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A reliable multi-period intermodal freight network expansion problem

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ABSTRACT

This paper addresses the intermodal freight network expansion problem consisting of multiple periods. In each period, the objective is to determine the locations of new intermodal terminals, the amount of capacity to add to existing terminals, and the existing rail links to retrofit. The multi-period planning problem has the added complexity of determining which period a particular improvement should be made given a limited budget for each time period. A probabilistic robust mathematical model is proposed to address these decisions and uncertainties in the network. Due to the complexity of this model, a hybrid Simulated Annealing (SA) algorithm is proposed to solve the problem and its applicability is demonstrated via two numerical examples. Important managerial insights are drawn and discussed on the benefits of utilizing the multi-period approach.

1. Introduction

An efficient freight transportation system is crucial to the competitiveness of the U.S. in global trade (Ortiz, Weatherford, Willis, Collins, & Mandava, 2007). In the last few decades, tax regulations, green policies (Macharis, Caris, Jourquin, & Pekin, 2011) and alternative options to move freight at a lower cost have promoted the use of intermodal transportation. Intermodal transportation is defined as movement of goods in the same load units with more than one mode of transport without handling goods themselves while transferring between modes at intermodal terminals (Lin, Chiang, & Lin, 2014). Around 10% of the total freight volume in U.S. are intermodal shipments (Transportation Statistics Annual Report, 2012). This volume is forecasted to increase 3.25 times by 2040 (Transportation Statistics Annual Report, 2012). To cope with the increasing freight demands and aging infrastructure, intermodal service providers need to continually plan for upgrades of their existing networks, as well as plan for expansion to grow their market share. These expansion plans are long term and are subject to various uncertainties such as changing demands and infrastructure changes. Additionally, the supply capacity of the network may be impacted by natural or man-made disruptions, such as the U.S. West Coast labor dispute in 2002 and damages to oil storage tanks in states of Texas and Louisiana due to hurricane Katrina in 2005 (D'Amico, 2002; Godoy, 2007; Sarkar, Armstrong, & Hua, 2002). Moreover, there are potential new markets which may not have been considered in freight prediction models such as the Freight Analysis Framework (Fotuhi & Huynh, 2015). These factors necessitate the consideration of demand and supply uncertainties in network expansion plans.

One of the principal features of intermodal network design and expansion models is their dynamic nature due to their variable parameters over time (cost, demand, and resources) (Contreras, Cordeau, & Laporte, 2011a; Contreras, Cordeau, & Laporte, 2011b). Additionally, expansion projects require extensive capital investment which may not be available to the stakeholder at the beginning of the planning horizon. These facts are often ignored in the traditional single-period network design problems (Melo, Nickel, & Da Gama, 2006). In the multi-period expansion problem, the planning horizon is divided into multiple time periods and the network is incrementally expanded over the planning period, much like how Class 1 railroad companies expand their network over time. In a report published in October 2014, CSX, a Class 1 railroad company undertook several expansion projects to provide additional capacity to their terminals to meet the increasing demand for intermodal services. They also expanded their network to Canada by building a new terminal close to Montreal to increase the trade opportunities in North America. Opening new terminals in Pittsburg and Central Florida were also planned to meet the long-term growth within these areas (Stagl, 2014). CSX also indicated that they have added a new terminal in Dallas, TX and Chambersburg, PA in October of 2015. (White, 2015). The multi-period approach provides the stakeholder benefits. First, it mitigates the financial burden on the company to acquire significant capital in a short period of time to expand the network. Second, it improves resource management by building terminals "just-in-time," that is, terminals are built only when they are needed. Third and lastly, a more accurate route planning can be done for different time periods utilizing the available resources at

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that period.

Nagy and Salhi (2007) introduced the concept of multi-period location-routing problems considering different time scales for location and routing decisions. They indicated that a multi-period location-routing framework with shorter routing periods within location decision periods is a better approach to modeling real world location-routing decisions. Their motivation for adopting the multi-period decision problem is the frequent changes in cost and demand over time which significantly impact routing decisions. The same case can be made for intermodal freight network expansion problem. A few studies have addressed the intermodal network expansion problem (Fotuhi & Huynh, 2016; Meng & Wang, 2011); However, to date, there has been only one study that used the multi-period approach for the intermodal network expansion problem (Benedyk, Peeta, Zheng, Guo, & Iyer, 2016). In their study, a new model was proposed to evaluate different expansion scenarios over multiple time periods. Their model finds the optimal location for new terminals, determines the optimal capacities for existing terminals and determines the allocation of origin-destination (OD) demand pairs to terminals. Note that in their model, expansion and allocation decisions are made within the same period regardless of possible disruptions that might happen in the network.

