Optimization Approaches Applied to the Strategic Planning of Transportation Infrastructures

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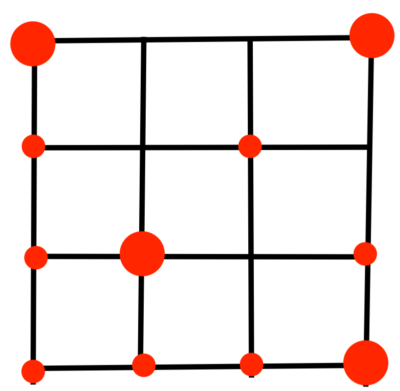
Motivation

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?

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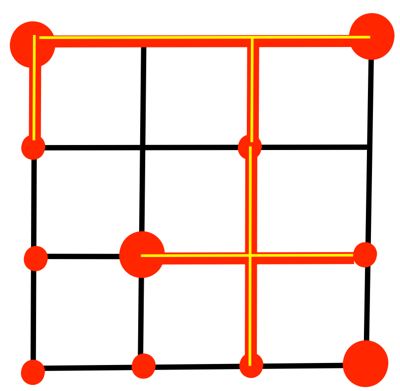

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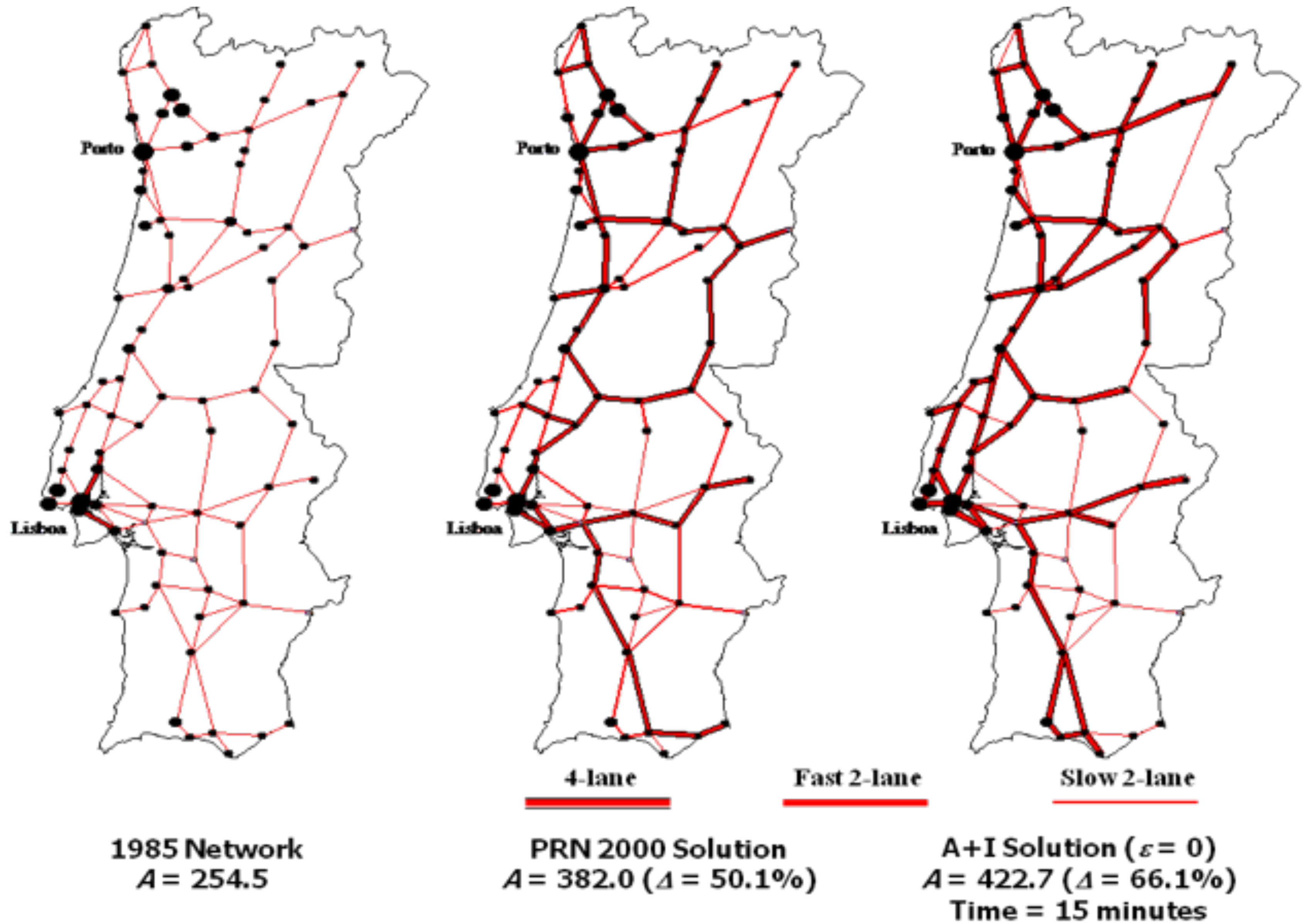
Answer: $P = 3^{24}$ = 282,429,536,481 ➔ $t \geq$ 90 years!!! (0.01 sec/plan)

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)

Antunes et al (2003) "Accessibility-maximization Approach to Road Network Planning, Computer-Aided Civil and Infrastructure Engineering, Vol.18, 224-240

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: Abdulaal 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)

Upper level model

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

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

$$Ef, Eq, En = \Phi\left(\text{decision variables}\right)$$

$$T_{jk} = \alpha \frac{P_i \times P_j}{c{*}_{jk}^{\beta}}, \forall j,k \in \boldsymbol{N}$$

OD traffic flows

$$V_l = \sum_{j \in N} \sum_{k \in N} T_{jk} \times x{*}_{ljk}, \forall l \in \boldsymbol{L}$$

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

$$V_l \leq \sum_{m \in \boldsymbol{M}_l} Z_m \times y_{lm}, \quad \forall l \in \boldsymbol{L}$$

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

$$\sum_{m \in \boldsymbol{M}_l} y_{lm} = 1, \ \forall l \in \boldsymbol{L}$$

Only one type for each link

$$\sum_{l \in \boldsymbol{L}} \sum_{m \in \boldsymbol{M}_l} b_{lm} \, y_{lm} \leq B$$

The budget for road improvements can not be exceeded

$$y_{lm} \in \{0,1\}, \ \forall l \in \boldsymbol{L}, m \in \boldsymbol{M}_l$$

1.1. Road network planning/design models

Efficiency Objectives

Aggregate accessibility
(or aggregate demographic or market potential)

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

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)

$$G = \frac{\sum_{j \in \boldsymbol{N}} \sum_{k \in \boldsymbol{N}} \left| a_j - a_k \right|}{2\, n^2\, \bar{a}}$$

(G = 0 means complete equity)

$\bar{a}$: average local accessibility of centers

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

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

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*

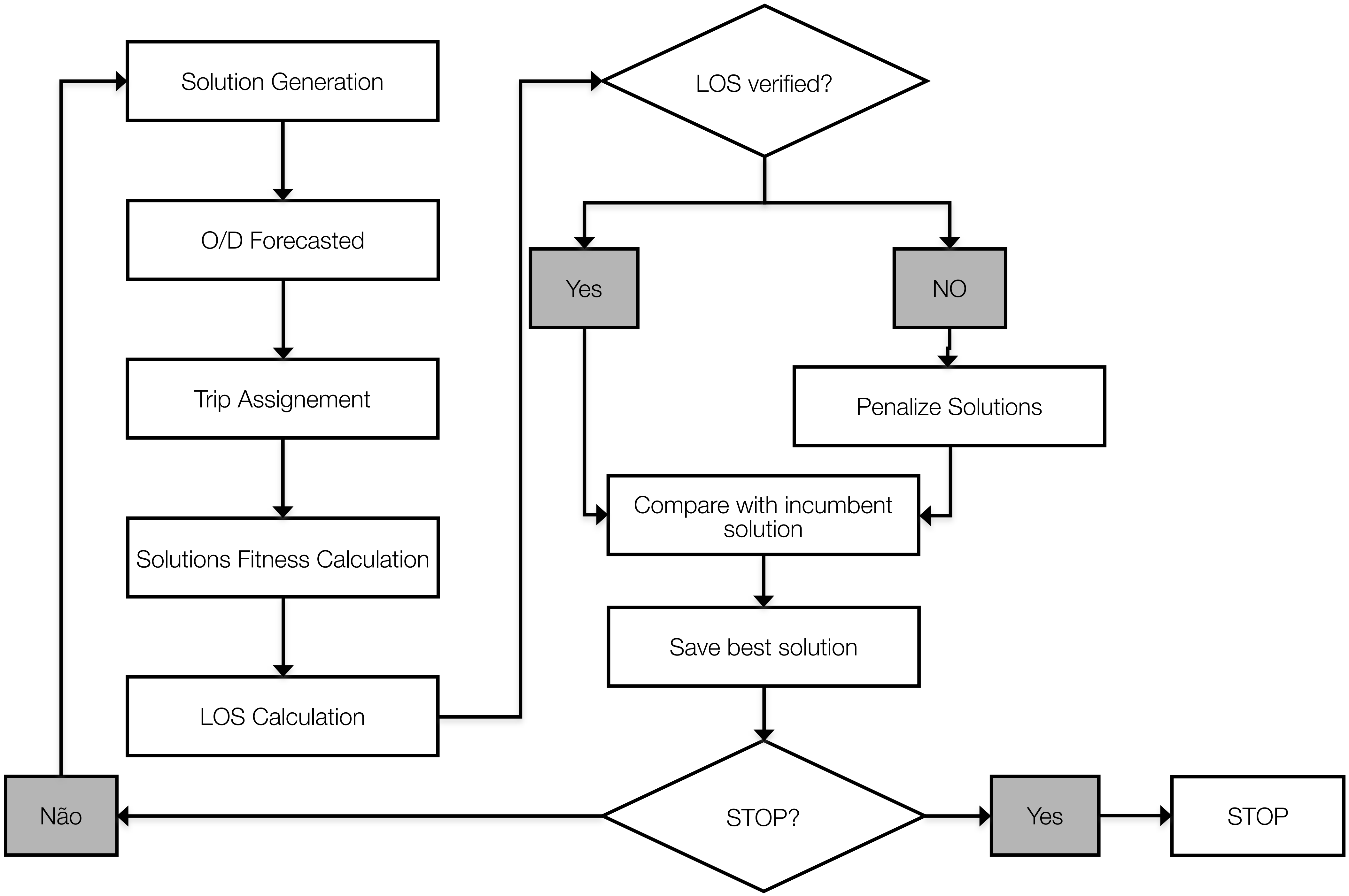
Average fuel consumption on each link was calculated running the COPERT program for various speeds considering the composition of the Paraná vehicle fleet, and then calibrating a quadratic function to describe the relationship between fuel consumption and speed. The results was:

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

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



1.1. Road network planning/design models

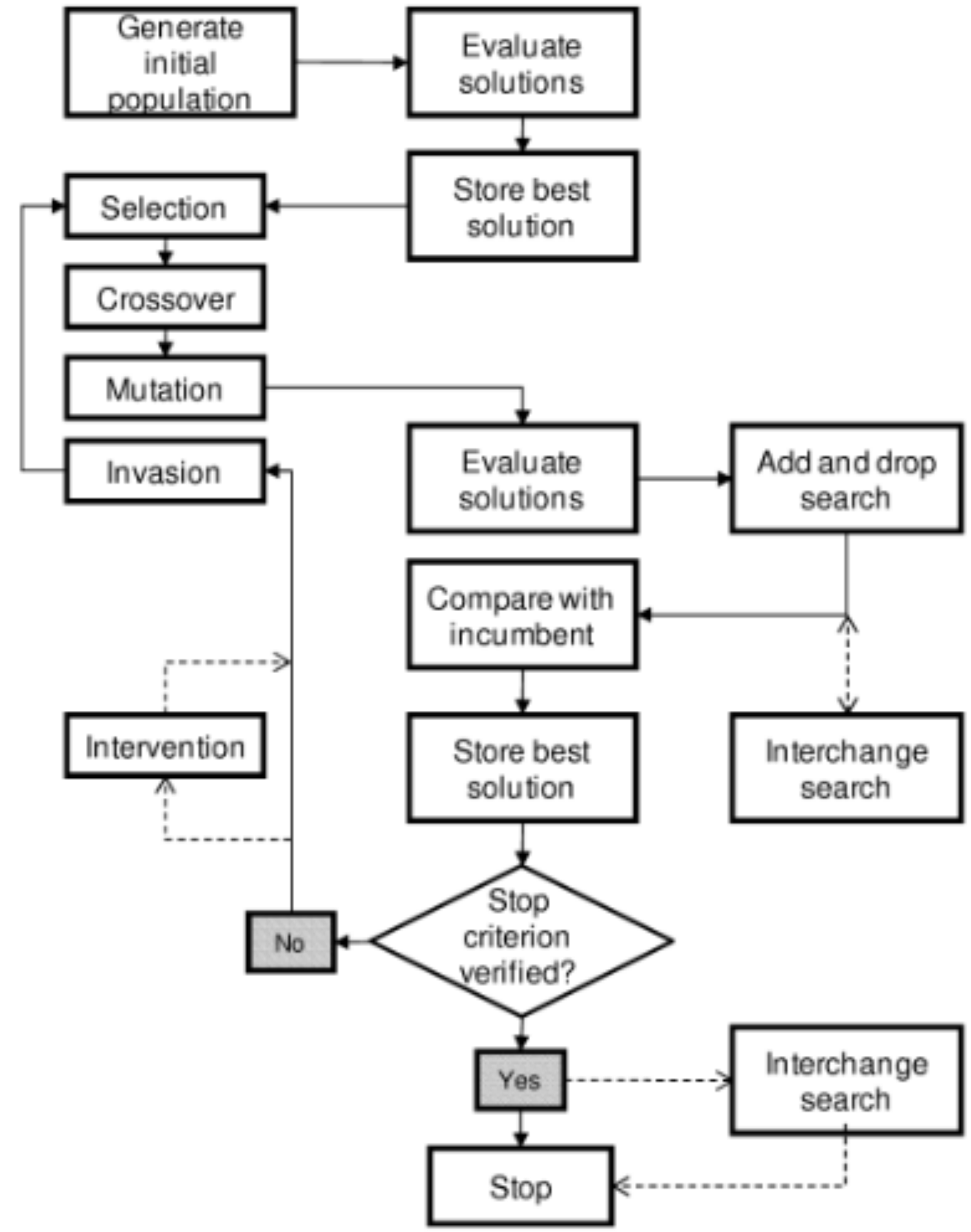
Road network planning models are generally considered to be among the optimization models most difficult to solve.

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)

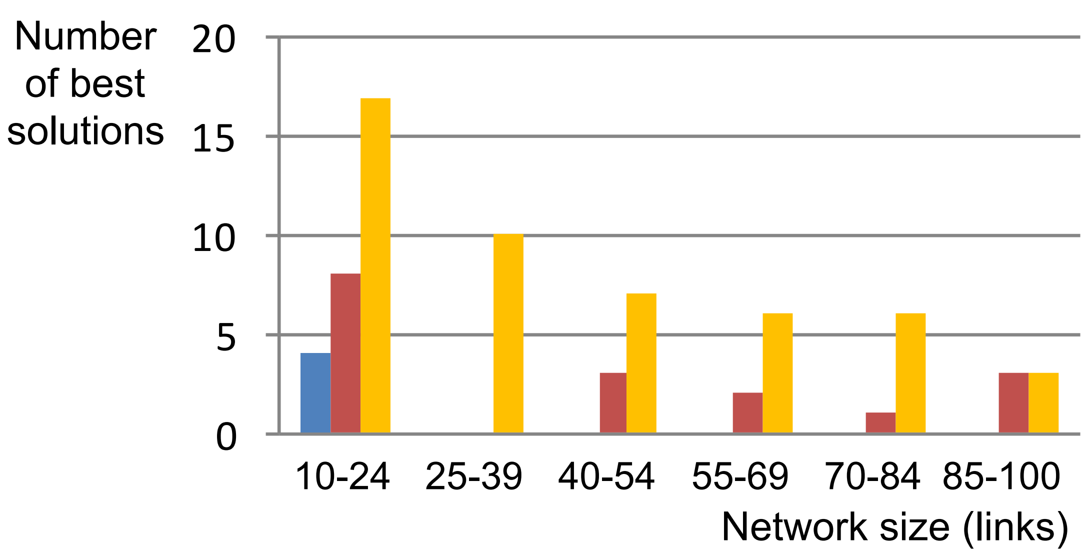
with the best results being obtained with EGA

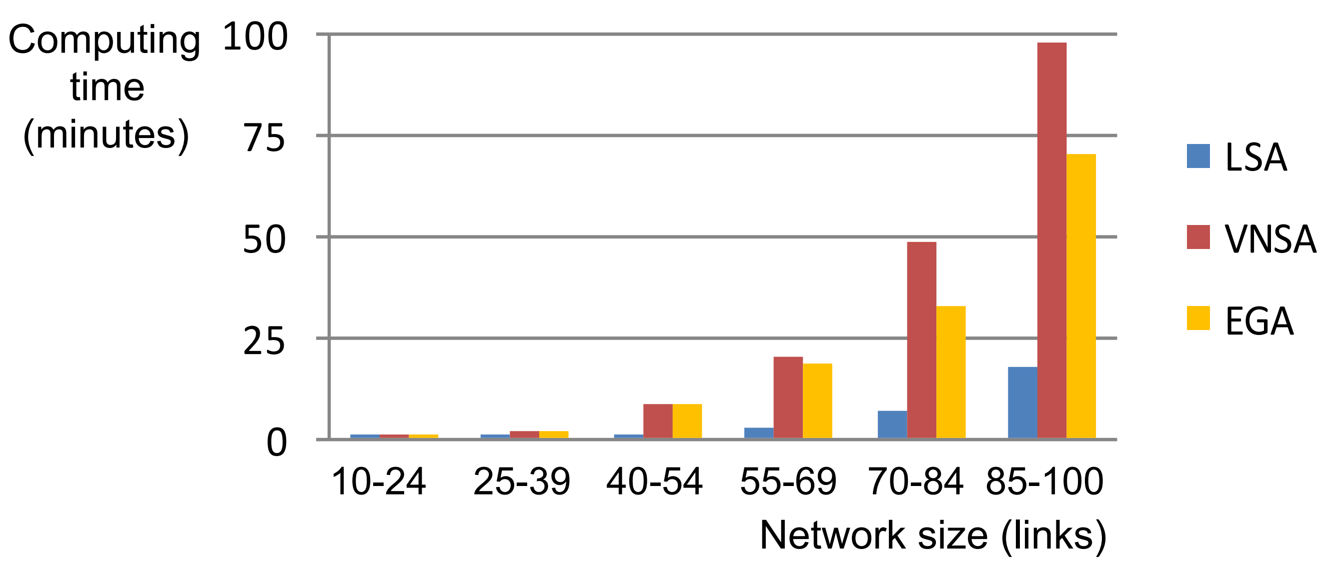


GA Structure

1.1. Road network planning/design models

Network size (links)	Number of networks	Number of best solutions			Average difference to best solution			Average computing time (minutes)		
		LSA	VNSA	EGA	LSA	VNSA	EGA	LSA	VNSA	EGA
10 - 24	20	4	8	17	-0.75%	-0.23%	-0.03%	0.01	0.03	0.64
25 - 39	10	0	0	10	-1.25%	-0.38%	0.00%	0.15	1.58	1.64
40 - 54	10	0	3	7	-1.01%	-0.17%	-0.14%	0.91	8.18	8.56
55 - 69	8	0	2	6	-0.89%	-0.28%	-0.01%	2.46	20.60	18.46
70 - 84	6	0	1	6	-0.98%	-0.19%	0.00%	7.18	48.88	32.81
85 - 100	6	0	3	3	-0.80%	-0.06%	-0.05%	17.91	98.56	70.77





