Robust & Online Railway Optimization
The ARRIVAL Experience

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Algorithms for Robust and online Railway optimization: Improving the Validity and realiAbility of Large scale systems

IST FET STREP FP6-021235-2

Project Goal

- Advanced Algorithmic Research for planning optimization of large-scale and highly-complex systems

- ARRIVAL case study: railway systems
  - Most complex & largest in scale transportation setting
  - *Railway Optimization Problems:* Planning & scheduling over several time horizons

ARRIVAL Consortium

CTI (R.A. Computer Technology Institute, Greece)
coordinator & site leader: *Christos Zaroliagis*

UniKarl (Universität Karlsruhe, Germany) – site leader: *Dorothea Wagner*
TUB (Technische Universitaet Berlin, Germany) – site leader: *Rolf Möhring*
UniGoe (Universität Goettingen, Germany) – site leader: *Anita Schöbel*

EUR (Erasmus University Rotterdam, Netherlands) – site leader: *Leo Kroon*
TUE (Techn. Universiteit Eindhoven, Netherlands) – site leader: *Leen Stougie*

ETHZ (Eid. Tech. Hochschule Zürich, Switzerland) – site leader: *Peter Widmayer*

ULA (Universita degli Studi dell' Aquila, Italy) – site leader: *Gabriele Di Stefano*
UniBo (University of Bologna, Italy) – site leader: *Paolo Toth*
DEI (Dept. of Information Engineering, University of Padova, Italy)
site leader: *Matteo Fischetti*

USE (University of Seville, Spain) – site leader: *Juan Mesa*
UPVLC (Universidad Politecnica de Valencia, Spain) site leader: *Federico Barber*

SNCF (Société Nationale des Chemins de Fer, France) site leader: *Christian Weber*

Project Focus

- Focus: deal with *disruptions*

  - *Robust planning* (proactive approach)
  - *Online planning* (reactive approach)

Project Focus

- ***Robust plan***
  - – maintains feasibility and as much as possible of the quality of an optimal solution

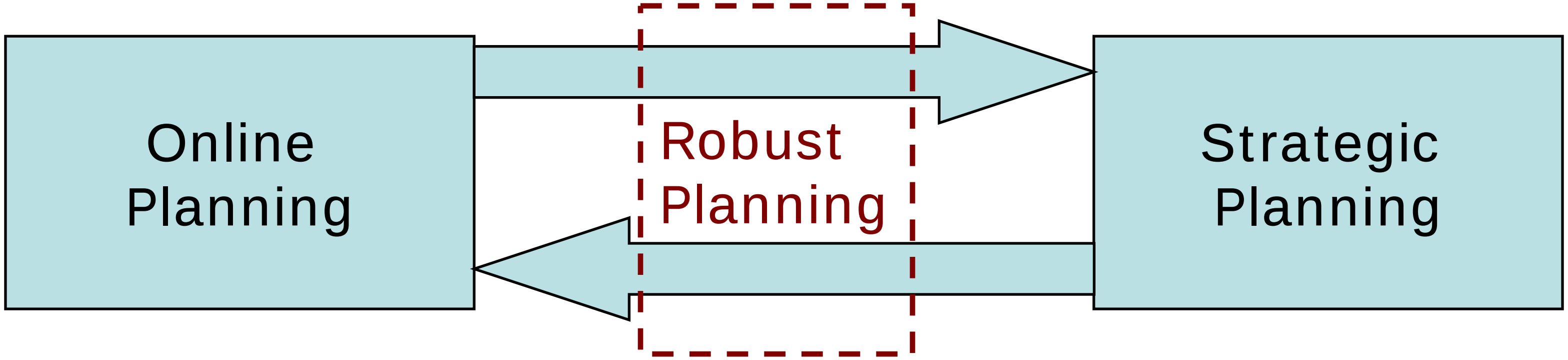
- ***Online plan***
  - – retains as much as possible of the quality of a solution that would have been achieved if the entire sequence of disruptions was known in advance

Project Main Objectives

- Foundational algorithmic research for robust and online planning of complex & large-scale (railway) systems

- Measuring (the "prices" of)
  - ***Robustness*** of a plan
    (trade-off between optimal & robust plan)
  - ***Recoverability*** of a plan
    (trade-off between online & optimal plan)

Project Main Objectives

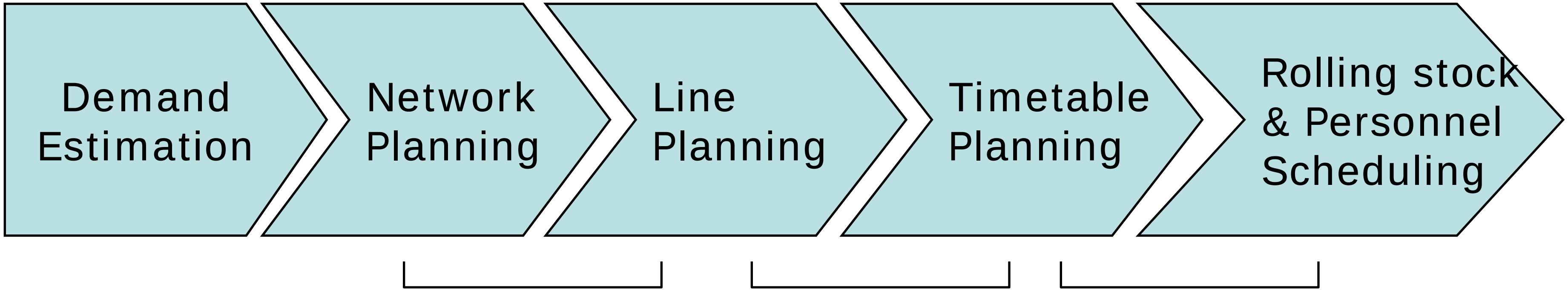


Interaction: may have conflicting objectives

- Understand the interplay between strategic (off-line) planning, robustness issues, and online planning

Project Main Objectives

- Hierarchical breakdown may waste optimization potential



- Can integration of planning stages gain optimization potential ?

