Structural gravity and transport policy analysis: a methodological proposal with an illustrative application

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Abstract

The structural gravity model is founded in economic theory and is used extensively for international trade analysis. Its use for transport policy analysis within decision support systems related to goods mobility is new. Choices of buy and sell markets are intertwined with choices of the transport mode chain, namely road only, road and rail, road and sea, road and air. The paper proposes a methodology to provide aggregate and mode chain-specific trade flows. Application is to Italy. Route choice and network models provide travel time and shipment price estimates. Logit is used for mode chain choices. The transport variable entering gravity is the expectation of the shipment price associated with the choice of maximum utility across mode chains. Input-output tables provide production and expenditure of NUTS3 zones in Italy. Gravity and mode chain choice models are estimated jointly based on Eurostat national and international traffic data using nonlinear least squares. The illustrative counterfactual relates to a national railway terminal project. Results of scenario analysis for dry bulk goods are discussed.

Keywords: goods mobility, Logit, mode chain choice, structural gravity, transport policy.

JEL: R15, R42, R58

1. Introduction

The structural gravity model is extensively used in trade analysis. The model owes its name and success to the theoretical foundation. Yotov et al. (2016) and Baier et al. (2017) provide a comprehensive review and guide. Classical references about theoretical foundation are Armington (1969) and Anderson (1979) for derivation from the demand side, and Eaton and Kortum (2002) for derivation from the supply side.

The use of the structural gravity is common primarily for international trade analysis. Related literature is extensive. Its use for sub-national trade analysis is less frequent due to lack of trade data. Olayle (2019) applies the model to analysis inside Canada and U.S. borders. Phillips (2024) considers sub-national trade in U.S.

The structural gravity model predicts trade using as masses the production value of the exporting zone and the expenditure of the importing zone. Trade depends, inversely, on the trade cost associated with the zone pair. The empirical gravity specification considers a trade cost markup modelled in terms of policy-sensitive covariates. For these, current practice uses variables that include geographic distance, contiguous borders, common language, tariffs, regional trade agreements. As such, the model is exclusively suited for trade policy analysis.

The present paper aims to extend the relevance and use of the structural gravity model to the analysis of transport policy. The following justifies this research effort. The link between economy and goods mobility is twofold. First, there is the direct link, since transport demand is derived from other production and consumption activities. Second, there is the reverse link, since the supply of transport infrastructure and services affects buy and sell markets, and, therefore, trade flows.

For its ability to model the reverse link, the gravity model can be one of the building blocks of Decision Support Systems (DSS) that government at regional and national levels may use for transport policy analysis related to goods mobility. Ivanova (2014) provides a review of the two approaches that have been used to model the reverse link, namely the one based on Multi-Regional Input-Output (MRIO) analysis with elastic trade coefficients (proposed by transportation engineers: Zhao and Kockelman, 2004; Cascetta et al., 2013), and the one based on Spatial Computable General Equilibrium (SCGE; the standard one of economists). The use of the gravity model is new.

In this respect, significant challenges and departures from the practice related to trade policy analysis are implied, because trade choices of the export and the import zone, the ones modelled with the gravity, are intertwined with those of transport mode chain and route. Mode chain is the sequence of transport modes: road only, road and rail, road and sea, road and air. Route is the sequence of links and nodes on the network of a specific mode. Intertwining occurs at both the model specification and model estimation levels. This is explained below.

For policy sensitiveness, specification of the gravity model needs to include the shipment price as covariate explaining the trade cost markup. There is extensive literature providing empirical evidence of the statistical significance of the geographic distance variable: trade flows from gravity models decrease with distance. No evidence exists in relation to shipment price. Shipment price is, clearly, mode-chain dependent.

To meet the needs of the policy maker, the DSS shall provide mode chain-specific trade flows. This calls for joint estimation of gravity and mode chain choice models. The logit mode chain choice model estimated for use in the EU-level DSS by Jensen et al. (2019) provides travel time and shipment price coefficients, and the associated values of travel time. This is because consistent estimates for the model coefficients can be obtained from non-representative samples (Manski and McFadden, 1981). By contrast, a new estimation is needed for alternative specific constants because they are spatially not transferable. For estimation, mode chain-specific traffic data from available statistical resources are appropriate.

The problem is even more complex, since mode chain choices are, in turn, intertwined with route choices. In regard to this, estimation of travel times and shipment prices needs to make reference to specific routes. Some assumptions need to be made for route choices in order to make estimation manageable. Assumptions are needed in particular, for the road-and-rail and road-and-sea chains, regarding the choice of the initial and final railway terminal and port.

The paper presents a proposal of methodology for the estimation of the production-consumption trade flows in monetary units (EUR/year). Both the aggregate and the mode chain-specific levels are addressed. The challenges that are described above are met. The application relates to Italy, for which NUTS3-level zones are considered. Zoning is at the level of country for Europe and the Mediterranean Sea, of (sub-)continent elsewhere.

Joint estimation of the gravity and the mode chain choice models uses Eurostat mode-specific traffic data from Italy to Italy, from Italy to other countries and from other countries to Italy. The gravity model is needed to predict national trade flows in the base year, because these are not provided from available statistical resources. The counterfactual relates to a national railway terminal project. With the gravity model, in addition to estimation of the direct impacts of the policy on trade flows, equilibrium analysis can be carried out. Equilibrium can be partial if only the Multi-lateral Resistance Indexes (MRI) change on the base year, or general if also production and expenditure change. For the base year and the counterfactual, numerical findings for one specific sector in terms of type of goods and type of load, the one of dry bulk, are provided for illustrative aims.

The paper has the following organisation. Section 2 presents the models. Section 3, the estimation methodology with results. Section 4, the methodology and results of the scenario analysis. The paper concludes with a critical discussion of the findings and directions of future research.

2. Models

2.1 The DSS framework

The spatial definition is, for Italy, at the level of former provinces (NUTS3): ten metropolitan cities in regions with ordinary statute (Roma Capitale, Torino, Milano, Venezia, Genova, Bologna, Firenze, Bari, Napoli, Reggio Calabria), four metropolitan cities in regions with special statute (Cagliari, Catania, Messina, Palermo), and 93 other former provinces. Outside Italy, at the country level for Europe and the Mediterranean Sea (53 countries), and at the continental or sub-continental level for the remaining countries (Africa, Asia, Pacific Ocean region, North America, South America; 11 zones). The total number of zones is 171. Figure 1 provides a geographical illustration.

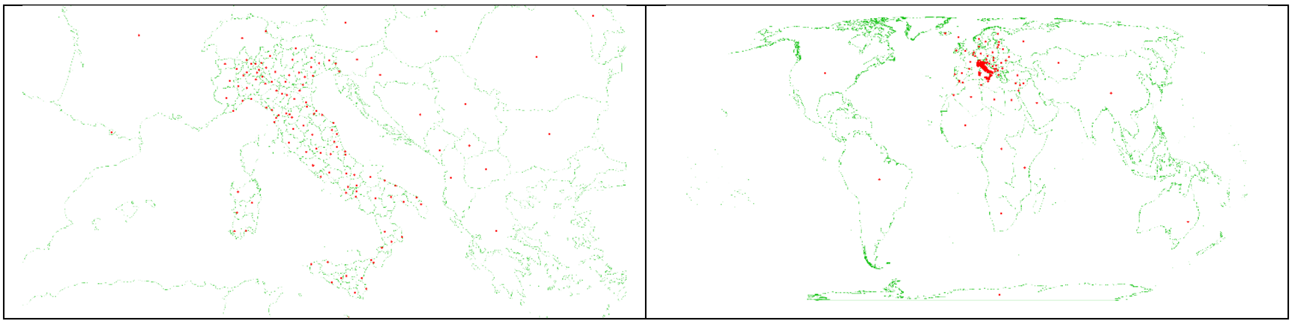

Figure 1. Zoning

Base year is 2019, the latest pre-pandemic.

