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INSULARITY AND THE DEVELOPMENT OF A LOCAL NETWORK: A SIMULATION MODEL APPLIED TO THE ITALIAN RAILWAY SYSTEM

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Insularity and the development of a local network: a simulation model applied to the Italian railway system*

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Abstract. A network on an island only serves the territory in which it is located, while on a mainland region the same network would also serve other regions. This paper quantitatively assesses this effect through a model which simulates the construction of a railway network in Italy. The negative effect of land discontinuity on the development of an insular railway network is found to be quite strong: while the railway lines located in the island of Sardinia are the least profitable under the factual scenario, their relative profitability is significantly boosted in every counterfactual scenario where land discontinuity is artificially removed.

JEL Classification: R41, C63.
Keywords: Insularity, Simulation Modeling, Graph Theory, Railway networks.

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1 Introduction

Islands - especially when small and remote - are usually considered disadvantaged regions from the social and economic perspective. According to EURISLANDS (2013)[1] ''Islands, of course, more often than not, face, albeit to varying degrees, a number of handicaps compared to their mainland counterparts, including limited accessibility, isolation, high dependence on a narrow range of economic activities, and tiny internal markets." Moreover, the majority of EU islands have lower performances than their overall national counterparts, with an average GDP per capita at just 79,2% of the European one [0].

In this work we propose a new channel through which the geographical conditions of islands may be a determinant of poor economic and welfare performance.

The idea behind this paper is the following: due to land discontinuity, and *ceteris paribus* (other geographical, demographic, economic and social factors being equal), the development of a vast class of physical networks (railway, road, data, energy) in an island implies higher unit costs (or lower net unit benefits) compared with the same network on a mainland region. Land discontinuity, the defining feature of an island, means that a network on an island only serves the territory in which it is located, while on a mainland region the same network would also serve other regions, spreading its net benefits among a greater number of users and reducing the cost per user.

The railway network on the island of Sardinia provides a clear example of this mechanism. If Sardinia were located on the Italian peninsula in, say, Tuscany, the railway line connecting Sassari and Cagliari (the two main cities in Sardinia) would also be used to connect people and goods moving from Milan (hypothetically north of Sassari) and Rome (hypothetically south of Cagliari), increasing its benefits or social profitability in terms of flow of passengers and goods. However, in reality Sardinia is surrounded by sea and therefore the railway line between Sassari and Cagliari is physically disconnected from any other railway lines on the Italian mainland and is not part of a larger railway network. In this paper we attempt to provide a quantitative estimate of the negative impact of insularity on the development of a railway network in Sardinia.

To this aim, we propose a simulation model based on graph theory, and in particular on the pathing algorithm by Dijkstra, aiming at simulating (under different scenarios) the development of a simplified version of the railway network taking into account the main economic mechanisms driving the construction of a railway network. To our knowledge this is the first simulation model in literature that simulates the development of a railway network solving an optimization problem whose solution represents the railway line to be built at each step of the simulation.

[1] EURISLANDS is part of the ESPON programme and its aim is to "deliver an appropriate reference work and a set of policy recommendations and strategic guidance to foster the sustainable development of the European islands within the framework of the Single Market, ensuring equal terms and opportunities with other non-handicapped regions"

We ran different computer simulations in order to analyze the proprieties of the model, its robustness and its capacity to replicate some features of the Italian railway network, albeit at a lower scale (we consider 107 railway stations out of the actual 2212) [2]. We constructed several different scenarios (counterfactuals) where Sardinia (keeping the number of its railway stations, surface, population size, regional income and real distances to all the other Italian destinations constant) is connected to the mainland either by transforming its ferry connections into rail connections or by swapping it with another Italian region, peripheral or central, which in turn becomes an island. The analysis of the evolution and the convenience of building a railway line in Sardinia at different stages of each scenario allowed us to assess the cost of Sardinian insularity in terms of forgone profitability of the investment in the railway network.

Our study is motivated by two main observations. Firstly, transport infrastructure in Sardinia is far less developed than in the rest of Italy. The development of a railway network has several dimensions, including extension in length, number of routes, route frequencies, and technological and organizational efficiency. We focused on the first dimension, extension in length. Fig. shows the relationship between population density (inhabitants per km^2 in 2011) and railway network density (km of national rail connections per $100km^2$, in 2010). Unsurprisingly, the two measures appear to be positively correlated: the most densely populated regions (e.g. Campania, Lombardia, Liguria, Lazio) have the most dense railway networks. Sardinia has the lowest railway density (less than 2 km every 100 km^2), notably lower than mainland regions with a similar population density (e.g. Valle d'Aosta, Trentino, Basilicata, Umbria, Abruzzo, Calabria, Molise). Its position far below the trend suggests that the limited development of its railway network cannot be explained purely by low population density. The underdevelopment of the Sardinian railway network is also illustrated by the ratio of population (above 14) who travelled at least once by train in a year, shown in Fig. . The value of this indicator for Sardinia is the lowest among all the Italian regions even those in the South, and shows no particular trend since the 2000. Insularity and land discontinuity may have an important role in explaining these stylized facts.

Secondly, regional transport infrastructure has a positive impact on economic and welfare performance of the region. This is true regardless of the particular sectoral structure of the economy, albeit in differing degrees, as emphasized in both empirical (Auscher [0] and Lall [0]) and theoretical (Martin [0] among other) works. In particular, Martin [0] argues that as transport infrastructure improves, transaction costs on goods produced and consumed in the region decrease, increasing the effective demand. National businesses characterized by increasing returns to scale are attracted by bigger markets and, as a result, may relocate to a region where local transport costs are lower. This in turn benefits immobile workers and immobile capital owners. But local transport infrastructure is all the more beneficial for a region like Sardinia, where the tourism sector

[2] Source: http://www.rfi.it updated at 01/29/2016

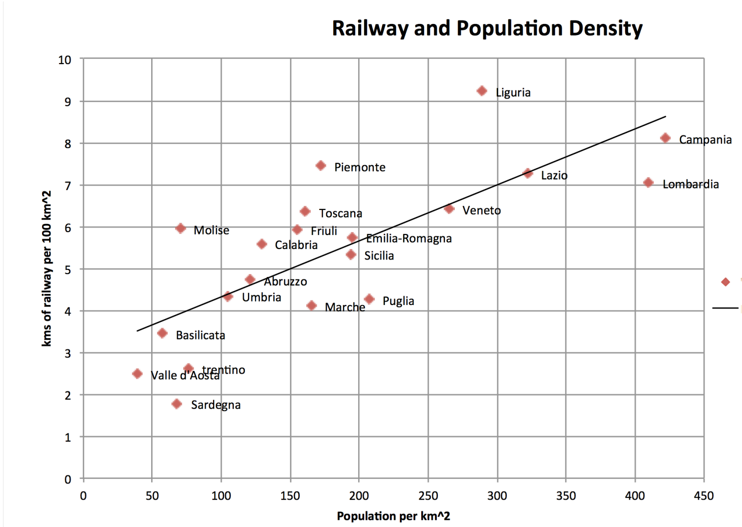

Fig. 1: Population density and railway network density in Italian Regions. Source: *CRENoS elaboration on data from Atlante Geografico De Agostini* [0].