Summary of Objectives

- Generic foundational framework for robust and online large-scale optimization
- Measure robustness and recoverability of plans
- Understand interaction between online, off-line, and robust planning
- Explore integration of planning stages
- Identify the technically mature methods and experimentally validate their theoretical performance

Main Achievements

- New concepts of measuring robustness and recoverability of plans
- Integration of planning stages to gain further optimization potential
- Algorithmic game-theoretic approaches for robust network and line planning
- New multidisciplinary models & methods for
  - Robust & online timetabling
  - Resource rescheduling
  - Timetable information querying and updating
  - Delay management

A few Key Results

- Robust Optimization
  - Recoverable Robustness & Related Concepts
  - Train Platforming
  - Delay Management
  - Timetabling
  - Line Planning

- Online Optimization
  - Crew Re-scheduling
  - Timetable Information Querying & Updating
  - Freight Train Classification

Recoverable Robustness

General & powerful model

- Distinguish between
  - original optimization problem
  - imperfection of information, introduced by some scenario *s*
  - limited recovery possibilities
- Planning phase
  - compute a (feasible) solution *x*
  - Scenario *s* turns *x* to infeasible (by adding more constraints)
  - choose recovery algorithm *A*
- Recovery phase
  - algorithm *A* turns *x* into feasible solution under s (new set of constraints)

Recoverable Robustness

Price of Robustness of instance *I*

$$PoR(I) = \frac{\min_{(x,A)\in P\times\mathcal{A}}\{f(x) \mid \forall s \in S : A(x,s) \in P_s\}}{\min\{f(x) \mid x \in P\}}$$

Price of Robustness = max{*PoR*(*I*): for all I}

Price of Recoverability = min{*PoR*(*I*): for all I}

	Flexible response	Compact model	Guaranteed Performance
2 Stage Stoch. Programming	✔	✖	✖
Strict (classical) Robustness	✖	✔	✔
Recoverable Robustness	✔	✔	✔

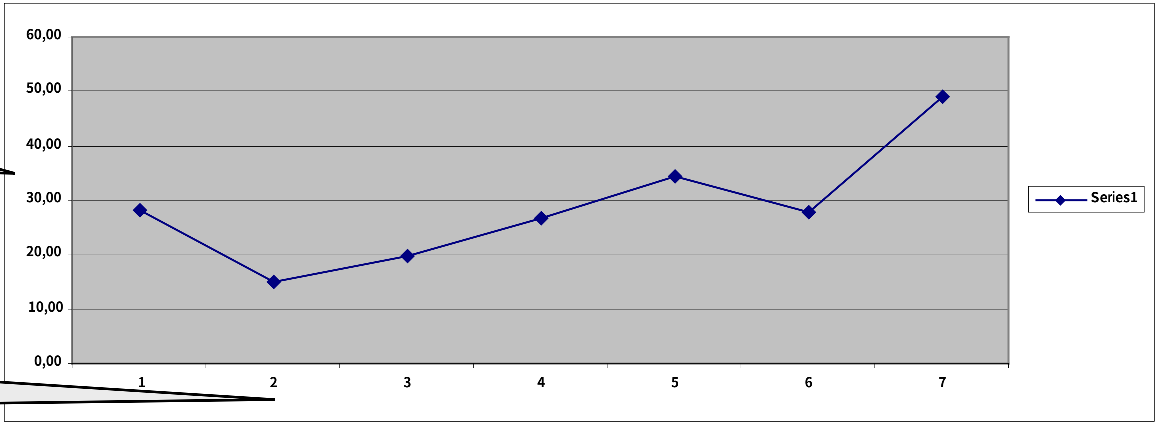
Train Platforming Problem (TPP)

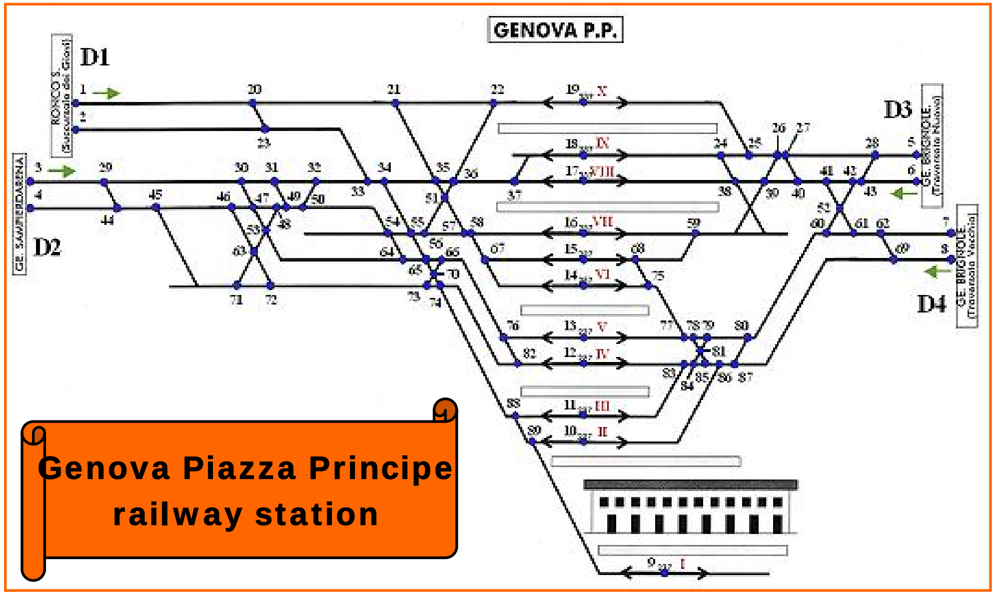
- Study on real-world data
- Heuristic robustification of standard TPP model replaced by exact recovery-robust model
- Same nominal quality (throughput)
- Delay reduced by 25% on average
- Re-use of existing algorithm for TPP (off-the-shelf implementation)

