Noname manuscript No.
(will be inserted by the editor)

Insularity and the development of a local railway network

Received: date / Accepted: date

Abstract This paper quantitatively assesses the negative impact of land discontinuity on the development of a railway network on an island. This implicit cost of insularity is because an insular railway network only serves the territory in which it is located while the same network on a mainland also serves other regions. We apply this idea to the case of a simplified Italian railway network and we implement it through a simulation model. The simulation results highlight the strong negative effect of land discontinuity: whereas the railway lines located on the island of Sardinia are the least profitable under the factual scenario, their relative profitability is significantly boosted in every counterfactual scenario where the land discontinuity is artificially removed.

Keywords Insularity · Simulation Modeling · Railway Networks · Regional Development

JEL Classification: R41, R12, R58, C63

1 Introduction

Islands - especially when small and remote - are usually considered disadvantaged regions from a 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."

[1] EURISLANDS is part of the ESPON program 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".

This is a post-print version. Please cite as
Cerina F. et al. (2020), “Insularity and the development of a local railway network”,
Economia Politica, 37, 683–702 , DOI: https://doi.org/10.1007/s40888-019-00158-4

The majority of EU islands have a lower economic performance than their national counterparts overall, with an average gross domestic product (GDP) per capita of just 79,2% of the European one (Espon (2013)). Therefore, the geographical conditions of islands may be a determinant of poor economic and welfare performance.

In this paper, we provide a quantitative estimate of the negative impact of insularity on the development of an insular railway network compared to the development of a railway network in the mainland. Specifically, we simulated the development of the Italian railway network by studying the impact of land discontinuity on the development of the railway network in Sardinia, the main Italian island. Our model can be easily applied to any railway network covering a territory composed of a mainland and one or more islands.

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) on an island implies higher unit costs (or lower net unit benefits) compared to the same network on a mainland. Land discontinuity, the defining feature of an island, means that a network on an island only serves the territory on which it is located, while on a mainland region the same network serves other regions, spreading its net benefits among a higher number of users and thereby reducing the cost per user. Indeed, if Sardinia were located on the Italian peninsula, such as, for example in the Tuscany region, 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). Accordingly, it would then increase its benefits or social profitability in terms of the 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 line on the Italian mainland and is not part of a larger railway network (see Figure 4 in Section 3.1).

Two considerations form the motivation for our model. First, the transport infrastructure in Sardinia is far less developed than in the rest of Italy, as illustrated in Figure. 1, which 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). The scatterplot shows a positive correlation: the most densely populated regions (e.g., Campania, Lombardia, Liguria, Lazio) have the densest 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 is far below the trend which 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 the population (above 14) who travel at least once by train in a year, shown in Figure 2. The value of this indicator for Sardinia is the lowest of all the Italian regions even those in the south, and shows no particular trend since 2000. Insularity and land discontinuity may have an essential role in explaining these stylized facts.

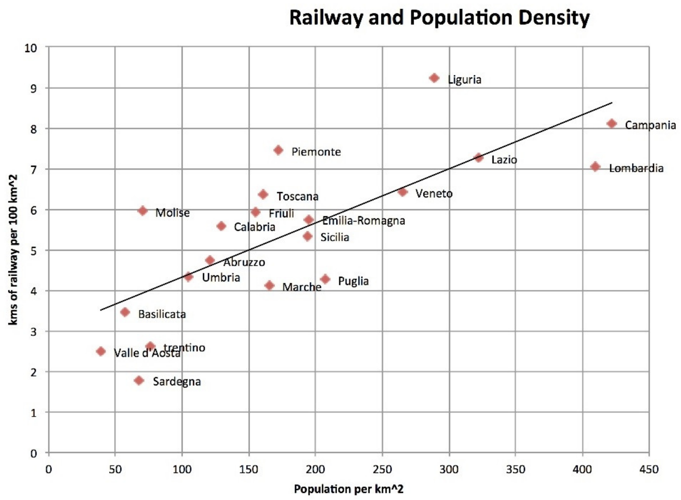

Fig. 1 Population density and railway network density in Italian regions. Source: *CRENoS elaboration on data from Atlante Geografico De Agostini* CRENoS (2014).

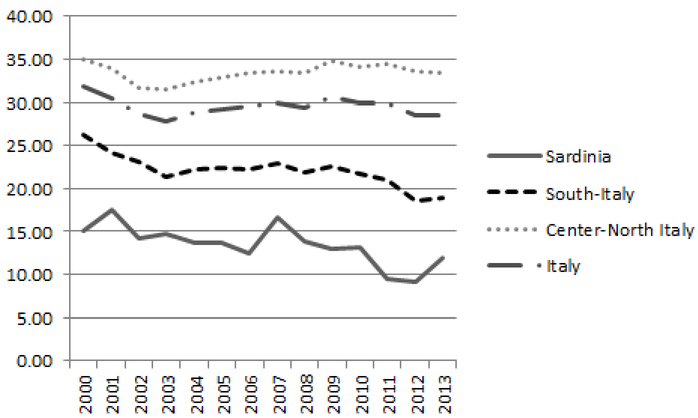

Fig. 2 Percentage of the population over 14 years who traveled by train in the last month from 2000 to 2013. Source: *CRENoS elaborations on Istat data* CRENoS (2015).