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

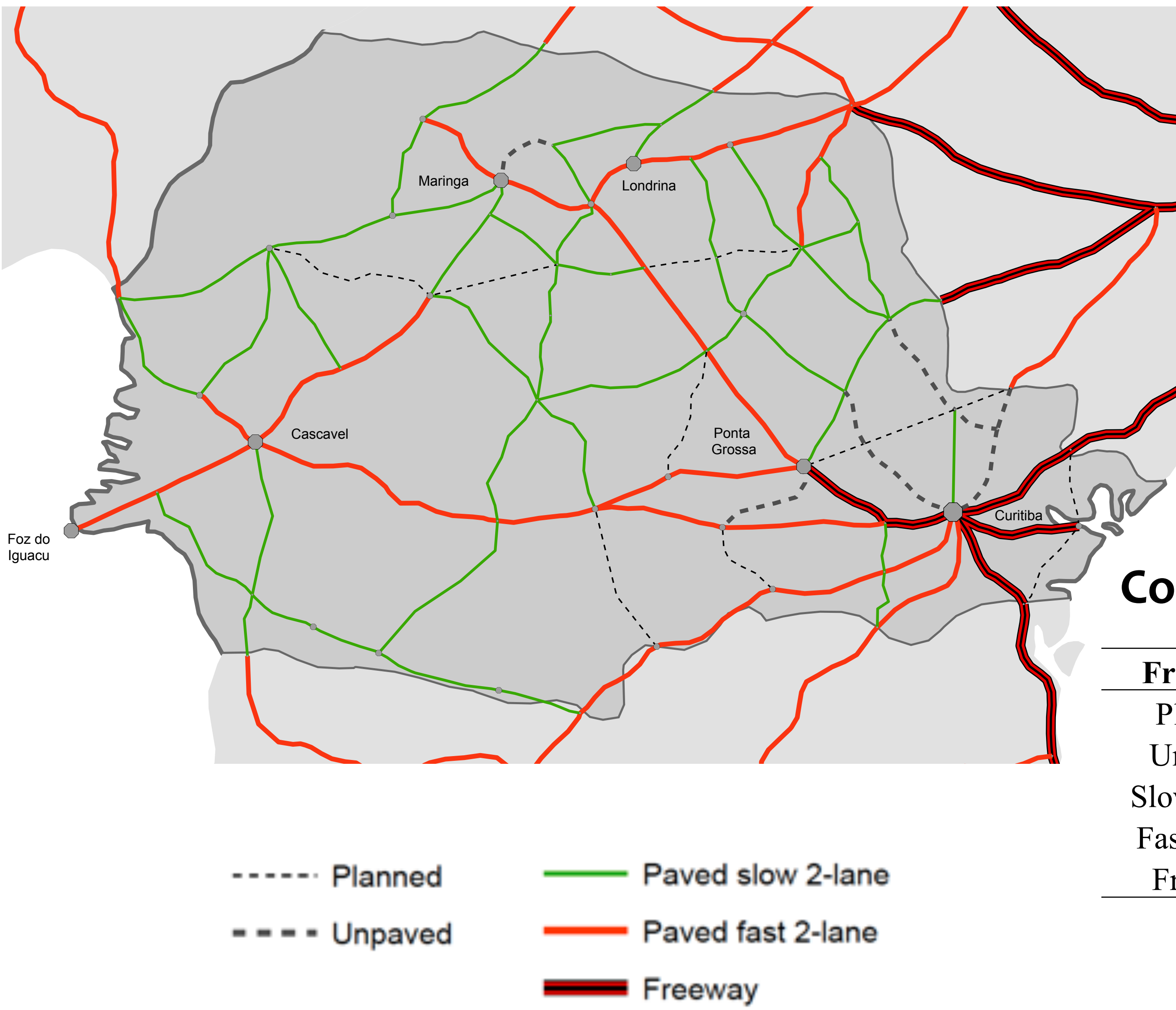
Analysis of the implications of 4 possible road network plans for the state of Paraná (differing on the weight assigned to the objectives)

- **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



Initial Network

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**

Road type	Length (km)
Planned	817
Unpaved	441
Slow 2-lane	3183
Fast 2-lane	1971
4-lane	370

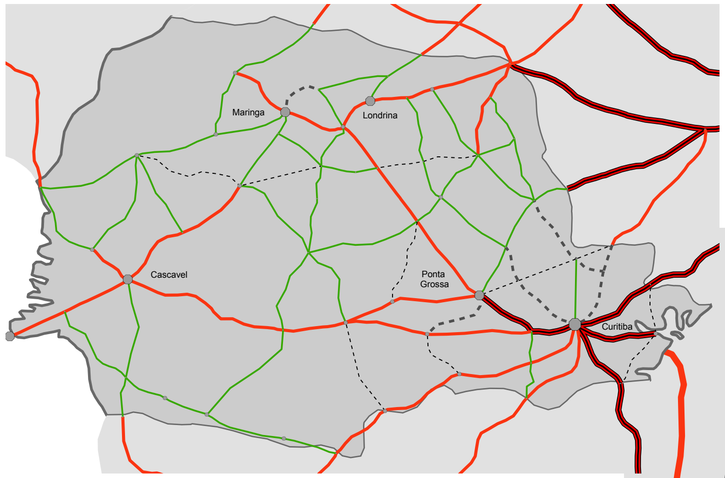
Costs of road network improvements (MU)

From/TO	Planned	Unpaved	Slow 2x1	Fast 2x1	Freeway
Planned	0	0.5	1	2.5	4
Unpaved	0	0	0.5	1.5	3
Slow 2-lane	0	0	0	1	2
Fast 2-lane	0	0	0	0	1.5
Freeway	0	0	0	0	0

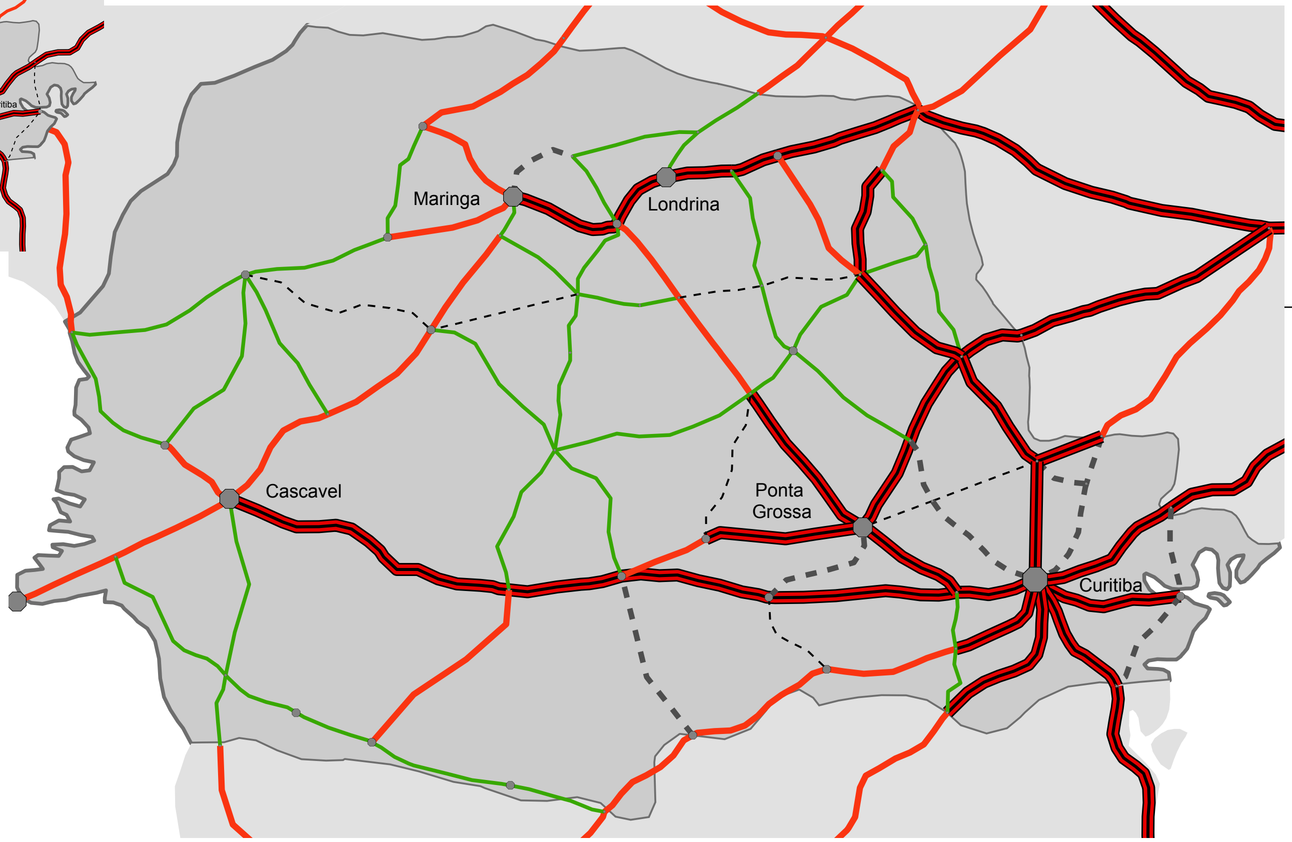
Budget = 40,000 MU
(1000 km of new 4-lane roads)

1.2. Case study of Paraná, Brazil

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



Initial network



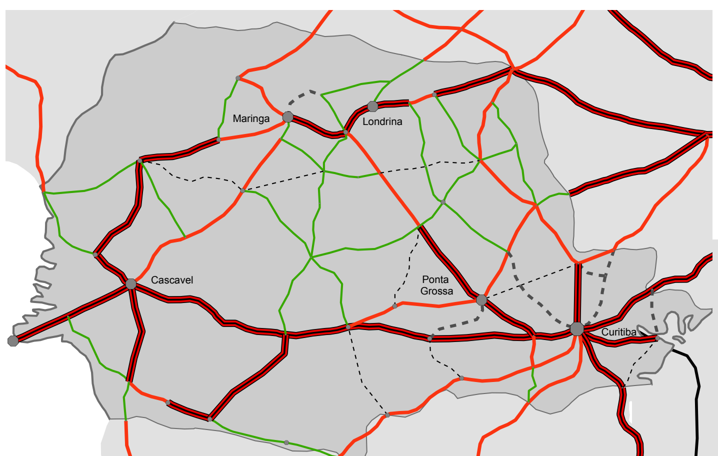
Plan 1

Road type	Length (km)		
	Inicial	Plan 1	Δ (%)
Planned	817	561	-31
Unpaved	441	583	32
Slow 2-lane	3183	2442	-23
Fast 2-lane	1971	1304	-34
4-lane	370	1892	412

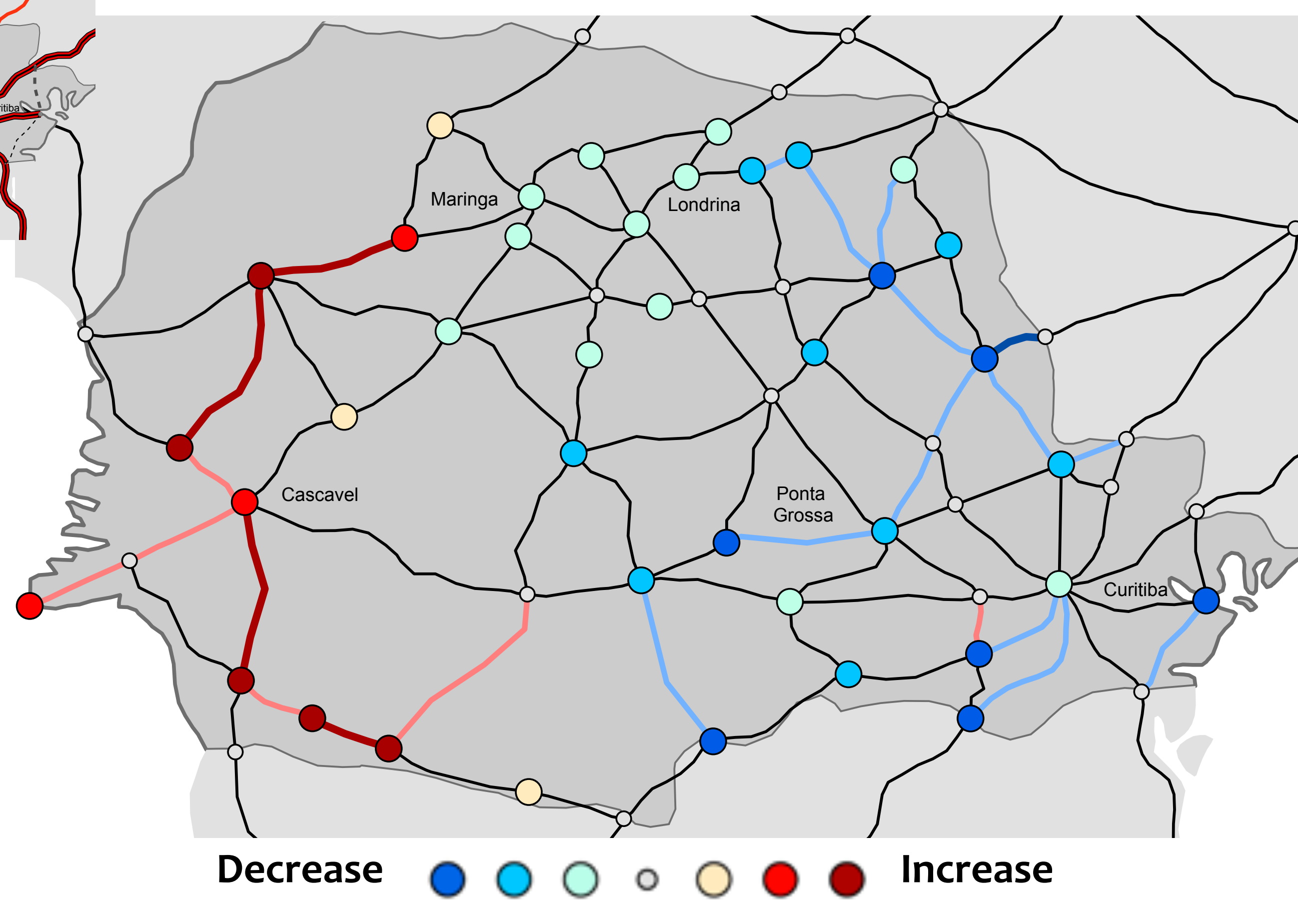
Indicator	Initial	Plan 1	Δ (%)
A	2.406	2.505	4.1
S (km/h)	90.7	106.7	17.6
G	0.139	0.147	6.0
F (g/km)	54.19	58.08	7.2

1.2. Case study of Paraná, Brazil

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



Plan 2



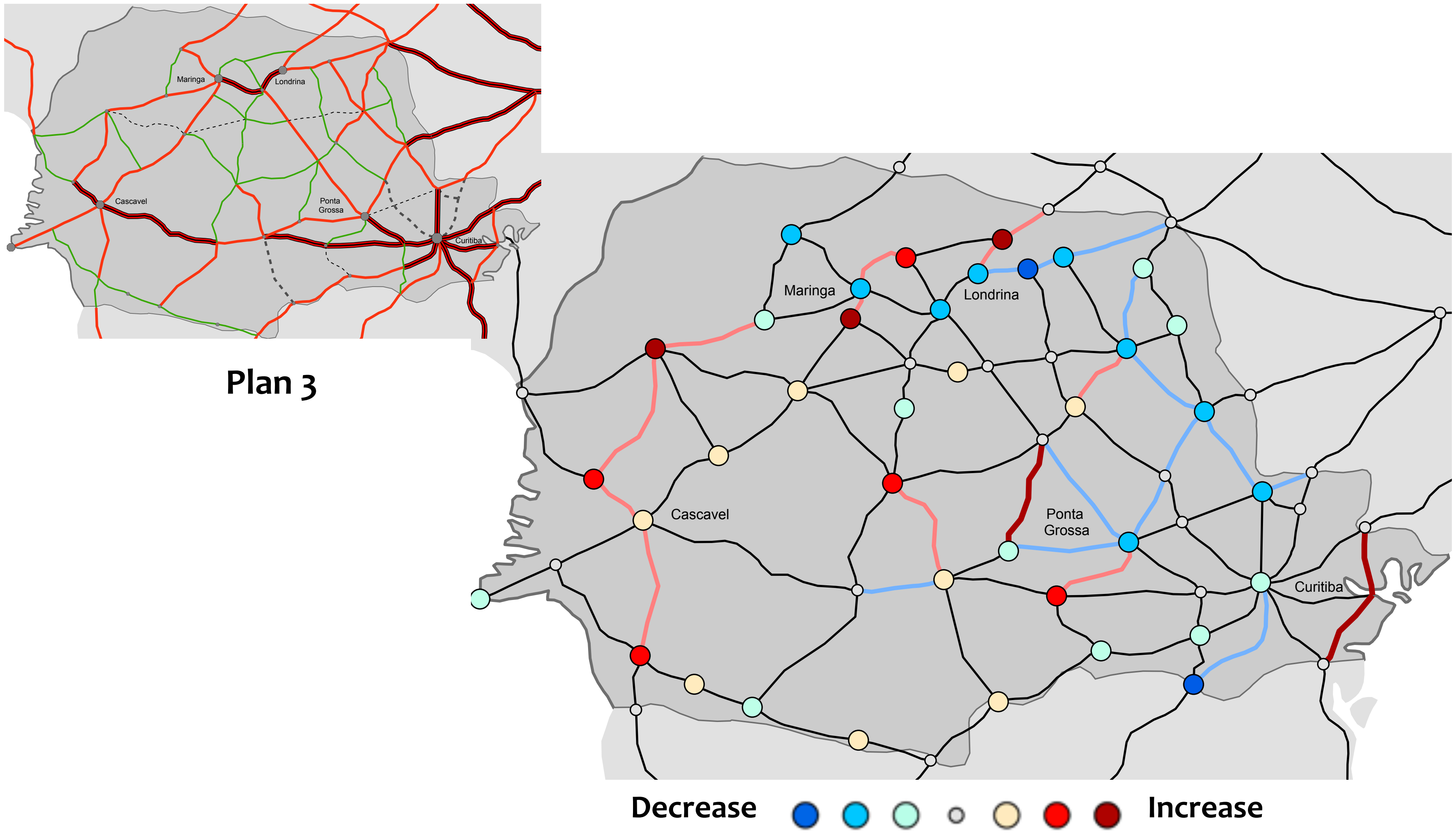
Difference to Plan 1

Road type	Length (km)		
	Plan 1	Plan 2	Δ (%)
Planned	561	727	30
Unpaved	583	417	-28
Slow 2-lane	2442	2134	-13
Fast 2-lane	1304	1651	27
4-lane	1892	1853	-2