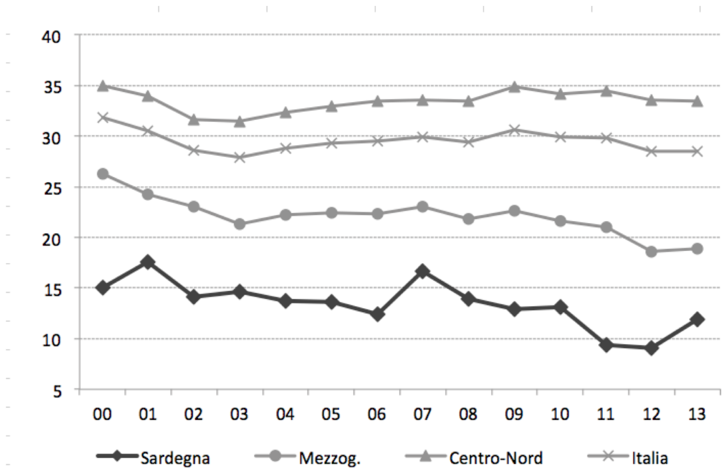

Fig. 2: % of population over 14 years who travelled by train in the last month. Source: *CRENoS elaborations on Istat data* [0].

is very important[3]: in the highly competitive Mediterranean context, an efficient and extensive local transport system can be crucial in making a destination more attractive for tourists. Finally, it is also important to mention that improving

[3] The CRENoS Annual Report on Sardinian Economics estimates that its contribution is more than 8% of the total regional value added [0].

the local transport network has a positive impact on the residents' quality of life.

Despite their relevance, issues related to the economic costs of insularity have been rather overlooked by the economic literature. The relationship between first nature geography and economic development has been intensively debated since the 90's (Henderson et al. [0], Gallup et al. [0] and Rodrik et al. [0]) and there are some theoretical papers that study the economic consequences of geographical remoteness (see Behrens et. al [0]). However, despite some insights on the additional cost of insularity can be derived from these works (see Cerina [0]), there are very few papers addressing this issue *per se.* Among these papers, surveyed by Deidda [0], we find Briguglio [0], and, more recently, Cocco et al. [0], De Benedictis and Pinna [0] and Del Gatto and Mastinu [0]. None of these papers, however, deals with the effect of insularity on the local transport network.

As far as the extension of an interregional transport network is an important determinant of local economic development, our findings have important economic policy implications. In particular, they suggest a role for central government to provide financial support for the extension of local railway networks where basic economic incentives are lacking.

The paper proceeds as follows. Section describes the model and the formalization of the main idea. Section applies the model to the specific case of the Italian network. Section presents the main results and Section concludes.

2 The Model

2.1 The Activation of a Railway line

In what follows we present a model aiming at assessing the effect of insularity on the development of a local network. As already anticipated, the model is theoretically suited to be applied to a wide class of network (road, data, electric or gas distribution, etc.) but here we focus on railway network. The model is based on a weighted graph of N nodes (or vertices), specifically created to take into account the main mechanisms that governs the building of an actual railway line.

Each node $i = 1, 2, ...N$ represents an urban center and each urban center has a railway station. The number of nodes is fixed to $N = 107$. Each edge connecting two nodes represents a railway line.

The simulation works step by step. At step 0 no line is activated so that each edge represents a *potential* railway line. These edges are indicated as *type 2* edges. At step 1, the potential railway line associated to the highest profitability (the latter being the weight attached to each edge) is activated and then it becomes an *effective* railway line or a *type 1* edge. At each following step a new potential line (type 2 edge) - the one associated to the highest profitability among the remaining potential lines - is converted into an effective line (type 1 edge). We assume that the profitability per km of a line of type 1 connecting two nodes i and j is the differences between expected discounted cash flows and expected discounted costs

$$\frac{\Pi_{ij}}{l_{ij}} = \pi_{ij} = C_{ij}^{tic} * \sum_{t=0}^{T_{ij}} f_{ijt} \frac{(1-\delta_{ij})^t}{(1+r)^t} - C_{0ij}^b \tag{1}$$

- Π_{ij} is total profitability
- l_{ij} is the geodesic length of the line connecting the nodes i and j. We estimate it using actual road distances;
- π_{ij} is profitability per km;
- C_{ij}^{tic} is the cost of a ticket per person-km of a trip from nodes i to j;
- f_{ijt} is the potential flow (number of trips) of a line connecting the nodes i and j at time t (below the definition of potential flow);
- T_{ij} is the expected lifetime of the railway line connecting i and j;
- δ_{ij} is the depreciation rate of the investment.
- r is the opportunity cost of the investment;
- C_{ij0}^b is the building cost per km at time 0 of a line connecting nodes i and j at time 0.

Since we want to focus on the effect of insularity on the development of a railway network, we neutralize all those determinants of the profitability of a railway line on which land discontinuities have no role. Hence, without significant losses of generality, we set $r = \delta_{ij} = 0$ and assumed $T_{ij} = T$, $C_{ij0}^b = C_0^b$ so that the previous expression becomes[4]:

$$\pi_{ij} = C^{tic} * f_{ij} T - C_0^b \tag{2}$$

Hence, at each step, the potential line connecting i and j associated to the highest value of π_{ij} will be built and therefore, the line activated at each step will be *the one associated to the highest passengers flow* [5] f_{ij}. So what are the determinants of passengers' flow?

