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Managing congestion in supply chains via dynamic freight routing: An application in the biomass supply chain

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ABSTRACT

This paper manages congestion in the supply chain via dynamic freight routing and using multi-modal facilities in different time periods of a year. The proposed mixed integer non-linear program (MINLP) model captures the trade-offs that exists between investment, transportation, and congestion management decisions. A linear approximation of the proposed MINLP model is then solved using a hybrid Benders-based rolling horizon algorithm. The performance of the algorithm is tested on a case study that uses data from the Southeast USA biomass supply chain network. Extensive numerical experiments provide managerial insights to manage congestion from the biomass supply chain network.

1. Introduction

The main objective of this paper is to develop models to help manage congestion in supply chains which rely on using multiple transportation modes and multi-modal facilities for freight delivery. The models proposed capture the trade-offs between congestion and facility location; congestion and transportation mode selection; transportation network design and product seasonality.

A number of applications for this model can be found in the agricultural sector. For example, in the USA grains are typically transported via railways. The amount shipped via railways has indeed increased in the last few years. In 2014, the amount of grains transported via rail increased by 26% as compared to 2013; and 25% as compared to the average during 2011–2013 (Energy Information Administration, 2014). Due to the physical capacity of railyards and railway lines, this increase in the amount of grain (and other bulk products) transported via railways caused congestion and, consequently, traffic delays. These delays impact railway companies and their customers in multiple ways. First, in response to customers' complains, railway companies have to submit weekly reports to federal regulators explanting the nature of the delays. Second, in order to reduce traffic delays, customers may seek other transportation service providers. The goal of this research is to show that transportation planning which relies on reducing congestion via dynamic freight rerouting impacts costs, traffic, and safety.

Multi-modal facilities such as railway yards, sea ports, airports have limited capacities. Capacity issues impact the time it takes to process shipments, and consequently, contribute to traffic delays and congestion. Researchers have investigated this problem and proposed strategies to prevent congestion and improve the performance of multi-modal facilities in a variety of

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application areas. For example, Pels and Verhoef (2004) and Raffarin (2004)propose a few pricing strategies to control flight congestion in airports. Ebery et al. (2000) and Sasaki and Fukushima (2003)add an additional capacity constraint in their model formulation to mitigate the impact of congestion in airports. To the best of the authors' knowledge, the impact of capacity limitations of multi-modal facilities on traffic congestion along multiple modes of transportation has not been carefully studied. To address this need we propose a congestion management strategy which dynamically allocates freight to different modes of transportation, and dynamically selects multi-modal facilities to use along the delivery routes. This allocation changes from one period to the next during a given time horizon. The facility allocation decisions are affected by transportation costs, product availability due to production seasonality, and transportation-related seasonality. The aim is to minimize the overall system costs, including transportation costs, shipment delay costs, and facility allocation costs.

Fluctuations of traffic flow at multi-modal facilities, due to either demand seasonality or weather conditions, have historically been managed via adjustments of capacity. For example, corn and other grains are delivered by barge from the Midwest to the Gulf of Mexico all year around, other than a few weeks during winter due to the drought in the northern section of the Mississippi river. During this time period corn and grains are delivered via rail or trucks. This practice minimizes delays at multi-modal facilities, and shifts transportation volumes from one to another transportation network. The model proposed in this study helps decision makers evaluate the (short-term and mid-term) impacts that dynamically allocating multi-modal facilities and transportation modes in the supply chain have on the overall system performance.

The model we propose is an extension of the fixed charge network design problem, which is known to be an $\mathcal{NP}$-hard (Magnanti and Wong, 1981). Therefore, solving large instances of our problem is a challenging task. This challenge motivated the development of solution approaches which solve the problem efficiently. The methods proposed are a rolling horizon heuristic, an accelerated Benders decomposition algorithm, and a combinatorial Benders decomposition algorithm. The extensive numerical analysis indicates that, the hybrid combinatorial Benders decomposition based rolling horizon algorithm provides high-quality solutions within a reasonable amount of time when used to solve small-sized problems. For large-sized problems, the stand-alone rolling horizon heuristics and hybrid Benders-based rolling horizon algorithm provide near optimal solutions in a reasonable amount of time. The performance of the algorithms proposed is evaluated using a case study developed based on real-world data from the Southeast USA. This case study is focused on the design of a biomass supply chain. The outcomes of the case study are a number of managerial insights, such as, a plan for dynamic deployment of multi-modal facilities and a plan about the amount of biomass to transport via different modes of transportation. These plans are created using data about biomass feedstock seasonality, facility congestion, and transportation costs. These plans aid decision makers in better managing supply chains.

The paper is organized as follows: Section 2 provides a comprehensive literature review; Section 3 formulates the mathematical model; Section 4 introduces the solution algorithms; Section 5 presents numerical results and draws managerial insights; and finally Section 6 provides conclusions and future research directions.

2. Literature review

The impacts of congestion on hub-and-spoke network design modeling have been studied in the literature. Grove and OKelly (1986) investigate the relationship that exists between hub-and-spoke networks and congestion by simulating the daily operations of a single assignment, hub-and-spoke network. Marianov and Serra (2003) model the hub-and-spoke network as an $M/D/c$ queuing network and solve the model using a Tabu search heuristic. Elhedhli and Hu (2005) introduce a non-linear cost term in the objective function of an uncapacitated hub location design problem in order to quantify the impacts of congestion on supply chain costs. In Elhedhli and Wu (2010), the authors extend their previous study to a capacitated hub-and-spoke network design problem. In both papers, the authors linearize the non-linear cost function by approximating it via a set of tangent hyperplanes. They propose a Lagrangian relaxation algorithm which solves the linearized model in a reasonable amount of time. Most recently, Camargo et al. (2009) model the congestion using a convex cost function. They develop a mixed integer nonlinear programming model for a multiple allocation hub-and-spoke network design problem. The authors successfully solve the problem on a network with 81 nodes by using a generalized Benders decomposition algorithm. A few studies (Miranda et al., 2011; Vidyarthi and Jayaswal, 2014) focus on the impact of congestion under demand uncertainty. A brief overview of the hub location problems and solution methodologies can be found in a recent study by SteadieSeifi et al. (2014).

A few researchers have already highlighted the importance of incorporating congestion in the modeling of biomass supply chain since it is a factor that greatly impacts the efficiency of transportation systems. Biomass is a bulk product, thus, modes of transportation such as rail and barge are typically used for long-haul and high volume deliveries. Hess et al. suggest that the use of hub-and-spoke transportation networks will greatly reduce high-volume and long-haul transportation costs of biomass (Hess et al., 2009). Bai et al. (2011) analyze the impacts of congestion on the supply chain performance by introducing a traffic congestion factor in the facility location model they use. This model decides the optimal location of refineries and the flow of biomass and ethanol in the transportation network. The authors propose a Lagrangian relaxation algorithm that is nested within a branch-and-bound framework which finds a high quality feasible solution in a reasonable amount of time. Finally, the authors conduct a sensitivity analysis to show the effects of highway congestion on biorefinery location and supply chain costs. Most recently, Hajibabai and Ouyang (2013) propose an integrated mathematical model that aims to minimize the total cost of facility construction, roadway capacity expansion, including highway links and railway segments,