Indicator	Plan 1	Plan 2	Δ (%)
A	2.505	2.493	-0.5
S (km/h)	106.7	105.3	-1.3
G	0.147	0.139	-5.4
F (g/km)	58.08	55.53	-4.4

1.2. Case study of Paraná, Brazil

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

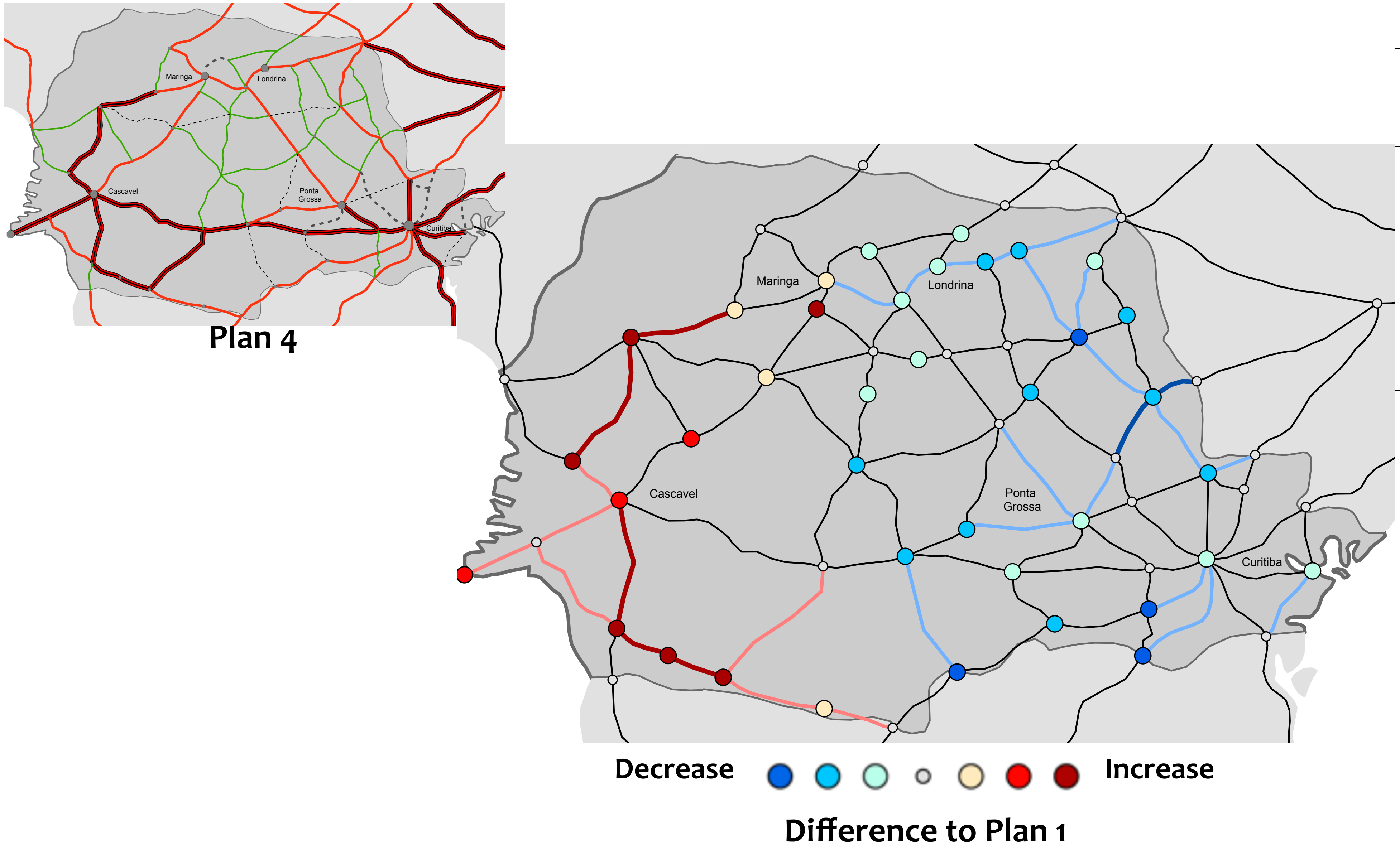


Road type	Length (km)		
	Plan 1	Plan 3	Δ (%)
Planned	561	471	-16
Unpaved	583	342	-41
Slow 2-lane	2442	2107	-14
Fast 2-lane	1304	2800	115
4-lane	1892	1061	-44

Indicator	Plan 1	Plan 3	Δ (%)
A	2.505	2.495	-0.4
S (km/h)	106.7	103.7	-2.8
G	0.147	0.145	-1.4
F (g/km)	58.08	52.58	-9.5

1.2. Case study of Paraná, Brazil

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



Road type	Length (km)		
	Plan 1	Plan 5	Δ (%)
Planned	561	727	30
Unpaved	583	417	-28
Slow 2-lane	2442	1986	-19
Fast 2-lane	1304	2080	59
4-lane	1892	1573	-17

Indicator	Plan 1	Plan 5	Δ (%)
A	2.505	2.476	-1.2
S (km/h)	106.7	102.6	-3.8
G	0.147	0.139	-5.6
F (g/km)	58.08	54.07	-6.9

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.

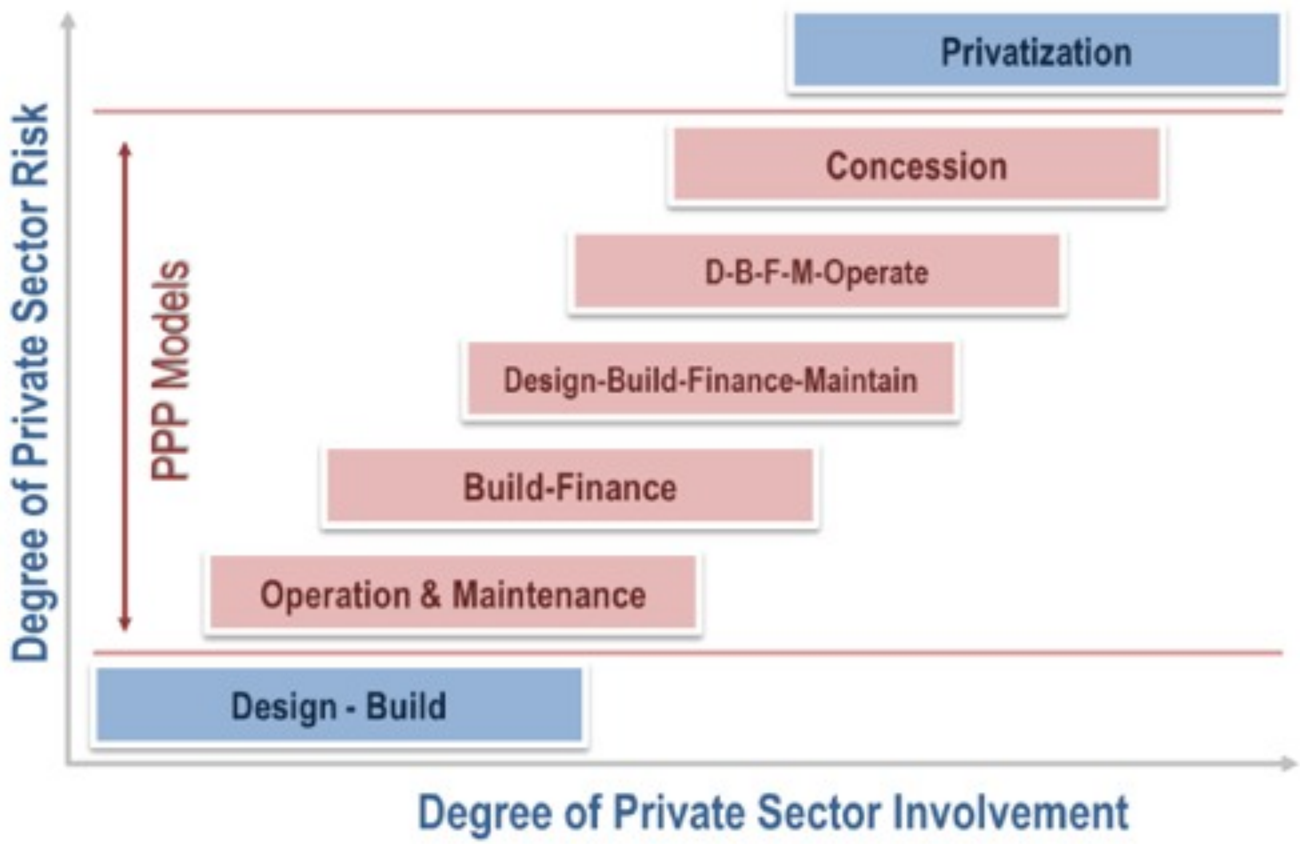
Small accessibility gains can be quite costly from social (equity) and environmental (fuel consumption ⇒ pollutant emissions) standpoints.

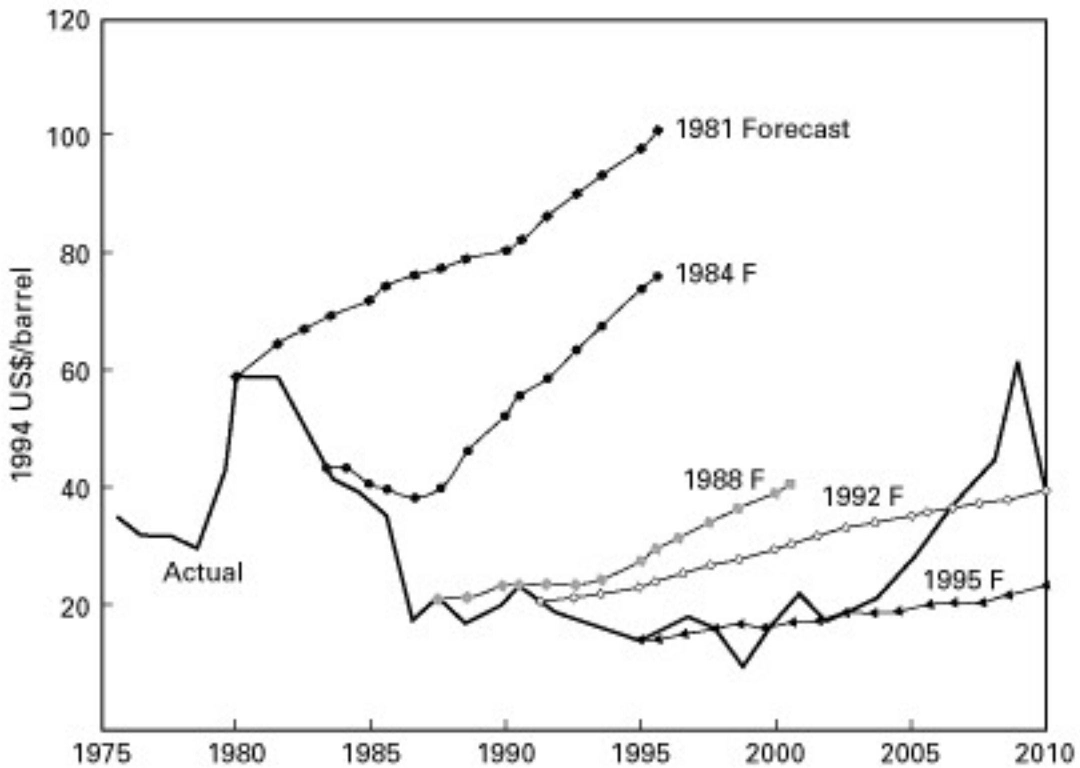
The case study shows that the approach is already useful in practical applications:

- 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





Uncertainty on forecasting - Neufville, R (MIT)

- ➡ Investment schemes - PPP and tolls
- ➡ Flexibility - uncertainty and investment scheduling
- ➡ Improve demand and assignment models

1.3. Final Comments

Papers Published:

- Santos, B.F. and Antunes, A.P. (in press), “Planejamento Sustentável de Redes Rodoviárias Interurbanas através de uma Abordagem Multi-objetivo” (Sustainable Planning of Interurban Road Networks through a Multi-objective Approach). Transporte em Transformação (Transportation in Transformation), Confederação Nacional do Transporte and Associação Nacional de Pesquisa e Ensino em Transporte, Brasília, Brazil. Forthcoming issue.

- Santos, B.F. and Antunes, A.P. (2012), “A Study on the Improvement of the Secondary Road Network of the Centro Region of Portugal”. Revista Portuguesa de Estudos Regionais (Portuguese Journal of Regional Studies), n.º 30, 2012, 2.º Quarter.

- Santos, B.F., Antunes, A.P., Miller, E. (2010), “Interurban Road Network Planning Model with Accessibility and Robustness Objectives”. Transportation Planning and Technology, Vol. 33, No. 3, pp. 297-331.

- Santos, B., Antunes, A., Miller, E. (2009), “A Multi-Objective Approach to Long-Term Interurban Multi-Level Road Network Planning”. Journal of Transportation Engineering - ASCE, Vol. 139, No. 9, pp. 640-649.

- Santos, B., Antunes, A., Miller, E. (2008), “Integrating Equity Objectives in a Road Network Design Model”, Transportation Research Record: Journal of the Transportation Research Board, No. 2089, pp- 35-42.

2. Multi-stakeholder Planning

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

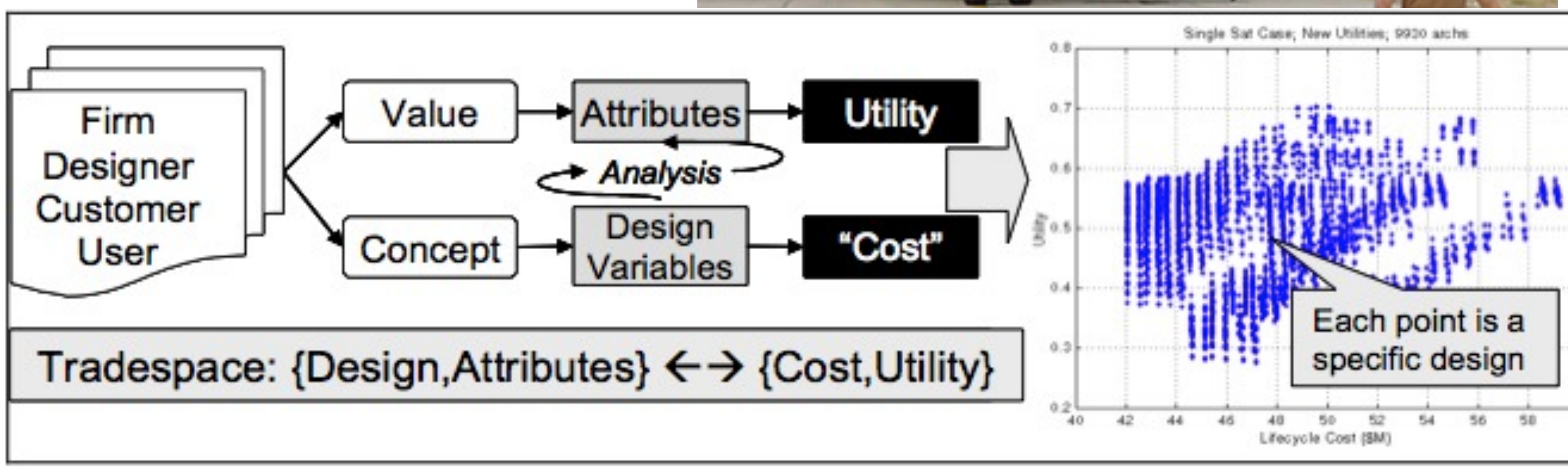
The perspectives and goals of these stakeholders upon the infrastructure investment project is usually divergent

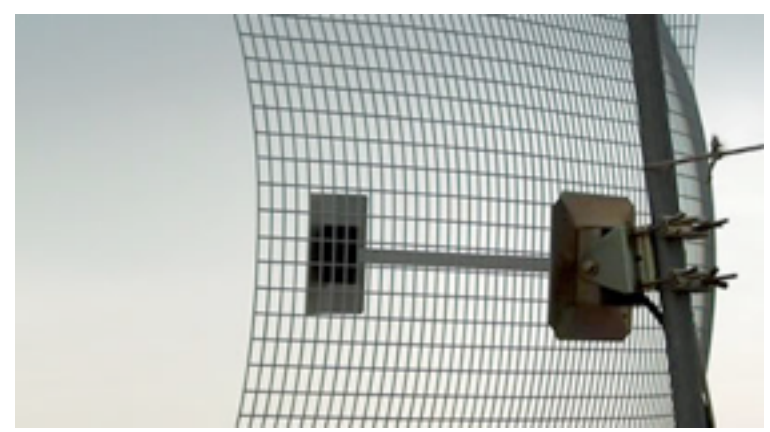
The optimal solution is a trade-off solution between stakeholders