2.2 The flow of passengers

Our model assigns a given flow of passengers passing through the edge (railway line) connecting any two adjacent nodes[6] (stations) according to a procedure

[4] Of course we admit that different railway lines can be associated to several building costs per km (it is certainly more expensive to build railway lines in mountain areas), expected durations and maintenance costs. Since our main aim is to evaluate the impact of insularity on the profitability of a railway line, we think that, as first approximation, there are not any a-priori reason why these elements should be significantly different from islands to the mainland.

[5] We derived this equation according to a 'market" approach but we can think that an hypothetical and benevolent central planner would take the expected flow of passengers between i and j into account when evaluating the social profitability of the investment in the construction of a railway line between i and j.

[6] According to graph theory, if nodes a and b are endpoints of one edge in a graph, then a and b are said to be *adjacent* to each other, and it is often convenient to write $a \sim b$. Nodes adjacent to a are called neighbors of a, and the set of all nodes adjacent to a is called the neighborhood of a, and denoted by $N(a)$.

based on the Dijkstra's algorithm. While the description of the algorithm is reported in the Appendix, we here provide an intuitive explanation of how the simulation model works.

At each step such flow, and then the profitability of the investment in each railway line, will be affected by the current structure of the whole railway network. Hence, in order to provide a clear insight of the mechanism, we proceed by steps adding degrees of complexity to the network and ending up to our simulated network of the Italian railway.

Computing the flow of an isolated railway line Motivated by the extensive literature on transportation economics (see [0], [0] and [0]), we assumed that the flow of passengers between two destinations results from a variant of a *gravity equation*. The expected flow of passengers between two railway stations is negatively affected by the distance between the two destinations and positively affected by the product of the "masses" (production and attraction potentials) associated to each destination. The "masses" are a Cobb-Douglas combination of the average per-capita incomes (proxying the level of economic activity, see [0]) and the population levels of the provinces where the two destinations are located.

More formally, the passengers' flow associated to an isolated edge (i.e. not adjacent to any other edge[7]) connecting two nodes i and j (either *type 1* or *type 2*) is defined as follows:

$$f_{ij} = \alpha \frac{(P_i P_j)^{\phi} (y_i y_j)^{1-\phi}}{(L_{ij})^{\beta}} \tag{3}$$

where

- $\alpha > 0$ is a normalization constant;
- P_i and P_j are the population of the nodes i and j respectively;
- y_i and y_j are per-capita income of nodes i and j respectively (proxying the level of economic activity of the area where each destination is located);
- L_{ij} is the geodesic length between nodes i and j;
- $\beta > 0$ allows to adjust the inverse dependence of the flow on the geodesic length l_{ij};
- $\phi \in (0, 1)$ defines the relative weight of the demographic and economic dimensions.

We emphasize that eq. 3 holds only for isolated railway lines belonging to a graph made of non-adjacent edges only, like the railway network R depicted in Fig. .

[7] Formally, two edges are adjacent if there exists a vertex to which they are both incident, i.e. which is an endpoint for both. Two edges are non-adjacent if they are not adjacent. An isolated edge can also be considered as a regular graph of degree 1, a regular graph being a graph where each vertex have the same degree, the latter being the number of edges connected to a vertex [0].

Fig. 3: A railway network R made of non-adjacent edges.

Here, at step 0, the algorithm estimates the flow of passengers travelling through the railway line $1-2$ as

$$f_{12}^{0} = \alpha \frac{(P_1 P_2)^{\psi}(y_1 y_2)^{1-\psi}}{L_{12}^{\beta}}, \tag{4}$$

where by f_{ij}^{k} we mean the estimated flow associated to railway line ij at step k.

Analogously, the estimated flow of passengers travelling through the railway line $3-4$ is the following:

$$f_{34}^{0} = \alpha \frac{(P_3 P_4)^{\psi}(y_3 y_4)^{1-\psi}}{L_{34}^{\beta}} \tag{5}$$

While, since 2 and 3 are disconnected (i.e. there is no edge connecting them), we have $f_{23}^{k} = 0$ and, for the same reason, also $f_{24}^{k} = f_{13}^{k} = f_{14}^{k} = 0$ at any step k.

At step 1, the algorithm selects the edge having the largest flow of passengers and transforms it in a *type 1* edge. At step 2 (the final step), there is only one edge of type 2 and the algorithm transforms it in an edge of *type 1*. It is easy to see that, when the network is made only of non-adjacent lines, then $f_{ij}^{k} = f_{ij}$ for any k: the flow of passengers associated to any line ij is the same at every step irrespective of what happens to the rest of the network since every edge is isolated.

Needless to say, the railway network here analysed is way too simple. In particular it does not take into account the fact that a given railway line (for instance Rome-Florence) can also be used by passengers who wants to reach Naples from Milan or vice versa. In the following we describe how we modeled this issue.

The flow of a railway line in a linear network We now make one step further and derive the flow of passengers in a railway line belonging to a railway network which can be modeled as a *linear* (or *path*) graph, i.e. a graph that can be represented in a straight line with n nodes and $n-1$ edges where the terminal nodes have degree 1 (i.e. they only have 1 edge connected) and the intermediate nodes are of degree 2 (each of them has 2 edges connected). An example is the one depicted in Fig. where the linear railway network R' can be viewed as a variant of the railway network R in Fig. , sharing same distances between stations, ($L'_{ij} = L_{ij}$ for $i, j = 1, 2, 3, 4$), same demography ($P'_i = P_i$ for

Fig. 4: The linear railway network R', step 0.

$i = 1, 2, 3, 4$) and same economic dimension ($y'_i = y_i$ for $i = 1, 2, 3, 4$) but with an additional *bridge* joining station 2 and 3.

The railway network R' has 3 railway lines, edge $1-2$, edge $2-3$ and edge $3-4$. What is the flow of passengers of each railway line? And how will our model work in this case?

At step 0, each of the three lines is of *type 2*, so our model estimates the flow of passengers associated to each railway line, as they were isolated line. At step 1, the one associated to the highest flow becomes of *type 1*. Hence, at step 0, the flows f'^0_{ij} associated to any edge ij of the railway network R' is:

$$f'^0_{12} = \alpha \frac{(P_1 P_2)^{\psi} (y_1 y_2)^{1-\psi}}{L_{12}^{\beta}}, \tag{6}$$

$$f'^0_{23} = \alpha \frac{(P_2 P_3)^{\psi} (y_2 y_3)^{1-\psi}}{L_{23}^{\beta}}, \tag{7}$$

$$f'^0_{34} = \alpha \frac{(P_3 P_4)^{\psi} (y_3 y_4)^{1-\psi}}{L_{34}^{\beta}}, \tag{8}$$

Since our aim is to focus on the insularity effect, we assume now that the distribution of weights among the 4 destination is such that $f'^0_{12} > f'^0_{23} = f'^0_{34}$. Hence, at step 1, the line $1-2$ becomes of *type 1*. The railway network R' at step 1 is then depicted in Fig. where the line $1-2$ is now of *type 1* and distinguished by a thicker line.