Recoverable-Robust Train Platforming

Y axis:
% difference on the maximum propagated delay

X axis:
7 time windows in a day





ARRIVAL-TR-0157, RailZurich 2009

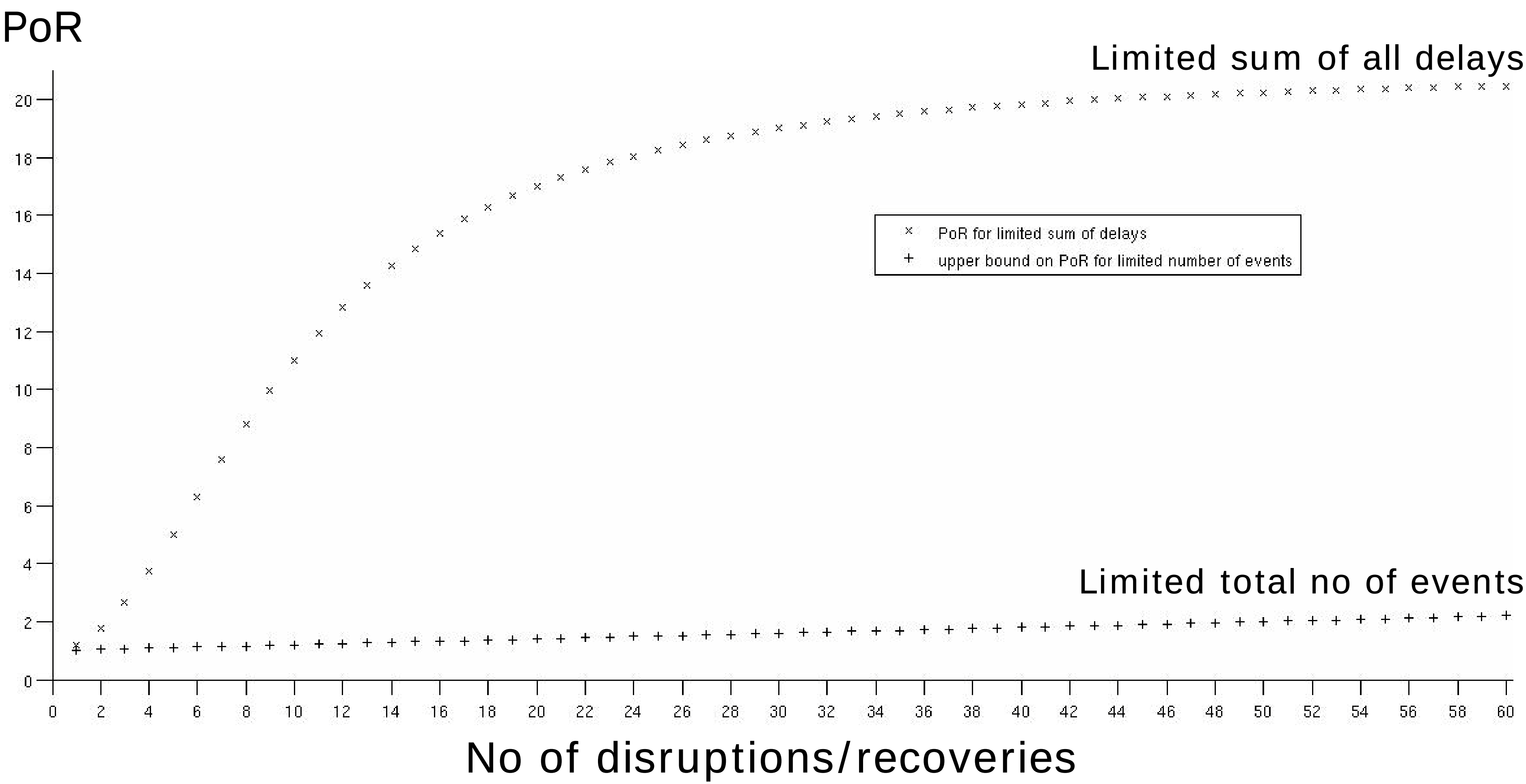
"Recovery-Robust Platforming by Network Buffering" by Alberto Caprara, Laura Galli, Sebastian Stiller, Paolo Toth.

Multistage recoverable robustness

- Usually a sequence of delays appears
- A recovered timetable has to be robust against the next delay
- The recovered solution should again be robust to the next delay, and so on ...

We identified algorithms which are robust for multiple recoveries

Graph = Path


PoR
Limited sum of all delays
PoR for limited sum of delays
upper bound on PoR for limited number of events
Limited total no of events
0
2
4
6
8
10
12
14
16
18
20
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60
No of disruptions/recoveries

