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HUB BASED NETWORK DESIGN: A REVIEW

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Abstract- Globalization of trade markets has increased the need for efficient logistics systems. Therefore, logistics systems have started to evolve based on cost and service quality measures. Hubs are transshipment points where shipments can be consolidated and disseminated by exploiting economies of scale. Hub based networks, hence, can provide promising solutions to current demand for efficient logistics systems. The objective of this paper is to review and present a classification of hub location problems based on the very recent publications. Our aim is to show the recent trends for hub location literature and compare it with previous trends and expectations.

Key words – Hub network, network design, review.

Introduction

Geographically dispersed logistics systems are getting more and more common in today's business world with a variety of applications such as airline network design, communication, postal delivery, and transportation networks. Unfortunately, it is not easy to handle such logistics systems. In real life, hubs are widely used facilities in large and geographically dispersed logistics networks. Hubs are basically transshipment points where shipments can be consolidated and disseminated, and even transportation modes can be changed. The popularity of hub based networks is increasing by emerging popularity of intermodal transportation networks in global marketplace [1]. The reason behind the idea of using hubs instead of serving each origin-destination pair directly is to pursue the advantage of economies of scale [2]. Consolidation of less-than-truckload shipments creates the economies of scale by decreasing the unit transportation cost. Hence, economies of scale create a non-linear cost structure where the unit transportation cost is a non-increasing function of the volume shipped [3].

The hub location problem, basically, includes locating hub nodes and allocating non-hub nodes to hubs. Depending on the assumptions made, number of additional features may be added to the raw hub location problem such as traffic management, transportation mode selection, congestion minimization, and different cost structures. Hub location problems have been studied extensively with various extensions. Nevertheless, the literature reflects a dichotomy between *single allocation* and *multiple allocation* hub networks. The former assumes all the incoming and outgoing flows of a non-hub node are passing through a single hub node, whereas the latter allows multiple hubs assignments of a single non-hub node. Fig. (1) shows a simple example for single and multiple allocation networks.

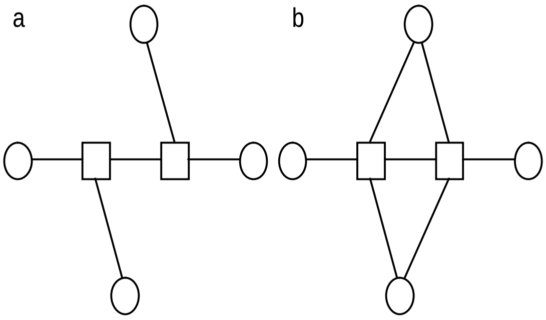

Fig. 1- Hub network examples where squares represent hub nodes and circles represent non-hub nodes. (a) Single allocation network and (b) Multiple allocation network

The objective of this paper is to review and present a classification of the studies on hub location problems after 2007. For a detailed survey up to 2007 the reader is referred to [2]. Fig. (2) shows the number of studies in the literature according to years. Please note that number of studies before 2007 is taken from [2]. According to the figure, trend of the number of studies follows a quasi-exponential form. If we analyze the 2007-2011 segment, it is clear that the same trend has been maintained. This trend points to the increasing popularity of hub based networks between academics as well as real life practitioners.

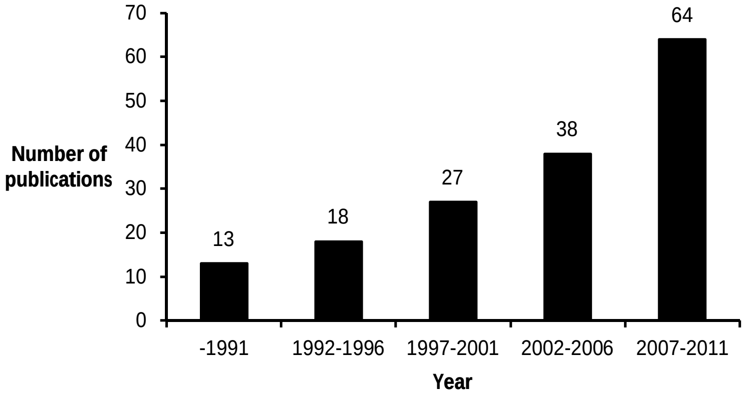

Fig. 2- Number of hub location related studies according to years

In the next four sections, we provide a survey for the *p*-hub median problem, the hub location problem with setup costs, the *p*-hub center problem, and the hub covering problem.

