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Railway Track Allocation
-
Simulation and Optimization

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Abstract

Today the railway timetabling process and the track allocation is one of the most challenging problems to solve by a railway infrastructure provider. Especially due to the deregulation of the transport market in the recent years several suppliers of railway traffic have entered the market. This leads to an increase of slot requests and therefore it is natural that conflicts occur among them. Furthermore, railway infrastructure networks consist of very expensive assets, even more they are rigid due to the long-term upgrade process.

In order to make best use of these valuable infrastructure and to ensure economic operation, efficient planning of the railway operation is indispensable. Mathematical optimization models and algorithmic methodology can help to automatize and tackle these challenges. Our contribution in this paper is to present a renewed planning process due to the liberalization in Europe and a general framework to support the integration of simulation and optimization for railway capacity allocation.

1 Introduction

Today the railway timetabling process and the track allocation is one of the most challenging problems to solve by a railway infrastructure provider. Especially due to the deregulation of the transport market in the recent years several suppliers of railway traffic have entered the market. This leads to an increase of slot requests and therefore it is natural that conflicts occur among them. Furthermore, railway infrastructure networks consist of very expensive assets, even more they are rigid due to the long-term upgrade process.

In order to make best use of these valuable infrastructure and to ensure economic operation, efficient planning of the railway operation is indispensable. Mathematical optimization models and algorithmic methodology can help

to automatize and tackle these challenges. Our goal is to resolve conflicts by producing a feasible and conflict free timetable, in which a maximum of utilization is attained.

From a mathematical point of view the optimization problem can be stated as a multi-commodity flow problem through an extremely large network in space and time with certain additional constraints. The problem is well known in the literature and in the seminal paper of [Caprara et al. \[2002\]](#) it was shown that it is \mathcal{NP} -hard.

Only recently practical problem sizes are tractable due to the development of improved models and algorithms. Nevertheless a decomposition of the problem remains necessary. On the one hand for networks, or at least for long railway corridors, only simplified macroscopic models with a simplified routing through the railway infrastructure are considered, as in [Cai & Goh \[1994\]](#); [Brännlund et al. \[1998\]](#); [Caprara et al. \[2002\]](#); [Borndörfer et al. \[2006\]](#); [Cacchiani \[2007\]](#); [Borndörfer & Schlechte \[2007\]](#); [Cacchiani et al. \[2008\]](#); [Fischer et al. \[2008\]](#); [Borndörfer et al. \[2009\]](#). On the other hand, routing or re-routing through complex stations can be considered on a more detailed, but of course only on a local level, see [Zwaneveld et al. \[1996a\]](#); [Caimi et al. \[2004\]](#); [Lusby et al. \[2006\]](#); [Caprara et al. \[2007\]](#); [Klabes \[2010\]](#). The only recent reference, to the best knowledge of the authors, describing the interaction of both levels is [Caimi et al. \[2009\]](#), in which a top-down approach is used.

We present a fully integrated bottom-up approach that is based on microscopic simulation data, automatic network creation and discrete optimization at the end. The contribution of this paper is to put several pieces or software tools together, i.e., `OpenTrack`, `NETCAST`, and `TS-OPT`, in order to release the optimization potential of the railway track allocation process. One challenging part is to establish interfaces between railway simulation software and state of the art mathematical optimization tools. However, to tackle large size instances of the track allocation problem sophisticated mathematical techniques are needed.

We will focus in that paper on the motivation and origin of our approach. Main contribution will be to discuss track allocation as part of a greater whole and to establish an interaction between microscopic simulation and macroscopic optimization. Section 2 will give a detailed description of the planning process of a railway system after the liberalization in Europe. The term railway capacity is discussed in Section 3. Finally, we present our framework of simulation based optimization of railway track allocations in Section 4.

2 Planning in Railway Transportation

The planning process in public transport can be divided into three major levels - strategic, tactical and operational planning, see Table 1. Public transport, especially railway transportation, is such a technically complex and large-scale system, that it is impossible to consider it at once to its full extend. Even though the different planning horizon of certain decisions enforce a decomposition. Therefore a sequence of hierarchical planning steps has emerged over the years. In addition several important parties are involved in railway transportation planning process, i.e., train operating companies and railway infrastructure providers. We will use analogously the term railway undertaking (RU) and infrastructure manager (IM) to stick to the terminology of the European committee. Furthermore, several national and international institutions have a huge political influence on railway transportation, which is therefore somehow in the borderline between a social or public good and a product that can be traded on a free liberalized market. The special case of the changing European environment is discussed in detail in [Klabes \[2010\]](#).

In contrast to that, fully private aviation companies or independent urban public transport companies can perform the complete planning almost internally. In the airline industry the needed capacity, that are the slots at the airports, are given by grandfather rights in forehand, see [Barnier et al. \[2001\]](#) and [Castelli et al. \[2010\]](#). [Borndörfer et al. \[2008, 2009\]](#) and [Hanne & Dornberger \[2010\]](#) give a recent survey about the potential of optimization for transportation systems and the differences between the planning process in the airline industry, the urban public transport, and the railway industry. In case of urban public transport the planning process is discussed in [Weider \[2007\]](#) and [Borndörfer et al. \[2007\]](#). A detailed description of the process in the airline industry can be found in [Grönkvist \[2005\]](#) and [Barnhart & Laporte \[2007\]](#). [Bussieck \[1997\]](#) describes the use of discrete optimization in the planning process of public rail transport in case of an integrated system. Analogous considerations can be found in [Liebchen \[2006\]](#) and [Lusby et al. \[2009\]](#). There the planning steps are classified with respect to the time horizon and their general purposes.

level	time horizon	goal
strategic	5-15 years	resource acquisition
tactical	1-5 years	resource allocation
operational	24h - 1 year	resource consumption

Table 1: Planning steps in railroad traffic, source: [Bussieck et al. \[1997\]](#).

