Integrated Freight Train Composition and Scheduling considering Energy Efficiency Aspects

BMBF supported joint project E-Motion

Frederik Fiand & Prof. Dr. Uwe Zimmermann

Aussois, January 2014
Outline

- Problem Description
- Estimating Energy Consumption
- Solution Approach
  - Preprocessing
  - MIP Model
  - Rolling Horizon & Shipment Aggregation
- Computational Results
- Outlook
Outline

- Problem Description
  - Estimating Energy Consumption
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  - Rolling Horizon & Shipment Aggregation
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- Outlook
Input Data - Shipments

For each shipment:
Input Data - Shipments

For each shipment:
1. Origin station
   - Earliest departure time
Input Data - Shipments

For each shipment:
1. Origin station
   - Earliest departure time
2. Destination station
   - Latest arrival time

Source: Kombiverkehr GmbH & Co. KG
Input Data - Shipments

For each shipment:
1. Origin station
   - Earliest departure time
2. Destination station
   - Latest arrival time
3. Weight
4. Length

Source: Kombiverkehr GmbH & Co. KG
Input Data - Trains

Trains can contain multiple sections.

Source: Kombiverkehr GmbH & Co. KG
Input Data - Trains

Trains can contain multiple sections.

For each train section:

1. Origin station
   - Departure time
   - Elevation AMSL
Input Data - Trains

Trains can contain multiple sections.

For each train section:

1. Origin station
   - Departure time
   - Elevation AMSL

2. Destination station
   - Arrival Time
   - Elevation AMSL

Source: Kombiverkehr GmbH & Co. KG
Input Data - Trains

Trains can contain multiple sections.

For each train section:

1. Origin station
   - Departure time
   - Elevation AMSL

2. Destination station
   - Arrival Time
   - Elevation AMSL

3. Capacities (weight, length)

4. Distance

Mon 3:00pm
LEIPZIG (113 AMSL)
400km, 1600 t, 800m

Mon 8:00pm
MUNICH (519 AMSL)
Mon 10:00pm

VERONA (59 AMSL)
Tue 7:00am
430km, 1400 t, 700m

Source: Kombiverkehr GmbH & Co. KG
Input Data - Trains

Trains can contain multiple sections.

For each train section:

1. Origin station
   - Set of possible departure times
   - Elevation AMSL

2. Destination station
   - Set of possible arrival times
   - Elevation AMSL

3. Capacities (weight, length)

4. Distance

Problem extension:
Variable departure/arrival times
Input Data - Trains

Trains can contain multiple sections.

For each train section:

1. Origin station
   - Set of possible departure times
   - Elevation AMSL
2. Destination station
   - Set of possible arrival times
   - Elevation AMSL
3. Capacities (weight, length)
4. Distance

Problem extension:
Variable departure/arrival times

Trucking costs for all OD pairs available
Solution = Transportation Plan & Adjusted Train Schedule

Assignment of shipments to trains/trucks:

1. Complete all shipments
2. Release and due dates
3. Capacity constraints
4. Whole trains can be rejected, single train sections cannot
Solution = Transportation Plan & Adjusted Train Schedule

Assignment of shipments to trains/trucks:

1. Complete all shipments
2. Release and due dates
3. Capacity constraints
4. Whole trains can be rejected, single train sections cannot

Objective?
- Max operator`s profit
- Min client`s cost
- Min Energy Consumption
- ...

Source: Kombiverkehr GmbH & Co. KG
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Estimating Energy Consumption $^{1,2}$

$B_i$ \quad empirical train specific coefficients

$E$ \quad energy consumption per tkm

$g$ \quad gravitational acceleration

$\Delta h$ \quad change in elevation

$l$ \quad trip length

$n_{\text{stops}}$ \quad number of stops

$v_{\text{avg}}$ \quad average speed

$v_{\text{max}}$ \quad maximum speed

$$
E = n_{\text{stops}} + 1 \cdot \frac{v_{\text{max}}^2}{2} + B_0 + B_1 \cdot v_{\text{avg}} + B_2 \cdot v_{\text{avg}}^2 + g \cdot \frac{\Delta h}{l}
$$

$$
= n_{\text{stops}} + 1 \cdot \frac{v_{\text{max}}^2}{2} + 24.7 + 0.0845 \cdot v_{\text{avg}}^2 + 9.81 \cdot \frac{\Delta h}{l}
$$