The *p*-hub median problem

The *p*-hub median problem involves locating a given number of hubs (*p*) and allocating non-hub nodes to hubs while minimizing the total transportation time (or distance). The review in here is constructed based on the previously mentioned dichotomy between single allocation and multiple allocation. To recall that single allocation enforces to assign a non-hub node to a single hub, whereas multiple allocation allows to assign a non-hub node to multiple hub points. We give an integer programming formulation for only the multiple allocation case since it is the generalized form of the problem. Let W_{ij} be the flow between nodes *i* and *j*. C_{ijkm} is the unit transportation cost from node *i* to *j* through hubs *k* and *m*. X_{ik} takes value of 1 if node *i* is allocated to hub k, and 0 otherwise. X_{kk} takes the value of 1 if node *k* is a hub node, and 0 otherwise. X_{ijkm} is the fraction of flow from node *i* to *j* through hubs *k* and *m*. The integer programming formulation proposed by [4] is:

$$\min \sum_i \sum_j \sum_k \sum_m W_{ij} X_{ijkm} C_{ijkm}$$

$$\text{s.t.} \sum_k X_{kk} = p$$

$$\sum_k \sum_m X_{ijkm} = 1 \text{ for all } i,j$$

$$X_{ijkm} \le X_{kk} \text{ for all } i,j,k,m$$

$$X_{ijkm} \le X_{mm} \text{ for all } i,j,k,m$$

$$X_{ijkm} \ge 0 \text{ for all } i,j,k,m$$

$$X_{ik} \in \{0,1\} \text{ for all } i,k$$

The literature consists of some neighborhood search based heuristics for the single allocation *p*-hub median problem (SPM). [5] proposed two genetic algorithms to solve the uncapacitated SPM problem (USPM). One of their algorithms finds all previously known optimal solutions and also provides the best known solutions for some large-scale instances from the well-known Civil Aeronautics Board (CAB) and Australia Post (AP) data sets. CAB data set includes 25 US cities based on airlines, whereas AP data set is based on a postal delivery in Sydney, Australia. [6] presented a new variable neighborhood search approach and provided a heuristic algorithm for USPM problem. They also used CAB and AP data sets and showed that their algorithm improves best known solutions for many instances.

The literature also includes different solution algorithms based on branch-and-bound, relaxations, and decompositions for SPM problems. [7] proposed a simple 3-approximation algorithm and randomized 2-approximation algorithm based on linear relaxation for USPM. [8] considered an international hub based railway network. In this study, an iterative procedure based on USPM problem and the multi-modal assignment problem is presented. Interestingly, the only application on capacitated SPM problem (CSPM) is developed by [9]. They proposed a non linear integer programming formulation and a Lagrangian heuristic to solve the CSPM problem in which congestion and capacity selection is also incorporated.

Other than general hub based networks, there also exist SPM problems in more specialized networks. [10] considered an USPM problem in a special network type called *star-star network*. In a star-star network, each non-hub nodes is connected to a hub node and each hub node is also connected to a central hub node. [10] provided two mathematical models which minimize the link installation cost for determining the hub locations. They also proposed a Lagrangian relaxation and a local search based heuristic for the problem. [11] addressed the USPM problem in a star-star network in which service quality requirements are also considered. [12] developed a new integer programming formulation and a new solution procedure for an USPM based problem called cluster hub location problem where nodes of the network are partitioned into clusters such that one node in each cluster is selected as a hub node. [13] addressed a similar problem called partitioning hub location routing problem in which a network is partitioned into clusters, at least one hub is located in each cluster and finally routing decisions are made in order to minimize the cost. [13] proposed an integer programming formulation and developed some valid inequalities to strengthen the formulation. Another extension for the USPM problem is called the tree of hubs location problem which includes a special network where the hubs are connected by a tree structure. [14] proposed a three indices integer programming formulation and some families of valid inequalities for the tree of hub location problem. In the numerical study it is shown that LP (Linear Programming) bounds of the proposed formulation are effective only for small size problems. Thus, [15] proposed a new four indices formulation which provides tighter LP bounds, yet high computational complexity. To be able to solve the new formulation, a Lagrangian relaxation approach is proposed.

