Freight demand and economic activities: modelling connections and multimodal transport networks

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The port and maritime sector: key developments and challenges
Antwerp, May 11-12, 2015
– introduction
– freight supply models
– freight demand models
– towards NEG models
– the container revolution and freight modelling challenges
Freight demand is the result of complex supply chains, involving all geographical levels …
two main types of models:

- *private oriented*, related to optimization and planning/management of company-related operations
- *public oriented*, for system-wide and social planning and governance

why mathematical models for planning and governance?

- forecasts and DSS
- missing data in current scenario:
  - unavailability
  - unsatisfactory coverage
  - unfeasible economic and time collection efforts

this presentation:

- international and national models for planning and governance
Planning and governance applications:

– design and assessment of transportation policies:
  
  • infrastructures (e.g. new road/rail links, new ports or logistics platforms)
  
  • regulation (e.g. time windows constraints for pickup/delivery, weight limits for lorries)
  
  • fiscal (e.g. gasoline taxes, subsidies to intermodal transport)

– assessment of economic impacts of transportation policies:
  
  • variations in industrial production
  
  • GDP impacts
  
  • number of jobs
  
  • spending effects
  
  • ...
Freight supply models

• planning and management of freight systems requires implementation of multimodal freight supply models

• a challenging task, especially in large geographical areas, because of three issues not properly addressed by existing literature:
  
  – presence of non-additive transport costs, e.g. EU regulation on rest/stop times for road drivers or non-additive fares/tariffs for rail and sea modes
  
  – multiple freight segments (e.g. for road/sea Ro-Ro transport: 1 driver/2 drivers, own account/hiring, accompanied/unaccompanied and so on)
  
  – not straightforward multimodal integration of single modes
Euro-Mediterranean model:
1508 traffic zones (NUTS3)

Study area and zoning
Network models: example

ROAD

RAIL

IWW

SEA
Network models: example

<table>
<thead>
<tr>
<th>mode</th>
<th># links</th>
<th>km links</th>
<th># nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>road</td>
<td>63.109</td>
<td>704.988</td>
<td>50.870</td>
</tr>
<tr>
<td>sea</td>
<td>28.319</td>
<td>n.s.</td>
<td>2.147</td>
</tr>
<tr>
<td>inland waterways</td>
<td>1.041</td>
<td>22.347</td>
<td>966</td>
</tr>
<tr>
<td>rail</td>
<td>90.259</td>
<td>406.973</td>
<td>83.462</td>
</tr>
</tbody>
</table>
The problem of non-additive impedances

- non-additive transport costs:
  - nonlinear fares/tariffs
  - EC 561/2006 on rest/stop times for drivers, simplifying:
    - daily driving period shall not exceed 9 hours, with an exemption of twice a week when it can be extended to 10 hours
  - *superadditivity* holds for monomodal networks (time and/or time-proportional cost impedances):
    \[ t_{dA} \leq t_{dB} \implies t_{sA}(t_{dA}) \leq t_{sB}(t_{dB}) \]
    \[ t_{totA} = t_{dA} + t_{sA}(t_{dA}) \leq t_{totB} = t_{dB} + t_{sB}(t_{dB}) \]
- ... but it does not hold for multimodal networks! →
Super-additivity on multimodal graphs
Super-additivity on multimodal graphs

The shortest path on multimodal network accounting only for additive link travel times is all-road (duration=20 h) ...
... but it leads to additional 16 hours of rest time (1 driver) or 8 hours (2 drivers), for a total of 36 hours. Therefore, the overall shortest path is the following (22 hours) ...
Super-additivity does not hold on multimodal networks:

- Need for “virtual” networks with macro-links representing overall connections between centroids and intermodal terminals.

