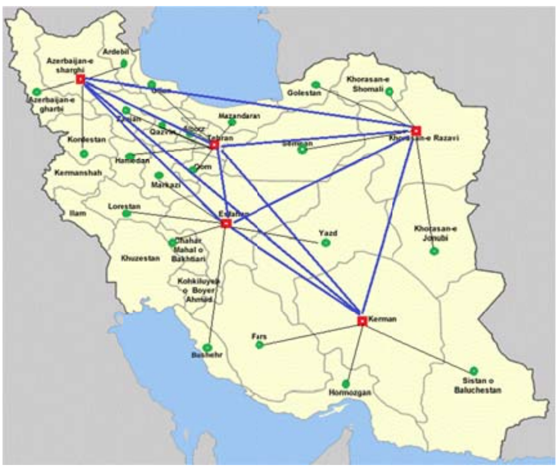

Fig. 3. Iran map by determined hubs

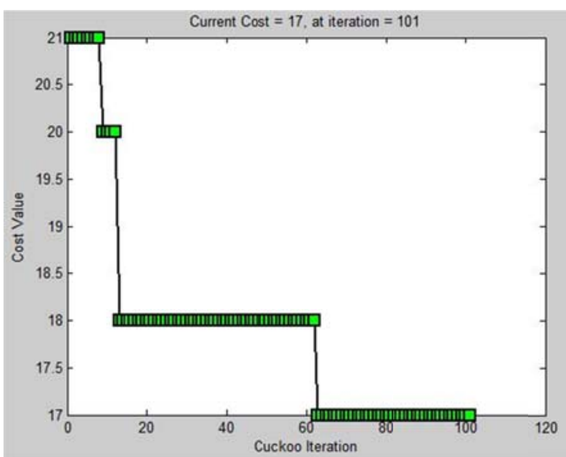

Fig. 4. Convergence of the proposed algorithm ($\times 10^5$)

6. Conclusion

Public transportation is a very challenging problem in many developed and developing countries. In addition, hubs are critical elements of telecommunication and transportation networks, because they play an important role in controlling the traffic. In this paper, we proposed a bi-objective model to find out the best strategy for establishing the hubs, allocating the demand nodes to the hubs, and determining the best path between two clients in order to minimize the cost and maximize the reliability. The model is solved by Cuckoo Optimization Algorithm for a country with 31 cities and different reliable paths are determined between origin and destination. The stochastic demand for the customers or different location-allocation problem with reliable path approach can be considered for future research studies. Furthermore, one can study a hub-tree network instead of fully interconnected hubs.

