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Research Article

A Study on Contestable Regions in Europe through the Use of a New Rail Cost Function: An Application to the Hinterland of the New Container Terminal of Leghorn Port

Marino Lupi,[1,2] **Antonio Pratelli**,[1,2] **Mattia Canessa**,[1,2] **Andrea Lorenzini**,[1,2] **and Alessandro Farina**[1,2]

[1] *Department of Civil and Industrial Engineering, University of Pisa, 56126 Pisa, Italy*
[2] *University Centre of Logistic Systems, University of Pisa, 57128 Leghorn, Italy*

Correspondence should be addressed to Marino Lupi; marino.lupi@unipi.it

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In this paper, the potential hinterland of the new container terminal of the port of Leghorn (Livorno in Italian) is studied. The study actually analyses the competitiveness of major European ports with respect to some of the most contestable regions in Europe. Travel time and monetary costs of railway paths, connecting ports to their hinterland, have been determined. The rail network of a large part of Europe was modelled using a graph. To each link, which represents a portion of the rail line, a cost function is associated. The travel time on the link is determined from the average speed, which has been determined from the maximum speed via formulae obtained through linear regression. The few cost functions that exist in current literature for the computation of the cost of a rail link are not detailed enough. Therefore, a new cost function has been developed. All cost components were determined in detail: the staff cost, the amortisation, maintenance, and insurance costs of locomotives and wagons, the cost of the usage of rail track, the traction cost. The traction cost was calculated in detail from all resistances to motion. Moreover, for each rail link, the number of locomotives needed to operate the train and the maximum towable weight were determined. The monetary value of time in freight transport registers a high variability; therefore, three different optimisations of the paths—by travel times, monetary costs, and generalised costs—between each origin–destination pair were carried out. The rates of competitiveness of the ports with respect to the examined European contestable regions were analysed.

1. Introduction

The hinterland of a port is defined as the area of the port through which the greater part of the trade passes (Notteboom and Rodrigue [1]). Port hinterlands are classified into "fundamental hinterland" and "competitive hinterland" (Rodrigue [2]). The fundamental hinterland is a port core market and consists of the port captive market, i.e., the areas which mainly, or exclusively, belong to the port market. This type of hinterland is usually formed by regions closest to the port. The "competitive hinterland" is an external area abutting the port hinterland, which overlaps the hinterlands of other ports.

The container terminal at the port of Leghorn (Livorno) in Italy faces challenges involving depth and space for ships manoeuvre, in particular considering the development of the newest container ships that are 400 metres long and 60 metres wide and have 15.5 m of draught. The container terminal can presently accommodate ships with a maximum length of 300 m, a maximum width of 40 m, and a maximum capacity of approximately 6,500 TEUs [3, 4]. To accommodate container ships with a capacity of approximately 15,000 TEUs, the 2015 port regulatory plan mandated that Leghorn develops a new container terminal, the so-called "Europe Platform" that is currently employed only in the most important Deep Sea Shipping (DSS) container routes, particularly in the Far East–Europe route.

Presently, the hinterland of the port of Leghorn consists mainly of the fundamental hinterland: some regions of Central Italy. However, the port, after construction of the new container terminal, will be able to include several new Italian and European regions into its hinterland's competition margin. Leghorn has a wide flat space on the immediate rear of its port, where an important logistic structure, the Guasticce freight village (2,000,000 m^2), was established. Moreover, Leghorn is part of the Ligurian ports which form the most important Italian multiport gateway system and is crossed by DSS container routes between the Far East and North and Central Americas [5]. As stated in Acciaro et al. [6], Switzerland, Austria, and southern Germany belong to the potential hinterland of northern Italian ports; these areas are contestable markets between northern European ports and northern Italian ports (some Slovenian and Croatian ports can also serve this area). In particular, Leghorn will be able to attract into its hinterland several areas of the Padan Plain (in particular, areas in north-east Italy), and—owing to its favourable position with respect to the Brenner corridor (Verona–Munich)—some regions of Central-Southern Europe (for example: the area of Munich). Adriatic ports on the other hand are in the best position on the land side to serve not only north-eastern Italy and several other destinations in Central-Eastern Europe (for example: Budapest), but also Central-Southern Europe (Vienna and Munich, for example) as it will be demonstrated in the following sections. Adriatic ports, however, are currently crossed mainly by feeder routes and are disadvantaged, on the sea side, for DSS routes to/from the Americas. Northern Italy, particularly the Padan Plain, which is the most productive region in Italy, belongs not only to the hinterland of the Italian Ligurian and northern Adriatic ports, but also to that of the northern European ports (it is, at least partially, an "island formation" of the hinterland of northern European ports (Ferrari et al. [7] p. 384; Notteboom [8] p. 15).