Need for calculating LOS related to specific mode sequences:

![Diagram showing multimodal network with road macro-links, mode transfer links, and sea macro-links. Centroids, ports (landside), ports (seaside), cloned ports (seaside), and cloned ports (landside) are connected with various links representing different modes of transport.](image)
Analytical cost model (cost functions)

• several supply segments, e.g. for road/sea Ro-Ro transport:
  – 1 driver/2 drivers
  – own account/hiring
  – accompanied/unaccompanied (i.e. tractor+trailer or only trailer)
  – ...
Analytical models: example

- Sevilla
- Valencia
- Barcelona
- Genoa
- Milan

Diagram showing shortest routes:
- Road network
- Road-sea accompanied
- Road-sea unaccompanied
- Road

Legend:
- Kilometers
  - 0
  - 60
  - 120
  - 180

Note: lower VTTS for trailers alone leads to longer maritime routes.
Analytical models: example

lower VTTS for trailers alone leads to longer maritime routes

the 1 driver/2 drivers option changes the maritime route
Freight demand simulation models may follow in principle the traditional “four step” structure of the passenger demand models:

**EMISSION/ATTRACTION**
- Econometric models
  - Growth factor models
  - Regression models

**DISTRIBUTION**
- Econometric models
  - Regression models

**MODE**
- Traditional mode choice models
- Mode choice models with logistic attributes
  - Logistic models
    - *freight transport service* choice rather than *mode* choice
- Path choice models

**Economic activity models**
Gravity models
singly constrained

in origin

\[ D_{od} = G_o \frac{A_d f(c_{od})}{\sum_{d'} A_{d'} f(c_{od'})} \]

\[ \approx \text{MNL distribution percentages} \]

supply driven

in destination

\[ D_{od} = A_d \frac{G_o f(c_{od})}{\sum_{o'} G_{o'} f(c_{o'd})} \]

\[ \approx \text{MNL acquisition percentages} \]

demand driven

\[ G_o = f(\text{Production units}_o, \text{Production level}_o) \]

\[ A_d = f(\text{Consumer}_d, \text{Consumption level}_d) \]

\[ f(c_{od}) = \text{function inversely proportional to cost}_{od} \text{ e.g. } \exp[-\theta c_{od}] \]
doubly constrained

\[ D_{od} = k_o \cdot k_d \cdot G_o \cdot A_d \cdot f(c_{od}) \]

\[ k_o = \frac{1}{\sum_d k_d \cdot A_d \cdot f(c_{od})} \quad \sum_d D_{od} = G_o \]

\[ k_d = \frac{1}{\sum_o k_o \cdot G_o \cdot f(c_{od})} \quad \sum_o D_{od} = A_d \]

\[ f(c_{od}) = \text{function inversely proportional to } c_{od} \]

Constants can be calculated in a double constrained gravity model through an iterative algorithm (given a cost function)
explicit representation of interdependence among different sectors of economy

the economic structure of production by sector, for a given region, can be represented by its input-output table:

<table>
<thead>
<tr>
<th>Region ( i )</th>
<th>Sectors of production</th>
<th>Final demand</th>
<th>Regional export</th>
<th>International export</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1 )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>( S_2 )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>( S_3 )</td>
<td>( \ldots )</td>
<td>( K_{ij} )</td>
<td>( \ldots )</td>
<td>( Y_i )</td>
</tr>
<tr>
<td>( S_4 )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( Y_{REG}^i )</td>
</tr>
</tbody>
</table>

Added value:

| \( \ldots \) | \( \ldots \) | \( \ldots \) | \( \ldots \) |

Value of production:

| \( \ldots \) | \( X_{ij} \) | \( \ldots \) | \( \ldots \) |

Regional import:

| \( \ldots \) | \( J_{REG}^i \) | \( \ldots \) | \( \ldots \) |

International import:

| \( \ldots \) | \( J_{EST}^i \) | \( \ldots \) | \( \ldots \) |
The consequences of sectorial interdependency:

\[ X_m \quad X_m \quad X_m \quad X_m \quad X_m \]

\[ B \quad A \quad C \quad D \quad E \]

\[ Y_m \]

\[ X = \text{production} \]

\[ Y = \text{consumption} \]

\[ m = \text{a final product (e.g. cars)} \]
The consequences of sectorial interdependency:

\[ X = \text{production} \]
\[ Y = \text{consumption} \]
\[ m = \text{a final product (e.g. cars)} \]
The consequences of sectorial interdependency:

\[ X_m \rightarrow X_n \rightarrow A \rightarrow E \leftarrow B \]

\[ X_n \leftarrow A \rightarrow D \]

\[ X_n \leftarrow C \rightarrow X_m \]

\[
X = \text{production} \\
Y = \text{consumption} \\
m = \text{a final product (e.g. cars)} - n = \text{an intermediate input (e.g. engines)}
\]
The consequences of sectorial interdependency:

\[ X = \text{production} \]

\[ Y = \text{consumption} \]

\[ n = \text{an intermediate input (e.g. engines)} \]

\[ k = \text{a raw material (e.g. steel)} \]
The consequences of sectorial interdependency:

X = production
Y = consumption

\[ \Delta Y_m \leftrightarrow \Delta X_m \]
\[ \Delta X_n, \Delta X_k, \Delta X_j, \ldots \]
Solving for \( X \), the functional form of the MRIO model is:

\[
X = \text{TAX} + T(Y+Y_{\text{EXT}}) \rightarrow X(I-\text{TA}) = [T(Y+Y_{\text{EXT}})]
\]

\[
X = (I-\text{TA})^{-1}[T(Y+Y_{\text{EXT}})]
\]

and therefore the data needed for estimation/application are:

– vectors of:
  • international exports \( Y_{\text{EXT}} \)
  • final demand \( Y \)

– matrices of:
  • technical coefficients \( A \)
  • trade coefficients \( T \)
trade coefficient $t_{mij}^\%$ → percentage of sector $m$ products acquired from zone $i$ and used in zone $j$ for whatever use.

trade coefficients can be modelled as a function of level of service attributes, representing generalized transport cost between zones.

explicit representation of the influence of transport system on freight production and distribution and therefore on the economic structure of each region.
trade coefficients can be modeled explicitly as a function of:

- transportation level of service attributes
- selling prices
- ...

\[ t_{ij}^m = \frac{\exp(V_{ij}^m / \theta^m)}{\sum_k \exp(V_{kj}^m / \theta^m)} \]

acquisition zone \( i \) is a compound alternative composed of the aggregation of a number \( ED^m_i \) of elementary origins for sector \( m \).

a Nested Logit model may be used to model \( t_{ij}^m \)

\[ t_{ij}^m = \frac{\exp[(V_{ij}^m / \theta^m + s_{ij}^m) / \theta^m]}{\sum_k \exp[(V_{kj}^m / \theta^m + s_{kj}^m) / \theta^m]} \]

various possible feedbacks:

- short term: trade coefficients elastic to transport LOS only
- long term: also significant macroeconomic feedbacks
The RUBMRIO model: short term

**MRIO MODEL**
- final demand by sector and country
- technical coefficients
- GDP and macroeconomic variables
- freight matrix in quantity
- value/quantity transformation

**TRANSPORT MODEL**
- freight supply model
- LOS
- mode choice model
- freight matrix in quantity by mode

**MRIO model**
- freight matrix in value
- trade coefficients in value
- trade coefficients model
- selling prices
- other attributes
- freight matrix in quantity
- average transport costs for all modes
The RUBMRIO model: long term

**MRIO MODEL**
- final demand by sector and country
- technical coefficients
- GDP and macroeconomic variables

**TRANSPORT MODEL**
- freight supply model
- LOS

**MRIO model**
- freight matrix in quantity
- value/quantity transformation
- freight matrix in quantity by mode

**Trade coefficients model**
- trade coefficients in value
- other attributes

**Selling prices model**
- selling prices for all modes

**Base reference matrix in quantity**
- freight matrix in value
Macroeconomic impacts generated by change in transport costs are **very difficult** to predict:

- countries with economic competitive advantages may benefit more from a decrease of transport costs (and vice versa), being able to increase their export

- competitive advantages may depend on different factors (availability of raw materials, developed technologies, low labor cost etc.) which are implicitly accounted for in the technical coefficients

- a *tout court* decrease of transport costs impacts differently on Countries depending on their geographical position within the study area, i.e. of their initial accessibility with respect to the other Countries
Example with two zones (A,B) and only one traded product
impact of transport changes in a MRIO model
Towards the NEG paradigm

- job market and migration
- cross-level of salaries
- final demand
- production costs of intermediate and final inputs
- ...