The strategic or long-term part (resource acquisition) concerns network design and line planning. On the tactical level (resource allocation) the offer,

usually a timetable or schedule has to be created, as well as the schedules for the needed resources. After that the resources, e.g., rolling stock, vehicles, aircrafts and crews, are considered on the operational stage (resource consumption).

Finally, on the day of operation re-scheduling and dispatching problems have to be faced. These kind of problems have a different flavor. On the one hand decisions and therefore solutions have to be made very fast because of the changing real-time setting. On the other hand only partial information about the "scenario" is given, usually data has to be taken into consideration with respect to its appearance, i.e., in a so called on-line fashion. More details on these kind of problems in general can be found in Grötschel et al. [2001]; Albers & Leonardi [1999]; Albers [2003]. Recent approaches are to establish fast methods which bring the "real" situation back to the "planned" one, if possible, see Potthoff et al. [2008]; Rezanova & Ryan [2010]; Jespersen-Groth et al. [2009].

In Klabes [2010] the planning process is newly considered for the case of the segregated European railway system. The responsibilities of the planning steps refer directly to either the railway undertakings or the infrastructure manager. Nevertheless the long-term decisions in up- or downgrading the network is highly influenced by the railway undertakings and their demands. In case of a passenger railway undertaking the desired timetable to implement a given line plan induces train slot requests, which is one input for the track allocation problem. The requirements of train slot requests for cargo or freight railway operators differ a lot because they usually have more flexibility, i.e., arrival and departures are only important at stations where loading has to be performed. In general freight railway operators need a mixture of annual and ad hoc train slots. This is of course highly influenced by the resident industry customers and freight concept of the operating railway undertakings. We have collected such data for the German subnetwork *hakafu_simple* to estimate the demand of the railway freight transportation, see Schlechte & Tanner [2010].

The essential connection between (RU) and (IM) is the step to determine the complete track allocation, which is the focus of this paper. However, we take mainly the point of view of a railway infrastructure provider, which is interested in optimizing the utilization of the network. That is to determine optimal track allocations with respect to utilization of infrastructure resources. In contrast to passenger timetabling where one asks for the ideal arrival and departure times to realize a timetable concept or a line plan. The result of that can be seen as a set of train slot requests without flexibility. Railway optimization methods from the railway undertaking point of view for passenger traffic can be found in Caprara et al. [2007]. State of the art modeling and optimization approaches to periodic timetabling, which is the usual type of schedule for passenger railway traffic, is widely studied by Liebchen [2006], Caimi et al. [2009] and others.

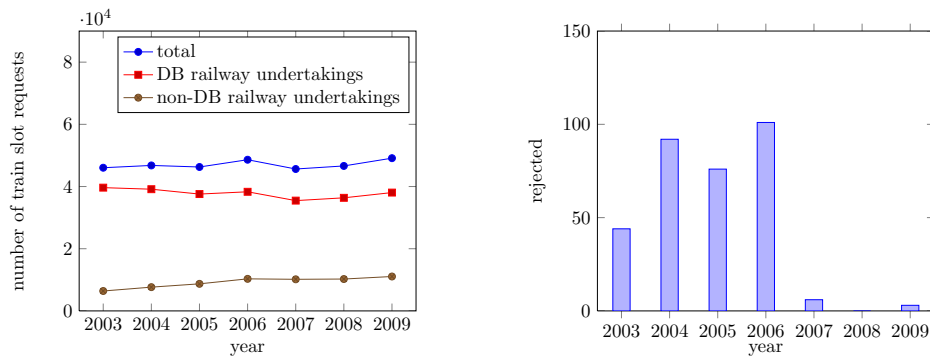


Figure 1: Requested train paths at DB, source: Klabes [2010]

The induced competition for railway capacity allocation in public railway systems in Europe severely impacts the allocation procedure. In the past a single integrated railway company performed the complete planning. Its segregation reduces the competences of the railway infrastructure manager to perform network planning, capacity allocation and re-scheduling with respect to the infrastructure aspects only. Thus the infrastructure manager has just limited information during the planning process and needs to respect the confidential information of the railway undertakings. Moreover, new railway undertakings enter the established market for railway operation, which increases the complexity of the planning process. On the left hand of Figure 1 the changing environment is illustrated by the growing number of train slot requests from railway undertakings independent from the former integrated railway company "Deutsche Bahn". However, it can be observed that it is a long-term process to release the liberalization potential in the railway market. On the right hand of Figure 1 the number of rejected train slot requests for the same periods are shown. It can be seen that at the start of the segregation from 2003 until 2006 a lot of requests had to be rejected by DB Netz. Efforts to decrease these numbers by providing alternative slots were apparently successful in the following years. This leads to the suspicion that the complexity of the novel process was underestimated and was badly managed in the beginning, see also Klabes [2010]. However, more transparency and flexibility of the allocation can be verified and documented. The business report for the year 2009 of the *Trasse Schweiz AG* [2009] documents this as well. In the Swiss network naturally a lot of different railway undertakings are operating, e.g., in 2009 they were 29 train operating companies which submitted train slot requests. The geographical position in central Europe and the limited transportation possibilities through the Alps causes that. The future challenge for Switzerland will be to handle the complex track allocation process as the following extract already highlights:

The regulation of the conflicts arising train slot orders of the annual timetable 2010 was despite or even because of the financial or economic crisis in comparison to the last years extensive and time-consuming. Indeed the number of submitted train slot requests by cargo operators for the annual timetable 2010 decreased up to 10 percent in comparison to the last year. However, railway undertakings (RM) concentrated her orders due to the cost pressure and competitive market conditions on the most attractive time windows and stick much longer to their original requests. Nevertheless, we managed together with all infrastructure providers to find for all conflicts alternative train slots, which were accepted by the railway undertakings. There are three different railway infrastructure providers in Switzerland, i.e., BLS, SBB, and SOB. No train slot request had to be rejected.

The competing railway undertakings should interact on a transparent and free market. The creation of such a market for railway capacity is a key target of the European Commission, hoping that it will lead to a more economic utilization of the railway infrastructure. Even more liberalization of the railway system should lead to a growing market and allow for innovation trends like in other old-established industries, e.g., aviation industry, telecommunication or energy market.

After the acceptance of train slots each railway undertaking determine the operating timetable, which acts as input for the planning of the needed resources. In case of the railway system the rolling stock rotations has to be constructed, which is very complex problem due to several regularities and maintenance requirements, see [Fioole et al. \[2006\]](#); [Anderegg et al. \[2003\]](#); [Eidenbenz et al. \[2003\]](#); [Peeters & Kroon \[2008\]](#).

In public transport vehicle scheduling and in airline industry aircraft rotation planning are the analogous tasks, see [Löbel \[1997\]](#) and [Grönkvist \[2005\]](#). Major objective is to reliable operate the timetable with a minimum cost, which is in general minimizing the number of engines, wagons, vehicles, aircrafts etc. Another key requirement for planning railway rolling stock rotations is to provide regularity of the solutions. This means, e.g., that a train that runs in the same way every day of the week, will also be composed in the same way every day of the week, always using the same cars from the same preceding trains. Such a regime simplifies the operation of a railway significantly. However, the rule can not always be followed. Trains may run later on weekends, or not at all on certain days, e.g., in order to perform a maintenance operation. Although it is intuitively clear, it is even not easy to give a precise definition what regularity actually means.

The output of this planning step are passenger trips, that are trips of the published timetable, and deadhead trips, i.e., "empty" movements of the

trains given by the constructed rolling stock rotation. These tasks need to be assigned to crews, which have to execute them. Recent work on railway crew scheduling can be found in [Abbink et al. \[2005\]](#) and [Bengtsson et al. \[2007\]](#). As already mentioned real time problems on the day of operation have quite different requirements, even if from a mathematical modeling point these problems can be formulated in a very similar way. In railway transportation disruption and delay management is very difficult because local decisions have a huge influence on the complete timetable system. Nevertheless, easy and fast rule of thumbs are used to decide which trains have to be re-routed, have to wait, or even have to be canceled. [D’Ariano et al. \[2008\]](#), [Corman et al. \[2010b\]](#), and [Corman et al. \[2010a\]](#) presented a real-time traffic management system to support local dispatching in practice by operations research methods. On the basis of this renewed timetable, rolling stock rosters and crew schedules have to be adopted, see [Jespersen-Groth et al. \[2007\]](#); [Clausen et al. \[2010\]](#); [Potthoff et al. \[2008\]](#); [Rezanova & Ryan \[2010\]](#).

Every single step in this idealized sequential planning process is a difficult task by itself or even more has to be further divided and simplified into subproblems. In [Figure 2](#) the novel process is illustrated in case of the segregated railway industry in Europe. The main application of track allocation is to determine if a requested timetable is operational implementable or not, which is the main focus of this work. But, we want to mention that due to the segregation the track allocation process directly gives information about the infrastructure capacity. This feedback for the department concerning network design is very important and can support the evaluation of several alternatives. Even more long-term infrastructure decisions could be evaluated by applying automatically the track allocation process, e.g., without full details on a coarse macroscopic level but with different demand expectations. Even if we did not developed our models and tools for this purpose, it is clear that suitable extensions or simplifications the other way around of our models could support infrastructure decisions in a quantifiable way. For example major upgrades of the German railway system like the high-speed route from Erfurt to Nürnberg or the extension of the main station in Stuttgart can be evaluated from reliable resource perspective. The billions of € for such large projects can then be justified by reasonable quantifications of the real capacity benefit with respect to the given expected demand.