Secondly, the regional transport infrastructure has a positive impact on the region's economic and welfare performance. It is true regardless of the particular sectoral structure of the economy, albeit in differing degrees, as emphasized in both empirical (Auscher (1989) and Lall (2007)) and theoretical (Martin (1999) among other) works. In particular, Martin argues that as transport infrastructure improves, transaction costs on goods produced and consumed in the region decrease, increasing the effective demand. Bigger markets attract national businesses characterized by increasing returns to scale and, as a result, they may relocate to a region where local transport costs are lower, which in turn benefits real estate workers and real estate capital owners. Moreover, a local transport infrastructure would be beneficial for a region like Sardinia, where the tourism sector is vital[2]: in the highly competitive Mediterranean context, an efficient and extensive local transport system can be a crucial determinant for making a destination more attractive to tourists. Finally, improving the local transport network has a positive impact on the residents' quality of life.

In light of all these considerations, this work seeks to provide a quantitative estimate of the impact of insularity on the development of a railway network on an island. By using a simulation model, we modeled and simulated the development of a railway network on the Italian territory, by implementing a profit-maximizing strategy that considers the main economic mechanisms that drive the construction of a railway network.
The paper is organized as follows. Section 2 provides a summary of the relevant background for our work. Section 3 describes the model, and Sections 3.1-3.2 illustrate some of its applications. Section 4 presents the case study, specifically, the model calibration, the simulation runs and the main results. Finally, Section 5 provides the conclusion.

2 Background

To our knowledge this is the first simulation model that investigates and provides a quantitative estimate of the effects of insularity on the development of a railway network in the mainland and its islands.

Despite their relevance, issues related to the economic costs of insularity tended to be overlooked in the economic literature. In this paper we try to fill this gap by bridging two main strands of research. The first strand of literature is the one which analyzes the impact of first nature geography on the local economic performance. Since the 1990s, the relationship between first nature geography and economic development has been intensively debated. From an empirical point of view, Henderson et al. (2001) reviewed the existing literature on geography and development and argued that rigorous theoretical and empirical analysis is needed to increase the understanding of the role of geography in development and to design development policy better. Gallup et al. (1999) investigated the complex relationship between geography and macroeconomic growth, specifically the role of geography on growth, controlling for economic policies and institutions and the effects of geography on

[2] The CRENoS Annual Report on Sardinian Economics estimates that its contribution is more than 8% of the total regional value added CRENoS (2014).

policy choices and institutions. Rodrik et al. (2004) estimated the contributions of institutions, geography, and trade in determining income levels around the world. From the theoretical perspective, some interesting insights can be found in Behrens et al. (2006) who studied the impacts of changes in international trade and domestic transport costs on the internal geography of countries in the presence of geographical asymmetries. Similarly, Krugman (1991), Ottaviano (2002) and Ottaviano and Thisse (2005) investigate the role of smallness and peripherality, without addressing explicitly the distinctive features of island economies. Some insights on the additional cost of insularity can be derived from the works cited above (see Cerina (2015)), but very few papers address the insularity issue *per se*. Among these papers, surveyed by Deidda (2015), we find Briguglio (1995), and, more recently, Cocco et al. (2018), De Benedictis and Pinna (2015) and Del Gatto and Mastinu (2015). None of these papers, however, deals with the effects of insularity on the local transport network as our work does.
The second strand of literature is the one concerning transport modeling and transport network design. Over the past 30 years, there has been a plethora of literature on the study of railroad economics, such as the evolution of railroad economics, railroad costs, freight transportation spatial demand, railroad passenger demand, railroad pricing, impacts of railroad abandonment on energy use and pollutant emissions. Such transportation theory uses of mathematical models that calculate the optimal design of the system to achieve maximum performance.
Ortuzar and Willumsen (2011) provide an overview of transport modeling techniques, by giving particular emphasis to modeling and planning. Dennis and Talley (2007) provide many original contributions to the study of railroad economics. In Espon (2015), a conceptual framework is applied to study accessibility: the benefits that households and firms enjoy from the existence and use of the transport infrastructure relevant for their area, at global, European and regional levels considering the four modes of transport road, rail, water and air. Wardman (2006) presented an enhanced model to forecast railway demand and to explain the high levels of growth experienced in the 1990s in Great Britain. Wardman et al. (2007) revisited cross-sectional models of rail travel demand, to allow for a detailed analysis of catchment areas, to investigate by refining the functions the access to and the egress from stations, and to model the station choice by using a multinomial logit model[3]

Our paper aims to model and simulate the development of a railway network considering the effect of land discontinuity on the development of this network on a mainland and its island. As described in detail in the next Section, to achieve this goal we kept the model as simple as possible. It is important to emphasize that, given our aims, we focus on the evolution of a single transport mode. Another related exciting topic is the impact of land disconti-

[3] We emphasize that our paper can be also related to policy-oriented literature. Among these groups of papers we find Armstrong and Read (1998), Armstrong and Read (2004), Armstrong et al. (2006) and Bertram and Karagedikli (2004) who discuss the evidence on the impact of insularity on economic growth.

nuity on the optimal choice of transport modes. As a study of this issue would mean the implementation of a different modeling strategy, we will leave the analysis of this interesting topic for future research.