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Appendix A- Data Gathering

Tab. A. 1. Cost of transshipment from hub *k* to hub *l*

City	Tehran	Mashhad	Isfahan	Karaj	Tabriz	Shiraz	Ahvaz	Ghom	Kermanshah	Rasht	Kerman	Urmia	Zahedan	Arak	Hamedan	Yazd	Ghazvin	Ardabil	Bandar e Abbas	Zanjan	Khoram Abad	Sanandaj	Gorgan	Sari	Shahrekord	Bushehr	Bojnurd	Birjand	Ilam	Semnan	Yasuj
Tehran	100000	883	446	51	626	939	967	151	502	333	1,047	768	1,579	288	321	626	152	592	1,530	334	629	492	414	280	538	1,068	825	1,120	670	217	783
Mashhad	883	100000	1,252	940	1,514	1,344	1,762	953	1,378	1,222	909	1,657	943	1,087	1,198	917	1,042	1,482	1,634	1,222	1,505	1,369	567	730	1,333	1,645	262	1,645	1,547	668	1,303
Isfahan	446	1,252	100000	462	936	480	522	316	641	645	734	1,079	1,275	333	530	313	471	904	988	651	768	702	852	718	123	615	1,190	900	810	586	330
Karaj	51	940	462	100000	579	944	1,004	187	524	287	1,084	722	1,631	309	343	662	106	546	1,567	287	651	514	423	319	574	1,104	879	1,172	692	271	819
Tabriz	626	1,514	901	579	100000	1384	1,097	766	778	492	1,662	152	2,210	726	597	1,241	471	277	1,891	295	905	455	1,032	898	989	1,518	1,452	1,751	757	848	1,233
Shiraz	939	1,344	570	944	1,384	100000	527	798	1,021	1,127	595	1,561	1,102	815	1,012	439	953	1,386	580	1,133	909	1,183	1,333	1,200	523	287	1,349	1,071	960	1,068	252
Ahvaz	967	1,762	522	1,004	1,097	527	100000	831	638	1,160	1,170	1,272	1,677	753	797	812	987	1,358	1,245	972	550	866	1,367	1,233	478	436	1,701	1,429	601	1,093	425
Ghom	151	953	316	187	766	798	831	100000	443	472	906	907	1,447	135	321	484	291	731	1,389	474	570	492	544	410	397	926	892	1,184	612	284	641
Kermanshah	502	1,378	641	524	778	1,021	638	443	100000	549	1,364	636	1,904	313	199	942	418	660	1,620	486	193	229	911	777	527	906	1,317	1,607	167	708	833
Rasht	333	1,222	645	287	492	1,127	1,160	472	549	100000	1,368	633	1,915	493	384	946	178	247	1,726	200	692	483	500	366	735	1,263	806	1,456	734	552	979
Kerman	1,047	909	734	1,084	1,662	595	1,170	906	1,364	1,368	100000	1,806	537	1,049	1,180	419	1,190	1,631	496	1,370	1,487	1,351	1,141	1,128	879	850	1,008	581	1,525	974	815
Urmia	768	1,657	1,079	722	152	1,561	1,272	907	636	633	1,806	100000	2,348	719	533	1,380	610	2,030	2,119	436	769	411	1,171	1,037	1,128	1,657	1,596	1,890	713	988	1,372
Zahedan	1,579	943	1,275	1,631	2,210	1,102	1,677	1,447	1,904	1,915	537	2,348	100000	1,590	1,722	960	1,735	2,175	710	1,917	2,026	1,893	1,300	1,423	1,375	1,346	1,108	453	2,067	1,364	1,311
Arak	288	1,087	333	309	726	815	753	135	313	493	1,049	719	1,590	100000	188	628	317	690	1,416	434	437	362	698	564	309	953	1,025	1,323	479	417	668
Hamedan	321	1,198	530	343	597	1,012	797	321	199	384	1,180	533	1,722	188	100000	764	242	566	1,595	305	312	175	735	601	464	1,132	1,136	1,431	353	528	847
Yazd	626	917	313	662	1,241	439	812	484	942	946	419	1,380	960	628	764	100000	766	1,206	916	949	1,060	927	752	740	463	730	938	638	1,101	581	388
Ghazvin	152	1,042	471	106	471	953	987	291	418	178	1,190	610	1,735	317	242	766	100000	435	1,550	179	545	409	558	424	560	1,089	980	1,277	587	372	804
Ardabil	592	1,482	904	546	277	1,386	1,358	731	660	247	1,631	2,030	2,175	690	566	1,206	435	100000	1,982	261	811	538	746	612	954	1,483	1,053	1,715	911	812	1,198
Bandar e Abbas	1,530	1,634	1,078	1,567	1,981	670	1,245	1,389	1,620	1,726	496	2,119	710	1,416	1,595	916	1,550	1,982	100000	1,730	1,574	1,780	1,555	1,543	1,120	952	1,719	1,174	1,162	1,388	932
Zanjan	334	1,222	608	287	296	1,091	972	474	486	200	1,370	436	1,917	434	305	949	179	261	1,599	100000	613	285	740	606	697	1,226	1,160	1,459	654	556	941
Khoram Abad	629	1,505	768	651	905	909	550	570	193	692	1,487	769	2,026	437	312	1,060	545	811	1,574	613	100000	357	905	771	354	818	1,444	1,297	292	835	660
Sanandaj	492	1,369	702	514	455	1,183	866	492	229	483	1,351	411	1,893	362	175	927	409	538	1,780	285	357	100000	898	764	647	1,062	1,307	1,593	303	699	1,010
Gorgan	414	567	852	423	1,032	1,333	1,367	544	911	500	1,141	1,171	1,300	698	735	752	558	746	1,555	740	905	898	100000	132	935	1,464	305	850	1,071	305	1,180
Sari	280	730	718	319	898	1,200	1,233	410	777	366	1,128	1,037	1,423	564	601	740	424	612	1,543	606	771	764	132	100000	804	1,334	436	968	940	197	1,049
Shahrekord	538	1,333	123	574	989	523	478	397	527	735	879	1,128	1,375	309	464	463	560	954	1,120	697	354	647	935	804	100000	554	1,271	1,017	697	663	269
Bushehr	1,068	1,645	615	1,104	1,518	287	436	926	906	1,263	850	1,657	1,346	953	1,132	730	1,089	1,483	952	1,226	818	1,062	1,464	1,334	554	100000	1,801	1,478	914	1,193	454
Bojnurd	825	262	1,190	879	1,452	1,349	1,701	892	1,317	806	1,008	1,596	1,108	1,025	1,136	938	980	1,053	1,513	1,160	1,444	1,307	305	436	1,271	1,801	100000	650	1,485	606	1,516

