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Designing an integrated distribution system for catering services for high-speed railways: A three-echelon location routing model with tight time windows and time deadlines ☆

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ABSTRACT

An emerging task in catering services for high-speed railways (CSHR) is to design a distribution system for the delivery of high-quality perishable food products to trains in need. This paper proposes a novel model for integrating location decision making with daily rail catering operations, which are affected by various aspects of rail planning, to meet time-sensitive passenger demands. A three-echelon location routing problem with time windows and time budget constraints (3E-LRPTWTBC) is thus proposed toward formulating this integrated distribution system design problem. This model attempts to determine the capacities/locations of distribution centers and to optimize the number of meals delivered to stations. The model also attempts to generate a schedule for refrigerated cars traveling from distribution centers to rail stations for train loading whereby meals can be catered to trains within tight time windows and sold before a specified time deadline. By relaxing the time-window constraints, a relaxation model that can be solved using an off-the-shelf mixed integer programming (MIP) solver is obtained to provide a lower bound on the 3E-LRPTWTBC. A hybrid cross entropy algorithm (HCEA) is proposed to solve the 3E-LRPTWTBC. A small-scale case study is implemented, which reveals a 9.3% gap between the solution obtained using the HCEA and that obtained using the relaxation model (RM). A comparative analysis of the HCEA and an exhaustive enumeration algorithm indicates that the HCEA shows good performance in terms of computation time. Finally, a case study considering 156 trains on the Beijing-Shanghai high-speed corridor and a large-scale case study considering 1130 trains on the Chinese railway network are addressed in a comprehensive study to demonstrate the applicability of the proposed models and algorithm.

1. Introduction

Many supply chains, from those providing medical blood, which must be consumed while in good condition (Shen et al., 2003; Shu et al., 2005), to perishable food products with limited lifespans (Federgruen et al., 1986; Zhang et al., 2003), are currently operated in time-critical modes in which tasks must be executed within a tight time frame. In regard to the delivery of perishable food products, whose quality deteriorates when they are subjected to extended travel times and frequent

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stops (Hsu et al., 2007), it is critical to design a distribution system that considers time constraints to maintain the food supply chain (FSC) (Nagurney et al., 2013).

In China, with the emerging development and construction of high-speed passenger lines, the China Railway Corporation is increasingly focusing on developing a distribution system for rail catering operations. It is estimated that in 2014, China Railway catered more than 1000 trips per day and purchased/produced approximately 171 million meals (Science and Technology Division of China's Ministry of Railways, 2010). The task of providing catering services for high-speed railways (CSHR) is thus an important component of passenger rail transport services (Wu et al., 2015). Furthermore, in China, food products for CSHR are currently divided into two classes: (1) ambient meals, with a lifespan of 6 months, and (2) "cold chain" meals, with a lifespan of 24 h. Meals of both types should receive microwave heating before being sold. Generally, "cold chain" meals taste better and satisfy passengers' needs better than do ambient meals. However, "cold chain" meals can spoil if the appropriate time deadlines are not met. To increase the level of service provided to train passengers and to improve the competitiveness of high-speed trains on the intermodal transportation marketplace, it is logical to begin to realize a time-critical cold food chain by searching for a well-designed distribution system; in this paper, the related problem is termed the distribution system design problem for CSHR (DSDP-CSHR).

The systematic integration of different optimized operation decisions is important for providing better passenger train services. Two types of integrated problems are important in this field. One is the integration of planning for the transitional processes that occur throughout the entire rail transport plan (RTP), such as line planning, timetabling and rolling stock planning (Goossens et al., 2006). The other is the integration of external support systems (e.g., a distribution system for catering services, as considered in this paper) with the components of the transportation system to better meet various passenger demands. These external support systems are closely related to the passenger service performance of a transportation system. For example, Ho and Leung (2010) demonstrated the importance of airline catering services for the Hong Kong International Airport and indicated that flight catering is strongly affected by the utilized flight plan. Tong et al. (2015b) discussed train trip package transportation that is realized by a specialized train. In the field of road transportation, Ruan et al. (2016) explained how to systematically optimize the locations of park-and-ride stations, the number of parking lots, and the schedules for bus rapid transit. The DSDP-CSHR is also an integrated optimization problem of the latter type. Compared with airline catering, the service locations for rail catering pose a more complex problem. The meals required for a flight are usually catered at its origin port (Goto et al., 2004); by contrast, in rail catering, a train may be catered either at the origin of a trip or at stations along the train's route. Hence, the locations of distribution centers (DCs) also constitute a prominent issue in CSHR. To the best of our knowledge, few studies have addressed these topics in the context of CSHR.

The planning for the distribution of perishable meals throughout a railway network should integrate the problem of distribution system design with the consideration of daily rail catering operations as affected by the RTP to ensure that time-sensitive passenger demands are met. An RTP consists of three components: a line plan, a train timetable and an electric multiple unit (EMU) circulation plan. A line is defined as a path between an origin and a destination along a given route on a railway network. A line plan specifies the frequency of the line services and their halting patterns, which define the rail stations along a line's route at which a train serving that line dwells (Bussieck, 1998; Goossens et al., 2006; Fu et al., 2015). A timetable specifies the arrival and departure times for each line in the form of a series of trips (Peeters, 2003; Zhang and Nie, 2016). An EMU circulation plan assigns trains to each trip (i.e., train path) in the timetable (Peeters and Kroon, 2008). The RTP gives rise to special characteristics of CSHR. Compared with a normal distribution system design problem, the time-critical aspect of the DSDP-CSHR is that the longest lead time from a food supplier to any accessible trip's **destination** is subject to time-deadline restrictions that limit the length of the routes. Furthermore, the meals must eventually be stowed on the trains within tight time windows as imposed by the RTP.

The purpose of this paper is to introduce a location routing model for integrating location-allocation decisions with daily catering operations in the DSDP-CSHR, whereby meals can be delivered to and stowed on trains within tight time windows and sold before a given time deadline. Based on this model, we can analyze the impacts of optimization on passenger service performance.

1.1. Previous related studies

Managerial decision making is classified into three hierarchical levels: strategic, tactical and operational. In past studies, the DSDP and other network design problems have been investigated as problems of strategic decision making (Geoffrion, 1974; Gelders et al., 1987; Pooley, 1994; Wouda et al., 2002; Zhang et al., 2003; Liu and Zhou, 2016). Most such studies consider only the determination of location decisions through the application of a mixed integer programming (MIP) model. Their objective functions minimize the total cost for opening alternative facilities and shipping products (Melo et al., 2009). Relevant studies mainly address facility location/network design problems (FLNDPs), which were initially introduced as generalizations of classical facility location problems (FLPs). Klose and Drexl (2005) provided an excellent review of the various types of FLNDP models. Adding budget constraints to the p-center problem gives rise to the center FLNDP with budget constraints (CFLNDB). The goal of the CFLNDB is to minimize the maximum travel time from any customer to that customer's allocated facility rather than to minimize the overall cost, as in typical FLNDPs (Contreras et al., 2012).

Several authors have studied location-allocation problems for specific FSC problems (Akkerman et al., 2010). Geoffrion (1974) described a DSDP using an MIP model to determine the locations of intermediate facilities between plants and customers for a food firm. Pooley (1994) and Wouda et al. (2002) studied a DSDP for a case study of a dairy industry. Another