[16] provided a model for capacitated *p*-hub median problem while introducing costs due to congestion in hubs each of which is modeled as an M/M/1 queuing system. Moreover, they developed a simulated annealing based algorithm to solve the model. Another study which considers congestion is proposed by [17]. This study presented two bi-criteria models one of which is based on uncapacitated multiple allocation *p*-median problem (UMPM), whereas the other aims to embed congestion into the objective function. They proposed evolutionary algorithms and tested their performance on the Turkish Postal System, AP, and CAB data sets. [18] developed a robust optimization method that uses a multi-objective genetic algorithm for the UMPM problem.

Literature also consists of some studies which, basically, extend the traditional UMPM problem in other aspects. [19] considered UMPM problems and multiple allocation hub arc location problems (MHAL). The hub arc location problem aims to locate hub locations as well as *hub arcs* which have discounted transportation costs. The objective of [19] is to incorporate cost oriented hub median problems with service level consideration. [20] integrated the hub location problem with a routing problem. They proposed a two-stage heuristic solution procedure for the problem. The first stage is devoted to determine hub locations, whereas the second stage aims to determine routing decisions by using the hub locations found in the first stage. The problem, basically, is a combination of the UMPM problem and the multiple vehicle routing problem. As a case study, they used the Turkish postal delivery system data. [3] extended the *p*-hub median problem by adding transportation mode selection, non-linear economies of scale, and service time requirements. They developed a mixed integer programming model and proposed a tabu search algorithm to solve the problem. [21] worked on a similar problem setting based on their previous study [3] without the non-linear cost function for economies of scale. They provided lower bounds by using a Lagrangian relaxation method. [22] integrated two solution approaches, i.e. the classical UMPM model and a simulation model, to determine the optimal locations of "*intermodal terminals*" in Serbia. The UMPM model is employed to find the terminal locations, whereas simulation is used to evaluate and estimate the performance of terminal locations in a variety of scenarios. [23] compared the allocation strategies for the *p*-hub median problem. A new problem is designed, called the *r*-allocation *p*-hub median problem where each non-hub node can be assigned at most *r* hubs. This problem is, obviously, a generalized version of single and multiple allocation problems. A computational study is performed on AP and CAB data sets by using the integer programming formulation proposed. Finally, it is shown that using the single allocation strategy may be significantly more expensive than the multiple allocation strategy. Moreover, even allowing a few numbers of assignments may result in significant cost savings.

The hub location problem with setup costs

In this problem class, a fixed setup cost is introduced to the hub location problem so that the number of hubs is also defined as a decision variable unlike the *p*-hub median problem. An integer programming formulation for the multiple allocation hub location problem with fixed costs is proposed by [24] as follows (with previously defined variables):

$$\min \sum_{i}\sum_{j}\sum_{k}\sum_{m} W_{ij}X_{ijkm}C_{ijkm} + \sum_{k} F_k X_{kk}$$
$$s.t. \sum_{k}\sum_{m} X_{ijkm} = 1 \text{ for all } i,j$$
$$X_{ijkm} \leq X_{kk} \text{ for all } i,j,k,m$$
$$X_{ijkm} \leq X_{mm} \text{ for all } i,j,k,m$$
$$0 \leq X_{ijkm} \leq 1 \text{ for all } i,j,k,m$$
$$X_{ik} \in \{0,1\} \text{ for all } i,k$$

[25] proposed a hybrid heuristic based on the simulated annealing, tabu list, and improvement procedures to solve the uncapacitated single allocation hub location problem with setup costs (USAHL). Additionally, they also provided two approaches to determine an upper bound for the number of hubs. In this paper, CAB and AP data sets are employed to test the proposed methods. [26] proposed four tabu search based heuristics for the USAHL problem. Their algorithms outperformed heuristics developed by [25]. [27] developed another hybrid heuristic based on a genetic algorithm and a simulated annealing method for the USAHL where the discount factor between hubs depends on the flow rather than a constant value.