In any case, the new terminal of Leghorn is deemed necessary in order to simply maintain the current hinterland and foreland (DSS container routes). Additionally, the phenomenon of "naval gigantism" takes place on all important DSS routes, including the Far East–Europe and the America–Europe routes (Northern and Central American ports are, traditionally, part of the foreland of the Leghorn port) (Lupi et al. [9]).

In this paper, the potential hinterland (competition margin) of the new container terminal of Leghorn (the Italian city and port of Livorno) is analysed. This study analyses the competitiveness of important European ports, for some of the most contestable regions of Europe. These regions are Switzerland, south Germany, Austria, and Italy's Padan Plain, which are some of the most productive regions in Europe, and Central-Eastern European countries such as Czech Republic, Slovakia, Hungary, Slovenia, and Croatia, which are fast emerging economies. The ports taken into account in this analysis, besides the Italian ones, are: three important Mediterranean ports, namely, Marseilles-Fos (France), Koper (Slovenia), and Rijeka (Croatia), and five major Northern Range European ports: Le Havre, Antwerp, Rotterdam, Bremerhaven, and Hamburg.

The ports concerned have been assumed as the origin points of the proposed railway network, while the most important cities in Central-Southern and Central-Eastern Europe have been assumed as destinations. The European railway network under study, which is a greater part of the entire European railway network, has been modelled through a graph. The nodes on the graph represent rail terminals, rail junctions, and points where the geometry of rail lines (for example, the slope) changes, and the links represent rail lines. The optimal rail routes from the origin ports to the destination cities, based on travel time and monetary costs, were calculated. Eventually, we address a European problem: we determine the travel time and monetary costs to reach some destinations among the most contestable regions in Europe, from the European ports that are in the most competitive positions to serve these destinations.

Generally, the optimal paths in a freight transport network are determined according to generalised costs, i.e., monetary costs plus monetised travel time. However, the monetary value of time, for freight transport, is highly variable, as will be discussed in Section 2.3. As a result, optimising the paths by generalised costs will not suffice enough. Therefore, two other separate optimisations were performed: in the first one, the travel time was minimised, and in the second one, the monetary costs were minimised. The results of these three optimisations were then compared.

Only a few cost functions for rail transport exist in literature, and they are not very detailed. Therefore, in this paper, a new cost function for rail freight transport has been developed. The proposed cost function takes into account all the cost components borne by the rail transport company and the geometry of the rail lines (in particular, their slope).

The paper is organised in the following order:

In Section 2, the state of the art on existing cost functions in rail transport networks is detailed.

In Section 3, the proposed cost function for rail transport networks is described in detail, and the methodology to calculate travel time and monetary costs on rail links is presented.

In Section 4, a complete collection of rail line data necessary to implement the proposed cost function in the targeted segment of the European rail network is presented.

In Section 5, the calculation of the optimal paths in the railway network, from origin ports to destination cities, is presented, and the results in terms of travel time, monetary costs and generalised costs are shown and discussed.

In Section 6, a sensitivity analysis aimed at understanding which components mostly affect the cost function values is performed.

Conclusions follow.

2. State of the Art of Cost Functions in Rail Sector and Monetary Value of Time

Several studies, such as in Gattuso [10], have been carried out to evaluate travel time and monetary costs of railway transport. However, these studies have dealt mainly with passenger transport. In another study, Yaghini et al. [11] developed a neural network to model a rail passenger network but only considered travel time. Li and Gao [12] used a car following model to predict train delays.

On the other hand, several other studies aimed at simulating and optimising the power consumption and motion of both passenger and freight trains have also been conducted. For instance, Keskin and Karamancioglu [13] evaluated the electric power consumption in various phases of a train's motion (traction, cruising, coasting, and braking) and developed algorithms aimed at minimising the same through specific train operation strategies. Xu et al. [14] proposed a novel method to simulate the motion of a train; in particular, the method analysed all the phases of a train's motion and calculated the traction for each phase of motion in detail. While these works calculated the power consumption in detail, they determined only a part of a possible cost function of rail transport.

For evaluating the cost function of a rail network link, two types of costs are considered:

(i) cost of producing the transport service,

(ii) cost of purchasing the service.