Birjand	1,120	1,645	900	1,172	1,751	1,071	1,429	1,184	1,607	1,456	581	1,890	453	1,323	1,431	638	1,277	1,715	1,174	1,459	1,297	1,593	850	968	1,017	1,478	650	100000	1,781	905	1,146
Ilam	670	1,547	810	692	757	960	601	612	167	734	1,525	713	2,067	479	353	1,101	587	911	1,162	654	292	303	1,071	940	697	914	1,485	1,781	100000	877	858
Semnan	217	668	575	271	847	1,058	1,093	284	708	552	974	988	1,364	417	528	581	372	812	1,566	560	835	699	305	197	663	1,193	606	905	877	100000	908
Yasuj	783	1,303	330	819	1,233	252	425	641	833	979	815	1,372	1,311	668	847	388	804	1,198	932	941	660	1,010	1,180	1,049	269	454	1,516	1,146	858	908	100000

Tab. A. 2. Cost of transportation between origin and destination

City	Tehran	Mashhad	Isfahan	Karaj	Tabriz	Shiraz	Ahvaz	Ghom	Kermanshah	Rasht	Kerman	Urmia	Zahedan	Arak	Hamedan	Yazd	Ghazvin	Ardabil	Bandar e Abbas	Zanjan	Khoram Abad	Sanandaj	Gorgan	Sari	Shahrekord	Bushehr	Bojnurd	Birjand	Ilam	Semnan	Yasuj
Tehran	1000000	8830	4460	510	6260	9390	9670	1510	5020	3330	10,470	7680	15,790	288	3,210	6260	1,520	5920	15,300	3340	6,290	4920	4,140	2800	5,380	10,680	8250	11,200	6,700	2170	7,830
Mashhad	8830	1000000	12,520	9400	15,140	13,440	17,620	9,530	13,780	12,220	9,090	16,570	9,430	1,087	11,980	9,170	10,420	14,820	16,340	12,220	15,050	13,690	5,670	7,300	13,330	16,450	2,620	16,450	15,470	6,680	13,030
Isfahan	4460	12,520	1000000	4620	9,360	4,800	5,220	3,160	6410	6,450	7,340	10,790	12,750	333	5,300	3,130	4,710	9,040	9,880	6,510	7,680	7,020	8,520	7,180	1,230	6,150	11,900	9,000	8,100	5,860	3,300
Karaj	510	9400	4620	1000000	5790	9440	10,040	1870	5240	2870	10,840	7220	16,310	309	3,430	6620	1,060	5460	15,670	2870	6,510	5140	4,230	3190	5,740	11,040	8790	11,720	6,920	2710	8,190
Tabriz	6260	15,140	9010	5790	1000000	13840	10,970	7660	7,780	4,920	16,620	1,520	22,100	726	5,970	12,410	4,710	2,770	18,910	2,950	9,050	4,550	10,320	8,980	9,890	15,180	14,520	17,510	7,570	8,480	12,330
Shiraz	9390	13,440	5700	9440	13,840	1000000	5270	7980	10,210	11,270	5950	15,610	11,020	815	10,120	4,390	9,530	13,860	5,800	11,330	9,090	11,830	13,330	12,000	5,230	2,870	13,490	10,710	9,600	10,680	2,520
Ahvaz	9670	17,620	5,220	10,040	10,970	5270	1000000	8,310	6,380	11,600	11,700	12,720	16,770	753	7,970	8,120	9,870	13,580	12,450	9,720	5,500	8,660	13,670	12,330	4,780	4,360	17,010	14,290	6,010	10,930	4,250
Ghom	1510	9,530	3,160	1870	7660	7980	8,310	1000000	4,430	4,720	9,060	9,070	14,470	135	3,210	4,840	2,910	7,310	13,890	4,740	5,700	4,920	5,440	4,100	3,970	9,260	8,920	11,840	6,120	2,840	6,410
Kermanshah	5020	13,780	6410	5240	7,780	10,210	6,380	4,430	1000000	5,490	13,640	6,360	19,040	313	1,990	9,420	4,180	6,600	16,200	4,860	1,930	2,290	9,110	7,770	5,270	9,060	13,170	16,070	1,670	7,080	8,330
Rasht	3330	12,220	6,450	2870	4,920	11,270	11,600	4,720	5,490	1000000	13,680	6,330	19,150	493	3,840	9,460	1,780	2,470	17,260	2,000	6,920	4,830	5,000	3,660	7,350	12,630	8,060	14,560	7,340	5,520	9,790