In addition to neighborhood search based algorithms, literature also consists of decomposition and relaxation based approaches. [28] proposed a hybrid algorithm that integrates an outer approximation and a Benders decomposition for the USAHL problem under congestion. They incorporated the congestion effect and the total cost into an objective function which eventually turns out to be non-linear. [29] presented two formulations and a Lagrangian relaxation based heuristic for the USAHL problem in a star-star network.

There are several solution algorithms for the classical single allocation hub location problem (CSAHL). [30] worked on an ant colony optimization technique to solve the CSAHL problem. [31] proposed a Lagrangian relaxation approach to the CSAHL problem which enabled them to decompose the problem into smaller subproblems and, consequently, provided tight upper and lower bounds. [32] showed that the formulation of the CSAHL, provided by [33] and mostly referred to as the most effective formulation, may not be complete and may lead to infeasible solutions. Then, [32] introduced a new set of constraints to the formulation which can be used as a cut that improves the computational performance.

There are also other studies in which the classical CSAHL problem is extended with additional features. For example, [34] proposed a new approach to the capacity concept and provided two different approaches for the bi-criteria CSAHL problem where minimization of time that the hubs need to process the flow is used as a second criterion rather than using a regular capacity constraint. [35] considered a CSAHL problem in which determining hub capacities is also embedded into the problem. [35] provided two formulations and proposed different sets of valid inequalities to increase the performance of the models. Then, [36] extended the problem by incorporating a balancing requirement that controls the maximum difference between numbers of non-hub nodes assigned to each hub. They provided two mixed integer programming models and compared their performances in terms of computation time and LP bounds.

To solve the classical uncapacitated multiple allocation hub location problem with setup cost (UMAHL), several approaches are proposed. [37] proposed a heuristic method based on a dual-ascent technique and embedded it into a branch and bound algorithm. [38] developed a new dual-based heuristic algorithm to solve UMAHL problem. They formulated the problem as a multi-commodity flow problem and exploited the special structure in the proposed heuristic. [39] presented a Benders decomposition algorithm for the UMAHL problem. This algorithm is able to solve the largest scale instances which have not been solved by other exact methods. [40] proposed a modified integer programming formulation to UMAHL problem which includes fewer constraints and variables than other models. Additionally, they proposed two evolutionary algorithms to solve large scale problems. One of their algorithms provided results for the largest instances that have been solved in the literature so far.

Other studies that are aiming to embed different considerations also exist. For example, [41] proposed a generalized Benders decomposition algorithm to solve the UMAHL problem under hub congestion which has a non-linear convex cost function. [42] presented a new Benders decomposition algorithm to the UMAHL problem with a non-linear cost function that includes convex economies of scale. [43] presented an integer programming formulation for the UMAHL problem with decentralized management. In this setting, different transportation companies operates in the same network under their own performance and quality measures.

Surprisingly, the literature has only several studies on stochastic models. [44] introduced a two stage stochastic programming model for air freight UMAHL under seasonal demand pattern. In the first stage, the number and the locations of hubs are determined, whereas the second stage is devoted to find the flight routes. [45] considered three stochastic UMAHL problems in which stochastic components are varied for each problem setting. They showed that the stochastic problem with uncertain demand or dependent transportation costs is equivalent to the deterministic problem in which expected values are employed. On the other hand, the stochastic problem with uncertain independent transportation costs is not equivalent to the deterministic problem. Thus, a simulation and Benders decomposition based solution algorithm is proposed for the independent transportation cost case.

The only study related to capacitated multiple allocation hub location problem with setup costs (CMAHL) is done by [46]. They developed two branch-and-cut algorithms based on a Benders decomposition technique.

