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Robust models for transportation service network design

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ABSTRACT

In this paper robust models are presented for the transportation service network design problem, using the ferry service network design problem as an example application. The base assumption is that only the mean and an upper bound on the passenger demand are known. In one robust model, this information is supplemented by a lower bound on the demand, whereas in a second robust model, the assumption is made that the variance of the demand is known, in addition to the mean and upper bound. The relationship between the two models is investigated and characterized analytically. A case study using the ferry service in Hong Kong is provided to illustrate the models.

1. Introduction

The service network design problem (SNDP) focuses on generating an operating plan of the service or carrier network for freight or passenger flow, with the purpose of achieving a certain goal while satisfying the transportation demand. The SNDP is typically formulated as a capacity restricted, multi-commodity or multi-mode problem where service provisions or connections are represented as integer decision variables and commodity flows as continuous variables (Magnanti and Wong, 1984; Wang and Lo, 2008; Wang, 2013). SNDP arises in the airlines, rail and maritime industries. For example, Bagloee and Ceder (2011) studied the transit network design problem to optimize the service quality under a budget constraint. Lin et al. (2012) optimized the train connection service network in China. In container shipping, studies focus on optimizing the liner shipping service network (e.g. Meng and Wang, 2011).

This paper presents new robust models for the SNDP, using the ferry SNDP as an illustrative application. The ferry SNDP has been examined in various studies, initially assuming determinism. For example, Lai and Lo (2004) developed a ferry fleet management model to optimize simultaneously the fleet size, routing, and service schedule. Wang and Lo (2008) formulated the problem with different service types, considering users' preferences for express versus ordinary services. In recognition of the importance of modelling uncertainty in transportation systems (Ng and Lo, 2013; Watling and Cantarella, 2013), An and Lo (2011), Lo et al. (2013), and An and Lo (2014) studied the stochastic ferry SNDP considering two types of services, regular and ad-hoc services, to minimize the total operating cost and passenger travel and waiting time. Regular services operate with a fixed schedule; whereas ad-hoc services can be considered as the possibility to subcontract or outsource these services to a third party, which generally incur a higher unit cost. The problem was formulated as a two-stage stochastic program.

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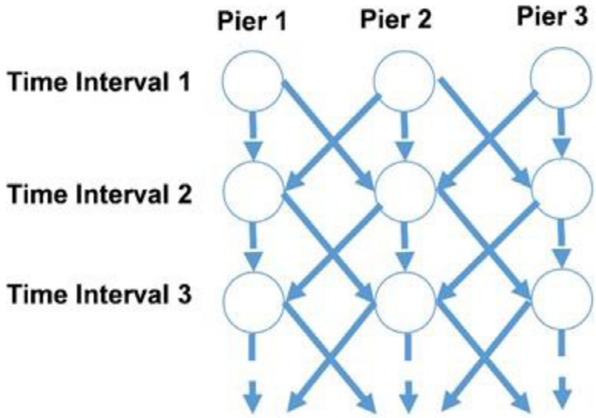

Fig. 1. Sample time space network.

This paper complements the literature by presenting new robust models for the SNDP, using the ferry SNDP as an illustrative example application. Particularly, unlike their stochastic programming based counterparts mentioned above that assume the availability of (accurate) probability distributions characterizing passenger demand, our assumption is that only limited knowledge on the passenger demand exists. More specifically, our base assumption is that only the mean and an upper bound on the passenger demand are known. This information is then supplemented with a lower bound or variance information. It is to be noted that other robust optimization approaches (assuming the same as well as other information, such as bounds on moment generating functions, symmetry and unimodality, e.g. see Ben-Tal et al., 2009) have been used in numerous other transportation applications, including in maritime transportation (e.g. Huynh and Walton, 2008; Ng, 2015; Fisher et al., 2016), disaster management (e.g. Ng and Waller, 2010), supply chain management (e.g. Li et al., 2016), congestion pricing (e.g. Lou et al, 2010), and beyond (see Gabrel et al., 2014).

The outline of this paper is as follows. Section 2 provides a concise review of a variation of the ferry SNDP. New robust models are then presented in Section 3, followed by a case study in Section 4. Section 5 summarizes and concludes the paper.

2. Ferry service network design

The proposed robust models in this paper are general and can be adopted for other SNDP. However, the ferry SNDP is used as an example application. Particularly, we build on a variation of the ferry SNDP reported in, for example, Lo et al. (2013). This section provides a concise review of this basic model. For more details, the reader is referred to Lo et al. (2013).

The ferry SNDP involves determining both the ferry routing and service schedule for the planning horizon, which requires specifying the time dimension within the formulation. We shall use a similar time-space network representation from previous studies (e.g. see Lai and Lo, 2004; Wang and Lo, 2008; Lo et al., 2013). There are two types of time-space networks: the ferry flow network and the passenger flow network. While they have the same structure (see Fig. 1 for a sample network), their network parameters are different.

Let $G(N, A)$ denote the ferry flow time-space network, where N represents the set of nodes, i.e. the piers at a specific time (e.g. if Fig. 1 represents the ferry network, then there are 3 piers shown at 3 different times) and the set of arcs which consists of two subsets: service arc set S (the diagonal arcs in Fig. 1) and waiting arc set W (the vertical arcs in Fig. 1), with $A = S \cup W$. Each service arc represents a direct ferry service between two different piers at different times, whereas each waiting arc connects two consecutive time nodes of the same pier. Each service arc has an operating cost C_{ij} associated with it, except for the service arcs emanating from the nodes associated with the first time interval that have a fixed cost in addition to the operating cost, to reflect the cost of owning and deploying ferries (e.g. maintenance and depreciation cost). The ferry flow from node i to node j in the ferry time-space network is denoted by the vector $\mathbf{Y} = \{Y_{ij}\}$.

The passenger time-space network for OD pair d has the same structure, and is defined by $G(N^d, A^d)$, where N^d refers to the set of nodes and A^d the set of arcs in the passenger flow network. Similar to A, A^d consists of two subsets, the service arc set S^d and waiting arc set W^d such that $A^d = S^d \cup W^d$. Each service arc has a cost of P_{ij}^2 to measure the disutility experienced by the passengers while traveling, whereas each waiting arc has a cost of P_{ij}^1 to reflect the undesirability of letting passengers wait. To increase the number of passengers arriving timely at their final destination, the values of P_{ij}^1 and P_{ij}^2 can be adjusted for the arcs emanating from nodes at the end of the planning horizon (cf. Lo et al., 2013). Finally, let $\mathbf{X} = \{X_{ij}^d\}$ denote the set of passenger flows on arc (i, j) in the passenger network $G(N^d, A^d)$. One variation of the ferry SNDP can now be formulated as follows.