- 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

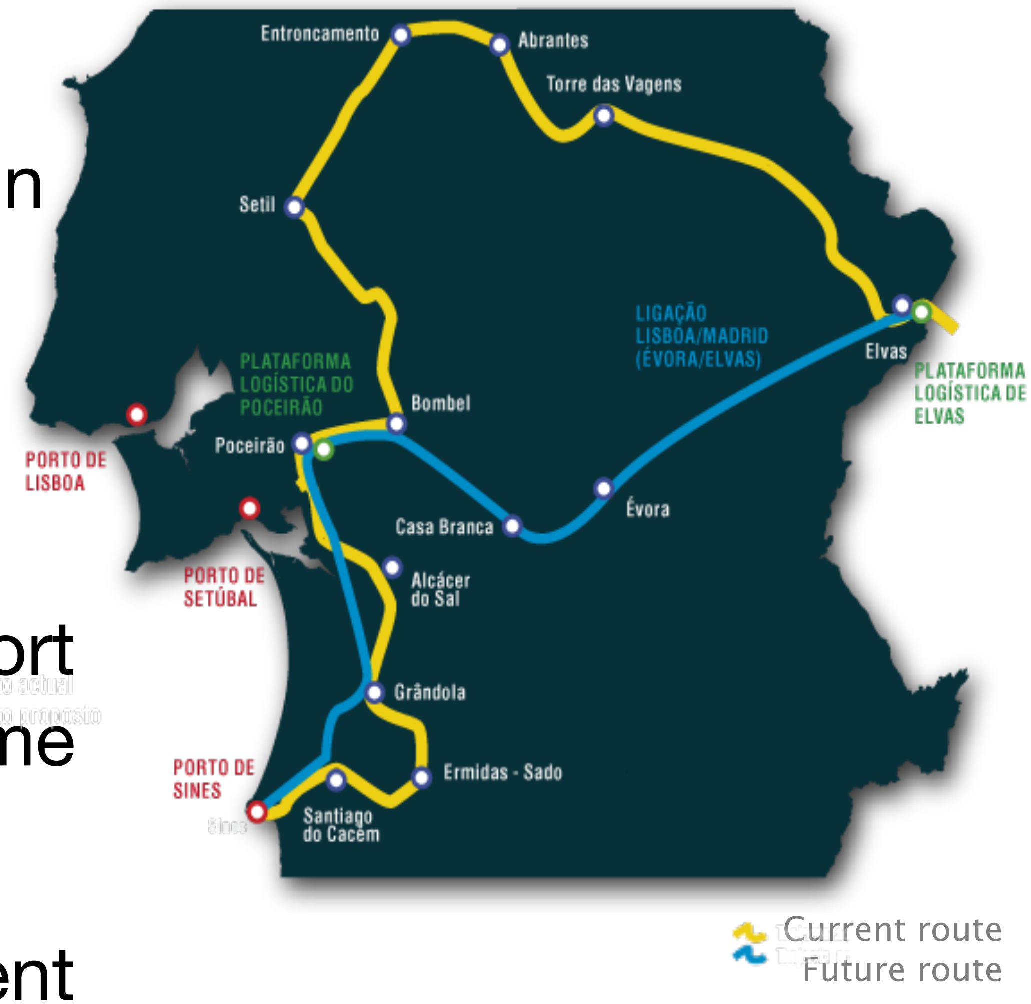
- 645km ⇒ 200km in Portugal & 445km in Spain

- 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

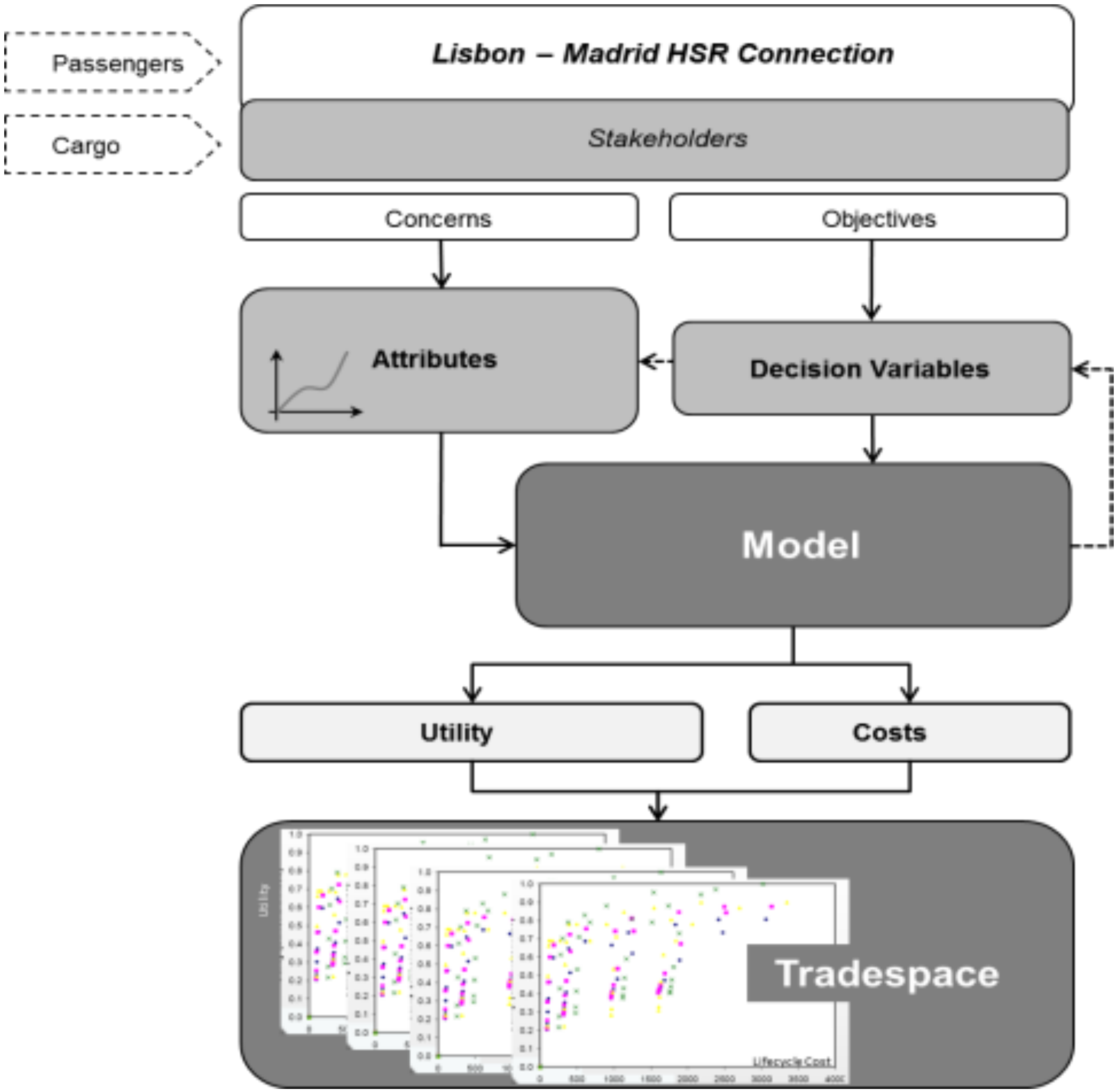
- Line design and demands are the same as predicted by RAVE;
- Two different passenger services were assumed:
  - International Service >> High Speed (250 km/h);
  - National Service >> Medium Speed (200 km/h);
- The rolling stock required for cargo delivery will have similar characteristics to the chosen 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 product's, electronic components;

2.2. Lisbon-Madrid HSR

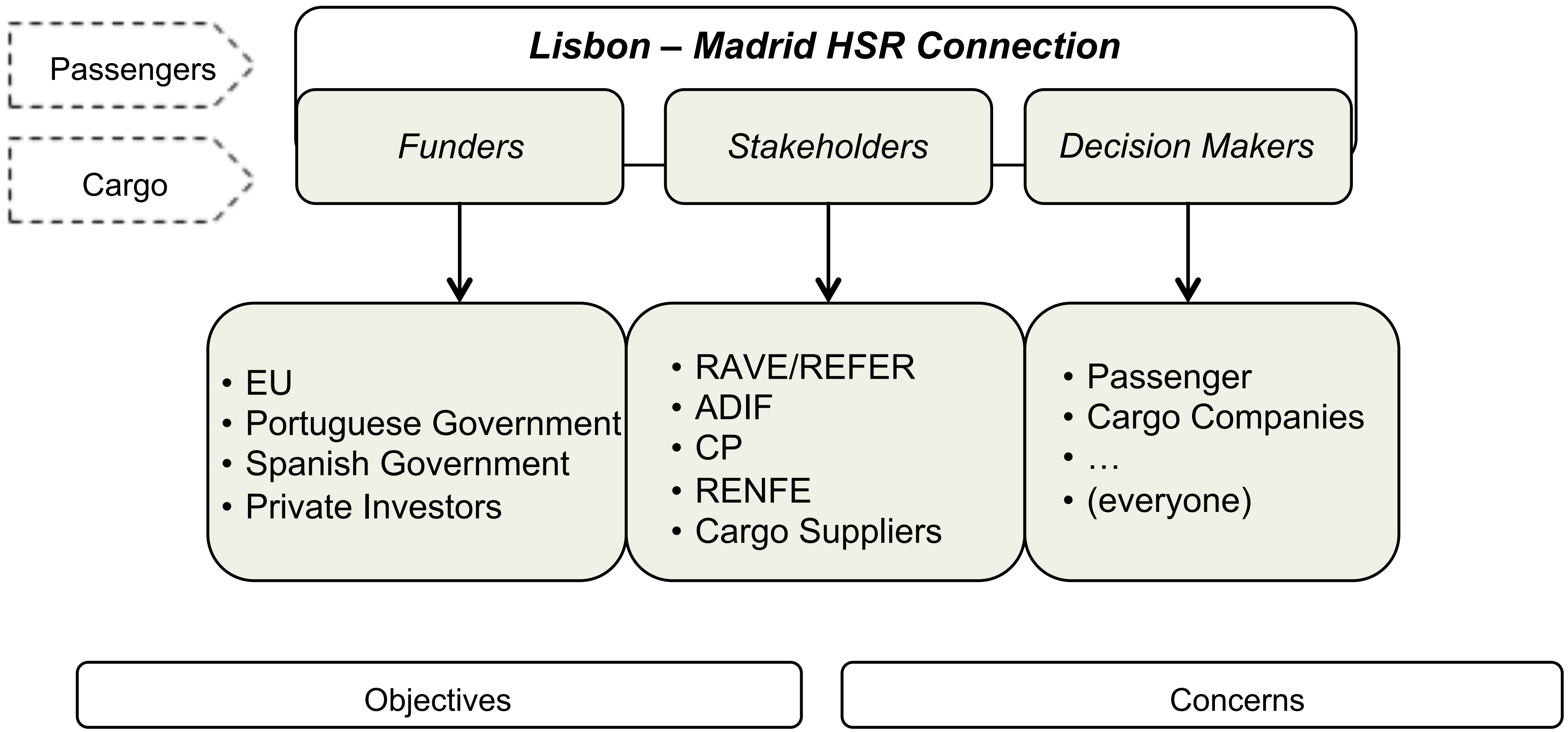
Two “new” rail-road terminals to be built:

- 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

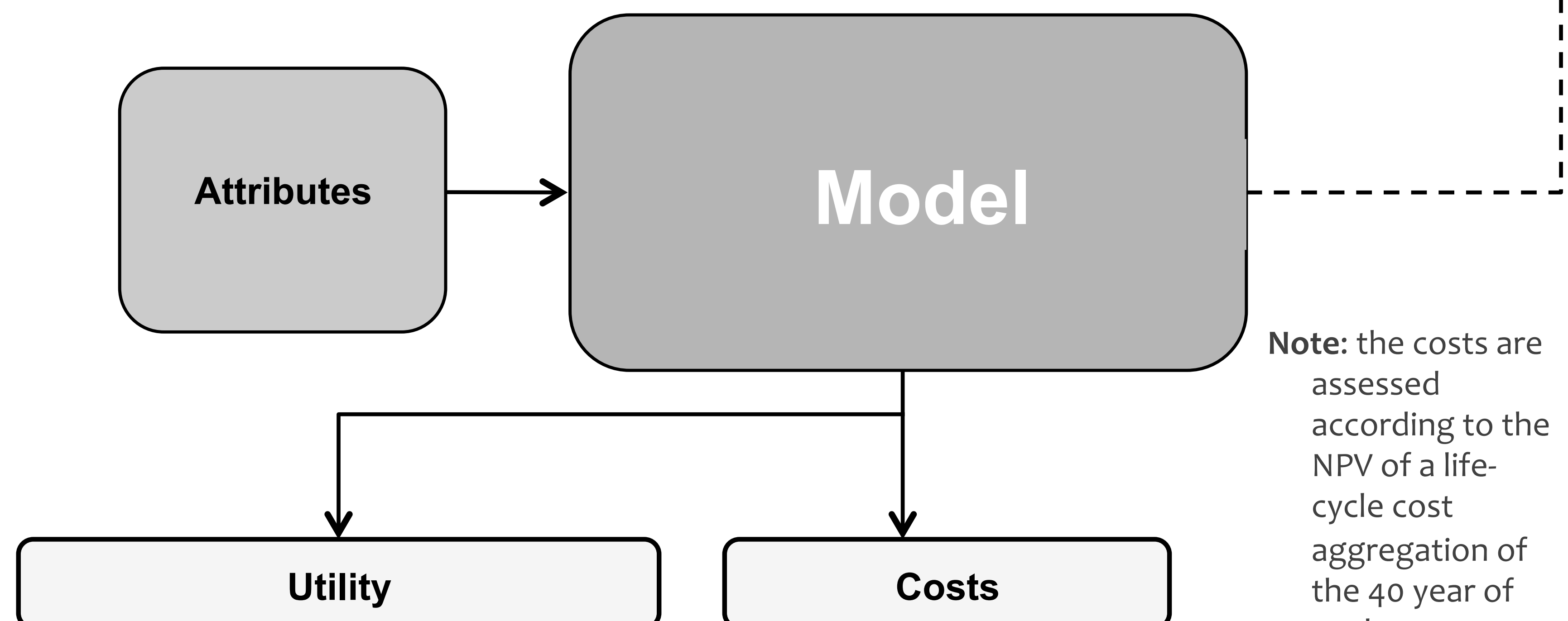
2.2. Lisbon-Madrid HSR

Decision Variables

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

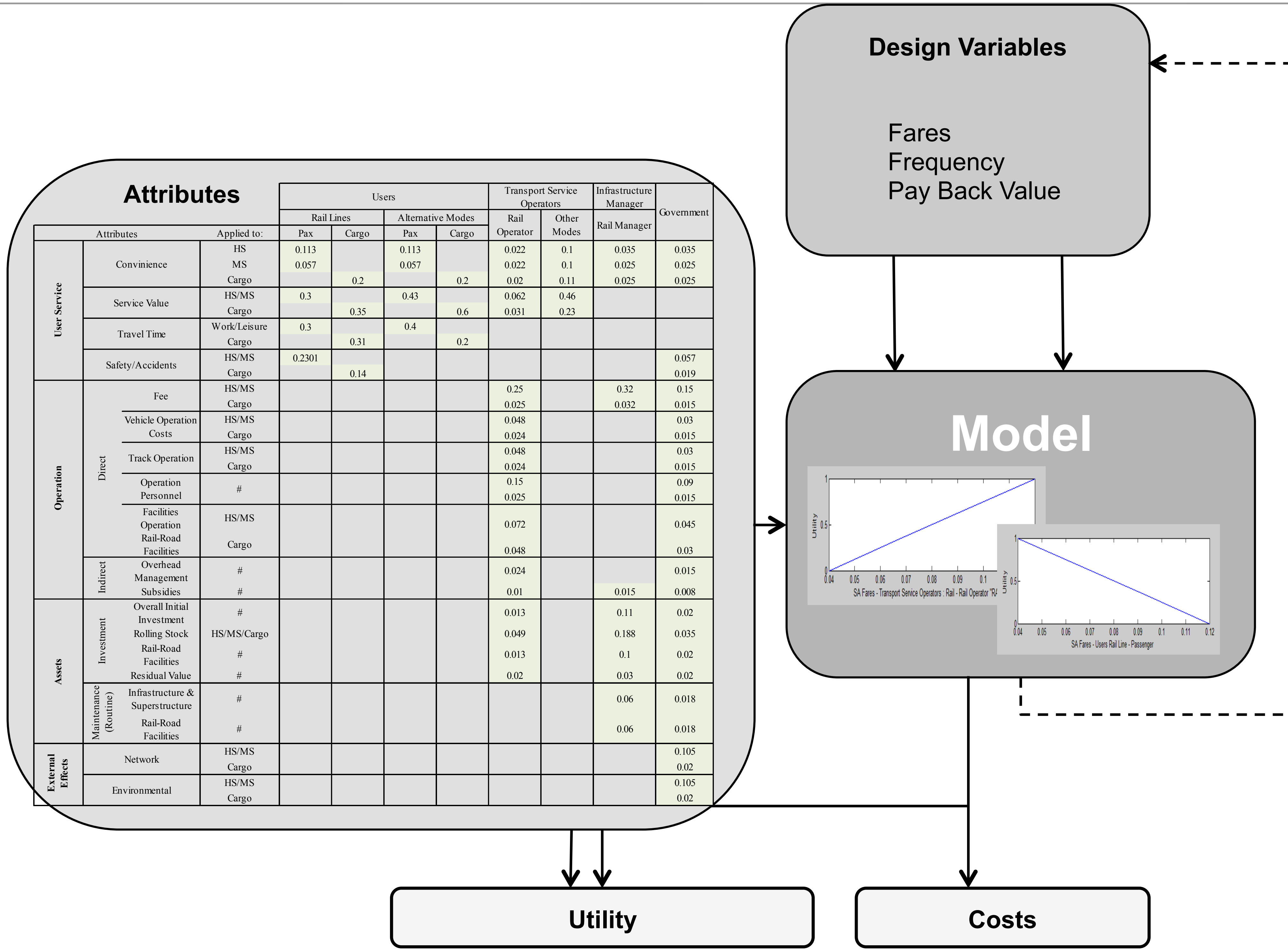
Δ Fare	Δ Demand	Elasticity
-50%	20%	-0,41
-20%	9%	-0,46
-10%	5%	-0,46
10%	-4%	-0,41
20%	-7%	-0,36
50%	-13%	-0,25

Δ Fare	Δ Cost	Elasticity
-5%	8%	-1,54
5%	8%	1,54



Note: the costs are assessed according to the NPV of a life-cycle cost aggregation of the 40 year of analyses;