Robust Timetabling

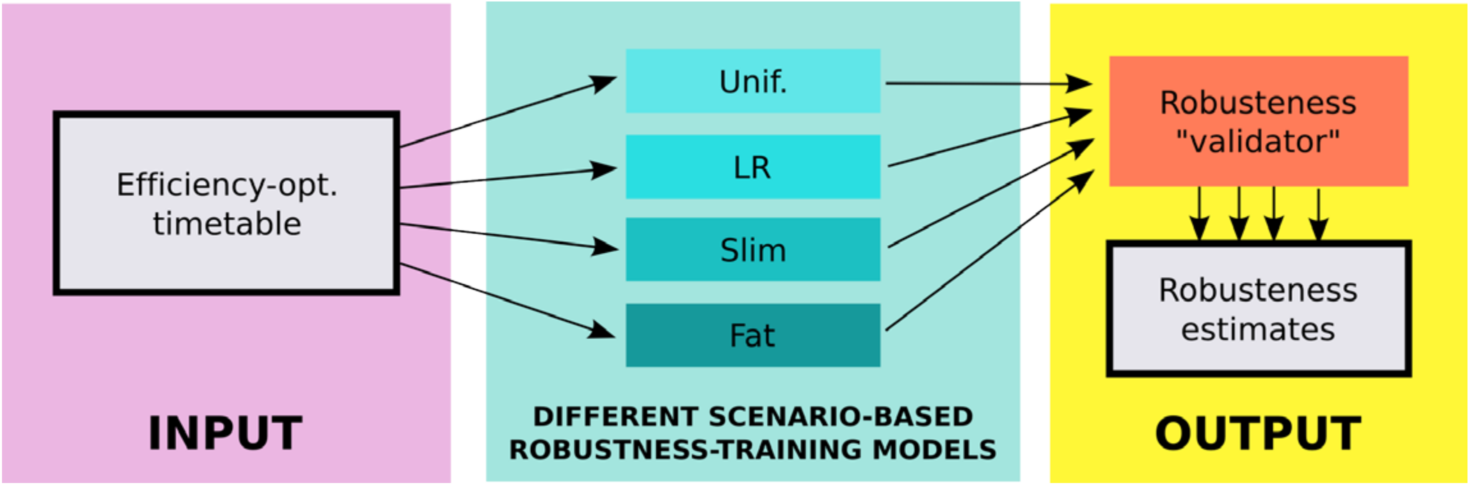
Problem:

- optimized timetables might be too sensitive to disturbances
- need to adjust a given optimal timetable to be robust (allowing for some efficiency loss)

Goal:

- To find a fast (yet accurate) algorithm to improve the robustness of a timetable

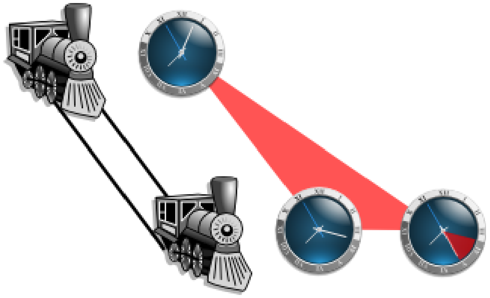
Testing framework:



Robust Timetabling

Common assumptions for “robustness training” methods:

- Allow for some percentage efficiency loss
- Limit the set of planning actions (good for small disturbances, leads to more tractable models)
  => add buffer times (= stretch travel times)

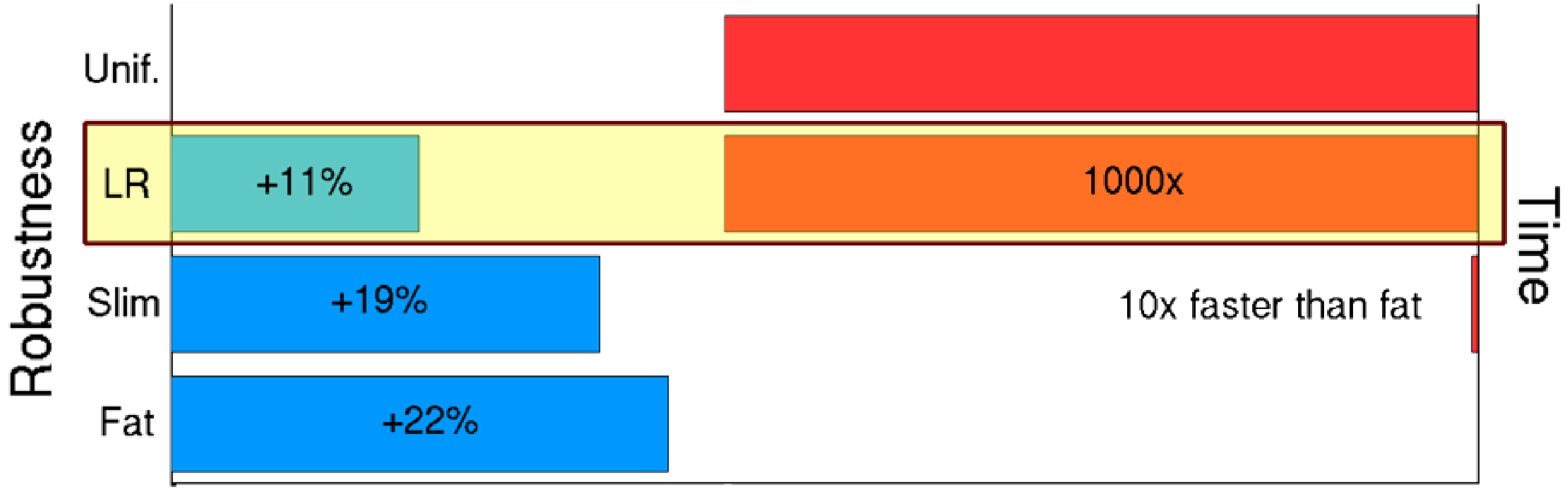


Robustness training methods tested:

- *Unif.*: uniform allocation of buffer times (e.g. 7% nominal travel time)
- *Fat*: scenario-based stochastic programming formulation, aiming at minimizing expected delay
- Slim: heuristic version of *Fat* leading to a more tractable MIP formulation
- ***LR*: Light Robustness** (Fischetti and Monaci '08, ARRIVAL-TR-0119)

Robust Timetabling

Results (10% efficiency loss w.r.t. the input timetable):(*)