Three sectors are considered: (i) dry bulk, (ii) liquid bulk, (iii) containers and general cargo. General cargo, also referred to as break bulk cargo, includes unitised cargo (pallet, crates, barrels) and loose cargo (such as new cars).

Figure 2 shows the different models with links. The gravity models receive the following inputs. First, exports and imports of zones, which, for Italy, are provided by Input-Output (IO) tables at NUTS3 level. These are obtained from IO tables at national level. Exports and imports of zones of Italy include intra-national trade. Second, for each zone pair, the sequence of nodes and links from route choice models, and travel times and shipment prices from network models. Route choice and network models provide essential inputs to the mode chain choice models as well. Trade flows by mode chain and zone pair are the outputs of the gravity and the mode chain choice models. These are inputs to the assignment models, which, finally, provide node and link flows over the networks of the individual transport modes (road, railway, maritime, air).

We have distinct gravity models for Italy to Italy (the national model), Italy to other countries (the international export model), and other countries to Italy (the international import model). For each of those, we have three distinct models according to sector. We have three mode chain choice models according to sector. We have distinct network and route choice models according to mode chain. We have distinct assignment models according to network: road, railway, ports, airports.

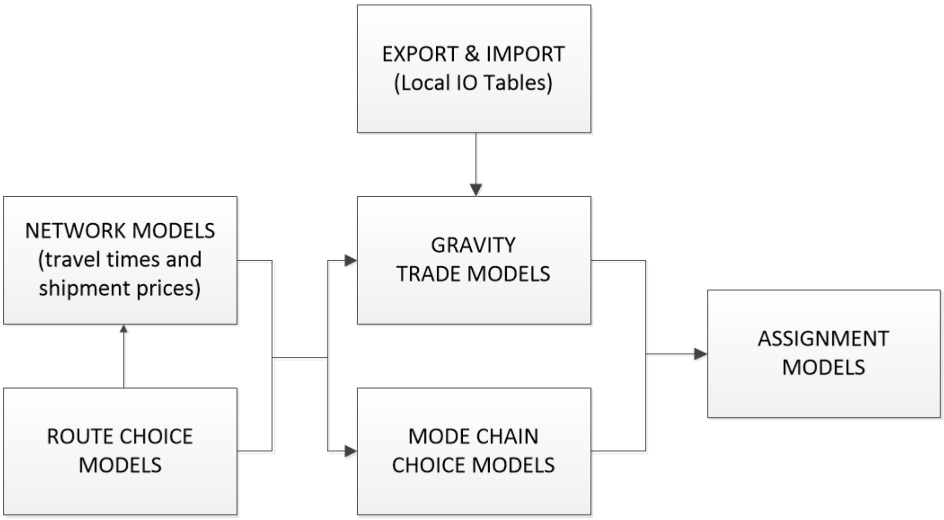

Figure 2. The DSS modelling framework

2.2 Gravity models

Trade flow equations of the structural gravity model can be derived from either the demand or the supply side. From the demand side, the model with Constant Elasticity of Substitution (CES) in consumer preferences across product varieties from different zones is obtained (Armington, 1969; Anderson, 1979; Anderson and van Wincoop, 2003):

$$X_{ij} = \frac{Y_i E_j}{Y} \left(\frac{\tau_{ij}}{\Pi_i \Omega_j} \right)^{1-\sigma}, i \in J_{ex}, j \in J_{im} \tag{1}$$

where:

X_{ij}	monetary trade flow between exporting zone i and importing zone j,
J_{ex}, J_{im}	sets of, respectively, exporting and importing zones,
Y_i	production of zone i,

$Y = \sum_{i \in J_{ex}} Y_i$,

E_j	expenditure of zone j,
σ	elasticity of substitution across product varieties, $\sigma > 1$,
τ_{ij}	transport cost markup between zone i and zone j, $\tau_{ij} > 1$,
$\mathit{\Pi}_i$	outward MRI of zone i,
$\mathit{\Omega}_j$	inward MRI of zone j.

When derived from the supply side, in the Ricardian model of trade (Eaton and Kortum, 2002), $1 - \sigma$ is replaced by $-\vartheta$, where ϑ is the trade cost elasticity, also the shape parameter of the Fréchet distribution of productivity across product varieties.

The transport cost markup τ_{ij} is the factor that needs to multiply the factory-gate price to yield the price paid by the importing zone.

Generally, the set of exporting zones may be different from the set of importing zones. According to the modelling framework here, there are three gravity models. In the gravity models for Italy to Italy we have $J_{ex} = J_{im} = J$. By contrast, in the gravity models from Italy to other countries we have $J_{ex} \neq J_{im}$. In the gravity models from other countries to Italy also, we have $J_{ex} \neq J_{im}$.

Two comments on Eqs (1) are in order. First, the model holds at both the aggregate and the sector level. For ease of notation, the sector index, commonly superscript, is omitted. Second, the model may not include intra-zonal flows, provided Y_i and E_j are re-defined accordingly.

In the structural gravity, trade flows satisfy the following constraints:

$$\sum_{j \in J_{im}} X_{ij} = Y_i, i \in J_{ex} \tag{2}$$

$$\sum_{i \in J_{ex}} X_{ij} = E_j, j \in J_{im} \tag{3}$$

and

$$\sum_{i \in J_{ex}} Y_i = Y = \sum_{j \in J_{im}} E_j \tag{4}$$

Eqs (2), (3) and (4) are consequence of the budget constraints of the representative consumers of the importing zones, and of the market clearing conditions.

The MRI $\mathit{\Pi}_i$ and $\mathit{\Omega}_j$ satisfy:

$$\Pi_i^{1-\sigma} = \sum_{j \in J_{im}} \frac{E_j}{Y} \left(\frac{\tau_{ij}}{\mathit{\Omega}_j} \right)^{1-\sigma}, i \in J_{ex} \tag{5}$$

$$\mathit{\Omega}_j^{1-\sigma} = \sum_{i \in J_{ex}} \frac{Y_i}{Y} \left(\frac{\tau_{ij}}{\mathit{\Pi}_i} \right)^{1-\sigma}, j \in J_{im} \tag{6}$$

The outward MRI $\mathit{\Pi}_i$ represents the aggregate export cost faced by the exporting zone i, regardless of the specific partner zone it is trading with. The inward MRI $\mathit{\Omega}_j$ represents the aggregate import cost faced by the importing zone j.