An obvious, but unavoidable, disadvantage of the decomposition is that the in some sense "optimal" solution for one step serves as fixed input for the subsequent problem. Therefore one cannot expect an overall "optimal" solution for the entire system in the end not even a feasible one. In that case former decisions have to be changed, and a part or the complete process has to be repeated. Prominent examples are regional scenarios for urban public transportation where traditional sequential approaches are not able to produce feasible schedules. [Weider \[2007\]](#) demonstrates in case of vehicle and

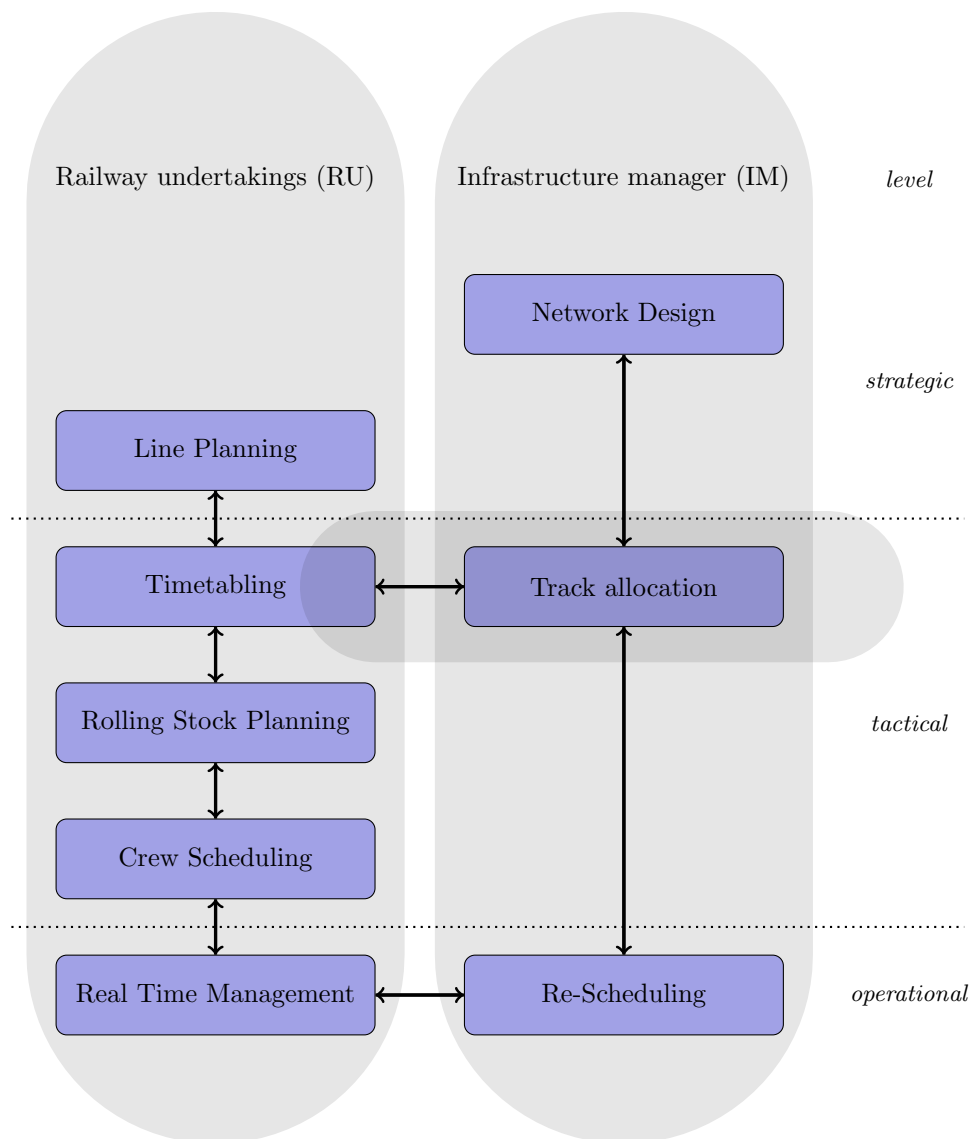


Figure 2: Idealized planning process for railway transportation in Europe.

duty scheduling how integrated models can cope with that and even more can increase the overall planning efficiency. Nevertheless, this hierarchic planning provides a partition of the traffic planning problem into manageable tasks. Tasks, which lead directly to quantifiable optimization problems and which nowadays can be solved by linear and integer programming to optimality or at least with proven optimality gaps. Problem standardization, automatization, organizing data, computational capabilities, mathematical modeling, and sophisticated algorithmic approaches on a problem specific

but also on a general level afford this success story. As an prominent example for this we refer to the dutch railway timetable - the first railway timetable which was almost constructed from scratch. In fact the entire planning process was decomposed and each planning problem at Netherlands Railways (NS) was solved by the support of exact or heuristic mathematical approaches and sophisticated techniques, in particular linear, integer and constraint programming. More details can be found in the prizewinning work [Kroon et al. \[2009\]](#), which was honored with the *Franz Edelman Award* 2008. A prize which is rewarded to outstanding examples of management science and operations research practice in the world.

3 Modeling Railway Capacity

To establish an optimization process for the allocation of “railway capacity”, we first have to define capacity and derive a resource based model for a railway system in an appropriate way. Railway capacity has basically two dimensions, a space dimension which are the physical infrastructure elements as well as a time dimension that refers to the train movements, i.e., occupation or blocking times, on the physical infrastructure. A major challenge of both dimensions is the granularity, the potential size, and the arbitrary smooth variation of time. We will not describe microscopic aspects of the railway system. However, the definition of resources and capacity is inspired by the work of [Landex et al. \[2008\]](#). In the literature several approaches work directly on a microscopic level with the disadvantage that only instances of small size can be handled, see [Zwaneveld et al. \[1996b, 2001\]](#); [Lusby et al. \[2009\]](#); [Fuchsberger \[2007\]](#); [Delorme et al. \[2009\]](#); [Klabes \[2010\]](#).

