Integrated Optimization of Timetable and Rolling Stock Rescheduling due to Temporary Maintenance Task

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PART ONE

Introduction
**Introduction**

**Unexpected perturbations**
- bad weather conditions
- rolling stock break down
- signal problems
- infrastructure failures

**Operation**

**Negative effects on running time**
- dwelling
- arriving and departing events

**Primary delays**

**Consecutive delays**
- High interdependency between train services
Introduction

- disturbance
- disruptions

Timetable rescheduling
- retiming, reordering, rerouting and reserviceing etc.

Rolling stock rescheduling
- adjusting the original circulation plan and maintenance plan etc.

Feedback

Input
Introduction

**disruptions**
unavailability of railway track segments
due to broken overhead wires or rolling stock breakdowns

**Timetable rescheduling**
retiming, reordering, rerouting and reserviceing etc.

**Rolling stock rescheduling**
adjusting the original circulation plan and maintenance plan etc.
PART TWO Literature review
## Literature review

### Timetable rescheduling

<table>
<thead>
<tr>
<th>Publications</th>
<th>Perturbation type</th>
<th>Infrastructure details</th>
<th>Model structure</th>
<th>Objective(s)</th>
<th>Rescheduling measures</th>
<th>Solution method</th>
<th>Rolling stock issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>D’Ariano et al. (2007)</td>
<td>Disturbance</td>
<td>Micro</td>
<td>MILP based on TSDG, AG</td>
<td>Min the maximum secondary delay for all trains at all visited stations</td>
<td>Retiming and reordering</td>
<td>B&amp;B, H</td>
<td>Ignored</td>
</tr>
<tr>
<td>Pellegrini et al. (2012)</td>
<td>Disturbance/disruption</td>
<td>Micro</td>
<td>MILP based on TSDG</td>
<td>Min the maximum secondary delay imposed to a train</td>
<td>Retiming, reordering and rerouting</td>
<td>EX</td>
<td>Considered (in constraints)</td>
</tr>
<tr>
<td>Corman et al. (2012)</td>
<td>Disturbance</td>
<td>Micro</td>
<td>MILP based on TSDG, AG</td>
<td>Min the consecutive delays between trains and max the total value of satisfied connections</td>
<td>Retiming and reordering</td>
<td>B&amp;B, H</td>
<td>Ignored</td>
</tr>
<tr>
<td>Sato et al. (2013)</td>
<td>Disruption</td>
<td>Marco</td>
<td>MIP based on TSDG</td>
<td>Min further inconvenience to passengers</td>
<td>Retiming reordering and rerouting</td>
<td>EX, H</td>
<td>Considered (in constraints)</td>
</tr>
<tr>
<td>Louwerse and Huisman (2014)</td>
<td>Disruption</td>
<td>Marco</td>
<td>IP based on EADG</td>
<td>Min the number of canceled train sub series and the delays of the trains that are not canceled, balance the number of trains in both directions and distribute the operated trains evenly over time</td>
<td>Retiming and reservicing</td>
<td>EX</td>
<td>Considered (in objectives and constraints)</td>
</tr>
<tr>
<td>Meng and Zhou (2014)</td>
<td>Disturbance</td>
<td>Micro</td>
<td>IP based on TSDG, CF</td>
<td>Min the total delay time of all involved trains at the destination</td>
<td>Retiming, reordering and rerouting</td>
<td>EX, LR</td>
<td>Ignored</td>
</tr>
<tr>
<td>Veelenturf et al. (2016)</td>
<td>Disruption</td>
<td>Marco</td>
<td>ILP based on EADG</td>
<td>Min the number of cancelled and delayed train services</td>
<td>Retiming, rerouting and reservicing</td>
<td>EX</td>
<td>Considered (in constraints)</td>
</tr>
<tr>
<td>Binder et al. (2017)</td>
<td>Disruption</td>
<td>Marco</td>
<td>ILP based on TSDG</td>
<td>Min the passenger inconvenience, operational cost and deviation from undisrupted timetable</td>
<td>Retiming, rerouting and reservicing</td>
<td>EX</td>
<td>Considered (in constraints)</td>
</tr>
<tr>
<td>Corman et al. (2017)</td>
<td>Disturbance</td>
<td>Micro</td>
<td>MILP based on TSDG</td>
<td>Min the total time spent in the system by all passengers</td>
<td>Retiming and reordering</td>
<td>EX, H</td>
<td>Ignored</td>
</tr>
<tr>
<td><strong>Our research</strong></td>
<td>Disruption</td>
<td>Macro</td>
<td>ILP based on SSTDG</td>
<td>Min the total cost of timetable rescheduling and rolling stock rescheduling</td>
<td>Retiming, reordering and reservicing</td>
<td>EX</td>
<td>Considered (in objectives and constraints)</td>
</tr>
</tbody>
</table>
# Literature review

