Optimization Approaches Applied to the Strategic Planning of Transportation Infrastructures

Bruno Filipe Santos
University of Coimbra

December 6th, 2012
Motivation

Given the costs of road construction (motorways: 10 M€/km), as well as its social and environmental implications, decisions need to be made carefully – and there are numerous possible decisions to make even when it may seem not to be so...

Consider this 24-segment road network, all links being of the slow 2-lane type. If the objective is to determine the plan providing the maximum net benefits and each link can be upgraded two levels (to fast 2-lane or 4-lane), how many possible plans \( P \) should be studied?
Motivation

Given the costs of road construction (motorways: 10 M€/km), as well as its social and environmental implications, decisions need to be made carefully – and there are numerous possible decisions to make even when it may seem not to be so…

Consider this 24-segment road network, all links being of the slow 2-lane type. If the objective is to determine the plan providing the maximum net benefits and each link can be upgraded two levels (to fast 2-lane or 4-lane), how many possible plans ($P$) should be studied?

Answer: $P = 3^{24} = 282,429,536,481 \Rightarrow t \geq 90$ years!!! (0.01 sec/plan)

Decisions are so numerous that they can only be handled properly through optimization techniques – specifically, road network planning/design models.
Motivation

The use of Trial-and-Error approaches can lead us to poor solutions

Analysis of the Portuguese National Road Plan (PRN2000)

Outline

1. Interurban Road Network Planning
   1.1. Road network planning/design models
       1.1.1. Main models
       1.1.2. Model developed
   1.2. Case study of Paraná, Brazil
   1.3. Final Comments

2. Multi-stakeholder Planning - High Speed Railway Line
   2.1. MATE - Multi-Attribute Trade Space
   2.2. Lisbon-Madrid HSR
   2.3. Final Comments

3. Optimal Location of Intermodal Terminals
   3.1. Methodology
   3.2. Optimization Model
   3.3. Case Study of Belgium
   3.4. Final Comments

4. Conclusion
1. Interurban Road Network Planning

Road network planning

- Making decisions on large-scale transformations of road networks
- Is no longer a major (direct) concern in developed countries
  The focus here is on maintenance & rehabilitation.
- But is a major issue in developing countries
  Brazil, China, India, and others will be unable to keep growing as they
  are doing now – and to be the engines of the world economy – if their
  road networks are not greatly improved.

… and (indirectly) in developed countries.
1.1. Road network planning/design models

In the literature, the models for planning of road networks is known as road network design (RND) problems.

- Literature review: Yang and Bell (1998)

- **Discrete Road Network Design Model** (DRND): determines which new links should be added to a road network
  - Main references: LeBlanc (1975) and Boyce and Janson (1980)

- **Continuous Road Network Design Model** (CRND): determines how much capacity should be added to each link of a road network, assuming capacity expansions to be continuous
  - Main references: Abdulaziz and LeBlanc (1979) and Friesz et al. (1992)
1.1. Road network planning/design models

Typically:

- Single efficiency objective
  - Minimization of user costs/travel time (with given budget), maximization of welfare (consumer surplus) gains
  - Some multi-objective models: equity (e.g. Feng and Wu, 2003); environmental (e.g, Cantarella and Vitetta, 2006);

- Single level or continuous capacity improvements
  - Few models multi-level, e.g. Janson (1991)
  - Possible levels are: slow two-lane highway; fast two-lane highway (grade-separated intersections, slow-vehicle lanes, no access from side construction); four-lane freeway; six-lane freeway.

- Inconsistent with Highway Capacity Manual (because not based on the concept of Level of Service)
  - Any models consistent?

This certainly explains why they are not so popular in practice (?)...
1.1. Road network planning/design models

Features of the Model Developed

- Hierarchy of roads:
  - Planning decisions involve the construction of new road links of given levels or the upgrading of existing road links to a higher level.

- Efficiency, equity, robustness, and environmental objectives are simultaneously taken into account.

- Planning decisions are consistent with the planning framework adopted in the Highway Capacity Manual.

- Consideration of the LOS concept.

- Travel demand is sensitive to road network changes.

- Environmental concerns may limit the set of road levels that can be assigned to links included (or to be built) in sensitive areas.
1.1. Road network planning/design models

(Bi-level, mixed-integer non-linear model)

Maximize normalized solution value taking into account the relative importance of efficiency ($Ef$), equity ($Eq$), and environmental ($En$) objectives.

$$\max V = w_{Ef} \times \frac{Ef - Ef_B}{Ef_B - Ef_W} + w_{Eq} \times \frac{Eq - Eq_W}{Eq_B - Eq_W} + w_{En} \times \frac{En - En_W}{En_B - En_W}$$