Nevertheless, on a planning stage it is not possible to consider all these details and also not necessary. Hence, the main application of a macroscopic model is to evaluate different timetable concepts or infrastructure decisions on a coarse granularity. Only recently approaches were developed to tackle larger corridors or even network instances by exact optimization approaches. [Lusby et al. \[2009\]](#) give a recent survey on the track allocation problem and railway timetabling. [Liebchen \[2006\]](#) and [Caimi \[2009\]](#) classified the approaches in the literature according to used solution methods and scale of the models. With respect to that general classification, we are tackling the problem of non-periodic scheduling with state of the art linear and integer programming methods, see [Borndörfer & Schlechte \[2007\]](#), [Borndörfer et al. \[2009\]](#), and [Borndörfer et al. \[2010\]](#). However, to tackle large size instances of the track allocation problem sophisticated mathematical techniques are needed. In [Borndörfer et al. \[2010\]](#) we focus on the ingredients of TS-OPT to produce high quality solutions in reasonable computation time; that are dynamic column generation, proximate bundle method and a rapid branching heuristic embedded in a branch and price scheme. [Fischer & Helmberg](#)

[2010] propose a dynamic graph generation to solve the pricing problems for very large graphs, i.e., the original objective function has to fulfill the requirement that an earlier arrival is always beneficial. These are only some examples that documents that track allocation is a fruitful research area and that further algorithmic improvements are still possible.

In Caimi [2009] a top-down approach is presented and used to handle the complete Swiss network by a priori decomposition of the network into different zones. In contrast to that, we use a bottom-up approach to define a macroscopic railway model, see Borndörfer et al. [2010a] and Borndörfer et al. [2010b]. On the one hand these models are precise enough to allow for valid allocations with respect to blocking times, on the other hand they are simplified and aggregated to a coarse level, which allows for solving large scale optimization instances. The main advantage of this approach is that we can estimate the quality of the macroscopic model, i.e., we developed bounds for the rounding error of running and headway times in Borndörfer et al. [2010a].

4 Closing the Cycle - from Simulation to Optimization and back again

The concept of our framework is shown in Figure 3. Starting point is an accurate simulation tool that describes the railway system as "real" as it can be. In our studies, we are using the microscopic simulation tool `OpenTrack`, see Hürlimann [2001]. However, one main idea of a general framework is to be as modular as possible, i.e., to allow for any railway simulation and optimization tool. Based on that microscopic representation of the railway system we automatically simplify to a macroscopic railway model, i.e., the network is aggregated and the times are appropriately rounded. Further details on the Micro-Macro Transformation and the tool `NETCAST` including error bounds to guarantee a certain quality of the macroscopic model can

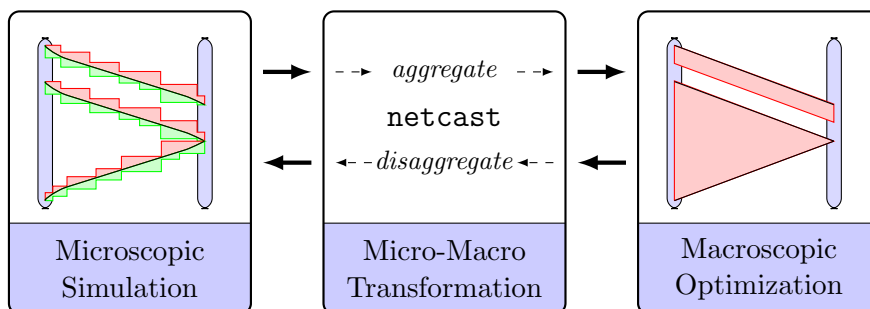


Figure 3: Idealized closed loop for optimization of railway track allocation based on simulation.

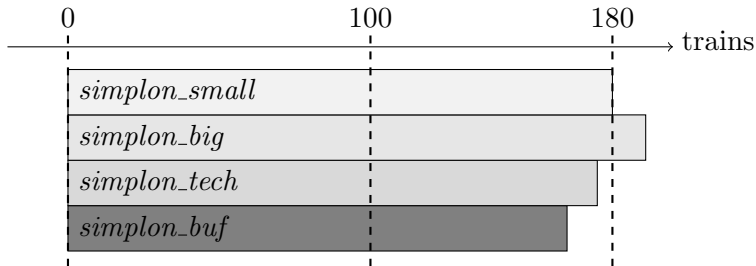


Figure 4: Comparing the "maximum" number of scheduled trains for different networks (*simplon_*) for instance 24h-tp-as using a 60s discretization.

be found in [Borndörfer et al. \[2010a\]](#). Furthermore, we applied our framework on real world data to analyze the technical and theoretical capacity of a railway corridor. As an example for the potential, Figure 4 shows the output of our optimization approach for four different railway models of the Simplon.

There are only two north-south railway connections through the Alps in Switzerland, namely, the Gotthard corridor and the Lötschberg-Simplon corridor. The Simplon connects Switzerland and Italy and is therefore of strategic importance for the international railway freight traffic. The four network models *simplon_small*, *simplon_big*, *simplon_tech*, and *simplon_buf* differ in their routing possibilities, buffer times, and hence in their theoretical "maximum" capacities, see Figure 4. The assumptions, details, i.e., the requested train mixture, and results of this case study on the Simplon corridor are presented in [Borndörfer et al. \[2010b\]](#).