## Rolling stock rescheduling

<table>
<thead>
<tr>
<th>Publications</th>
<th>Model structure</th>
<th>Objective(s)</th>
<th>Solution method</th>
<th>Considered characteristics of rolling stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budai et al. (2010)</td>
<td>ILP, FB</td>
<td>Min the number of off-balances, carriage kilometers, shortage kilometers and the number of composition changes</td>
<td>H</td>
<td>Rolling stock balance</td>
</tr>
<tr>
<td>Nielsen et al. (2012)</td>
<td>ILP, FB</td>
<td>Min the difference from original assignments of compositions to trips, the carriage kilometer costs, seat shortage kilometer costs, deviations from the original shunting operation and deviations from end-of-day balance</td>
<td>EX, H</td>
<td>Type, inventory, coupling and uncoupling; end-off-day balance, capacity</td>
</tr>
<tr>
<td>Kroon et al. (2015)</td>
<td>MILP, FB</td>
<td>Minimize the system related cost of a rolling stock assignment and the service related cost of a passenger flow</td>
<td>EX, H</td>
<td>Type, inventory, coupling and uncoupling; end-off-day balance, capacity</td>
</tr>
<tr>
<td>Wagenaar et al. (2015)</td>
<td>MILP, FB</td>
<td>Min the number of cancelled trips, the capacity shortages, the number of carriage kilometers, modified shunting movements, and the total deviation from the end of day balance</td>
<td>EX</td>
<td>Type, inventory, coupling and uncoupling, end-of-day balance, capacity</td>
</tr>
<tr>
<td>Lusby et al. (2017)</td>
<td>ILP, PB</td>
<td>Min the cost of cancellations and seat-shortage, end-of-day balance shortage cost, and the (de)coupling and mileage cost</td>
<td>CGA, B&amp;B</td>
<td>Type, inventory, coupling and uncoupling, end-of-day balance, capacity, composition length</td>
</tr>
<tr>
<td>Haahr et al. (2016)</td>
<td>MILP, PB</td>
<td>Min the trip cancelation, seat shortage, operational costs, the shunting costs and the end-of-day shortage costs</td>
<td>EX, CRGA</td>
<td>Type, inventory, coupling and uncoupling, end-of-day balance, capacity</td>
</tr>
<tr>
<td><strong>Our research</strong></td>
<td>ILP, PB</td>
<td>Min the total cost of timetable rescheduling and rolling stock rescheduling</td>
<td>EX</td>
<td>Type, inventory, coupling and uncoupling, end-of-day balance, capacity</td>
</tr>
</tbody>
</table>
## Literature review

### Integrated rescheduling of timetable and rolling stock

<table>
<thead>
<tr>
<th>Publications</th>
<th>Infrastructure details</th>
<th>Model structure</th>
<th>Objective(s)</th>
<th>Solution framework and method</th>
<th>Considered characteristics of timetable</th>
<th>Considered the characteristics of rolling stock</th>
<th>Considered timetabling rescheduling measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fekete et al. (2011)</td>
<td>Marco</td>
<td>IP</td>
<td>Max the number of recovered trips in a conflict-free new timetable, possibly with delay</td>
<td>EX</td>
<td>Headway times</td>
<td>No details</td>
<td>Retiming, reordering and reservicing</td>
</tr>
<tr>
<td>Cadarso et al. (2013)</td>
<td>Macro</td>
<td>MILP</td>
<td>Min the operating costs of planned and emergency services, operating costs of empty movement, composition changes, cancellation of services, denied passenger, deviation from the schedule of commercial services, and deviation from the schedule of the empty movements</td>
<td>Two-step algorithm in an iterative heuristic framework, EX</td>
<td>Headway times</td>
<td>Type, inventory, coupling and uncoupling, end-of-day balance, capacity</td>
<td>Reservicing</td>
</tr>
<tr>
<td>Cadarso et al. (2015)</td>
<td>Marco</td>
<td>ILP</td>
<td>Min the operating costs of planned, empty and emergency services, composition changes, cancellation of services, denied passenger, deviation from the planned schedule, and the penalty cost of every time period during which the recovery is active</td>
<td>EX</td>
<td>Headway times</td>
<td>Type, inventory, coupling and uncoupling, end-of-day balance, capacity</td>
<td>Reservicing</td>
</tr>
<tr>
<td>Dollevoet et al. (2017)</td>
<td>Marco</td>
<td>MILP</td>
<td>Min the total duration of cancelled train services.</td>
<td>An iterative framework, EX and GA for timetable rescheduling, EX for rolling stock rescheduling, CGA and LRA for crew rescheduling</td>
<td>Headway times</td>
<td>Type, inventory, coupling and uncoupling, end-of-day balance, capacity</td>
<td>Retiming and reservicing</td>
</tr>
<tr>
<td>Veeenturf et al. (2017)</td>
<td>Macro</td>
<td>ILP</td>
<td>Min the total costs of the rolling stock rescheduling, the passenger flows (sum of delays) and the timetable rescheduling</td>
<td>An iterative heuristic framework, EX</td>
<td>No details</td>
<td>Type, inventory, coupling and uncoupling, end-of-day balance, capacity</td>
<td>Retiming and reservicing which is limited to the adaptations of stopping patterns</td>
</tr>
<tr>
<td><strong>Our research</strong></td>
<td>Marco</td>
<td>ILP</td>
<td>Min the total cost of timetable rescheduling and rolling stock rescheduling</td>
<td>EX</td>
<td>Headway times</td>
<td>Type, inventory, coupling and uncoupling, end-of-day balance, capacity</td>
<td>Retiming, reordering and reservicing</td>
</tr>
</tbody>
</table>
Literature review