Fig. 5: The linear railway network R', step 1.

Now, after step 1, the algorithm re-computes the flow associated to each of the remaining *type 1* railway line (only $2-3$ and $3-4$). In doing so, it will take into account a clear asymmetry between these two lines. Consider first line $2-3$: if this line becomes effective, then its *own* flow (expressed by equation 6 which considers $2-3$ as it was isolated) would be boosted by the flow of those people who wants to travel from station 1 to station 3 (or vice versa), it was impossible at step 0 and that if line $2-3$ is built becomes a feasible option since line $1-2$ is already effective. Hence, after step 1, the estimated flow of the railway line $2-3$ is:

$$f_{23}'^{1} = \alpha \frac{(P_2P_3)^{\psi}(y_2y_3)^{1-\psi}}{L_{23}^{\beta}} + \alpha \frac{(P_1P_3)^{\psi}(y_1y_3)^{1-\psi}}{(L_{12}+L_{23})^{\beta}} = f_{23}'^{0} + \alpha \frac{(P_1P_3)^{\psi}(y_1y_3)^{1-\psi}}{(L_{12}+L_{23})^{\beta}} \tag{9}$$

By contrast, the flow associated to the (peripheral) line $3-4$ will be the same as step 0 because the edge 3-4 is not adjacent to any edges of *type 1* and then it could not enjoy from passing travelers. The estimated flows of line $3-4$ is:

$$f_{34}'^{1} = \alpha \frac{(P_3P_4)^{\psi}(y_3y_4)^{1-\psi}}{L_{34}^{\beta}} = f_{34}'^{0} \tag{10}$$

As above mentioned, the flow of passengers of the lines $2-3$ and $3-4$ considered as isolated edges are identical ($f_{23}'^{0} = f_{34}'^{0}$), then for sure $f_{23}'^{1} > f_{34}'^{1}$ so that at step 2 line $2-3$ will be converted in a *type 1* line by taking advantage of the higher connectivity. The railway network will then look as in Fig. .

Fig. 6: The linear railway network R', step 2.

This example provides one of the possible analytical representation of the idea we described in the introduction. Consider the flow associated to the *type 2* line $1-2$ at step 2 in the last example. This is given by:

$$f_{12}'^{2} = \alpha \frac{(P_1P_2)^{\psi}(y_1y_2)^{1-\psi}}{L_{12}^{\beta}} + \alpha \frac{(P_1P_3)^{\psi}(y_1y_3)^{1-\psi}}{(L_{12}+L_{23})^{\beta}} = f_{12}'^{0} + \alpha \frac{(P_1P_3)^{\psi}(y_1y_3)^{1-\psi}}{(L_{12}+L_{23})^{\beta}} \tag{11}$$

Now compare this flow to the one associated to the line $1-2$ in the railway network R in Fig. where this flow is equal to $f_{12} = f_{12}'^{0} < f_{12}'^{2}$ at any step of the algorithm. In words, when the railway line $1-2$ is located in an *island*, just like in the railway network R in Fig. , then it is able to serve only the territory within the boundaries of the sea because of land discontinuity. Hence, at any step of the algorithm, its flow will be equal to f_{12}. The exact same railway line, located in the exact same territory (same population, same income, same distances between stations), will experiment a higher passengers' flow if only, as in the railway network R' depicted in Fig. , land discontinuity were neutralized by a *bridge* connecting station 2 to station 3.

The algorithm ends at step 3 when only one *type 2* edge remains so line 34 will be converted in *type 1* and its estimated flow will be

$$f'^{2}_{34} = \alpha \frac{(P_3 P_4)^{\psi} (y_3 y_4)^{1-\psi}}{L_{34}^{\beta}} + \alpha \frac{(P_1 P_4)^{\psi} (y_1 y_4)^{1-\psi}}{(L_{12} + L_{23} + L_{34})^{\beta}} + \alpha \frac{(P_2 P_4)^{\psi} (y_2 y_4)^{1-\psi}}{(L_{23} + L_{34})^{\beta}} \quad (12)$$

The flow of a railway line in a disconnected linear network In order to better appreciate our argument, we now provide another example in which, at the beginning of step 3, the railway network is the one depicted in Fig. :

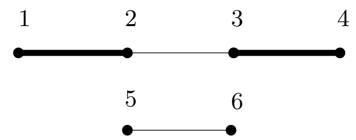

Fig. 7: A very stylized representation of the Italian railway network.

The railway network in this case is represented by a disconnected graph made of two independent linear sub-graphs: 1) the linear sub-graph I consisting in the edges $1-2$, $2-3$ and $3-4$, as in the previous example; 2) the simple sub-graph S represented by the edge $5-6$. One might think that the sub-graph I represents the railway network in continental Italy (with, for instance, 1 being Milan, 2 being Florence, 3 being Rome and 4 being Naples) and the sub-graph S represents the railway network in the island of Sardinia (with 5 being Sassari and 6 being Cagliari). Now, without loss of generality, imagine that after 2 steps for some reasons (for instance because of the largest weights associated to destination 1 and 4) the algorithm decided that lines $1-2$ (Milan-Florence) and $3-4$ (Rome-Naples) have been converted in *type 1* lines. The only thing important for our argument is that at the beginning of step 3 the algorithm must decide whether to convert in *type 1* line the (central) line $2-3$ or the (insular) line $5-6$. In doing so, the algorithm will as usual compare the potential flows of the two *type 2* lines remaining. As for line $5-6$ we have:

$$f^{2}_{56} = \alpha \frac{(P_5 P_6)^{\psi} (y_5 y_6)^{1-\psi}}{L_{56}^{\beta}} = f_{56} \quad (13)$$