The *p*-hub center problem

Similar to the *p*-hub median problem, the *p*-hub center problem (PCP) is to locate a given, *p*, number of hubs and to allocate non-hub nodes to hubs in such a way that maximum travel time (cost) between any O-D (origin-destination) pair or on a single link is minimized. Roughly speaking, the *p*-hub center problem aims to moderate the worst case instances. Let r_k be the maximum cost between hub *k* and the non-hub nodes that are assigned to hub *k*. Additionally, recall that α is the discount factor to represent economies of scale for hubs. An integer programming formulation of the *p*-hub center problem proposed by [47] is:

$$
\begin{aligned}
&\min \quad Z \\
&s.t. \sum_k X_{ik} = 1 \text{ for all } i \\
&\sum_k X_{kk} = p \\
&X_{ij} \le X_{jj} \text{ for all } i, j \\
&r_k \ge C_{ik} X_{ik} \text{ for all } i, k \\
&Z \ge r_k + r_m + \alpha C_{km} \text{ for all } k, m \\
&X_{ik} \in \{0,1\} \text{ for all } i, k \\
&r_k \ge 0 \text{ for all } k
\end{aligned}
$$

[47] also proved that the allocation sub problem with a given number of hubs is NP-Hard. [48] proposed a 2-phase algorithm to solve the uncapacitated single allocation PCP (USPCP). The proposed algorithm is able to solve the largest scale instances of the problem in the current literature. [49] studied a sub-problem of the *p*-hub center problem called *p*-hub center allocation problem where hub locations are given. Thus, the only decision is to allocate non-hub nodes to given hubs. [49] provided integer programming formulations for both capacitated/uncapacitated and single/multiple allocation cases and additionally, presented complexity results for the problems. [50] worked on an aggregation concept to be able to deal with large instances of hub location problems. Although they worked on many different problem types, such as USPM, UMPM, USPCP, they presented the formulation for only the USPCP problem.

As was the case of the UMAHL problem, there are only a few studies related to uncertainty in PCP. [51] worked on a stochastic USPCP with chance constraints under uncertain travel times and proposed a few heuristic algorithms. [52] addressed a similar problem where the objective is to maximize the minimum service level for a given maximum path length. They used a similar approach to [51] by employing chance constraints, and proposed a genetic algorithm to solve the problem. [53] also worked on a stochastic USPCP but with discrete time distributions.

[54] proposed multi-objective programming approach to both capacitated and uncapacitated multiple allocation PCP in which the objective is to minimize total cost and minimize maximum travel time. This work is the only one in recent literature to compose cost and maximum time minimization.

Hub covering problem

Hub covering problem is to locate hubs while minimizing the total cost of opening hubs in such a way that cost (time/distance) between any O-D pair cannot exceed a specified value. Let β be the radius for a hub node. Then, an integer programming model for the hub covering problem proposed by [55] is:

$$\begin{aligned}
&\min \sum_k X_{kk} \\
&s.t. \sum_k X_{ik} = 1 \text{ for all } i \\
&\quad X_{ij} \le X_{jj} \text{ for all } i, j \\
&\quad r_k \ge C_{ik} X_{ik} \text{ for all } i, k \\
&\quad r_k + r_m + \alpha C_{km} \le \beta \text{ for all } k, m \\
&\quad X_{ik} \in \{0,1\} \text{ for all } i, k \\
&\quad r_k \ge 0 \text{ for all } k
\end{aligned}$$

Interestingly, there are several studies addressing the hub covering problem. [56] proposed a tabu search based heuristic to the single allocation hub covering problem (SHCP) over an incomplete network. The objective of this model is to locate hubs, establish links between the located hubs, and allocate non-hub nodes to the hubs. [57] worked on the same problem with one additional restriction that is to limit number of visited hubs on a route. [58] proposed a neighborhood search heuristic algorithm based on a path relinking approach. The proposed heuristic algorithm provides reliable results for medium sized problems on the AP data set.

Other studies

In addition to the problem types based on the classification of hub networks, the literature includes models with different considerations. One of the widely used considerations is to determine routes or schedules for vehicles and/or containers and/or trailers rather than locating hub points. [59] developed an integer programming model to determine service frequency and routes for railways to minimize total cost. So, the objective of this study is to determine schedule of trains rather than locating hubs. [60] proposed a procedure to determine the smallest fleet size and their route in a capacitated network which integrates different types of hub networks. [61] addressed a hub scheduling problem in which the schedules of inbound trailers are determined by minimizing the maximum workload. [62] formulated mathematical models in which routing of swap containers and vehicles are both integrated. The problem is, actually, a hybrid of vehicle routing and resource allocation problems. [63] proposed a tabu search based heuristic algorithm to determine the fleet size, routes and schedules for cargo carrier operations. [64] proposed an integer programming formulation and a Benders decomposition method to the fleet deployment problem for liner shipping companies. The aim is to determine routes of shipments, allocation of non-hub nodes to hubs and determining the optimal vessel types. [65] also worked on hub location and routing problems for liner shipping companies. [66] proposed a procedure to determine schedules and routes of shipments in a hub network where dual service is allowed. Briefly, the objective of this study is to integrate secondary routes into the problem. [67] developed a two objective formulation to determine routing, ship size, and shipment frequency. They pointed the trade-off between shipping costs and inventory holding costs and determined Pareto optimal solutions to the model. [68] compared two shipping networks: a multi-port network with conventional ships and a hub and spoke network with mega-ships. The comparison is performed with respect to container management issues including empty container repositioning.