3 The Model

The model focuses on the railway network, but it can be generalized to investigate the insularity effects on the development of a wide class of networks such as roads, data, electric or gas distribution.

We modeled the railway network on a graph. Initially, each node $i = 1, 2, ..., N$ represents an urban center[4], and each edge, connecting two nodes, represents a potential railway line. At each step the simulation model computes the profitability of each *potential line* (*type 2* edges) and then converts the potential line having the highest potential profitability into an *effective* line (*type 1* edges).

We define the profitability per km of a line, π_{ij}, as the difference between the expected discounted cash flows, DC_{ij}, and expected discounted costs[5], C^b_{0ij}:

$$\pi_{ij} = DC_{ij} - C^b_{0ij} = C^{tic}_{ij} * \sum_{t=0}^{T_{ij}} f'_{ijt} \frac{(1-\delta_{ij})^t}{(1+r)^t} - C^b_{0ij} = \frac{\Pi_{ij}}{L'_{ij}} \tag{1}$$

- C^{tic}_{ij} is the cost of a ticket per person-per km of a trip from nodes i to j;
- f'_{ijt} is the flow (number of trips) of a line connecting the nodes i and j at time t;
- 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^b_{ij0} is the building cost per km at time 0 of a line connecting nodes i and j at time 0;
- Π_{ij} is total profitability;
- L'_{ij} is the geodesic length of the line connecting the nodes i and j.

To simplify the model, we assumed $r = \delta_{ij} = 0$, $T_{ij} = T$ and $C^b_{ij0} = C^b_0$ without significant losses of generality on the results[6].

[4] To manage the computational complexity, we simulated the evolution of a railway network in which a railway station can be located only in an urban center.

[5] This equation stems from a "market" approach but, normally, a central planner assesses the expected flow of passengers to evaluate the social profitability of the investment in the construction of a railway line.

[6] Of course we admit that different railway lines can be linked to several building costs per km (it is certainly more expensive to build railway lines in mountainous areas), including different expected duration period and maintenance costs. As our main aim is to evaluate the impact of insularity on the profitability of a railway line, we think that, as a first approximation, there are not any a-priori reasons why there should be a significant difference in these elements between islands and the mainland.

Equation 2 becomes:

$$\pi_{ij} = C^{tic} * f'_{ij} T - C_0^b \tag{2}$$

and hence, C^{tic}, T and C_0^b being constants, each potential line, connecting i and j, is characterized by a specific flow of passengers, f'_{ij}.

The flow of passengers, f'_{ij}, is given by:

$$f'_{ij} = \alpha \frac{(P_i P_j)^{\phi} (y_i y_j)^{1-\phi}}{(L'_{ij})^{\beta}} \tag{3}$$

Where

- α is a normalization constant;
- P_i and P_j are the populations 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;
- β allows to adjust the inverse dependence of the flow on the geodesic length L'_{ij};
- ϕ defines the relative weight of the demographic and economic dimensions.

The potential flow of passengers is defined as a variant of a *gravity equation* as in Ortuzar and Willumsen (2011), Wardman (2006) and Wardman et al. (2007). The expected flow of passengers between the 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 potential) associated with each destination. The "masses" are a Cobb-Douglas combination of the average per-capita incomes (proxying the level of economic activity, as in work Wardman et al. (2007)) and the population levels of the urban centers where the two destinations are located.

The model works as follows. To find the edge with the maximum potential profitability/flow, which is the one which will be converted into a *type 1* edge, the model calculates the total potential flow in each *type 2* edge $a - b$, F_{ab}, by considering the flow, f'_{ij}, coming from the upstream and/or downstream nodes, of passengers traveling along the lines $a - b$, under the assumption that passengers choose the shortest path. In the case of multiple paths having the same length, the passengers' flow, f'_{ij}, is divided equally among the paths. Specifically, the model calculates the total potential flow in each *type 2* edge ab, F_{ab}, summing for each pair of nodes i and j the hypothetical flow, g_{ij}, that is computed as function of the flow f'_{ij}, as illustrated in the following:

Repeat:
  $F_{ab} = 0$
    for i=1 **to** N **do**
      for j=i+1 **to** N **do**

1. compute the geodesic distance, L_{ij} between the nodes i and j across type 1 edges ignoring the edge ab[7];
2. compute the geodesic distance, L'_{ij} between the nodes i and j across type 1 edges including also edge ab, and define it as $L'_{ij} = l'_{ij} + d_{ab}$, where
   - $l'_{ij} = min\,\{[l(a,i) + l(b,j)], [l(a,j) + l(b,i)]\}$[8].
   - d_{ab} is the length of the edge ab.
3. put $f'_{ij} = 0$
4. **if** $L'_{ij} < \infty$ **then**

(a) compute f'_{ij}[9] 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) $F_{ab} = F_{ab} + g_{ij}$

end for

end for

Until all type 2 edges, ab, have been analyzed.

