Railway timetable optimization in Europe – Which model for which type of company? And which typical pitfalls should be avoided in R&D projects?

joint work with C. Caimi, L. Kroon †, and H. Schülldorf (ICROMA 2017 and 2019, resp.)

Christian Liebchen | TH Wildau | Apr 28th, 2021
Contents (Part I)
Which model for which type of company?

- The Timetabling Problem (TTP)
- Optimized Timetables in Practice
- The European Railway Market
- Planning Process for Railway Networks in Europe
- Further Timetabling Models
- Comparison of the Models and Their Specific Application Fields
- Suggestions for further research

MODELING AND SOLVING THE TRAIN TIMETABLING PROBLEM

ALBERTO CAPRARÀ
DEIS, University of Bologna, Italy

MATTEO FISCHETTI
DEI, University of Padova, Italy

PAOLO TOTH
DEIS, University of Bologna, Italy, ptoth@deis.unibo.it

(Received August 2000; revision received May 2001; accepted May 2001)

The train timetabling problem aims at determining a periodic timetable for a set of trains that does not violate track capacities and satisfies some operational constraints. In particular, we concentrate on the problem of a single, one-way track linking two major stations, with a number of intermediate stations in between. Each train connects two given stations along the track (possibly different from the two major stations) and may have to stop for a minimum time in some of the intermediate stations. Trains can overtake each other only in correspondence of an intermediate station, and a minimum time interval between two consecutive departures and arrivals of trains in each station is specified.

In this paper, we propose a graph theoretic formulation for the problem using a directed multigraph in which nodes correspond to departures/arrivals at a certain station at a given time instant. This formulation is used to derive an integer linear programming model that is relaxed in a Lagrangian way. A novel feature of our model is that the variables in the relaxed constraints are associated only with nodes (as opposed to arcs) of the aforementioned graph. This allows a considerable speed-up in the solution of the relaxation. The relaxation is embedded within a heuristic algorithm which makes extensive use of the dual information associated with the Lagrangian multipliers. We report extensive computational results on real-world instances provided from Ferrovie dello Stato SpA, the Italian railway company, and from Ansaldo Segnalamento Ferroviario SpA.
TTP: Corridors and an „ideal timetable“ as input

The Timetabling Problem (2/4, Caprara, Fischetti, Toth, 2002)

- General Setting and Input
- “We address [...] a single, one-way track linking two major stations [...] (called also ‘corridors’)”
- “The timetable of each train is periodic, i.e., it is kept unchanged every period. [...] The time period considered is one day, and the time discretization is one minute (i.e., q = 1440).”
- “Set of trains which are candidate to be run”
- “Each train is assigned an ideal timetable, which would be the most desirable timetable for the train, that may, however, be modified to satisfy the track capacity constraints [...] or even cancel the train.”
Objective

- “The profit achieved for each train $j$ depends on the train \textit{ideal profit}, on the \textit{shift}, defined as the absolute difference between the departure times from [starting] station in the ideal and actual timetables, and on the \textit{stretch}, defined as the (nonnegative) difference between the running [stopping] times in the actual and ideal timetables.”

- Profit of train $j$: $\pi_j - \phi_j (\nu_j) - \gamma_j \mu_j$, where
  - $\pi_j$ is the \textit{full profit} of train $j$ if it is scheduled on its \textit{ideal path}
  - $\nu_j$ is the \textit{shift} of train $j$ at the starting station w.r.t. the ideal path
  - $\mu_j$ is the total \textit{stretch} added in all running & stopping activities
Comments
- Shift and stretch may cancel out on parts of a track – but are always penalized both
- Time-expanded graph model
- Transfer activities of passengers are not considered

Selected Case Studies
- Italian Railways
- “Trassenbörse” (D)
- Simplon-Tunnel (CH)
TTP not able to match feeder/connect pairs
Example of the 1st/2nd train problem

- Consider two railway lines
  - feeding line 1: A-B-Y
  - connecting line 2: X-B-C
- Both lines served every 30min
- Many passengers travel A-B-C
- Line 1 has a relatively small stretch penalty, line 2 a relatively small shift penalty
- What are the correct pairs of trains, between which we shall measure (optimize) transfer times?

Do we have to measure the time from the arrival of the first grey train to the departure of the first red train...?