Fally (2015; lemma 3) proves that, if a solution to Eqs (5) and (6) exists, this is unique up to a positive scaling constant λ. Indeed, as noted by Anderson and Yotov (2010), if $\Pi_i^{1-\sigma}$ and $\mathit{\Omega}_j^{1-\sigma}$ are solution to Eqs (5) and (6), then $\lambda\Pi_i^{1-\sigma}$ and $\frac{1}{\lambda}\mathit{\Omega}_j^{1-\sigma}$ are also solution for any $\lambda > 0$. Normalization is needed. Having chosen a reference zone R, $\mathit{\Omega}_R = 1$ or $\mathit{\Omega}_R^{1-\sigma} = 1$ may be imposed.

Assume now that $J_{ex} = J_{im} = J$, the case of the national, Italy to Italy gravity model. Then, we have:

$$E_i = \varphi_i Y_i = \varphi_i p_i q_i, \qquad i \in J \tag{7}$$

where:

φ_i	exogenous parameter of zone i indicating trade deficit ($\varphi_i > 1$) or trade surplus ($\varphi_i < 1$),
p_i	factory-gate price of zone i,
q_i	exogenous (fictional) supplied quantity of goods of zone i according to the iceberg cost assumption,

and factory-gate prices satisfy:

$$p_i = \left(\frac{Y_i}{Y}\right)^{\frac{1}{1-\sigma}} \frac{1}{\alpha_i \mathit{\Pi}_i}, \qquad i \in J \tag{8}$$

where α_i is the exogenous CES preference parameter of zone i.

The iceberg cost assumption, introduced by Samuelson (1954) and clearly synthesised in Bosker and Buringh (2020), means that, to account for transport cost, it is as if, to deliver one unit, $\tau_{ij} > 1$ units need to be shipped, because a quantity equal to $\tau_{ij} - 1$ melts enroute. The transport cost c_{ij} is the cost of producing the quantity that melts:

$$c_{ij} = p_i(\tau_{ij} - 1), \qquad i \in J_{ex}, j \in J_{im} \tag{9}$$

The iceberg assumption implies that the transport sector produces transport services using the same production function as the firms producing the goods that are shipped.

From Eqs (9), we obtain the following relationship between transport cost markup τ_{ij} and transport cost c_{ij}:

$$\tau_{ij} = c_{ij}/p_i + 1, \qquad i \in J_{ex}, j \in J_{im} \tag{10}$$

The transport cost c_{ij} is the shipment price. This is dependent on the choice of the mode chain. Estimation needs, therefore, to be consistent with the mode chain choice model.

2.3 Mode chain choice models

Multinomial Logit (McFadden, 1974) is used to model mode chain choices. This is standard practice in freight modelling (de Jong, 2014). The mode chain alternative chosen for the zone pair i, j is the one that maximizes random utility $u_{ij,n}$ where n is the alternative index. Random utility is additive and includes a systematic component $v_{ij,n}$ and a random component $\epsilon_{ij,n}$:

$$u_{ij,n} = v_{ij,n} + \epsilon_{ij,n}, \qquad i \in J_{ex}, j \in J_{im}, n \in M \tag{11}$$

where M is the set of mode chain alternatives.

The systematic utility $v_{ij,n}$ depends on travel time $t_{ij,n}$, shipment price $c_{ij,n}$ and the average ASC_n of other, unobserved characteristics of the alternative that have an impact on choice:

$$v_{ij,n} = \beta_t t_{ij,n} + \beta_c c_{ij,n} + ASC_n, \qquad i \in J_{ex}, j \in J_{im}, n \in M \tag{12}$$

where β_t and β_c are estimation coefficients.

When the random components $\epsilon_{ij,n}$ are i.i.d. according to a Gumbel, we have the multinomial Logit model. Then, choice probabilities are given by:

$$P_{ij,n} = \frac{e^{v_{ij,n}}}{\sum_{n' \in M} e^{v_{ij,n'}}}, \qquad i \in J_{ex}, j \in J_{im}, n \in M \tag{13}$$

Eqs (13) hold also in the case where one or more alternatives n' of the full set M are unavailable for the zone pair i, j (it is sufficient to impose $v_{ij,n'} = -\infty$).

Once the chain choice model is set, it is possible to estimate the shipment price c_{ij} that enters the specification of the gravity model. For this, we take, for each vector of random components, the shipment price of the alternative of maximum utility. Then, we average with respect to the joint distribution of the random terms. The resulting shipment price is, simply, the average of shipment prices of the different alternatives weighted with choice probabilities:

$$c_{ij} = \sum_{n \in M} P_{ij,n} c_{ij,n}, \qquad i \in J_{ex}, j \in J_{im} \tag{14}$$

2.4 Export and import modelling

Productions Y_i of exporting zones and expenditures E_j of importing zones in base year in Italy, separately for national and international trade, are provided based on the development of local IO tables, at NUTS3 level, the one of former provinces, from national tables published by the Istituto Nazionale di Statistica (Istat[1]). For zones outside Italy, the Trade and Transport dataset from the United Nations Conference on Trade and Development (UNCTAD[2]) is used. Figure 3 shows the inputs

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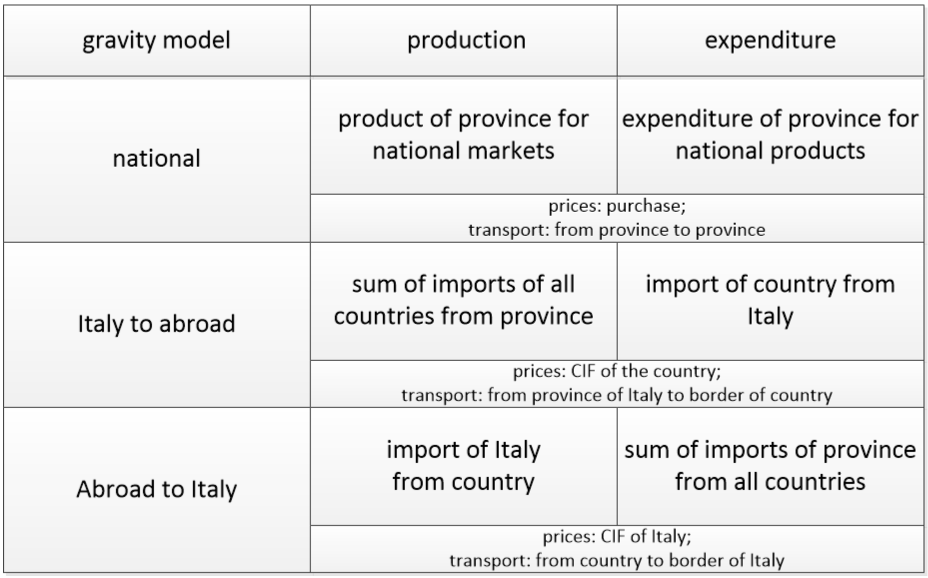
[1] http://dati.istat.it/, latest access on 21-10-2025.

[2] https://unctadstat.unctad.org/datacentre/, latest access on 21-10-2025.

to the gravity models, while Figure 4 provides a clarification on the definition of Free-On-Board (FOB) and of Cost Insurance and Freight (CIF) prices.



