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Integrated Urban Hierarchy and Transportation Network Planning

Application to the Centro Region of Portugal

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Introduction [1]

- The spatial distribution of urban centers and transportation infrastructure has considerable implications on the economic and social development of a country (or region).
- In particular, this is a major issue in the European Union, formally recognized in the European Spatial Development Perspective (signed by the Council in 1999), whose policy guidelines include:
  - "development of a balanced and polycentric urban system"
  - "securing parity of access to infrastructure and knowledge".
- Specifically, what is at stake is the accessibility (easiness of access) of population to facilities/services that typically are available in cities – such as schools/education and hospitals/health care.

Introduction [2]

- Within spatial development plans, there are two main types of actions that can be implemented to improve accessibility to facilities (services):
  - Upgrade the hierarchic level of urban centers (each level being associated with a "consistent" set of services)
    - 1st level: elementary schools & basic health care units
    - 2nd level: secondary schools & local hospitals
    - 3rd level: universities & central hospitals
  - Upgrade the hierarchic level of transportation links (higher levels correspond to higher speeds)
    - 1st level: slow 2-lane, 60 kph
    - 2nd level: fast 2-lane, 90 kph
    - 3rd level: 4-lane, 120 kph (expressway)

Introduction [3]

- In this presentation, we describe an optimization model for integrated urban hierarchy and transportation network planning.
- The model is intended at helping to find strategic-level answers to the following question:

  "Which urban centers and which transportation links of a given region should be promoted to a new level of hierarchy so as to maximize the accessibility of population to the services of all levels available in the region?"
- The practical interest of the model is illustrated with an application to a Portuguese planning region (the Centro region).

Outline

- Introduction
- Literature Overview
- Optimization Model
- Model Solving
- Real-World Application
- Conclusion

Literature Overview[1]

- Traditionally, urban hierarchy planning and transportation network planning – have been dealt with separately in the optimization literature.
- Urban hierarchy planning problems can be addressed through hierarchical (or multi-level) facility location models
  - Surveys: Narula (1984), Klose & Drexl (2005), Şahin & Sürai (2007) and Melo et al. (2009)
  - Urban hierarchy planning model: Antunes et al. (2009) – does not consider transportation network actions; but takes population dynamics effects into account.
- In the facility location models, accessibility gains are typically achieved through the introduction of new facilities, but Berman et al. (1992, 1994) consider instead the improvement of transportation networks.

Literature Overview[2]

- Transportation network design problems have been addressed through a wide variety of optimization models (continuous and discrete/multilevel)
    - Surveys: Magnanti & Wong (1984) ,Yang & Bell (2001) /RND
    - Multilevel transportation network planning models: Current et al. (1986), Jansson (1991), Balakrishnan et al. (1994), Antunes et al. (2003), Yoon & Current (2008), Santos et al. (2009), Obreque et al. (2010)
- Coupled facility location and network design models: Melkote and Daskin (2001a, 2001b) – single-level (building new facilities and new transportation links).

Optimization Model [1]

Assumptions

- A class of facilities is associated with each level of urban hierarchy. Lower-level services may always be obtained from higher-level centers.
- People residing in any urban center require all levels of service and travel to the closest center offering the adequate level of service.
- The travel time between two centers depends on the level of the network link that connects them. The higher the level of the link, the shorter the travel time.

Resources {

- The number of urban centers to promote to each level of hierarchy is pre-defined.
- Improvements in the transportation network must not exceed a pre-defined length, expressed in length reference units that take into account the fact that a different unit cost (i.e., cost per km) is associated with each link-level.