In the following subsections, some simple applications of the simulation model are shown.

3.1 The flow of railway lines in a disconnected linear network

In order to better illustrate the idea described in Section 1, we analyze the railway network depicted in Fig. 3.

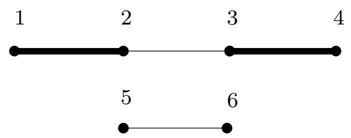

Fig. 3 A very stylized representation of the Italian railway network.

The railway network is represented by a disconnected graph made of two independent linear sub-graphs:

[7] The simulation model computes the geodesic distance according to a procedure based on Dijkstra's algorithm. Specifically, at each simulation step, the model updates a distance origin-destination matrix, where the $ij - th$ element defines the geodesic distance between the $i - th$ origin node and the $j - th$ destination node.

[8] $l(a, i)$ 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.

[9] f'_{ij} is defined as in Eq. 3.

1. the linear sub-graph I consisting in the edges $1-2$, $2-3$ and $3-4$, as in the previous example; and
2. the simple sub-graph S is represented by the edge $5-6$.

The sub-graph I may represent a small railway network in continental Italy (where the nodes 1, 2, 3 and 4 respectively represent, for example Milan, Florence, Rome and Naples) whereas the sub-graph S may represent a small railway network on an island, for example in Sardinia (where the nodes 5 and 6 respectively represent, e.g., Sassari and Cagliari).

The real locations of this Italian cities are shown in Figure 4.

Fig. 4 Italy.

At steps 0 and 1, the simulation model converts line $1-2$ (for example Milan-Florence) and line $3-4$ (Rome-Naples) respectively, to *type 1* lines. At step 2 the model has to decide whether to convert to the *type 1* line the (central) line $2-3$ or the (insular) line $5-6$. To do so, the model compares the potential flows of the two *type 2* lines remaining.

The potential flow of the line $5-6$ is computed as follows:

$$f'^2_{56} = \alpha \frac{(P_5 P_6)^{\psi} (y_5 y_6)^{1-\psi}}{L'^{\beta}_{56}} = f'_{56} \tag{4}$$

while the potential flow of the line $2-3$ as:

$$F_{23}^2 = \alpha\frac{(P_2P_3)^{\psi}(y_2y_3)^{1-\psi}}{L'^{\beta}_{23}} + \alpha\frac{(P_1P_3)^{\psi}(y_1y_3)^{1-\psi}}{L'^{\beta}_{13}} + + \alpha\frac{(P_1P_4)^{\psi}(y_1y_4)^{1-\psi}}{L'^{\beta}_{14}} + \alpha\frac{(P_2P_4)^{\psi}(y_2y_4)^{1-\psi}}{L'^{\beta}_{24}}, \quad (5)$$

It is important to highlight that, compared to the insular line, the potential flow of line $2-3$ is boosted by both the flow coming from the upstream nodes (Milan and Florence) and by the one coming from the downstream nodes (Rome and Naples). In other words, the construction of this line would benefit passengers traveling between Milan and Rome, between Milan and Naples and between Florence and Naples

Let us assume that the geodesic length between Florence and Rome is not significantly shorter than the one between Cagliari and Sassari ($L'_{23} \approx L'_{56}$)[10] and that the economic and demographic dimensions of Florence (2) and Rome (3) are not significantly smaller than those of Cagliari (6) and Sassari (5)[11], $f'_{23} \approx f'_{56}$, specifically:

$$\alpha\frac{(P_2P_3)^{\psi}(y_2y_3)^{1-\psi}}{L'^{\beta}_{23}} \approx \alpha\frac{(P_5P_6)^{\psi}(y_5y_6)^{1-\psi}}{L'_{56}}. \quad (6)$$

This implies that F_{23}^2 is larger than f'^2_{56}. Consequently, the simulation model will convert the central line $2-3$ to a *type 1* line one step ahead of the insular line $5-6$.

In short, due to land-discontinuity and *ceteris paribus* (i.e., economic, demographic and geographic dimensions being equal), the insular line Cagliari-Sassari cannot benefit from any upstream or downstream flow. That is, the insular line Cagliari-Sassari cannot take advantage of the passengers who wish to reach Cagliari from Milan and Sassari from Naples. The feasibility set for these passengers is then restricted with respect to those who want to reach Naples from Milan or vice versa. They are forced to choose other means of transport (airplane or ferry) apart from the railways (or even cars), with increased time and money costs.

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.

3.2 The flow of a railway line in a non-linear network

Figure 5 shows a network very similar to that in Figure 3 except that now line $5-6$ is no longer isolated because of the existence of two *type 1* lines:

[10] The actual road distance between Cagliari and Sassari is actually shorter (214 km) than the one between Rome and Florence (274 km).