We tested our framework using `OpenTrack`, `NETCAST`, and `TS-OPT`, to evaluate the Micro-Macro Transformation, to analyze macroscopic railway track allocations, and to provide a proof of concept. Finally, Figure 5 shows a track allocation produced by our approach and re-translated to `OpenTrack`, i.e., closing the loop between microscopic and macroscopic railway models. On the one hand the constructed macroscopic railway model is coarse enough to allow for complex optimization. On the other hand it is accurate enough to appropriately model the railway capacity and to produce timetables that can be re-translated into the microscopic model. Moreover, the core of the framework is to close the loop from simulation to optimization or from microscopic railway models to macroscopic ones. Establishing such interfaces between simulation and optimization is a very important point to allow for innovation. On the one hand it activates the optimization potential of railway planning, e.g., railway track allocation. On the other hand it automatically integrates further developments of simulation tools. A fruitful and successful transfer of knowledge is only possible if bridges between theory and practice are built. Simulation tools are widespread and commonly used

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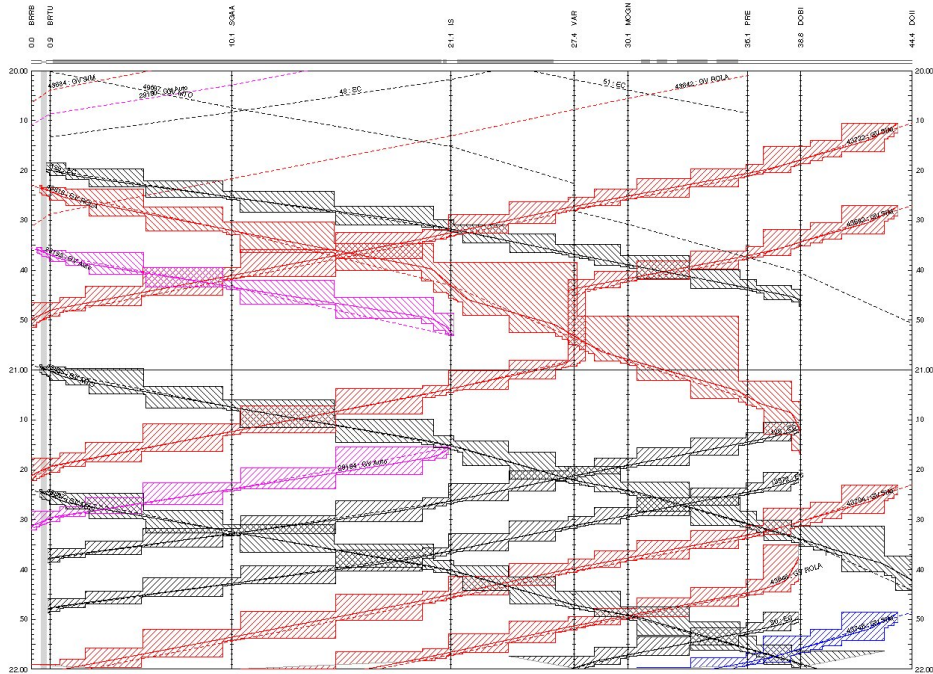


Figure 5: Traffic diagram of re-translated solution in `OpenTrack`.

in almost all railway operating companies. However, innovative and state of the art discrete optimization has still potential to contribute to railway planning challenges. We believe that our framework is a great example for that and will support railway planning, i.e., the process of railway track allocation, in the future.

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References

- Abbinck, Fischetti, Kroon, Timmer & Vromans (2005). Reinventing Crew Scheduling at Netherlands Railways. *Interfaces* 35(5), 393–401.
- Albers (2003). Online algorithms: a survey. *Math. Program.* 97(1-2), 3–26.
- Albers & Leonardi (1999). On-line Algorithms. *ACM Comput. Surv.* 31(3es), 4.