$Ef, Eq, En = \Phi$ (decision variables)

$$T_{jk} = \alpha \frac{P_j \times P_i}{c_{jk}}, \forall j, k \in N$$

$$V_l = \sum_{j \in N} \sum_{k \in N} T_{jk} \times x_{j,k}, \forall l \in L$$

OD traffic flows

Traffic flow on links (obtained by adding least-cost route OD traffic flows)

$$V_l \leq \sum_{m \in M_l} Z_m \times y_{lm}, \forall l \in L$$

Traffic in each link must not exceed the maximum service flow for the road type of the link

$$\sum_{m \in M_l} y_{lm} = 1, \forall l \in L$$

Only one type for each link

$$\sum_{l \in L} \sum_{m \in M_l} b_{lm} y_{lm} \leq B$$

The budget for road improvements can not be exceeded

$$y_{lm} \in \{0,1\}, \forall l \in L, m \in M_l$$

Upper level model
1.1. Road network planning/design models

Efficiency Objectives

Aggregate accessibility
(or aggregate demographic or market potential)

\[ A = \sum_{j \in N} a_j \times P_j, \text{ with } a_j = \sum_{k \in N \setminus j} \frac{P_k}{f(c^*_{jk})} \]

\(a_j\): local accessibility of center \(j\)

Average speed

Average travel cost to higher-level population centers

Welfare (consumer surplus) gains
1.1. Road network planning/design models

**Equity Objectives**

**Gini Index (of local accessibilities)**

\[
G = \frac{\sum_{j \in N} \sum_{k \in N} |a_j - a_k|}{2 \overline{n^2 \overline{a}}} \quad \overline{a}: \text{average local accessibility of centers}
\]

\( (G = 0 \text{ means complete equity}) \)

**Aggregate accessibility of low-accessibility centers**

**Theil Index**

Takes into account the dispersion of accessibility values across all centers (as the Gini Index) and across the centers of the same region.
1.1. Road network planning/design models

Robustness Objectives

**Network Spare Capacity**

\[
R = \sum_{l \in L} [F_l(y) - T_l(y)]^\alpha \times T_l(y) \times L_l
\]

- \( F_l \): Maximum capacity for the LOS for link \( l \)
- \( T_l \): Flow in link \( l \)
- \( L_l \): length of link \( l \)

**City Evacuation Capacity**

**Network Vulnerability**

Assess the susceptibility of a network to a significant reduction in accessibility in case of loss (or degradation) of a small number of links.
1.1. Road network planning/design models

Environmental Objectives

Average fuel consumption

\[ F = \frac{\sum_{l \in L} F_l \times L_l \times V_l}{\sum_{l \in L} L_l \times V_l} \]

- \( F_l \): average fuel consumption on link \( l \)
- \( L_l \): length of link \( l \)

Average fuel consumption on each link was calculated running the COPERT program for various speeds considering the composition of the Paraná vehicle fleet, and then calibrating a quadratic function to describe the relationship between fuel consumption and speed. The results was:

\[ F_l = 97.056 - 1.274 \times S_l + 0.008 \times S_l^2 \quad \left( R^2 = 0.938 \right) \]

- \( S_l \): speed on link \( l \) (function of \( V_l \)) in km/h
- \( F_l \) in g/km (petrol-equivalent)

Alternatives being considered …
1.1. Road network planning/design models

- Solution Generation
- O/D Forecasted
- Trip Assignment
- Solutions Fitness Calculation
- LOS Calculation

- LOS verified?
  - Yes
  - NO
    - Compare with incumbent solution
    - Save best solution
    - Penalize Solutions

- STOP?
  - Yes
  - STOP

- Não

Bruno Filipe Santos - Universidade de Coimbra
EPFL - École Polytechnique Fédérale de Lausanne, December 2012
1.1. Road network planning/design models

Road network planning models are generally considered to be among the optimization models most difficult to solve.

Only small instances (say, 25 links) can be solved to exact optimality. Hence, most (all) real-world cases need to be handled through heuristics.

Three types of heuristics have been tested

- **Classic Local Search** (LSA)
- **Variable Neighborhood Search** (VNS)
- **Enhanced Genetic Algorithm** (EGA)

with the best results being obtained with EGA.
1.1. Road network planning/design models

<table>
<thead>
<tr>
<th>Network size (links)</th>
<th>Number of networks</th>
<th>Number of best solutions</th>
<th>Average difference to best solution</th>
<th>Average computing time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LSA</td>
<td>VNSA</td>
<td>EGA</td>
</tr>
<tr>
<td>10 - 24</td>
<td>20</td>
<td>4</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>25 - 39</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>40 - 54</td>
<td>10</td>
<td>0</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>55 - 69</td>
<td>8</td>
<td>0</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>70 - 84</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>85 - 100</td>
<td>6</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Number of best solutions

Computing time (minutes)
1.2. Case study of Paraná, Brazil

Focus of this case study

- How does the consideration of social (equity) and environmental objectives in addition to economic (efficiency) objectives affect optimization-based road network planning solutions?

- What methodology can be used to assess this?

- What results can be obtained in practice?