<table>
<tr><th>gravity model</th><th>production</th><th>expenditure</th></tr>
<tr><td rowspan="2">national</td><td>product of province for national markets</td><td>expenditure of province for national products</td></tr>
<tr><td colspan="2">prices: purchase;
transport: from province to province</td></tr>
<tr><td rowspan="2">Italy to abroad</td><td>sum of imports of all countries from province</td><td>import of country from Italy</td></tr>
<tr><td colspan="2">prices: CIF of the country;
transport: from province of Italy to border of country</td></tr>
<tr><td rowspan="2">Abroad to Italy</td><td>import of Italy from country</td><td>sum of imports of province from all countries</td></tr>
<tr><td colspan="2">prices: CIF of Italy;
transport: from country to border of Italy</td></tr>
</table>

Figure 3. Inputs to the gravity models

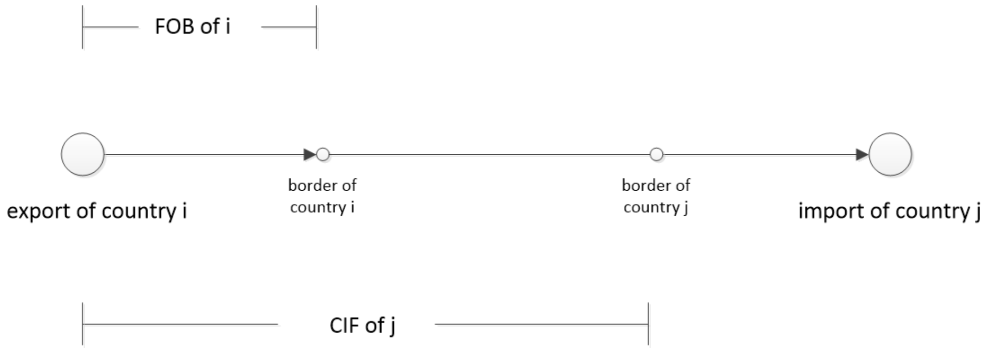


Figure 4. FOB and CIF prices

The national supply table represents Italy’s yearly resources (domestic production by industries and import) of goods and services at basic prices, the trade margins, transport, and taxes minus contributions. The national use tables show the consumptions of goods and services of all resources at both basic prices and purchase prices, as well as the consumptions of imported resources at basic prices. CPA2.1 is used to classify commodities, NACE rev.2 to classify industries.

There are three account balances between supplies and uses:

a) for every commodity imported from abroad, the import value at Cost Insurance and Freight (CIF) prices in the supply table is equal to the value of total uses of imported resources at basic prices;
b) for every commodity of all resources, the value of total uses is equal to the value of total supply, at both basic prices and purchase prices;
c) for every industry, the value of its total uses at purchase prices plus the added value, is equal to its total production at basic prices.

Regional IO tables, here at NUTS3 level, should demonstrate the local production, the consumption of commodities that are locally supplied and imported from areas outside; the latter part is divided again into two groups: domestic and foreign commodities. Like the national tables, the provincial IO tables should also follow the account balances mentioned before. Starting from the national supply and use tables, a two-steps local IO table generation process is designed: first, we estimate the provincial production as well as the consumption of foreign and non-foreign products; then the consumption of local supplied products is estimated among the consumed non-foreign products.

The national use table of domestic resources is obtained by subtracting the use of imported resources from the use of all resources, all at basic prices. The national tables at basic prices are localized directly to provincial level, to avoid any geographic assignment/limitation of trade flows during the localization process: if the national tables are localized first at regional level and then provincial level, it will automatically imply a certain part of flows as intra-regional. Different localization coefficients are applied to different industries and final users; they are calculated based on the percentage of local employment per industry, population, added value per inhabitant, number of public institutions, and taxable income. The localization coefficient for export represents the ratio of the provincial production in the national production of the commodity.

The Regional Economic Accounts, which contain the added value by industry, are used in an iterative apportionment process to calibrate the local production, the local use of national and imported commodities estimated by the localization coefficients. The national tables at basic prices are adopted because both the balances per commodity and industry at basic prices are necessary for obtaining a local table with balanced supply and use and give the possibility to use the Regional Economic Accounts as constraints.

To determine the provincial consumption of locally supplied commodities, the Flegg's Location Quotients (FLQ) method is applied to estimate the self-sufficiency level of each industry in each province. Location quotient (LQ) methods are among the most popular non-survey tools for assessing the degree of regional self-sufficiency. They consider the specialization of production in the region, the relative size of the industries and the region (Round, 1978).

FLQ method was developed and reformulated to overcome the limitation of Cross-Industry Location Quotients (CILQ) of not considering the relative size of the study area, and the limitation of Simple Location Quotients (SLQ) of ignoring the relative size of the consumer sector (Flegg, et al., 1995; Flegg and Webber, 1997). The FLQ offers better accuracy in regionalising the national IO table (Flegg and Webber, 1997; Tohmo, 2004; Bonfiglio and Chelli, 2008; Flegg and Tohmo, 2013).

Comparing to the other two LQ methods, its application requires, additionally, the assignment of the parameter δ. At the time of our computations, a uniform δ=0.3 is adopted for all provinces, as suggested by various studies that have investigated the impact of the value of δ on the result obtained (e.g., Flegg et al., 1995; Flegg and Webber, 1997; Tohmo, 2004; Bonfiglio and Chelli, 2008; Flegg and Tohmo, 2013). However, a very recent study on the estimation of regional economic flows in Italy (Socci et al., 2025) has determined for each Italian region the value of δ which corrects the data discrepancies with the national accounts; the result is concentrated more in the 0.2-0.4 class and the average value is 0.35 with three regions having δ>0.6.

To fit our purpose of estimating the self-sufficiency of commodities instead of sectoral productions, the size of the province's supplier sector in the FLQ's formula has been replaced by the export localization coefficient.

The consumption tax rate per commodity and per user is calculated on the basis of the national use table of all resources at basic prices and the one at purchase prices, assuming that the tax rate on consumption is identical for both domestic supplied and imported resources. Then we have obtained the tax on consumption of imported commodities. According to the account balance a) and b), for each commodity, the tax on domestic production is derived by subtracting the tax on consumption of imported resources from the sum of 'Commercial margins and transport' and 'Taxes less subsidies on products'. Then this tax is distributed among industries according to their production value while assuming that for the same commodity different industries have the same production tax rate. The previously estimated provincial productions and consumptions at basic prices are then converted to purchase prices by applying the production/consumption tax rates.

Inter-provincial and international import/export values are determined through a provincial account balancing process. It is assumed that each Italian province exports locally produced commodities to any other zones and can re-export foreign products exclusively to international destinations. For each commodity, the local production is first allocated to meet internal demand for local products within the province; any surplus production is designed for export. The value of international exports from each province is determined in proportion to its share in the total export of all provinces; any remaining part is exported to other provinces. In case where the previously estimated local production is insufficient to satisfy internal demand, the shortfall is compensated by imports from other Italian provinces, resulting in an increase in domestic inter-provincial trade flows.

At this stage, for every province, the values of international export are expressed in Free On Board (FOB) terms, international import values are in Cost Insurance and Freight (CIF) terms, and all international and national export/import are reported at purchase prices. To provide all necessary input to the gravity model, the provinces' international export should be expressed in CIF terms, and the trade flows of foreign areas with Italy are needed.