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Time Discrete Unsplittable Multi-Commodity Flow

- Original train schedule
Time Discrete Unsplittable Multi-Commodity Flow

- **Original train schedule**

- **Digraph**
  - vertices = stations
  - arcs = trains with fixed departure and arrival times
Time Discrete Unsplittable Multi-Commodity Flow

- Original train schedule
- Digraph
  - vertices = stations
  - arcs = trains with fixed departure and arrival times
- Time expanded network

Solution Approach – Basic Problem
Time Discrete Unsplittable Multi-Commodity Flow

• Original train schedule
  • Digraph with parallel arcs
    • vertices = stations
    • arcs = trains with fixed departure and arrival times

• Time expanded network
Time Discrete Unsplittable Multi-Commodity Flow

- **Original train schedule**
- **Digraph with parallel arcs**
  - vertices = stations
  - arcs = trains with fixed departure and arrival times

- **Time expanded network**

```
Mon, 6am  Shipment release date
Mon, 7:30am
Mon, 8am
Mon, 8:30am
```
```
Mon, 12:30pm
Mon, 1:30pm
Mon, 5:30pm
Mon, 6pm
Mon, 6:30pm
```
```
Mon, 7:30am - 8:30am
Mon, 8:30am - 9:30am
```
```
Mon, 12:30pm - 1:30pm
Mon, 5:30pm - 6:30pm
```

Stations
Time Discrete Unsplittable Multi-Commodity Flow

- **Original train schedule**
- **Digraph with parallel arcs**
  - vertices = stations
  - arcs = trains with fixed departure and arrival times

**Solution Approach – Extended Problem**

- **Time expanded network**

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January, 2015
Time Discrete Unsplittable Multi-Commodity Flow

- **Original train schedule**
  - Vertices = stations
  - Arcs = trains with fixed departure and arrival times

- **Digraph with parallel arcs**

- **Time expanded network**

  Preprocessing:
  Check whether a train can be used for the transport of a certain shipment
Time Discrete Unsplittable Multi-Commodity Flow

- **Original train schedule**
- **Digraph with parallel arcs**
  - vertices = stations
  - arcs = trains with fixed departure and arrival times

**Solution Approach – Extended Problem**

### Original train schedule
- Mon, 8am
- Mon, 6pm
- Mon, 9pm
- Mon, 1pm
- Mon, 5pm
- Mon, 6:30pm

### Digraph with parallel arcs
- Vertices = stations
- Arches = trains with fixed departure and arrival times

### Time expanded network

**Preprocessing:** Check whether a train can be used for the transport of a certain shipment

**Model:** MIP-Formulation

**时间离散不可分割多商品流量**

- **原始列车时刻表**
- **有向图与并行弧**
  - 顶点 = 站点
  - 边 = 固定出发和到达时间的列车

**解决方案 - 扩展问题**

### 原始列车时刻表
- 周一，8am
- 周一，6pm
- 周一，9pm
- 周一，1pm
- 周一，5pm
- 周一，6:30pm

### 有向图与并行弧
- 顶点 = 站点
- 边 = 固定出发和到达时间的列车

### 时间扩展网络

**预处理：** 检查是否可以使用一辆列车运输某种货物

**模型：** MIP-形式化
Preprocessing

Shipment

STUTTGART
Tue 5am

HAMBURG
Mon 6am

Trains

COLOGNE
Mon 6pm

STUTTGART
Mon 9pm
Preprocessing

Shipment

- HAMBURG
  - Mon 6am

- STUTTGART
  - Tue 5am

Trains

- COLOGNE
  - Mon 6pm

- STUTTGART
  - Mon 9pm
Preprocessing
Preprocessing

Integrated Freight Train Composition and Scheduling considering Energy Efficiency Aspects

January, 2015
Preprocessing
Preprocessing

**Shortest Path Tree “backward”**

- Hamburg
- Cologne
- Stuttgart

- Mon, 10am
- Shipment release

- Tue, 5pm
- Due date

Solution Approach
Preprocessing
Preprocessing
Preprocessing

Suitable train sections for transport of shipment \( i \)

- Hamburg
- Cologne
- Stuttgart

Time

Mon, 10am
Shipment \( i \) release

Tue, 5pm
Due date
## Unsplittable Multi-Commodity Flow

<table>
<thead>
<tr>
<th>$i \in I$</th>
<th>Shipments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \in T$</td>
<td>Trains</td>
</tr>
<tr>
<td>$e \in E$</td>
<td>Train sections</td>
</tr>
<tr>
<td>$v \in V$</td>
<td>Stations</td>
</tr>
</tbody>
</table>

