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# Recent success stories on integrated optimization of railway systems ☆,☆☆

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ABSTRACT

Planning and operating railway transportation systems is an extremely hard task due to the combinatorial complexity of the underlying discrete optimization problems, the technical intricacies, and the immense size of the problem instances. Because of that, however, mathematical models and optimization techniques can result in large gains for both railway customers and operators, e.g., in terms of cost reductions or service quality improvements. In the last years a large and growing group of researchers in the OR community have devoted their attention to this domain developing mathematical models and optimization approaches to tackle many of the relevant problems in the railway planning process. However, there is still a gap to bridge between theory and practice (e.g. Cacchiani et al., 2014; Borndörfer et al., 2010), with a few notable exceptions. In this paper we address three individual success stories, namely, long-term freight train routing (part I), mid-term rolling stock rotation planning (part II), and real-time train dispatching (part III). In each case, we describe real-life, successful implementations. We will discuss the individual problem setting, survey the optimization literature, and focus on particular aspects addressed by the mathematical models. We demonstrate on concrete applications how mathematical optimization can support railway planning and operations. This gives proof that mathematical optimization can support the planning of railway resources. Thus, mathematical models and optimization can lead to a greater efficiency of railway operations and will serve as a powerful and innovative tool to meet recent challenges of the railway industry.



## 1. Introduction

Planning and operating railway transportation systems is extremely hard due to the combinatorial complexity of the underlying discrete optimization problems, the technical intricacies, and the immense sizes of the problem instances. Precisely because of that, however, mathematical models and optimization techniques can result in huge gains for both railway

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customers and operators, e.g., in terms of cost reductions or service quality improvements. This observation is not new. In fact, railway planning was one of the originating applications for operations research and mathematical optimization, see the account of Schrijver (2002) for a historic overview from the early work of Tolstoĭ on augmenting cycles to the Ford and Fulkerson theory of network flows, or the article of Charnes and Miller (1956) for an early set partitioning approach. Indeed, the development of many mathematical key concepts was motivated by railway applications.

One reason why little of that was put into practice is probably that for a long time railway companies operated in de facto monopolies such that there was not enough incentive to standardize and optimize the planning tasks. The airline and later also the public transportation industry, however, moved ahead in implementing optimization solutions for related problems. Their successes are a strong motivation to investigate the potential of railway optimization from today's point of view. It is now broadly understood that the development of industry standards for railway planning and the mathematical solution of the associated optimization problems are the key to improve the efficiency of railway systems.

In the last years a large and growing group of researchers in the OR community have devoted their attention to this domain developing mathematical models and optimization approaches to tackle many of the relevant problems in the railway planning process. While there is still a gap to bridge between theory and practice, see, e.g. Cacchiani et al. (2014) and Borndörfer et al. (2010) for surveys, substantial progress is undeniable. This paper addresses three from only a few success stories of the deployment of operations research methods in railway planning, namely:

1. long-term freight train routing (Section 2, see Borndörfer et al., 2016),
2. mid-term rolling stock rotation planning (Section 3, see Reuther et al., 2012),
3. and, real-time train dispatching (Section 4, see Lamorgese and Mannino, 2015).

In each case, we describe real-life, successful implementations. We discuss the respective problem setting, survey the optimization literature, and focus on special aspects addressed by the mathematical models. We will demonstrate on the concrete applications how mathematical optimization can support individual railway planning steps and operations. We perceive the success in very different forms. On the one hand all presented implementations are integrated into the tool landscape of the corresponding railway companies. On the other hand the usage is quite different from daily deployment to monthly or yearly application with cost savings achieved through reduced planning time and improved results. What they all share in particular is that they are or at least can be effectively used at the corresponding department of the railway cooperation partner as a decision support tool.

The three example problems are at different levels of the planning process of a railway system, which are typically handled by separate companies (in Europe the railway system is segregated into train operating companies, namely, passenger and freight train operators, and railway infrastructure providers).

Fig. 1 shows an idealized planning process for such a segregated railway system. Such a standard process is in comparison to the urban public transport or the airline industry only present in a latent state in the railway market. Because of the former monopolistic national railway system, see Borndörfer et al. (2010) and Schlechte (2012), On the left hand side the perspective of a railway undertaking is shown from planning the lines or freight routes to operate (strategic), constructing a timetable, allocating rolling stock resource and crews (tactical) to real time management of those resources (operational). On the right hand side the view of an infrastructure manager or network provider is described. which is basically responsible for the railway infrastructure usage. That refers to long term network design questions, yearly track allocation planning for and together with all operating railway undertakings, and the crucial task of train dispatching all the time.

In today's practice, however, each railway company seems to have its own internal and proprietary process to organize their planning. Assumptions on essential problem characteristics as well as on principal purposes can differ strongly, e.g., between a regional passenger railway operator and an international freight train operator. This situation must be taken into account.

The motivation of this paper is to encourage the railway industry to build up a planning process on the basis of an integrated data model to release further economic potentials.

## 2. Freight train routing

One of the first steps in the planning process of a railway company, is to find a strategic routing for an estimated demand of a transportation network. We distinguish two types of traffic. On the one hand, there is the passenger traffic with a routing that is mostly determined by political and historical presets. In addition, passenger train routes are limited by several intended intermediate stops with strict time windows and some planned connections to other trains. It is also widely assumed that passengers expect a stable and frequently reoccurring service. On the other hand, there is the freight traffic with often less strict departure and arrival time requirements and less constrained routes. Furthermore, the freight train demand is much more volatile in comparison to the repetitive number of passengers.

The goal for both types of traffic is to find routes for a set of origin-destination pairs that obey the network capacities and minimize the resulting cost. Typical cost functions for passenger traffic are the operating cost or the experienced traveling times. In the case of public transport this is a well studied problem, for a recent survey see Schöbel (2012).