The UNCTAD dataset provides, for commodities classified under the HS17 system, the FOB value at origin country, international transport costs and weight. The records are first aggregated according to our zoning system, then converted from HS17 to CPA2.1 via the CN17 classification. To ensure the data consistency, these trade flow values are adjusted to reflect those reported in the Italian national

IO tables, while preserving the original FOB cost per kilogram and the ratio of transport cost. This procedure yields the CIF value for the international export of Italy. Accordingly, for each commodity, the conversion factor from FOB to CIF prices for Italy's international export is calculated and applied to the provinces' international exports. Also, the adjustments of trade flow values under CPA2.1 are brought back to values under HS17 to minimize error in the following conversion from commodities to three freight types (solid bulk, liquid bulk, other goods).

The initial nominal correspondence CN17/CPA08-Freight via NST/R is defined on the basis of the Swedish national freight transport system SAMGODS (Vierth and Lindgren, 2017) and the correspondence table CN17-CN07-CPA08-NST/R. We have then modified the initial correspondence to improve the conversion accuracy. At the beginning, the trade flows of foreign zones with Italy (derived from UNCTAD data and aligned with IO tables) are categorized into freight types using the correspondence HS17-CN17-Freight; on the basis of the correspondence HS17-CN17-CPA2.1, the actual share of each freight type in the international trade commodities is calculated. For converting the import/export of Italian provinces (estimated from IO tables) to freight types, the share of freight types calculated previously is applied to the international trades, and the nominal CPA2.1-CPA08-Freight correspondence to the national trade flows. For simplification purpose, it is assumed that the freight shares are identical in products for intermediate and final use. This simplification could potentially mask heterogeneities in production structures and import propensities across commodity groups, as different sectors exhibit varying supply chain configurations and trade dependencies. However, given our focus on macro-level freight flow estimation rather than detailed sectoral analysis, this approximation is necessary for computational tractability and practical transport modelling and represents a reasonable trade-off between model complexity and practical applicability.

2.5 Route choice and network models

Centroids of zones in Italy and the European continent are located in capital cities. Each centroid is connected to the road network. Road and railway networks in the continents other than Europe are not modelled, only main international ports and airports are modelled. Georeferenced networks are handled using TransCAD transportation planning software (Guo and Guo, 2022).

The initial European road network is based on Euro-Geographics data. For countries that are not covered, networks are integrated manually. The final road network model comprises over 460 000 links, for approximately 240 000 kilometres.

The initial European railway network also is based on Euro-Geographics data. After integration of countries that are not covered, the final railway network model comprises over 100 000 links, for approximately 210 000 kilometres.

The initial dataset of maritime ports is acquired from the World Food Programme's Global Ports database. The final network comprises 91 international ports.

Multimodal routes are based on the following criteria. For road-only transport, the shortest route is chosen. Notice that the road only mode includes connection to islands by ferry and strait crossing by ferry. For the road-and-rail chain, access and egress by road to and from the nearest railway terminal is considered. The mainhaul connection between origin and destination railway terminal is direct and based on shortest route. For the road-and-sea chain, access and egress by road to and from the nearest port is considered. The mainhaul connection between origin and destination port is direct and based on shortest route.

Travel times $t_{ij,n}$ are obtained as summation of leg-specific times: access, mainhaul, and egress. Travel times on links are based on average speed values from educated guess. For road, rest times are added, on the basis of European Union obligations (Regulation EC No 561/2006, amended by Regulation EU 2020/1054). For delays at rail terminals and ports, average times between truck arrival and train/vessel departure and between train/vessel arrival and truck departure are estimated, based on values from different available sources.

These include reports and data portals by governments, international organizations and industry, which provide values for different metrics related to trucks, trains, vessels, intermodal transport units. Most bibliographic sources are from U.S. (U.S. Government Accountability Office, 2022, for rail terminals; U.S. Bureau of Transportation Statistics, 2025, for ports) and international organizations (Ducruet, 2014, and The World Bank Group, 2023, for ports). Industry reports include J.B. Hunt (2015) on rail terminals. For Italy, Russo and Sansone (2015) deal with intermodal transport at the Verona Quadrante Europa rail terminal. Reports may address specific goods, as in the case of agricultural products in U.S. (U.S. Department of Agriculture, 2025). In-depth interviews with operators in Italy also are used.

Shipment prices $c_{ij,n}$ are those paid by shippers. They are obtained as summation of leg-specific costs. For road and rail transport, they are estimated on the basis of service production cost components, with a markup to take profits of carriers into account (cost functions in Marzano et al., 2022). For maritime transport, they are estimated directly on the basis of data on charges that are collected from internet resources[3]. For all transport modes, typical carrying capacity is considered to derive values per tonne shipped.

3. Joint estimation of gravity and mode chain choice models

Transport data from Eurostat are classified according to the NST2007 system for road and rail modes. They are aggregated into the three sectors (dry bulk, liquid bulk, containers and general cargo) based on the correspondence table NST/R-CN2008-CPA2008-NST2007 in conjunction with the SAMGODS model. For maritime, Eurostat data are already classified according to the three sectors.

As illustrative application, we consider the dry bulk sector. This includes, among the others, iron ore, scrap metals, coal, timber, wheat and other cereals. Let J_f be the set of foreign zones. For this sector, after processing, the following origin-destination flows in weight (tonnes/year) by mode chain are available for the year 2019:

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[3] www.searates.com, latest access on 21-10-2025.

- road traffic from Italy to foreign zones, $S_{j,road}$, $j \in J_f$, and from foreign zones to Italy, $S_{i,road}$, $i \in J_f$;
- total rail traffic involving Italy as origin and/or destination, S_{rail};
- maritime traffic from Italian ports to Italian ports, S_{sea};
- maritime traffic from Italian ports to ports of foreign zones, $S_{j,sea}$, $j \in J_f$, and from ports of foreign zones to Italian ports, $S_{i,sea}$, $i \in J_f$.

Consider, exclusively for the estimation aim, Italy as a single zone indexed as 1. Assume that origin-destination flows equal the production-consumption flows that are provided by the gravity model. Weight trade flows are obtained from monetary flows X_{ij} from division by delivered prices $p_i\tau_{ij}$. Then, the least squares estimation problem has the following objective function:

$$\sum_{j\in J_f}\left(\frac{X_{1j}}{p_1\tau_{1j}}P_{1j,road}-S_{j,road}\right)^2+\sum_{i\in J_f}\left(\frac{X_{11}}{p_1\tau_{i1}}P_{i1,road}-S_{i,road}\right)^2+$$

$$\left(\frac{X_{11}}{p_1\tau_{11}}P_{11,rail}+\sum_{j\in J_f}\frac{X_{1j}}{p_1\tau_{1j}}P_{1j,rail}+\sum_{i\in J_f}\frac{X_{i1}}{p_i\tau_{i1}}P_{i1,rail}-S_{rail}\right)^2+$$

$$\left(\frac{X_{11}}{p_1\tau_{11}}P_{11,sea}-S_{sea}\right)^2+$$

$$\sum_{j\in J_f}\left(\frac{X_{1j}}{p_1\tau_{1j}}P_{1j,sea}-S_{j,sea}\right)^2+\sum_{i\in J_f}\left(\frac{X_{11}}{p_1\tau_{i1}}P_{i1,sea}-S_{i,sea}\right)^2 \qquad (15)$$

Travel times and shipment prices involving Italy as origin and/or destination are obtained as averages from values related to NUTS3 zoning.