By contrast, the flow associated to the line Florence-Rome $(2-3)$ will be boosted either by the upstream flows of passengers traveling from Milan to Rome, from Milan to Naples and from Florence to Naples *and* by the downstream flows of passengers traveling along the same lines but in the opposite direction. In formulas, the potential flow through the line $2-3$ at step 2 is:

$$f_{23}^2 = \alpha\frac{(P_2P_3)^{\psi}(y_2y_3)^{1-\psi}}{L_{23}^{\beta}} + \alpha\frac{(P_1P_3)^{\psi}(y_1y_3)^{1-\psi}}{(L_{12}+L_{23})^{\beta}} + \\ + \alpha\frac{(P_1P_4)^{\psi}(y_1y_4)^{1-\psi}}{(L_{12}+L_{23}+L_{34})^{\beta}} + \alpha\frac{(P_2P_4)^{\psi}(y_2y_4)^{1-\psi}}{(L_{23}+L_{34})^{\beta}} \quad (14)$$

Now, if without loss of generality we assume that the distance between Florence and Rome is not significantly shorter than the one between Cagliari and Sassari ($L_{23} \approx L_{56}$)[8] and that the economic and demographic dimensions of Florence (2) and Rome (3) are not significantly smaller than the ones of Cagliari (6) and Sassari (5). As a result we have[9]: $\alpha\frac{(P_2P_3)^{\psi}(y_2y_3)^{1-\psi}}{L_{23}^{\beta}} \approx \alpha\frac{(P_5P_6)^{\psi}(y_5y_6)^{1-\psi}}{L_{56}}$. This of course implies that f_{23}^2 is surely larger than f_{56}^2 so that the central line $2-3$ will be converted in a *type 1* line one step in advance with respect to the insular line $5-6$.

The message in words will be the following: due to land-discontinuity and *ceteris paribus* (i.e. economic, demographic and geographic dimensions being equal), the insular line Cagliari-Sassari cannot enjoy from any upstream and downstream flow of either those passengers who would like to reach Cagliari from, say, Milan or those who would like to reach Sassari from, say, Naples. The feasibility set of these passengers is then restricted with respect to those who wants to reach Naples from Milan or vice versa and they are forced to choose another means of transport (airplane or ferry) different from railways (or even cars), with other costs in terms of time and money.

By contrast, the line Florence-Rome can also be used as a transit for those passengers who leave from Milan (Naples) and wants to reach Rome (Milan) or Naples (Florence) and for this reason is more (socially) profitable.

The flow of a railway line in a non-linear network How would things change if a bridge between Sassari and Florence could be built? Evaluating the effect of this counterfactual experiment is important in order to quantitatively assess the effect of insularity on the development of a railway network. To answer to this question, it is necessary adding a further level of complexity in the network and study a non-linear network (see Fig.) where a node (node 5 in this case) can be the endpoint of two or more different edges.

This network is very similar to that in Fig. except that now line $5-6$ is no longer isolated because of the existence of two *type 1* lines: $2-5$ (representing a counterfactual bridge from Florence to Sassari) and $1-5$ representing a counterfactual bridge from Milan to Sassari.

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[8] The actual road distance between Cagliari and Sassari is actually shorter (214 km) then the one between Rome and Florence (274 km). This of course will reinforce our argument.

[9] In the real world, Rome and Florence are actually more populated and richer than Cagliari and Sassari, which would of course reinforce our argument.

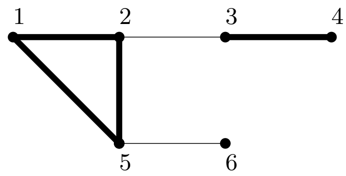

Fig. 8: A very stylized representation of the Italian railway network with bridges.

In order to evaluate the insularity effect on the development of a railway line it is interesting to assess to what extent the presence of these additional bridges (which increases the connectivity of the graph representing the railway network) boosts the flow (and then the profitability) of the former insular line $5-6$. From the comparison between the flow of $5-6$ in this counterfactual railway network and the flow of $5-6$ in the actual network, without bridges, we can derive a quantitative measure of the insularity effect we are looking for.

First we need to solve the following problem. Consider the travelers who want to reach Milan from Sassari (and vice versa). They have two different options: 1) they can go directly from Sassari to Milan along the railway line $1-5$; 2) they can choose the path $1-2-5$ going through Florence (Milan-Florence-Sassari). Which path will they choose? Answering this question is crucial in order for our model to take a decision at step 5.

We adopt here the most natural assumption: *travelers always choose the shortest path*[10]. If the spatial length of a path is positively correlated with the time length and since we have assumed that the cost of a ticket is a linear function of the spatial length of a path, then this choice will be consistent with a traveler which is a cost-minimizer.

If on the one hand this assumption might look a bit extreme option (the choice of the longest path might be motivated by reasons linked to habit or beauty of the landscape), on the other hand any alternative assumption would have brought additional complexity to the model without changing the results significantly [11]. Moreover, any other assumption different from the one induced by a cost-minimizing behaviour would have been difficult to motivate without a fully-specified microfounded model of passengers' behaviour.

Given this assumption and assuming for simplicity that each line has the same length ($L_{ij} = L$ for any pair of adjacent nodes i, j) all the passengers that wants to reach destination 6 from destination 1 (or vice versa) will choose the path $1-5-6$ instead of the longest $1-2-5-6$. Hence, at the beginning of step 5, the potential flow of line $5-6$ will be equal to:

[10] See the details of the algorithm in the appendix.

[11] A less extreme option would be for instance that each passenger chooses the shortest path if and only if it is sufficiently shorter than the longest path while a certain fraction of passengers will pass through the longest path if the latter is not sufficiently longer than the shortest path. At the limits, if two paths are of equal length, then the flow of passengers will be equally divided between the two paths. We developed a model with a variant of this alternative assumption and results - which are available at requests - are very close to this more simple version of the algorithm.

$$f_{56}^4 = f_{56} + \alpha\frac{(P_1P_6)^{\psi}(y_1y_6)^{1-\psi}}{(L_{15}+L_{56})^{\beta}} + \alpha\frac{(P_2P_6)^{\psi}(y_2y_6)^{1-\psi}}{(L_{25}+L_{56})^{\beta}} > f_{56} \tag{15}$$

Where the value of f_{56} is given by (13). Notice that, given the previous assumption of distance-minimizer travelers, no people from Cagliari (destination 6) will choose to use the line $2-5$ to reach Milan (1) as they will all use the shortest path Cagliari-Sassari-Milan $1-5-6$. Still, the line $5-6$ will be associated to a larger flow of passengers (and then to a higher profitability) in this counterfactual experiment than in the previous example (Fig.) where it was an isolated line.

