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Collaborative optimization for train scheduling and train stop planning on high-speed railways ☆

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ABSTRACT

Focusing on providing a modelling framework for train operation problems, this paper proposes a new collaborative optimization method for both train stop planning and train scheduling problems on the tactic level. Specifically, through embedding the train stop planning constraints into train scheduling process, we particularly consider the minimization of the total dwelling time and total delay between the real and expected departure times from origin station for all trains on a single-track high-speed railway corridor. Using the stop planning indicators as important decision variables, this problem is formally formulated as a multi-objective mixed integer linear programming model, and effectively handled through linear weighted methods. The theoretical analyses indicate that the formulated model is in essence a large-scale optimization model for the real-life applications. The optimization software GAMS with CPLEX solver is used to code the proposed model and then generate approximate optimal solutions. Two sets of numerical examples are implemented to show the performance of the proposed approaches. The experimental results show that, even for the large-scale Beijing–Shanghai high-speed railway, the CPLEX solver can efficiently produce the approximate optimal collaborative operation strategies within the given gaps in acceptable computational times, demonstrating the effectiveness and efficiency of the proposed approaches.

1. Introduction

With the development of social economy, a large scale of high-speed railways have been put into operation or been being under construction in some countries to meet large passenger flow demands. Thus, effectively managing and operating the high-speed railways then becomes an important issue for the different railway companies. On the high-speed railway corridors, train stop planning and train scheduling, which are regarded as the most important parts of train operations and managements, have often been studied separately up to now due to the complexity of each involved problem. In practice, as a sub-problem of the train operating managements, the train stop plan is usually made on the basis of predictions of the potential passenger flow for different origin–destination pairs, and the generated stop plan needs to be adjusted repeatedly in order to satisfy the realistically changing requirements over the service time horizon. With the specified stop plan design, the scheduling process then aims to determine the arrival and departure times at each predetermined service station such that no operational conflicts occur between different trains, and expectedly, the resource utilization of the railway traffic system can be maximized. Typically, in comparison to the train stop plan, a train schedule can provide more detailed operational instructions for all the involved trains on the tactic level-based decision strategies.

In general, train stop planning and train scheduling are usually included in different pre-trip planning stages. For clarity, Lusby et al. [36] gave a detailed flowchart to show the railway planning process, as shown in Fig. 1. In this process, once a pre-specified train stop plan is changed according to the realistic requirements (for instance, busy transport during the Spring Festival in China), a new train schedule on the railway needs to be regenerated to satisfy the varied stop plan constraints. Obviously, this process essentially increases the complexity of railway operations. Aiming to produce a comprehensive operational plan on the tactic levels, we are particularly interested in how to design effective methods to collaboratively optimize these two problems, and then generate a system-optimization based planning strategy. Since this topic still has not attracted sufficient attention in the literature, we hereinafter shall address this issue formally.

1.1. Literature review

Practically, the line planning and train scheduling are two significant parts for determining a detailed train operation plan. In the stage of line planning, one needs to specify the number of trains, type of trains, the stop plan for each train, etc., which is

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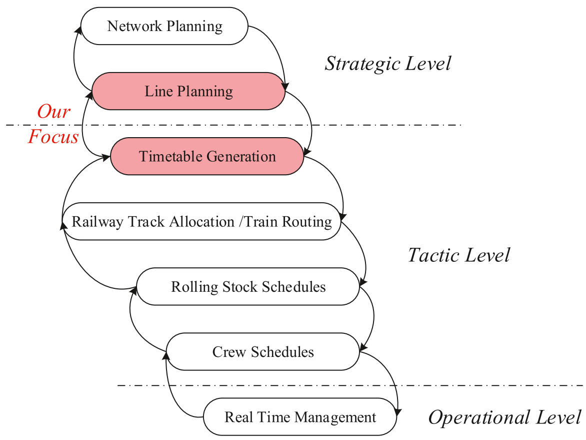

Fig. 1. The railway planning process.

usually included in the strategic level-based decision making. In this process, the train stop planning is of particular importance for the real-world operations once the number and type of trains are provided. For this problem, the main task is to determine the stopping stations for each train on railway lines to satisfy the passenger demands with the minimum cost. In the literature, five kinds of train stop plans are often be considered in reality, including the all-stop operation, skip-stop operation, zonal operation, express/local operation and combined stop operation. Each type of these stop plans has its own advantages, disadvantages and applicable conditions. Typically, although the all-stop operation is obviously the simplest stop planning for satisfying all passenger demands, it might probably enhance the total travel time of long-distance passengers. With this concern, Vuchic [45] further considered the skip-stop operation, zonal operation and express/local operation, and gave evaluation methods of using these stop strategies by summarizing, analyzing and comparing each of them. Zolfaghari et al. [56] pointed out that although stop skipping can effectively reduce the waiting times for passengers on boarding a vehicle and those at downstream stops, it still might increase the waiting time for passengers at skipped stops and those who are requested by the driver to alight at a given stop to wait for the next vehicle in service. According to the operating experience of Japanese Shinkansen, Lan [30] proposed that in designing operation plans of Beijing–Shanghai high-speed railway, staggered stop plan, direct and other forms of stops programs should be taken into account. In addition, Cheng and Peng [6] considered the combined stop plan with elastic demands. The computational results showed that the combined stop plan is more suitable for some special passenger flow.

