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*
**UniGoethe** (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** (Università 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)
  - \textit{Robustness} of a plan
    (trade-off between optimal & robust plan)
  - \textit{Recoverability} of a plan
    (trade-off between online & optimal plan)
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 $I$

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

Price of Robustness $= \max\{PoR(I) : \text{for all } I\}$

Price of Recoverability $= \min\{PoR(I) : \text{for all } I\}$

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<th>Flexible response</th>
<th>Compact model</th>
<th>Guaranteed Performance</th>
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<td>Recoverable Robustness</td>
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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)
ARRIVAL-TR-0157, RailZurich 2009
“Recovery-Robust Platforming by Network Buffering” by Alberto Caprara, Laura Galli, Sebastian Stiller, Paolo Toth.
Delay Management

**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
Delay Management

Graph = Path

PoR

Limited sum of all delays

Limited total no of events

No of disruptions/recoveries
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:
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

- **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 Solution

- **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
New techniques based on shortcutting & arc flags (SHARC)
Online Train Classification

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


- Robust and Online Large-Scale Optimization, forthcoming, 2009.

- Cooperation with railway companies (NS, SNCF, DB, SBB, FI, ...)

SpringerLink
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!