Kerman	10,470	9,090	7,340	10,840	16,620	5950	11,700	9,060	13,640	13,680	1000000	18,060	5,370	1,049	11,800	4,190	11,900	16,310	4,960	13,700	14,870	13,510	11,410	11,280	8,790	8,500	10,080	5,810	15,250	9,740	8,150
Urmia	7680	16,570	10,790	7220	1,520	15,610	12,720	9,070	6,360	6,330	18,060	1000000	23,480	719	5,330	13,800	6,100	20,300	21,190	4,360	7,690	4,110	11,710	10,370	11,280	16,570	15,960	18,900	7,130	9,880	13,720
Zahedan	15,790	9,430	12,750	16,310	22,100	11,020	16,770	14,470	19,040	19,150	5,370	23,480	1000000	1,590	17,220	9,600	17,350	21,750	7,100	19,170	20,260	18,930	13,000	14,230	13,750	13,460	11,080	4,530	20,670	13,640	13,110
Arak	2880	10,870	3,330	3090	7,260	8,150	7,530	1,350	3,130	4,930	10,490	7,190	15,900	100000	1,880	6,280	3,170	6,900	14,160	4,340	4,370	3,620	6,980	5,640	3,090	9,530	10,250	13,230	4,790	4,170	6,680
Hamedan	3,210	11,980	5,300	3,430	5,970	10,120	7,970	3,210	1,990	3,840	11,800	5,330	17,220	188	1000000	7,640	2,420	5,660	15,950	3,050	3,120	1,750	7,350	6,010	4,640	11,320	11,360	14,310	3,530	5,280	8,470
Yazd	6260	9,170	3,130	6620	12,410	4,390	8,120	4,840	9,420	9,460	4,190	13,800	9,600	628	7,640	1000000	7,660	12,060	9,160	9,490	10,600	9,270	7,520	7,400	4,630	7,300	9,380	6,380	11,010	5,810	3,880
Ghazvin	1,520	10,420	4,710	1,060	4,710	9,530	9,870	2,910	4,180	1,780	11,900	6,100	17,350	317	2,420	7,660	1000000	4,350	15,500	1,790	5,450	4,090	5,580	4,240	5,600	10,890	9,800	12,770	5,870	3,720	8,040
Ardabil	5920	14,820	9,040	5460	2,770	13,860	13,580	7,310	6,600	2,470	16,310	20,300	21,750	690	5,660	12,060	4,350	1000000	19,820	2,610	8,110	5,380	7,460	6,120	9,540	14,830	10,530	17,150	9,110	8,120	11,980
Bandar e Abbas	15,300	16,340	10,780	15,670	19,810	6,700	12,450	13,890	16,200	17,260	4,960	21,190	7,100	1,416	15,950	9,160	15,500	19,820	1000000	17,300	15,740	17,800	15,550	15,430	11,200	9,520	17,190	11,740	11,620	13,880	9,320
Zanjan	3340	12,220	6080	2870	2,960	10,910	9,720	4,740	4,860	2,000	13,700	4,360	19,170	434	3,050	9,490	1,790	2,610	15,990	1000000	6,130	2,850	7,400	6,060	6,970	12,260	11,600	14,590	6,540	5,560	9,410
Khoram Abad	6,290	15,050	7,680	6,510	9,050	9,090	5,500	5,700	1,930	6,920	14,870	7,690	20,260	437	3,120	10,600	5,450	8,110	15,740	6,130	1000000	3,570	9,050	7,710	3,540	8,180	14,440	12,970	2,920	8,350	6,600
Sanandaj	4920	13,690	7,020	5140	4,550	11,830	8,660	4,920	2,290	4,830	13,510	4,110	18,930	362	1,750	9,270	4,090	5,380	17,800	2,850	3,570	1000000	8,980	7,640	6,470	10,620	13,070	15,930	3,030	6,990	10,100
Gorgan	4,140	5,670	8,520	4,230	10,320	13,330	13,670	5,440	9,110	5,000	11,410	11,710	13,000	698	7,350	7,520	5,580	7,460	15,550	7,400	9,050	8,980	1000000	1,320	9,350	14,640	3,050	8,500	10,710	3,050	11,800
Sari	2800	7,300	7,180	3190	8,980	12,000	12,330	4,100	7,770	3,660	11,280	10,370	14,230	564	6,010	7,400	4,240	6,120	15,430	6,060	7,710	7,640	1,320	1000000	8,040	13,340	4,360	9,680	9,400	1,970	10,490