Optimization Model [2]

Decision variables

y_{il} = 1 if center i is designated as level-l center, y_{il} = 0 otherwise

Initial formulation

r_{ijm} = 1 if the undirected link $\{i,j\}$ is designated as level-m link, r_{ijm} = 0 otherwise

x_{ijlm} – flow of people using the directed level-m link (i,j) en route to obtaining level-l service

Improved formulation

x^{k}_{ijlm} – fraction of flow from center k using level-m link (i,j) en route to obtaining level-l service

Optimization Model [3]

Mathematical formulation

- Combines a facility location model with a minimum cost flow model

$$\min F = \sum_{(i,j)\in I} \sum_{l\in L} \sum_{m\in M} t_{ijm} x_{ijlm}$$

Minimize total travel time to all levels of urban centers (weighted)

$$\sum_{i\in N} \sum_{m\in M} x_{ijlm} + u_j = \sum_{i\in N_S} \sum_{m\in M} x_{jilm}, \forall j \in N_S, l \in L$$

Flow conservation constraints

$$x_{ijlm} \le U \times r_{ijm}, \forall \{i,j\} \in I_1, l \in L, m \in M$$

$$x_{jilm} \le U \times r_{ijm}, \forall \{i,j\} \in I_1, l \in L, m \in M$$

$$x_{iSlm} \le U \times y_{il}, \forall i \in N, l \in L, m \in M$$

Assignment constraints – assign traffic to transportation links and urban centers

$$\sum_{i\in N} y_{il} \le Y_l, \forall l \in L$$

Resource constraints – number of urban centers of each level

$$y_{i(l-1)} \ge y_{il}, \forall i \in N, l \in \{L \mid (l-1) \ge 2\}$$

Urban hierarchy constraints

$$\sum_{m\in\{M \mid m>1\}} r_{ijm} \le 1, \forall \{i,j\} \in I_1$$

Transportation hierarchy constraints

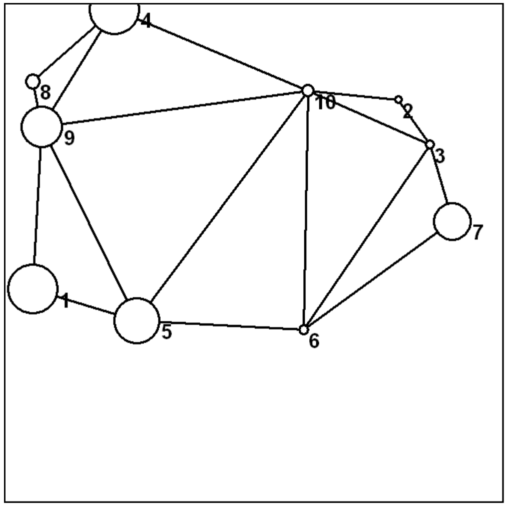
$$\sum_{\{i,j\}\in I_1} \sum_{m\in M} w_{ijm} r_{ijm} \le W$$

Resource constraint – weighted length of transportation network

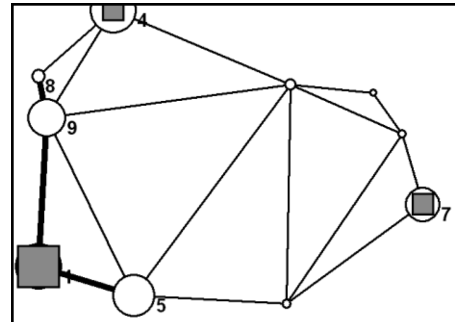
Optimization Model [4]

Application Example (Random)

How to improve accessibility in the region below for a 3-level urban hierarchy and transportation network, with $Y_3 = 1$, $Y_2 = 3$, and $2*W_3+W_2 \leq 150$?