[11] In reality, Rome and Florence are actually much more populated and richer than Cagliari and Sassari.

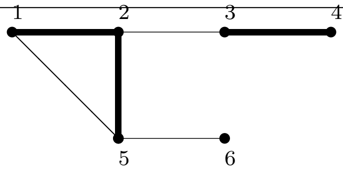

Fig. 5 A very stylized representation of the Italian railway network with bridges.

1. $2-5$ (representing a counterfactual bridge from Florence to Sassari)
2. $1-5$ (representing a counterfactual bridge from Milan to Sassari).

To evaluate the insularity effect on the development of a railway line, we assess the extent to which the presence of the additional bridges (which increase the connectivity of the graph representing the railway network) boosts the flow (and then the profitability) of line $5-6$, which represents a insular line in the previous example. From the comparison between the potential flow $F_{5-6} \neq f'_{5-6}$ in this counterfactual railway network (see Figure 5) and the potential flow of $F_{5-6} = f'_{5-6}$ in the network without bridges (see Figure 3), we derive a quantitative measure of the insularity effect.

Assuming for simplicity that each line has the same length (L'_{ij} for any pair of adjacent nodes i, j) all the passengers who want to reach destination 6 from destination 1 (or vice versa) choose the path $1-5-6$ (represented by Milan-Sassari-Cagliari) instead of the longest $1-2-5-6$ (represented by Milan-Florence-Sassari-Cagliari).

Although this assumption might look a bit extreme[12], any alternative assumption will add additional complexity[13] to the model there being any significant change in the results.[14].

At step 5, the potential flow of line $5-6$ is equal to:

$$F^5_{56} = f'_{56} + \alpha \frac{(P_1P_6)^{\psi}(y_1y_6)^{1-\psi}}{L'^{\beta}_{16}} + \alpha \frac{(P_2P_6)^{\psi}(y_2y_6)^{1-\psi}}{L'^{\beta}_{26}} > f'_{56} \quad (7)$$

[12] Travelers can also choose the longest path. The choice of the longest path might be motivated by reasons linked to habit or the beauty of the landscape.

[13] Any other assumption different from the one induced by a cost -minimizing behavior is difficult to motivate without a fully-specified micro-founded model of passengers' behavior.

[14] We implemented the model using an alternative different assumption. We assumed that passengers choose a given path if and only if it is sufficiently shorter than others. Specifically, the "point 4" of the procedure, illustrated in Section 3 to compute F_{ab}, was modified as follows:

1. compute f'_{ij} and put $g_{ij} = f'_{ij}$
2. **if** $L'_{ij} < \gamma L_{ij}$ **then** $g_{ij} = f'_{ij}$
3. **if** $L_{ij} \leq \gamma L'_{ij}$ **then** $g_{ij} = 0$
4. **if** $\gamma L_{ij} < L'_{ij} \leq L_{ij}$ **then** $g_{ij} = \frac{1}{2}[1 + \frac{L_{ij}-L'_{ij}}{L_{ij}(1-\gamma)}]f'_{ij}$
5. **if** $L_{ij} \leq L'_{ij} \leq \frac{L_{ij}}{\gamma}$ **then** $g_{ij} = \frac{1}{2}[1 - \frac{L'_{ij}-L_{ij}}{L'_{ij}(1-\gamma)}]f'_{ij}$
6. $F_{ab} = F_{ab} + g_{ij}$

The results obtained are very close to those related to the simple version of the procedure presented in Section 3.

where the value of f'_{56} is given by (4).

Note that in this counterfactual network (Figure 5) the line $5-6$ is associated with a larger flow of passengers (and then with greater profitability) than the flow in the previous network (Figure. 3), where the line $5-6$ was an isolated line.

4 Case Study: A Simulated Railway Network for Italy

4.1 Model Calibration

We implemented the model using Smalltalk programming language to simulate the development of a simplified version of the Italian railway network and to highlight the effects of insularity on the development of the railway network on an island, specifically in Sardinia.

As a way of reducing the computational complexity, we restricted the number of railway stations by selecting those Italian provinces where a railway station is located and created a potential railway line for each pair of provinces connected by one or more railway lines. The final result is a graph with 107 railway stations (nodes)[15] and 142 railway lines (edges).

We assigned the parameters in equation 3 by assuming that the interchange between the two urban areas affects 10% of their population, and thereby setting the parameter α equal to 0.1, whereas the parameter β, that is the interchange between two urban areas is set to 0.5. As for P_i, P_j and y_i, y_j, we used the population and the per-capita GDP of the whole province, respectively. Data for the provincial population and GDP were extracted from the ISTAT repository (2012). Finally, we approximated d_{ab}, that is the length of each edge (line) $a-b$, with the geodesic road distance from destination i to destination j taken from Google Maps.

Figure 6 describes the design scheme of the railway network to be built by the simulation. Each node represents a destination, with its 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 in steps. At step 0, there is 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 flow of passengers) is built and then becomes an *actual* railway line. At each subsequent step, the potential railway line that has the maximum profitability from the remaining railway lines is built. In the factual scenario, the simulation stops at step number 142 when the least profitable railway line is built.

