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A simulation-optimization approach for scheduling in stochastic freight transportation

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ABSTRACT

In this paper, a new Simulation-Based Optimization Model (SBO-Model) is proposed to solve scheduling problem in stochastic multimodal freight transportation systems. The model is applied to find optimal services schedule in a real-world case study. In order to handle demand and travel time inherent variability, the stochastic service network design problem is addressed. Simulation modeling is used to efficiently account for real stochastic behavior with skewed continuous distributions. Such distinctive distribution shapes were commonly reported in transportation research studies that addressed the travel time reliability modeling. Results indicate that the SBO-Model can indeed provide reliable service schedules even under realistic complex stochasticity. The main finding is that, in order to solve efficiently such stochastic optimization problem, we need to go beyond the mean and variance estimates by considering the empirical distributions of uncertain parameters. Specifically, when the data exhibit skewness and/or multimodality, which are commonly found due to the traffic congestion.

The originality of this work lies in the integration of stochastic models, commonly used in the transportation research field, for solving logistics planning problem generally addressed by Operations Research community.

1. Introduction

Global freight transportation has grown exponentially in the context of the globalized economy. Multimodal freight transportation has become consequently a key success factor for logistics service firms. Multiple transportation modes such as railway, roadway and waterway services are combined for efficient containerized freight delivery. In this context, determining the optimal service schedule which satisfies the delivery requirements for a set of commodities has become a fundamental tactical planning problem (Wang & Wallace, 2016). This NP-hard optimization problem has attracted since early 90s a considerable amount of attention from the Operations Research community (Crainic, 2000). More recent research studies (e.g. Chávez, Castillo-Villar, Herrera, & Bustos, 2017; Demir et al., 2016, Lium, Crainic, & Wallace, 2009; Meng, Wang, & Wang, 2012) have shown that solving Service Network Design Problem (SND) with the assumption that planning elements, such as demand and travel time, are deterministic might result in a complete failure of the transportation planning. Therefore, they addressed the Stochastic SND problem to handle demand and travel times variability. Commonly, the problem is modeled as a multi-stage stochastic program where demand and travel times values are assumed to follow discrete distributions. The reliability of the found freight schedules is then evaluated under different levels of disturbances.

However, it is well established in roadways, railways and waterways transportation related literature, that travel times follow skewed continuous distributions and not discrete distributions (Chalumuri & Yasuo, 2014; Harrison & Fichtinger, 2013; Krüger, Vierth, & Fakhraei Roudsari, 2013; Rakha, El-Shawarby, & Arafeh, 2010; Wen et al., 2017). In the last decade, in order to develop travel time reliability metrics, the transportation research community has intensively studied travel time distribution fitting. They found that travel time's variability has to be modeled with skewed continuous distribution such as the Lognormal and Gamma distributions. Besides, very often due to congestion, travel times data in roadway and waterway exhibit bimodality. Then, it was necessary to recourse to Mixture distributions (Guessous, Aron, Bhouri, & Cohen, 2014; Harrison & Fichtinger, 2013; Krüger et al., 2013; Lee, Lee, & Zhang, 2015; Rakha et al., 2010; Taylor & Somenahalli, 2010; Wen et al., 2017). In addition, continuous distributions is commonly used to model demand variability (Garrido & Mahmassani, 2000; Juan, Grasman, Caceres-Cruz, & Bekta ş, 2014).

Therefore, our objective is to solve the Stochastic SND problem while considering such continuous distributions of demand and travel time variabilities. Under the proposed resolution scheme, these parameters are not deterministic values but they are random stochastic variables from the fitted probability distributions to their corresponding empirical data. The accurate modeling of such stochastic aspects aims

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to construct more reliable schedule. This issue is a major research challenge in freight transportation planning. According to SteadieSeifi, Dellaert, Nuijten, Van Woensel, and Raoufi (2014), Hrušovský, Demir, Jammernegg, and Van Woensel (2016), Lee and Song (2017), Chávez et al. (2017), taking real stochasticity, i.e. of empirical data, into account will greatly improve schedule reliability in real-world applications. For that purpose, we do not try to develop another analytical model for solving such stochastic problem. Instead, we seek to implement a different modeling paradigm, the Simulation-Based Optimization (SBO) approach to solve the freight stochastic SND problem. This SBO approach, also known as Simulation-Optimization (Fu, 2002), has proven to be a very powerful tool to solve stochastic problems. According to Oliveira, Lima, and Montevechi (2016) and Chica, Juan Pérez, Cordon, and Kelton (2017), the success of this approach in decision making is mainly due to the capability of Simulation models to incorporate uncertainties, and the real stochastic nature of the environment.