The cost of producing the service is, for example, the cost incurred on the rail transport companies to operate the train. The cost of purchasing the service is the price railway companies pay to shippers and customers. In this research, we evaluate the cost of producing the service.

We considered the cost of transporting Intermodal Transport Units (ITUs), which are 20 or 40 feet maritime containers (i.e., containers which have been unloaded from container ships or which are going to be loaded on them).

We will deal with two cost components:

(i) cost of loading/unloading containers at the rail terminal,

(ii) cost of transporting containers by rail from the terminal to the destination.

The cost of loading/unloading an ITU is 32.5 € in Italy (source: Terminali Italia [15]); however, as suggested by Multimodal Transport Operators (MTOs) and terminal operators, similar values, between 30 and 35 € per load unit, can be considered for other European countries considered in this study.

2.1. Cost Functions for Rail-Based Intermodal Transport in Literature. Some well-known cost functions for rail-based intermodal transport are described in the following section.

2.1.1. Cost Functions Taking into Account the Cost of Rail Transport in an Aggregate Way. In existing literature, several cost functions determine the cost of rail transport or rail-based intermodal transport. In other words, the average cost of rail transport, without considering cost components such as locomotive amortisation cost, driver charge, and traction cost, is determined.

For example, in Kim and Van Wee [16], the cost of rail-based intermodal transport, in €/container, depends on: the cost of loading (at the origin) and unloading (at the destination) the container; the distance of the rail link and the monetary cost per unit of the distance travelled by the railway vehicle; the cost of transhipment at intermodal terminals; and the pre and post haulage distances and monetary costs (i.e., the distances covered and costs incurred by road transport from the origin point to the loading intermodal centre and from the unloading intermodal centre to the final destination). However, as for the cost of rail transport, only an average quantity per unit of the distance travelled is given, and no details on the cost components are provided.

Similarly, Brummersted, Flish, and Jahn [17] calculated the price (€/container) of rail-based intermodal transport as a function of: the distance, speed, and fares of rail transport, pre and post haulage distances, speed and fares of road transport, transhipment time and monetary costs at rail terminals, and monetary value of time in rail and road transport. Only an average value of monetary cost per unit of distance of a rail link was taken.

Sawadogo et al. [18] developed a route choice model for intermodal (road + rail) transport based on an intermodal graph, where the link costs (links could be both road and rail ones) depended on: travel time, monetary costs, and damage due to transhipment, pollution, energy consumption, accident risk, and noise. Sawadogo, too, provided only an average value for monetary costs per unit of distance of a rail link.

Janic [19] gave two different cost functions for road and rail transport, in which external (environmental) costs are also taken into consideration. The transport cost by rail, for a given shipment of load units, depends on: the overall weight of the shipment, the internal and external costs incurred by each train to perform the shipment, the cost due to each load unit both at the intermodal terminal and in the rail haulage, the travel time, distance, speed and delay of each train used to perform the shipment. Janic, similarly to the authors mentioned before, gave an average quantity for the cost of rail transport, without considering the components of rail cost such as driver charge, amortisation cost, and traction costs. They also did not consider components of cost which vary depending on geometric characteristics of the line, such as slope, or number of locomotives used.

2.2. Detailed Cost Functions for Rail Transport. Detailed cost functions for rail transport have been proposed by Grosso [20] and Baumgartner [21]. These cost functions provide in detail the monetary costs incurred by each train service. The considered cost components are those supported by rail transport companies. These cost functions were taken as the point where our research departs from the previous works to find a new cost function for rail network links.

2.2.1. Grosso. Grosso [20], after giving interviews to rail transport companies, proposed the following cost function:

$$\begin{aligned} C = {} & \left(P + I + R/L \bullet n_L + OV\right) \bullet t + SH \bullet n_{SH} + L/UNL \\ & \bullet n_{ITU} + \left(E + MR/L \bullet n_L + MR/W \bullet n_W + RT\right) \\ & \bullet d \end{aligned} \quad (1)$$

The cost C is expressed in € and calculated for each train service connecting a given origin/destination (O/D) pair.