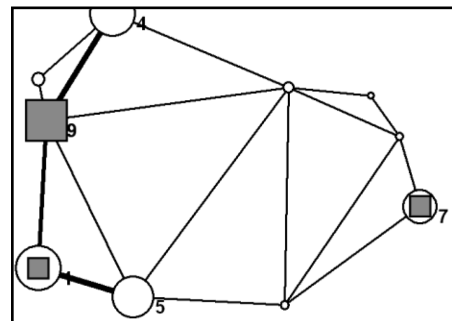


Center	Population
1	90
2	13
3	15
4	91
5	83
6	17
7	68
8	25
9	75
10	21
Region	498



Model solution

***F* = 20517**



Incremental solution (U+T)

***F* = 21981 (+7% !)**

Model Solving [1]

Initial vs Improved Formulation

Instance				Result	Formulation					
					Initial			Improved		
Centers	Links*	Y_3, Y_2	W		Gap	Time (seconds) LP	Time (seconds) IP	Gap	Time (seconds) LP	Time (seconds) IP
10	19	1, 3	150	Avg.	43.1%	0.3	5.5	10.4%	1.1	3.0
				Max.	60.3%	1.0	14.1	16.7%	2.0	4.6
				Min.	24.2%	< 0.0	2.3	2.4%	1.0	1.5
20	45	1, 3	50	Avg.	40.9%	2.8	62.0	7.0%	7.6	18.2
				Max.	49.8%	4.0	140.9	9.4%	15.0	38.2
				Min.	30.3%	2.0	16.7	3.5%	5.0	7.2
			150	Avg.	55.9%	3.4	2963.9	10.7%	13.0	155.1
				Max.	64.2%	5.0	8704.3	13.8%	18.0	384.3
				Min.	44.2%	2.0	237.4	6.2%	9.0	28.8
		1, 5	50	Avg.	40.4%	2.7	36.2	6.1%	6.0	12.9
				Max.	51.4%	4.0	108.4	8.3%	10.0	25.1
				Min.	29.1%	2.0	14.1	3.7%	4.0	5.1
			150	Avg.	55.2%	2.9	1599.3	10.1%	10.7	123.1
				Max.	64.2%	4.0	7610.8	15.3%	17.0	228.6
				Min.	44.1%	2.0	171.0	6.5%	7.0	35.1
50	127	1, 10	50	Avg.	54.1%	16.7	11792.4	5.1%	358.3	3691.2
				Max.	58.2%	28.0	31412.6	5.9%	560.0	6334.4
				Min.	45.6%	10.0	5268.8	4.1%	164.0	1407.6
Total				Avg.	48.3%	-	-	8.2%	-	-
				Max.	64.2%	-	-	16.7%	-	-
				Min.	24.2%	-	-	2.4%	-	-

* Average number of links in the *n*-center instances

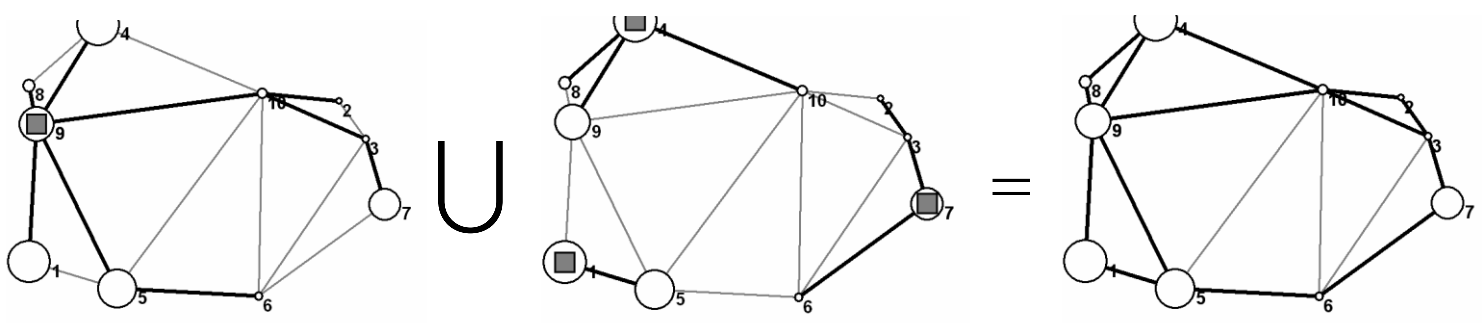
11792.4
31412.6
5268.8

3691.2
6334.4
1407.6

Model Solving [2]

Heuristic method

- Nested Partition Algorithm–based heuristic (Shi & Ólafsson, 2000)
- Three stages:
    1. Selects the links more likely to be improved – e.g. the union of the links used to reach the centers to upgrade, considering one hierarchic level at a time.
    2. Solves the model (improved formulation) allowing improvements only on the selected links
    3. Performs a link-interchange procedure (in order to guarantee that at least a local optimum is reached).