- Anderegg, Eidenbenz, Gantenbein, Stamm, Taylor, Weber & Widmayer (2003). Train Routing Algorithms: Concepts, Design Choices, and Practical Considerations. In Ladner (Ed.), *ALLENEX*, pp. 106–118. SIAM.
- Barnhart & Laporte (2007). *Handbooks in Operations Research & Management Science: Transportation*. North-Holland.
- Barnier, Brisset, Rivire & Ere (2001). Slot Allocation with Constraint Programming: Models and Results. In *In Proc. of the Fourth International Air Traffic Management R&D Seminar ATM*.
- Bengtsson, Galia, Gustafsson, Hjorring & Kohl (2007). Railway Crew Pairing Optimization. In F. Geraets, L. Kroon, A. Schoebel, D. Wagner, & C. Zaroliagis (Eds.), *Algorithmic Methods for Railway Optimization*, LNCS pp. 126–144. Springer-Verlag.
- Borndörfer, Erol, Graffagnino, Schlechte & Swarat (2010a). Aggregation Methods for Railway Networks. ZIB Report 10-23, ZIB, Takustr. 7, 14195 Berlin.
- (2010b). Optimizing the Simplon Railway Corridor. ZIB Report 10-24, ZIB, Takustr. 7, 14195 Berlin.
- Borndörfer, Erol & Schlechte (2009). Optimization of macroscopic train schedules via TS-OPT. In Hansen, Wendler, Weidmann, Lüthi, Rodriguez, Ricci & Kroon (Eds.), *Proceedings of the 3rd International Seminar on Railway Operations Modelling and Analysis - Engineering and Optimisation Approaches*, Zürich, Switzerland.
- Borndörfer, Grötschel & Jaeger (2008). Planungsprobleme im öffentlichen Verkehr. In M. Grötschel, K. Lucas, & V. Mehrmann (Eds.), *PRODUKTIONSFAKTOR MATHEMATIK – Wie Mathematik Technik und Wirtschaft bewegt*, acatech DISKUTIERT pp. 127–153. acatech – Deutsche Akademie der Technikwissenschaften und Springer. ZIB Report 08-20.
- (2009). Planning Problems in Public Transit. ZIB Report 09-13, ZIB, Takustr. 7, 14195 Berlin. To appear in English translations of acatech book.
- Borndörfer, Grötschel, Lukac, Mitusch, Schlechte, Schultz & Tanner (2006). An Auctioning Approach to Railway Slot Allocation. *Competition and Regulation in Network Industries 1(2)*, 163–196.
- Borndörfer, Grötschel & Pfetsch (2007). A Column-Generation Approach to Line Planning in Public Transport. *Transportation Science 41(1)*, 123–132.
- Borndörfer & Schlechte (2007). Models for Railway Track Allocation. In Liebchen, Ahuja & Mesa (Eds.), *ATMOS 2007 - 7th Workshop on Algorithmic Approaches for Transportation Modeling, Optimization, and Systems*, Dagstuhl, Germany. Internationales Begegnungs- und Forschungszentrum für Informatik (IBFI), Schloss Dagstuhl, Germany.

- Borndörfer, Schlechte & Weider (2010). Railway Track Allocation by Rapid Branching. In Erlebach & Lübbecke (Eds.), *Proceedings of the 10th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems*, volume 14 of *OpenAccess Series in Informatics (OASISs)*, pp. 13–23., Dagstuhl, Germany. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik.
- Brännlund, Lindberg, Nou & Nilsson (1998). Railway Timetabling using Langangian Relaxation. *Transportation Science* 32(4), 358–369.
- Bussieck (1997). *Optimal lines in public rail transport*. PhD thesis, TU Braunschweig.
- Bussieck, Winter & Zimmermann (1997). Discrete optimization in public rail transport. *Mathematical Programming* 79B(1–3), 415–444.
- Cacchiani (2007). *Models and Algorithms for Combinatorial Optimization Problems arising in Railway Applications*. PhD thesis, DEIS, Bologna.
- Cacchiani, Caprara & Toth (2008). A column generation approach to train timetabling on a corridor. *4OR* 6(2), 125–142.
- Cai & Goh (1994). A fast heuristic for the train scheduling problem. *Comput. Oper. Res.* 21(5), 499–510.
- Caimi (2009). *Algorithmic decision support for train scheduling in a large and highly utilised railway network*. PhD thesis, ETH Zurich.
- Caimi, Burkolter & Herrmann (2004). Finding Delay-Tolerant Train Routings through Stations. In Fleuren, den Hertog & Kort (Eds.), *OR*, pp. 136–143.
- Caimi, Burkolter, Herrmann, Chudak & Laumanns (2009). Design of a Railway Scheduling Model for Dense Services. *Networks and Spatial Economics* 9(1), 25–46.
- Caprara, Fischetti & Toth (2002). Modeling and Solving the Train Timetabling Problem. *Operations Research* 50(5), 851–861.
- Caprara, Galli & Toth (2007). Solution of the Train Platforming Problem. In Liebchen, Ahuja & Mesa (Eds.), *ATMOS*, volume 07001 of *Dagstuhl Seminar Proceedings*. Internationales Begegnungs- und Forschungszentrum fuer Informatik (IBFI), Schloss Dagstuhl, Germany.
- Caprara, Kroon, Monaci, Peeters & Toth (2007). Passenger Railway Optimization. In C. Barnhart & G. Laporte (Eds.), *Handbooks in Operations Research and Management Science*, volume 14 chapter 3, pp. 129–187. Elsevier.
- Castelli, Pellegrini & Pesenti (2010). Airport slot allocation in Europe: economic efficiency and fairness. Working Papers 197, Department of Applied Mathematics, University of Venice.
- Clausen, Larsen, Larsen & Rezanova (2010). Disruption management in the airline industry-Concepts, models and methods. *Comput. Oper. Res.* 37(5), 809–821.