3 A simulated railway network for Italy

In this section we describe the application of the proposed model to a simplified version of the Italian railway network. The simplified railway network was built selecting the most populated cities and the main railway lines for each Italian region. The graph representing the railway network is composed by 107 nodes and - in the factual scenario to be described below - by 142 railway lines.

The main targets of our analysis are the expressions that determine the profitability of the investment in the construction of a railway line: eq. 2 and primarily eq. 3. We have calibrated the model by assigning values to the parameters: $C^{tic}, T, C_0^b, \alpha, \psi$ and β. The choice of these values has been guided by both the need to fit the real-world as much as possible and the aim to focus on the insularity effect and isolate it from other possible effects.

In equation 2 the parameter T is set equal to 10 years, and hence, equal to 3650 days, being a simulation step equal to one day. The cost of a ticket per person-km, C^{tic}, was set equal to 0.1127 Euros. This value is the average value computed on all regional fares in Italy[12]. The building cost C^b per km is set equal to 10 million euros.

In Eq. 3 we set parameters $\alpha = 0.1$ (the interchange between two urban areas affects 10% of their population) and $\beta = 0.5$ (the interchange between two urban areas depends on the square root of their distance).

As for P_i, P_j and y_i, y_j, we used respectively the population and the per-capita GDP of the whole province where the railway station i or j is located. Data for provincial population and GDP and are from ISTAT (2012). Finally, we approximated L_{ij} with the geodesic road distance from destination i to destination j taken from Google Maps[13].

[12] The source of our computation is http://www.trenitalia.com/cms/v/index.jsp?vgnextoid=1b97fe9cd30 e7310VgnVCM1000008916f90aRCRD

[13] We have performed a sensitivity analysis in order to test the theoretical robustness of the model by letting the value of the set of parameters (in particular α, β and ϕ in equation (3)) change running different Montecarlo simulations. Results are not significantly different from what we report below suggesting that the model is fairly robust in this respect. Results are available at request.

Fig. describes the design scheme of the railway network to be built at the initial step of the simulation. Each node represents a destination, with size proportional to the geometric weighted average of the number of its inhabitants and its per-capita GDP ($P^{\psi}y^{1-\psi}$). Each edge represents a potential railway line.

The simulation proceeds by steps.[14]. At step 0, there are no active railway line, and every line is a *potential* one. At each step the potential line having the highest profitability (which in our model corresponds to the highest passengers' flow) is built and then becomes an *effective* railway line. At each subsequent step, the potential railway line having the maximum profitability among the remaining is built. The simulation stops at step number 142 where the least profitable railway line is built.

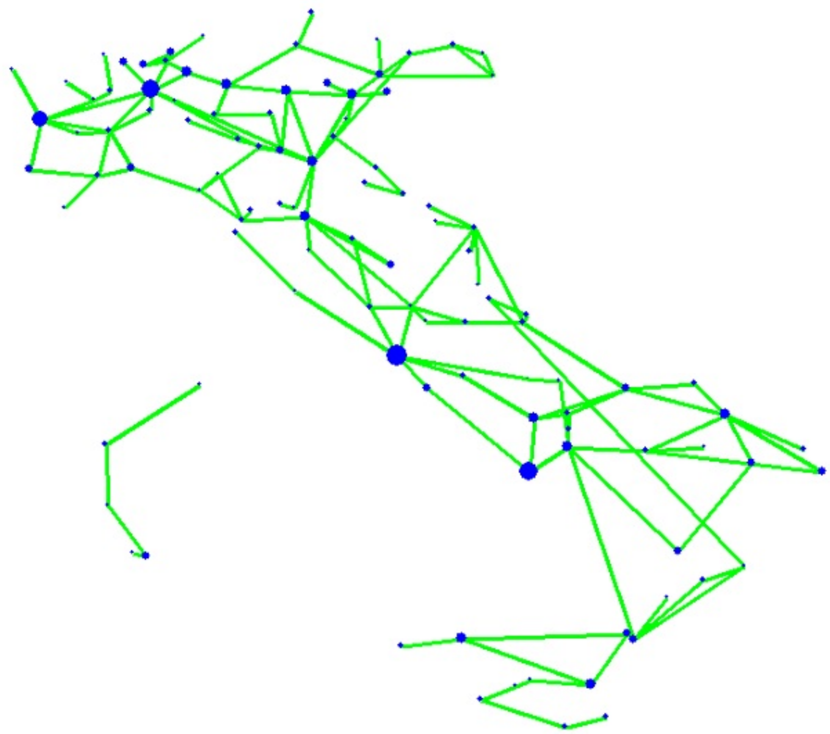

Fig. 9: Scheme of the simplified Italian railway network. Sardinian cities are the five nodes on the left, which forms a sub-graph disconnected to the rest of the graph.

We report here the results related to 6 different scenarios, one of them factual and 5 counterfactual. To the purpose of focusing on the effect of land discontinu-

[14] The details of the algorithm are described in the appendix.

ity only, in any of these counterfactual scenarios distance, incomes, population size are invariant with respect to the factual scenario.

- **Scenario 1 - Factual**: actual location of Italian regions.
- **Scenario 2 - Bridges**: ferry connections turn into potential or effective railway connections.
  - *Lines added*: Cagliari-Roma, Cagliari-Palermo, Cagliari-Trapani, Cagliari-Napoli, Sassari-Genova, Olbia-Roma, Olbia-Livorno, Olbia-Genova. No lines are removed.
- **Scenario 3 - Calabria**: Sardinia located in place of Calabria and vice versa:
  - *Lines added*: Olbia-Salerno, Olbia-Taranto, Sassari-Teramo, Cagliari-Messina, Cagliari-Salerno.
  - *Lines removed*: Cosenza-Salerno, Cosenza-Taranto, Crotone-Teramo, Reggio Calabria-Messina, Reggio Calabria-Salerno.
- **Scenario 4 - Puglia**: Sardinia located in place of Puglia and vice versa.
  - *Lines added*: Sassari- Potenza, Olbia-Chieti, Olbia-Caserta, Olbia-Benevento, Cagliari-Potenza, Oristano-Cosenza .
  - *Lines removed*: Bari- Potenza, Foggia-Chieti, Foggia-Caserta, Foggia-Benevento, Lecce-Potenza, Taranto-Cosenza.
- **Scenario 5 - Sicily**: Sardinia located in place of Sicily and vice versa.
  - *Lines added*: Cagliari-Reggio Calabria.
  - *Lines removed*: Messina-Reggio Calabria.
- **Scenario 6 - Tuscany**: Sardinia located in place of Tuscany and vice versa.
  - *Lines added:* Olbia-Perugia, Olbia-Viterbo, Oristano-Perugia, Oristano-Terni, Oristano-Bologna, Cagliari-Rome, Sassari-La Spezia, Carbonia-Viterbo.
  - *Lines removed:* Arezzo-Perugia, Arezzo-Viterbo, Florence-Perugia, Florence-Terni, Florence-Bologna, Grosseto-Rome, Pisa-La Spezia, Siena-Viterbo, Bologna-Prato.