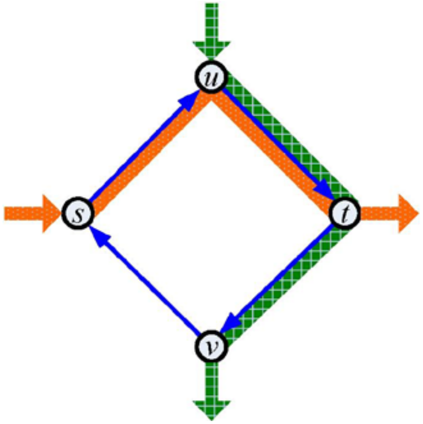


- Unif. is very fast but is the worst as to robustness
- Fat achieves the best robustness but is very slow
- LR is a good compromise between robustness and performances (~1000x faster than Fat)

(*) average on 4 real congested corridors from Italian railway company

Incentive-Compatible Robust Line Planning

Line planning problem

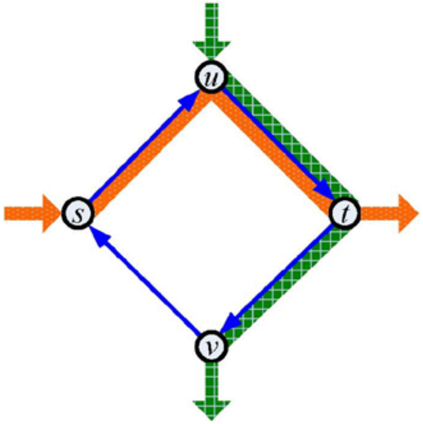


$$R = \begin{array}{c|c|c|} & p & q \\ \hline su & 1 & 0 \\ \hline ut & 1 & 1 \\ \hline vs & 0 & 0 \\ \hline tv & 0 & 1 \\ \hline \end{array}$$

- Line operator (LOP)
  - Competing entity: bids for getting frequency
  - Private utility function
- Network operator: ensure fairness in …
  - Max satisfaction of LOPs (social optimum)
  - Cost sharing of resources
- Provide solution that is robust against ...
  - Unknown preferences
  - Elastic frequency demands

Incentive-Compatible Robust Line Planning

Incentive-Compatible Robust Solution



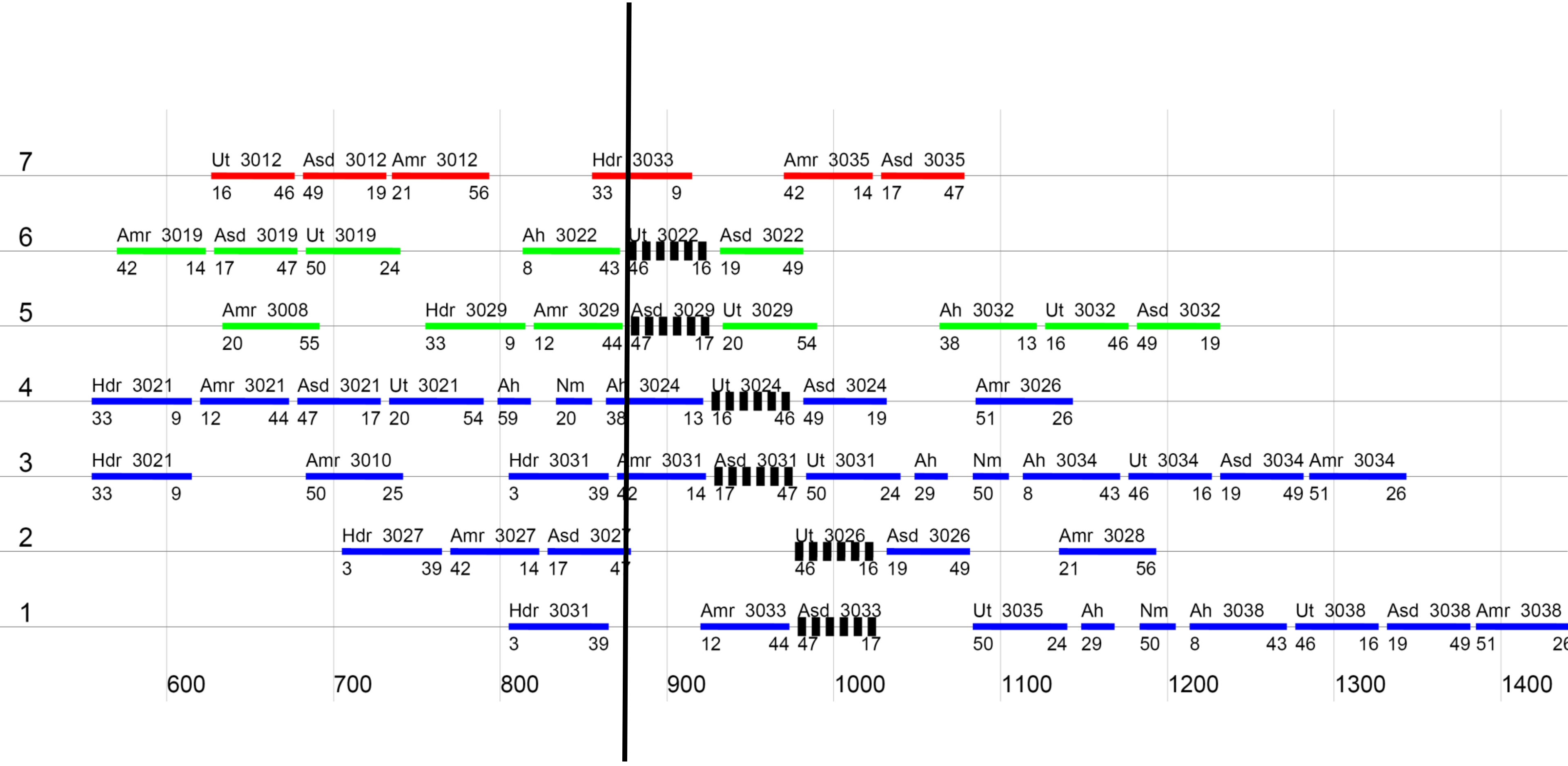
$R =$

	p	q
su	1	0
ut	1	1
vs	0	0
tv	0	1

- *Robustness* against imperfect knowledge (unknown utilities)