Model Solving [3]

Optimum vs heuristic solution

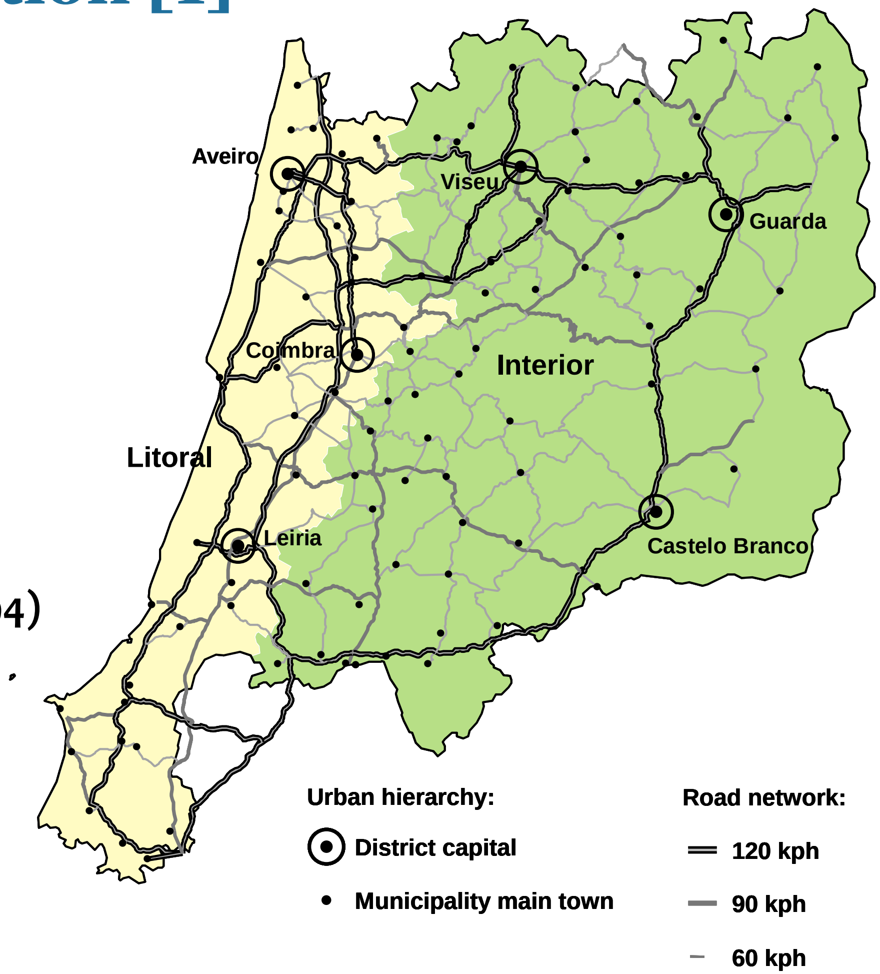
Instance set				Optimum solution		Heuristic solution						
				Time (sec.)		Optimum found	Deviation		Time (sec.)		Links**	
Centers	Links*	Y_3, Y_2	W	Avg.	Max.		Avg.	Max.	Avg.	Max.	Avg.	Max.
10	19	1, 3	150	3,0	4,6	10	-	-	2,1	3,0	12	14
20	45	1, 3	50	18,2	38,2	10	-	-	9,7	20,4	28	30
			150	155,1	384,3	7	0,1%	0,3%	23,7	49,0		
		1, 5	50	12,9	25,1	10	-	-	7,9	14,1	27	28
			150	123,1	228,6	6	0,8%	1,9%	19,4	30,4		
50	127	1, 10	50	3691,2	6334,4	9	1,2%	1,2%	755,2	2615,4	71	74