Thus, we developed a Simulation model for freight SND. Then, we coupled this Simulation model, based on the Arena language with optimizer, Optquest, in order to solve the SND problem. We first validated this SBO-model on a recently addressed real-world case study of deterministic freight transportation problem combining roadway, railway and waterway (Demir et al., 2016). It was shown that we can reach the optimal service schedule. We also investigated the capability of our SBO-model to solve the Stochastic SND problem. We went beyond simplistic uncertainties, generally modeled as levels of disturbances, by considering continuously distributed demand and travel times. It was found that our SBO-model can deal with complex stochasticity and provide a reliable solution. We were able to reach an On Time and In Full delivery (OTIF) of more than 90%. The OTIF is a key indicator for logistics systems expressed as the percentage of orders arriving on time and in the right quantity (Rushton, Croucher, & Baker, 2014). Finally, we used an extension of the Value of the Stochastic Solution (VSS) indicator to measure the sensitivity of the output performance to the distribution type of stochastic processes. The VSS is a commonly used measure, in stochastic programming, to calculate the expected loss from using the deterministic solution rather than its stochastic counterpart. This research is among the first to analyze the sensitivity to different distribution types with specific shapes as symmetry, skewness, bimodality and uniformity. We found that the performance is not only sensitive to the variance as shown in former works (Bai, Wallace, Li, & Chong, 2014; Wang, Crainic, & Wallace, 2014), but also to the shape of data distribution.

This paper is organized as follows: Literature review is discussed in Section 2. In Section 3 adequacy of SND problem to solve freight transportation tactical planning is described. The Real-world case study is also presented. Section 4 details the implementation of the SBO model for the SND problem. Section 5 presents computational results and analysis. Finally, conclusions are discussed in Section 6.

2. Literature review

Over the last decades, many works addressed the Service Network Design Problem (SND) to solve the tactical planning issue of services selection, and scheduling in multimodal freight transportation. In early studies, only deterministic SND formulations were proposed in which demand and travel times are considered as deterministic Inputs (Crainic & Rousseau, 1986; Crainic, 2000). More recently, with the need for more reliable planning, a special emphasis is made to address Stochastic Service Network Design in freight transportation. As stated in SteadieSeifi et al. (2014) and Sun, Lang, and Wang (2015), assuming the planning elements such as demand and travel time as deterministic might result in the complete failure of the computed multimodal transportation planning.

To deal with stochastic demand, Lium et al. (2009) proposed a stochastic optimization model based on scenario tree. They used a discrete version of the triangular distribution to consider three different levels of uncertainty in demand; high, low, and no uncertainty. A Mixed-integer programming model was formulated with the objective of minimizing the expected cost over all scenarios. They showed the existence of structural differences between solutions reached under deterministic assumptions versus solutions when stochastic demand is considered. Meng et al. (2012) assumed that demand follows the Normal distribution and formulated the problem as a two-stage stochastic integer programming model. A solution algorithm, integrating the sample average approximation with a dual decomposition and Lagrangian relaxation is then proposed. Demand variability was tested through different scenarios based on random sampling from the Normal distribution. They found that demand variability has a significant effect on the solution. Bai et al. (2014) assumed also that demand uncertainty follows a discrete version of the triangular distribution and extend the model of Lium et al. (2009) by introducing rerouting options to face the demand uncertainty. Wang et al. (2014) and Bai et al. (2014) recourse to the Value of the Stochastic Solution, (VSS), measure to calculate the expected loss from using the solution generated from the deterministic model rather than its stochastic counterpart. They found that when the Coefficient of Variation, CV, is high, i.e. CV $\geqslant$ 30%, the VSS could be high which indicates a bad deterministic solution. Recall that, a CV is the ratio of the standard deviation to the mean. It is a statistical measure of the dispersion of data around the mean (Krishnamoorthy, 2016). Zhang, Li, Huang, Li, and Qian (2015) used robust optimization to address the network design problem. Their objective was to find the worst-case scenario when the uncertain demand is predefined in an interval. The results show that robust optimization can reduce worst-case cost. It is also found that the variability of the uncertain demand has an effect on the solutions.

Even though the assumption of deterministic travel time was criticized, very few works addressed travel time variability (e.g. (Bai et al., 2014; SteadieSeifi et al., 2014)). Andersen, Crainic, and Christiansen (2009) propose to add a slack variable and they formulate the problem as a mixed integer programming model with a nonlinear objective function. They add a penalty cost in their objective function to consider variability. Chávez et al. (2017) consider the inspection time variability at the border ports of entry. A triangular distribution is used to model this stochastic continuous time disruption. In their work, only road transportation mode is considered and travel time between nodes is assumed deterministic. The main finding was that ignoring the continuously distributed inspection time lead to inefficient routing plan. To the best of our knowledge, Demir et al. (2016) is the only work which addressed both demand and travel time uncertainties for solving SND problem in multimodal freight transportation. However, demand and travel times uncertainties are also assumed to follow a simple three-point discrete distribution. They formulate the problem as a stochastic linear mixed integer programming model. A real-world case study including road, rail and inland waterway services is solved using the sample average approximation method. They showed that the solution of the optimal schedule is more sensitive to travel time uncertainty than to demand uncertainty.

From this literature review, we can see that considering the variability is essential for more efficient tactical planning in multimodal freight transportation. Besides, according to Mönch, Lendermann, McGinnis, and Schirrmann (2011), SteadieSeifi et al. (2014), Chávez et al. (2017), Lee and Song (2017), for more reliable planning in freight transportation problems a challenging issue is to take into account real stochasticity, i.e. found in empirical data. Such empirical data analysis for travel times modelling have widely been addressed by researchers in the traffic and transportation field to develop reliability metrics. Rakha et al. (2010), Taylor and Somenahalli (2010), Guessous et al. (2014), Chalumuri and Yasuo (2014) have shown that roadway travel times data are skewed and possess long upper tail. Additionally, bimodality is often present. The first mode represents driving under free flow conditions, i.e. when there is no delay and congestion, the second mode