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Stochastic service network design with rerouting

Ruibin Bai [a,*], Stein W. Wallace [b], Jingpeng Li [d], Alain Yee-Loong Chong [c]

[a] Division of Computer Science, University of Nottingham Ningbo China, Ningbo 315100, China
[b] Department of Business and Management Science, Norwegian School of Economics, NO-5045 Bergen, Norway
[c] Nottingham University Business School China, University of Nottingham Ningbo China, Ningbo 315100, China
[d] Department of Computer Science and Mathematics, University of Stirling, Stirling FK9 4LA, UK

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ABSTRACT

Service network design under uncertainty is fundamentally crucial for all freight transportation companies. The main challenge is to strike a balance between two conflicting objectives: low network setup costs and low expected operational costs. Together these have a significant impact on the quality of freight services. Increasing redundancy at crucial network links is a common way to improve network flexibility. However, in a highly uncertain environment, a single predefined network is unlikely to suit all possible future scenarios, unless it is prohibitively costly. Hence, rescheduling is often an effective alternative. In this paper, we proposed a new stochastic freight service network design model with vehicle rerouting options. The proposed model explicitly introduces a set of integer variables for vehicle rerouting in the second stage of the stochastic program. Although computationally more expensive, the resultant model provides more options (i.e. rerouting) and flexibility for planners to deal with uncertainties more effectively. The new model was tested on a set of instances adapted from the literature and its performance and characteristics are studied through both comparative studies and detailed analyses at the solution structure level. Implications for practical applications are discussed and further research directions are also provided.

1. Background and motivation

Service network design is one of the fundamental problems faced by the freight transportation industry. It is normally viewed as a tactical planning problem in which the company has to decide which terminals will have direct transportation services and at what frequency. In some cases, it also determines the best combination of transportation modes, and periodic vehicular schedules to ensure the continuity of services. Although closely related to classic network flow problems (Ahuja et al., 1993), which can be solved very efficiently, the service network design problem has proven to be one of the most difficult combinatorial optimisation problems around (Crainic and Kim, 2007). Solving real-life problem instances to optimality is generally not possible. Opportunities to develop practical decision support systems for this problem have been strengthened by the latest advances in high performance computing and hybrid optimisation techniques. This has led to increased research attention in service network design in the past decade. Detailed reviews of such research efforts can be found in Christiansen et al. (2007) for maritime transportation, Crainic (2003) for long-haul transportation and Crainic and Kim (2007) for intermodal transportation. Most research cited in these reviews is concerned with models and solution methods for deterministic cases. However, freight services are subject to various

* Corresponding author. Tel.: +86 574 88180278.
E-mail addresses: ruibin.bai@nottingham.edu.cn (R. Bai), stein.wallace@nhh.no (S.W. Wallace), jli@cs.stir.ac.uk (J. Li), alain.chong@nottingham.edu.cn (A.Y.-L. Chong).

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uncertainties (in terms of demands, travel time, vehicle breakdowns, etc.) and their estimation by mean values is incapable of capturing the nature of the real-world problems.

Indeed, handling uncertainties in demand for freight transportation has become one of the most challenging problems for freight forwarding companies. Previously, freight service companies was faced with challenges of satisfying fluctuating demands with cyclic patterns. According to one of the largest Chinese parcel express delivery companies, Shentong Express, back in 2009 freight transportation demand often peaked during the weekdays and fell drastically during the weekends. This was because of the fact that their major transportation demands were production supply chain related and there are more business engagements during weekdays than weekends. However, in the past 5 years or so, e-commerce, online shopping, and recent mobile commerce have truly transformed the landscape and expanded the scale of the freight transportation market. In 2012, Amazon recorded USD 61 billion in sales, a 27.1% increase from 2011. Fuelled by massive sales, the Chinese online shopping site, Taobao, secured more than USD 3 billion in sales on a single day on November 11, 2012, generating 80 million delivery requests which were simply too much for logistic companies to handle. The total online shopping sales in 2012 in China were estimated to be USD 1.3 trillion, up 27.9% from 2011 while the total number of deliveries is estimated to be 6 billion (CECRC, 2013). The diversities and uncertainties of online shoppers (in terms of their physical locations, shopping time, and types and quantities of items that they buy) have made freight service network design extremely difficult. Scientific research is badly needed to address the problem more efficiently.