### Preprocessing

- $i \in I_e \subseteq I$: Shipments that can be transported via $e$
- $e \in E_i \subseteq E$: Trains suitable for transport of shipment $i$
- $v \in V_i \subseteq V$: Stations that can be visited during transport of $i$
## Unsplittable Multi-Commodity Flow

| $i \in I$ | Shipments |
| $t \in T$ | Trains |
| $e \in E$ | Train sections |
| $v \in V$ | Stations |

Preprocessing

- $i \in I_e \subseteq I$ : Shipments that can be transported via $e$
- $e \in E_i \subseteq E$ : Trains suitable for transport of shipment $i$
- $v \in V_i \subseteq V$ : Stations that can be visited during transport of $i$

### Constraints

- $x_i(e) \in \{0, 1\}$ \( \forall i \in I, e \in E_i \) = 1, iff shipment $i$ uses train $e$ during transport
- $y_t \in \{0, 1\}$ \( \forall t \in T \) = 1, iff train $t$ is operated
- $z_i \in \{0, 1\}$ \( \forall i \in I \) = 1, iff shipment $i$ uses truck transport
### Unsplittable Multi-Commodity Flow

| i ∈ I | Shipments |
| t ∈ T | Trains |
| e ∈ E | Train sections |
| v ∈ V | Stations |

- **Preprocessing**
  - \( x_i(e) \in \{0, 1\} \quad \forall i \in I, e \in E_i \)
  - \( y_t \in \{0, 1\} \quad \forall t \in T \)
  - \( z_i \in \{0, 1\} \quad \forall i \in I \)

\( x_i(e) = 1 \), iff shipment \( i \) uses train \( e \) during transport

\( y_t = 1 \), iff train \( t \) is operated

\( z_i = 1 \), iff shipment \( i \) uses truck transport

- Min energy consumption
- Flow conservation
- Inbound time < outbound time
- Ship once
- Weight capacity
- Length capacity
- No train duplicates
# Unsplittable Multi-Commodity Flow

| $i \in I$ | Shipment | $i \in I_e \subseteq I$ | Shipments that can be transported via $e$ |
| $t \in T$ | Trains | $e \in E_i \subseteq E$ | Trains suitable for transport of shipment $i$ |
| $e \in E$ | Train sections | $v \in V_i \subseteq V$ | Stations that can be visited during transport of $i$ |
| $v \in V$ | Stations |

- **Preprocessing**

\[
x_i(e) \in \{0, 1\} \quad \forall i \in I, e \in E_i = 1, \text{ iff shipment } i \text{ uses train } e \text{ during transport}
\]

\[
y_t \in \{0, 1\} \quad \forall t \in T = 1, \text{ iff train } t \text{ is operated}
\]

\[
z_i \in \{0, 1\} \quad \forall i \in I = 1, \text{ iff shipment } i \text{ uses truck transport}
\]

## Solution Approach

- **Min energy consumption**

\[
\min f(x, y, z)
\]

- **Flow conservation**

\[
x_i(\delta^- (v)) - x_i(\delta^+ (v)) = 0 \quad \forall i \in I, v \in V_i \setminus \{s_i, t_i\}
\]

- **Inbound time < outbound time**

\[
\sum_{e \in \delta^- (v)} x_i(e) \cdot \tau^d_e - \sum_{e \in \delta^+ (v)} x_i(e) \cdot \tau^o_e \leq 0 \quad \forall i \in I, v \in V_i \setminus \{s_i, t_i\}
\]

- **Ship once**

\[
x_i(\delta^+ (s_i)) + z_i = 1 \quad \forall i \in I
\]

- **Weight capacity**

\[
\sum_{i \in I_e} x_i(e) \cdot w_i \leq W_e \cdot y_t(e) \quad \forall e \in E
\]

- **Length capacity**

\[
\sum_{i \in I_e} x_i(e) \cdot l_i \leq L_e \cdot y_t(e) \quad \forall z \in Z, e \in E_z
\]

- **No train duplicates**

\[
\sum_{t' \in T : t^{\text{orig}}(t') = t} y_{t'} \leq 1 \quad \forall t \in T^{\text{orig}}
\]
### Solution Approach