For the transport cost markups τ_{ij} of Eqs (10), a proxy derived from the following empirical specification is used:

$$\tau_{ij}=a+bc_{ij}, \qquad i\in J_{ex}, j\in J_{im} \qquad (16)$$

where a and b are estimation coefficients, and c_{ij} is the shipment price that enters the gravity specification and that is obtained from Eqs (14).

Now, in Eq. (15), replace $\frac{X_{ij}}{p_i\tau_{ij}}$ by $\delta_i\gamma_j\left(\tau_{ij}\right)^{-\sigma}$, where δ_i and γ_j are zone-specific outward and inward coefficients, also referred to as fixed effects. The use of fixed effects coefficients is common practice in the estimation of empirical trade gravity models. Notice that factory-gate prices p_i cancel out of the estimation problem. Computation of trade flows by the use of Eqs (1) is postponed to scenario analysis. Therefore, in the later stage of scenario analysis only, base-year MRI indexes will be computed using Eqs (5) and (6).

The estimation problem consists in the minimization of the objective function in Eq. (15). Decision variables are the zone-specific outward and inward fixed effects coefficients δ_i and γ_j, the elasticity of substitution σ of the gravity model, the coefficients a and b of Eq. (16), and the alternative specific constants ASC_{rail} and ASC_{sea} of the mode chain choice Logit model. The alternative specific constant of the road-only mode chain alternative is normalized to zero.

The β_t and β_c coefficients of the Logit mode chain choice model are taken from Jensen et al. (2019): $\beta_t = -0.02946$ (time attribute in h), and $\beta_c = -0.1473$ (shipment price attribute in EUR/tonne). The ratio of these two coefficients provides a value of travel time of 0.2 EUR/h/tonne, in the range typical for this type of goods (de Jong, 2007)

The resulting non-linear least squares problem, with observation-specific functions, is solved using a code written in Python language. The IPOPT solver of the GEKKO optimization library is used (Beal et al., 2018). The IPOPT solver implements an interior point line search filter method (Wächter and Biegler, 2006). Solution is provided in less than 5 seconds on a 2.70 GHz CPU, 16 GB RAM personal computer.

To compute the standard errors, bootstrapping, i.e. resampling with replacement, is used (Efron and Tibshirani, 1986). This choice is dictated by the lack of evidence from mathematical statistics literature on asymptotic theory of nonlinear least squares estimators with observation-specific functions. The number of generated samples is 902.

Table 1 shows the results of the estimation that are used in the subsequent scenario analysis. The coefficients have the expected sign. The elasticity of substitution is higher than 1, consistently with the theoretical underpinnings of the structural gravity.

Estimates for the Rome to Milan pair provide a check for realism of the results. The share of the road-only mode chain alternative is 92.8%, the share of the road-and-rail alternative is 7.2%. The only figures available on mode shares in 2019 are from Eurostat (European Commission, 2020). In Italy, for all goods and land modes, shares with respect to tonne-km are 87% road, 13% rail. Shares of the model here are with respect to tonnes and are lower. This is acceptable, since, on average, rail travel is on longer distances than road.

Table 1. Estimation results: dry bulk (zone-specific outward and inward fixed effects omitted)

coefficient		estimate (standard error)
σ	elasticity of substitution	1.432 (0.032)
a	constant on trade cost markup regression line	3.189 (0.159)
b	slope on trade cost markup regression line	1.002 (0.120)
ASC_{rail}	alternative specific constant of road-and-rail chain	-3.984 (0.242)
ASC_{sea}	alternative specific constant of road-and-sea chain	4.020 (0.532)

4. Scenario analysis

For the illustrative application, the gravity model from Italy to Italy and the dry bulk sector are considered. For counterfactual scenarios, the Orte Interporto, a major logistics infrastructure located in the Viterbo province in the centre of Italy, is considered. Currently, the Orte Interporto is connected to the motorway network only. The project of the counterfactual consists in the access to the railway network, for which funding was allocated in Spring 2025. This project is expected to reduce travel times and shipment prices for the connections that will benefit from a closer railway terminal.

4.1 Approach

We have four scenarios depending on the endogeneity assumptions related to the four problem variables: MRI, productions of the exporting zones, expenditures of the importing zones, factory-gate prices.

- Base Year Scenario: transport cost markups are τ_{ij}^{0}; MRI are the only endogenous variables; productions, expenditures and factory-gate prices are exogenous.
- Counterfactual Direct Impact Scenario: transport cost markups change to τ_{ij}^{1}, only trade flows change, while MRI, productions, expenditures and factory-gate prices are unchanged on the base year.
- Counterfactual Partial Equilibrium Scenario: transport cost markups are τ_{ij}^{1}, MRIs are the only endogenous variables; productions, expenditures and factory-gate prices are unchanged on the base year.
- Counterfactual General Equilibrium Scenario: transport cost markups are τ_{ij}^{1}; MRI, productions, expenditures and factory-gate prices are endogenous variables.

In each scenario, the endogenous variables are the solutions of a fixed-point problem (Table 2). Notice that factory-gate prices do not enter computations. For computation of MRI, the following power transformations are applied (scenario superscripts omitted):

$$A_i = \lambda \Pi_i^{1-\sigma}, i \in J \tag{17}$$

$$B_j = \frac{\Omega_j^{1-\sigma}}{\lambda}, j \in J \tag{18}$$

where $\lambda > 0$, and J is the set of Italian zones (provinces).

The fixed point problems are shown in Table 2. The last equation of the counterfactual general equilibrium scenario follow from the condition:

$$\frac{p_i^{(2)}}{p_i^{(0)}} = \frac{Y_i^{(2)}}{Y_i^{(0)}}, i \in J \tag{19}$$

where superscripts (0) and (2) denote, respectively, base year and counterfactual general equilibrium scenarios. Eqs (19) are derived from the assumption of constant q_i in Eqs (7).

Table 2. Fixed-point problems by scenario

Scenario	Fixed-point problem
Base year	$A_i^{(0)} = \sum_{j \in J} \frac{E_j^{(0)}}{Y^{(0)}} \frac{\tau_{ij}^{(0)1-\sigma}}{B_j^{(0)}}, i \in J$ $B_j^{(0)} = \sum_{i \in J} \frac{Y_i^{(0)}}{Y^{(0)}} \frac{\tau_{ij}^{(0)1-\sigma}}{A_i^{(0)}}, j \in J$
Counterfactual - Partial equilibrium	$A_i^{(1)} = \sum_{j \in J} \frac{E_j^{(0)}}{Y^{(0)}} \frac{\tau_{ij}^{(1)1-\sigma}}{B_j^{(1)}}, i \in J$ $B_j^{(1)} = \sum_{i \in J} \frac{Y_i^{(0)}}{Y^{(0)}} \frac{\tau_{ij}^{(1)1-\sigma}}{A_i^{(1)}}, j \in J$
Counterfactual - General equilibrium	$A_i^{(2)} = \sum_{j \in J} \frac{\varphi_i Y_j^{(2)}}{Y^{(2)}} \frac{\tau_{ij}^{(1)1-\sigma}}{B_j^{(2)}}, i \in J$ $B_j^{(2)} = \sum_{i \in J} \frac{Y_i^{(2)}}{Y^{(2)}} \frac{\tau_{ij}^{(1)1-\sigma}}{A_i^{(2)}}, j \in J$ $Y_i^{(2)} = Y_i^{(0)} \left(\frac{Y_i^{(2)}}{Y_i^{(0)}} \frac{Y^{(0)}}{Y^{(2)}} \frac{A_i^{(0)}}{A_i^{(2)}} \right)^{1/(1-\sigma)}, i \in J$

To compute MRI in the base year and in the partial equilibrium counterfactual scenarios, the Minimize solver of the Python Scipy library is used. The fixed-point problems are transformed into least squares problems where each residual is the difference between the left-hand and the right-hand side of the fixed-point formulation. The L-BFGS-B (Limited Memory – Broyden – Fletcher – Goldfarb – Shanno – with Bounds) method is used. The BFGS is a quasi-Newton optimization algorithm (Nocedal and Wright, 2006). Solution from one starting point is obtained in less than five minutes.