Previous research studies (Garrido and Mahmassani, 2000; Sanchez-Rodrigues et al., 2010) showed that freight transport demands are indeed highly uncertain over both space and time and estimating their actual distributions can be very challenging but possible. At the same time, research has shown that ignorance of these stochastic factors could potentially result in poor quality of service and high set-up and operational costs (Lium et al., 2009). Lium et al. (2009) and Hoff et al. (2010) represent some of the very limited research on stochastic service network design. One of Lium et al. (2009)'s main contributions is an extension of the classic multi-period service network design model by introducing demand stochasticity in the form of a scenario tree. A mixed integer programming model was developed with the objective of minimising the expected cost over all scenarios. The problem was solved by a two-stage stochastic programming approach in which the master problem (or the first-stage problem) was the determination of a cost-effective service network. The second-stage problem was to find, for a given demand realisation, a cost-minimal flow based on the network obtained in the first stage and outsourcing. The second stage problem serves as a feedback mechanism to the master problem to achieve a balance between the degree of redundancy in network capacity, the network's structure, and the amount of outsourcing (which is often very expensive and strategically unpopular for freight companies). The experiments on a large number of small problem instances showed that stochastic service network design could potentially reduce the costs substantially compared with the solution obtained by a deterministic model. Several interesting patterns have been observed from the experiments, which have profound implications for service network design. A limitation of the model is that the only alternative to using the service network established in the first stage is outsourcing. In practice, a freighter could also re-adjust this network based on observed values of the uncertainties. Hoff et al. (2010) is the continuation of Lium et al. (2009), with the primary aim of developing efficient approaches that can solve large real-sized instances. A Variable Neighbourhood Search (VNS) based approach was proposed and its performance was evaluated on a set of instances of large sizes, which, according to Hoff et al. (2010), is promising.

Our research paper extends the work done in Lium et al. (2009) by incorporating rerouting as a second means of achieving flexibility. This was motivated by the fact that rerouting is a popular means used by freighters to adapt to unforeseeable changes and uncertainties. Compared with outsourcing, rerouting is favourable for freighters in terms of service quality control and long term development strategies. It is not in a freighter's long-term interest to outsource large amounts of demand to its competitors. Additionally, we are also interested in investigating: (1) in what way rerouting will lead to a different network compared with the deterministic network and the network obtained through Lium et al. (2009)'s stochastic model; (2) how the nature of demand stochasticity will affect the performance of different models.

The main contribution of this paper is twofold: primarily, we propose a stochastic programming model for stochastic service network design with options of both vehicle rerouting and service outsourcing to address demand stochasticity more efficiently. Secondly, some interesting observations and insights drawn from our experimental studies could have important implications for stochastic service network design practices. Application of the proposed model could potentially substantially reduce network setup costs and expensive outsourcing, but maintain a similar level of flexibility to those that can be offered by other related models in the literature.

We set the model in the framework of stochastic programming. The main result is a model that provides a design with operational flexibility that can handle varying demand scenarios. This operational flexibility can be useful also if the stochastics is mis-specified, i.e. is different from what we assume. However, in this paper the focus is not on ambiguity (interesting as that is), but rather on understanding the role of rerouting and its effect on operational flexibility. It is also worth noting that for many applications that fit into this modelling scheme, particularly trucking, but also air airfreight transportation, data is normally available in large amounts, and estimating distributions is not unreasonable.

As for earlier papers, we have formulated our model in a two-stage setting. This is not primarily for simplicity, but because we see this as the most appropriate framework. The problem we are discussing in this paper is what has been called an "inherently two-stage problem", see Chapter 1 of King and Wallace (2012). These are problems where the first stage is structurally different from all the others. In our case the first stage is to set up the service network, the rest amount to using/operating the network from Stage 1 in an uncertain environment. Typically, the first stage decisions are either