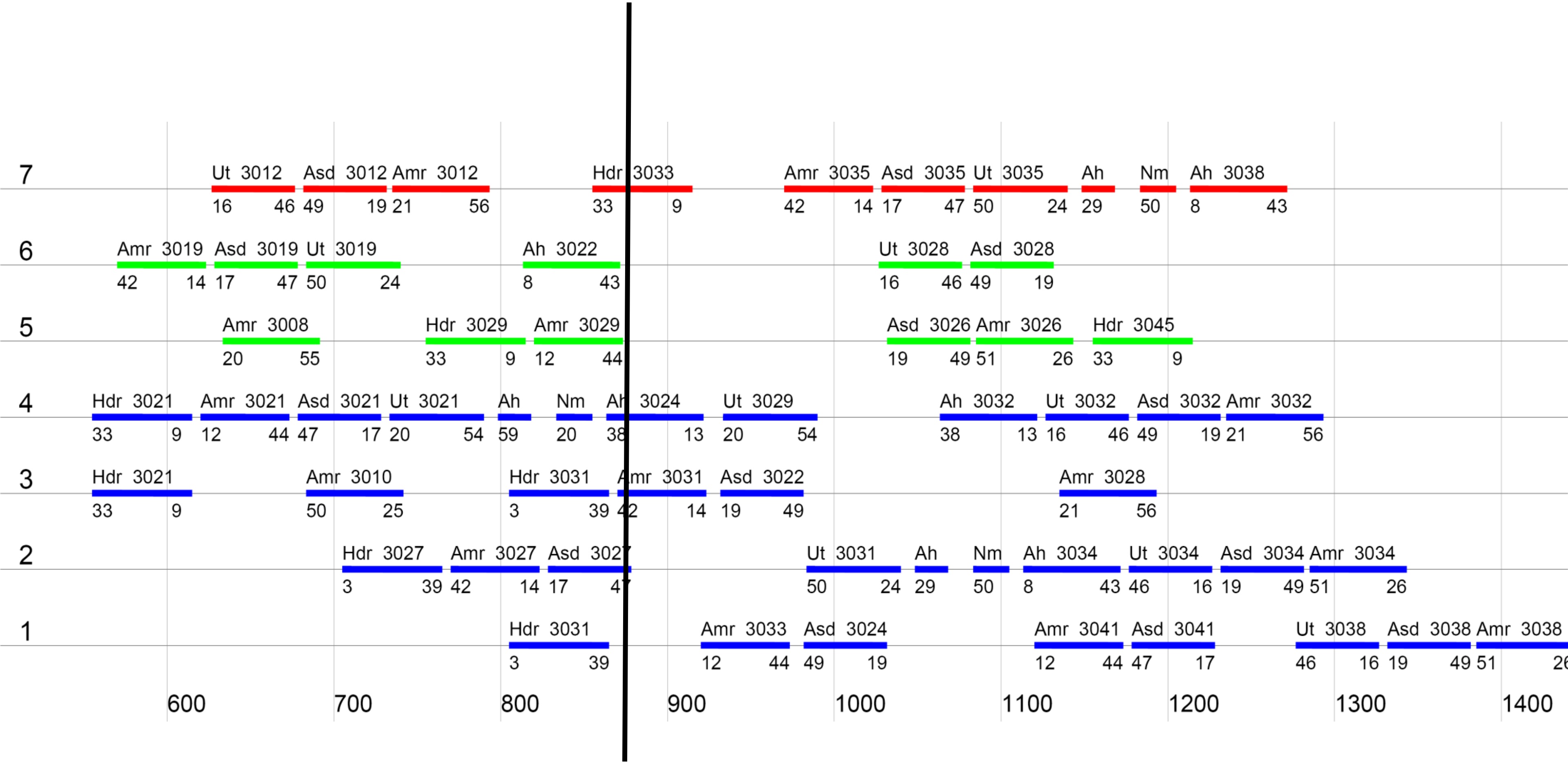
- *Recovery Scheme* to the unknown social optimum
  - Mechanism-design instance of a frequency game
  - Decentralized, dynamic, resource pricing and frequency allocation algorithm that converges to the social optimum

