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Integrated Urban Hierarchy and Transportation Network Planning
Application to the Centro Region of Portugal

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Collaboration from Oded Berman and Dmitry Krass (U. of Toronto)
is thankfully acknowledge
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
  - 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

- 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.
- 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

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

\[ r_{ilm} = 1 \text{ if the undirected link } \{i,j\} \text{ is designated as level-}m \text{ link, } r_{ilm} = 0 \text{ otherwise} \]

\[ x_{ilm} \] - flow of people using the directed level-\( m \) link \( (i,j) \) en route to obtaining level-1 service

\[ x_{ijlm}^{k} \] - 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

\[
\min F = \sum_{(i,j) \in I} \sum_{l \in L} \sum_{m \in M} c_{ijlm} x_{ijlm}
\]

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

\[
\sum_{i \in N} \sum_{m \in M} x_{ijlm} + u_j = \sum_{i \in N} \sum_{l \in L, m \in M} x_{ijlm}, \forall j \in N, I_l \in L
\]

Flow conservation constraints

\[
x_{ijlm} \leq U \times r_{ijm}, \forall \{i, j\} \in I_1, l \in L, m \in M
\]

Assignment constraints – assign traffic to transportation links and urban centers

\[
x_{jilm} \leq U \times y_{jl}, \forall i \in N, l \in L, m \in M
\]

Resource constraints – number of urban centers of each level

\[
\sum_{i \in N} y_{il} \leq Y_l, \forall l \in L
\]

\[
y_{i(l-1)} \geq y_{il}, \forall i \in N, l \in \{L | (l-1) \geq 2\}
\]

Urban hierarchy constraints

\[
\sum_{m \in \{M | m \geq 1\}} \sum_{\{i, j\} \in I_1} r_{ijm} \leq 1, \forall \{i, j\} \in I_1
\]

Transportation hierarchy constraints

\[
\sum_{\{i, j\} \in I_2} \sum_{m \in M} w_{ijm} r_{ijm} \leq W
\]

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 $2^*W_3 + W_2 \leq 150$?

<table>
<thead>
<tr>
<th>Center</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>91</td>
</tr>
<tr>
<td>5</td>
<td>83</td>
</tr>
<tr>
<td>6</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>68</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>75</td>
</tr>
<tr>
<td>10</td>
<td>21</td>
</tr>
</tbody>
</table>

Region: 498

Model solution
$F = 20517$

Incremental solution (U+T)
$F = 21981 (+7\%)$
## Model Solving [1]

### Initial vs Improved Formulation

<table>
<thead>
<tr>
<th>Instance</th>
<th>Centers</th>
<th>Links</th>
<th>$Y_1$, $Y_2$</th>
<th>$W$</th>
<th>Result</th>
<th>Initial</th>
<th>Formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gap</td>
<td>Time (seconds)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LP</td>
<td>IP</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>1, 3</td>
<td>150</td>
<td></td>
<td>Avg.</td>
<td>43.1%</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>60.3%</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>24.2%</td>
<td>&lt; 0.0</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1, 3</td>
<td></td>
<td>150</td>
<td>Avg.</td>
<td>40.9%</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>49.8%</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>30.3%</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>45</td>
<td></td>
<td>150</td>
<td>Avg.</td>
<td>55.9%</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>64.2%</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>44.2%</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1, 5</td>
<td></td>
<td>150</td>
<td>Avg.</td>
<td>40.4%</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>51.4%</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>29.1%</td>
<td>2.0</td>
</tr>
<tr>
<td>50</td>
<td>127</td>
<td>1, 10</td>
<td>50</td>
<td></td>
<td>Avg.</td>
<td>55.5%</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>64.2%</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>44.1%</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Avg.</td>
<td>54.1%</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>58.2%</td>
<td>28.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>45.6%</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Avg.</td>
<td>48.3%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>64.2%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>24.2%</td>
<td>-</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Instance set</th>
<th>Optimum solution</th>
<th>Heurisitic solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (sec.)</td>
<td>Deviation</td>
</tr>
<tr>
<td>10 19 1,3 150</td>
<td>3,0</td>
<td>4,6</td>
</tr>
<tr>
<td>20 45 1,3 50</td>
<td>18,2</td>
<td>38,2</td>
</tr>
<tr>
<td></td>
<td>155,1</td>
<td>384,3</td>
</tr>
<tr>
<td></td>
<td>12,9</td>
<td>25,1</td>
</tr>
<tr>
<td></td>
<td>123,1</td>
<td>228,6</td>
</tr>
<tr>
<td>50 127 1,10 50</td>
<td>3691,2</td>
<td>6334,4</td>
</tr>
</tbody>
</table>

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

** Number of links in the reduced networks
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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Regional capital</th>
<th>Number of sub-regional centers</th>
<th>Length of link improvements (km)</th>
<th>Weight of Interior</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0</td>
<td>12</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>W</td>
<td>0</td>
<td>12</td>
<td>400</td>
<td>2</td>
</tr>
<tr>
<td>Y</td>
<td>0</td>
<td>18</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>12</td>
<td>200</td>
<td>1</td>
</tr>
</tbody>
</table>

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 %

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 $\to$ 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?