The components of this cost function are as follows:

(i) staff cost (P) [€/h]: cost of the train drivers;

(ii) insurance (I) [€/h];

(iii) cost of renting or leasing of locomotives (R/L) [€/(h • locomotive)];

(iv) n_L = number of locomotives in the train;

(v) overhead costs (OV) [€/h]: indirect costs (administrative and operative costs) incurred by the rail transport company;

(vi) t [h] = time taken by the train to travel from the origin to the destination;

(vii) shunting operations costs (SH) [€/operation]: cost of preparing the train at the rail terminals;

(viii) n_{SH} = number of shunting operations performed on the train;

(ix) loading/unloading costs (L/UNL) [€/ITU]: costs of the vertical handling of load units to/from wagons at rail terminals;

(x) n_{ITU} = number of Intermodal Transport Units transported on the train;

(xi) energy cost (E) [€/km]: in the case of electric locomotives it is relative to the price of the electric energy for traction (€/kWh) multiplied by the electric energy consumption (kWh/km). As for electric traction, Equation (1), it does not depend on the number of locomotives. In the case of diesel locomotives, however, E [€/km] is estimated depending on the number of locomotives. In particular, it is given by the product of the fuel consumption, in l/(km•locomotive), the fuel price in €/l, and the number of locomotives;

(xii) maintenance and repair cost of a locomotive (MR/L) [€ /(km•locomotive)];

(xiii) maintenance and repair cost of a wagon (MR/W) [€ /(km•wagon)];

(xiv) n_W = number of wagons;

(xv) rail track costs (RT) [€ / km]: price of the usage of rail infrastructure, which is paid by the rail transport company to the rail infrastructure manager;

(xvi) d [km] = distance travelled by the train from the origin to the destination.

The cost function proposed by Grosso provides the advantage of considering a greater number of variables than those examined by other authors.

However, it does not take into account the variation of energy consumption with slope, or resistances to motion. Also, values of the cost function components are not consistent with those proposed in other literature, particularly those found in the Baumgartner cost function, which will be described in the following sections. Another disadvantage is that it does not clearly state the number of locomotives considered for each train, for each network link. However, the cost function proposed by Grosso is one of the points at which our research departs from existing literature.

2.2.2. Baumgartner. The cost function proposed by Baumgartner [21] is made of several components. Considering freight trains with electric traction and flat wagons for containers, the cost function, where the cost is expressed in € per train service (connecting a given O/D pair), is given as follows:

$$C\,[€] = \left(C_L \bullet n_L + MR_L \bullet n_L + C_W \bullet n_W + MR_W \bullet n_W + T\right) \bullet d \quad (2)$$

(i) C_L = electric locomotive purchase/amortisation cost [€/(km•locomotive)]: the average price of a locomotive is approximately 3 million €, and the economic life of a locomotive is approximately 25 years or 5 million kilometres. Therefore, an amortisation cost of a locomotive of approximately 0.6 €/km can be considered;

(ii) n_L = number of locomotives;

(iii) MR_L = electric locomotive maintenance and repair cost [€ /(km•locomotive)], usually equal to approximately 20% of the purchase/amortisation cost calculated above. Therefore, if the locomotive amortisation cost is approximately 0.6 €/km, the maintenance cost is approximately 0.12 €/(km•locomotive);

(iv) C_W = flat wagon (for containers) purchase cost [€/(km•wagon)]: an average price for a flat wagon is approximately 65,000 € per wagon, with an economic life of approximately 20 years or 1 million kilometres. Therefore, the amortisation cost of wagons is approximately 0.065 €/(km•wagon);

(v) n_W = number of wagons;

(vi) MR_W = flat wagon (for containers) maintenance cost [€/(km•wagon)]: the maintenance cost of a flat wagon for containers is approximately 0.07 €/(km•wagon);

(vii) T = electric traction power consumption (€/km): Baumgartner (2001) proposed the values reported in Table 1;

(viii) d = distance (from the origin to the destination) [km].

In Table 1 the energy consumption in Wh/(t•km) is reported. The average cost of electricity for a rail traction company is around 0.11 €/kWh. Multiplying the energy consumption in Wh/(t • km) by the total mass of the train and dividing this quantity by 1,000 it is obtained the energy consumption in kWh/km. Multiplying the energy consumption, in kWh/km, by the cost of electricity, in €/kWh, the cost of traction, in €/km, is obtained.

The cost function proposed by Baumgartner provides details on several cost components, and the proposed cost values are consistent with those proposed in existing literature. For example, the purchase cost of a locomotive or the total distance travelled by the locomotive or wagon in a year is consistent with the values commonly considered by rail transport companies and Multimodal Transport Operators

Table 1: Electric energy consumption, in Wh/TKBC (unit of measure: Wh/(t • km)), according to the slope value. Source: Baumgartner [21].