  ○ Exemplification: State of Paraná, Brazil
    - Area ≈ 200,000 km²
    - Population ≈ 10.5 mil. inhabitants
1.2. Case study of Paraná, Brazil

Analysis of the implications of 4 possible road network plans for the state of Paraná (differing on the weight assigned to the objectives)

Plan 1 - $w_{Ef} = 1 \ w_{Eq} = 0 \ w_{En} = 0$

Plan 2 - $w_{Ef} = 2/3 \ w_{Eq} = 1/3 \ w_{En} = 0$

Plan 3 - $w_{Ef} = 2/3 \ w_{Eq} = 0 \ w_{En} = 1/3$

Plan 4 - $w_{Ef} = 1/3 \ w_{Eq} = 1/3 \ w_{En} = 1/3$

with respect to

Aggregate accessibility - $A$ (and average speed - $S$)
Gini index (of local accessibility) - $G$
Fuel consumption - $F$
1.2. Case study of Paraná, Brazil

Characteristics of road network

- 76 nodes
- 39 pop. centers inside Paraná
- 11 pop. centers outside Paraná
- 26 intersections
- 133 links
- 100 inside Paraná
- 33 outside Paraná

Costs of road network improvements (MU)

<table>
<thead>
<tr>
<th>From/TO</th>
<th>Planned</th>
<th>Unpaved</th>
<th>Slow 2x1</th>
<th>Fast 2x1</th>
<th>Freeway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>Unpaved</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>Slow 2-lane</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Fast 2-lane</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Freeway</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Budget = 40,000 MU
(1000 km of new 4-lane roads)
1.2. Case study of Paraná, Brazil

Plan 1 - $w_{Ef} = 1$ $w_{Eq} = 0$ $w_{En} = 0$

<table>
<thead>
<tr>
<th>Road type</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inicial</td>
</tr>
<tr>
<td>Planned</td>
<td>817</td>
</tr>
<tr>
<td>Unpaved</td>
<td>441</td>
</tr>
<tr>
<td>Slow 2-lane</td>
<td>3183</td>
</tr>
<tr>
<td>Fast 2-lane</td>
<td>1971</td>
</tr>
<tr>
<td>4-lane</td>
<td>370</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Initial</th>
<th>Plan 1</th>
<th>Δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.406</td>
<td>2.505</td>
<td>4.1</td>
</tr>
<tr>
<td>S (km/h)</td>
<td>90.7</td>
<td>106.7</td>
<td>17.6</td>
</tr>
<tr>
<td>G</td>
<td>0.139</td>
<td>0.147</td>
<td>6.0</td>
</tr>
<tr>
<td>F (g/km)</td>
<td>54.19</td>
<td>58.08</td>
<td>7.2</td>
</tr>
</tbody>
</table>
### 1.2. Case study of Paraná, Brazil

Plan 2 - $w_{Ef} = 2/3$ $w_{Eq} = 1/3$ $w_{En} = 0$

<table>
<thead>
<tr>
<th>Road type</th>
<th>Length (km)</th>
<th>Length (km)</th>
<th>Δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned</td>
<td>561</td>
<td>727</td>
<td>30</td>
</tr>
<tr>
<td>Unpaved</td>
<td>583</td>
<td>417</td>
<td>-28</td>
</tr>
<tr>
<td>Slow 2-lane</td>
<td>2442</td>
<td>2134</td>
<td>-13</td>
</tr>
<tr>
<td>Fast 2-lane</td>
<td>1304</td>
<td>1651</td>
<td>27</td>
</tr>
<tr>
<td>4-lane</td>
<td>1892</td>
<td>1853</td>
<td>-2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Plan 1</th>
<th>Plan 2</th>
<th>Δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.505</td>
<td>2.493</td>
<td>-0.5</td>
</tr>
<tr>
<td>S (km/h)</td>
<td>106.7</td>
<td>105.3</td>
<td>-1.3</td>
</tr>
<tr>
<td>G</td>
<td>0.147</td>
<td>0.139</td>
<td>-5.4</td>
</tr>
<tr>
<td>F (g/km)</td>
<td>58.08</td>
<td>55.53</td>
<td>-4.4</td>
</tr>
</tbody>
</table>

Decrease

Increase

Difference to Plan 1
1.2. Case study of Paraná, Brazil

Plan 3 - $w_{Ef} = \frac{2}{3}$ $w_{Eq} = 0$ $w_{En} = \frac{1}{3}$

<table>
<thead>
<tr>
<th>Road type</th>
<th>Length (km)</th>
<th>Plan 1</th>
<th>Plan 3</th>
<th>$\Delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned</td>
<td>561</td>
<td>471</td>
<td>-16</td>
<td></td>
</tr>
<tr>
<td>Unpaved</td>
<td>583</td>
<td>342</td>
<td>-41</td>
<td></td>
</tr>
<tr>
<td>Slow 2-lane</td>
<td>2442</td>
<td>2107</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>Fast 2-lane</td>
<td>1304</td>
<td>2800</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>4-lane</td>
<td>1892</td>
<td>1061</td>
<td>-44</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Plan 1</th>
<th>Plan 3</th>
<th>$\Delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.505</td>
<td>2.495</td>
<td>-0.4</td>
</tr>
<tr>
<td>S (km/h)</td>
<td>106.7</td>
<td>103.7</td>
<td>-2.8</td>
</tr>
<tr>
<td>G</td>
<td>0.147</td>
<td>0.145</td>
<td>-1.4</td>
</tr>
<tr>
<td>F (g/km)</td>
<td>58.08</td>
<td>52.58</td>
<td>-9.5</td>
</tr>
</tbody>
</table>
1.2. Case study of Paraná, Brazil