To compute MRI and productions in the general equilibrium counterfactual scenario, the same solver is used. Solution from one starting point is obtained in less than one minute.

A guess is needed for the starting point. To this aim, unitary values for all MRI are a sound choice, because these are the values in a model where transport costs do not play any role. Indeed, in a model of bi-proportional allocation without friction (see, among the others, Fotheringham et al., 1989), where exporters sell to importing zones in proportion to the share of the importing zone on total sales, and importers buy from exporter zones in proportion to the share of the exporting zone on total sales, we have:

$$X_{ij} = \frac{Y_i E_j}{Y}, i, j \in J \tag{20}$$

For productions, a natural choice are productions in base year from local IO tables.

Table 3 provides the trade flow equations by scenario.

Table 3. Trade flows by scenario

Scenario	Trade flows
Base year	$X_{ij} = \frac{Y_i^{(0)} E_j^{(0)}}{Y^{(0)}} \left(\frac{\tau_{ij}^{(0)}}{\Pi_i^{(0)} \Omega_j^{(0)}} \right)^{1-\sigma}, i, j \in J$
Counterfactual - Direct impact	$X_{ij} = \frac{Y_i^{(0)} E_j^{(0)}}{Y^{(0)}} \left(\frac{\tau_{ij}^{(1)}}{\Pi_i^{(0)} \Omega_j^{(0)}} \right)^{1-\sigma}, i, j \in J$
Counterfactual - Partial equilibrium	$X_{ij} = \frac{Y_i^{(0)} E_j^{(0)}}{Y^{(0)}} \left(\frac{\tau_{ij}^{(1)}}{\Pi_i^{(1)} \Omega_j^{(1)}} \right)^{1-\sigma}, i, j \in J$
Counterfactual - General equilibrium	$X_{ij} = \frac{Y_i^{(2)} E_j^{(2)}}{Y^{(2)}} \left(\frac{\tau_{ij}^{(1)}}{\Pi_i^{(2)} \Omega_j^{(2)}} \right)^{1-\sigma}, i, j \in J$

Finally, it is possible to provide welfare statistics. As argued by Arkolakis et al. (2012), a useful statistic is the relative change in real consumption between the base year and the counterfactual general equilibrium scenarios:

$$\frac{W_i^{(2)}}{W_i^{(0)}} = \frac{E_i^{(2)}/\Omega_i^{(2)}}{E_i^{(0)}/\Omega_i^{(0)}}, i \in J_{ex} \tag{21}$$

The numerators and denominators in the right-hand side can be interpreted as real consumption since E_i is the expenditure and Ω_i is, according to the CES interpretation of the structural gravity, the exact price index faced by the consumers of the zone.

4.2 Numerical results

Figure 5 to 7 show the direct impact of a change in shipment price on the trade flow from Rome to Milan. The variables on the horizontal axis are, respectively, the empirical proxy for the transport cost markup τ_{ij}, the shipment price by road $c_{ij,road}$, and the shipment price by rail $c_{ij,rail}$. Base-year values are marked. Clearly, trade flows are decreasing with these variables.

Figures 8 and 9 and Tables 4 and 5 refer, as examples, to the four provinces of Perugia, Terni, Viterbo and Rieti. These change access and egress to and from the railway network, and use, in counterfactual scenarios, the terminal at Orte Interporto. Additionally, the province of Milan is included.

Figure 8 shows trade flows between each of the four aforementioned provinces and Milan. The values for the counterfactual scenarios are comparable with base year. Figure 9 shows rail shares to and from Italy of each of the four provinces. Values are weighted averages, weights are trade flows.

Table 4 shows productions. Perugia, Terni, Viterbo and Rieti decrease the values of productions when moving from base year to counterfactual general equilibrium scenario. Intuition is as follows. The decrease can be explained by the competition between each other which arises from reduced transport costs.

As an example, Perugia products need to compete with Terni products which become more convenient. Therefore, for these four provinces with improved access to the railway network, there is a downward pressure on factory-gate prices. This is because, based on Eqs (7), the endowment is fixed. An effect that is standard result from gravity models. Then, prices adjust in all zones to clear markets, with, as an example, Milan decreasing its production value.

Table 5 shows real consumption. For the four provinces of Perugia, Terni, Viterbo and Rieti, there is an increase when moving from base year to counterfactual general equilibrium scenario. This is in the interval between 0.1 and 0.5 per thousand. For Milan also, there is an increase of 1.7 per thousand. This means consumers of the five provinces gain.

These are results of comparative statics analysis where endowment, the supplied quantity q_i, is assumed unchanged in all scenarios. Dynamic gravity subsuming growth of endowment is out of the scope of the paper.

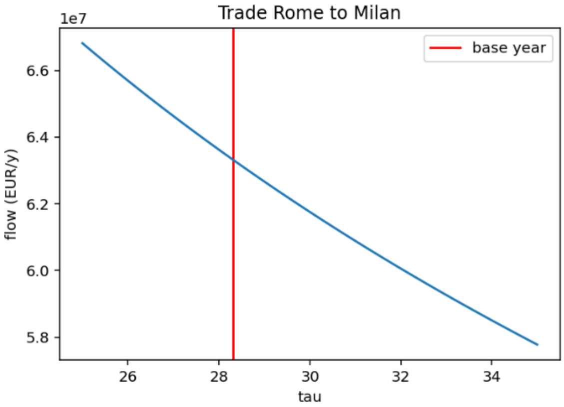

Figure 5. Direct impact of the proxy for transport cost markup: Rome to Milan trade, dry bulk

