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Train scheduling and circulation planning in urban rail transit lines

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A R T I C L E I N F O

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A B S T R A C T

This paper proposes a two-stage optimization approach to optimize the train schedule and circulation plan with consideration of passenger demand for an urban rail transit line. A train scheduling model is based on the operation of train services, which results a mixed integer nonlinear programming problem. Moreover, a train circulation model is formulated to adjust the departure and arrival times obtained by the train scheduling model to reduce the number of trains required, which results in a mixed integer linear programming problem. The case study based on the Beijing Yizhuang line illustrates the effectiveness of the proposed model and solution approach.

1. Introduction

Urban rail transit systems play an important role in urban public transportation since millions of passengers use them for their daily commute. The passenger demand for urban rail transit keeps growing with the expansion of urban rail transit systems. The frequency of train operations is becoming very high, especially in large cities like Beijing, Shanghai, Tokyo, New York, and Paris, where the headway between trains is often less than 10 min and even close to 2 min for some lines. Hence, the planning process for the urban rail transit systems is becoming more and more significant for reducing the operation costs of rail operators and for guaranteeing passenger satisfaction. The planning process is traditionally a sequential process as given in Fig. 1, which consists of five phases (Bussieck, Winter, & Zimmermann, 1997): demand analysis, line planning, train schedule planning, train (or rolling stock) planning, and crew scheduling. In particular, rolling stock circulation is an important aspect of rolling stock planning. This paper focuses on the passenger-demand-oriented train scheduling and circulation planning for an urban rail transit line to satisfy the passenger demand and to reduce the operation cost. In particular, the passenger-demand-oriented train scheduling here involves the line planning and train scheduling planning as given in Fig. 1 for urban rail transit lines. The type of line services, such as full-length train services and short-turning train services, and the headway between train services are generally determined during the line planning for urban rail transit lines. However, since most of the urban rail transit lines only employ only one type of train services, i.e., the full-length train services, only the headway between train services is decided in the line planning.

Train scheduling for regional or national rail transit systems has been studied by many researchers (Cordeau, Toth, & Vigo, 1998; D'Ariano, Pranzoand, & Hansen, 2007; Ghoseiri, Szidarovszky, & Asgharpour, 2004; Higgins, Kozan, & Ferreira, 1996; Kraay, Harker, & Chen, 1991; Petersen, Taylor, & Martland, 1986; Szpigel, 1972), where trains could overtake or cross each other at the sidings and crossings. So the train routing and platforming are considered together with the train scheduling for regional and national rail transit systems in Sama, Pellegrini, D'Ariano, Rodriguez, and Pacciarelli (2016, 2017), Pellegrini, Marlière, and Rodriguez (2014), and Dewilde, Sels, Cattrysse, and Vansteenwegen (2013), where mixed integer linear programming models are formulated to tackling these problems. In addition, the passenger demands and flows are involved more and more in the train scheduling and delay management for regional or national rail transit systems (Corman, D'Ariano, Pacciarelli, & Pranzo, 2012, 2014, 2016; Dollevoet, Huisman, Schmidt, & Schöbel, 2012, 2014; Sato, Tamura, & Tomii, 2013), where the passenger flows are optimized in case of disruptions. Furthermore, the train circulation problem (also called train assignment problem or rolling stock circulation problem) for regional or national rail transit systems has also been researched widely (Alfieri, Groot, Kroon, & Schrijver, 2006; Cacchiani, Caprara, & Toth, 2010, 2013; Fioole, Kroon, Maróti, & Schrijver, 2006), where the train units are coupled or decoupled based on the passenger demand and are scheduled through the whole rail network. In this paper, we focus on urban rail transit systems, where the overtaking and crossing of trains are normally not allowed during the operations. Moreover, the trains or electrical multiple units[1]

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[1] An electric multiple unit (EMU) is a multiple unit train consisting of self-propelled carriages, using electricity as the motive power. An EMU requires no separate locomotive, as electric traction motors are incorporated within one or a number of the carriages.

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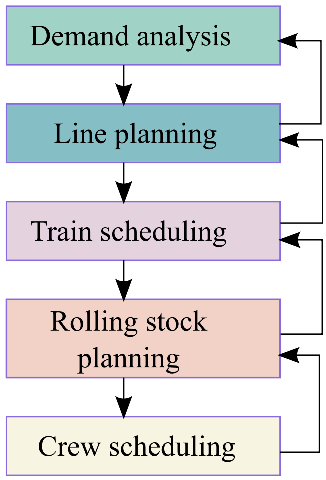

Fig. 1. The hierarchical planning process of rail transit system (Bussieck et al., 1997).

(EMUs) are employed only in the operation of a specific line and the setting of the trains or EMUs does not change in general.