These scenarios were chosen with the aim of isolating and measuring the effect of insularity and land discontinuity on the profitability of regional railway networks. We gain a quantitative idea of this effect by comparing the first scenario to the other five counterfactual scenarios. In the second scenario we remove land discontinuities and imagine that Sardinia is not an island and is connected to the mainland by means of railway 'bridges'. In the third, fourth and fifth scenarios we again imagine that Sardinia is not an island and we swap it with another peripheral Italian region, which in turn becomes an island. These scenarios allow us to evaluate the additional cost of insularity with respect to geographic remoteness as considered in the European regional policy programs. In the sixth scenario we imagine that Sardinia becomes a (geographically) core region while the latter becomes an island: in this case some Sardinian railway lines (especially Sassari-Oristano and Oristano-Cagliari) might also be used by passengers travelling from Milan to Rome with a clearly positive effect on the flow of passengers and thus on the profitability of the investment.

4 Results

Since in our simulation a new railway line is activated at each step according to the maximum profitability of the remaining lines not activated yet, one simple and intuitive way to quantify the effect of insularity is to compare the profitability ranking[15] of the Sardinian railway lines in the factual and in each counterfactual scenario. This information is provided by the first set of rows of Table .

The table reports the ranking of each railway line in the factual and in the five counterfactual scenarios. As for the latter only, each column also contains a sub-column where the change in the percentile of the ranking with respect to the factual scenario is reported. Positive changes are reported in green while negative changes are reported in red.

Several observations are worth highlighting:

- The four Sardinian lines considered in the model are the least profitable in the factual scenario.
- Each of these four lines improves its ranking in any of the other counterfactual scenarios.
- In Scenario 2 - Bridges - the profitability of internal lines is boosted by the newly added interregional connections. Sardinian internal lines improve their ranking by more than 11% on average and they are not the least profitable (the four least profitable lines are now Aquila-Rieti, Bari-Barletta, Cosenza-Taranto and Trieste-Udine. The improvement is more evident for Oristano-Sassari and Cagliari-Oristano (about 14%) and less for Carbonia-Cagliari and Sassari-Olbia- This result is driven by the fact that the first two lines are on the direction of the main flow of passengers while the last two lines are longitudinal to this flow.
- The ranking improvements are even higher ($12 - 13\%$ on average) when Sardinia is located in remote Italian regions such as Calabria, Apulia and Sicily (the latter is not considered to be an island because of the Messina-Reggio Calabria railway line, which ranks 76th in the factual scenario).

These results aim to capture, from two different perspectives, the additional cost implied by land discontinuity with respect to geographical remoteness, which is a necessary but not sufficient condition for insularity.

Improvements are significantly larger in Scenario 5 where Sardinia is located in place of Tuscany, which therefore becomes an island. In this scenario, the average gain in ranking is almost 42% (with Cagliari-Oristano and Oristano-Sassari gaining respectively 88 and 83 positions, leading to a 62 and a 58% improvement in profitability ranking).

Another related and potentially more striking finding is generated by comparing the ranking of the regional railway lines of Calabria, Puglia, Sicily and

[15] We focus on ranking rather than the resulting values of the investment profitability because the model is too simplified to consider these values a good approximation of reality. We then employ an ordinal approach, rather than a cardinal one.

Table 1: Changes in the relative profitability of some railway lines across scenarios.

	Scenario 1	Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
Railway line	**Factual**	**Bridges**		**Calabria**		**Apulia**		**Sicily**		**Tuscany**	
	Rank	Rank	%Δ	Rank	%Δ	Rank	%Δ	Rank	%Δ	Rank	%Δ
Cagliari-Carbonia	139	**135**	7,9%	**125**	9,9%	**124**	10,6%	**122**	12%	**107**	22,3%
Cagliari-Oristano	140	**127**	13,9%	**118**	15,5%	**131**	6,3%	**119**	14,8%	**52**	62%
Oristano-Sassari	141	**128**	14%	**119**	15,5%	**116**	17,6%	**120**	14,8%	**58**	58,4%
Sassari-Olbia	142	**137**	8,7%	**132**	7%	**115**	19%	**125**	12%	**110**	22,5%
Cagliari-Roma	-	68									
Cagliari-Palermo	-	69									
Sassari-Genova	-	103									
Olbia-Roma	-	122									
Cagliari-Trapani	-	123									
Cagliari-Napoli	-	136									
Olbia-Genova	-	145									
Olbia-Livorno	-	146									
Catanzaro-R. Calabria	109			**140**	-21,8%						
Crotone-R. Calabria	119			**142**	-16,2%						
Catanzaro-Crotone	120			**141**	-14,8%						
R. Calabria-V.Valentia	121			**139**	-12,7%						
Bari-Foggia	63					**141**	-54,9%				
Bari-Lecce	64					**139**	-52,8%				
Bari-Taranto	67					**136**	-48,6%				
Barletta-Foggia	70					**138**	-47,9%				
Bari-Brindisi	79					**140**	-43%				
Bari-Barletta	136					**137**	-0,7%				
Catania-Messina	77							**133**	-39,4%		
Messina-Palermo	78							**141**	-44,4%		
Palermo-Trapani	107							**135**	-19,7%		
Caltanissetta-Enna	123							**137**	-9,9%		
Agrigento-Caltanissetta	124							**138**	-9,9%		
Agrigento-Ragusa	125							**139**	-9,9%		
Ragusa-Siracusa	126							**140**	-9,9%		
Catania-Enna	132							**136**	-2,8%		
Catania-Palermo	134							**134**	0%		
Firenze-Pisa	38									**136**	-69%
Lucca-Pisa	39									**135**	-67,6%
Arezzo-Firenze	40									**137**	-68,3%
Pistoia-Prato	49									**140**	-64,1%
Firenze-Siena	50									**138**	-62%
Grosseto-Livorno	106									**142**	-25,3%
Massa Carrara-Pisa	132									**139**	-4,9%

Tuscany in the factual and each counterfactual scenarios. This information is provided by the last 4 sets of rows in table 1.