Plan 4 - $w_{Ef} = 1/3$ $w_{Eq} = 1/3$ $w_{En} = 1/3$

<table>
<thead>
<tr>
<th>Road type</th>
<th>Length (km)</th>
<th></th>
<th>Δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned</td>
<td>561</td>
<td>727</td>
<td>30</td>
</tr>
<tr>
<td>Unpaved</td>
<td>583</td>
<td>417</td>
<td>-28</td>
</tr>
<tr>
<td>Slow 2-lane</td>
<td>2442</td>
<td>1986</td>
<td>-19</td>
</tr>
<tr>
<td>Fast 2-lane</td>
<td>1304</td>
<td>2080</td>
<td>59</td>
</tr>
<tr>
<td>4-lane</td>
<td>1892</td>
<td>1573</td>
<td>-17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Plan 1</th>
<th>Plan 5</th>
<th>Δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.505</td>
<td>2.476</td>
<td>-1.2</td>
</tr>
<tr>
<td>S (km/h)</td>
<td>106.7</td>
<td>102.6</td>
<td>-3.8</td>
</tr>
<tr>
<td>G</td>
<td>0.147</td>
<td>0.139</td>
<td>-5.6</td>
</tr>
<tr>
<td>F (g/km)</td>
<td>58.08</td>
<td>54.07</td>
<td>-6.9</td>
</tr>
</tbody>
</table>

Decrease | Increase

Difference to Plan 1
1.3. Final Comments

Application of the model provided us with good insights into how sustainable development decisions are affected with road network planning solutions.

Small accessibility gains can be quite costly from social (equity) and environmental (fuel consumption ⇒ pollutant emissions) standpoints.

The case study shows that the approach is already useful in practical applications:

- It can give meaningful results to long-term interurban road network planning problems, and provide a good starting point for the study of detailed solutions.
1.3. Final Comments

Future work - PhD

- Investment schemes - PPP and tolls
- Flexibility - uncertainty and investment scheduling
- Improve demand and assignment models
1.3. Final Comments

Papers Published:


2. Multi-stakeholder Planning

Transportation planning problems are complex problems that usually involve many stakeholders in the decision process.

The perspectives and goals of these stakeholders upon the infrastructure investment project is usually divergent.

The optimal solution is a trade-off solution between stakeholders:

- Simple CBA analysis are not comprehensive enough;
- The model of stakeholders goals is usually complex to handle with.
2.1. MATE - Multi-Attribute Trade Space

**MATE** - Multi-Attribute TradeSpace tool
2.2. Lisbon-Madrid HSR

The HSR line

- 645km ⇒ 200km in Portugal & 445km in Spain
- To be built in 2014 (?)
- Mixed Traffic;
- Passengers demand is not enough to support all the investment cost - according to some studies,
- Take advantage of the additional investment planned to provide a mixed traffic line.
2.2. Lisbon-Madrid HSR

The example from Central Europe

EUROCAREX - The European High-speed Rail Freight Network

20 & 21 March - Lyon-Saint Exupéry, Paris-CDG & London-St Pancras
2.2. Lisbon-Madrid HSR

Main Assumptions

- Line design and demands are the same as predicted by RAVE;

- Two different passenger services were assumed:
  - International Service >> High Speed (250 km/h);
  - National Service      >> Medium Speed (200 km/h);

- The rolling stock required for cargo delivery will have similar characteristics to the chosen passengers rolling stock:
  - Load per axel;
  - Compatible with Medium Speed;

- Cargo is shipped using the free slots of the line;

- The products to be delivered are high value product:
  - Post, pharmaceutical items, fresh products, electronic components;
2.2. Lisbon-Madrid HSR

Two “new” rail-road terminals to be built:

- Poceirão
- Toledo >> PK 50
2.1. MATE - Multi-Attribute Trade Space
2.2. Lisbon-Madrid HSR

Database construction;
Debate with stakeholders;
Scenarios construction and evaluation
2.2. Lisbon-Madrid HSR

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>Definition</th>
<th>High Speed Service (HS)</th>
<th>Medium Speed Service (MS)</th>
<th>Cargo Service</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>Trains per day</td>
<td>[11 12 13 14 15 16]</td>
<td>[1 2 3 4 5 6]</td>
<td>[5 7 9 10 12 14]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Portugal</td>
<td>*Spain</td>
<td>[3 5 6 7 8 9]</td>
</tr>
<tr>
<td><strong>Fares</strong></td>
<td>Price to pay for one trip per km</td>
<td>[0.0695 0.1112 0.1251 0.1390 0.1529 0.1668 0.2085]</td>
<td>[0.0415 0.0664 0.0747 0.083 0.0913 0.0996 0.1245]</td>
<td>[0.0554 0.0583 0.0612]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*€/pass.km</td>
<td>*€/pass.km</td>
<td>*€/ton.km</td>
</tr>
<tr>
<td><strong>Rent</strong></td>
<td>Return value to pay regarding the use of the track, rolling stock and terminals</td>
<td>[2 2.5 3 3.5 4 4.5 5]%</td>
<td>[2 2.5 3 3.5 4 4.5 5]%</td>
<td>[2 2.5 3 3.5 4 4.5 5]%</td>
</tr>
</tbody>
</table>

