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A perishable food supply chain problem considering demand uncertainty and time deadline constraints: Modeling and application to a high-speed railway catering service

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ABSTRACT

This paper attempts to optimize the flow patterns in a perishable food supply chain network for a high-speed rail catering service. The proposed variational inequality models describe the uncertain demand on trains using the Newsvendor model and impose time deadline constraints on paths considering flow-dependent lead time. The constraints are then reformulated based on the Dirac delta function so that they can be directly dualized. An Euler algorithm with an Augmented Lagrangian Dual algorithm is developed to solve the model. A case study using 246 trains in the Beijing-Shanghai high-speed corridor is applied to demonstrate the applicability of the method.

1. Introduction

Timely delivery is becoming a critical strategy that is as important as lean manufacturing and innovation strategy in modern supply chain management, particularly in perishable food supply chains (PFSCs) (Nagurney et al., 2013; Yu and Nagurney, 2013). Timely delivery imposes a time-critical mode on PFSCs in which each task is executed within a tight time frame (Federgruen et al., 1986; Zhang et al., 2003).

This research is motivated by catering services for high-speed railways (CSHRs). This paper focuses on developing a PFSC for CSHRs (PFSC-CSHRs) in China. It is estimated that China Railway must provide food products for more than 1000 high-speed trains per day across the rail network. With the development of high-speed passenger service, it is important for China Railway to develop profitable catering services for high-quality cold chain meals while guaranteeing time-sensitive quality and food safety (Wu et al., 2015, 2017a,b).

A PFSC-CSHRs network is composed of pathways from food suppliers (FSs), involves distribution centers (DCs) and rail stations (RSs), and ends at high-speed trains (HTs) throughout a given rail network. The food products demanded by HTs within a planning horizon are outsourced from cooperative FSs. DCs operated by rail companies order food products from the FSs and then deliver the meals to RSs. Each train is labeled with a train number (i.e. a trip line) in a train timetable. HTs are served as the end user of the distribution network (see Fig. 1). The PFSC-CSHRs problem is a product flow-assignment problem that aims to assign product flows in each distribution network. On HTs, services provided to different travel classes are quite different. However, either high level or economy class passengers can buy cold chain or ambient food products on the trains. This paper focuses on the on-demand catering retail services for cold chain food products provided in the dinning compartments of HTs for all travel classes.

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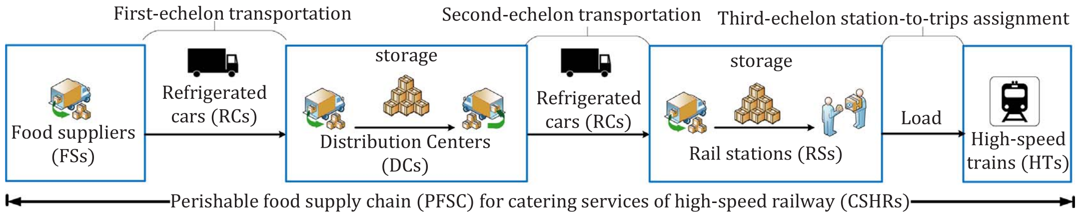

Fig. 1. The catering service process in the CSHR supply chain (Wu et al., 2017a).

1.1. Characteristics of the PFSC-CSHRs problem and literature review

The PFSC-CSHRs problem shares common features with other supply chain problems (Sloof et al., 1996; Miller, 2012; Trienekens and Zuurbier, 2008). However, particular characteristics merit further discussions.

(1) **Influence by rail transport plan**

First, all possible station-to-train assignments in the PFSC-CSHRs network are characterized by the HTs' operating line plan and timetable (Bussieck, 1997; Goossens et al., 2006; Peeters, 2003; Zhang and Nie, 2016).The paper's first task is to incorporate the information from line plans and train timetables into PFSC-CSHRs networks.

(2) **Deterioration of food products**

Second, the quality of cold chain meals deteriorates throughout the distribution process (Zhang et al., 2003; Yu and Nagurney, 2013; van der Vorst, 2000; Akkerman et al., 2010). Zhang et al. (2003) considered the perishability of chilled and frozen meals by limiting the total network degradation within a permitted range. However, that study did not investigate the degradation from the perspective of path-based models. In supply chain analytics for perishable products,path-based supply chain models are widely used to describe the degradation that occurs over the relevant links (Masoumi et al., 2012; Nagurney and Nagurney, 2012; Yu and Nagurney, 2013). The paper's second task is to introduce the framework to describe the deterioration of cold chain rail catering meals.

(3) **Flow-dependent lead time and time deadline constraints**

Third, the delivery process of cold chain meals must be restricted by time deadline constraints that restrict the pathways'lead time within a lifespan. In this paper, a pathway's lead time is different from a pathway's time impedance. Here, we define a pathway's time impedance as the total time impedance of the pathway from a food supplier to a high-speed train (as shown in Fig. 1). Differently, we define a pathway's lead time as the time impedance from a food supplier to its served trains' destination, which is the sum of the pathway's time impedance and the travel time of the train from its catered station to its destination.

Liu and Nagurney (2012) formulated a path-based model to impose that a path whose lead time is longer than a given time deadline would not be assigned any flows. However, the model does not describe the flow-dependent property of the lead time. Congestion effects usually occur in real-world situations because of the limited availability of skilled workers, redundant trimming and equipment turnover. As the amount of shipping on a path increases, the pathways' lead time increases. As a result, it is important to restrict the flow-dependent lead time within a given time deadline. In traffic equilibrium problems, Larsson and Patriksson (1999) proposed a strategy to price generalized side constraints (Lasdon, 1970, chap.8). Patriksson (1994) developed the Augmented Lagrangian Dual (ALD) algorithm to efficiently price capacity constraints. Nagurney and Nagurney (2012) introduced the same idea into a medical nuclear supply chain problem to achieve the dualization of capacity constraints. However, the flow-dependent lead-time property and time deadline constraints have not been addressed simultaneously. The time deadline constraint is described by conditional statements as follows:

If the amount of the flow on a path is greater than zero, then the pathway's flow-dependent lead time should be limited within a given time deadline.A free-flow pathway might have an arbitrarily long lead time, where a free-flow path is defined as a pathway without flows on it.

The third task of this paper is to formulate the time deadline constraints and limit the flow-dependent lead time of any pathway within a given deadline.

(4) **Uncertainty of food demand**

Fourth, the number of meals required by HTs is uncertain. For one thing, train tickets usually do not include meals. For another thing, numerous passengers purchase their tickets on the day of departure or even a few minutes prior to departure. The final number of passengers is unknown until minutes before departure. Thus, it is difficult to estimate demand based on the number of booked passengers. The literature has discussed the uncertainty of airline food products (Ho and Leung, 2010). Goto et al. (2004) indicated that the final number of passengers on a flight varies from the booked number of passengers on a flight by as much as 10% even one hour prior to the departure.

The literature usually exploits the uncertain demands of supply chain networks from the perspective of spatial pricing equilibrium problems (Nagurney and Aronson, 1989, 1999, chap.4). In spatial pricing equilibrium problems, market demand is associated with the price using demand functions (Nagurney, 1999, chap.2,3). In supply chain network equilibrium problems, the spatial pricing equilibrium condition is then used to account for consumer behaviors (Nagurney et al., 2002) in the long term. Nagurney et al. (2002) proposed a supply chain network equilibrium problem consisting of manufacturers, retailers and consumers in which competition occurs in a non-cooperative manner (Nash, 1950, 1951; Dafermos and Nagurney, 1987). The problem corresponds to the analogs of