The specific objective of this paper is to develop a model for Reliable Multi-Period Intermodal Network Expansion Problem (RMPINEP). RMPINEP includes both strategic and operational decisions. Intermodal network expansion involves strategic, tactical and operational planning levels. At the strategic level, location of new terminals, expansion capacity and links to retrofit are determined. At the tactical level, the modes of transport and shipment schedules are determined. Lastly, at the operational level, the routes are determined for each shipment. An inherent challenge with developing such a model is that expansion and routing decisions are made at different time periods. To model this, it is assumed that the planning horizon is divided into a set of short time periods for routing decisions. However, expansion decisions are made at a subset of these periods and they remain unchanged throughout the planning horizon. It is also assumed that disruptions only happen at expansion time periods and the network recovers from them through the subsequent routing periods until the next expansion period. A robust optimization approach is used to account for forecasted demand errors and possible disruptions during the planning horizon. The contributions of this paper are: (1) development of a new model for multi-period intermodal freight network expansion problem, (2) the developed model considers different time periods for expansion and routing decisions, (3) the developed model incorporates different sources of uncertainty, and (4) development of a meta-heuristic to solve the developed model for large-sized instances.

2. Literature review

Recently, SteadieSeifi, Dellaert, Nuijten, Van Woensel, and Raoufi (2014) provided a comprehensive review of previous studies in multimodal freight transportation planning classified into strategic, tactical and operational planning levels. Strategic decisions deal with investment in infrastructure which may involve adding and/or maintaining intermodal terminals and network links. The intermodal terminal location problem was first studied by Arnold, Peeters, Thomas, and Marchand (2001). They proposed a model to find optimal locations of uncapacitated intermodal terminals in a rail-road intermodal network with unimodal (direct) and intermodal shipping options. In a follow-up work, they improved their previous model by considering intermodal terminals as network arcs to reduce number of decision variables in their model (Arnold, Peeters, & Thomas, 2004). Ishfaq and Sox (2011) formulated a model for finding the optimal locations of intermodal terminals and allocation of commodities with limited time windows to pairs of terminals. Their model ignored the direct shipping option between origins and destinations. Sörensen, Vanovermeire, and Busschaert (2012) added limited capacity at intermodal terminals and direct shipping option to the Ishfaq and Sox (2011) model, but ignored the time window constraints for shipments. Their model was modified by Lin et al. (2014) to reduce redundant variables.

The aforementioned articles assumed there is no uncertainty involved in problem parameters. However, terminal locations are long-term decisions with many uncertainties arising from changes in demand, cost, capacity, and network disruptions. Uncertainty in demand have been widely investigated in network design problems in the last decade. Atamturk and Zhang (2007) proposed a robust two-stage network design model with uncertain demands. The binary link design variables were defined in the first stage and flow was assigned to the network after the actual values of the demand were revealed in the second stage. Yang (2009) formulated a stochastic two-stage air freight hub network design problem. He assumed that the demand is uncertain and varies seasonally. Its model found the optimal number and location of hubs in the first stage and subsequently determined the freight routes in the second stage. Contreras et al. (2011a, 2011b) proposed a model for stochastic uncapacitated hub location problem with uncertain demand and transportation costs. Shahabi and Unnikrishnan (2014) considered uncertain demand within a hub network design problem and showed that more hubs should be opened compared to the deterministic hub network design decisions. Fotuhi and Huynh (2015) were the first to consider uncertain demand for competitive intermodal terminal location problem. They proposed a robust model to find the optimal number, location and size of intermodal terminals and allocation of freight flow to the network for a private rail road company. They showed that terminals that have larger capacities are better equipped in dealing with demand variations.

Capacity is another source of uncertainty which may be caused by natural or human-made disasters in network elements (links or nodes). These disruptions can lead to delay in order delivery, loss of market share, and higher transportation costs. For this reason, it is recommended that capacity be included in models to incorporate reliability in network design decisions (Peng, Snyder, Lim, & Liu, 2011). D'Este and Taylor (2003) suggested that it is best to invest on the weakest elements in the network to reduce network vulnerability to disruptions. Several studies have incorporated disruptions in transportation network design decisions. Rios, Marianov, and Gutierrez (2000) formulated a capacitated network design problem with disruptions to network links. Their model determined which set of links to open and their corresponding capacities to guarantee network survival in case of disruptions. Viswanath and Peeta (2003) proposed a multi-commodity maximal covering network design model to address network risks due to earthquakes. Their model identified critical routes in the network and higher risk bridges within those routes that need to be retrofitted. Desai and Sen (2010) considered link failure risk in a reliable network design model which allocated resources to mitigate the disruption impacts on higher risk links in the network. Peeta, Salman, Gunnec, and Viswanath (2010) formulated an investment model to retrofit higher risk links in a highway network. A few studies have incorporated facility (node) disruptions in logistics and transportation network design problems. Peng et al. (2011) proposed a model for reliable logistics network design problem with disruption risk at suppliers and distribution centers. Their model found optimal locations for these facilities and flow allocation to the corresponding network minimizing disruption risks. An, Zhang, and Zeng (2015) considered disruptions in transshipment nodes for a hub-and-spoke network design problem. Their model found the optimal locations of backup hubs while minimizing the expected transportation cost for normal and disrupted situations. Marufuzzaman, Eksioglu, Li, and Wang (2014) incorporated disruptions at intermodal terminals in a biofuel supply chain design problem. Their model found locations of intermodal terminals and biorefineries while minimizing total fixed and transportation costs. Miller-Hooks, Zhang, and Faturechi (2012) considered disruptions in both network links and terminals of an intermodal network design problem. They found best recovery and pre-disaster policies to maximize network