* Average number of links in the n-center instances
** Number of links in the reduced netw orks

Real-World Application [1]

Basic data

- Centro Region of Portugal
- Area: 28,000 km²
- Population: 2,3 million
- 100 municipalities
- 2 urban hierarchy levels:
  - District capital (6)
  - Municipality main town (94)



Real-World Application [2]

Strategic options

- Strategic options for the Centro Region adopted in the National Spatial Policy Program (PNPOT – Decree-Law 58/2007)
  - Promote the polycentric nature of the urban system of the region through the support of sub-regional urban systems.
  - Strengthen the structural potential of the major roads in the region in order to encourage complementarities among urban centers (especially in the Interior) and to assure the intra-regional connections that are relevant for regional cohesion.

- Perfect!

  But what exactly should be done?

Real-World Application [3]

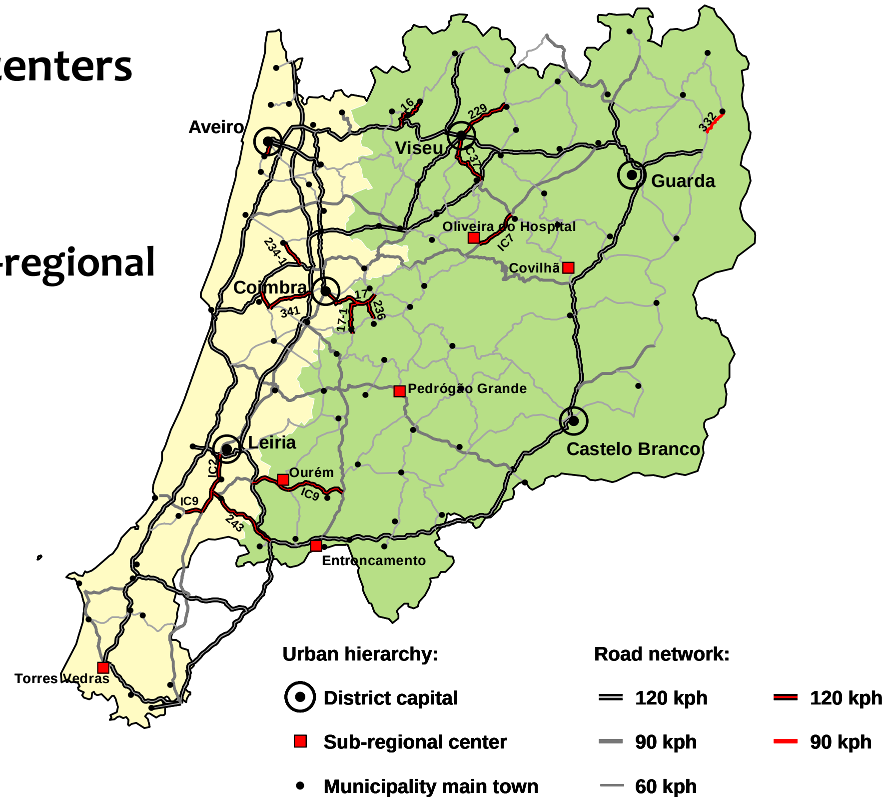
Planning Scenarios

Scenario	Regional capital	Number of sub-regional centers	Length of link improvements (km)	Weight of Interior
B	0	12	200	2
W	0	12	400	2
Y	0	18	200	2
E	0	12	200	1

Real-World Application [4]

Results – Scenario B (base)