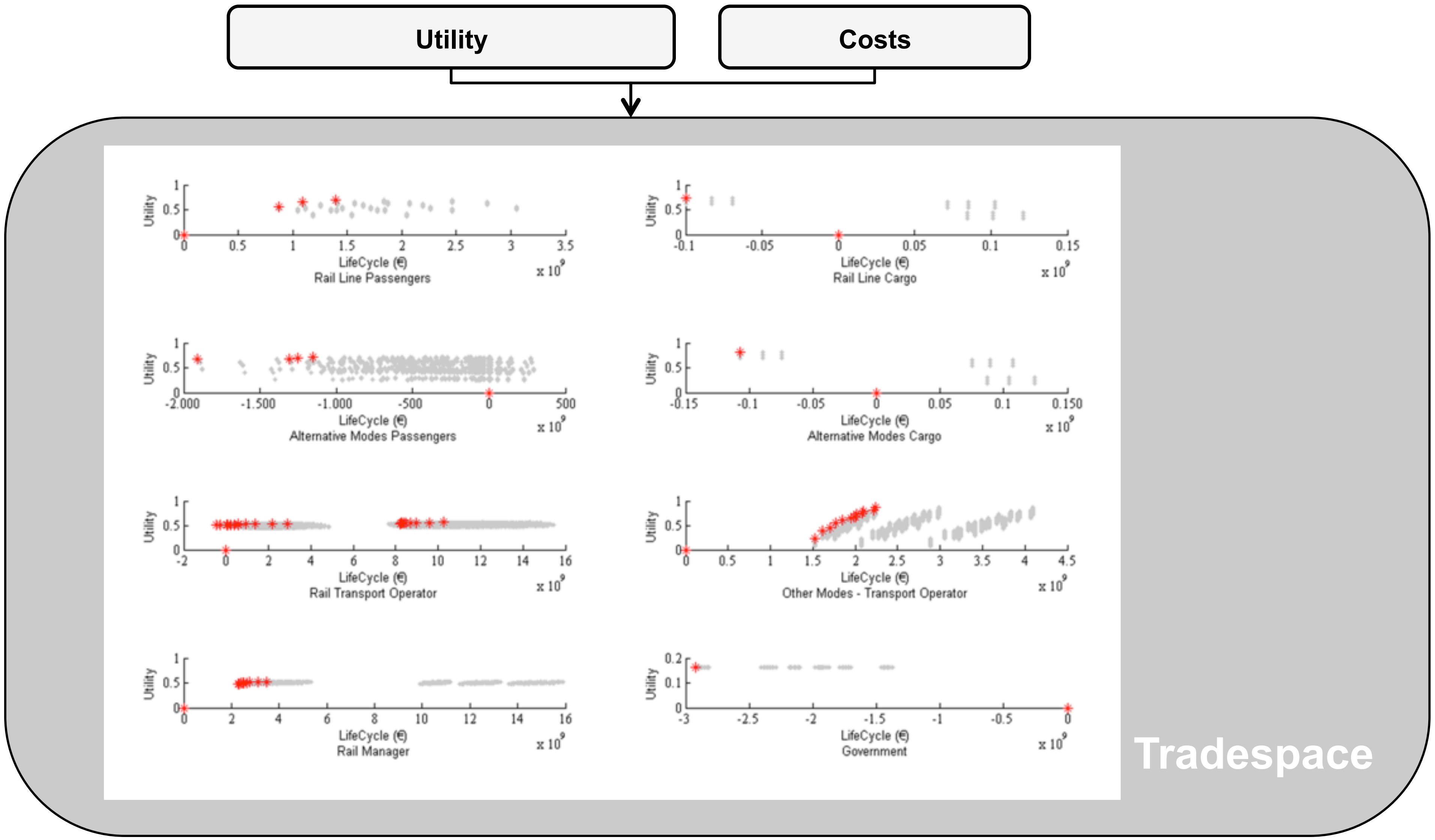
2.2. Lisbon-Madrid HSR



Attributes

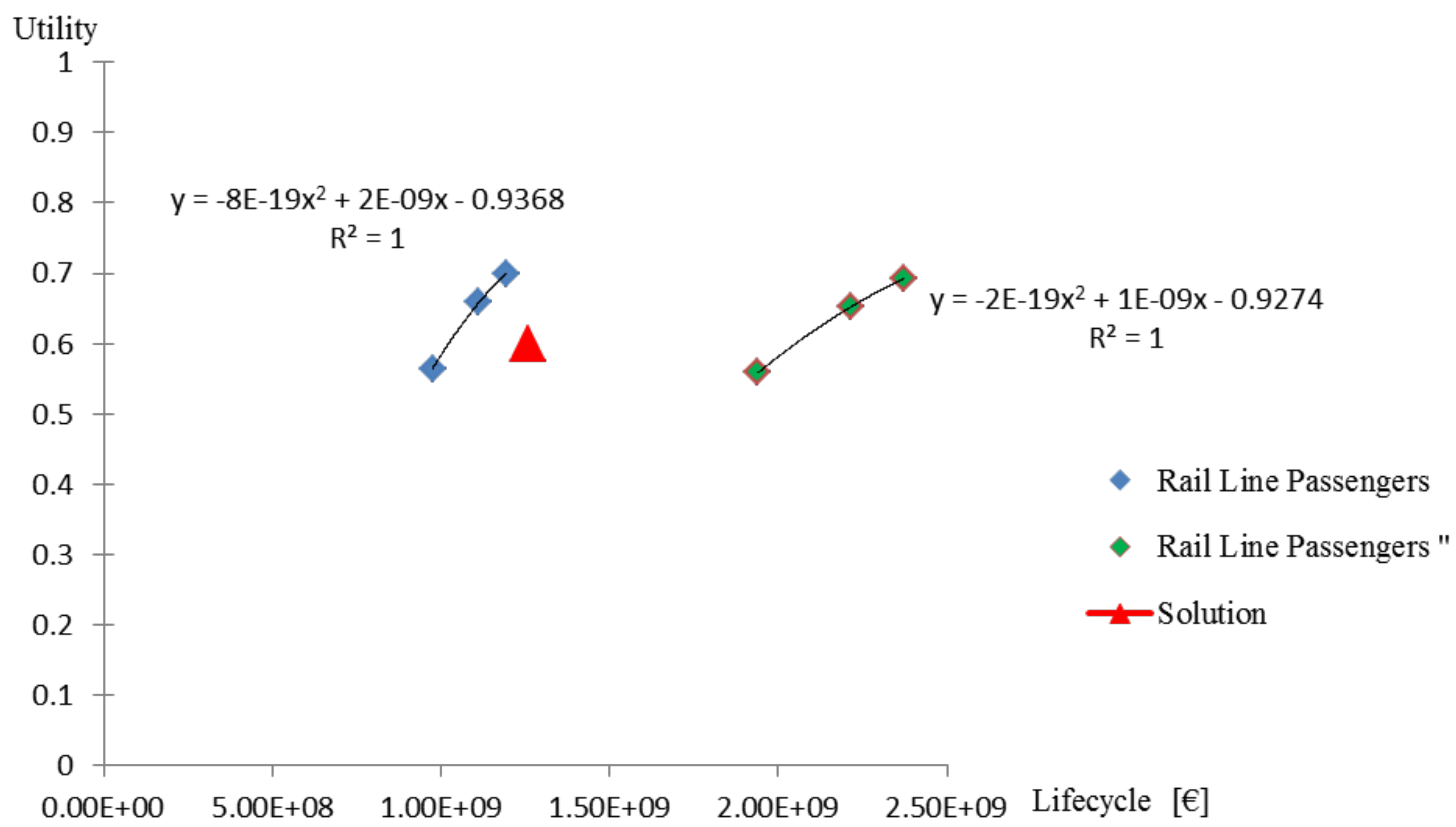
				Users				Transport Service Operators		Infrastructure Manager	Government
				Rail Lines		Alternative Modes		Rail Operator	Other Modes	Rail Manager	
Attributes			Applied to:	Pax	Cargo	Pax	Cargo				
User Service		Convinience	HS	0.113		0.113		0.022	0.1	0.035	0.035
			MS	0.057		0.057		0.022	0.1	0.025	0.025
			Cargo		0.2		0.2	0.02	0.11	0.025	0.025
		Service Value	HS/MS	0.3		0.43		0.062	0.46		
			Cargo		0.35		0.6	0.031	0.23		
		Travel Time	Work/Leisure	0.3		0.4					
			Cargo		0.31		0.2				
		Safety/Accidents	HS/MS	0.2301							0.057
			Cargo		0.14						0.019
Operation	Direct	Fee	HS/MS					0.25		0.32	0.15
			Cargo					0.025		0.032	0.015
		Vehicle Operation Costs	HS/MS					0.048			0.03
			Cargo					0.024			0.015
		Track Operation	HS/MS					0.048			0.03
			Cargo					0.024			0.015
		Operation Personnel	#					0.15			0.09
								0.025			0.015
		Facilities Operation	HS/MS					0.072			0.045
		Rail-Road Facilities	Cargo					0.048			0.03
	Indirect	Overhead Management	#					0.024			0.015
		Subsidies	#					0.01		0.015	0.008
Assets	Investment	Overall Initial Investment	#					0.013		0.11	0.02
		Rolling Stock	HS/MS/Cargo					0.049		0.188	0.035
		Rail-Road Facilities	#					0.013		0.1	0.02
		Residual Value	#					0.02		0.03	0.02
	Maintenance (Routine)	Infrastructure & Superstructure	#							0.06	0.018
		Rail-Road Facilities	#							0.06	0.018
External Effects		Network	HS/MS								0.105
			Cargo								0.02
		Environmental	HS/MS								0.105
			Cargo								0.02

2.2. Lisbon-Madrid HSR



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

Decision Variables	Definition	High Speed Service (HS)	Medium Speed Service (MS)	Cargo Service
Frequency	Trains per day	[11 13 16]	[1 3 6] *Portugal; [5 9 14] *Spain	[3 6 9]
Fares	Price to pay for one trip per km	[0.0695 0.1390 0.2085] * €/pass.km	[0.0415 0.083 0.1245] * €/pass.km	[0.0554 0.0583 0.0612] * €/ton.km
Rent	Return value to pay regarding the use of the track, rolling stock and terminals		[2 3.5 5]%	

Δ Fare	Δ Demand	Elasticity
-50%	20%	-0,41
-20%	9%	-0,46
-10%	5%	-0,46
10%	-4%	-0,41
20%	-7%	-0,36
50%	-13%	-0,25

Δ Fare	Δ Cost	Elasticity
-5%	8%	-1,54
5%	-8%	1,54

Frequency (#)			
HS	MS Pt	MS Pt	Cargo
16 ↑	6 ↑	5 ↓	3 ↓

	Fares (€/X.km)		
	HS	MS	Cargo
	0.1390	0.0415	0.0554
Δ Fare	0%	-50%	-5%
Δ Demand	0%	20%	8%

Rate (%)
5%

Design solution: 4464

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

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

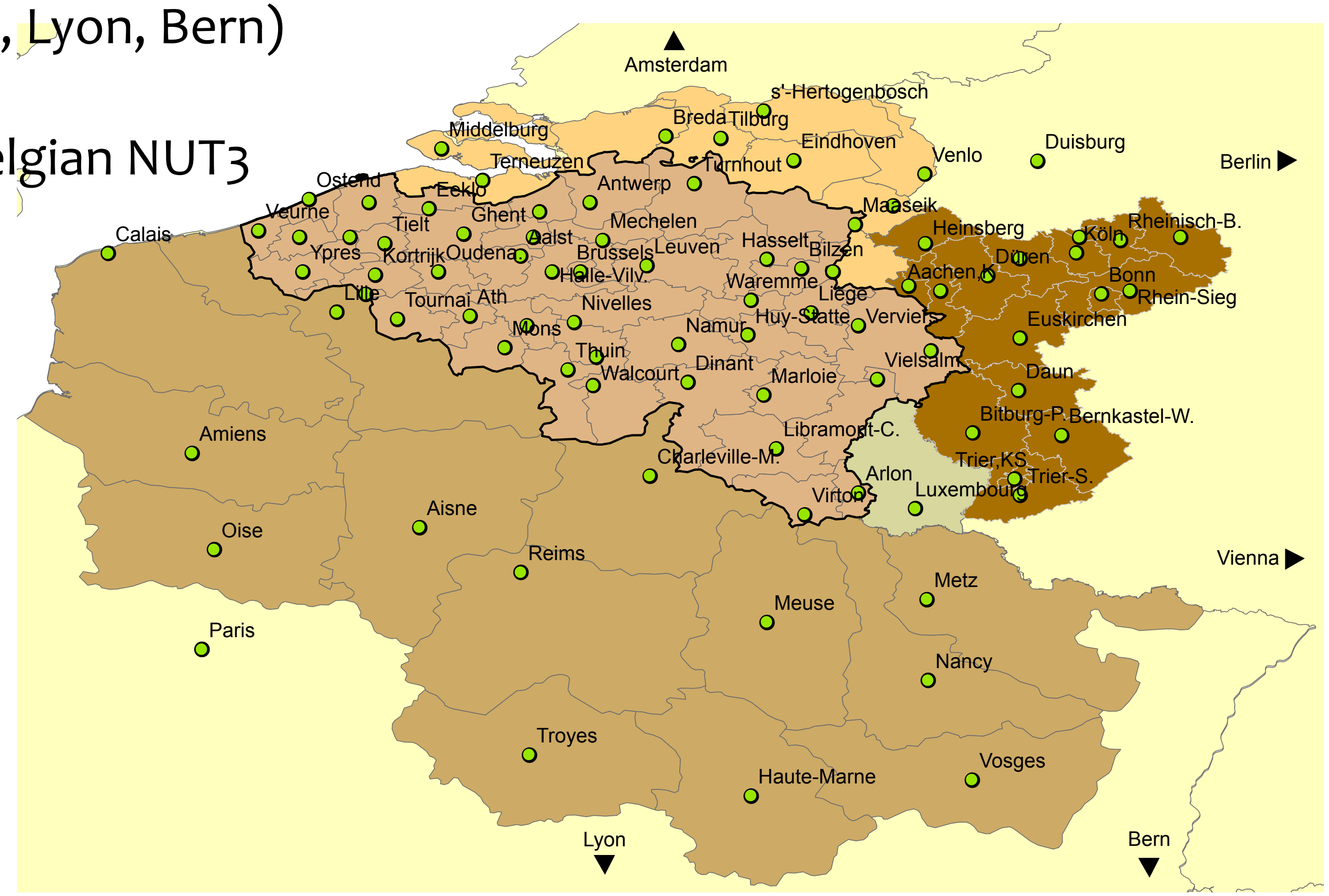
- Is intermodal freight transport (road-rail) competitive even for a small country like Belgium?
- How the Belgian government subsidies can influence the location of freight terminals and the modal split for freight in Belgium?

3.1. Methodology

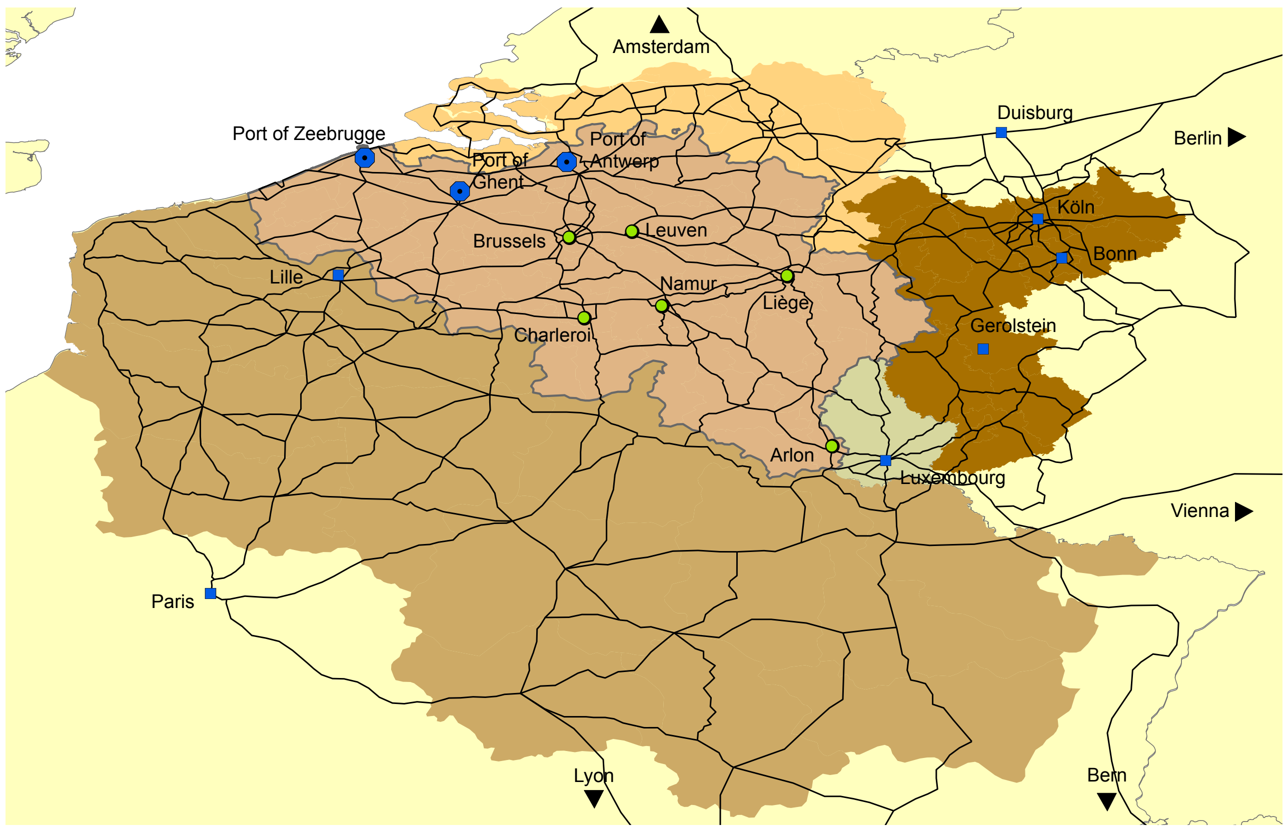
Optimal terminals location problem – road-rail terminals