#### Unsplittable Multi-Commodity Flow

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Preprocessing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i \in I$</td>
<td>Shipments</td>
<td></td>
</tr>
<tr>
<td>$t \in T$</td>
<td>Trains</td>
<td></td>
</tr>
<tr>
<td>$e \in E$</td>
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<td></td>
</tr>
<tr>
<td>$v \in V$</td>
<td>Stations</td>
<td></td>
</tr>
</tbody>
</table>

- $i \in I_e \subseteq I$: Shipments that can be transported via $e$
- $e \in E_i \subseteq E$: Trains suitable for transport of shipment $i$
- $v \in V_i \subseteq V$: Stations that can be visited during transport of $i$

#### Preprocessing

- $x_i(e) \in \{0, 1\}$, $\forall i \in I, e \in E_i$: $= 1$, iff shipment $i$ uses train $e$ during transport
- $y_t \in \{0, 1\}$, $\forall t \in T$: $= 1$, iff train $t$ is operated
- $z_i \in \{0, 1\}$, $\forall i \in I$: $= 1$, iff shipment $i$ uses truck transport

#### Min energy consumption

$$\min f(x, y, z)$$

$$f(x, y, z) = \sum_{t \in T} y_t \cdot c_{fix}^t$$

$$+ \sum_{e \in E} \sum_{i \in I_e} x_i(e) \cdot w_i \cdot d_e \cdot \left(24.7 + \frac{n_{stops,e}}{d_e} + 1 \cdot \frac{v_{e,\max}^2}{2} + 0.0845 \cdot v_{avg,e}^2 + 9.81 \cdot \frac{\Delta h_e}{d_e}\right)$$

$$+ \sum_{i \in I} z_i \cdot c_{truck}^i$$

- **Fixed costs for operating trains**
- **Load dependent train section costs**
- **Trucking costs**
## Unsplittable Multi-Commodity Flow

**Shipments**
\[ i \in I \]

**Trains**
\[ t \in T \]

**Train sections**
\[ e \in E \]

**Stations**
\[ v \in V \]

**Shipments that can be transported via**
\[ i \in I_e \subseteq I \]

**Trains suitable for transport of shipment**
\[ e \in E_i \subseteq E \]

**Stations that can be visited during transport of**
\[ v \in V_i \subseteq V \]

**Preprocessing**

\[ x_i(e) \in \{0, 1\}, \quad \forall i \in I, e \in E_i \]

\[ = 1, \text{ iff } \text{shipment } i \text{ uses train } e \text{ during transport} \]

\[ y_t \in \{0, 1\}, \quad \forall t \in T \]

\[ = 1, \text{ iff } \text{train } t \text{ is operated} \]

\[ z_i \in \{0, 1\}, \quad \forall i \in I \]

\[ = 1, \text{ iff } \text{shipment } i \text{ uses truck transport} \]

**Min energy consumption**
\[
\min f(x, y, z)
\]

**Flow conservation**
\[
x_i(\delta^-(v)) - x_i(\delta^+(v)) = 0 \quad \forall i \in I, v \in V_i \setminus \{s_i, t_i\}
\]

**Inbound time < outbound time**
\[
\sum_{e \in \delta^-(v)} x_i(e) \cdot \tau^d_e - \sum_{e \in \delta^+(v)} x_i(e) \cdot \tau^o_e \leq 0 \quad \forall i \in I, v \in V_i \setminus \{s_i, t_i\}
\]

**Ship once**
\[
x_i(\delta^+(s_i)) + z_i = 1 \quad \forall i \in I
\]

**Weight capacity**
\[
\sum_{i \in I_e} x_i(e) \cdot w_i \leq w_e \cdot y_t(e) \quad \forall e \in E
\]

**Length capacity**
\[
\sum_{i \in I_e} x_i(e) \cdot l_i \leq l_e \cdot y_t(e) \quad \forall z \in Z, e \in E_z
\]

**No train duplicates**
\[
\sum_{t' \in T: t_{\text{orig}}(t') = t} y_{t'} \leq 1 \quad \forall t \in T_{\text{orig}}
\]
**Unsplittable Multi-Commodity Flow**

- \( i \in I \) Shipments
- \( t \in T \) Trains
- \( e \in E \) Train sections
- \( v \in V \) Stations

\( x_i(e) \in \{0, 1\} \quad \forall i \in I, e \in E_i \)