Online Crew Re-scheduling



Disrupted crew duties

Online Crew Re-scheduling



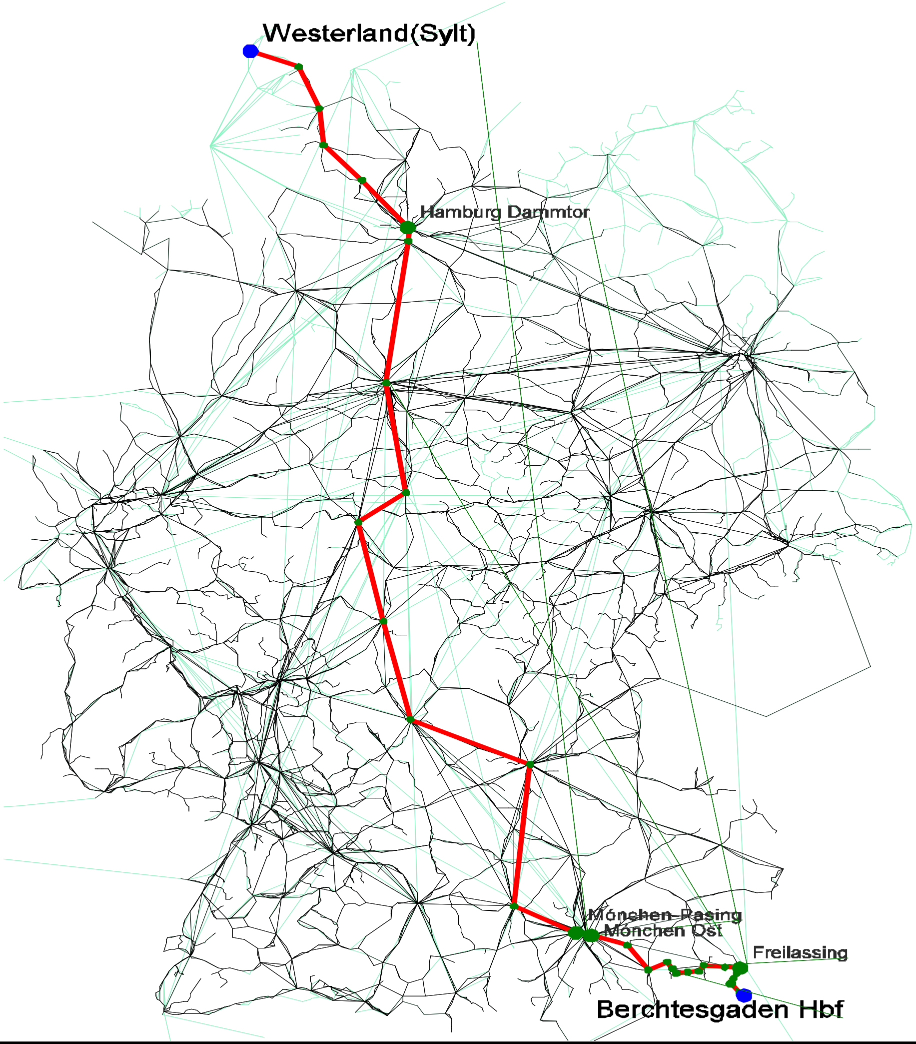
Rescheduled crew duties

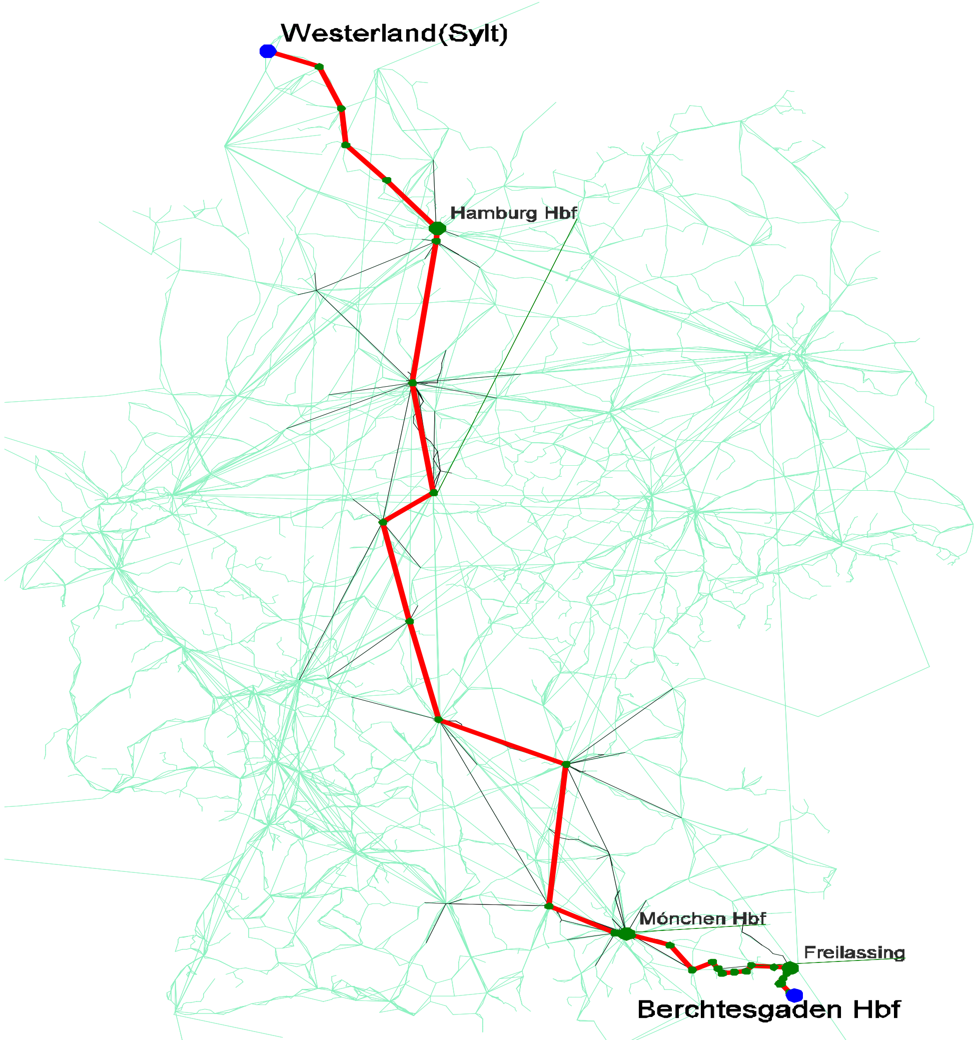
Online Crew Re-scheduling

- New method does not start from scratch
  - Implemented in practice
  - Reduces the re-scheduling throughput time significantly
- Adopted and used on a daily basis by NS