Distance between two successive stops [km]	Maximum running speed [km/h]	Gradient [‰ or mm/m]	Unit consumption [Wh/TKBC][(1)]
100	140	0 to 5	40 (35 to 50)
100	120	0 to 5	30 (25 to 35)
100	100	0 to 5	22 (17 to 27)
100	80	0 to 5	15 (10 to 20)
50	60	0 to 5	15 (10 to 30)
50	60 to 80	25	45 (45 to 50)
5	80	0 to 5	25 (20 to 30)
5	60	25	50 (45 to 55)

[(1)]TKBC= total gross tonne-kilometre (including the mass of locomotive(s)).

(MTOs). On the other hand, Baumgartner's cost function does ignore some components of the cost function such as rail track cost, staff cost, and locomotive and wagon insurances.

2.3. Monetary Value of Time for Rail Freight Transport in Literature. There is a high disagreement in existing literature on the monetary value of time (VOT) in freight transport because the VOT changes according to the typology of freight carried and the mode of transport. An overview of monetary values of time in existing literature is presented in Lupi et al. [22]. Regarding road-rail intermodal transport, Jiang and Calzada [23] proposed for shipments performed in France monetary values of time ranging from 1.03 €/(t·h) (shipments of chemical products) to 7.77 €/(t·h) (shipments of manufactured products). In De Jong [24] (p. 656, tab. 2) several VOTs for rail transport, present in literature, are reported. Fowkes et al. [25] proposed a VOT ranging from 0.08 to 1.21 €/(t·h) while De Jong et al. [26] proposed a VOT ranging from 0.25 to 1.10 €/(t·h). Other authors proposed a VOT ranging from 0.03 €/ (t·h) (in Widlert and Bradley [27]) to 0.96 €/(t·h) (in De Jong et al. [28]).

3. The Proposed Cost Function

As stated in Lupi et al. [32], after interviews to experts in the field, and in Russo [33], monetary costs and travel times are the variables mostly taken into account by carriers and shippers in their transport mode choice.

For modelling a multimodal freight transport network, the following generalised cost function can be used:

$$C_g = C_m + VOT \bullet t \tag{3}$$

where C_g = generalised cost [€], C_m = monetary cost [€], VOT = value of time [€/h], and t = time [h].

However, as underlined in the preceding paragraph, a high variability in VOT has been observed among studies in existing literature. Consequently, in the analysis carried out in this paper, travel times and monetary costs have been considered separately. However, in this paper also generalised costs have been taken into account. The VOT considered for the calculation of generalised costs is 0.96 €/ (t·h), which is consistent with that proposed by De Jong in 2004 [28]. We chose this VOT as it is an average value, and we think it is the most reliable among those proposed in existing literature.

3.1. The Calculation of Travel Time. Travel time of a freight train is calculated from its average speed in each line section.

The average speed is calculated from the speed in rank A (the maximum speed for freight trains) by a linear formula, calibrated through regression analysis by RFI (Rete Ferroviaria Italiana), the Italian rail network manager:

$$V_m = 0.60231 \bullet V_A \ \ [\text{km/h}] \tag{4}$$

where V_m is the average speed and V_A is the speed in rank A.

The speed rank A, in Italy, refers to freight trains, which tolerate a maximum uncompensated lateral acceleration in curve of 0.6 m/s^2 (the residual part of the centrifugal lateral acceleration is compensated by slope).

The other ranks existing in the Italian rail network are:

(i) rank B for passenger trains, which can travel up to 140 km/h; the maximum uncompensated lateral acceleration for rank B is 0.8 m/s^2;

(ii) rank C for fast passenger trains, which can travel at more than 160 km/h; the maximum uncompensated lateral acceleration for rank C is 1 m/s^2;

(iii) rank P for tilting trains.

The speed values for each rank, and in particular for rank A, refer generally to short line sections (1-3 km long). However, in this research, much longer rail links, at a minimum range of 15–20 km, have been taken into account. Therefore, the speed in rank A on a rail link has been taken equal to a weighted average of speeds of all line sections included in the link, considering as weight the percentage of the length of the link with the given speed in rank A.

The values of the speed in rank A are publicly available only in Italy, and in a few other European countries, on the website of the rail infrastructure managers, which will be shown in detail in Section 4. However, in other countries, the speed in rank A is not publicly available, and only the speed in rank C is provided in the rail infrastructure manager websites. Therefore, an equation has been derived to determine the speed in rank A from the speed in rank C.

Table 2: Summary of the procedure adopted in this paper for the calculation of link travel times.