- currency exchange
- availability of raw materials
- ...

...
Towards the NEG paradigm

Input Output
(Leontief)

New Economic Geography
(Krugman)
Towards the NEG paradigm
Towards the NEG paradigm
Freight demand and supply chains

... and the “container revolution” made the world smaller and has allowed worldwide supply chains:
Examples of supply chains

Personal Computer

Canada: Assembly

Ireland: Disk production

UK: Assembly

Germany: Disk production

Taiwan: Assembly

Malaysia: Disk production

USA: Disk production

Mexico: Assembly with motherboard
Examples of supply chains

**UK:**
4. Commercialization

**India:**
3. Packaging

**Tanzania:**
1. Coffee beans plantation
2. Coffee beans processing

Sainsbury's
Examples of supply chains

Scotland:
1. Fishing
2. Deep freezing
3. Transportation in reefer
4. Distribution

Thailand:
5. Maturation in reefer
6. Processing
7. Packaging
8. Manual cleaning

Prawns
Impacts of containerization

- **CONTAINER**
- **ORGANIZATIONAL AND TECHNOLOGICAL INNOVATIONS**
  - **REDUCTION OF VESSEL LOADING/UNLOADING TIMES**
  - **INTENSIVE USE OF TRANSSHIPMENT**
- **REGULAR NETWORK OF SERVICES FOR GENERAL CARGO FLOWS**
  - **SCALE AND SCOPE ECONOMIES**
  - **CONCENTRATION OF FREIGHT FLOWS**
  - **REDUCTION OF TOTAL TRANSPORT TIMES/COSTS**
- **REGULAR LINER SERVICES**
  - **NETWORK OF REGULAR LINER SERVICES**
  - **HIGHER ACCESSIBILITY FOR LOW-DEMAND O-D PAIRS**
Analysis of costs on different trade lanes

Scale economies on the three main trade lanes

- Rotta Europa-Far East
  lunghezza pari a ca. 18.500 km
  Variazione costi: -58%

- Rotta Trans-Pacifica
  lunghezza pari a ca. 12.900 km
  Variazione costi: -54%

- Rotta Trans-Atlantica
  lunghezza pari a ca. 6.450 km
  Variazione costi: -45%

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Data availability and ease of implementation</th>
<th>Applications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity models</td>
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</tr>
<tr>
<td>MRIO models</td>
<td><img src="https://example.com/neutral.png" alt="Neutral" /> <img src="https://example.com/green.png" alt="Green" /> <img src="https://example.com/yellow.png" alt="Yellow" /> <img src="https://example.com/red.png" alt="Red" /></td>
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<tr>
<td>RUBMRIO models</td>
<td><img src="https://example.com/neutral.png" alt="Neutral" /> <img src="https://example.com/green.png" alt="Green" /> <img src="https://example.com/green.png" alt="Green" /> <img src="https://example.com/red.png" alt="Red" /></td>
<td><img src="https://example.com/green.png" alt="Green" /> <img src="https://example.com/green.png" alt="Green" /> <img src="https://example.com/green.png" alt="Green" /> <img src="https://example.com/red.png" alt="Red" /></td>
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</tbody>
</table>
Thank you!

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Study area:

- 21 EU Countries
- 2005 base year for model estimation
Type of data source:
- input-output tables (for $X$, $Y_{\text{EXT}}$, $Y$, $A$)
- import/export trade flows in value (for $T$)

Two examples of application of the proposed system of models:

- **Scenario 1**: 10% increase in road costs, e.g. coming either from an increase of oil price or from a reduction of public subsidies for lorries
- **Scenario 2**: 20% reduction of maritime fares, so as to mimic a policy of public subsidies towards motorways of the sea within the European Union
tons/km²/year generated by NUTS3 zone in the base scenario
tons/km²/year generated by NUTS3 zone in the scenario 2