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Two-stage approach to the intermodal terminal location problem

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ABSTRACT

Multimodal transportation means to transport freight using at least two transportation modes. Intermodal freight transportation, a particular form of multimodal transportation, transports freight in an intermodal container without handling of the freight itself when changing modes. The intermodal terminal location problem involves selecting terminals that constitute an intermodal transportation network and routing freight flows with minimal total transportation and operating costs. Arnold et al. first presented mathematical programming models for the problem. Sörensen et al. recently proposed another model for the problem. However, Lin et al. have shown that the model of Sörensen et al. is complex and time-consuming and therefore developed a modified mixed integer programming model to increase computation efficiency. This study shows that the model of Lin et al. can be further improved by separating the selection of intermodal terminals from the routing of transportation flows. A two-stage programming approach is proposed along with a modified, more efficient matheuristic.

1. Introduction

As global trade expands, long-haul transportation is increasingly important. Unimodal long-haul transportation that uses only one transportation mode (e.g., road, rail, or water) is literally impossible for global trade. Managing multimodal transportation is thus important both practically and academically. Multimodal transportation transports goods by using at least two transportation modes. Intermodal transportation, a particular form multimodal transportation, has received considerable attention in recent years. According to the European Conference of Ministers of Transport [1], intermodal transportation refers to the movement of goods in the same loading unit without handling the goods themselves during transfers between modes. Intermodal transportation is well recognized as environmentally friendly, capable of reducing congestion, accessible, and highly feasible for global trading.

The multi-faceted literature on multimodal and intermodal transportation addresses issues such as decision of the number and location of terminals, route selection [2], cost analysis [2,3], transport policy [4] and intermodal decision support [5]. Literature reviews on multimodal transportation followed a common framework of the decision horizon of planning: strategic, tactical, and operational planning. Macharis and Bontekoning [6] intercrosses the decision horizon and the decision maker horizon (drayage, terminal, network, and intermodal operators) to classify existing works and identify potential applications of OR methods to intermodal transportation. In addition to adopting the decision horizon, Bektas and Crainic [7] stress the importance of intermodal terminals that form the most critical components of the entire intermodal transportation chain. The efficiency of the latter heavily depends on the speed and reliability of the operations performed by the former.

Adopting the decision horizon, SteadieSeifi et al. [8] depicted multimodal decision-making problems in each of the categories respectively with a number of features. They found that the terms multimodal and intermodal are used interchangeably in the literature and thus use multimodal consistently in their survey. However, as mentioned above, some still recognize intermodal transportation as a special case of multimodal transportation. The difference lies in whether the goods themselves are handled during transfers between modes. Multimodal problems appear more complicated than intermodal because translation of flow units between different modes is required. SteadieSeifi et al. [8] focused on the decision planning problem in infrastructure investment decisions, the setup of multimodal terminals, a fundamental problem underlying other management issues. Intermodal terminals constitute the foundation of an intermodal transportation network. This network design problem is usually formulated as a hub location problem, which is also the main body of the decision planning problems in [8].

In a many-to-many distribution system, hubs usually aggregate flows from different origins and dispatch them to different destinations through other hubs. The hub location problem concerns itself with locating hubs and routing flows of origin-destination

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pairs to pass through them. Surveying the literature before 2008, Alumur and Kara [9] identified two basic types of allocating flows to hubs: single allocation and multiple allocation. In single allocation, all of the outgoing/incoming flow of an origin/destination is allocated to a single hub, while in multiple allocation, the outgoing/incoming flow of an origin/destination can be distributed among multiple hubs. Moreover, hub location problem generally assumes that the network between hubs is a complete graph and that links between hubs cost less than others links. Additionally, allowance of direct flows between non-hub nodes depends on the decision-making context. For example, the hub location problem of Santos et al. [10] allows direct flows between non-hub nodes.

Furthermore, Alumur and Kara [9] have classified hub location problems into four categories: the p-hub median problem, the hub location problem with fixed costs, the p-hub center problem and the hub covering problem. The p-hub center problem is a minmax type problem, while the hub covering problem is a facility covering problem, in which demand nodes are considered to be covered if they are within a specified distance of a facility. The p-hub median problem minimizes only the total transportation cost and does not consider the costs of the intermodal terminals. The hub location problem with fixed costs can be regarded as an extension of the p-hub median problem. The term p-hub assumes that the number of hubs must be below or, in some cases, exactly equal p. However, depending on the optimal solution, the number of hubs is no longer a constant in the hub location problem with fixed costs. Both the p-hub median problem and the hub location problem with fixed costs can be further divided into single allocation and multiple allocation problems. The hub location problem with fixed costs also concerns itself with the capacities of hubs. Therefore, the p-hub median problem can also be divided into uncapacitated and capacitated problems. Combinations of these features create different problem variations. For example, the hub and spoke networking problem is a single-allocated p-hub median problem with fixed costs. Hub location problems are multiplex. The reader can also refer to a recent survey by Farahani et al. [11]. Unlike the survey of Alumur and Kara [9] that considers only studies on network-type hub location problems, Farahani et al. [11] have reviewed the most recent advances pf all variants of hub location problems from 2007.

