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A green intermodal service network design problem with travel time uncertainty

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ABSTRACT

In a more and more competitive and global world, freight transports have to overcome increasingly long distances while at the same time becoming more reliable. In addition, a raising awareness of the need for environmentally friendly solutions increases the importance of transportation modes other than road. Intermodal transportation, in that regard, allows for the combination of different modes in order to exploit their individual advantages. Intermodal transportation networks offer flexible, robust and environmentally friendly alternatives to transport high volumes of goods over long distances. In order to reflect these advantages, it is the challenge to develop models which both represent multiple modes and their characteristics (e.g., fixed-time schedules and routes) as well as the transhipment between these transportation modes. In this paper, we introduce a Green Intermodal Service Network Design Problem with Travel Time Uncertainty (GISND-TTU) for combined offline intermodal routing decisions of multiple commodities. The proposed stochastic approach allows for the generation of robust transportation plans according to different objectives (i.e., cost, time and greenhouse gas (GHG) emissions) by considering uncertainties in travel times as well as demands with the help of the sample average approximation method. The proposed methodology is applied to a real-world network, which shows the advantages of stochasticity in achieving robust transportation plans.

1. Introduction

Freight transportation activities are closely related to the movement of goods between different locations within a supply chain network. Global outsourcing activities of companies aim to use advantages and expertise of suppliers from all over the world (Kotabe and Murray, 2004). The growing specialization and internalization of the world trade has led to increasing distances between suppliers, producers and final customers. This development resulted in the increasing volumes of global transportation operations during the last decade (see, e.g., OECD, 2010; UNCTAD, 2013).

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The growth in international shipping also influences the volume of inland transportation operations. Within the EU-28 (European Union's 28 countries), about 2,100 billion ton-kilometers of goods were transported in 2012, with road transportation accounting for about three quarters (75.5%) of this volume (Eurostat, 2013). The high share of road transportation can be explained by a relatively dense transportation network enabling fast door-to-door transports and high flexibility in route planning (Kummer, 2006). However, the growing volumes of road transportation contribute to congestion on road, which leads to delay, disruption, and other negative impacts on the reliability of transportation (European Commission, 2012). Moreover, transportation is one of the main attributes to the growth of carbon dioxide equivalent (CO_2e) emissions (European Commission, 2014), where the impact of road transportation is significant. Therefore, companies are searching for alternative transportation options that allow them to minimize the negative impacts of road transportation and improve the economic and environmental performance of their distribution systems (see, e.g., Forkenbrock, 1999; Demir et al., 2015).

Freight transportation services involve various transportation modes - road, rail, maritime, air and pipeline. The number of transportation alternatives can be increased by using different transportation modes and combining them in multimodal transportation chains. Multimodal transportation not only promotes advantages of each transportation mode but also releases their disadvantages. Multimodal transportation is mainly used on routes with high volumes and long distances where the economies of scale and environmental advantages offered by rail or maritime outweigh the additional costs and possible mode-connection delays (Vannieuwenhuyse et al., 2003). The handling activities during transhipment can be facilitated by using a standardized loading unit (i.e., container) which is normally required in intermodal transportation (ECMT, 1993).

As defined by the ECMT (1993) intermodal freight transportation is a specialization of multimodal transportation. It consecutively uses multiple modes while moving the goods within a loading unit. Thus, the goods themselves do not have to be handled, but only the loading unit. Since a loading unit is often a standardized container, intermodal transportation is also referred to as containerized transportation.

Intermodal transportation has numerous advantages in addition to the noted flexibility offered by multimodal transportation. Standard sizes, faster transhipments, and reduced packaging expenses are essential benefits for shippers with large volumes (Jennings and Holcomb, 1996). Intermodal transportation offers a fast alternative to unimodal transportation by road especially for long distances and, therefore, its volume has been growing significantly over the last decade. Thereby, an effective intermodal transportation is necessary for bringing maritime containers arriving to European ports to hinterland customers. In particular, rail and maritime play an important role in sustainable transportation (UIC, 2012). The complexity of transportation plans lies in the use of multiple transportation modes and uncertainty in travel times and demands. In addition, constraints (e.g., fixed time schedules and routes, transhipment, sequence of transportation services, etc.) need to be considered in the planning phase.

In response to the above-mentioned complexities, this paper presents a stochastic mixed integer linear programming formulation based approach for an advanced intermodal transportation planning problem on a transportation network including different transportation modes and transhipment locations. The aim of the paper is to generate optimal and robust transportation plans using the intermodal transportation network. Capacity, travel and service times as well as costs and greenhouse gases (GHGs) of each specific service are taken into account. Moreover, the proposed methodology allows planners to optimize their transportation plans according to weightable objectives (i.e., cost, time and GHG emissions) and considers uncertainties connected with travel times as well as demands.

The paper is structured as follows. Section 2 describes the problem definition and gives an overview of the literature. Section 3 then outlines some of the modeling methodologies used for incorporating uncertainties as well as environmental criteria into the solution methodology while Section 4 describes the mathematical formulation. Section 5 focuses on the application of the proposed methodology to a sample case study based on real-world intermodal transportation network combining road, rail and inland waterway. Section 6 discusses the computational results when applying the stochastic approach to bigger real-life instances. Conclusions and future research directions are stated in Section 7.

2. Problem description

In intermodal transportation, containers can be transported by different transportation modes operated between terminals. While most of the transports on the road are not scheduled, transportation services (rail, air and maritime) in intermodal transportation networks normally follow fixed schedules. In that case, Service Network Design (SND) provides intriguing possibilities for the reproduction of transportation flows on more than one mode including schedules. Moreover, it offers methodological possibilities which enable the representation of transhipments as well as the consolidation of containers.

The problem addressed in this paper is routing and scheduling of customers' transportation orders by selecting available as well as also planning transportation services within an intermodal transportation network. A service can be characterized by its origin, destination, intermediate terminals, transportation mode, route, service capacity and starting time window (SteadieSeifi et al., 2014). While research on the design of services within networks is quite extensive, SND literature concerned with the selection of available services for specific shipments is scarce and less advanced (see, e.g., Crainic, 2000; 2003; Wieberneit, 2008). The orders are characterized by a certain number of containers which have to be transhipped from origin to destination within specified time windows. Whereas the transportation cannot start before a specified release time, late arrivals to destinations are allowed with a penalty cost.

Since some of the services depart according to fixed schedules, it is not possible to wait for late containers due to unexpected delays during transportation. Fig. 1 displays a transportation network which shows one possible intermodal route for an order with origin *A* and destination *D*. The pickup time thereby is T_{dep} while the due date at the destination is T_{due}. The presented route