**Decision Variables**

- Δ Fare
- Δ Demand
- Elasticity

<table>
<thead>
<tr>
<th></th>
<th>Δ Fare</th>
<th>Δ Demand</th>
<th>Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50%</td>
<td>-0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20%</td>
<td>-0.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-10%</td>
<td>-0.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>-0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>-0.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>-0.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Δ Fare</th>
<th>Δ Cost</th>
<th>Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5%</td>
<td>1.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5%</td>
<td>1.54</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** the costs are assessed according to the NPV of a life-cycle cost aggregation of the 40 year of analyses;
### 2.2. Lisbon-Madrid HSR

#### Model

<table>
<thead>
<tr>
<th>Design Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fares Frequency</td>
</tr>
</tbody>
</table>

#### Attributes

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Applied to</th>
<th>Users</th>
<th>Transport Service Operations</th>
<th>Infrastructure Manager</th>
<th>Government</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistency</td>
<td>HS MS Cargo</td>
<td>0.117</td>
<td>0.113</td>
<td>0.092</td>
<td>0.102</td>
</tr>
<tr>
<td>Service Value</td>
<td>HS MS Cargo</td>
<td>0.3</td>
<td>0.43</td>
<td>0.082</td>
<td>0.046</td>
</tr>
<tr>
<td>Travel Time Work/Leisure Cargo</td>
<td>0.3</td>
<td>0.31</td>
<td>0.4</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Safety/Accidents</td>
<td>HS MS Cargo</td>
<td>0.120</td>
<td>0.14</td>
<td>0.007</td>
<td>0.029</td>
</tr>
<tr>
<td>Fares</td>
<td>HS MS Cargo</td>
<td>0.25</td>
<td>0.23</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Vehicle Operation Costs</td>
<td>HS MS Cargo</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Track Operation</td>
<td>HS MS Cargo</td>
<td>0.004</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation Personnel</td>
<td>HS MS Cargo</td>
<td>0.15</td>
<td>0.15</td>
<td>0.089</td>
<td>0.089</td>
</tr>
<tr>
<td>Facilities Operation Rail-Road Facilities</td>
<td>HS MS Cargo</td>
<td>0.0072</td>
<td>0.045</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overhead Management Subsidies</td>
<td>HS MS Cargo</td>
<td>0.0024</td>
<td>0.0024</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subsidies</td>
<td>HS MS Cargo</td>
<td>0.0</td>
<td>0.015</td>
<td>0.388</td>
<td>0.388</td>
</tr>
<tr>
<td>Investment Rolling Stock</td>
<td>HS MS Cargo</td>
<td>0.013</td>
<td>0.1</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Rail-Road Facilities</td>
<td>HS MS Cargo</td>
<td>0.009</td>
<td>0.009</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>Infrastructure &amp; Superstructure</td>
<td>HS MS Cargo</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Network</td>
<td>HS MS Cargo</td>
<td>0.015</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>HS MS Cargo</td>
<td>0.015</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Utility

<table>
<thead>
<tr>
<th>Utility</th>
</tr>
</thead>
</table>

#### Costs

<table>
<thead>
<tr>
<th>Costs</th>
</tr>
</thead>
</table>
2.2. Lisbon-Madrid HSR

Utility

Costs

Tradespace
2.2. Lisbon-Madrid HSR

- No solutions common to all stakeholders were found;
- It would be assumed that stakeholders will have to be “loss-acceptance” (negotiation)
- That is, we “relaxed” the Pareto front and considered solutions that were not included in the Pareto front but are close to for all stakeholders
2.2. Lisbon-Madrid HSR

### Decision Variables

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>Definition</th>
<th>High Speed Service (HS)</th>
<th>Medium Speed Service (MS)</th>
<th>Cargo Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Trains per day</td>
<td>[11 13 16]</td>
<td>[13 6]</td>
<td>[3 6 9]</td>
</tr>
<tr>
<td>Fares</td>
<td>Price to pay for one trip per km</td>
<td>[0.0695 0.1390 0.2085]</td>
<td>[0.0415 0.083 0.1245]</td>
<td>[0.0554 0.0583 0.0612]</td>
</tr>
<tr>
<td>Rent</td>
<td>Return value to pay regarding the use of the track, rolling stock and terminals</td>
<td>[2 3.5 5]%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Stakeholders

