Computers & Operations Research 38 (2011) 1656–1666

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

The uncapacitated hub location problem in networks under decentralized management

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ARTICLE INFO

Available online 21 March 2011

Keywords:
Hub location
Network
Integer programming
Intermodal

ABSTRACT

We propose a new hub location model defined by the minimization of costs. The main contribution of this work is to permit the analysis of a hub-and-spoke network operated under "decentralized management". In this type of network, various transport companies act independently, and each makes its route choices according to its own criteria, which can include cost, time, frequency, security and other factors, including subjective ones. Therefore, due to the diversity of the various companies' criteria, one can expect that between each origin–destination pair, a fraction of the flow will be carried through hubs and a fraction will be carried by the direct route. to resolve this problem, it becomes necessary to determine the probability that any network user will choose the hub route for each trip to be made (or for each load to be carried). We present an integer programming formulation, subject the new model to experiments with an intermodal general cargo network in Brazil and address questions regarding the solution of the problem in practice.

1. Introduction

In a hub-and-spoke network, the hub vertices are connected to common nodes by routes called spokes. The connections between the hubs themselves are made by shuttle services (Fig. 1), which provide the greatest transport capacities, economies of scale and pollution reduction. The latter two advantages are the main reasons for establishing such a transportation system.

A hub has three principal functions: to aggregate flows arriving from any vertices of the network, to redistribute flows toward each destination point and to send aggregated flow to another hub for further redistribution.

The location of hubs in networks is a nondeterministic polynomial time complete (NP-complete) combinatorial optimization problem with a two-part solution: determination of the network's vertices, which should function as hubs, and attribution of the origin and destination nodes of each flow to their respective hubs. The solution aims to provide the lowest total network cost for routing the flows between all O–D (origin–destination) pairs. The uncapacitated multiple allocation hub location problem (UMHLP) is the specific case that does not include flow capacity limits, neither in the net links nor at the vertices. Its multiple allocation feature allows a vertex to be connected to every hub, contrarily to the single allocation problems that restrict each vertex to send or receive flows by only one hub.

The aim of this work is to resolve an uncapacitated multiple allocation hub location problem (UMHLP) in a hub-and-spoke network operated under decentralized management. To the best of our knowledge this case has not yet been examined in the published models of this problem, but it is a very common case in the analysis of networks of regional or greater scope.

The existing models are only applicable to networks managed by a central entity, which establishes a uniform criterion for choosing the best route such that all vehicles belonging to the network must follow that criterion. For example, an express delivery firm that has its own transport network can establish the deterministic criterion of lowest cost for choosing the route to be followed by its vehicles. With this uniform criterion established throughout the network, the location of the hubs and the allocation of the flows can be determined through use of published hub location models, since, in these models, the flows between any two points *i* and *j* occur "totally" over a single route that is considered optimal.

However, in a system under decentralized management, the flow between an O–D pair does not go by a single route because such a system does not have a single criterion for determining the best route. In this type of system, in which different transport firms act independently, each of them makes its own route choices based on its own particular criterion. Hence, with a diversity of criteria from

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doi:10.1016/j.cor.2011.03.004

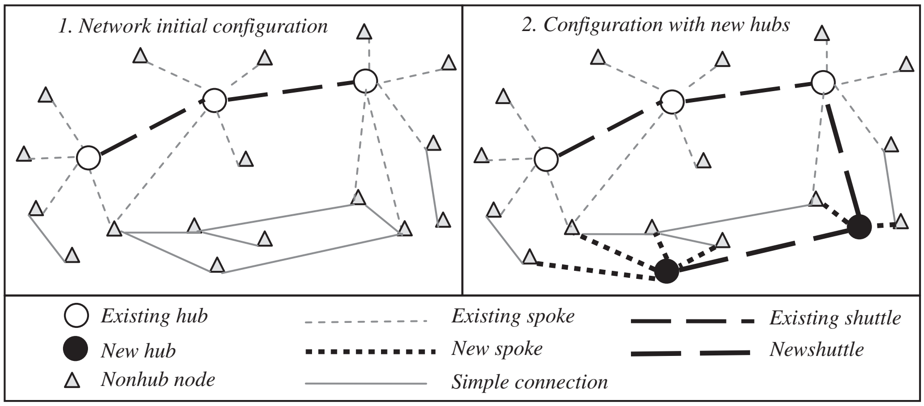

Fig. 1. Example of the establishment of a set of new hubs in a network.

multiple companies, one can expect each O–D pair to account for a fraction of the flow, carried through hubs, and another fraction to be carried by direct routes.

