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Improving robustness of rolling stock circulations in rapid transit networks

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ABSTRACT

The rolling stock circulation depends on two different problems: the rolling stock assignment and the train routing problems, which up to now have been solved sequentially. We propose a new approach to obtain better and more robust circulations of the rolling stock train units, solving the rolling stock assignment while accounting for the train routing problem. Here robustness means that difficult shunting operations are selectively penalized and propagated delays together with the need for human resources are minimized. This new integrated approach provides a huge model. Then, we solve the integrated model using Benders decomposition, where the main decision is the rolling stock assignment and the train routing is in the second level. For computational reasons we propose a heuristic based on Benders decomposition. Computational experiments show how the current solution operated by RENFE (the main Spanish train operator) can be improved: more robust and efficient solutions are obtained.

1. Introduction

The globally growing demand and the inability to build more transport infrastructures to increase capacity in most of the world have led to a problem of severe congestion of urban and suburban areas. Congestion threatens our ability to get people where they need to be, with severe economic impacts; it also results in delays that also contribute to negative environmental impacts due to emissions resulting from inefficient system performance: the impacts pose an economic and health threat. Demand for transportation is increasing, so this threat is not going away and must be addressed. Many cities round the world have constructed railway Rapid Transit Networks (RTN) to improve their transport system performance. Our proposal is to meet with the growing demand through improved design and operation of rail RTN. Underground and suburban rail RTN problems are known as high-density network problems, in which the distances between the stations are relatively short and the frequencies are high.

Planning processes related to railway systems are fields that are rich in combinatorial optimization problems. Well-known examples of these are strategic and tactical problems addressed during the planning process. Due to the tremendous size of the planning process, it is usually divided into several steps such as network design, line planning, timetabling and rolling stock (RS) scheduling (i.e., rolling stock assignment and train routing (TR)) [17,18,6]:

1. *Network design*: Designing a RTN is a vital strategic subject due to the fact that it reduces the future traffic congestion, travel time and pollution. The location decisions and the maximum coverage of the demand for the new network are the main goal.
2. *Line planning*: The following step after designing a RTN is planning its lines (origin and destination stations, stops and frequencies). The problem of designing a line system aims at satisfying the travel demand while maximizing the service towards the passengers or minimizing the operating costs of the railway system.
3. *Timetabling*: The general aim of the railway timetabling problem is to construct a train schedule that matches the frequencies determined in the line planning problem.
4. *RS scheduling*: RS circulations are determined once the RS assignment and TR problems are solved:
   - Given a train fleet and finding the optimal composition assignment to each train to satisfy both the timetable and the demand in a dense RTN is known as the rapid transit RS assignment problem; shunting operations are also taken into account in this phase.
   - The train routing (TR) problem is the process of determining a sequence for each train unit in the network once the RS assignment is known. The goal is to obtain sequences that minimize some cost such as the propagated delay in order to achieve a robust solution; a different objective might be

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to maximize maintenance opportunities. Train routing planning must allow for each train unit to undergo different types of maintenance checks requirements. However, in our case light maintenance is done during valley hours, and train units that require maintenance are assigned to sequences with maintenance opportunities during valley hours (i.e., train units are swapped at the beginning of the planning period). We assume that the fleet size is large enough to remove any train unit requiring heavy maintenance from the network (this assumption holds true for our case study network).

Traditionally, this planning process has been solved within a hierarchical process, i.e. sequentially. However, this approach may lead the system to operate in an inefficient way (i.e., determining the RS assignment and shunting operations without accounting for train units' sequences and the likely delays might produce suboptimal plans). An integrated approach may increase the flexibility and the robustness degree of the railway system; therefore, in this paper we propose an integrated mathematical model so as to improve the circulations of the RS in rapid transit networks. The word circulation refers to both the RS assignment and the TR problems.

We present a Robust Circulation of the RS Model (RCRSM), which considers the RS assignment and TR problems in an integrated way. Here robustness means that (1) difficult shunting operations, which may produce negative cascading effects in case of malfunction, are selectively penalized so as to be minimized, (2) propagated delays are minimized, which indirectly minimizes the number of train swapping operations and (3) the need for human resources to perform train units' sequences is minimized.