- 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

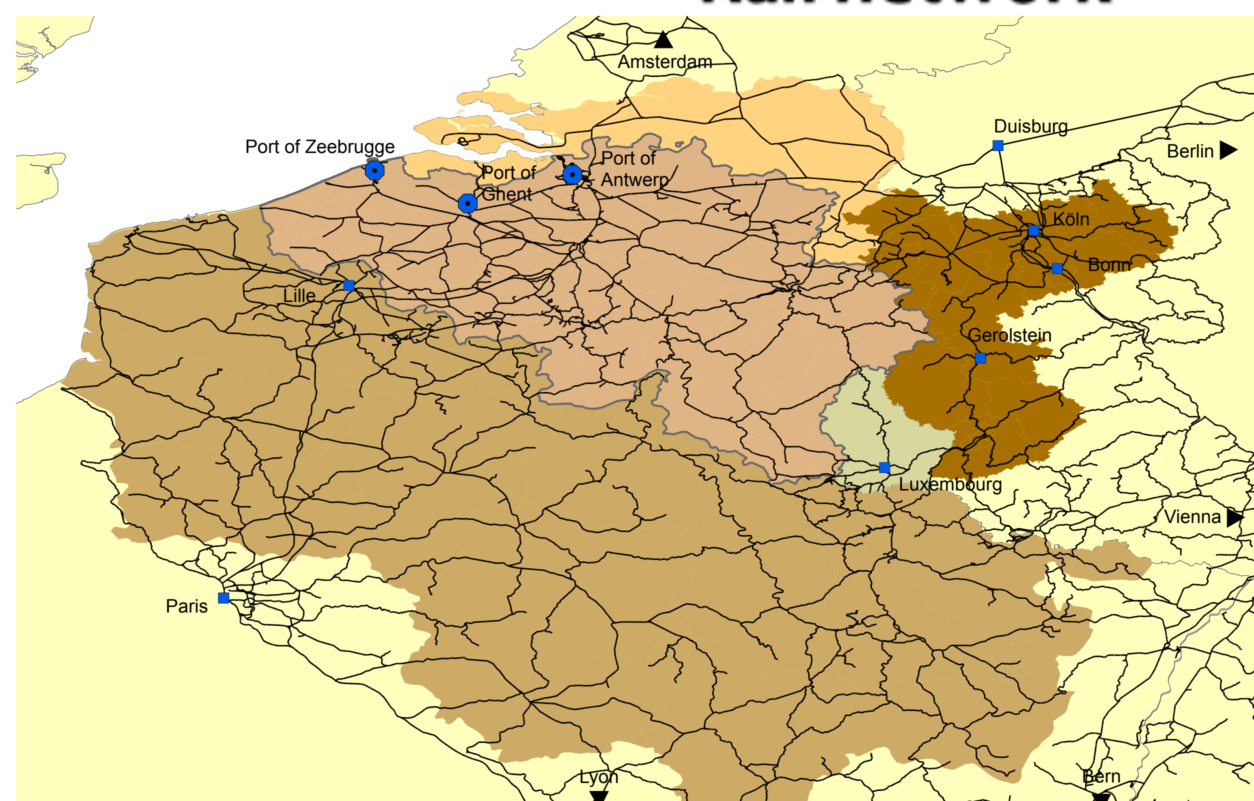


3.1. Methodology



Road network

Rail network



3.2. Model

Hub-based Network Design

<u>Traditional</u>

- 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

$$\min \sum_{i\in N} \sum_{m\in N} d_{im}\ (C^o_{im} + C^e_{im}\ e)\ W_{im}$$

Transportation cost of road flows

$$+ \sum_{i\in N_0} (T^o_i + T^e_i\ e)\ W_{im} + \sum_{m\in N_0} (T^o_m + T^e_m\ e)\ W_{im}$$

Transshipment costs at the ports between sea and road

$$+ \sum_{i\in N} \sum_{j\in N'} \sum_{k\neq j\in N'} [d_{ij}\ (C'^o_{ij} + C'^e_{ij}\ e) + T^o_j + T^e_j\ e]\ X^i_{jk}$$

Pre-haulage costs between origin and a rail-road terminal

$$+ \sum_{i\in N} \sum_{j\in N'} \sum_{k\neq j\in N'} (R^o_{jk} + R^e_{jk}\ e - s\ (\alpha_{jk}\ \tilde{R} + \tilde{T}_{jk}))\ X^i_{jk}$$

Long-haul transportation cost by rail

$$+ \sum_{i\in N} \sum_{k\in N'} \sum_{m\in N} [d_{km}\ (C'^o_{km} + C'^e_{km}\ e) + T^o_k + T^e_k\ e]\ Q^i_{km}$$

Post-haulage costs between a rail-road terminal and the destination

3.2. Model

Subject to,

$$\sum_{k \in N_1} y_k = p$$ → **Number of terminals to locate**

$$y_k = 1 \quad \forall k \in N_0 \cup N_3 \cup N_4$$ **Existing terminals remain open**

$$D_{im} = W_{im} + \sum_{k \in N'} Q^i_{km} \quad \forall i \in N, \ \forall m \in N$$ **Demand = road + intermodal**

$$\sum_{m \in N} D_{im} = \sum_{j \in N'} \sum_{k \in N'} X^i_{jk} + \sum_{m \in N} W_{im} \quad \forall i \in N$$ **Exiting flow at node *i***

$$\sum_{i \in N} D_{im} = \sum_{i \in N} \sum_{k \in N'} Q^i_{km} + \sum_{i \in N} W_{im} \quad \forall m \in N$$ **Entering flow at node *m***

$$\sum_{i \in N_4} (W_{ij} + W_{ji}) = 0 \quad \forall j \in N$$ **Rail flows from outside network arrive on train**

$$\sum_{k \in N'} X^i_{jk} \leq y_j \sum_{m \in N} D_{im} \quad \forall i \in N, \ \forall j \in N'$$

$$\sum_{j \in N'} X^i_{jk} \leq y_k \sum_{m \in N} D_{im} \quad \forall i \in N, \ \forall k \in N'$$

Attribution possibility

$$\sum_{j \in N'} X^i_{jk} = \sum_{m \in N} Q^i_{km} \quad \forall i \in N, \ \forall k \in N'$$ **Flow continuation**

3.2. Model

Transport costs (based on Janic, 2008):

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

Road (line-hauling; collection and distribution)

Operational $$C_{kj}^{op} = \left({Q_{kj}}/{\lambda_j M_j} \right) . c_{op}(d_{kj})$$

External $$C_{kj}^{ext} = \left({Q_{kj}}/{\lambda_j M_j} \right) . c_{ext}(d_{kj})$$

$$\lambda_j = 0.85 \; or \; 0.60$$

$$M_j = 2 \times 14.3 \; ton$$

Terminals

Operational $$T_k^{op} = Q_k . (2 \times c_t^{op})$$

External $$T_k^{ext} = Q_k . (2 \times c_t^{ext})$$

Janic M (2008) "An Assessment of the Performance of the European Long Intermodal Freight Trains (LIFTS)". Transp Res Part A 42(10):1326–1339.

3.2. Model

Transport costs (based on Janic, 2008):

Rail (line-hauling)

Operational $$R_k^{op} = \left({}^{Q_k}/_{q_t}\right) r_{op}(W, q_t, l_{km})$$

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

External $$R_k^{ext} = \left({}^{Q_k}/_{q_t}\right) r_{ext}(W, q_t, l_{km})$$

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

$$W = 1550\ ton$$

(locomotive + 26 wagons)

$$q_t = 0.75 \times 26 \times 3 \times 14.3\ ton$$

3.2. Model

Transportation Costs Policies

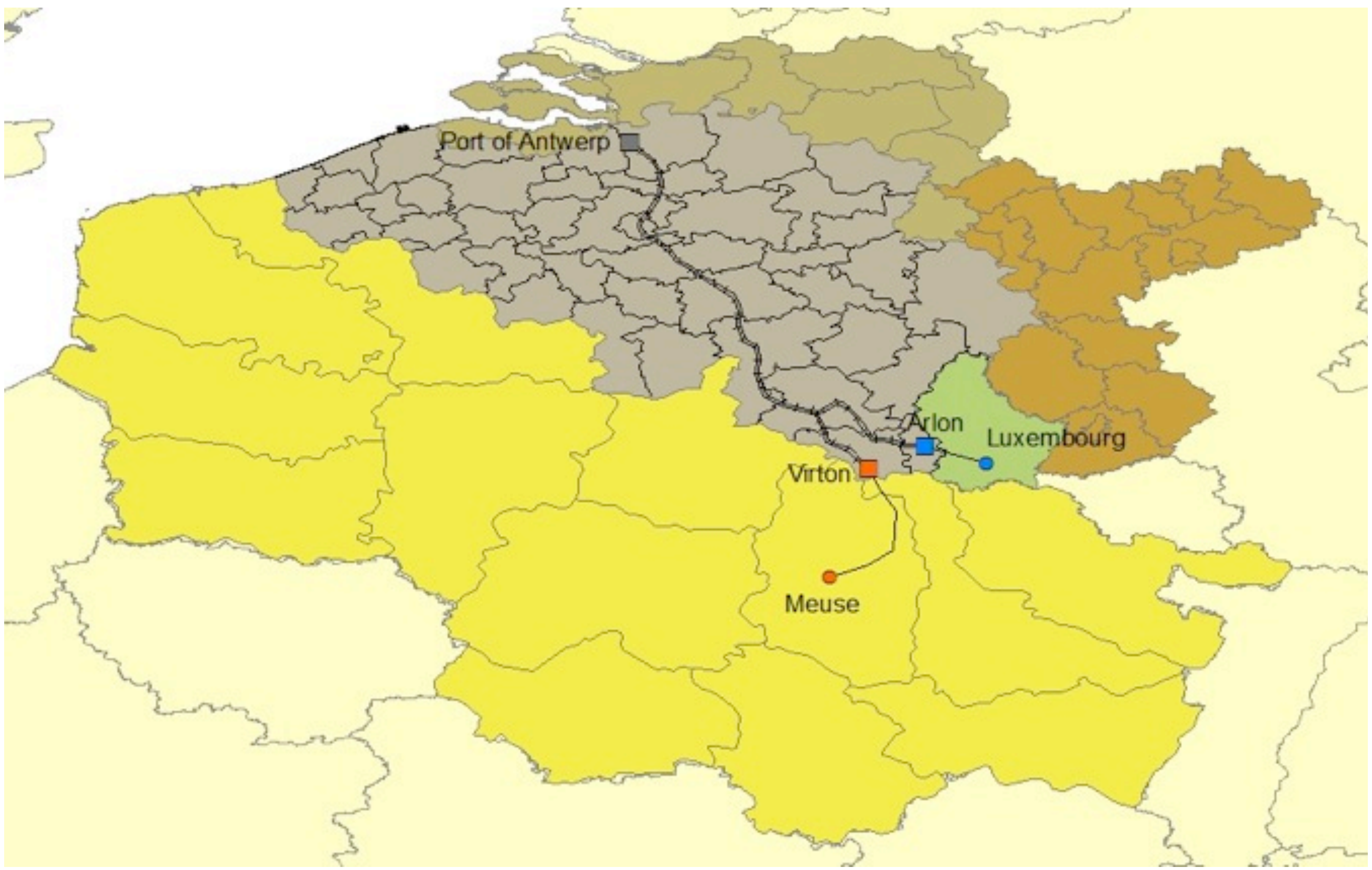
- Policy I: Only operational costs
  - a situation of free market, with no intervention from the government, where transportation and intermodal terminal operators will minimize their direct costs of operation.
- Policy II: Operational costs and subsidies
  - this is the current situation in Belgium. 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:

258 km · 77.7 km

Antwerp — Virton — Meuse

2.80 € + 4.66 € + 2.80 € + 5.21 € = **15.47 € / ton**

350.6 km

Antwerp — Meuse

15.50 €

15.50 € / ton

- 0.03 €

---

258 km · 79.0 km

Antwerp — Virton — Metz

2.80 € + 4.66 € + 2.80 € + 5.28 € = **15.54 € / ton**

323.4 km

Antwerp — Metz

14.62 €

14.62 € / ton

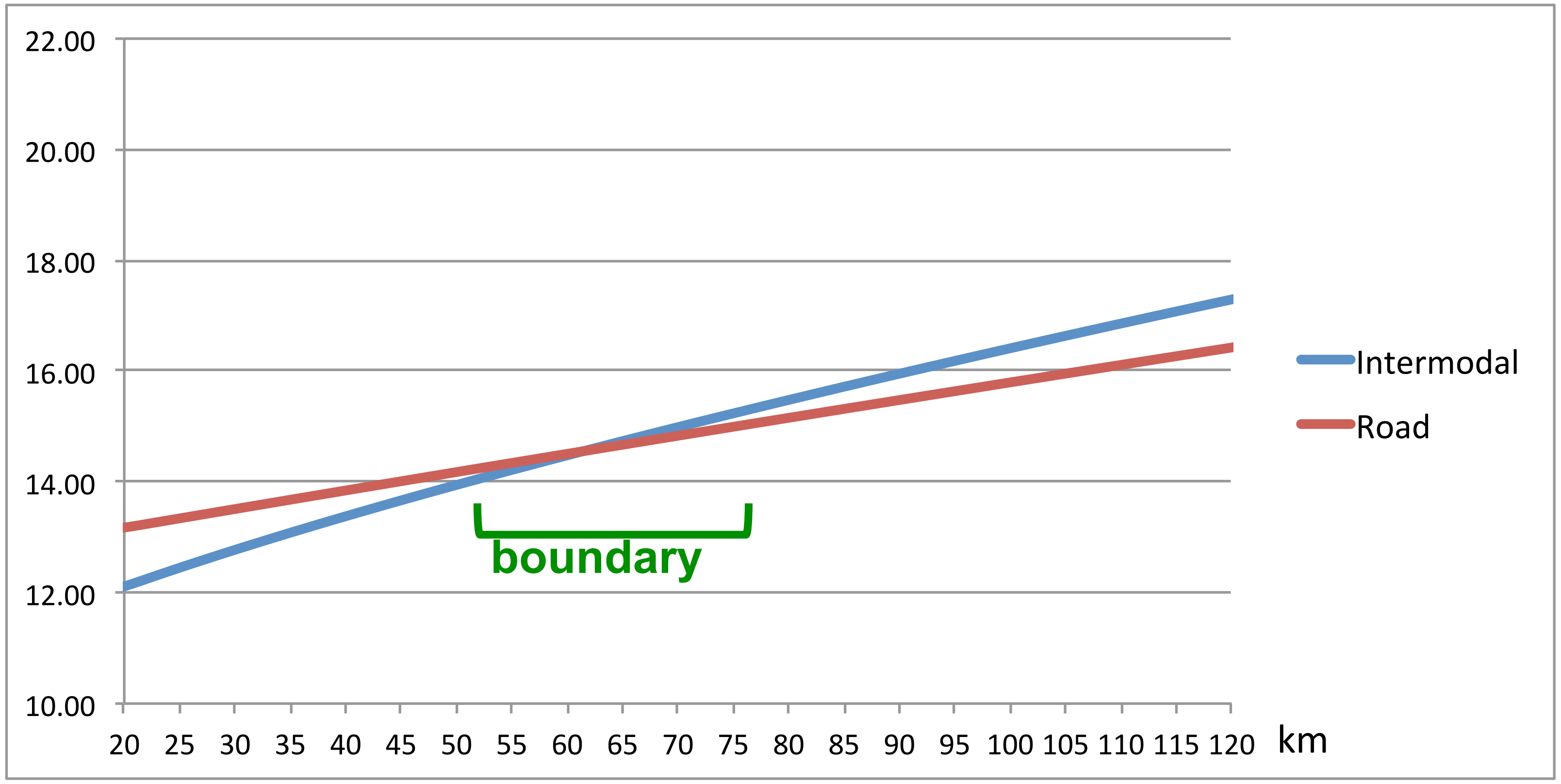
+ 0.92 €

3.3. Case Study of Belgium

There is a market area around the terminals!

Lets 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

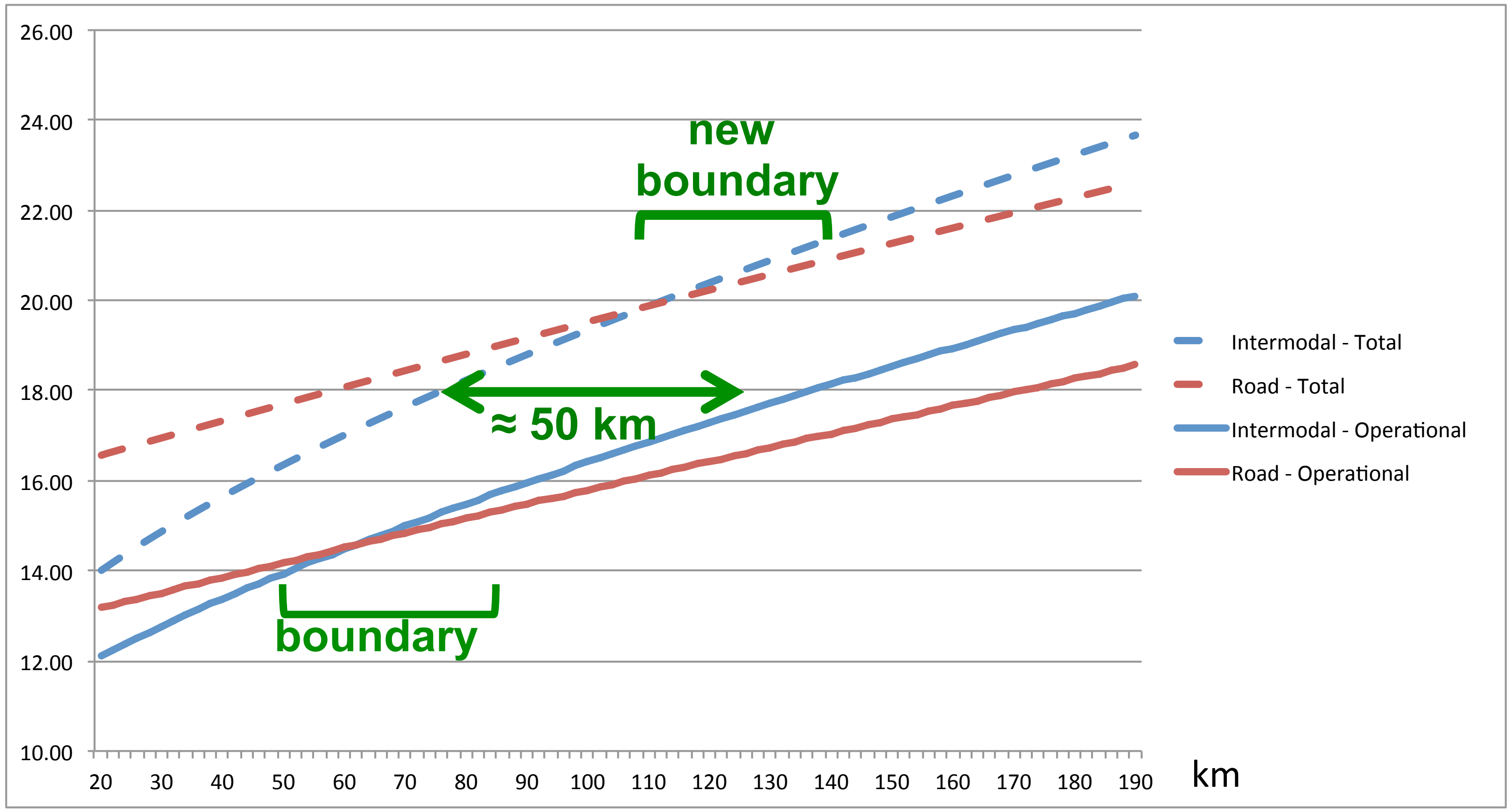


3.3. Case Study of Belgium

There is a market area around the terminals!