[15] We considered 107 railway stations out of the actual 2212. Source: http://www.rfi.it updated at 01/29/2016

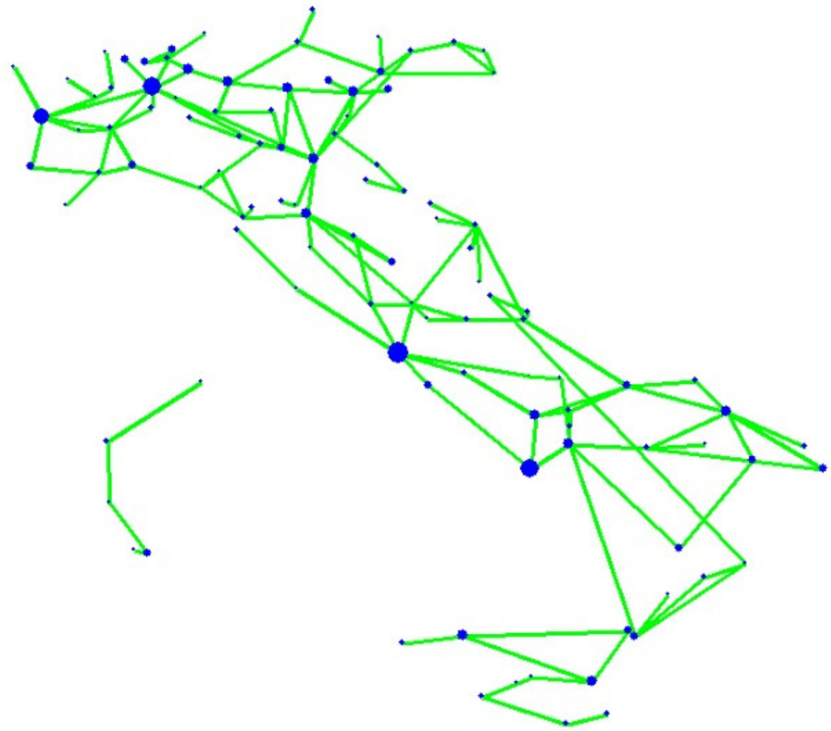

Fig. 6 Simulated Italian railway network. The Sardinian cities are the five nodes on the left, which form a sub-graph disconnected from the rest of the graph.

4.2 Simulation Scenarios

We implemented six simulation scenarios, each of them related to a different railway potential network. We ran one benchmark scenario and five counterfactual scenarios keeping the model parameters, i.e. P, y, d, β and α, fixed in each of them. While the benchmark scenario is meant to represent the actual geographical location of Italian regions, all the counterfactual scenarios were chosen with the aim of isolating and measuring the effects of insularity and land discontinuity on the profitability of regional railway networks. Accordingly, in the counterfactual scenarios Sardinia is either linked to the mainland through counterfactual bridges, or it is located in the mainland in place of another region which in turns has become an island.

More specifically, the six scenarios are defined as follows:

– **Scenario (1)** models a railway network, comprising of 107 railway stations and 142 railway lines as described in detail in Section 4.1.
– **Scenario (2)** models a railway network comprising of 107 railway stations and 150 potential railway lines. Concerning Scenario (1), eight potential railway connections are added. These potential railway lines represent

counterfactual bridges from Sardinia to the mainland. This scenario aims to isolate the effect of land discontinuity by counterfactually removing it in the model. Notwithstanding that the benchmark scenario only involves Sardinia, we can see that the profitability of the whole network will be affected.
Lines added: Cagliari-Roma, Cagliari-Palermo, Cagliari-Trapani, Cagliari-Napoli, Sassari-Genova, Olbia-Roma, Olbia-Livorno, Olbia-Genova. No lines are removed.

The aim of counterfactual scenarios (3-6) is slightly different from that of scenario (2). In the following we also aim to quantify the decrease in the profitability of railway lines located in the regions (with different degrees of centrality in the network) that are artificially removed from the mainland to become islands. More precisely:

- **Scenario (3)** models a railway network in which the locations of Sardinia and Calabria are swapped. So, starting from Scenario 1, some potential lines were added and some were removed. Our aim here is to compare the development of an internal network of an insular and remote region to that of a region which is remote but not insular.
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)** models a railway network in which the locations of Sardinia and Apulia are swapped.
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)** models a railway network in which the locations of Sardinia and Sicily are swapped.
Lines added: Cagliari-Reggio Calabria;
Lines removed: Messina-Reggio Calabria.
- **Scenario 6** models a railway network in which the locations of Sardinia and Tuscany are swapped. This counterfactual scenario aims to assess the impact of land discontinuity relative to a situation of centrality in a network.
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.

4.3 Results

In our simulation, a new railway line is activated at each step according to the maximum profitability of the remaining lines not yet activated. So, one intuitive and straightforward way to quantify the effect of insularity is to compare the profitability ranking of the Sardinian railway lines for both the factual scenario and for each counterfactual scenario[16].