Actual timetable

Ideal train paths

... or is the time from the arrival of the first grey train to the departure of the second red train indeed relevant?
The model that we used for timetable generation describes the cyclic timetabling problem in terms of the periodic event scheduling problem (PESP) constraints. This is a generic model for scheduling a set
The First Optimized Railway Timetable in Practice

Christian Liebchen
Kombinatorische Optimierung und Graphenalgorithmen, Technische Universität, D-10623 Berlin, Germany,
(1993). The PESP has proven to be an exceptionally rich model (Liebchen and Möhring 2007). It not only served as the groundwork for the computation of the Berlin subway timetable, as we are about to report in this article; rather, the new timetable in The Netherlands that has been in operation since December 10, 2006 has also been designed with the help of CADANS (according to comments made by an anonymous referee in 2007).
Improvements include quality and efficiency

Optimized Timetables in Practice (3/3) – Berlin Underground (2005), PESP

- **Transfer quality**
  - average transfer waiting time reduced from 2:48min to 2:30min

- **Stopping times**
  - cut maximum stopping time from 3:30min to 2:30min

- **Number of trains**
  - One train less

Source: L., Möhring & Stiller, „Periodic Timetable Optimization“, MathFilm Festival (2008)
https://vimeo.com/60162039
PESP assigns points within period time to events

Periodic Event Scheduling Problem (1/2, Serafini and Ukovich, 1989)

General Setting and Input
- empty network, i.e. **no** („ideal“) timetable required as input!
- period time typically much less than one day (e.g. 60 minutes, or 20 half-minutes \(\triangleq 10\) minutes)
- Timetable is encoded by assigning points in time\(^1\) to „events“
- Requirements are encoded as lower & upper bounds on the time durations along „activities“ (time difference of two events)

Objective
- **minimize** sum of weighted **slack** times (e.g. for stopping acti-vities, but also full support of transfers & trains at terminus!)

\(^1\) Initial model not stated in time-expanded graph – Borndörfer et al. (2016): time-expansion („XPESP“)
Arrivals/Dep’s of directed lines in stations
Periodic Event Scheduling Problem (2/2, Serafini and Ukovich, 1989)

Line network (excerpt)

Graph model (excerpt)

Optimization model

► Compute points in time within period time of the nodes \(v\) (variables), e.g. \(\pi_v \in [0,10]\)

► Along the arcs \((v,w)\), impose minimum and maximum time durations of the activities e.g.

\[
2 \leq \pi_w - \pi_v \leq 7 \tag{1}
\]

► ATTENTION! Always compute with the „modulo“ (integer division)

► Actually, we must enrich (1) with additional integer variables \(p_a: \)

\[
2 \leq \pi_w - \pi_v + 10 \cdot p_a \leq 7
\]

1 The actual travel time U6 Mehringdamm-Leopoldpl. is apx. 17min

2 dep/arr directed line at station
A First Short Comparison of TTP and PESP

To what extent could the TTP framework “emulate” PESP?

- **Periodicity** – Also for TTP in principle one could consider period times as small as they are considered for PESP → *not* the most striking difference between the models!

- **Ideal train paths as input** – On the one hand...
  ... with zero shift penalty, in fact TTP acts on an empty network
On the other hand... then the excellent quality of its LP relaxation might suffer, moreover the 1\(^{\text{st}}\)/2\(^{\text{nd}}\)-train problem still persists

- **So, if there are PESP features that cannot be emulated by TTP adequately, is it really „the“ (better?) train timetabling problem?**

- **Well... are PESP & TTP concurring at all??**
EU legislation: two types of railway companies
EU Directive 2012-34 (1/3)

- „railway undertaking‘ means any public or private undertaking licensed according to this Directive, the principal business of which is to provide services for the transport of goods and/or passengers by rail with a requirement that the undertaking ensure traction [...]“ (EU Directive 2012-34, Art. 3 (1))

- „infrastructure manager‘ means any body or firm responsible in particular for establishing, managing and maintaining railway infrastructure, including traffic management and control-command and signaling [...]“
EU legislation: two types of railway companies
EU Directive 2012-34 (2/3)

- “1. Member States shall ensure that separate profit and loss accounts and balance sheets are kept and published, on the one hand, for business relating to the provision of transport services by railway undertakings and, on the other, for business relating to the management of railway infrastructure. Public funds paid to one of these two areas of activity shall not be transferred to the other.” (EU Directive 2012-34, Art. 6, No. 1)

- “1. Railway undertakings shall be granted, under equitable, non-discriminatory and transparent conditions, the right to access to the railway infrastructure in all Member States for the purpose of operating all types of rail freight services.” (Art. 10, No. 1)
To summarize...