Many researchers have studied the passenger-demand-oriented train scheduling problem for urban rail transit systems. Regular schedules with different fixed headways for peak hours and off-peak hours are often applied in the current practice for urban rail transit systems. For example, every three minutes there is a train entering a station in the peak hours and every eight minutes there is a train entering a station in the off-peak hours. The train scheduling problem is formulated as a periodic event-scheduling problem based on a graph model in Liebchen (2006), which is then solved using integer programming methods. The approach proposed by Liebchen has been applied in Berlin subway systems (Liebchen, 2008). A heuristic-based evolutionary approach is proposed in Kwan and Chang (2005) to optimize the frequency (or headway) between trains to reduce the operation costs and the passenger dissatisfaction. A demand-oriented timetable design is proposed in Albrecht (2009), where the optimal train frequency and the capacity of trains are first determined and then the schedule of trains is optimized. More and more researchers focus on the nonperiodic or irregular train scheduling with consideration of passenger demand. Cury, Gomide, and Mendes (1980) presented a hierarchical methodology to generate nonperiodic schedules for metro lines based on a model of the train movements and of the passenger behavior. Based on the model in Cury et al. (1980), Assis and Milani (2004) proposed a model predictive control algorithm to optimize the train schedule, which can effectively generate train schedules for the whole day. Niu and Zhou (2013) applied genetic algorithms to optimize train schedules for a heavily congested urban rail transit line. A bi-level approach and an iterative convex programming approach are proposed in Wang, De Schutter, van den Boom, Ning, and Tang (2014a) and Wang, Ning, Tang, van den Boom, and De Schutter (2015), respectively, to obtain the optimal train schedule for an urban rail transit line with consideration of time-varying passenger demand. Sun, Jin, Lee, Axhausen, and Erath (2014) proposed three models to design demand-driven train schedules to fully capture the heterogeneity of passenger arrival time by minimizing total passenger waiting time. Canca, Barrena, Algaba, and Zarzo (2014) considered variable demand within a long time period in the train scheduling model, where train capacity is considered and useful measures of timetable quality were presented. Barrena, Cana, Coelho, and Laporte (2014) proposed three exact linear formulations and a branch-and-cut algorithm to design train schedules with dynamic demand. Furthermore, we considered the passenger-demand-oriented train scheduling for an urban rail transit network in Wang, Tang, Ning, van den Boom, and De Schutter (2015), where the train schedules of two lines are optimized simultaneously to satisfy the passenger demand and the transfer between different lines is included in the model formulation. However, in the previous studies, the turnaround operation and the train circulation are not considered. The turnaround operation is usually the bottleneck of the urban rail transit line and the constraints proposed by the train circulation are critical for the train scheduling.

Cadarso and Marin (2011) proposed a multicommodity flow model for the train utilization planning problem for urban rail transit systems, where the shunting operation and the passenger demand for each train services based on a fixed train schedule are considered. Furthermore, an integrated train scheduling and rolling stock planning model is proposed in Cadarso, Marin, and Maroti (2012) for urban rapid transit networks. Based on this integration model, the recovery measures for the train schedule and rolling stock circulation are studied under the disruptions of urban rail transit networks (Cadarso, Marín, & Maróti, 2013). However, the train composition can be changed in the depot by coupling and decoupling of train units in Cadarso and Marin (2011) and Cadarso et al. (2012, 2013). In addition, an integrated optimization model of train scheduling and utilization planning is proposed in Chang, Jong, and Lai (2015), where the difference between the expected train schedule and the optimal train schedule obtained with consideration of train utilization planning is minimized. The passenger demand is not considered in the train scheduling model of Chang et al. (2015) but there exists a predefined train schedule for the train utilization planning problem.

In this paper, a two-stage optimization approach is introduced to optimize the train schedule and circulation with consideration of passenger demand. First, nonlinear programming methods (e.g., sequential quadratic programming) can be used to obtain the train schedule on the basis of train services by solving the formulated nonlinear train scheduling problem. Then the train circulation plan is decided by adjusting the optimal train schedule using mixed integer linear programming. The train scheduling and circulation planning is considered in our previous research (Wang et al., 2016) and the current paper extends the research in the following aspects:

- The integrated line planning and train scheduling model in Wang et al. (2016) is based on the circulation of available trains, however, the two-stage optimization approach proposed in this paper is based on train services, where the arrival and departure times of train services are optimized at first and are then adjusted to generate the train circulation plan.
- The resulting problem in Wang et al. (2016) is a mixed integer nonlinear programming problem and is solved by the bi-level optimization method. However, the two-stage optimization approach in this paper results in two sequential problems, where one problem is a mixed integer nonlinear programming (MINLP) problem and the other problem is a mixed integer linear programming (MILP) problem.

The rest of the paper is structured as follows. Section 2 formulates the two-stage optimization model, which involves the train scheduling model and the train circulation planning model. In particular, the train scheduling model includes the operation of train services, the passenger demand characteristics, and the objective function. Section 3 proposes the solution approaches for the resulting train scheduling problem and train circulation planning problem. Section 4 illustrates the performance of the train scheduling model and circulation planning model with a case study based on the data of the Beijing Yizhuang line. Finally, Section 5 concludes the paper.

2. Two-stage optimization model

2.1. Notations and assumptions

Tables 1 and 2 summarize, respectively, the parameters and variables used in this paper to describe the train scheduling and