Timetable Information Querying & Updating

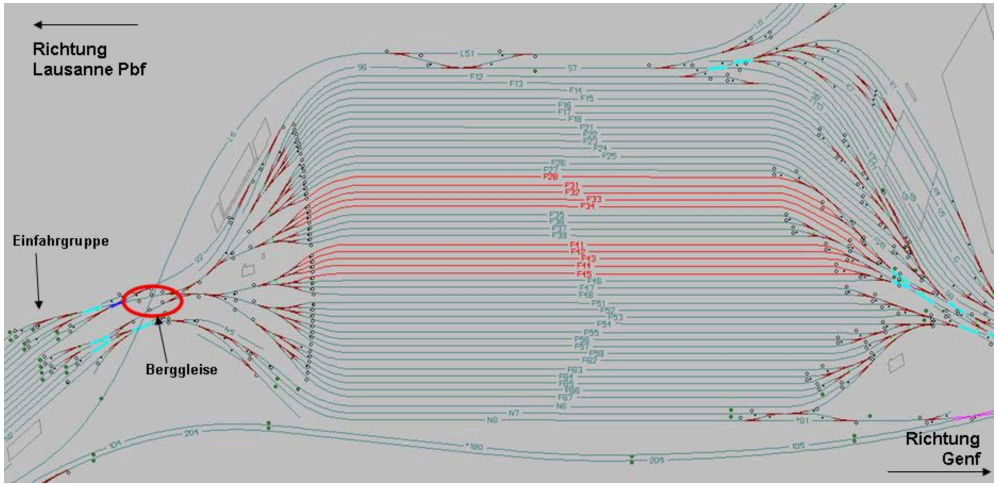
New techniques based on shortcutting & arc flags (SHARC)





Freight Train Classification

- Developed powerful encoding for classification schedules
- Conducted algorithmic study yielding deeper understanding of optimal multistage sorting methods
- Derived useful integer programming formulation from encoding
- Modeled additional real-world constraints
- Found improved classification schedule on classification yard Lausanne-Triage



AWARDS

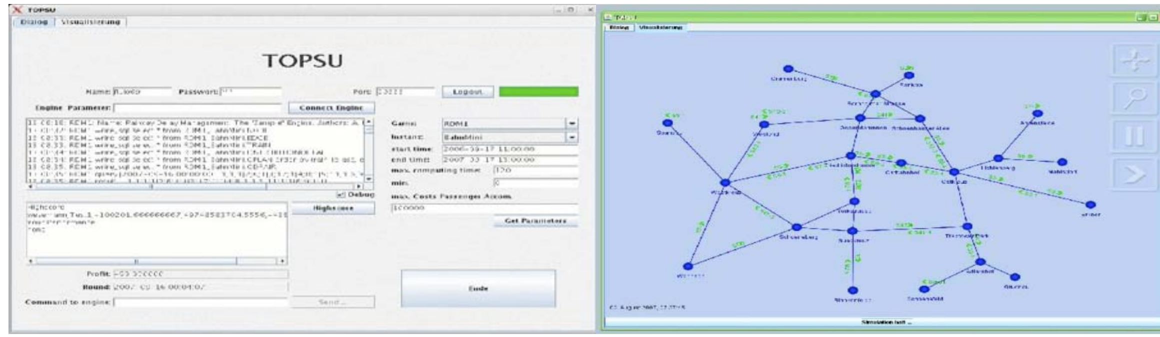
- **EUR and DEI teams** won the *2008 Edelman Award* of INFORMS for the practical applicability of their methods to develop the 2007 timetable of NS
- **Anita Schoebel** (UniGoe site leader) received the *2007 Klaproth-Preis* for her railway-related research
- **Cor Hurkens** (TUE member) received the *First Prize of the 2007 ROADEF Challenge* for his algorithm to sequence maintenance and repair jobs
- **Christian Liebchen** (TUB member) received the *2007 HEUREKA Foerderpreis* of young scientists for his theoretical and practical work on Transport Optimization
- **Denis Huisman** (EUR member) finalist in the *2007 EURO Excellence in Practice award* for his crew rescheduling algorithm

Extensive Collaboration

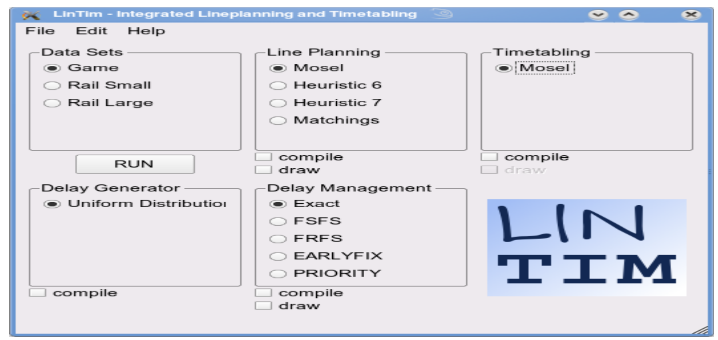
- 40% common publications, 5 common PhDs
-
  - ***Algorithmic Methods for Railway Optimization,*** LNCS Volume 4359, 2007.
  - ***Robust and Online Large-Scale Optimization,*** forthcoming, 2009.
- Cooperation with railway companies (NS, SNCF, DB, SBB, FI, ...)

Optimization Tools

- TOPSU - Tool for Optimal planning & Steering under Uncertainty



- LinTim - Interaction between line planning, timetabling and delay management



- Time-dependent routing prototype (TomTom)

CONCLUSIONS

ARRIVAL ...

- has not solved all problems in robust & online railway optimization
- .. but has done quite some progress
- Formed a critical mass of researchers, who
  - have understood real-world problems
  - advanced the theory to solve them
  - ready to bring this knowledge into practice

Thank you!