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Integrated optimization of regular train schedule and train circulation plan for urban rail transit lines

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This paper presents an integrated model to optimize the train schedule and circulation plan simultaneously based on a given service pattern generated by the demand analysis and line planning. The operation of train services, the turnaround operations, the entering/exiting depot operation, and the number of available trains are involved in the model. The proposed integrated and extended integrated optimization problems are transformed into mixed integer linear programming (MILP) problems, which can be efficiently solved by the CPLEX solver. Numerical examples based on the Beijing Yizhuang line are implemented to demonstrate the performance of the proposed models and solution approach.

1. Introduction

Urban rail transit systems play an important role in public transportation since it combines high transport capacity and high efficiency. With the increasing of passenger demands, 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 traditionally consists of five sequential processes (Bussieck et al., 1997): demand analysis, line planning, train scheduling, train (or rolling stock) circulation planning, and crew scheduling. In particular, the line planning decides the service pattern, which involves the type of line services (e.g., full-length and short-turning services), the frequencies or the headways between train services, train compositions, etc. The train scheduling process then generates a feasible train schedule that satisfies the requirements specified in the service pattern. Based on the feasible train schedule, a train circulation plan is then scheduled. Finally, the crew schedule is generated based on the train circulation plan. If one of the process cannot generate feasible results, then the previous process or even the whole sequential processes should be calculated again. This paper only focuses on the generation of the train schedule and train circulation plan based on a given service pattern specified by the demand analysis and line planning for an urban rail transit line.

The train scheduling and circulation planning are handled separately in general due to the complexity of the integrated problem. However, if we solve the train scheduling problem without considering the train circulation, then there could be no feasible train circulation plan for a feasible train schedule, especially when the number of available trains is limited. In the train circulation planning phase, the train schedules need to be adjusted in general to satisfy the constraints presented by the

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train circulation, where the departure and arrival times of the train services should be changed and some of the train services even need to be cancelled if there are not enough trains. Hence, we propose the integration of the train scheduling and circulation planning to obtain the train schedules and circulation plans simultaneously.

1.1. Literature review

Train scheduling for regional or national rail transit systems has been studied by many researchers (Szpigel, 1972; Petersen et al., 1986; Kraay et al., 1991; Higgins et al., 1996; Cordeau et al., 1998; Ghoseiri et al., 2004; D'Ariano et al., 2007b,a; Corman et al., 2012), where trains could overtake or cross each other at the sidings and crossings. In particular, the integration of the train scheduling and train routing/platforming has been considered for regional and national rail transit systems in Samà et al. (2017, 2016), Pellegrini et al. (2014), Dewilde et al. (2013), where mixed integer linear programming models are formulated to tackle these problems. Moreover, the integration of train scheduling and delay management has been researched in Dollevoet et al. (2014), Corman et al. (2014, 2016) to obtain a better trade-off between the passenger travel time minimization and train delay minimization. The train circulation planning problem is also called train assignment problem or rolling stock circulation problem. Many studies, e.g., Alfieri et al. (2006), Fioole et al. (2006), Peeters and Kroon (2008), Cacchiani et al. (2010, 2013) and Giacco et al. (2014), have tackled the train circulation planning, 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. Furthermore, the trains or electrical multiple units (EMUs) are employed only in the operation of a specific line and the composition of the trains or EMUs does not change in general.

There are two types of train schedules that are concentrated by the researchers. The first type is regular (or periodic) train schedules, which have different fixed headways for peak hours and off-peak hours. The regular train schedules are often applied in the current practice of 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. Nachtigall and Voget (1996) applied genetic algorithm to optimize regular train schedules by minimizing the passenger waiting times. 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. Ceder (2009) proposed a methodology framework to determine the departure times of train services with even headway and to provide smooth transitions between different time periods. 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 regular train schedules generated by the approach proposed by Liebchen have been applied in Berlin subway systems (Liebchen, 2008). In addition, 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 are optimized. Moreover, a regular train schedule is optimized together with the train speed profiles to saving energy by maximize the utilization of regenerative energy in Su et al. (2013) and Li and Lo (2014). The second type is irregular (or non-periodic) train schedules, which have attracted more and more attentions from researchers. Cury et al. (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) and 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 an heavily congested urban rail transit line. A bi-level approach is proposed in Wang et al. (2014) to obtain the optimal train schedule for an urban rail transit line with consideration of time-varying passenger demand and stop-skipping. Sun et al. (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 et al. (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 et al. (2014) proposed three exact linear formulations and a branch-and-cut algorithm to design train schedules with dynamic demand. Furthermore, the passenger-demand-oriented train scheduling for an urban rail transit network is considered in Wang et al. (2015), where the train schedules of two lines are optimized simultaneously to satisfy the passenger demand and the transfer between different lines are included in the model formulation. Since the regular train schedules are still widely used in the current practice of the urban rail transit systems, we focus on the regular train schedules in this paper.

Both the train scheduling and train circulation planning have significant impacts on the quality of train operations, thus collaboratively optimizing these two stages has great potential benefits. Liebchen and Möhring (2007) proposed to integrate the train circulation into the periodic train scheduling to minimize the number of trains required for the operation. A discrete-time model with granularity of minutes is proposed by Cadarso et al. (2012, 2013) to integrate the train scheduling and rolling stock planning for suburban rapid transit networks, where the maximum and minimum frequencies for train services are predefined by the line planning process. In addition, Chang et al. (2015) presented an integrated optimization model for train scheduling and circulation planning, where they assume that there exists an expected train schedule and the difference between the expected and optimized train schedule are minimized. Furthermore, an integration of line planning, timetabling, vehicle scheduling is proposed by Michaelis and Schöbel (2009) for bus transit systems, where the route of each bus is first determined, then the lines and periodic timetables are calculated.