Variable	Formula	Details of the calculation
Average speed: V_m	$V_m = 0.6 \bullet V_A$	The link travel times are calculated from the average speed on each link. The average speed is calculated from the speed in rank A through a factor of 0.6 as proposed by Rete Ferroviaria Italiana (RFI).
Speed in rank A: V_A	$V_A = 0.86 \bullet V_C + 2.87$	The speed in rank A is publicly available only in Italy and in a few other countries. In the other countries only the speed for fast passenger trains, which could be assimilated to the Italian rank C, is publicly available; for these countries, the speed in rank A is calculated from the speed in rank C through a formula which has been calibrated on Italian data.

This equation was determined through linear regression analysis based on rail data from Italy:

$$V_A = 0.8636 \bullet V_C + 2.8732 \ \ [\text{km/h}] \tag{5}$$

where V_A is the speed in rank A and V_C is the speed in rank C.

The regression has been performed with the help of the statistical software "R". The quality of fit is high as the (adjusted) R^2 value is 0.954.

The equation has been used with data from other European countries for which the speed of fast passenger trains, which could be assimilated to the Italian rank C, was publicly available.

The procedure for the calculation of the link travel time is summarised in Table 2.

3.2. Calculation of Monetary Costs. The monetary costs of rail transport have been calculated partially based on the research performed by Baumgartner [21] and on the methodology proposed by Grosso [20]. In addition, some reference costs, regarding staff, locomotives, and wagons, have been determined based on [30]. The proposed cost function is the following:

$$\begin{aligned} C\,[€] = {} & t\,[h] \bullet (n_d \bullet P) + l\,[\text{km}]\,\{n_L \bullet (A_L + M_L + I_L) \\ & + n_W \bullet (A_W + M_W + I_W) + R + T(V_A, i, R_c)\} + 2 \\ & \bullet H \bullet n_{ITU} \end{aligned} \tag{6}$$

where

(i) C, expressed in € per train service, is the monetary cost on each rail link having length l and travel time t.

(ii) P = staff cost [€ /(h•driver)]: cost of the train drivers. The staff cost is not the same all over Europe. For instance, in Italy, the average cost per hour for each train driver is 35 € (the cost comprises not only the net salary but also pension contributions and healthcare) (Source: Trenitalia, relazione annuale [29]), while in Germany it is 42 € per hour per driver [30]. Therefore, for the entire Europe, an average staff cost of 38.5 €/h per European driver has been considered.

(iii) n_d is the number of drivers in each freight train (independently of the number of locomotives). Two train drivers per freight train have been considered for Italy, while one driver has been considered for the rest of Europe (sources: interviews to Rete Ferroviaria Italiana and [34]).

(iv) A_L = amortisation cost of a locomotive: in [30], it is reported that the reference amortisation cost for a locomotive used for freight transport was 330,670 € per year. Mercitalia Rail (the main Italian rail freight company) has provided a reference value for the number of kilometres a locomotive covers each year (200,000 km). Therefore, the average cost of a locomotive, expressed in €/(locomotive•km), has been estimated at 1.653 €/(locomotive•km). It is interesting to note that some transport companies sign contracts with the locomotive producer, which include not only the purchase cost but also the cost of maintenance. For example, some Italian MTOs have entered in contracts with Bombardier for 5 million € per locomotive, including purchase and maintenance for 10 years.

(v) M_L = maintenance cost of locomotives: in [30], an M_L of 5.5% of the amortisation cost, which is 0.091 €/(locomotive•km), has been recommended.

(vi) I_L = insurance cost of locomotives: in [30], an I_L of 1.5% of the amortisation cost, which is 0.025 €/(locomotive • km), has been recommended.

(vii) n_L = number of locomotives: the number of locomotives depend on the gradient of the rail link, and it ranges from one to two. In some exceptional case, a triple traction (three locomotives) has been considered. The calculation of the number of locomotives is described in detail in a following section.

(viii) A_W = amortisation cost of a wagon: we considered Sgns flat wagons for containers. In [30], it is reported that the amortisation cost of a Sgns is 4,898 €/year. Mercitalia Rail has provided a reference value of 50,000 km for the number of kilometres travelled by a wagon each year. Therefore, the average amortisation cost of a wagon is 0.098 €/(wagon•km).

(ix) M_W = maintenance cost of wagons: in [30], an M_W of 10% of the amortisation cost, which is 0.0098 €/(wagon•km), has been recommended.

(x) I_W = insurance cost of wagons: in [30], an I_W of 1.3% of the amortisation cost is 0.0013 €/(wagon•km).