This information is provided by the first set of rows of Table 1. The table shows the ranking of each railway line in the factual scenario and the five counterfactual scenarios. In the latter scenarios, each column also contains a sub-column where the change in the percentile of the ranking for the respect to the factual scenario is reported. Several observations emerge from the analysis of Table 1.

First, in the factual scenario, the four Sardinian (insular) railway lines are the least profitable. By contrast, all Sardinian lines significantly improve their ranking in all other counterfactual scenarios.

Second, in Scenario (2) (Bridges) the newly added interregional connections boost the profitability of internal lines. Sardinian internal lines improve their rankings 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). This improvement can be seen more clearly for Oristano-Sassari and Cagliari-Oristano (about 14%) and less for Carbonia-Cagliari and Sassari-Olbia. This result is because the first two lines are in the direction of the main flow of passengers, whereas the last two lines are longitudinal to this flow.

Third, the ranking improvements are even higher (12-13% on average) in Scenarios (3), (4) and (5), when Sardinia's location is swapped for 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).

As written above, these results seek to capture, from different angles, the additional cost implied by land discontinuity with respect to that of geographical remoteness, which is a necessary but not sufficient condition for insularity.

Finally,it is apparent that the improvements are substantially larger in Scenario (5), where Sardinia is swapped with Tuscany. In this scenario, the average gain in ranking is almost 42% (with Cagliari-Oristano and Oristano-Sassari gaining 88 and 83 ranks respectively, leading to an improvement of 62% and 58% in the profitability ranking).

Another related and potentially more striking finding is generated by comparing the ranking of the regional railway lines of Calabria, Apulia, Sicily and Tuscany in the factual scenario and each counterfactual scenario. Looking at Table 1, moving down to below the seventh row, we first highlight that, except for the railway line Trieste-Udine (which is the least profitable in every counterfactual scenario), all the 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

[16] We focus on ranking rather than the resulting values of the investment profitability because the model is too simplified to consider these values as a good approximation of reality. Thus, we employ an ordinal approach, rather than a cardinal one. However, this approach is able to generate some interesting quantitative predictions.

and population size are above the Italian average and whose main railway lines are quite profitable in the factual scenario (Florence-Pisa ranks 38th and Lucca-Pisa 39th). This finding 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 loses a lot of its profitability despite the intra-regional flow of passengers. Also, notice that pattern is even stronger for remote regions such as Calabria and Sicily. It is notable how the Messina-Palermo railway line goes from 78th to 141st 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). The main message here is that the upstream flow of passengers, which is artificially removed in the counterfactual scenario, generates a remarkably high profitability.

Finally, we emphasize that our focus here is on the effect of removing land discontinuity only on intra-regional railway lines. However, there is another more direct effect: land discontinuity does not only lower the profitability of the intra-regional railway network but it also reduces the number of inter-regional railway lines to zero. In this respect, we observe that in each counterfactual scenario the new interregional lines created from Sardinia to the mainland are quite profitable, even though Sardinian local flow of passengers is not particularly significant (due to the relatively low population and per-capita income). For example, Cagliari-Roma and Cagliari-Palermo rank 68th and 69th in Scenario (2) respectively, Cagliari-Salerno and Cagliari-Messina rank 85th and 86th in Scenario (3) respectively, Cagliari-Potenza and Potenza-Sassari rank 68th and 90th in Scenario (4) respectively, Cagliari-Reggio Calabria ranks 76th in Scenario (5), Oristano-Bologna and Cagliari-Roma rank 51th and 54th in Scenario (6) respectively.

5 Conclusions

This study provides a quantitative analysis of the adverse effects 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 highlighting the negative effects of insularity on the development of the railway network on a mainland and its islands.

The adverse effects of land discontinuity work both by physically preventing any interregional connection to the mainland network and by reducing the flow of passengers using the intra-regional railway network (and thereby reducing its profitability) because the latter can only serve to connect destinations within a region and not between regions.

We emphasize that although we applied the model to a simplified version of the railway network in Italy and the island of Sardinia, the model can be easily generalized to any railway network on any territory composed of a mainland and one or more islands. Also, our approach can be easily generalized to a wide

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	
	(Factual)	(Bridges)		(Calabria-Sardinia)		(Apulia-Sardinia)		(Sicily-Sardinia)		(Tuscany-Sardinia)	
	Rank	Rank	%Δ	Rank	%Δ	Rank	%Δ	Rank	%Δ	Rank	%Δ
Railway line in Sardinia											
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%
Bridges											
Cagliari-Roma	-	68									
Cagliari-Palermo	-	69									
Sassari-Genova	-	103									
Olbia-Roma	-	122									
Cagliari-Trapani	-	123									
Cagliari-Napoli	-	136									
Olbia-Genova	-	145									
Olbia-Livorno	-	146									
Railway line in Calabria											
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%						
Railway line in Apulia											
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%				
Railway line in Sicily											
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%		
Railway line in Tuscany											
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%

class of other physical networks, not only related to ground transportation (like road and buses) but also to data and energy networks.