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Cost (10^8 €)</th>
<th>Utility</th>
<th>k</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rail Line</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passengers</td>
<td>7.860</td>
<td>0.638</td>
<td>1%</td>
<td>0.023</td>
</tr>
<tr>
<td>Cargo</td>
<td>-0.695</td>
<td>0.618</td>
<td>17%</td>
<td>0.120</td>
</tr>
<tr>
<td><strong>Alternative Modes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passengers</td>
<td>-12219.951</td>
<td>0.616</td>
<td>15%</td>
<td>0.160</td>
</tr>
<tr>
<td>Cargo</td>
<td>-0.747</td>
<td>0.811</td>
<td>1%</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Transport Service Operators</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rail Operator</td>
<td>25.166</td>
<td>0.476</td>
<td>10%</td>
<td>0.055</td>
</tr>
<tr>
<td>Other Modes</td>
<td>14.776</td>
<td>0.335</td>
<td>1%</td>
<td>0.156</td>
</tr>
<tr>
<td><strong>Infrastructure Manager</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rail Manager</td>
<td>106.829</td>
<td>0.498</td>
<td>1%</td>
<td>-1.999</td>
</tr>
<tr>
<td>Government</td>
<td>-14.647</td>
<td>0.163</td>
<td>1%</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### Design Solution

- Frequency (º)
  - HS: 16 (↑)
  - MS Pt: 6 (↑)
  - MS Pt: 5 (↓)
  - Cargo: 3 (↓)

- Fares (€/X.km)
  - HS: 0.1390
  - MS: 0.0415
  - Cargo: 0.0554

- Design Solution: 4464
2.3. Final Comments

- The approach allows a multi-stakeholder analysis of this complex transport planning problem;

- Stakeholders have different interests and influence upon design variables:

- But, do all stakeholders have the same influence on the decision discussion?

- Preliminary results, shown that:

  ◦ Results diverge with demand elasticity;

  ◦ There is room for light cargo - at least 3 services per day (both directions).
3. Optimal Location of Intermodal Terminals

European Conference of Ministers of Transport, 1997

- The movement of goods (in one and the same loading unit or vehicle) by successive modes of transport without handling of the goods themselves when changing modes.

Road Transport

- Responsible for 44% of goods’ transport in Europe.

Potentially strong competitor to road transport (long distances)

- Guarantees the transport of large amounts of goods in each transport unit
- Lower costs, as the transport distance increases
- Mode of transport environmentally-friendly
3. Optimal Location of Intermodal Terminals

**Aim of the work**

- Develop an optimization model capable to define the optimal location of transshipment terminals (road-rail-road), so that the total transport costs can be minimized.

**General research questions**

- How the location of intermodal terminals (road-rail) influence the competitiveness of intermodal freight transport?

- How different transportation cost policies can influence intermodal transport competitiveness?

**The case study of Belgium**

- Is intermodal freight transport (road-rail) competitive even for a small country like Belgium?

- How the Belgian government subsidies can influence the location of freight terminals and the modal split for freight in Belgium?
3.1. Methodology

Optimal terminals location problem – road-rail terminals

• Flows Between:
  - Belgian NUTS 3
  - Belgian Ports (Antwerp, Ghent, Zeebrugge)
  - Neighboring NUT3 regions (France, Germany, Luxembourg, The Netherlands)
  - Amsterdam, Berlin, Vienna, Paris, Lyon, Bern

• Potential locations for terminals - Belgian NUT3
• Belgium road and rail networks
• Road, rail and transshipment costs
• Intermodal terminals in the border France, Luxembourg, Germany
3.1. Methodology
3.2. Model

Hub-based Network Design

Traditional
- In hub-and-spoke networks, the goods are transported from their origin to a hub, from this hub to a second one, and finally to their destination.
- The inter-hub links consolidate the total flow coming from the origin hub to a destination hub.
- Constraints:
  (i) all the hubs are connected directly to each other;
  (ii) there is no direct connection between non-hub nodes; and
  (iii) the non-hub nodes are connected to a single hub.
3.2. Model

Hub-based Network Design

**Ours**

- Generation nodes can be connected with using terminals (hubs);
- A generation node can be assigned to more than one terminal; and
- Not all terminals have a direct freight service.

- As a result, our model adjusts to the multiple assignment network, with node connections and not having complete inter-hub connections.
3.2. Model

Objective Function

\[
\min \sum_{i \in N} \sum_{m \in N} d_{im} (C_{im}^o + C_{im}^e e) W_{im}
\]

\[+ \sum_{i \in N_0} (T_i^o + T_i^e e) W_{im} + \sum_{m \in N_0} (T_m^o + T_m^e e) W_{im}\]

\[+ \sum_{i \in N} \sum_{j \in N'} \sum_{k \neq j \in N'} [d_{ij} (C_{ij}^o + C_{ij}^e e) + T_j^o + T_j^e e] X_{jk}^i\]

\[+ \sum_{i \in N} \sum_{j \in N'} \sum_{k \neq j \in N'} (R_{jk}^o + R_{jk}^e e - s (\alpha_{jk} \tilde{R} + \tilde{T}_{jk})) X_{jk}^i\]

\[+ \sum_{i \in N} \sum_{k \in N'} \sum_{m \in N} [d_{km} (C_{km}^o + C_{km}^e e) + T_k^o + T_k^e e] Q_{km}^i\]