### Design Phase within Passenger Railway Undertaking

<table>
<thead>
<tr>
<th></th>
<th>Line planning</th>
<th>„basic hourly patterns“ (for peak, off-peak, night service etc.)</th>
<th>Special single trips</th>
<th>Deadhead trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties /</td>
<td>Defines capacities that are offered to the passengers</td>
<td>for EACH traffic time</td>
<td>Definition of first and last trips for (off-) peak hours</td>
<td>Based on rolling stock circulation planning: extra trips (e.g. deadhead, regular maintenance)</td>
</tr>
<tr>
<td>Specialities</td>
<td>Already consider amount of available trains</td>
<td>routing as input</td>
<td>Rules how to glue the basic hourly patterns together</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>time durations according to infra. manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process step /</td>
<td>In regional traffic: Design by public authorities</td>
<td>In regional traffic: Public authority confirms „basic hourly patterns“</td>
<td>complete and consistent timetable and vehicle rotation</td>
<td></td>
</tr>
<tr>
<td>Documents</td>
<td>Railway undertaking approves feasibility</td>
<td></td>
<td>train path requests for infrastructure manager</td>
<td></td>
</tr>
<tr>
<td>Optimization</td>
<td>e.g. „SLP“ (Borndörfer et al, ATMOS 13)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Result</td>
<td>Lines &amp; Frequencies</td>
<td>departure minutes</td>
<td>times of all passenger services</td>
<td>times of all train trips (path requests)</td>
</tr>
</tbody>
</table>
Processing of train path requests by infrastructure manager

- May shift train path requests for passenger services by +/- 3min
- May shift train path requests for freight services by +/- 30min
- NO accordance by railway undertaking required!

- Regular interval services or „integrated network services“
- Cross-border train paths
- Freight services

1 Picture source: L., Eisenbahnwesenseminar, TU Berlin, (2016, Jan 18, in German)
In the design process of the Working Timetable („annual timetable“), we distinguish between two major phases:

1. The Railway Undertakings come up with train service requests first!
2. The Infrastructure Manager must eliminate any conflict between these „ideal train paths“ (of many RU!), by shifting and stretching them within (relatively) tight bounds.

Fig. 2. Workflow of major steps in the design of the annual working timetable.
FDP requires major decisions made by hand
Further Timetabling Models (1/2) – Feasible Differential Problem (FDP)

- Considered by Vansteenwegen & van Oudheusden (2007)
- General Setting
  - Event-based model similar to PESP (copies of cycle time)...
    but:
  - “In this research, continuous linear programming is used instead of mixed-integer linear programming, since continuous LP takes much less time to solve very large instances and sensitivity analysis can be performed easily. To avoid integer variables [...], a limited number of ‘preliminary decisions’ is made, before the model is solved.” → 1st/2nd train problem right as in TTP!
- Yet, more recent developments enrich the basic approach
Another non-cyclic flexible model is known

Further Timetabling Models (2/2) – Individually Scheduled Trips Problem

- For each line, model each of its trains individually
  \(\rightarrow\) The headways between two trains of the same line may vary!
- Trains do not rely on any „ideal train paths“ as input
- Model applies to intermeshed networks
- No „preliminary decisions“ are necessary
<table>
<thead>
<tr>
<th>Comparison of the Models and Their Specific Application Fields</th>
<th>PESP</th>
<th>FDP</th>
<th>TTP</th>
<th>ISTP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Timetable in the sense of ideal train paths (e.g. train requests) required already as input?</strong></td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td><strong>Ordering of the trains required as fixed input (thus not taking these key decisions on its own)?</strong></td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>(no)</td>
</tr>
<tr>
<td><strong>Definition of fixed pairs of trains for particular transfers required as fixed input (not taking decisions on its own)?</strong></td>
<td>no</td>
<td>yes</td>
<td>(yes)</td>
<td>no</td>
</tr>
<tr>
<td>Does the optimization model require the trains to be operated periodically?</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td><strong>Post-processing required to derive a weekly timetable?</strong></td>
<td>yes</td>
<td>(yes)</td>
<td>(no)</td>
<td>(yes)</td>
</tr>
<tr>
<td><strong>Post-processing required to combine corridor timetables into a timetable for an intermeshed network?</strong></td>
<td>no</td>
<td>(no)</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

Entries in parantheses refer to features that the original authors did not discuss initially, and thus are based on assumptions in Caimi, Kroon, L. (2017)
Suggestions for Further Research


- Integrate passenger routing, in particular to the PESP setting, too (cf. Borndörfer et al., 2016, Schiewe 2019)
- Practical PESP computations with different frequencies of lines\(^1\)
- Apply ISTP e.g. to build bridge between peak and night traffic
- In TTP, consider connection commitments
- Let TTP cover an entire closed week (as considered by infrastructure managers)

\(^1\) e.g. based on Galli & Stiller (2010)
Contents (Part II)
which typical pitfalls should be avoided in R&D projects?

- Observation of a Certain Gap and a Key Question
- Project-Specific Properties why Projects could risk not to succeed
- Parameters of the Survey
- Results of the Survey
  - Perspective of Railway Managers
  - Perspective of Optimization Experts
  - Further Comments by the Experts
- Conclusions

Observation of a Certain Gap

“Success Stories” which attain this goal

Project goal in the beginning: application of the developed mathematical optimization methods on a regular\(^1\) basis

Projects in which mathematical optimization experts and railway practitioners work together

\(^1\) not limited to daily operations, only, but also include strategic questions (such as in the context of public tenders), if the methods were applied on a regular basis
Key Question
Let’s try to answer it by means of a survey

- In the projects which
  - in the beginning had the goal to apply the developed mathematical optimization methods on a regular basis but
  - did *not* attain this goal...