The rest of this paper is organized as follows. A literature overview and our contributions are presented in Section 2. We describe the rolling stock circulation problem in Section 3. In Section 4, the mathematical formulation is presented in detail. Section 5 contains the solution approach based on Benders decomposition. Section 6 shows computational results based on realistic case studies drawn from RENFE. Conclusions and references follow in the next sections.

2. State of the art

Several researchers have dealt with railway industry planning and managing problems. Alfieri et al. [1] propose an integer programming model so as to determine the RS circulation for multiple RS material types on a single line and on a single day; they use the concept of a transition graph to deal with the RS circulations; this concept is based on the assumption that for each trip, the next trip is known a priori. The objective is to minimize the number of train units such that the given passenger demand is satisfied. The approach is tested on real-life examples from *Nederlandse Spoorwegen* (NS), the main operator of passenger trains in the Netherlands. The model described by Alfieri et al. [1] is extended by Fioole et al. [16], to include combining and splitting trains, as happens at several locations in the Dutch timetable. They use an extended set of variables to locally obtain an improved description of the convex hull of the integer solutions. Robustness is considered by counting the number of composition changes. Maróti [23] focuses on planning problems that arise at NS. He identifies tactical, operational and short-term rolling stock planning problems and develops operations research models for describing them. Peeters and Kroon [26] describe a model and a branch-and-price algorithm to determine a railway rolling stock circulation on a set of train lines. Given the timetable and the passengers' seat demand, the model determines an allocation of rolling stock to the daily trips. They evaluate the solution on three criteria: the service to the passengers, the robustness, and the cost of the circulation. Cadarso and Marín [8] propose a mixed integer optimization model to study suburban rapid transit robust RS assignment. They minimize total costs including service trips, robustness-relevant empty train movements and composition change costs. Almeida et al. [2] state that robustness can be improved by reducing the propagation of delays and increasing the number of feasible resource allocation exchanges. Cadarso and Marín [7] present an integer programming model to determine a sequence of operations to be rolled by the train units such that each operation is included exactly in one sequence and there is always the number of necessary train units available for every operation execution. Cacchiani et al. [5] describe a two-stage optimization model for determining robust rolling stock circulations for passenger trains. They also use the concept of a transition graph. Here robustness means that the rolling stock circulations can better deal with large disruptions of the railway system. They evaluate their approach on the real-life rolling stock-planning problem of NS.

All the previous research address the railway planning problems in a sequential manner. Even the authors who study RS circulations employ the concept of transition graph, which assumes that for each trip, the next trip is known. However, sequential solving approach has many drawbacks [4]. Although practical, the sequential nature of rolling stock assignment and routing optimization leads to suboptimal plans, with potentially significant economic losses. Improved plans can be generated by building and solving integrated models of some of the planning problems. The airline industry has been a leader in the development of integrated approaches for schedule planning and recovering from disruptions. There has been research in the integration of problems such as flight schedule and fleet assignment [20,9,11], fleet assignment and aircraft routing [25], aircraft routing and crew scheduling [24], and scheduling and competition [27,13]. All these problems were first developed and solved in a sequential fashion. However, the integration of them has outperformed sequential approaches. This fact is demonstrated in every cited paper.

Cadarso and Marín [10] and Cadarso et al. [12] demonstrate that this fact also applies in the railway industry where the integrated timetable planning and RS assignment and integrated disruption management are studied, respectively. Marín et al. [22], López et al. [21] and Walker et al. [29] also develop integrated approaches within the railway industry. Marín et al. [22] and López et al. [21] deal with the integration of railway network design and line planning problems while Walker et al. [29] deal with the simultaneous disruption recovery of a train timetable and crew roster.

Contributions: As we have showed before, the RS assignment and TR problems have been traditionally solved in a sequential fashion. As this sequential solving approach may lead to inefficient (and even infeasible) solutions, we propose a new comprehensive approach to determine optimal train circulations, which integrates RS assignment and TR decisions. The major contributions of this paper include:

1. Development of an integrated schedule optimization model that includes rolling stock assignment and train routing decisions. We avoid using the concept of transition graph, thus developing a more comprehensive decision support tool.
2. Introduction of robustness in the integrated model through different approaches:
   - Penalization of difficult shunting operations, which minimizes negative cascading effects in case of malfunction.
   - Minimization of propagated delays, which means that the number of swapping operations are minimized obtaining robust and improved RS circulations.