The *intermodal terminal location problem* (ITLP) is a special form of the hub location problem. In their pioneering work, Arnold et al. [12] formulated an extension of the p-hub median problem with fixed costs and unlimited capacities. Although the model allows for transportation between non-hub nodes, unimodal and multimodal transportation between each pair of origin and destination are mutually exclusive. Subsequently, Arnold et al. [13] developed another model to improve the inefficient model in [12], by decreasing the large number of 0–1 variables. This p-hub median problem denotes terminals as arcs rather than nodes to reduce the number of decision variables. The uncapacitated hub location problem with fixed costs of Racunica and Wynter [14] allows no direct flow between non-hub nodes. In the p-hub location problem of Limbourg and Jourquin [15], each origin can be assigned to several hubs, and setup cost is considered. Ishfaq and Sox [16] proposed another model which considers more service and cost issues than related models. Uniquely, the problem is a p-hub median problem with fixed costs. However, no capacities are considered.

Sörensen et al. [17] recently developed a model for the ITLP and proved it to be NP-hard. They then developed heuristics to solve it. The representative work of Sörensen et al. [17] was classified by SteadieSeifi et al. [8] as a strategic planning problem with multi-allocation, direct shipment, and capacitated hubs. However, these features are themselves insufficient to distinguish the ITLP from similar problems.

Lin et al. [18] indicated that single allocation seems to be unrealistic in a transportation network and prohibitive in terms of minimizing transportation costs. Furthermore, terminals are unlikely to have an unlimited capacity. If terminals were to be capacitated, a limited number of hubs and prohibiting of direct flows between non-hub nodes also appear to be unrealistic. They distinguished the ITLP from hub location problems by the following features:

1. Unconstrained number of terminals;
2. Capacitated terminals usually with setup costs;
3. Multiple allocation between nodes;
4. Direct shipment between non-hub nodes.

The last three characteristics conform to the classification features applied by SteadieSeifi et al. [8] to the work of Sörensen et al. [17]. However, whether the hub number is limited is not a concern of SteadieSeifi et al. [8].

Although the model of Sörensen et al. [17] conforms to all four features of ITLP, Lin et al. [18] have shown that the model can be improved by eliminating some of its redundant variables and constraints. They also developed two matheuristics to obtain solutions very close to the optimal solutions within a short computation time, especially for large problems. Nonetheless, room for improvement remains. The difficulty in solving the 0–1 programming problem lies mainly in the selection of terminals. Given a set of intermodal terminals, routing the flows with respect to the terminals can be solved by a linear programming problem without 0–1 variables. Further, as mentioned earlier, selecting intermodal terminals is crucial to the ITLP, far more important than routing the transportation. The latter task can become weightless after the terminals are determined. With this in mind, this study proposes to separate the selection of terminals from that of transportation routes in a two-stage optimization approach.

The rest of this paper is organized as follows: Section 2 reviews existing models for the ITLP. Section 3 presents the proposed two-stage approach, along with proofs of its validity. Section 4 then states a modified matheuristic to solve the ITLP more efficiently. Section 5 experimentally compares models and heuristics. Conclusions and recommendations for future research are offered in Section 6.

2. Models for the ITLP

Arnold et al. [12] developed a core model with many extensions to determine the optimal rail/road network in Belgium, which represents a typical intermodal transportation decision-making problem. Most of the mixed 0–1 programming models are p-hub median problems. One of the extensions is a hub location problem with fixed costs, which was modified by Sörensen et al. [17] in developing their own extension. Later, Arnold et al. [13] developed another model for the same problem. That study viewed the terminals as arcs rather than nodes, allowing for a significant reduction in the number of decision variables. Following the course of Arnold et al. [13], Ishfaq and Sox [16] developed a sophisticated model to allow for more practical considerations.

Sörensen et al.[17] recently developed another model for the ITLP. Their model is as follows. Let I denote the set of all origin (destination) nodes and K denote the set of all potential terminals in the network such that $I \cap K = \varnothing$. Each pair of origin and destination nodes (i,j) is associated with a transportation cost c_{ij} and a demand q_{ij} that should be transported. Without a loss of generality, assume that $q_{ii} = 0$. The term w_{ij} represents the direct transport from node i to j while x_{ij}^{km} represents the goods transported from node i to j through terminals k and m, respectively.