= 1, iff shipment \( i \) uses train \( e \) during transport

\( y_t \in \{0, 1\} \quad \forall t \in T \)

= 1, iff train \( t \) is operated

\( z_i \in \{0, 1\} \quad \forall i \in I \)

= 1, iff shipment \( i \) uses truck transport

**Solution Approach**

- Min energy consumption
  \[
  \min f(x, y, z)
  \]

- Flow conservation
  \[
  x_i(\delta^- (v)) - x_i(\delta^+ (v)) = 0 \quad \forall i \in I, v \in V_i \setminus \{s_i, t_i\}
  \]

- Inbound time < outbound time
  \[
  \sum_{e \in \delta^- (v)} x_i(e) \cdot \tau_e^d - \sum_{e \in \delta^+ (v)} x_i(e) \cdot \tau_e^o \leq 0 \quad \forall i \in I, v \in V_i \setminus \{s_i, t_i\}
  \]

- Shipment \( i \) from \( v_1 \) to \( v_3 \), look at intermediate node \( v_2 \)

\[
\sum_{e \in \delta^- (v)} x_i(e) \cdot \tau_e^d - \sum_{e \in \delta^+ (v)} x_i(e) \cdot \tau_e^o \leq 0 \quad \forall i \in I, v \in V_i \setminus \{s_i, t_i\}
\]
# Unsplittable Multi-Commodity Flow

- **Shipments** $i \in I$
- **Trains** $t \in T$
- **Train sections** $e \in E$
- **Stations** $v \in V$

### Preprocessing

$x_i(e) \in \{0, 1\} \quad \forall i \in I, e \in E_i$

- $= 1$, iff shipment $i$ uses train $e$ during transport

$y_t \in \{0, 1\} \quad \forall t \in T$

- $= 1$, iff train $t$ is operated

$z_i \in \{0, 1\} \quad \forall i \in I$

- $= 1$, iff shipment $i$ uses truck transport

## Solution Approach

### Min energy consumption

$$\min f(x, y, z)$$

### Flow conservation

$$x_i(\delta^-(v)) - x_i(\delta^+(v)) = 0 \quad \forall i \in I, v \in V_i \setminus \{s_i, t_i\}$$

### Inbound time < outbound time

$$\sum_{e \in \delta^-(v)} x_i(e) \cdot \tau^d_e - \sum_{e \in \delta^+(v)} x_i(e) \cdot \tau^o_e \leq 0 \quad \forall i \in I, v \in V_i \setminus \{s_i, t_i\}$$

### Ship once

$$x_i(\delta^+(s_i)) + z_i = 1 \quad \forall i \in I$$

### Weight capacity

$$\sum_{i \in I_e} x_i(e) \cdot w_i \leq \$e \cdot y_t(e) \quad \forall e \in E$$

### Length capacity

$$\sum_{i \in I_e} x_i(e) \cdot l_i \leq \ell_e \cdot y_t(e) \quad \forall z \in Z, e \in E_z$$

### No train duplicates

$$\sum_{t' \in T : t'_{\text{orig}}(t') = t} y_{t'} \leq 1 \quad \forall t \in T_{\text{orig}}$$
Rolling Horizon

Planning Horizon

Planning of the entire horizon at once might not be possible
Rolling Horizon

- Planning Horizon
- Planning of the entire horizon at once might not be possible
- Consider smaller sub-instance
- Control via shipment release dates
Rolling Horizon

Planning Horizon

Planning of the entire horizon at once might not be possible

Consider smaller sub-instance

Implement solution

Control via shipment release dates
Rolling Horizon

Planning Horizon

Planning of the entire horizon at once might not be possible

Consider smaller sub-instance

Control via shipment release dates

Implement solution

- Fix some variables
- Update capacities

Implement solution
Rolling Horizon

Planning Horizon

Planning of the entire horizon at once might not be possible

Consider smaller sub-instance

Implement solution
- Fix some variables
- Update capacities

Control via shipment release dates
Rolling Horizon

Planning of the entire horizon at once might not be possible

Consider smaller sub-instance

Implement solution
- Fix some variables
- Update capacities

Control via shipment release dates

Control instance size and overlap

Implement solution
- Fix some variables
- Update capacities...