Simulation results show that the additional costs of insularity are quite strong. In the benchmark scenario, Sardinian railway lines are shown to be the least profitable within the whole (simplified) Italian railway network. However, when Sardinia is connected to the mainland (see Scenario (2) to Scenario (6) in which its land discontinuity is removed), there is a remarkable increase in the profitability of the Sardinian railway lines. Besides, when all the railway lines in the Italian mainland's regions are converted to islands and relocated in place of Sardinia (see Scenario (3) to Scenario (6)), they become the least profitable, even when the region's income and population size (i.e potential railway users) are above average.

Our work shows that insularity may have a vital role in explaining the poor 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. 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.

References

Armstrong H. W. and Read R., Trade and growth in small states: the impact of global trade liberalisation, World Economy, 21, pp 563–585, 1998.

Armstrong H. W.and Read R., Insularity, remoteness, mountains and archipelagos: a combination of challenges facing small states?, Paper presented for the Regional Studies Association Conference Europe at the Margins: EU Regional Policy, Peripherality and Rurality, University of Angers, 2004.

Armstrong H. W., Ballas D. and Staines A., A Comparative Analysis of the Economic Performance of Greek and British Small Islands, Paper presented at the 36th Regional Science Association International (British and Irish Section) conference, Jersey, Channel Islands, 2006.

Auscher D.A. (1989), "Is Public Expenditure Productive?", *Journal of Monetary Economics*, 23: 177-200.

Behrens K., Gaign C., Ottaviano G.I.P., Thisse J.F. (2006) "Is remoteness a locational disadvantage?", *Journal of Economic Geography*, 6: 347-368.

Bertram G. and Karagedikli XX, Are Pacific Economies Converging or Diverging?, In Poot, J. (ed), On the Edge of the Global Economy (Cheltenham: Edward Elgar, 2004), 2004.

Briguglio L. (1995), "Small island developing states and their economic vulnerabilities", *World Development*, 23: 1615-1632.

Cerina F. (2015), "Insularity: insights from the New Economic Geography", *CRENoS working paper* 15/21.

Cocco L., Deidda M., Marchesi M., Pigliaru F. (2018), "Can islands profit from economies of density? An application to the retail sector", Regional Studies; 10.1080/00343404.2018.1490500

CRENoS (2014), "Economia della Sardegna, XXI Rapporto", CUEC.

CRENoS (2015), "Economia della Sardegna, XXII Rapporto", CUEC.

De Benedictis L. and Pinna A.M. (2015), "Islands as ?Bad Geography?. Insularity, Connectedness, Trade Costs and Trade", *CRENoS working paper* 15/04.

Deidda M., Insularity and economic development: a survey, International Review of Economics, 2015, 1–22.

Del Gatto M., Mastinu C.S. (2015), "Geography, Cultural Remoteness and Economic Development: A Regional Analysis of the Economic Consequences of Insularity", *CRENoS working paper* 15/03.

Dennis S. M., Talley W. K., 2007, Railroad Economics Research in Transportation Economics, 20.

Espon (2013), The Development of the Islands - European Islands and Cohesion Policy (EUROISLANDS), Interim Report.

Espon (2015), Transport Accessibility at Regional/Local Scale and Patterns in Europe, Volume 1b, TRACC Main Report.

Gallup J.L., Sachs J.D., Mellinger A.D (1999), "Geography and Economic Development", *International Regional Science Review*, 22: 179-232.

Henderson J.V., Shalizi Z., Venables A.J. (2001), "Geography and Development", *Journal of Economic Geography*, 1: 81-105.

Krugman P., Geography and Trade, MIT Press, Cambridge MA, 1991.

Lall S.V. , (2007), "Infrastructure and regional growth, growth dynamics and policy relevance for India", *Annals of Regional Science*, 41: 581-599.

Martin P. (1999), "Public Policies, Regional Inequalities and Growth", *Journal of Public Economics*, 73, 85-105.

Ortuzar J.D, Willumsen L.G. (2011), *Modelling Transport*, Wiley, 4th Edition.

Ottaviano G. I. and Tabuchi T. and Thisse J. F., Agglomeration and trade revisited, International Economic Review, 43, pp 409–436, 2002.

Ottaviano G. I. and Thisse J. F., New economic geography: what about the N?, Environment and Planning A, 37(10), pp 1707–1725, 2005.

Rodrik D., Subramaniam A., Trebbi F. (2004), "Institutions Rule: The Primacy of Institutions Over Geography and Integration in Economic Development", *Journal of Economic Growth*, 9: 131-65.

Wallis W.D. (2007), *A Beginner's Guide to Graph Theory*, Birkhauser, Boston, 2nd edition.

Wardman M. (2006), "Demand for rail travel and the effects of external factors", *Transportation Research Part E: Logistics and Transportation Review*, 42(3): 129-148.

Wardman M., Lythgoe W. and Whelan G. (2007), "Rail Passenger Demand Forecasting: Cross-sectional models revisited", *Research in Transportation Economics*, 20: 119-152.