By considering the external costs, this catchment area extends:

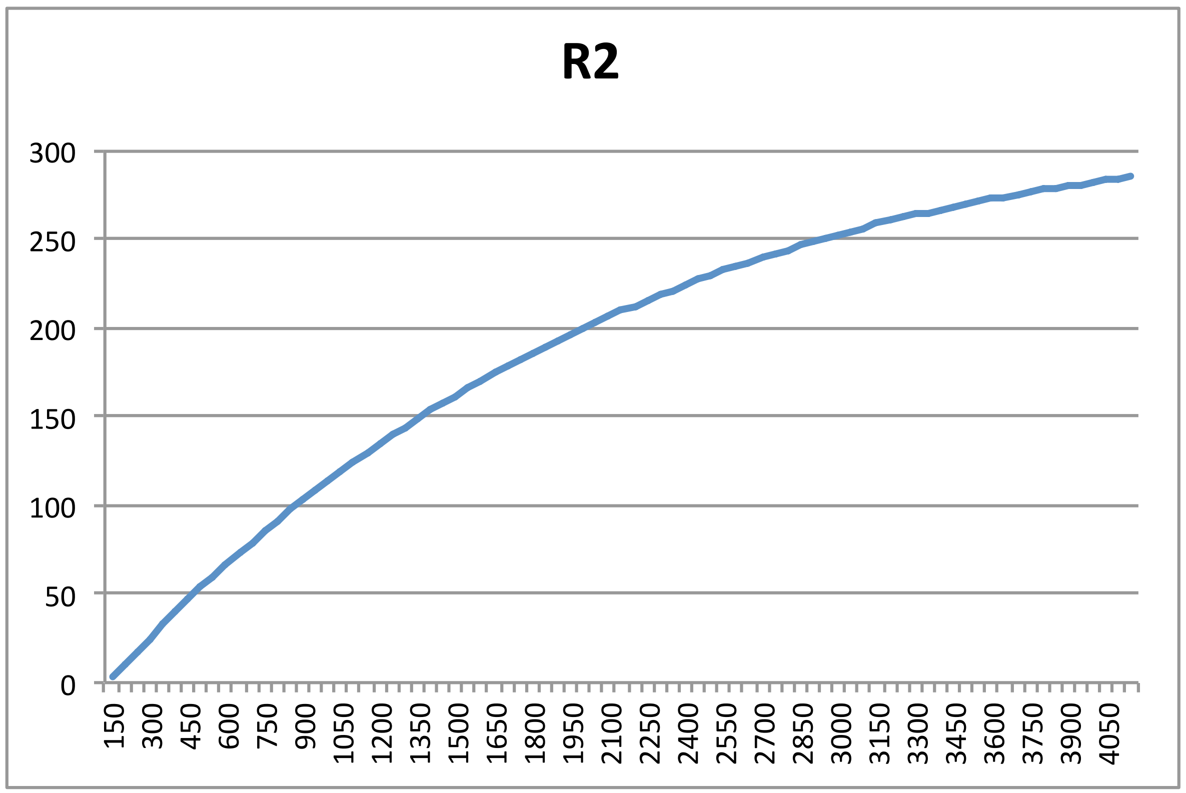
Operational and external costs per tone by distance between terminal and node

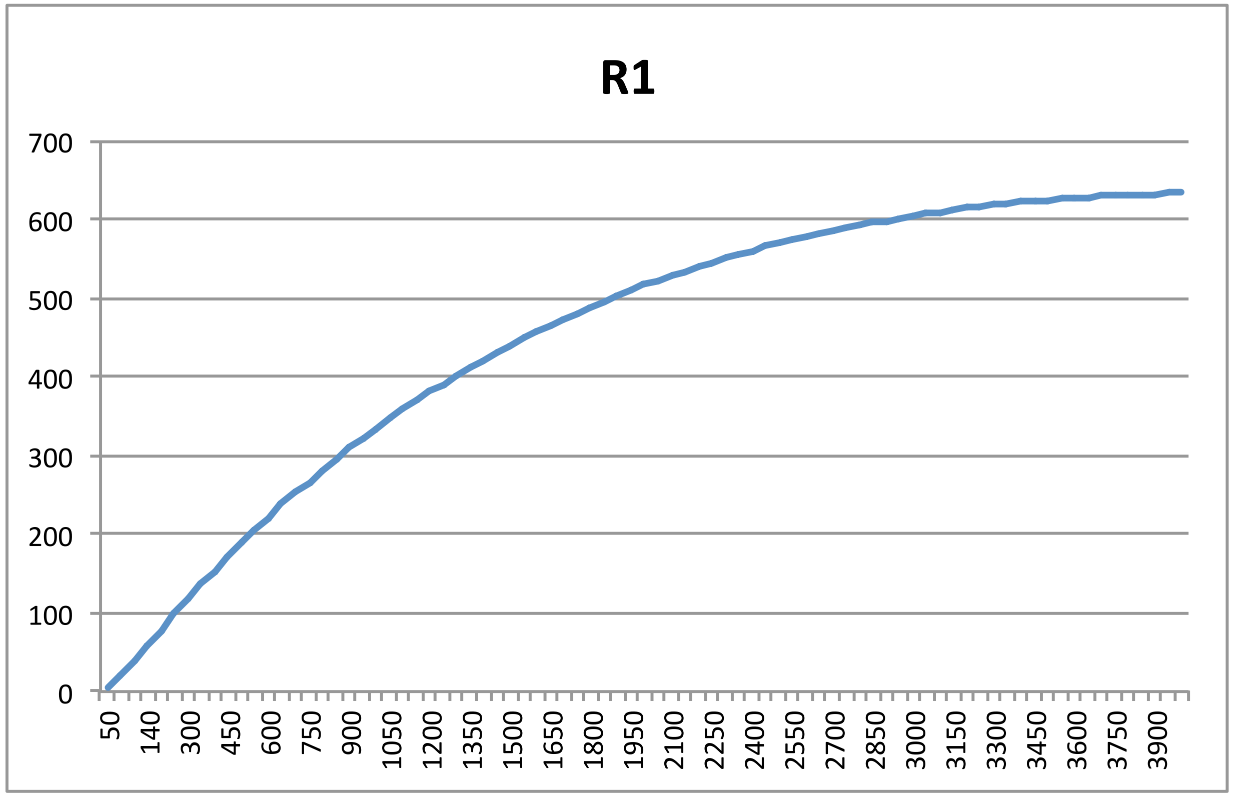


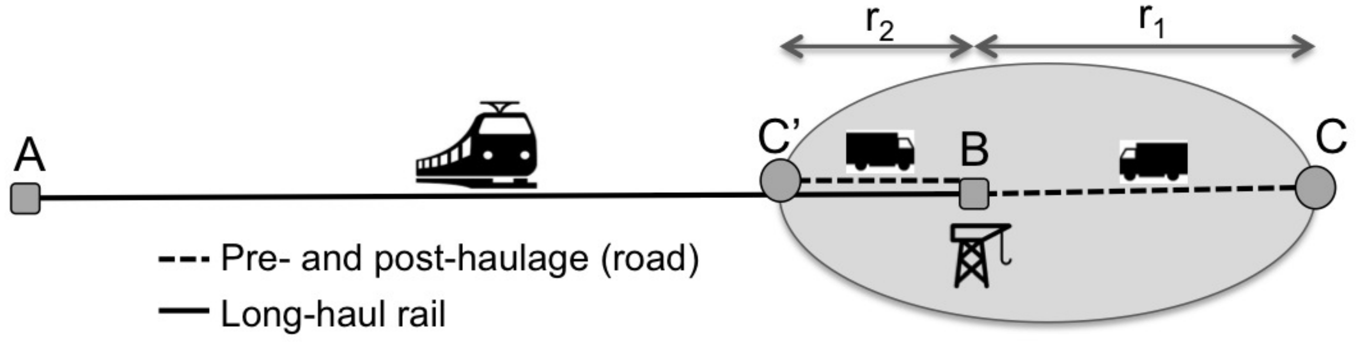
3.3. Case Study of Belgium

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

By considering operational costs only, it seems there is a maximum distance (r1 = 285 km; r2 = 630 km)







3.3. Case Study of Belgium

Summary of the results - terminals

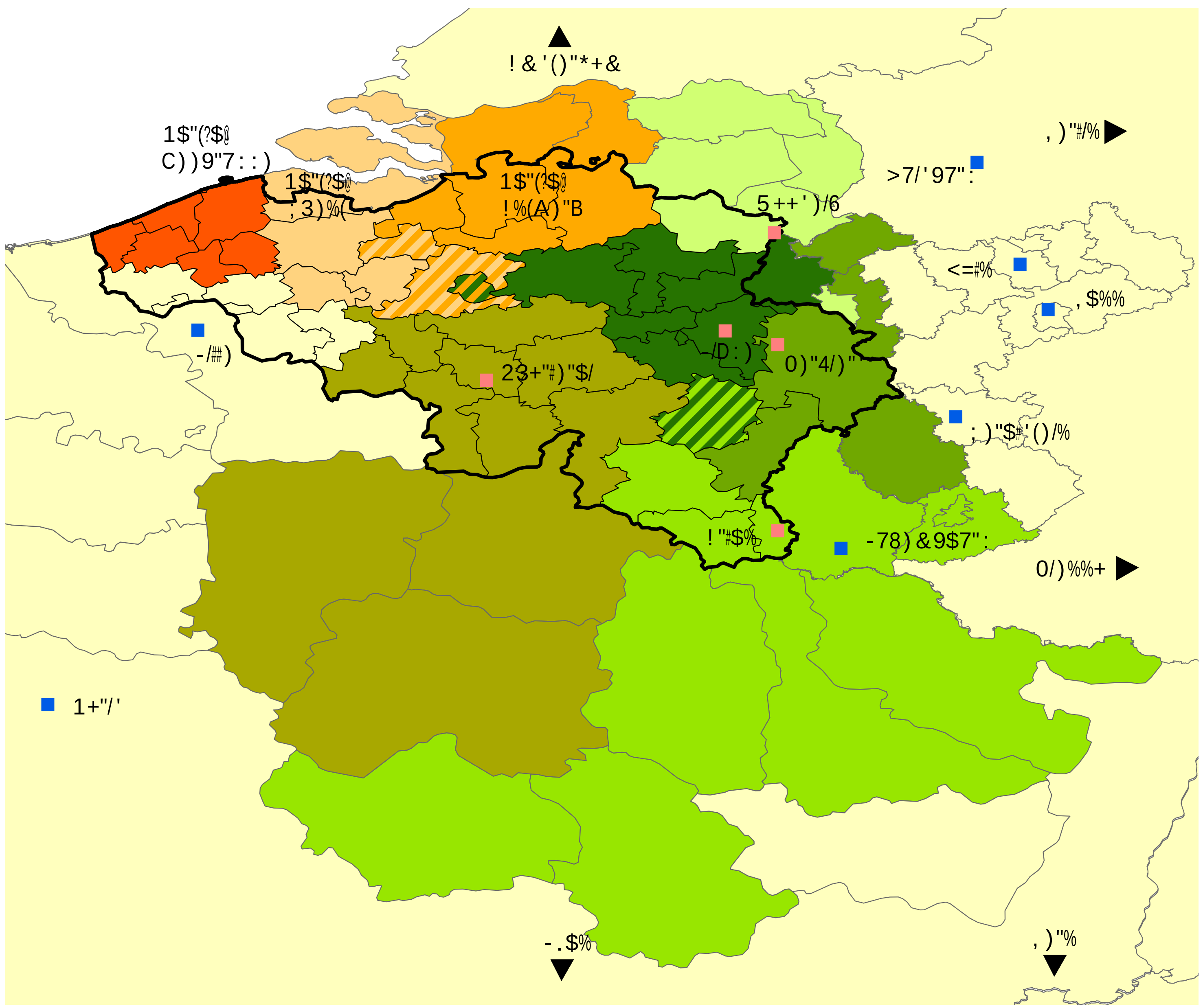
	Policy			
p	I	II	III	IV
1	10	5	10	5
2	10,13	5,13	10,13	5,13
3	4,10,13	4,5,13	4,10,13	4,5,13
4	4,8,10,13	3,4,10,13	4,5,10,13	3,4,10,13
5	4,8,10,11,13	3,4,7,10,13	4,5,8,10,13	3,4,8,10,13
6	1,4,8,10,11,13	1,3,4,8,10,13	1,4,5,8,10,13	1,3,4,8,10,13
7	1,4,5,8,10,11,13	1,3,4,8,10,12,13	1,4,5,8,10,11,13	1,3,4,8,10,12,13
8	1,4,5,8,9,10,11,13	1,3,4,8,9,10,12,13	1,4,5,8,9,10,11,13	1,3,4,8,10,12,13,14
9	1,2,4,5,8,9,10,11,13	1,3,4,8,9,10,12,13,14	1,4,5,8,9,10,11,13,14	1,3,4,8,9,10,12,13,14
10	1,2,4,5,8,9,10,11,12,13	1,3,4,8,6,9,10,12,13,14	1,2,4,5,8,9,10,11,13,14	1,3,4,6,8,9,10,12,13,14

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

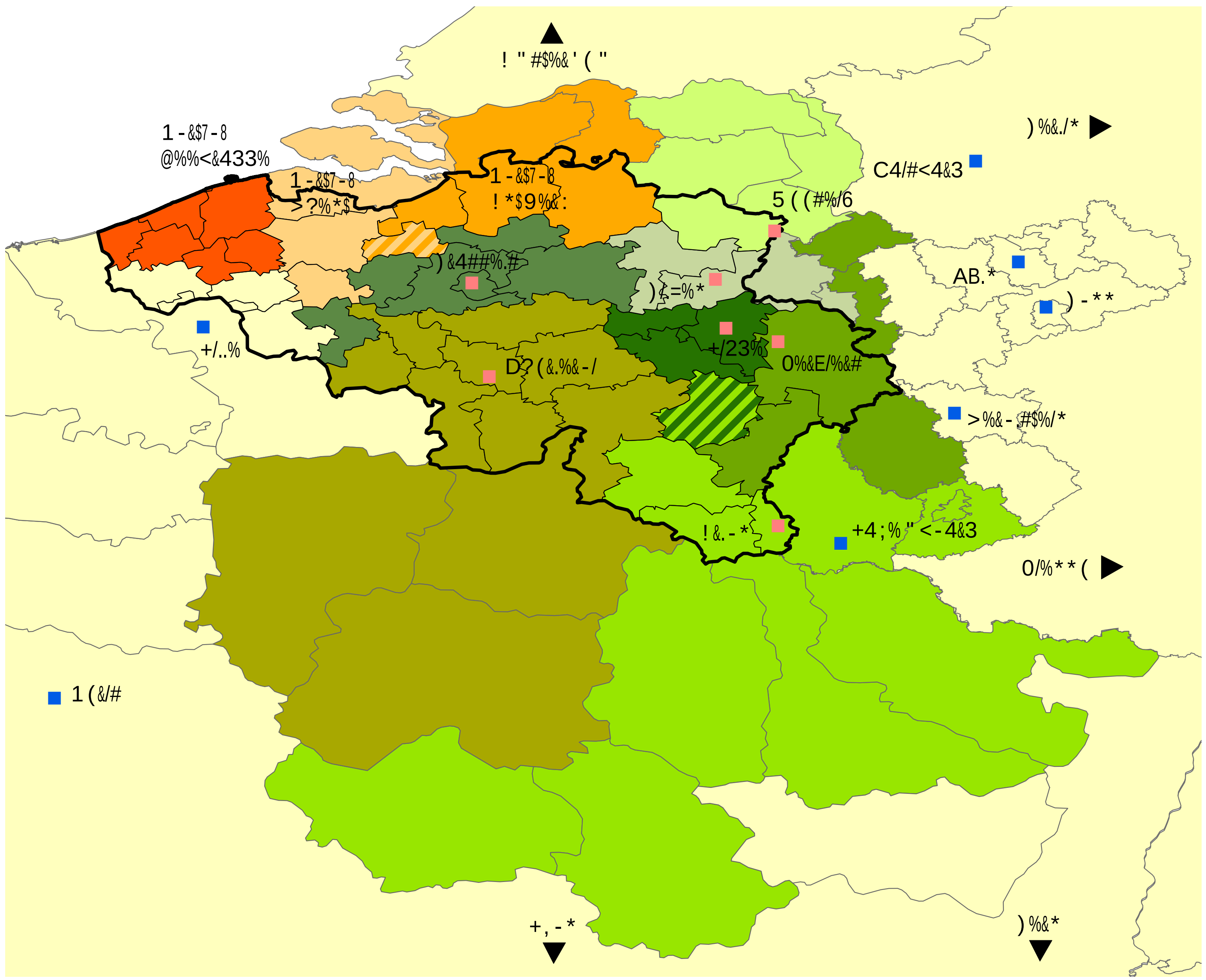
Policy I

Operational Costs (p = 5)



