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# Integrated optimization on train scheduling and preventive maintenance time slots planning ☆

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A B S T R A C T

We address the problem of simultaneously scheduling trains and planning preventive maintenance time slots (PMTSs) on a general railway network. Based on network cumulative flow variables, a novel integrated mixed-integer linear programming (MILP) model is proposed to simultaneously optimize train routes, orders and passing times at each station, as well as work-time of preventive maintenance tasks (PMTSs). In order to provide an easy decomposition mechanism, the limited capacity of complex tracks is modelled as side constraints and a PMTS is modelled as a virtual train. A Lagrangian relaxation solution framework is proposed, in which the difficult track capacity constraints are relaxed, to decompose the original complex integrated train scheduling and PMTSs planning problem into a sequence of single train-based sub-problems. For each sub-problem, a standard label correcting algorithm is employed for finding the time-dependent least cost path on a time-space network. The resulting dual solutions can be transformed to feasible solutions through priority rules. Numerical experiments are conducted on a small artificial network and a real-world network adapted from a Chinese railway network, to evaluate the effectiveness and computational efficiency of the integrated optimization model and the proposed Lagrangian relaxation solution framework. The benefits of simultaneously scheduling trains and planning PMTSs are demonstrated, compared with a commonly-used sequential scheduling method.



## 1. Introduction

Railway transport plays a crucial role in addressing the ever-growing needs for mobility of population and goods. In order to fulfill the growing demand and achieve higher competitiveness in a multimodal transport market, the infrastructure needs to be well utilized (in terms of a train timetable) to meet passenger and goods transport demand. Meanwhile, railway infrastructure should be in a good shape (well-maintained by means of preventive maintenance time slots (PMTSs)) for ensuring that tracks are in the appropriate states for running trains. However, performing preventive maintenance (PM) tasks in a time slot normally needs a possession of the tracks, which implies a complete capacity breakdown of the tracks; no train

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is allowed to run on them during the possession. Thus, an effective train schedule with joint consideration of PMTS plans is typically desired, especially for the bottleneck area(s) of a railway network during peak hours.

Train schedules are tactical plans, which specify for each train a physical network route, arrival time and departure time at passing stations. PMTS plans define work-space and work-time possession for each PM task. The former aim at delivering railway services to customers, and the latter have the role of supporting railway services by preventing infrastructure failures. In practice, train schedules and PMTS plans are usually designed separately by different departments/planners. However, the interaction between those two is critical, as they take possession of infrastructure (utilizing capacity) competitively. Operating more trains leads to less time slots available for performing maintenance, and vice versa. The tension is especially high when infrastructure capacity is inadequate, which is the case in many bottleneck areas now. When generating a train schedule (or a PMTS plan), an unavoidable issue is to coordinate PMTS plans (or train schedules), by simultaneously considering train scheduling (TS) and PMTSs planning. Inappropriate coordination would result in inefficient use of capacity, and even conflicts between those two: for example, when considering a plan of pre-determined PMTSs, the planned trains might not be able to be completely scheduled in a timetable. Moreover, situations of interchange stations on a railway network would be even more complex. The capacity of an interchange station might be underutilized, due to unsynchronized occupancy of PMTSs for different lines. It is hardly possible to find a timetable with efficiently utilized capacity for trains and maintenance tasks, if the two tasks – schedule trains and PMTSs – would not be simultaneously considered.

This brings about the motivation of this paper, to achieve the integration of TS and PMTSs planning and further improve the utilization of capacity. Integrated scheduling could be a step forward to improve coordination and further towards efficient use of capacity, as stated in the study "Cost and Contribution of the Rail Sector" by the European Commission (EC, 2015), which aims at exploiting potential infrastructure capacity by better deployment and coordination.

A growing scientific literature is available for these two problems, see the recent surveys on TS (Cacchiani and Toth, 2012; Turner et al., 2015) and PMTSs planning (Soh et al., 2012; Turner et al., 2015). Studies related to PM mostly concern for minimizing total PM costs and delays of PM tasks, and pay little attention to train schedules. Most TS models assume that the infrastructure is always available for the trains (neglecting maintenance), or unavailable only during some certain time periods representing PMTSs (considering pre-determined PMTSs), which may result in a sub-optimal solution. A better solution could be expected by simultaneously scheduling trains and planning PMTSs. However, this integration is far from easy to accomplish, see the survey papers by Budai et al. (2008), Hadidi et al. (2011). In the railway transport field, there are only a few explicit discussions on how train schedules and PMTSs interact, and most of them schedule one function by minimizing its impact on the other. To the best of our knowledge, integrated optimization models of scheduling trains and planning PMTSs are not seen in railway transport systems.

In this paper, we aim to integrate the TS and PMTSs planning processes, through an optimization method. Given some demand of trains and PMTSs, we simultaneously optimize trains' routes, orders, departure times and arrival times at passing stations, as well as work-time of PM tasks (PMTSs). By applying a network cumulative flow variables-based modeling technique (Meng and Zhou, 2014), a novel integrated mixed-integer linear programming (MILP) model is proposed, to deliver a global optimal or satisfactory schedule for both trains and PMTSs with microscopic feasibility details. This means that PMTSs are also scheduled and no longer pre-determined in TS process; they are positioned in time so as to have the best impact. To achieve this integration, a modeling technique is especially presented, which naturally provides an easy formulation method through modeling PMTSs as virtual trains. Complex track capacity is modelled by side constraints and further dualized through a Lagrangian relaxation solution framework, in which the original complex integrated TS and PMTSs planning problem is decomposed into a sequence of single train-based sub-problems. For each sub-problem, a standard label correcting algorithm is employed for finding the time-dependent least cost path on a time-space network. The resulting dual solutions can be transformed to feasible solutions through priority rules. Numerical experiments are conducted on a small artificial network and a real-world network adapted from a Chinese railway network, to evaluate the performance (in terms of effectiveness and computational efficiency) of the integrated optimization model and the proposed Lagrangian relaxation solution framework. The benefits of simultaneously scheduling trains and planning PMTSs are demonstrated, compared with a commonly-used *sequential scheduling method*, which will be described in Section 3.1.

The remainder of this paper is organized as follows. Section 2 provides a detailed literature review on relevant studies. In Section 3, a conceptual illustration is presented for interpreting the integration of TS and PMTSs planning. Two key modeling techniques, i.e., cumulative flow variables-based modeling technique and virtual train-based modeling technique, are further introduced. Section 4 presents the integrated optimization model for scheduling trains and planning PMTSs. The Lagrangian relaxation based solution framework is proposed in Section 5. Section 6 systematically examines the effectiveness and computational efficiency of the proposed model and algorithms, through numerical experiments on the artificial and realistic test cases, followed by concluding remarks and extensions for future research in Section 7.

## 2. Literature review

In this section, we present a detailed literature review on relevant studies. We first review studies on TS problem at macroscopic or/and microscopic level, where maintenance is ignored or pre-determined. Then, we focus on studies dealing with PM planning problem in railway systems, which neglect train schedules. We further discuss studies on jointly scheduling trains and PMTSs in railway systems, addressing decisions on one side. Furthermore, we also review studies on inte-