- ... are there any common patterns?

- To find out, we set up an anonymous *survey* and
  - asked 100+ railway managers and optimization experts
  - to weigh the importance of 15 possible project-specific properties why their project did not attain its goal
(1) **Data**
   The available input data finally did not meet the quality that was necessary to be able to come up with high-quality optimization results

(2) **Partial Fixing**
   The optimization missed the ability to accept some particular fixation for certain “variables” that were key in the point of view of the railway practitioners

(3) **Features**
   During the project timeline, the optimization model had been confronted with more and more detailed requirements, which finally let the performance and/or quality of the optimization methods collapse
Problem-specific Properties of the Projects (2/4)

Full list of properties – selected full text of the questions

(4) Validation
The railway company didn’t allocate a sufficient amount of expert staff to validate in detail the results of the optimization methods during the entire project timeline

(5) Post-processing

(6) Quality

(7) Regularity

(8) Transparency

(9) Integration

1 Please refer to the 14-pages-abstract for the precise formulation of the other properties
(10) **Strict Feasibility**  
The optimized solution satisfied all constraints – but other “solutions” have been preferred (e.g. designed manually by railway practitioners), although they violated some less important constraints

(11) **Reliability**

(12) **Obsolescence**  
During the project duration, there have been new algorithmic findings which made the optimization methods in the project obsolete
(13) Cost
The cost to make the optimization methods available in a productive context blast the cost which has been assumed in the cost-benefit-analysis that had been the basis to initiate the project.

(14) Attention
During the project duration, the “management attention” decreased, e.g. because some protagonist within the railway company left the project.

(15) Others
Parameters of the Survey

Design

- Two groups
  - railway managers and
  - optimization experts
- Anonymous\(^1\)
- 2 weeks online using LamaPoll (January 2019)
- 100+ protagonists in the field invited

Replies

- 24\(^2\) filled questionnaires
- 5 late informal replies were NOT included in results
  (some extra aspects that were raised in their messages)

1 but participants could provide the name of the project they were reporting on (optionally)
2 the authors provided four filled online questionnaires
Rating of the Properties by Railway Managers

Railway Managers (N=10)

<table>
<thead>
<tr>
<th>Property</th>
<th>Minimum</th>
<th>25% Quantil</th>
<th>75% Quantil</th>
<th>Maximum</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attention</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Validation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial Fixing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-processing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strict Feasibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Features</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regularity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transparency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obsolescence</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Rating of the Properties by Optimiz. Experts

Optimization Experts (N=12 or N=14)

Minimum  25% Quantil  75% Quantil  Maximum  Mean

Validation  Attention  Strict Feasibility  Cost  Data  Post-processing  Transparency  Integration  Partial Fixing  Features  Quality  Regularity  Reliability  Obsolescence
Deviation of Mean Rating of Managers vs. Optimization Experts

Mean of Managers' Rating Minus Mean of Optimization Experts' Rating
Selected Correlation between...
... General Framework and Selected Properties of the Projects

- 0.65
  The more academic the partner who has been mainly responsible for the R&D part (3 = university, 2 = research institution, 1 = software company)...
  ... the more severe the lack of railway expert capacity for validation
Further Comments by the Experts...
... including those of experts whose answers unfortunately reached us too late

- Complexity of control
- Employee participation (unions etc.)
- Management implementation
- Managerial consistency
- Organizational changes
- Performance
- Rolling horizon
- to be continued...
Conclusions (1/2)
Things worth to have in mind from the very start of any project

- Avoid a lack of expert capacity within the railway companies for the validation of intermediate results
- Pay significant attention to the
  - availability,
  - consistency, and
  - quality

of input data: The R&D partner shall evaluate the quality of the input data in detail *prior to* launching the actual project for the development of algorithms – occasionally postpone the optimization project until the input required for it is available.
Conclusions (2/2)

Things worth to have in mind from the very start of any project

- Railway managers shall put much emphasis on detailed description of requirements for the optimization tool, prevent any “lazy specification”
- A thought on “management attention”

Is management attention (goals) likely to change?

Only, if company’s strategy changes (or the project was not conform to it)

Well...?
Questions & Comments?

- Thank you...
  - ... to the audience, for your attention!
  - ... to the participants, for sharing their experience with us!

- Technische Hochschule Wildau
  Prof. Dr. Christian Liebchen

liebchen@th-wildau.de

Picture source: https://www.openstreetmap.de/karte.html (07.04.2017)