An example of a decentralized management network is the domestic transport of containers in a country, where each company can choose the route and transport mode (or modes) to be used based on a particular combination of parameters (cost, transport time, frequency of shipments, security and other subjective parameters).

Even if this free market does not appear to be an organized system, it is a transport network with flows that can be probabilistically modeled. In this case the hub location problem (HLP) becomes more complex.

It can be intuitively argued that even in a transport system without central management, the conventional hub location model could be applied if a generalized cost function[1] were used by computing all criteria for choosing the best route, including subjective criteria. So, if the generalized costs were computed for all existing routes between an O–D pair, it would be possible to compare them and choose the optimal route (the route with the lowest generalized cost). However, this argument fails because the objective function and constraints of a conventional UMHLP would determine that "all" flows between an O–D pair should take a single route with the lowest generalized cost, which cannot be expected in practice.

As stated before, in real-world decentrally managed networks, an O–D flow is splitted into the O–D available routes (direct or via hubs). As seen in Domencich and McFadden [6], this division is better represented by discrete choice models—such as the Logit Model. These models estimate the probability that a user will choose an available route. Hence, this probability also represents the proportion of users that is expected to choose a route type in a determined period (e.g., a year). And, according to these kinds of models, if a new lower-cost route is created due to the establishment of a new hub, the existing direct flow (with higher cost) cannot be expected to migrate "totally" to this new route. This means that the probabilities of using both types of routes are non-zero. And, in transportation modeling, they are usually significant. Therefore, a conventional hub location model based on generalized cost cannot be applied as described in the previous paragraph.

Even if one could assume in a specific case that "all" of the flow between an O–D pair would migrate from a route with higher generalized cost to a new one with lower generalized cost, it would still not be correct to use the same generalized cost function for all of the network's vertices. It would instead be necessary to divide the network into homogeneous areas and to determine a single generalized cost function for each of these areas because each variable of this function has a different value for each region (e.g., time spent in a highly industrialized region might be more costly than that spent in an agricultural region). Due to the specific probabilistic process utilized to generate generalized cost functions, cost values calculated by different generalized cost functions cannot be compared. Therefore, in many cases these figures cannot be used as absolute values for an objective function that computes the costs of all of the parties of a network.

Due to these limitations on application of the conventional UMHLP model in systems with decentralized management, we believe that development of a new hub location model would be useful. This aim is the most important innovation of this work.

Such a model is of interest to both public policymakers (concerned, for example, with allocating investments in new public terminals) and private operators of large transport systems, such as railroads, cabotage, etc. (interested in attracting customers from competing systems, mainly those that only use trucking).

For background on the hub location problem, we urge readers to consult Alumur and Kara [1], who provide a complete and detailed discussion of the various aspects of the problem and the state of the art of its different formulations and solution methods. Some new solution models for the UMHLP were not mentioned in that survey or have been published since then, so they are commented as follows.

The model of Cánovas et al. [4] included a heuristic based on the dual-ascent technique and an original algorithm to resolve the UMHLP. In this model, a preprocessing step is carried out before performing iterations of the base algorithm. According to the authors, this approach substantially improves the method's efficiency. The algorithm that coordinates all of the functions is of the branch-and-bound type. At each node of the implicit enumeration, a dual-ascent heuristic routine is executed as a fundamental tool of the process. Those authors noted that the most difficult problems are those in which there is symmetry in transport costs or in which values of the discount coefficient for interhub costs (α—described in Section 2.1) are low.

Among all of the solution methods published to date, the only one that outperforms that of Cánovas et al. [4] in solving this problem is that presented in Camargo et al. [3].

Camargo et al. [3] created an algorithm that currently performs best in solving the UMHLP. In addition, their algorithm is an exact optimization method. The procedure is based on the classic Benders decomposition and is able to resolve cases of up to 200 vertices in less than 10,000 s of processing time (using a Sun

[1] Sum of the financial cost and other monetary amounts representing the other transport impedances.