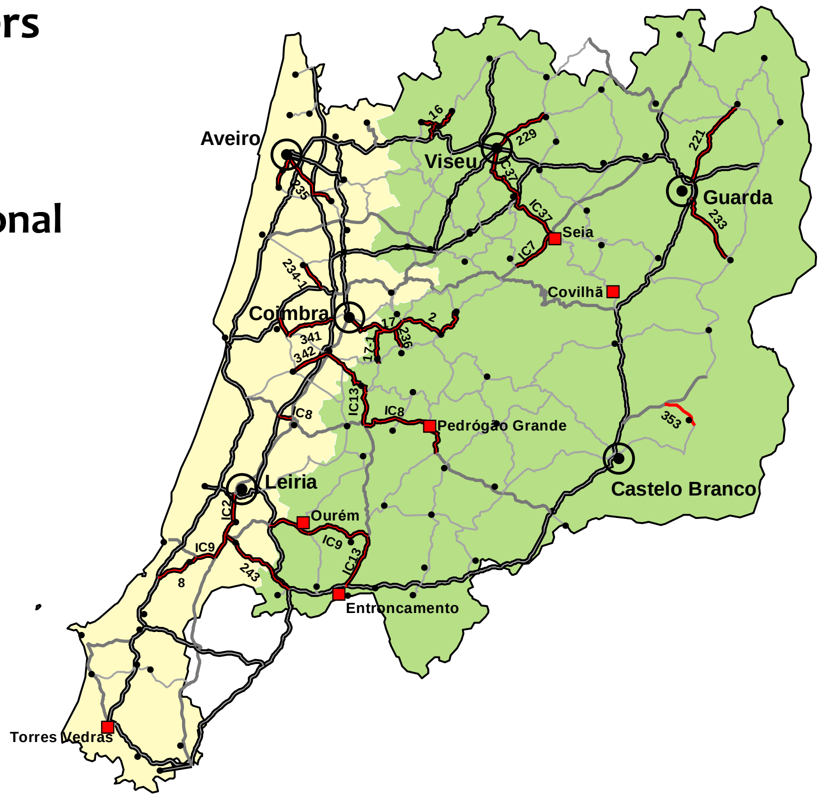
- Number of sub-regional centers
  - Litoral: 1
  - Interior: 5
- Weighted travel time to sub-regional centers
  - Litoral: 215,512 hours
  - Interior: 143,711 hours



Real-World Application [5]

Results – Scenario W (more transport)

- Number of sub-regional centers
  - Litoral: 1 (=)
  - Interior: 5 (=)
- Weighted travel time to sub-regional centers
  - Litoral: -4 %
  - Interior: -8 %