• Summary

Timetable rescheduling

Considering rolling stock compositions as a type of resource

Constraint

We consider a high dimension decision variable.

Literature review

Pellegrini et al. (2012)
Louwerse and Huisman (2014)
Veelenturf et al. (2016)

Veelenturf et al. (2017)
Dollevoet et al. (2017)
PART THREE

Problem statement
In this research

Disruptions

a temporary maintenance task due to infrastructure break-down, resulting in unavailability of railway track segments

Timetable rescheduling

retiming, reordering and reserviceing

Rolling stock rescheduling

adjusting the original circulation plan
Input

- Railway network
- Timetable
- Rolling stock and circulation schedule
- A set of candidate shunting operations
- A set of disruptions
Key decisions

- For *each train service*, we need to determine whether it is *canceled*, if not, the *detailed arrival and departure times* at relevant stations in the railway network will be obtained.

- For each train service operated in the adjusted timetable, we need to determine which *rolling stock composition available* to operate it, and the specific *order* of above rolling stock units in the composition. That is to say, the adjusted rolling stock circulation schedule will be obtained.
Feasible *timetable* and *rolling stock circulation plan*

- Total delay times
- Number of canceled train services
- Deviation of shunting plans
- Seat shortage
- End-of-day off-balances

Minimize the total *cost of timetable rescheduling* and *rolling stock rescheduling*

A number of *operational constraints*, like capacity constraint
Assumptions

• The *capacity of every station* depends on *the number of tracks* in the station

• The *preferred terminal stations and intermediate stations* of train services cannot be changed.

• We don’t consider *passenger demand changing* due to disruptions.
State-space-time Network

- $SST = (\Phi, A)$ with a set of vertices $\Phi$ and a set of arcs $A$

Figure: An illustration of a state-space-time network
State-space-time Network

- State dimension
  a vector with four elements $[ts_{rol}, td_{rol}, task_{rol}, com_{rol}]$
State-space-time Network

- **State dimension**
  a vector with four elements $[ts_{rol}, td_{rol}, com_{rol}, task_{rol}]$

  Train service ID operated by the rolling stock unit $rol$
State-space-time Network

- **State dimension**
  a vector with four elements \([ts_{rol}, td_{rol}, com_{rol}, task_{rol}]\)

  Total travel distance until rolling stock unit \(rol\) finishes operating train service \(ts\)
State-space-time Network

- **State dimension**
  
  A vector with four elements $[ts_{rol}, td_{rol}, com_{rol}, task_{rol}]$

  Rolling stock composition $com$

  Which operates train service $ts$
State-space-time Network

- **State dimension**
  a vector with four elements $[t_{srol}, t_{drol}, c_{omrol}, t_{askrol}]$

  Task of rolling stock unit $rol$
State-space-time Network

- **State dimension**
  a vector with four elements $[ts_{rol}, td_{rol}, com_{rol}, task_{rol}]$

$$w_0 = [0, 0, 0, 0]$$

Figure: (a) Three possible compositions (l), (m) and (n) for Train Service 3 (b) Possible tasks (1)-(6) for three different types of rolling stock units (o), (p) and (q)
• **State dimension**

A vector with four elements $[ts_{rol}, td_{rol}, com_{rol}, task_{rol}]$

[3, 20, op, 1/2], [3, 20, op, 2/2], [3, 20, q, 1/1],

[3, 20, ppp, 1/3], [3, 20, ppp, 2/3], [3, 20, ppp, 3/3]

