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Efficient model and heuristic for the intermodal terminal location problem

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ABSTRACT

A multimodal transportation system transports freight using at least two transportation modes. Among available transportation modes, intermodal freight transportation transports freight in an intermodal container or conveyance without handling the freight itself when changing modes. The locations of intermodal terminals constitute the foundation of an intermodal transportation network. The intermodal terminal location problem therefore aims to determine terminal locations and routes within a transportation network in order to minimize the total transportation and operation costs through collaborations of unimodal road transport and intermodal transport chains. Relevant research includes that of Arnold et al., who first presented mathematical programming models for the problem. Sorensen et al. recently proposed a standard model for the same problem. However, these models are complex and time consuming. Some decision variables and constraints of Sorensen et al.'s model are proven to be redundant. A modified mixed integer programming model is then developed to increase computation efficiency. The modified model finds more optimal solutions to the benchmark problems than current approaches do, within a reasonable time. Furthermore, two matheuristics are presented to solve the problem more efficiently while obtaining near optimal solutions.

1. Introduction

Multimodal transportation transports goods by using at least two transportation modes. Intermodal freight transportation, or simply intermodal transportation, has received considerable attention in recent years, owing to its comparable results with those of conventional unimodal transportation modes. According to [1], *intermodal freight transport* refers to the movement of goods in the same loading unit or vehicle which uses successive and various modes of transport (e.g., road, rail or water) without handling the goods themselves during transfers between modes. As is well recognized, intermodal transportation is environmentally friendly, capable of reducing congestion, accessible and highly feasible for global trading.

Literature on multimodal and intermodal transportation is multi-faceted, having addressed issues such as route selection [2], cost analysis [3,4], transport policy [5] and intermodal decision support [6]. A review of applications of OR methods to intermodal freight transport can be found in [7]. However, a fundamental problem lying under these management issues is how to locate intermodal terminals which constitute the foundation of an intermodal transportation network.

Notably, the *intermodal terminal location problem* (ITLP) is a special case of the hub location problem. Hubs function as switching, transshipping and sorting nodes 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 allocating flows of origin-destination pairs to pass through them. While thoroughly surveying related literature before 2008, Alumur and Kara [8] identified two basic allocation types to assign transport 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 whereas, in multiple allocation, the outgoing/incoming flow of an origin/destination can be distributed among multiple hubs. Moreover, previous studies in the hub location problem assume the following: the hub network is complete with a link between each hub pair; a discount factor between 0 and 1 exists for using the link between hubs; and no direct flow is allowed between non-hub nodes.

Alumur and Kara [8] 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. Further details regarding these problems can be found in

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[8]. The p-hub center problem is a minimax 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 that can serve their demand. The p-hub median problem minimizes only the total transportation cost and does not consider costs of intermodal terminals. The term p-hub assumes that the number of hubs must be exactly equal to p. However, depending on the optimal solution, the number of hubs is no longer a constant in the hub location problem with fixed costs, which attempts to minimize the total transportation cost plus the total setup cost of terminals. 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 problem can also be divided into uncapacitated and capacitated hub location problems.

In computer networks, single allocation usually occurs in the local area network layer. Facilities in the Internet layer are mostly multiple-allocated to disperse flows to prevent from congestion. Similarly, in a transportation network, single allocation seems to be unrealistic and prohibitive in terms of minimizing transportation costs. Furthermore, terminals unlikely have an unlimited capacity of operation. Assuming that no direct flow between non-hub nodes is allowed or that exactly p hubs must/can be opened is also unrealistic, especially when terminals have restricted capacities. Moreover, some terminals might have low utilization rates if the number of terminals is fixed. We can infer that an ITLP is a specific variant within the family of hub location problems with the following characteristics:

1. The number of terminals is not fixed and depends on the total costs;
2. Each terminal is associated with a setup cost and an operating capacity;
3. Each origin/destination can be assigned to multiple terminals; and
4. Freight can be simultaneously transported through terminals or between non-hub nodes.