(xi) R = rail track cost [€/km], i.e., the cost for the usage of rail infrastructure paid by the rail transport company to the infrastructure manager. This cost has been determined for all countries involved in this research, according to the values provided in [35] for Italy and in [36] for other European countries. The rail track cost is different from one country to another and from one line to another. It also depends on the weight of the train. For example, in Austria, the track cost for a train weighing above 900 tonnes on the Brenner railway is equal to 4.968 €/(train•km); the cost on the Westbahn (the line from Vienna to the German border) is 4.474 €/(train•km); the costs on the Tarvisio–Semmering and Tarvisio–Tauern lines are 3.749 €/(train • km) each.

(xii) H = cost of handling at rail terminals [€/ITU]: this cost is available on the Terminali Italia website (source: Terminali Italia [15]), and it is equal to 32.5 € per Intermodal Transport Unit (ITU) for all terminals in Italy. This is also the rate for loading an ITU on a train at a rail terminal inside the maritime container terminal, as well as the rate for handling an ITU from a train to a truck at the freight village/intermodal centre destination. It does not comprise the cost for a container idle time at the terminal for a time period greater than two days. As far as non-Italian terminals are concerned, some terminal operators in Belgium, the Netherlands, and Germany have been interviewed, and they have provided similar values of approximately 32-35 € per ITU.

(xiii) n_{ITU} = number of Intermodal Transport Units (ITUs) transported on each train: the cost of handling a train at rail terminals is multiplied by two because two transhipment movements have been considered, with the first one at the rail terminal located in the container terminal of the unboarding port and the second one at the freight village/intermodal centre destination.

(xiv) $T(V_A, i, R_c)$ = electric traction cost [€/km]: $T(V_A, i, R_c)$ has been determined from the power consumption, in kWh/km, multiplied by the cost of electricity, in €/kWh. The power consumption was calculated considering all resistances to motion. This detailed power consumption determination, to the authors' best knowledge, has not been applied to rail networks of the scale considered in this research. Details on the calculation of the power consumption are provided in the following section. Only electrified lines have been considered because in Europe, usually, non electrified lines show bad geometrical characteristics, particularly high gradient and sharp horizontal curves. Therefore, the diesel traction cost was not taken into account in our research. The traction cost is a function of the speed in rank A of freight trains on the link (V_A), the link grade (i), and the curvature resistance (R_c). The resistances to motion have been calculated from the speed in rank A, i.e., V_A.

In Table 3, the proposed cost function is compared with cost functions in existing literature. Because cost functions by Kim and Van Wee [16], Brummersted et al. [17], Sawadogo et al. [18], and Janic [19] are not detailed, they cannot be compared with the proposed one. Therefore, the comparison with cost functions of Grosso [20] and Baumgartner [21] alone could be performed, and it has been shown in detail in Table 3. Again, in Table 3, a summary of all components of the proposed cost function has been provided, and the methodology for their calculation is explained.

3.2.1. Details on the Calculation of the Electric Traction Cost. As stated before, the electric traction cost, $T\ (V_A, i, R_c)$ [€/km], has been determined from power consumption, in kWh/km, multiplied by the cost of electricity, in €/kWh. In the Prospetto Informativo di Rete of 2018 [37] (p. 160), it is shown that, currently, the price of electricity for rail freight transport in Italy has been raised to 0.434 €/(train·km).

However, the situation in the rest of Europe is different. In addition, a traction cost formalised in this way does not take into account the actual energy consumption on each rail link (for example, because of speed and slope). Therefore, it was decided to take the average prices, in €/kWh, for the cost of electricity applied to companies in general (not railway companies in particular), in each European country. For example, the average price of electricity incurred on companies in Italy in the second half of 2017 was approximately 0.0813 €/kWh (source: Il Sole 24 Ore website [38]; Eurostat [39]). A different electricity price for each European country has been considered. The electricity price for each European country was taken from Eurostat [39].

The power consumption was calculated based on all resistances to motion. The resistances to motion considered in the calculation, as suggested in Micucci and Mantecchini [40], are: rolling resistance, aerodynamic resistance, and grade and curve resistances. In the calculation of these resistances, the speed in rank A, i.e., V_A, has been used. The inertial resistance, however, was neglected because the traction is calculated at regime (acceleration and deceleration transitories have been neglected). Freight trains do not make scheduled intermediate stops between the origin and the destination; however, sometimes, they halt to let faster trains pass by. Because the localisation and time instant at which the stops are made cannot be estimated, they have been neglected in this study. The resistances were determined according to the methodology proposed in Vicuna [41]; however, the formulae for resistances, which were obsolete, have been updated.