In the literature, the majority of existing researches focus on investigating different train stop strategies through a variety of optimization methods. For instance, the zonal operation was studied by Salzbom [41] and Ghoneim and Wirasinghe [16]; skip-stop operation by Suh et al. [43], Zheng et al. [55], Wang et al. [46], and Cao et al. [3]; and express/local operation by Nemhauser [38], Song et al. [42], and Xiong [47]. In addition, Guo [21] explicitly studied the characteristics and applicable conditions of these three stop planning types, and formulated the corresponding optimization models for these three stop strategies. By considering different realistic conditions, Lee et al. [31,32] proposed a mathematical model to optimize the skip-stop operation strategy in urban rail transit systems, and also designed an efficient genetic algorithm to search for a near-optimal solution. Goossens et al. [18,19] and Chang et al. [5] treated train stop planning problem as a subproblem of the entire operation plan. Note that stakeholders of the train operation plans are associated with both passengers and railway companies, the objective function can be considered as (i) minimization of total operation cost and passengers total travel time loss (e.g., Chang et al. [5]), (ii) maximization of the saved total passenger travel time (e.g., Zheng et al. [55]) and (iii) minimization of the generalized travel cost and stop quantity (e.g., Deng et al. [13]).

With the given stop plan for each train, a train timetable can be scheduled to instruct the detailed operations of different trains on the railway, which is included in the framework of the job-shop scheduling problem and its variants (e.g., Pan and Ruiz [39] and Rustogi and Strusevich [40]). An efficient train timetable on a railway line or a railway network is always required to ensure that the resources of railway infrastructure can be utilized optimally. Since Szpigel's [44] work with the objective of minimizing the total travel time, motivated by Greenberg's [20] branch-and-bound approach for the job-shop scheduling problem, the research of the train scheduling problem has attracted tremendous attention from numerous researchers and engineers. In general, there are three classes of techniques proposed to obtain a desirable operation plan, as pointed by Yang et al. [51], namely, (1) optimization methods studied by Szpigel [44], Higgins et al. [23], Barrena et al. [1], Harrod [22], Yang et al. [50,53], Kang et al. [26], Jaehn et al. [25], Li et al. [35] and D'Ariano et al. [11,12]; (2) simulation methods studied by Dorfman and Medanic [14], Li et al. [34] and Xu et al. [48,49]; and (3) expert systems studied by Chang and Thia [4], Iida [24] and Komaya et al. [27,28]. For optimization approaches, Higgins et al. [23] presented a two-objective optimization model on single line rail corridor to minimize the delay time and fuel consumption cost; with the purpose of optimizing the energy consumption and passengers' total travel time, Ghoseiri et al. [17] investigated a multi-objective train scheduling model on a railroad network which includes single and multiple tracks, as well as multiple platforms with different train capacities; Barrena et al. [1] presented three formulations for designing and optimizing train timetable adapted to a dynamic demand environment, with the aim of minimizing passenger average waiting time; D'Ariano et al. [11,12] and Corman et al. [7–10] explored a series of realistic railway traffic management problems (routing, scheduling, dispatching, etc.) and proposed efficient solution methodologies, such as the local search, branch and bound algorithm and tabu search algorithm. Considering the complexity of real-world situations, many researchers focused on using uncertain programming to get a more robust train timetable. Kroon et al. [29] proposed a stochastic optimization model to improve the robustness of a given cyclic railway timetable; Meng and Zhou [37] presented a two-stage stochastic model to find the robust rescheduling strategies when an incident occurs on the railway link under different forecasted operational conditions, in which the purpose is to minimize the expected additional delay; Yang et al. [51] formulated the rescheduling problem as a two-stage expected fuzzy optimization model on a two-way double-track railway line to minimize the expected total delay; by using a space–time network to represent the choice of train trajectories and introducing a fuzzy variable-based recovery time to capture the uncertainty of incident duration, Yang et al. [52] formulated a credibilistic two-stage fuzzy 0–1 integer optimization model to find a reliable rescheduling plan for trains in a double-track railway network when the capacity reduction is caused by a low-probability incident.

1.2. The proposed methods

From the viewpoints of system optimization, both train stop planing and train scheduling problems can only produce the suboptimal solutions for the entire train operation process. Note that, although the train stop planning and train scheduling were often studied independently in the literature due to the complexity of