- Transportation cost of road flows
- Transshipment costs at the ports between sea and road
- Pre-haulage costs between origin and a rail-road terminal
- Long-haul transportation cost by rail
- Post-haulage costs between a rail-road terminal and the destination
3.2. Model

Subject to,

\[ \sum_{k \in N_1} y_k = p \]

\[ y_k = 1 \]

\[ D_{im} = W_{im} + \sum_{k \in N'} Q_{km}^i \]

\[ \sum_{m \in N} D_{im} = \sum_{j \in N'} \sum_{k \in N'} X_{jk}^i + \sum_{m \in N} W_{im} \]

\[ \sum_{i \in N} D_{im} = \sum_{i \in N'} \sum_{k \in N'} Q_{km}^i + \sum_{i \in N} W_{im} \]

\[ \sum_{i \in N_4} (W_{ij} + W_{ji}) = 0 \]

\[ \sum_{k \in N'} X_{jk}^i \leq y_j \sum_{m \in N} D_{im} \quad \forall i \in N, \forall j \in N' \]

\[ \sum_{j \in N'} X_{jk}^i \leq y_k \sum_{m \in N} D_{im} \quad \forall i \in N, \forall k \in N' \]

\[ \sum_{j \in N'} X_{jk}^i = \sum_{m \in N} Q_{km}^i \quad \forall i \in N, \forall k \in N' \]

Number of terminals to locate

Existing terminals remain open

Demand = road + intermodal

Exiting flow at node \( i \)

Entering flow at node \( m \)

Rail flows from outside network arrive on train

Attribution possibility

Flow continuation
3.2. Model

Transport costs (based on Janic, 2008):

Road (line-hauling; collection and distribution)

Operational
\[ c_{kJ}^{op} = \left( \frac{Q_{kj}}{\lambda_j M_j} \right) \cdot c_{op} (d_{kj}) \]

External
\[ c_{kJ}^{ext} = \left( \frac{Q_{kj}}{\lambda_j M_j} \right) \cdot c_{ext} (d_{kj}) \]

Terminals

Operational
\[ T_k^{op} = Q_k \cdot (2 \times c_t^{op}) \]

External
\[ T_k^{ext} = Q_k \cdot (2 \times c_t^{ext}) \]

collection and distribution for a terminal in the NUTS 3 (distance = 12 km)

\[ \lambda_j = 0.85 \text{ or } 0.60 \]

\[ M_j = 2 \times 14.3 \text{ ton} \]

3.2. Model

Transport costs (based on Janic, 2008):

Rail (line-hauling)

Operational

\[ R_{k}^{op} = \left( \frac{Q_k}{q_t} \right) r_{op} (W, q_t, l_{km}) \]

Includes costs of: depreciation and maintenance of rolling stock, assembling/decomposing train cars, usage of train infrastructure, energy, and staff wages;

External

\[ R_{k}^{ext} = \left( \frac{Q_k}{q_t} \right) r_{ext} (W, q_t, l_{km}) \]

Includes costs of: noise, local and global air pollution from energy consumption, accidents, congestion;

\[ W = 1550 \text{ ton} \]

(locomotive + 26 wagons)

\[ q_t = 0.75 \times 26 \times 3 \times 14.3 \text{ ton} \]
3.2. Model

Transportation Costs Policies

- Policy I: Only operational costs
  - a situation of free market, with no intervention from the government, where transportation and intermodal terminal operators will minimize their direct costs of operation.

- Policy II: Operational costs and subsidies
  - this is the current situation in Belgium. Handling subsidies are granted to flows shipped between terminals (or ports) located in Belgium, while the rail transportation subsidy is given according to the distance travelled inside Belgium, independently of the origin and destination of the goods.

- Policy III: Operational and external costs
  - this policy is inline with EU policies that aim at internalizing externalities of freight transportation to strengthen the competitiveness of intermodal transportation.

- Policy IV: Operational and external costs and subsidies
  - a combination of the two previous policies, in which the additional cost of internalizing the externalities is balanced with the subsidies from the Belgian Government.
3.3. Case Study of Belgium

**Policy I**

Operational Costs
(but only considering flows to/from the Port of Antwerp and not terminals in the other side of the border)

**Terminals:**
- Arlon
- Virton
3.3. Case Study of Belgium

Analysis with operational costs:

- **Meuse?**
  - Antwerp to Virton: 258 km
  - 2.80 € + 4.66 € + 2.80 € + 5.21 € = 15.50 € / ton

- **Meuse?**
  - Antwerp to Virton: 350.6 km
  - 2.80 € + 4.66 € = 7.46 € (15.50 € / ton)

- **Metz?**
  - Antwerp to Virton: 258 km
  - 2.80 € + 4.66 € + 2.80 € + 5.28 € = 15.54 € / ton

- **Metz?**
  - Antwerp to Virton: 323.4 km
  - 2.80 € + 4.66 € = 7.46 € (14.62 € / ton)
3.3. Case Study of Belgium

There is a market area around the terminals!

Let's check the case in which
- the distance between the terminal and Antwerp = 260 km
- the distance between the nodes and Antwerp by road is equal to the total distance by intermodal transportation

Operational costs per tone by distance between terminal and node
3.3. Case Study of Belgium

There is a market area around the terminals!