Although hub location problems usually do not allow for direct flows between origins and destinations, ITLP does. The ITLP does not allow transportation using only one terminal but only using exactly two terminals. Therefore, the fourth characteristic distinguishes the ITLP from the hub location problem.

In a pioneering study, Arnold et al. [9] determined the locations of intermodal terminals based on the concept of hub location problems. The basic formulation in [9] is a p-hub median problem. As an extension of this problem, a hub location problem with fixed costs and unlimited capacities is also formulated. Notably, these models allow for transportation of freight between non-hub nodes. However, freight between each pair of origin and destination can only be transported through either unimodal or multimodal transport. Arnold et al. [10] developed another model to solve the inefficient models in [9], due to large numbers of 0–1 variables. In that study, the terminals are assumed to be arcs rather than nodes, allowing for a significant reduction in the number of decision variables. The formulation is a simple p-hub median problem. None of the models in [9,10] conform to characteristic 1–4, explaining why they can be regarded as special ITLPs.

Alternately, as a standard uncapacitated hub location problem with fixed costs, the model of Racunica and Wynter [11] allows no direct flow between non-hub nodes. In the p-hub location problem proposed by Limbourg and Jourquin [12], each origin is assigned to only one hub, and no setup cost is considered. Ishfaq and Sox [13] proposed another model which considers more service and cost issues than related ones do. Uniquely, the problem is a p-hub median problem with fixed costs; however no capacities are considered.

According to a recent literature survey, problems regarding the location of intermodal terminal vary in their assumptions. While recently identifying the intermodal terminal location problem, Sorensen et al. [14] also developed a model for the problem, in order to provide the necessary tools for decision-making processes such as a “what if” analysis that might occur in policy-making or business operation. In addition to proving that the model is NP-hard, that study also developed heuristics to solve it. Although that model [14] conforms to characteristic 1–4, the model efficiency can be further improved to ensure its further applicability. This study demonstrates that some of the variables and constraints in the model of [14] are redundant and can be removed to simplify the model. Two matheuristics are also developed to obtain solutions very close to the optimal ones within a short time, especially for large problems.

The rest of this paper is organized as follows: Section 2 reviews existing models for ITLP. Section 3 then presents the proposed model, along with corresponding propositions and proofs. Next, Section 4 describes the matheuristics that can solve the ITLP more efficiently. Section 5 compares available models and heuristics. Conclusions are finally drawn in Section 6, along with recommendations for future research.

2. Current models

Arnold et al. [9] developed mixed 0–1 programming models to determine the optimal rail/road network in Belgium, which represents a typical intermodal transportation decision-making problem. More important than determining the routes through which goods are transported, selecting intermodal terminals plays a major role in the model. That study also developed a core model with many extensions, which are p-hub median problems. Among the extensions, one is a hub location problem with fixed costs, which was modified by Sorensen et al. [14] to develop a new one. Two of the representative models of Arnold et al. [9] are stated as follows:

Let I denote the set of all origin (destination) nodes and K denote the set of all potential terminals in the network. Each pair of origin and destination nodes (i,j) is associated with a transportation cost c_{ij} and a 0–1 variable w_{ij}. The goods are transported directly from node i to node j if $w_{ij}=1$; otherwise, the goods are transported from node i to j through terminals k and m with $x_{ij}^{km}=1$ and associated transportation cost c_{ij}^{km}. Each terminal $k \in K$ is associated with a fixed setup cost F_k. The 0–1 variable y_k signals the state of terminal k, open or not. Terminal k is open when $y_k=1$ and closed when $y_k=0$. The basic model of Arnold et al. [9] is laid out below.

2.1. Model Arnold-1

$$\text{Min} \sum_{i,j \in I} \sum_{k,m \in K} c_{ij}^{km} x_{ij}^{km} + \sum_{i,j \in I} c_{ij} w_{ij} \tag{1}$$

$$\text{subject to} \sum_{k \in K} y_k = p, \tag{2}$$

$$\sum_{k,m \in K} x_{ij}^{km} + w_{ij} = 1, \quad \forall i,j \in I \tag{3}$$