Integrated Freight Train Composition and Scheduling considering Energy Efficiency Aspects
January, 2015
Rolling Horizon

Planning Horizon

Considered planning horizon

Overlap

Implement solution

- Fix some variables
- Update capacities

...
Rolling Horizon

Several control parameters:
- Size of sub-instances (step size)
- Overlap
- Solver termination criteria
  - Time limit
  - Gap

Good parameter choice is difficult!
Rolling Horizon with parallel MIP & Preprocessing

Solution time

Sequential

PP1 MIP1 PP2 MIP2 PP3 MIP3 PP4 MIP4 PP5 MIP5 PP6 MIP6 PP7 MIP7
Rolling Horizon with parallel MIP & Preprocessing

Solution time

Sequential

Parallel

Runtime reduction up to 30 %
Shipment Aggregation

Same color means:

1. Same origin
2. Same destination
3. Same release date
4. Same due date
Shipment Aggregation

Same color means:
1. Same origin
2. Same destination
3. Same release date
4. Same due date

Common train capacity: 6
Shipment Aggregation

Same color means:
1. Same origin
2. Same destination
3. Same release date
4. Same due date

Rolling Horizon & Shipment Aggregation

Common train capacity: 6
Shipment Aggregation

Same color means:
1. Same origin
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Common train capacity: 6

Rolling Horizon & Shipment Aggregation

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Computational Results

• Hardware & Tools:  
  - Intel Core i7-4930K, 6 cores, 3.4GHz, 32GB RAM
  - Preprocessing: C
  - Modeling and Rolling Horizon: GAMS
## Computational Results

- **Hardware & Tools:**
  - Intel Core i7-4930K, 6 cores, 3.4GHz, 32GB RAM
  - Preprocessing: C
  - Modeling and Rolling Horizon: GAMS

- **Instance Characteristics:**

<table>
<thead>
<tr>
<th></th>
<th>none</th>
<th>weak</th>
<th>medium</th>
<th>strong</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># Shipments</strong> $i \in I$</td>
<td>145,911</td>
<td>47,242</td>
<td>29,003</td>
<td>25,177</td>
</tr>
<tr>
<td><strong># Train sections</strong> $e \in E$</td>
<td>24,643</td>
<td>24643</td>
<td>24,643</td>
<td>24,643</td>
</tr>
<tr>
<td><strong># Stations</strong> $v \in V$</td>
<td>1,130</td>
<td>1,130</td>
<td>1,130</td>
<td>1,130</td>
</tr>
</tbody>
</table>

| # Variables          | $O(|I| \cdot |E|)$ | $O(|I| \cdot |E|)$ | $O(|I| \cdot |E|)$ | $O(|I| \cdot |E|)$ |
|----------------------|-----------------|-----------------|-----------------|-----------------|
| **no PP**            | $3.6 \cdot 10^9$ | $1.1 \cdot 10^9$ | $7.1 \cdot 10^8$ | $6.2 \cdot 10^8$ |
| **PP**               | $2.2 \cdot 10^7$ | $7.4 \cdot 10^6$ | $5.0 \cdot 10^6$ | $4.5 \cdot 10^6$ |

| # Constraints        | $O(|I| \cdot |V|)$ | $O(|I| \cdot |V|)$ | $O(|I| \cdot |V|)$ | $O(|I| \cdot |V|)$ |
|----------------------|-----------------|-----------------|-----------------|-----------------|
| **no PP**            | $3.3 \cdot 10^8$ | $1.1 \cdot 10^8$ | $6.4 \cdot 10^7$ | $5.6 \cdot 10^7$ |
| **PP**               | $1.0 \cdot 10^7$ | $4.0 \cdot 10^6$ | $2.5 \cdot 10^6$ | $2.3 \cdot 10^6$ |
### Computational Results

- **Hardware & Tools:**
  - Intel Core i7-4930K, 6 cores, 3.4GHz, 32GB RAM
  - Preprocessing: C
  - Modeling and Rolling Horizon: GAMS