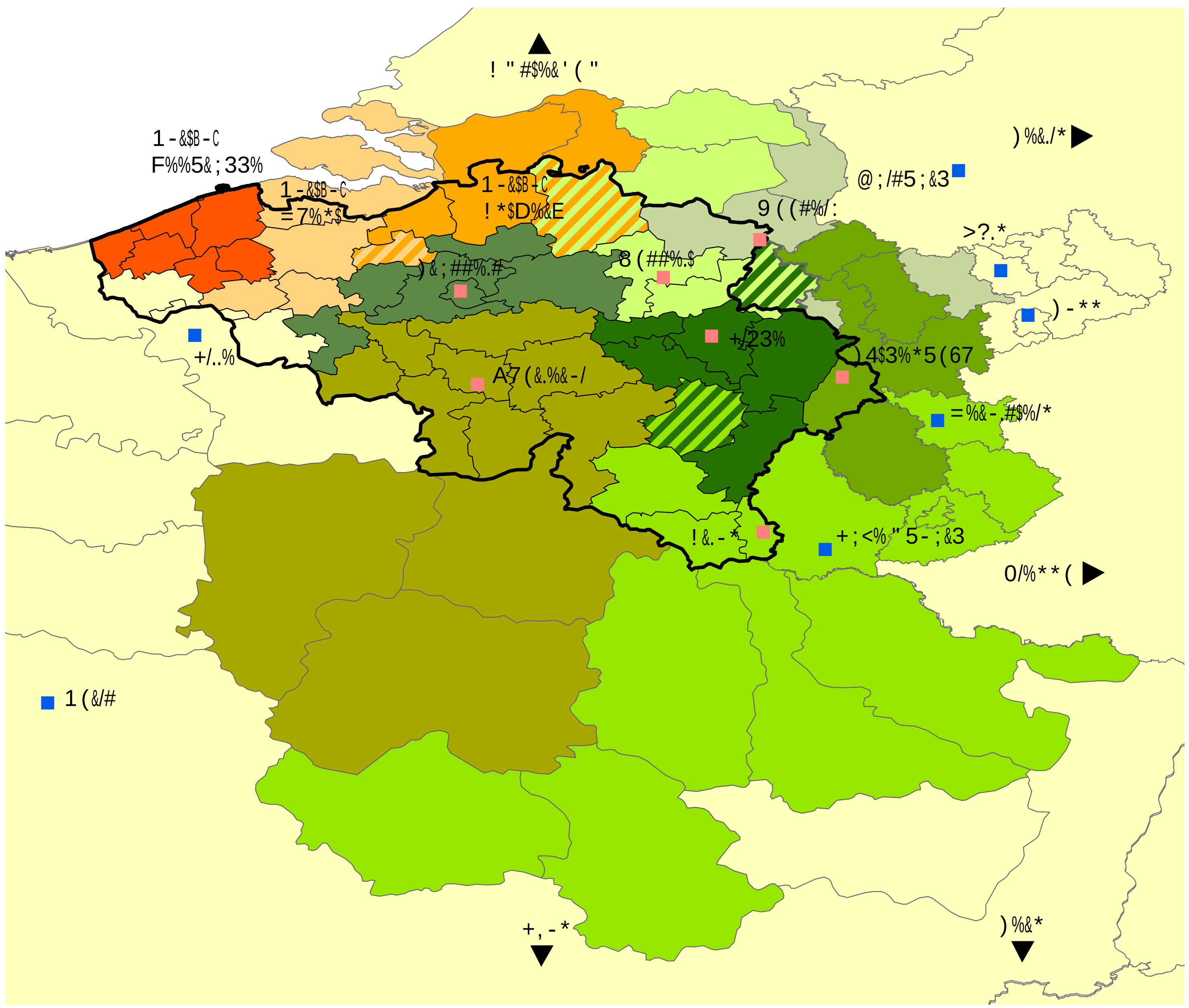
3.3. Case Study of Belgium

Policy I Operational Costs ($p = 7$)



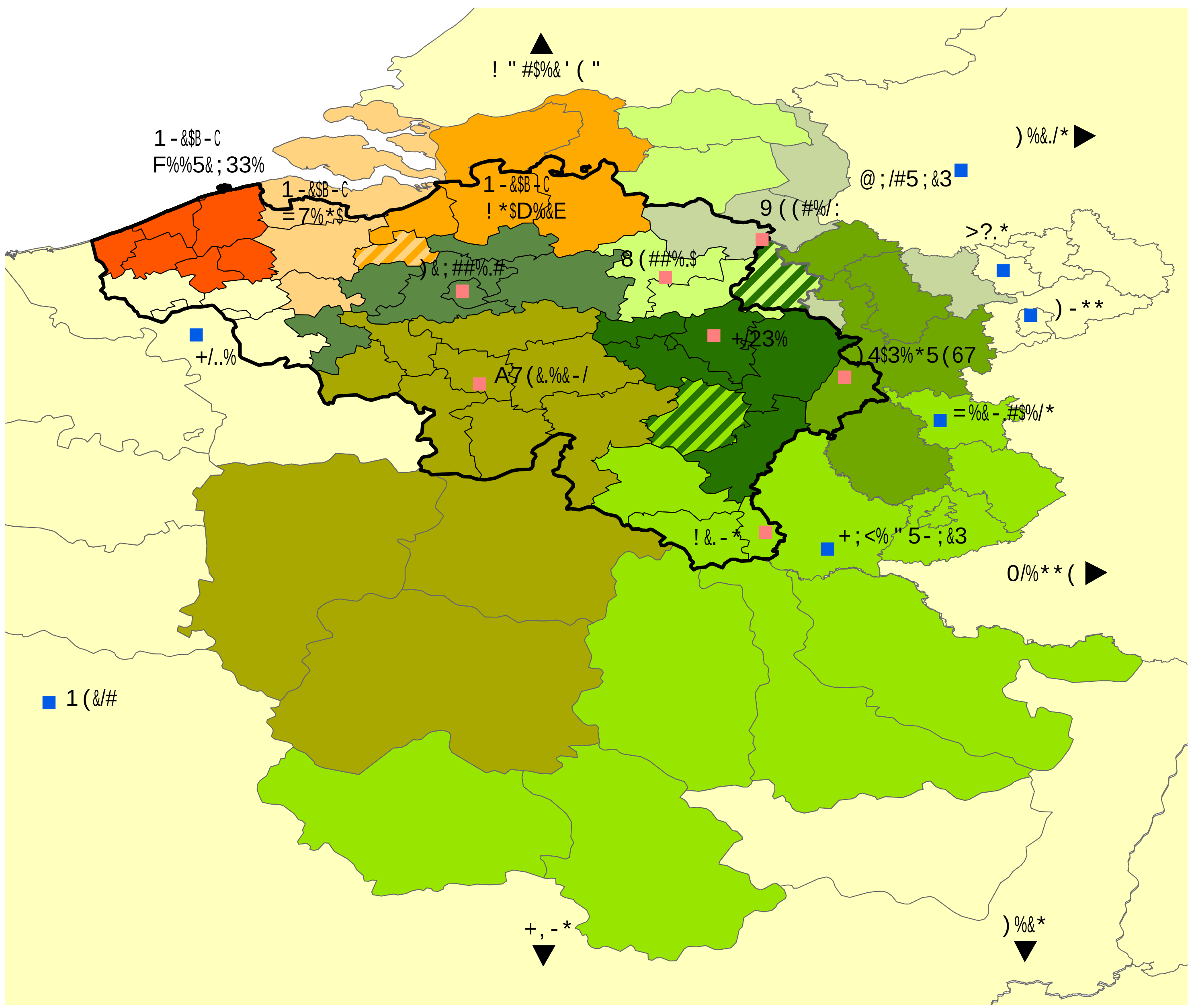
3.3. Case Study of Belgium

Policy II Operational Costs and Subsidies (p = 7)



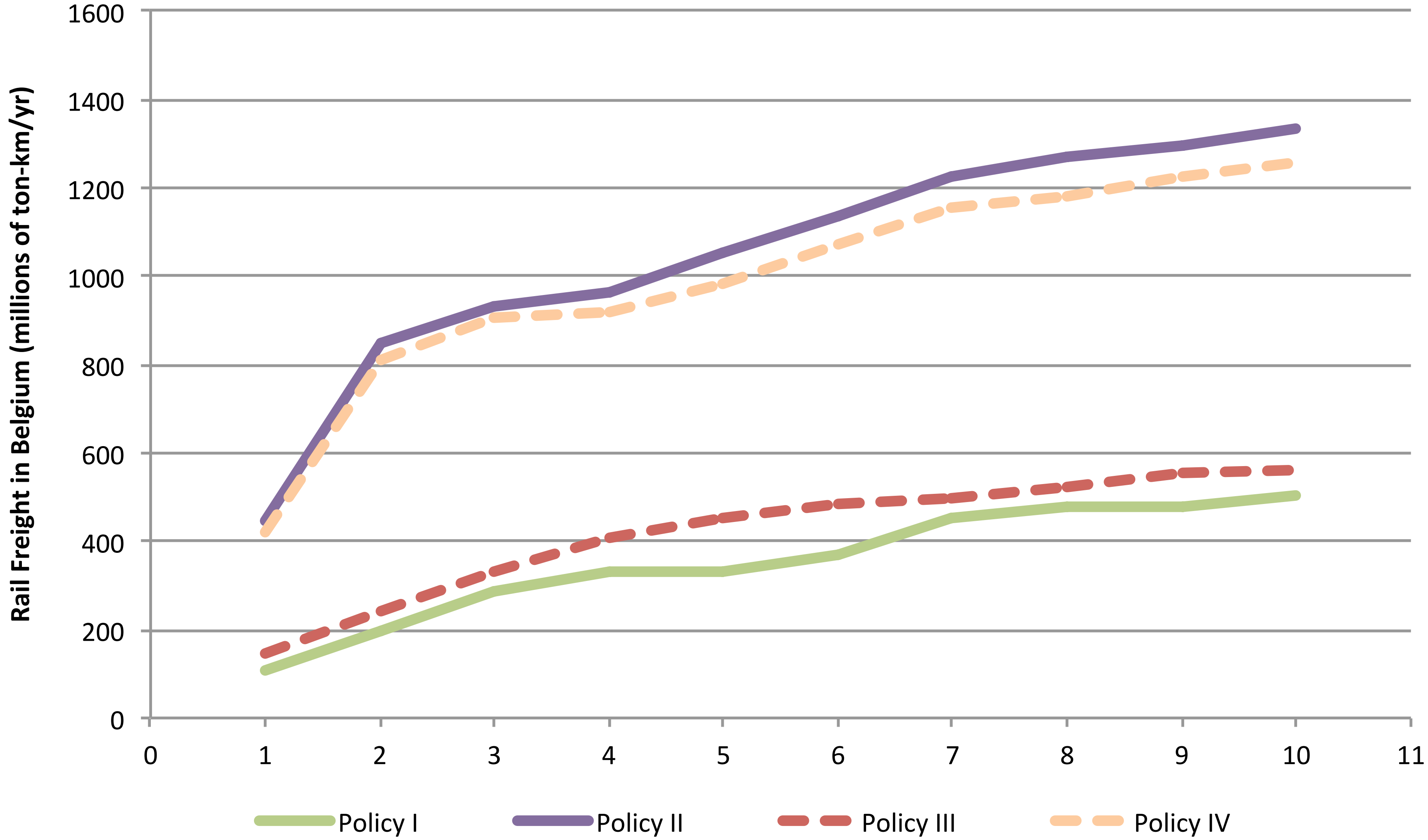
3.3. Case Study of Belgium

Policy IV Operational Costs, External Costs and Subsidies (*p* = 7)



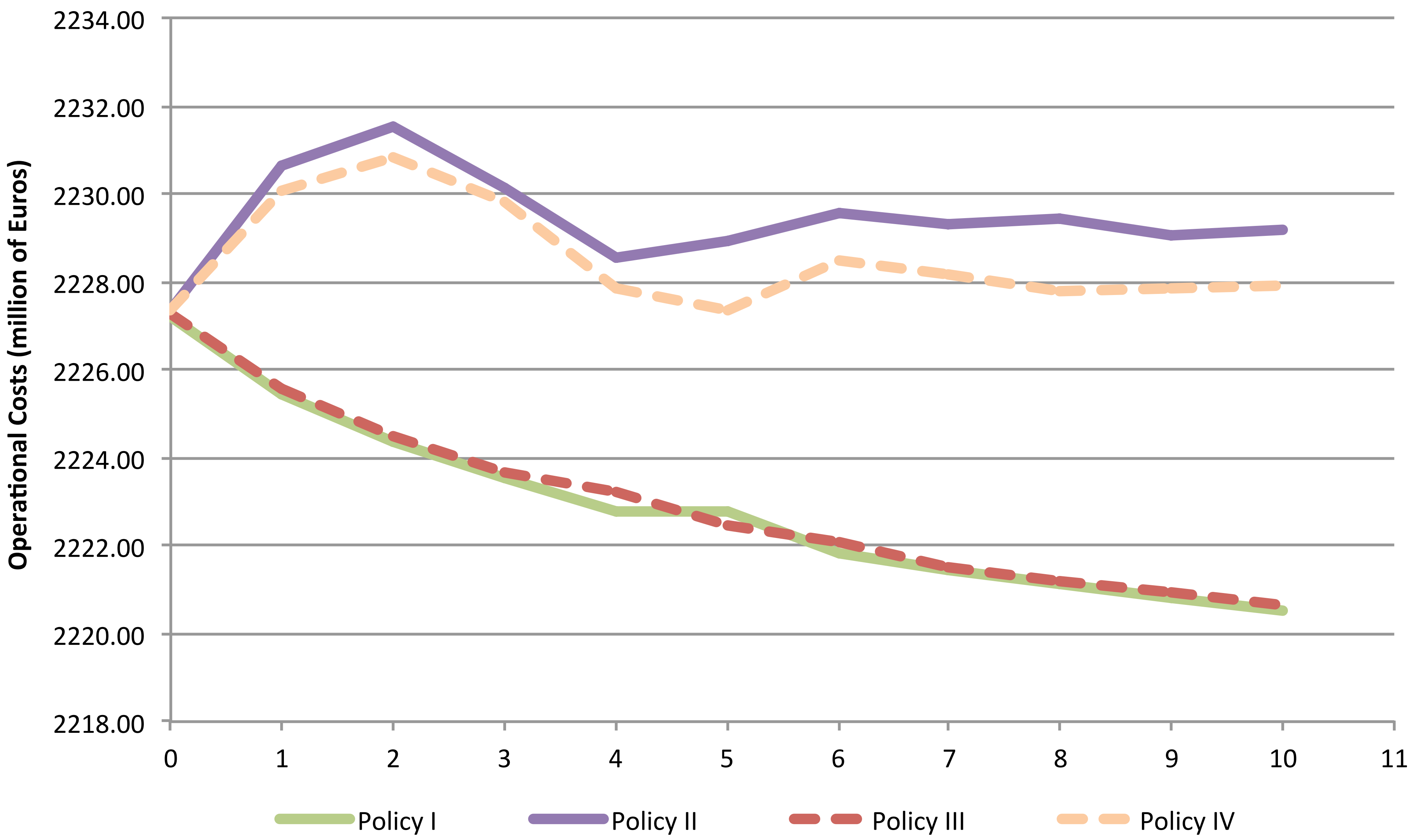
3.3. Case Study of Belgium

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



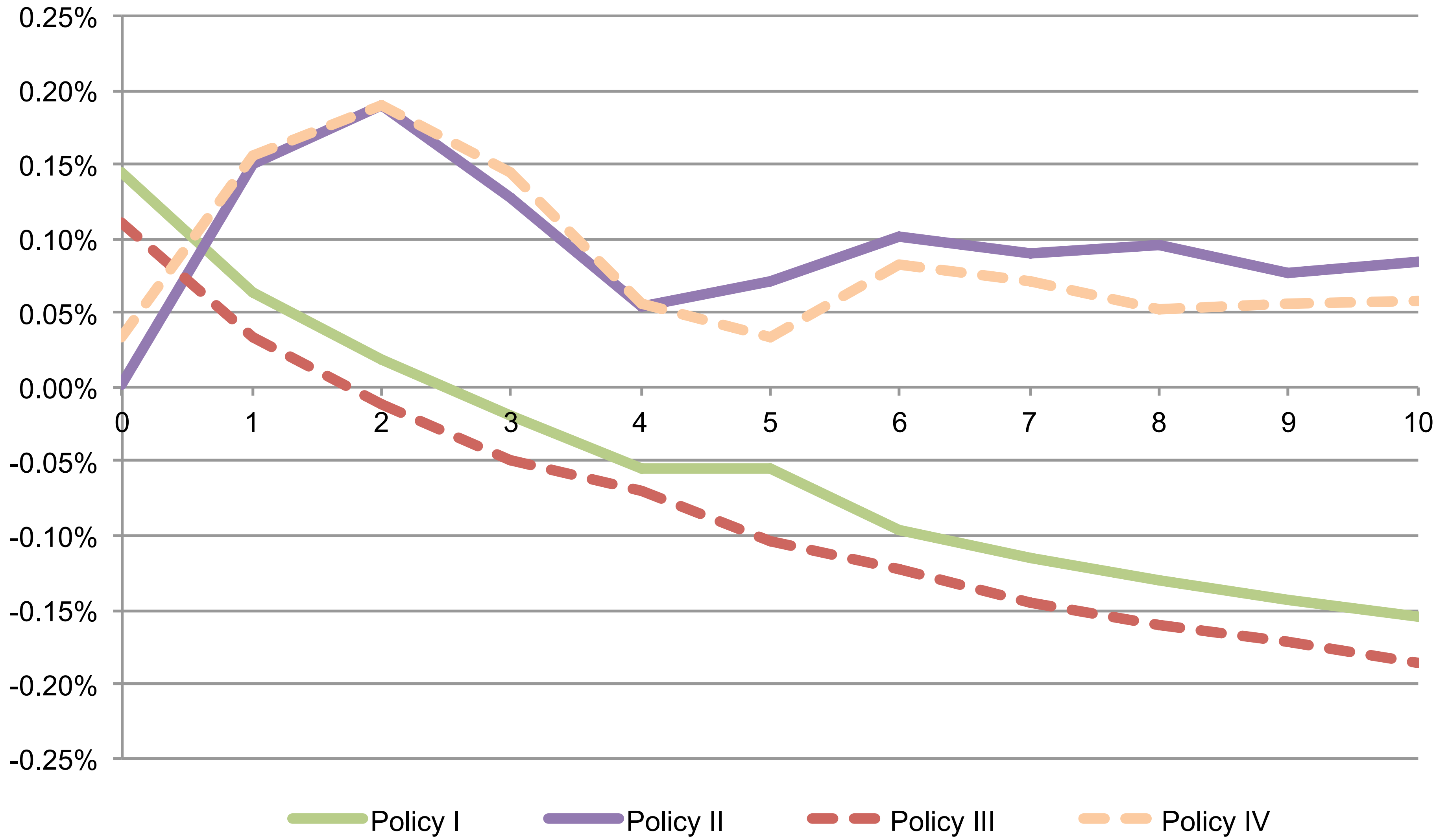
3.3. Case Study of Belgium

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

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