[69] presented integer programming formulations to "*the latest arrival hub location problem*" where transient times spent in hubs for unloading, loading, and sorting operations are considered. [70] also worked on the latest arrival hub location problem. They developed a mathematical model in which multiple stopovers are also allowed. Additionally, they strengthened their model by using some set of valid inequalities. In a similar manner, [71] worked on routing the traffic at hubs in order to improve service quality of hubs.

A few researchers analyzed the effects of competition in hub-based networks. [72] addressed a competitive hub location problem where a number of hubs is located by considering utility functions of customers. [73] developed an integer programming formulation to locate a predetermined number of hubs under competition between a newcomer and an existing dominant company. [74] worked on a hub location problem in a competitive market by using a game theoretic approach. [75] proposed a framework to analyze the hub network alliances under price competition for the airline industry. They developed another game theoretic approach in which profit maximization and cost based network design problems are combined. Another similar study is done by [76]. In this study, multiple stakeholders that are operating in the same network and multi type container transportation are integrated with hub network design problem.

One distinctive study is done by [77] related to *p*-hub location problems. In this study, the aim is to provide a reliable *p*-hub network that leads to minimum disruptions in the case of a problem at a hub.

Another interesting study is completed by [78]. In this study, efficient formulations are proposed for *p*-hub median problems, hub location problems with fixed cost, *p*-hub covering problems, and hub covering problems in which complete network assumption is relaxed and the network design is assumed to be incomplete.

Concluding remarks

In this paper, we have reviewed the literature related to the hub network problem published after 2007. Based on this review, one can claim that the popularity of hub based networks is increasing year by year. Additionally, researchers are trying to plug in more features to traditional hub network problems in order to represent real life problems adequately. Fig. 3 demonstrates the distribution of total number of publications with respect to aforementioned problem types.

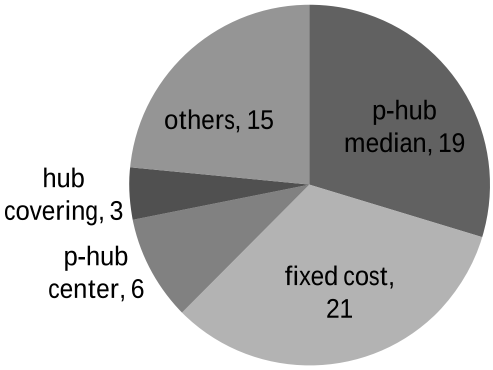

Fig. 3- Number of publications with respect to presented models

As [2] stated, hub network problems were generally based on *p*-hub median problems before 2000. Thereafter, hub location problems with fixed costs, which constitutes the natural extension of *p*-hub median problems, began to be the core of focus, yet *p*-hub median problems are still prevalent. In recent years, researchers have generally focused on novel solution algorithms to solve the problems. Especially, branch and bound algorithms, decomposition algorithms such as Benders decomposition, and relaxations such as Lagrangian relaxation are widely used methods.

Number of studies related to hub covering and *p*-hub center problems are not comparable with other models. On the other hand, they have an increasing trend about the popularity of these two problem types especially in recent years.

According to our review, it is obvious that hub network problems have been extensively studied, although there is still room for novel studies especially about multi-objective and stochastic models. Even though stochastic models have constituted a huge application area in other optimization domains, there are only a few studies on hub based network problems. Furthermore, there is also some room for novel solution algorithms which can solve large realistic instances with additional real life aspects.

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