By considering the external costs, this catchment area extends:

Operational and external costs per tone by distance between terminal and node

- Intermodal - Total
- Road - Total
- Intermodal - Operational
- Road - Operational

New boundary: ≈ 50 km
3.3. Case Study of Belgium

What is the influence of long-haul distance in the market area?

By considering operational costs only, it seems there is a maximum distance ($r_1 = 285$ km; $r_2 = 630$ km)
### 3.3. Case Study of Belgium

#### Summary of the results - terminals

<table>
<thead>
<tr>
<th>p</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>10,13</td>
<td>5,13</td>
<td>10,13</td>
<td>5,13</td>
</tr>
<tr>
<td>3</td>
<td>4,10,13</td>
<td>4,5,13</td>
<td>4,10,13</td>
<td>4,5,13</td>
</tr>
<tr>
<td>4</td>
<td>4,8,10,13</td>
<td>3,4,10,13</td>
<td>4,5,10,13</td>
<td>3,4,10,13</td>
</tr>
<tr>
<td>5</td>
<td>4,8,10,11,13</td>
<td>3,4,7,10,13</td>
<td>4,5,8,10,13</td>
<td>3,4,8,10,13</td>
</tr>
<tr>
<td>6</td>
<td>1,4,8,10,11,13</td>
<td>1,3,4,8,10,13</td>
<td>1,4,5,8,10,13</td>
<td>1,3,4,8,10,13</td>
</tr>
<tr>
<td>7</td>
<td>1,4,5,8,10,11,13</td>
<td>1,3,4,8,10,12,13</td>
<td>1,4,5,8,10,11,13</td>
<td>1,3,4,8,10,12,13</td>
</tr>
<tr>
<td>8</td>
<td>1,4,5,8,9,10,11,13</td>
<td>1,3,4,8,9,10,12,13</td>
<td>1,4,5,8,9,10,11,13</td>
<td>1,3,4,8,10,12,13,14</td>
</tr>
<tr>
<td>9</td>
<td>1,2,4,5,8,9,10,11,13</td>
<td>1,3,4,8,9,10,12,13,14</td>
<td>1,4,5,8,9,10,11,13,14</td>
<td>1,3,4,8,9,10,12,13,14</td>
</tr>
<tr>
<td>10</td>
<td>1,2,4,5,8,9,10,11,12,13</td>
<td>1,3,4,8,6,9,10,12,13,14</td>
<td>1,2,4,5,8,9,10,11,13,14</td>
<td>1,3,4,6,8,9,10,12,13,14</td>
</tr>
</tbody>
</table>

1 Brussels; 2 Turnhout; 3 Hasselt; 4 Maaseik; 5 Bilzen; 6 Leuven; 7 Nivelles; 8 Charleroi; 9 Soignies; 10 Liège; 11 Verviers; 12 Bütgenbach; 13 Arlon; 14 Namur
3.3. Case Study of Belgium

Policy I  Operational Costs \( (p = 5) \)
3.3. Case Study of Belgium

Policy I

Operational Costs ($p = 7$)
3.3. Case Study of Belgium

Policy II

Operational Costs and Subsidies ($p = 7$)
3.3. Case Study of Belgium

Policy IV Operational Costs, External Costs and Subsidies ($p = 7$)
3.3. Case Study of Belgium

Evolution of rail freight in Belgium for the different policies ($10^6$ ton-km/yr)

![Graph showing the evolution of rail freight in Belgium for different policies.](image-url)
3.3. Case Study of Belgium

Operational costs evolution by policy (10^6 Euros)
3.3. Case Study of Belgium

Comparison of operational costs evolution by policy with the current situation in Belgium (terminals at Liège, Muizin, Charleroi, Athus, Genk)
3.4. Final Comments

- The location of terminals is important for intermodal freight transport
  - There is a market area around the transshipment terminals

- Optimal location of terminals is not very sensitive to cost policies
  - 14 out of 44 locations were selected (in 40 solutions)
  - The first 5 to 7 locations chosen are usually similar

- However, cost policies can have a significant impact on model split
  - Subsidies increase the market area
    - increasing the freight on rail
    - decreasing external costs
    - but, increasing operational costs
  - Internalization of external costs has a minimum impact on the results
3.4. Final Comments

Future work...

- Consider inland waterways;

- Consider international cargo arriving by train or being diverted to rail transportation;

- Take into account the costs associated with the construction of transshipment terminals;

- Consider railway lines capacity given the current reduced available capacity in Central Europe railway lines.
4. Conclusion

Optimization approaches are suitable to tackle complex strategic problems;

They can provide solutions that can be a good starting point for the study of detailed solutions;

They can provide more comprehensive analysis than trial-and-error approaches based on CBA or on MCA;

Complemented with simulation tools and within (simple) CBA, they can be very powerful tools.
Optimization Approaches Applied to the Strategic Planning of Transportation Infrastructures

Bruno Filipe Santos
University of Coimbra
bsantos@dec.uc.pt