- Except from the railway line Trieste-Udine (which is the least profitable in every counterfactual scenarios), all railway lines of each region represented in the counterfactual scenarios become the least profitable within our simplified Italian railway network. This is true even for Tuscany whose per capita income and population size are above the Italian average and whose mail railway lines are quite profitable in the factual scenario (Florence-Pisa ranks 38th and Lucca-Pisa 39th). This suggests that the negative effect of insularity on the development of a railway network is very strong: when a railway network is not connected to the mainland, it looses much of its profitability despite the intraregional flow of passengers.
- This is most evident for remote regions such as Calabria and Sicily. It is notable how the Messina-Palermo railway line goes from the 78th to the 141th position purely because of losing its connection to the mainland railway network (granted by the railway line Messina-Reggio Calabria which is replaced in the Sicilian counterfactual scenario by the Cagliari-Reggio Calabria line).

It is important to emphasize that our focus here is on the effect of land continuity/discontinuity only on the intraregional railway lines. There is, however, another more direct effect: land discontinuity does not only lower the profitability of the intraregional railway network but it also reduces (to zero) the number of interregional railway lines. In this respect, we observe that in each counterfactual scenario the new interregional lines created from Sardinia to the mainland are quite profitable, despite the fact that Sardinian local flow of passengers is not particularly large (due to relatively low population and per-capita income). For example: Cagliari-Roma and Cagliari-Palermo rank respectively 68th and 69th in the Bridges scenario (2); Cagliari-Salerno and Cagliari-Messina rank respectively 85th and 86th in the Calabria scenario (3); Cagliari-Potenza and Potenza-Sassari rank respectively 68th and 90th in the Apulia scenario (4); Cagliari-Reggio Calabria ranks 76th in the Sicily scenario (5); Oristano-Bologna and Cagliari-Roma rank respectively 51th and 54th in the Tuscany scenario (6).

5 Conclusions

This study provides a qualitative and quantitative analysis of the negative effect that insularity, and its implied land discontinuity, have on the development of a railway network. To the best of our knowledge this is the first time that a mathematical model simulates the development of a railway network solving an optimization problem whose solution represents the railway line to be built at each step of the simulation.

The negative effect of land discontinuity works either by physically preventing any interregional connection to the mainland network and by reducing the flow of passengers using the intraregional railway network (and thereby reducing the profitability) because the latter can only serve to connect destinations within a region and not between regions. Simulation results show that these negative effects are quite strong.

1. In the factual scenario, Sardinian railway lines are shown to be the least profitable within the whole (simplified) Italian railway network.
2. If Sardinia were connected to the mainland (i.e. land discontinuity were removed), there would be a remarkable increase in the profitability of the Sardinian railway lines.
3. All railway lines of each region in the last four counterfactual scenarios - where each is relocated to Sardinia - become the least profitable, even when the region's income and population (i.e potential railway users) are above average.

This model shows that insularity may have an important role in explaining the limited development of transport infrastructure in Sardinia. To the extent that the presence of an efficient and diffused transport network is an important determinant of local economic development (as argued by some important pieces of economics literature), the results of this study have important policy implications because they suggest that there is a role for central government to financially support the extension of the local railway network where economic incentives are lacking.

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Appendix

A Algorithm Description

The model described in the previous sections investigates the insularity effects starting from a potential railway network (a graph), made of railway stations (the nodes) and lines (the edges), and solving over all simulation period a profit maximization problem whose solution step by step is the railway line to be built at the current simulation step. The model was implemented in Smalltalk language and works as follows.

At first, all the edges in the graph represent the possibility to create a railway line. No railway line exist and all edges are indicated as edges of *type 2*. Over time, the edges of *type 2* are converted in the edges of *type 1* when the railway line associated to that edge is built. To evaluate the possibility to build a new line between a pair of edges a and b, the model calculates the total potential flow in edge a_b, F_{ab}, obtained summing for each pair of nodes i and j the hypothetical flow g_{ij}, as illustrated in the algorithm description below.

ALGORITHM: Computation of the Potential Flux, F_{ab}
Repeat: for all type 2 edges.
$F_{ab} = 0$
for$_1$ i=1 **to** N **do**
for$_2$ j=i+1 **to** N **do**
1. compute the geodesic distance, L_{ij} between the nodes i and j accross type 1 edges ignoring the edge ab;
2. compute the geodesic distance, L'_{ij} between the nodes i and j accross type 1 edges including also edge ab, and define it as $L'_{ij} = l'_{ij} + d_{ab}$, where

- $l'_{ij} = min\left\{[l(a,i)+l(b,j)],[l(a,j)+l(b,i)]\right\}$[16].
- d_{ab} is the lentgh of the edge ab.

3. put $f'_{ij} = 0$
4. **if** $L'_{ij} < \infty$ **then**
   (a) compute f'_{ij}[17] and put $g_{ij} = f'_{ij}$
   (b) **if** $L'_{ij} < L_{ij}$ **then** $g_{ij} = f'_{ij}$
   (c) **if** $L_{ij} > L'_{ij}$ **then** $g_{ij} = 0$
   (d) **if** $L_{ij} = L'_{ij}$ **then** $g_{ij} = \frac{1}{2} f'_{ij}$
   (e) $F_{ab} = F_{ab} + g_{ij}$

endFor$_1$

endFor$_2$

EndRepeat

[16] $l(a,i)$ indicates the geodesic distance between the nodes a and i: $l(a,i) > 0$ if the geodesic distance is computed accross a path in which nodes a and i are different and that does not include type 2 edges; $l(a,i) = 0$ if the geodesic distance is computed accross a path in which nodes a and i are coincident; and $l(a,i) = \infty$ if the geodesic distance is computed accross a path including a type 2 edge.

[17] f'_{ij} is defined as in Eq. 3 except the denominator that is equal to $(L'_{ij})^{\beta}$.

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