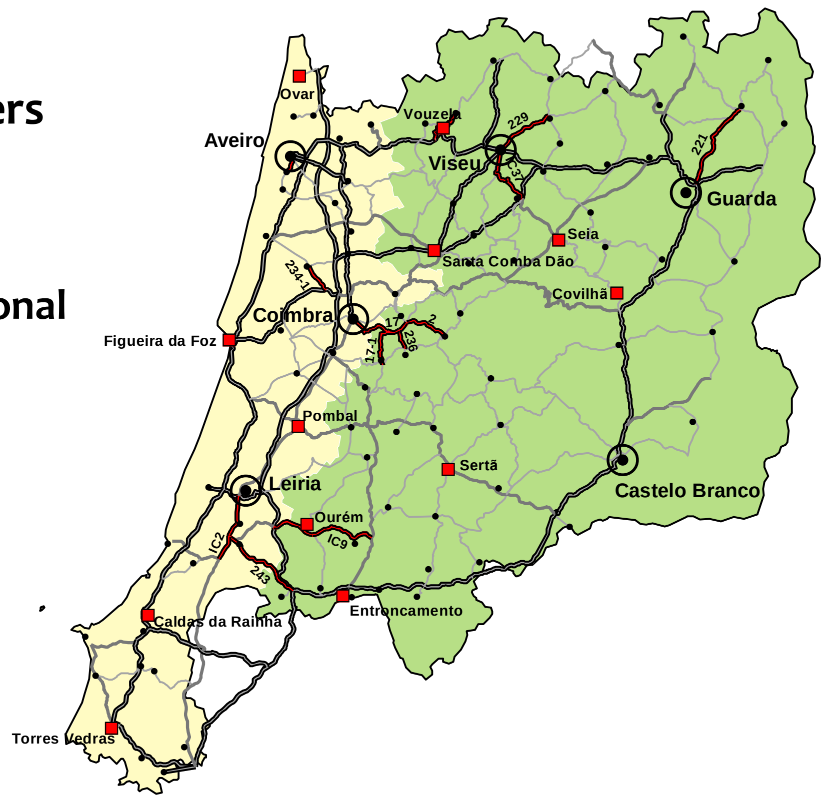


Real-World Application [6]

Results – Scenario Y (more urban)

Comparison with base scenario

- Number of sub-regional centers
  - Litoral: 5 (+4)
  - Interior: 7 (+2)
- Weighted travel time to sub-regional centers
  - Litoral: -41 %
  - Interior: -18 %

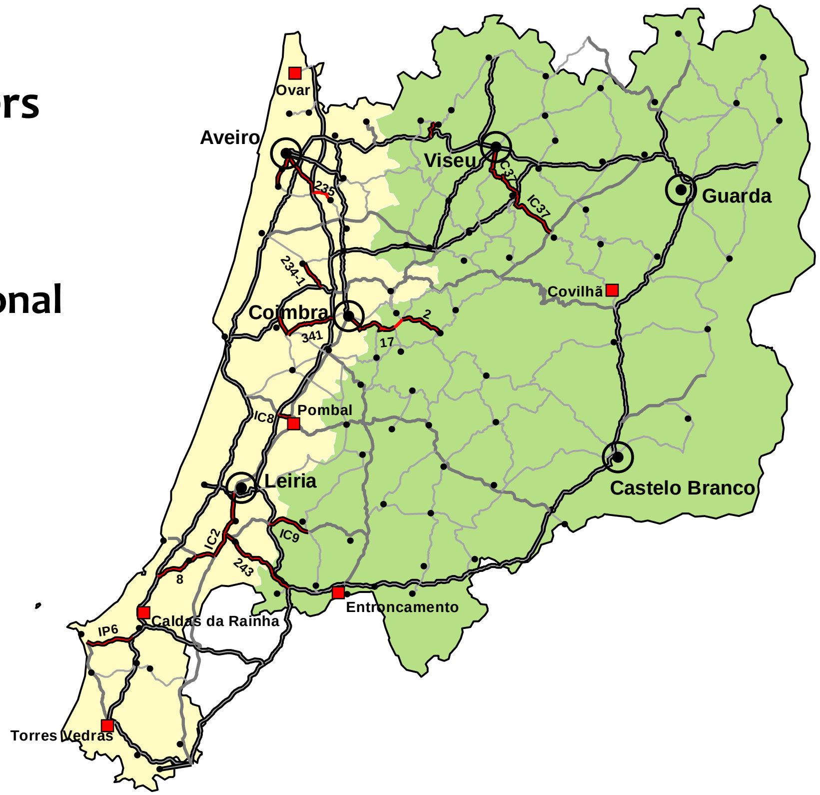


Real-World Application [7]

Results – Scenario E (equity cost)

Comparison with base scenario

- Number of sub-regional centers
  - Litoral: 4 (+3)
  - Interior: 2 (-3)
- Weighted travel time to sub-regional centers
  - Litoral: -34 %
  - Interior: -18 %



Conclusion

- An optimization model to address strategic urban hierarchy and transportation network planning issues – help in discussions / provide insights – has been presented.
- The model can already be quite useful, as demonstrated with the Centro region case study.
- However: "cities → regions are not trees". The type of urban hierarchy implicit in the model is too rigid – an out-of-fashion view.
- Future research: How can this be coped with?