- **Instance Characteristics:**

<table>
<thead>
<tr>
<th></th>
<th>none</th>
<th>weak</th>
<th>medium</th>
<th>strong</th>
</tr>
</thead>
<tbody>
<tr>
<td># Shipments $i \in I$</td>
<td>145,911</td>
<td>47,242</td>
<td>29,003</td>
<td>25,177</td>
</tr>
<tr>
<td># Train sections $e \in E$</td>
<td>24,643</td>
<td>24643</td>
<td>24,643</td>
<td>24,643</td>
</tr>
<tr>
<td># Stations $v \in V$</td>
<td>1,130</td>
<td>1,130</td>
<td>1,130</td>
<td>1,130</td>
</tr>
</tbody>
</table>

|                  | $\mathcal{O}(|I| \cdot |E|)$ | $\mathcal{O}(|I| \cdot |E|)$ | $\mathcal{O}(|I| \cdot |E|)$ | $\mathcal{O}(|I| \cdot |E|)$ |
|------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| # Variables      |                                |                                |                                |                                |
| no PP            | $3.6 \cdot 10^9$               | $1.1 \cdot 10^9$               | $7.1 \cdot 10^8$               | $6.2 \cdot 10^8$               |
| PP               | $2.2 \cdot 10^7$               | $7.4 \cdot 10^6$               | $5.0 \cdot 10^6$               | $4.5 \cdot 10^6$               |

|                  | $\mathcal{O}(|I| \cdot |V|)$ | $\mathcal{O}(|I| \cdot |V|)$ | $\mathcal{O}(|I| \cdot |V|)$ | $\mathcal{O}(|I| \cdot |V|)$ |
|------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| # Constraints    |                                |                                |                                |                                |
| no PP            | $3.3 \cdot 10^8$               | $1.1 \cdot 10^8$               | $6.4 \cdot 10^7$               | $5.6 \cdot 10^7$               |
| PP               | $1.0 \cdot 10^7$               | $4.0 \cdot 10^6$               | $2.5 \cdot 10^6$               | $2.3 \cdot 10^6$               |

~Factor 6
### Computational Results

- **Hardware & Tools:**
  - Intel Core i7-4930K, 6 cores, 3.4GHz, 32GB RAM
  - Preprocessing: C
  - Modeling and Rolling Horizon: GAMS

- **Instance Characteristics:**

<table>
<thead>
<tr>
<th></th>
<th>Shipment Aggregation Level</th>
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<tr>
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<td>1,130</td>
</tr>
</tbody>
</table>

- **# Variables**
  - no PP: $3.6 \cdot 10^9$ (O(|I| \cdot |E|))
  - PP: $2.2 \cdot 10^7$ (O(|I| \cdot |E|))

- **# Constraints**
  - no PP: $3.3 \cdot 10^8$ (O(|I| \cdot |V|))
  - PP: $1.0 \cdot 10^7$ (O(|I| \cdot |V|))
### Computational Results

- **Hardware & Tools:**
  - Intel Core i7-4930K, 6 cores, 3.4GHz, 32GB RAM
  - Preprocessing: C
  - Modeling and Rolling Horizon: GAMS

- **Instance Characteristics:**

<table>
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</tr>
</tbody>
</table>

|                      | O(|I| · |E|) | O(|I| · |E|) | O(|I| · |E|) | O(|I| · |E|) |
|----------------------|---------|---------|---------|---------|
| **# Variables**      |         |         |         |         |
|                      |         |         |         |         |
| no PP                | 3.6 · 10^9 | 1.1 · 10^9 | 7.1 · 10^8 | 6.2 · 10^8 |
| PP                   | 2.2 · 10^7 | 7.4 · 10^6 | 5.0 · 10^6 | 4.5 · 10^6 |

|                      | O(|I| · |V|) | O(|I| · |V|) | O(|I| · |V|) | O(|I| · |V|) |
|----------------------|---------|---------|---------|---------|
| **# Constraints**    |         |         |         |         |
|                      |         |         |         |         |
| no PP                | 3.3 · 10^8 | 1.1 · 10^8 | 6.4 · 10^7 | 5.6 · 10^7 |
| PP                   | 1.0 · 10^7 | 4.0 · 10^6 | 2.5 · 10^6 | 2.3 · 10^6 |
Computational Results

- Hardware & Tools: Intel Core i7-4930K, 6 cores, 3.4GHz, 32GB RAM
- Preprocessing: C
- Modeling and Rolling Horizon: GAMS

- Instance Characteristics:

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<td>1,130</td>
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<td>1,130</td>
</tr>
</tbody>
</table>

| # Variables | $O(|I| \cdot |E|)$ | $O(|I| \cdot |E|)$ | $O(|I| \cdot |E|)$ | $O(|I| \cdot |E|)$ |
|--------------|-------------------|-------------------|-------------------|-------------------|
| no PP        | $3.6 \cdot 10^9$  | $1.1 \cdot 10^9$  | $7.1 \cdot 10^8$  | $6.2 \cdot 10^8$  | ~Factor 100 |
| PP           | $2.2 \cdot 10^7$  | $7.4 \cdot 10^6$  | $5.0 \cdot 10^6$  | $4.5 \cdot 10^6$  |

| # Constraints | $O(|I| \cdot |V|)$ | $O(|I| \cdot |V|)$ | $O(|I| \cdot |V|)$ | $O(|I| \cdot |V|)$ |
|---------------|------------------|------------------|------------------|------------------|
| no PP         | $3.3 \cdot 10^8$ | $1.1 \cdot 10^8$ | $6.4 \cdot 10^7$ | $5.6 \cdot 10^7$ | ~Factor 30 |
| PP            | $1.0 \cdot 10^7$ | $4.0 \cdot 10^6$ | $2.5 \cdot 10^6$ | $2.3 \cdot 10^6$ |

None of these instances can be solved within 24h!

⇒ Combine Rolling Horizon & Shipment Aggregation
Computational Results

Rolling Horizon - Results and Computation Times

Instance: Strong Aggregation, no train shifts
Termination criteria: 1% Gap, step size dependent time limit
Solver: Cplex 12.6.1

Energy Consumption in MWh
Solution time in sec.

<table>
<thead>
<tr>
<th>Step Size Rolling Horizon</th>
<th>Energy Consumption (overlap = 0)</th>
<th>Energy Consumption (overlap = step size)</th>
<th>Solution time (overlap = 0)</th>
<th>Solution time (overlap = step size)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5h</td>
<td>72000</td>
<td>69000</td>
<td>60000</td>
<td>21600</td>
</tr>
<tr>
<td>1h</td>
<td>72000</td>
<td>69000</td>
<td>60000</td>
<td>18000</td>
</tr>
<tr>
<td>1.5h</td>
<td>72000</td>
<td>69000</td>
<td>60000</td>
<td>14400</td>
</tr>
<tr>
<td>3h</td>
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<td>69000</td>
<td>60000</td>
<td>10800</td>
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<tr>
<td>6h</td>
<td>72000</td>
<td>69000</td>
<td>60000</td>
<td>7200</td>
</tr>
</tbody>
</table>
Computational Results

Rolling Horizon - Results and Computation Times

Instance: Strong Aggregation, no train shifts
Termination criteria: 1% Gap, step size dependent time limit
Solver: Cplex 12.6.1

- Energy Consumption in MWh
- Solution time in sec.

Graph showing energy consumption and solution time for different rolling horizons with and without overlap.

Legend:
- Red: energy consumption (overlap = 0)
- Dotted red: instance bound
- Pink: energy consumption (overlap = step size)
- Black: global bound
- Blue: solution time (overlap = 0)
- Dotted blue: solution time (overlap = step size)
Rolling Horizon - Results and Computation Times

Instance: Strong Aggregation, no train shifts
Termination criteria: 1% Gap, step size dependent time limit
Solver: Cplex 12.6.1

- Energy consumption (overlap = 0)
- Energy consumption (overlap = step size)
- Instance bound
- Global bound
- Solution time (overlap = 0)
- Solution time (overlap = step size)

Solution time in sec.

Energy Consumption in MWh
Computational Results

Rolling Horizon - Results and Computation Times

Instance: Strong Aggregation, no train shifts
Termination criteria: 1% Gap, step size dependent time limit
Solver: Cplex 12.6.1

Average Impact of train shifts ± 15 minutes

Energy savings: ~4%
Solution time increase: 212%
Outline

- Problem Description
- Estimating Energy Consumption
- Solution Approach
  - Preprocessing
  - MIP Model
  - Rolling Horizon & Shipment Aggregation
- Computational Results
- Outlook
Outlook

- Subsequent Min Max Optimization to reduce cost relevant peak height

\[
\text{Time} \quad (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30)
\]

\[
\begin{align*}
\text{E in MWh per h} \\
0 & 10 & 20 & 30 & 40 & 50
\end{align*}
\]

- \( \text{obj} = \text{min total energy consumption} \)
- \( \text{obj} = \text{min max energy consumption} \)
Outlook

• Subsequent Min Max Optimization to reduce cost relevant peak height

In the network, every node can be assigned to one specific shunting yard.

Aggregated Instance with simplified network

„coarse to fine“
Thank You

Frederik Fiand
f.fiand@tu-braunschweig.de