Shahrekord	5,380	13,330	1,230	5,740	9,890	5,230	4,780	3,970	5,270	7,350	8,790	11,280	13,750	309	4,640	4,630	5,600	9,540	11,200	6,970	3,540	6,470	9,350	8,040	1000000	5,540	12,710	10,170	6,970	6,630	2,690
Bushehr	10,680	16,450	6,150	11,040	15,180	2,870	4,360	9,260	9,060	12,630	8,500	16,570	13,460	953	11,320	7,300	10,890	14,830	9,520	12,260	8,180	10,620	14,640	13,340	5,540	1000000	18,010	14,780	9,140	11,930	4,540
Bojnurd	8250	2,620	11,900	8790	14,520	13,490	17,010	8,920	13,170	8,060	10,080	15,960	11,080	1,025	11,360	9,380	9,800	10,530	15,130	11,600	14,440	13,070	3,050	4,360	12,710	18,010	1000000	6,500	14,850	6,060	15,160
Birjand	11,200	16,450	9,000	11,720	17,510	10,710	14,290	11,840	16,070	14,560	5,810	18,900	4,530	1,323	14,310	6,380	12,770	17,150	11,740	14,590	12,970	15,930	8,500	9,680	10,170	14,780	6,500	1000000	17,810	9,050	11,460
Ilam	6,700	15,470	8,100	6,920	7,570	9,600	6,010	6,120	1,670	7,340	15,250	7,130	20,670	479	3,530	11,010	5,870	9,110	11,620	6,540	2,920	3,030	10,710	9,400	6,970	9,140	14,850	17,810	1000000	8,770	8,580
Semnan	2170	6,680	5750	2710	8,470	10,580	10,930	2,840	7,080	5,520	9,740	9,880	13,640	417	5,280	5,810	3,720	8,120	15,660	5,600	8,350	6,990	3,050	1,970	6,630	11,930	6,060	9,050	8,770	1000000	9,080
Yasuj	7,830	13,030	3,300	8,190	12,330	2,520	4,250	6,410	8,330	9,790	8,150	13,720	13,110	668	8,470	3,880	8,040	11,980	9,320	9,410	6,600	10,100	11,800	10,490	2,690	4,540	15,160	11,460	8,580	9,080	1000000

Tab. A.3. Reliability and cost of some paths

Path	*a*	Cost	Reliability
M-Te-I	1	1329	0.805
M-Sh-I	2	1914	0.812
M-Te-Sh-I	3	2392	0.733
M-Sh-Te-I	4	2729	0.698
M-Te-k	1	934	0.777
M-Sh-k	2	2288	0.856
M-Te-Sh-k	3	2766	0.818
M-Sh-Te-k	4	2334	0.674
M-Te-Ta	1	1509	0.932
M-Sh-Ta	2	2728	0.733
M-Te-Sh-Ta	3	3206	0.701
M-Sh-Te-Ta	4	2909	0.808
I-Te-M	1	1329	0.805
I-Sh-M	2	1914	0.812
I-Te-Sh-M	3	2729	0.698
I-Sh-Te-M	4	2392	0.734
I-Te-k	1	497	0.717
I-Sh-k	2	1424	0.876
I-Te-Sh-k	3	2329	0.754
I-Sh-Te-k	4	1560	0.690
I-Te-Ta	1	1072	0.859
I-Sh-Ta	2	1954	0.751

I-Te-Sh-Ta	3	2769	0.646
I-Sh-Te-Ta	4	2135	0.827
K-Te-M	1	934	0.777
K-Sh-M	2	2288	0.856
K-Te-Sh-M	3	2334	0.674
K-Sh-Te-M	4	2766	0.818
K-Te-I	1	497	0.717
K-Sh-I	2	1424	0.876
K-Te-Sh-I	3	1560	0.690
K-Sh-Te-I	4	2329	0.754
K-Te-Ta	1	677	0.829
K-Sh-Ta	2	2328	0.791
K-Te-Sh-Ta	3	2374	0.623
K-Sh-Te-Ta	4	2509	0.872
Ta-Te-M	1	1509	0.932
Ta-Sh-M	2	2728	0.733
Ta-Te-Sh-M	3	2909	0.808
Ta-Sh-Te-M	4	3206	0.701
Ta-Te-I	1	1072	0.859
Ta-Sh-I	2	1954	0.751
Ta-Te-Sh-I	3	2135	0.827
Ta-Sh-Te-I	4	2769	0.646
Ta-Te-k	1	677	0.829
Ta-Sh-k	2	2328	0.791
Ta-Te-Sh-k	3	2509	0.872
Ta-Sh-Te-k	4	2374	0.623

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