Figure: (a) Three possible compositions (l), (m) and (n) for Train Service 3 (b) Possible tasks (1)-(6) for three different types of rolling stock units (o), (p) and (q)
State-space-time Network

- Two types of arcs

  **Transportation arcs**
  - Traveling arcs
  - Waiting arcs

  **Operation arcs**
  - Take-over operation arcs
  - Accomplishment operation arcs

Figure: An illustration of a state-space-time network
Strategies for generating state-space-time network

**Firstly.** Searching all **feasible states** for every rolling stock unit

**Secondly.** Searching all **feasible arcs** for every train service **in space-time network**

**Thirdly.** Searching **feasible arcs** in **state-space-time network** by combining feasible states and feasible arcs in space-time network

*Reduce the scale of state-space-time network*
Strategies for generating state-space-time network

- Searching feasible arcs in space-time network

**Rule 1: Overlapping time windows**

**Rule 2: Turnaround time is sufficient**
Strategies for generating state-space-time network

- Searching feasible arcs in space-time network

**Rule 3:** A node is not too far away from the starting or ending depots of rolling stock units

**Rule 4:** Minimum dwelling time of train services is sufficient
Strategies for generating state-space-time network

- Searching feasible arcs in space-time network

**Rule 5: Time window of rolling stock units is sufficient for time window of train services**

- The earliest departure time for train service $s_1$ is the latest departure time for rolling stock composition $rol$.
- The earliest departure time for rolling stock composition $rol$ is the latest arrival time for rolling stock composition $rol$.
- The latest departure time for train service $s_1$ is the departure time window.
- The latest arrival time for rolling stock composition $rol$ is the arrival time window.
Strategies for generating state-space-time network

- Searching feasible arcs in state-space-time network
PART FOUR

Mathematical formulation
Mathematical Formulation

- Decision variable

\[ x(rol, i, j, t, s, w, w') = \begin{cases} 
1, & \text{arc } (i, j, t, s, w, w') \text{ is used by } rolling \text{ stock unit } rol \\
0, & \text{otherwise} 
\end{cases} \]

\[ y(com, i, j, t, s, w, w') = \begin{cases} 
1, & \text{arc } (i, j, t, s, w, w') \text{ is used by } rolling \text{ stock composition } com \\
0, & \text{otherwise} 
\end{cases} \]
Mathematical Formulation

- **Objective function**

\[
\text{Min } Z = \sum_{\text{rol} \in (ROL \cup ROL^*)} \sum_{(i,j,t,t',w,w') \in A_{\text{rol}}} c(\text{rol}, i, j, t, t', w, w') x(\text{rol}, i, j, t, t', w, w')
\]
Mathematical Formulation

• Objective function

\[
\min Z = \sum_{rol \in (ROL \cup ROL^*)} \sum_{(i,j,t,t',w,w') \in A_{rol}} c(rol, i, j, t, t', w, w') x(rol, i, j, t, t', w, w')
\]

• Constraints

Flow balance constraints

Train services operated constraints

Capacity constraints (section and station)

Matching constraint between arcs for rolling stock unit and arcs for corresponding rolling stock composition

Rolling stock unit inventory constraint

Rolling stock unit end-of-day balance constraint
PART FIVE

Numerical study
**Numerical Study**

- Original timetable and rolling stock circulation plan
Track failure in the section between station B and Station C, a temporary maintenance task executed with the duration from time point 1 to time point 31.
## Cost Setting

### Cost for the timetable rescheduling

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cancelled trip</td>
<td>$100,000 + 1000 \times \text{running time of the train service}$</td>
</tr>
<tr>
<td>Per arrival delay minute</td>
<td>1</td>
</tr>
</tbody>
</table>

### Cost for the rolling stock rescheduling

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per positive seat capacity deviation</td>
<td>\text{travel distance of the train service}</td>
</tr>
<tr>
<td>Per cancelled shunting movement</td>
<td>100</td>
</tr>
<tr>
<td>Per new shunting movement</td>
<td>1000</td>
</tr>
<tr>
<td>Per exceeding turnaround minute</td>
<td>1</td>
</tr>
</tbody>
</table>
Numerical Study

solution time: 0.55 sec
Future Research

• Consider more detailed information about infrastructure, like a microscopic network
• Consider the uncertainty for the duration of disruption
• Design algorithm to solve large scale problems with efficiency
• Do more contrast experiments to examine the effectiveness and applicability of our model and solution method
Thanks for your attention! Any questions?

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Beijing Jiaotong University