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Multi-period hub location problems in transportation

Shahin Gelareh [a,b,*,1], Rahimeh Neamatian Monemi [c], Stefan Nickel [d,e]

[a] Université Lille Nord de France, F-59000 Lille, France
[b] Laboratoire Génie Informatique et Automatique, Université d'Artois, F-62400 Béthune, France
[c] Ifsttar, Univ. Lille Nord de France, rue Élisée Reclus 20, F-59666 Villeneuve d'Ascq, Lille, France
[d] Institute for Operations Research, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[e] Fraunhofer Institute for Industrial Mathematics (ITWM), Kaiserslautern, Germany

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ABSTRACT

Many transport service providers operate on hub-and-spoke network structures. Major operators may have several dedicated hub facilities that are leased for a time horizon rather than being owned or constructed. For a given discrete planning horizon, service providers must decide on the location of the hub ports (i.e. terminals), the period when the lease contract starts, the period when the existing contracts must be terminated and the flow routing over the entire planning horizon so as to minimize the total operational cost. Thus, we propose a mathematical model for a *Multi-period Uncapacitated Multiple Allocation Hub Location Problem with Budget Constraint*. The proposed model incorporates several features of practice, particularly from maritime and land transport practices. We also propose a meta-heuristic solution algorithm that produces high-quality solutions in a reasonable amount of time. By exploiting the decomposable structure of the model, we extended a Benders decomposition approach by proposing several improvements. Extensive computational experiments confirm the efficiency of the proposed methods and also show its limitations.

1. Introduction

Hub-and-spoke network structures play a crucial role in the performance of today's transportation networks. Currently, models of hub-and-spoke networks are implemented in almost all modes of transport. Moreover, as governments impose further tax regulations promoting green (environment-friendly) policies (or as fuel prices fluctuate due to economic turbulence and political tension), investments in such structures become even more critical. According to UNCTAD (2012), about 80% of global trade by volume (over 70% by value) is transported by sea and handled by ports worldwide. While a single hub transshipment strategy is used in some applications, such as airlines, in ocean-going services of the liner shipping industry a multiple transshipment strategy is typically used. Singapore and Hong Kong in Asia, Rotterdam and Hamburg in Europe and Long Beach in the U.S. are examples of the world's major hub ports. The airline industry adopted hub-and-spoke strategies a few decades ago. Frankfurt (FRA) and Paris (CDG) in Europe, Hong Kong (HKG) and Singapore (SIN) in Asia and Atlanta (ATL) and Chicago (ORD) in the U.S. are examples of the world's major airports. The concept of cross docking (Boysen and Fliedner,

* Corresponding author.
E-mail addresses: shahin.gelareh@univ-artois.fr, shahin.gelareh@gmail.com (S. Gelareh).

[1] A part of this work has been carried out at:
Department of Optimization, Fraunhofer Institute for Industrial Mathematics (ITWM), Kaiserslautern, Germany, and
Department of Mathematics, Technical University of Kaiserslautern, D-67653 Kaiserslautern, Germany.

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2010) in land transport where cross docks receive less-than-truck-load deliveries, sort them, concentrate them and ultimately generate truckload deliveries is in fact, a kind of hub-and-spoke operation exploiting economies of scale.

In certain cases, the network design is flexible and represents a seasonal decision rather than a long-term strategic decision. An example of such a case is maritime transport. In maritime transport, particularly the liner shipping industry, the concept of network design deals with a relatively short period of time. A hub node (i.e., a container port) is not constructed by a liner company; rather one interface – called a *container terminal* – of its several interfaces is leased for a certain time horizon. The major liner companies then compete to have dedicated container terminals at hub ports in order to minimize turnaround times by reducing the waiting times of their vessels.

The fact that liner companies do not own the hub nodes makes it easier for them to decide to relocate their calling ports, depending on their market share and freight rate in the future. However, as a rule of thumb, once a liner company has decided to terminate the lease of a dedicated terminal at a certain ports, it will be a long time before they can reclaim it – if they can reclaim it at all. This is because, first of all, there is fierce competition among the major liner companies for obtaining such dedicated container terminals. Secondly, due to political reasons, the authorities ruling the port are reluctant to return it to a company that has previously quit. Experience and observation have shown it may take more than the lifetime of one or two governments before a company is able to reclaim a terminal. Therefore, we can imagine that, in the planning horizon considered in our model, once a hub facility (hub port and inter-hub edge) is removed, it will not be re-established in the course of the planning horizon.

Usually, experience shows that when a liner company decides to have a dedicated terminal, it also negotiates that the terminal will be operated by its own port operator sister company. Therefore, there is a fixed setup cost for taking over operations from another operator and staffing the terminal, as well as costs associated with the periodic maintenance of the installations at the terminal, over the period of operation. Moreover, the termination/expiration of a lease contract usually incurs a kind of fixed cost. This cost depends on the number of on-site personnel, administrative costs, demounting and moving assets, mobile port technology and so on.

A similar situation applies to the hub edges. Once a direct hub-to-hub leg of call (hub edge) is established, a fixed cost is incurred to deploy the new service, obtain insurance and, eventually, to sign agreements between the liner company and both endpoint ports. The insurance rate, of course, depends on many factors, most importantly the regional and political factors, but also the financial risks associated with that leg of call. When a hub-to-hub connection is abandoned, it incurs a fixed cost composed of compensations, relocation and logistic costs.

The example of a *dedicated container* terminal might be extreme. However, even if a liner company does not have a dedicated terminal, for many of the major liner companies, there are still some agreements between the company as a major client and the related port operators under which our aforementioned assumptions hold.

1.1. Contribution and motivation

To the best of our knowledge, this is one of the first models proposed for the *uncapacitated multi-period multiple allocation hub location problem*, which was initially proposed in Gelareh (2008). This multi-period model incorporates realistic features of real-world hub-and-spoke transport as follows: (1) *multiple allocation* of clients (non-hub/spoke ports) to hub ports, which helps client nodes diversify their service providers in order to avoid monopoly and reserve the possibility of negotiation; (2) emphasis on the connectivity of the hub-level network instead of completeness, as is known in the classical models of hub location; and (3) the unique opportunity for change in the status of a hub element (node or edge) over the planning horizon, as exercised by many operators in the industry, is reflected in this model. While these assumptions make the formulation much more involved and affect computational performance, they contribute to a better approximation of real-life practice.

A meta-heuristic approach equipped with escape mechanisms is proposed. The method is shown to be very efficient at producing high-quality solutions while being a computationally *inexpensive* and *robust* procedure.

We extend and improve the Benders decomposition algorithm proposed in Gelareh and Nickel (2011) by proposing a different MIP model as the master problem (MP), which results in faster convergence. The new MP eliminates a large part of the original MP polyhedron that contains infeasible solutions of the original model. Several techniques and tricks have been used to improve the performance of the decomposition, including several branching rules, the use of an analytic center in generating cuts and dealing with degeneracy and examining the possibility of incorporating (meta-) heuristics during the Benders decomposition process.

1.2. Literature review

Hub location problems (HLPs) originate from the seminal work by Hakimi (1964) on finding the optimal location of a single switching center that minimizes the total wire length in a communication network. He showed that one can restrict oneself to find the vertex median of a corresponding graph. Later, Goldman (1969) proved that Hakimi's argument holds even for more general cases.

While studies on the hub-and-spoke network structures in transportation date back to Toh and Higgins (1985), the models by (O'Kelly, 1986a,b) were the first continuous location models for HLPs that could locate two hub nodes in a plane. Later, with the quadratic integer programming model in O'Kelly (1987), the research mostly focused on discrete variants.