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Discrete intermodal freight transportation network design with route choice behavior of intermodal operators

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ABSTRACT

We consider a discrete intermodal network design problem for freight transportation, in which the network planner needs to determine whether or not to build up or expand a link to minimize the total operating cost of carriers and hub operators under a general route choice model of intermodal operators. We formulate the problem as a mixed-integer nonlinear and non-convex program that involves congestion effects, piecewise linear cost functions, and a fixed-point constraint. We develop a series of relaxed and equivalent models to reduce the hardness of the problem and provide theoretical results to show the equivalences. We present two solution methods to solve the problem with one returning heuristic solutions and the other generating a globally optimal solution. We offer two numerical experiments to test the two solution algorithms and also shed light on their performance comparisons.

1. Introduction

In this paper, we look into the discrete *intermodal transportation network design (ITND)* problem, in which there exists a *network planner* who attempts to re-design an existing intermodal freight transportation network, while taking care of the benefits of other stakeholders involved, such as carriers and hub operators, and taking into account the route choice behavior of intermodal operators. It is worth noting that, we do not restrict the applications of our study to the setting where a network has to pre-exist. As will be seen later in Section 4, our study can be applied to a special case where there is no existing network and the network planner needs to build up a network from scratch. We will use “cargo” and “freight” interchangeably in this paper.

The network planner could represent a regional, national, or international government division that has made a plan to improve/design an intermodal freight transportation network to foster intermodal cargo flows within its governed area. One example is a port city that intends to develop a dedicated hinterland network to help cargo flows access the port in a smoother and cheaper fashion (Wang et al., 2016). Another example is the Economic and Social Commission for Asia and the Pacific (ESCAP) of the United Nations which has advocated building an integrated transport network, including road, rail, dry ports, and their efficient linkages to seaports and airports, within its member countries (ESCAP, 2007). *Carriers* refer to land transport companies or ocean shipping companies that provide cargo transport services using vehicles, crew, and equipment.

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Hub operators could be thought of as operating companies that provide cargo transfer services at intermodal hubs, such as dry ports, seaports, and border crossing terminals between two adjacent countries, at which cargo needs to be transshipped from one country's vehicles to the vehicles of the other one. We herein use *intermodal operators* to represent all types of entities who make mode and route selections for cargo shipments that need to be transported through the intermodal network and coordinate the entire intermodal transportation processes for cargo flows between origin-destination (O–D) pairs (Meng and Wang, 2011). Examples of intermodal operators include freight forwarders, the third-party logistics companies, and shippers having their own transport departments.

Different stakeholders intervene in the ITND problem with quite different characteristics and behaviors. We now describe how each stakeholder participates in the play.

Carriers and hub operators. Carriers and hub operators are end users of network infrastructures such as vehicles, road lanes, and rail tracks. They could bear a fixed installation cost even when they handle no cargo flows. Moreover, the operations of carriers and hub operators are often believed to exhibit the so-called economies of scale, which refer to the phenomenon that the unit cargo handling cost declines with the growth of the total volume of cargo transported/transferred (Kimms, 2006). We will, therefore, formulate the cost functions for carriers and hub operators to be *piecewise linear* functions with decreasing segment slopes to reflect the economies of scale and with a constant term to model the fixed installation cost.

The network planner. One of the prominent features that distinguish the ITND problem from the traditional unimodal transportation network design problem (cf. Meng et al., 2001; Liu and Wang, 2015) lies at that, in addition to physical links such as rail and road legs, which we refer to as *carrier links* throughout the rest of paper, the network planner needs to determine whether or not to improve/establish transfer links that represent cargo transfer processes between transportation modes/links at intermodal hubs. Thus, the network planner's decisions are *binary* and four-fold: (i) establish a new carrier link (or not), (ii) expand the capacity of an existing carrier link (or not), (iii) establish a new transfer link, and (iv) expand the capacity of an existing transfer link. Note that locating a potential intermodal hub is determined at the same time with the decision on building new transfer links at that hub. If it is optimal to build at least one transfer link at a non-existing but candidate hub, the hub should be opened too; the hub location shall not be chosen otherwise.

Since carriers and hub operators are final users of the network, the network planner is motivated to minimize the total operating cost of carriers and hub operators while making decisions on network design, in order to attract more business and retain more users. Meanwhile, there is a maximum budget that the network planner must not overspend when making decisions.

The network planner would have to acquire the exact distribution of cargo flows over the network before she/he could move forth to calculate the total operating cost of carriers and hub operators under a proposal of network design. The network planner determines the network structure, but the cargo flow distribution is out of her/his control; instead, the cargo flow distribution is a result of the route choice of intermodal operators.

Intermodal operators. Intermodal operators are decision makers who route cargo shipments through intermodal routes between each O–D pair using the services of carriers and hub operators along the routes, assigning cargo flows over the whole network. As a reward, the carriers and hub operators make revenue by earning service fees from intermodal operators.

From the viewpoint of an analyst/modeler, the network planner could use a viable model to forecast the cargo flow distribution over the intermodal network. There exists a variety of models that have been used to predict the network flow distribution based on various assumptions on the choice behavior of route selectors. Classical studies on hub-and-spoke network design (Ernst and Krishnamoorthy, 1998; O'Kelly, 1987) assumed that unit transportation cost is constant on each link, no congestion effects (also known as the flow-time interaction that the unit travel/transfer time over each carrier/transfer link increases as more cargo flows are dealt with on the link) exist, and all cargo flows will be routed through the least-cost route between each O–D pair. Meng and Wang (2011) considered that congestion effects exist, each route's utility (a weighted sum of transport time and cost, which measures the preferences of intermodal operators towards the route) is *deterministic*, and the route choice of intermodal operators follows the user-equilibrium principle that each intermodal operator would choose the largest-utility route, and at equilibrium, no intermodal operator could be better off by shifting to use another route.

However, the assumption of deterministic utilities seems somewhat restrictive, especially when we consider a population of intermodal operators who have quite distinct perceptions on which route is of the largest utility. Discrete choice models, such as multinomial logit (MNL) model, nested logit model, and mixed logit model, can be used to fix the drawback (Ben-Akiva and Lerman, 1985; Train, 2003). Within the framework of discrete choice modeling, route utilities are considered to be *random* over the population of decision makers (i.e., intermodal operators in our study) and a decision maker chooses each route from a set of available routes with a certain probability.

We will thus describe the choice behavior of intermodal operators with random route utilities using discrete choice models and the user-equilibrium principle that no intermodal operator would be better off by changing to choose another route at equilibrium. Unlike as is often assumed in the literature, we do not limit ourselves to a particular distribution for random route utilities and will use a fixed-point equation to model the cargo flow distribution over the network under a general discrete choice model. Such a treatment generalizes a broad family of cases where the choice behavior is described by a specific choice model such as the MNL model, nested logit model, or the mixed logit model.