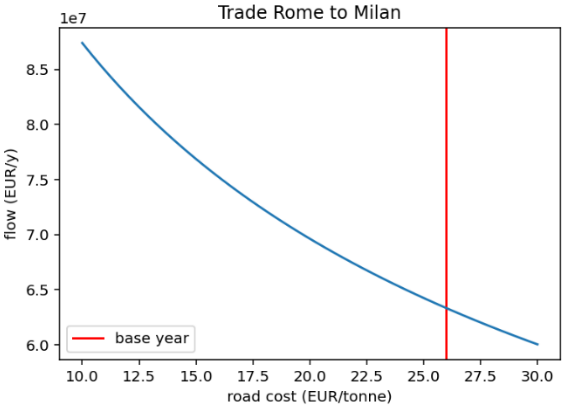

Figure 6. Direct impact of shipment price by road: Rome to Milan trade, dry bulk

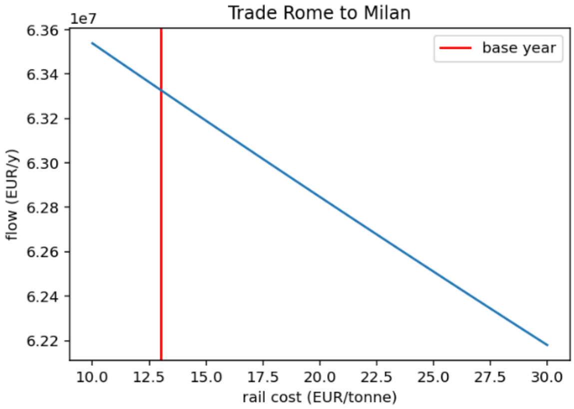

Figure 7. Direct impact of shipment price by rail: Rome to Milan trade, dry bulk

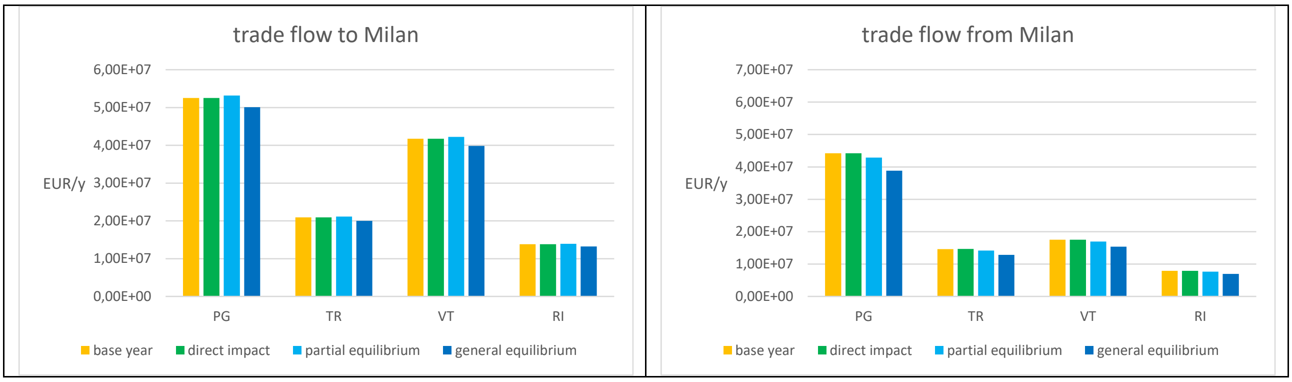

Figure 8. Scenario analysis: trade flows to and from Milan of provinces accessing rail at Orte Interporto

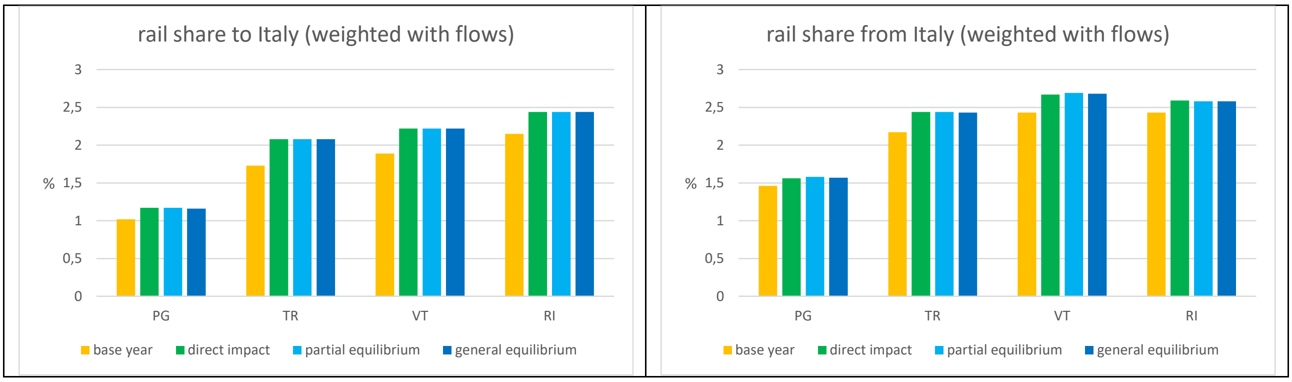

Figure 9. Scenario analysis: rail share to and from Italy of provinces accessing rail at Orte Interporto

Table 4. Scenario analysis: production in base year and in counterfactual general equilibrium scenario with the Orte Interporto rail project

Province	Base year scenario (MEUR/year)	Counterfactual general equilibrium scenario (MEUR/year)
Perugia (PG)	929.8	884.3
Terni (TR)	401.9	382.3
Viterbo (VT)	819.8	779.7
Rieti (RI)	276.8	263.3
Milano (MI)	3795.6	3609.7

Table 5. Scenario analysis: real consumption in base year and in counterfactual general equilibrium scenario with the Orte Interporto rail project

Province	Base year scenario	Counterfactual general equilibrium scenario
Perugia (PG)	1.2739e+09	1.2746e+09
Terni (TR)	4.5459e+08	4.5468e+08
Viterbo (VT)	5.5648e+08	5.5659e+08
Rieti (RI)	2.6007e+08	2.6010e+08
Milano (MI)	6.6418e+09	6.6537e+09

5. Conclusions

The models that have been presented are related to the direct and the reverse link between economy and goods mobility. Monetary trade flows, aggregate and by mode chain, in base year and counterfactual scenarios, are provided. Flows are between a production and a consumption zone. Furthermore, flows are specific of sector, which is identified on the basis of load type.

The models exhibit sensitiveness with respect to transport policy. The gravity models include as independent variables the shipment prices of the mode chain alternatives. The mode chain choice models include as independent variables both travel times and shipment prices. Therefore, policies are not restricted to new infrastructure. They extend to changes in the characteristics of any transport service. Another advantage of the approach is that it is entirely non-survey, because only data from available statistical resources are used. Surveys are complex and costly due to the multiplicity of types of decision makers and goods.

Numerical challenges have to be faced, because of the nonlinear minimization problems of both the estimation and the scenario analysis stage. Since there is no evidence of convexity of the objective functions, algorithms provide a local solution only. The solution found may change if a different starting point is used. The approach needs to be trial and error, and there is no certainty that the exact global solution is obtained. This appears to be an overlooked problem in the literature on gravity models as far as the fixed-point problems of scenario analysis are concerned.

A limitation of the present framework is the deterministic, all-or-nothing assignment of flows to the nearest rail terminal and port. Future research may try a stochastic approach to this choice. This would be more realistic, since heterogenous choices of port and rail terminal are likely to occur for the flows of the same production, or consumption, zone. The challenge here is, clearly, the estimation of the choice model, which might, in principle, be performed jointly with the gravity and chain choice models.

The scenario analysis adopts the approach of comparative statics. The use of dynamic gravity models, subsuming growth of endowment, has certainly the potential to provide different results in terms of welfare. It is left for future research.

As to the overarching DSS, additional models are needed to provide weight flows on links and nodes of the modal networks. Conversion from money (EUR) to weight (tonnes) is a key and challenging step in this respect. Then, there is the step related to the construction of the origin-destination matrices. Generally, with goods mobility, production-consumption flows and origin-destination flows are distinct quantities. This is because of warehouses and of the organisation of transport services within a mode based on the consolidation principle. This organisation, groupage by road in particular, may include multi-trip patterns, typically according to the hub-and-spoke model.

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