- Corman, D’Ariano, Pacciarelli & Pranzo (2010a). Bi-objective conflict detection and resolution in railway traffic management. *Transportation Research Part C: Emerging Technologies In Press, Corrected Proof*, –.
- (2010b). A tabu search algorithm for rerouting trains during rail operations. *Transportation Research Part B: Methodological* 44(1), 175–192.
- D’Ariano, Corman, Pacciarelli & Pranzo (2008). Reordering and Local Rerouting Strategies to Manage Train Traffic in Real Time. *Transportation Science* 42(4), 405–419.
- Delorme, Gandibleux & Rodriguez (2009). Stability evaluation of a railway timetable at station level. *European Journal of Operational Research* 195(3), 780–790.
- Eidenbenz, Pagourtzis & Widmayer (2003). Flexible Train Rostering. In Ibaraki, Katoh & Ono (Eds.), *ISAAC*, volume 2906 of *Lecture Notes in Computer Science*, pp. 615–624. Springer.
- Fioole, Kroon, Maróti & Schrijver (2006). A rolling stock circulation model for combining and splitting of passenger trains. *European Journal of Operational Research* 174(2), 1281–1297.
- Fischer & Helmberg (2010). Dynamic Graph Generation and Dynamic Rolling Horizon Techniques in Large Scale Train Timetabling. In Erlebach & Lübbecke (Eds.), *Proceedings of the 10th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems*, volume 14 of *OpenAccess Series in Informatics (OASISs)*, pp. 45–60., Dagstuhl, Germany. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik.
- Fischer, Helmberg, Janßen & Krostitz (2008). Towards Solving Very Large Scale Train Timetabling Problems by Lagrangian Relaxation. In Fischetti & Widmayer (Eds.), *ATMOS 2008 - 8th Workshop on Algorithmic Approaches for Transportation Modeling, Optimization, and Systems*, Dagstuhl, Germany. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, Germany.
- Fuchsberger (2007). Solving the train scheduling problem in a main station area via a resource constrained space-time integer multi-commodity flow. Master’s thesis, Institut for Operations Research ETH Zürich.
- Grönkvist (2005). *The Tail Assignment Problem*. PhD thesis, Chalmers University of Technology and Göteborg University.
- Grötschel, Krumke & Rambau (2001). *Online Optimization of Large Scale Systems*. Springer.
- Hanne & Dornberger (2010). Optimization Problems in Airline and Railway Planning - A Comparative Survey. In *Proceedings of the The Third International Workshop on Advanced Computational Intelligence*.
- Hürlimann (2001). *Object oriented modeling of infrastructure elements and business processes in railways*. PhD thesis, ETH Zürich.

- Jespersen-Groth, Potthoff, Clausen, Huisman, Kroon, Maróti & Nielsen (2007). Disruption management in passenger railway transportation. Econometric Institute Report EI 2007-05, Erasmus University Rotterdam, Econometric Institute.
- Jespersen-Groth, Potthoff, Clausen, Huisman, Kroon, Maróti & Nielsen (2009). Disruption Management in Passenger Railway Transportation. In R. K. Ahuja, R. H. Möhring, & C. D. Zaroliagis (Eds.), *Robust and Online Large-Scale Optimization*, volume 5868 of *Lecture Notes in Computer Science* pp. 399–421. Springer.
- Klabes (2010). *Algorithmic railway capacity allocation in a competitive European railway market*. PhD thesis, RWTH Aachen.
- Kroon, Huisman, Abbink, Fioole, Fischetti, Maróti, Schrijver, Steenbeek & Ybema (2009). The New Dutch Timetable: The OR Revolution. *Interfaces* 39(1), 6–17.
- Landex, Schittenhelm, Kaas & Schneider-Tilli (2008). Capacity measurement with the UIC 406 capacity method. In Tomii, Allan, Arias, Brebbia, Goodman, Rumsey & Sciuotto (Eds.), *Computers in Railways XI*. WIT Press.
- Liebchen (2006). *Periodic Timetable Optimization in Public Transport*. PhD thesis, Technische Universität Berlin.
- Löbel (1997). *Optimal Vehicle Scheduling in Public Transit*. Aachen: Shaker Verlag. Ph.D. thesis, Technische Universität Berlin.
- Lusby, Larsen, Ehrgott & Ryan (2009). *Railway track allocation: models and methods* *OR Spectrum* .
- Lusby, Larsen, Ryan & Ehrgott (2006). Routing Trains Through Railway Junctions: A New Set Packing Approach. Technical report, Informatics and Mathematical Modelling, Technical University of Denmark, DTU, Richard Petersens Plads, Building 321, DK-2800 Kgs. Lyngby.
- Peeters & Kroon (2008). Circulation of railway rolling stock: a branch-and-price approach. *Computers & OR* 35(2), 538–556.
- Potthoff, Huisman & Desaulniers (2008). Column generation with dynamic duty selection for railway crew rescheduling. Econometric Institute Report EI 2008-28, Erasmus University Rotterdam, Econometric Institute.
- Rezanova & Ryan (2010). The train driver recovery problem-A set partitioning based model and solution method. *Comput. Oper. Res.* 37(5), 845–856.
- Schlechte & Tanner (2010). Railway capacity auctions with dual prices. In *Proceedings of the 12th World Conference on Transport Research*.
- Trasse Schweiz AG (2009). Business report 2009. <http://www.trasse.ch>.
- Weider (2007). *Integration of Vehicle and Duty Scheduling in Public Transport*. PhD thesis, TU Berlin.

- Zwaneveld, Kroon, Romeijn, Salomon, Dauzere-Peres, Van Hoesel & Ambergen (1996a). Routing Trains Through Railway Stations: Model Formulation and Algorithms. *Transportation Science* 30(3), 181–194.
- (1996b). Routing Trains Through Railway Stations: Model Formulation and Algorithms. *Transportation Science* 30(3), 181–194.
- Zwaneveld, Kroon & van Hoesel (2001). Routing trains through a railway station based on a node packing model. *European Journal of Operational Research* 128(1), 14–33.