The rolling resistance has been calculated according to Szanto [42] (p. 2). The air resistance is due to the excess pressure generated on the front surface of the locomotive, the depression created on the rear surface of the last wagon, the friction of the air along the lateral surfaces of the train, and the friction along the under-chassis of the train [40] and has been calculated according to Lai et al. [43] (p. 823). The grade resistance has been calculated considering the slope of each line section in detail, while the curve resistance has been calculated from the Von Röckl formula.

The resistances to motion depend on the weight of the train (locomotive + wagons). An E189 locomotive (produced

Table 3: Comparison of the proposed cost function with similar cost functions existing in literature: namely those proposed by Grosso [20] and Baumgartner [21].

Component	Grosso	Baumgartner	The proposed cost function
Staff cost	Maximum, average, minimum values provided	Not taken into account in the cost function	Two reference values for the driver cost per hour were found in literature: in Italy [29] and Germany [30]. An average of these two values (38.5 €/h) has been considered. Two drivers are necessary to operate a train in Italy, while only one driver is necessary in the rest of Europe.
Number of locomotives	Not explicitly calculated	Not explicitly calculated	Calculated in detail. The number of locomotives depends on the grade and curve resistances of each line section and it has been determined, for each rail line, from the "Operating Rules" ("Norme di Esercizio") [31]. The operating rules used by the rail transport companies, which effectively operate the services, have been assumed.
Amortization / rental / leasing cost of a locomotive	Maximum, average, minimum values provided	Calculated from an average purchase cost of a locomotive	In [30] an amortization cost in €/year, valid for locomotives specifically used for freight transport, is provided. In order to calculate the amortization cost in €/km, the number of km/year travelled by a locomotive for freight transport has been provided by Mercitalia Rail.
Maintenance cost of a locomotive	Maximum, average, minimum values provided	Calculated as a percentage of the amortization cost	Calculated as a percentage of the amortization cost as suggested by [30].
Insurance cost of a locomotive	Maximum, average and minimum insurance costs are provided for the entire train and not for simply a locomotive	Not taken into account in the cost function	Calculated as a percentage of the amortization cost as suggested by [30].
Amortization cost of a flat wagon	Maximum, average, minimum values provided	Calculated from an average purchase cost of a flat wagon	In [30] an amortization cost in €/year for a flat wagon is provided. In order to calculate the amortization cost in €/km, the km/year travelled by a flat wagon has been provided by Mercitalia Rail.
Maintenance cost of a flat wagon	Maximum, average, minimum values provided	Calculated as a percentage of the amortization cost	Calculated as a percentage of the amortization cost as suggested by [30].
Insurance cost of a flat wagon	Maximum, average, minimum values provided	Not taken into account in the cost function	Calculated as a percentage of the amortization cost as suggested by [30].
Handling cost at terminals	Maximum, average, minimum values provided	Not taken into account in the cost function	Calculated according to the costs provided by Terminali Italia [15] and by northern European terminals, as €/load unit. The handling cost at an Italian terminal is 32.5 €/load unit and between 30 and 35 €/ITU in the rest of Europe. The total number of ITUs (Intermodal Transport Units) to be considered for each train has been collected from interviews to the main MTOs operating between Italian and northern European terminals.
Rail track cost	Maximum, average, minimum values provided	Not taken into account in the cost function	Rail track costs, in €/km, have been collected for each rail line. Rail track costs are not only different from a country to another, but often also from a line to another in the same country.
Traction cost	Maximum, average, minimum values provided	Reference values have been provided for different values of line slope	It has been determined from the power consumption, in kWh/km, multiplied by the cost of electricity, in €/KWh. The power consumption has been calculated considering all resistances to motion on each line section.

by Siemens) with a weight of 87 tonnes has been considered [44]. This type of locomotive is currently used in the international freight transport across the Alpine Passes of Brenner and Tarvisio by the rail company called Rail Traction Company. Because this locomotive is multitension, it must not be changed at the border between Italy and the other countries: in Italy the electric rail lines (with the exception of the new high speed lines) are operated with direct current (DC) at 3 kV, while in Germany, Switzerland, and Austria they are operated with alternating current (AC) with 15.000 V and 16 2/3 Hz.

One of the most common flat wagons used for the transport of containers is the Sgns, with an unladen weight of 17.5 t/wagon (source: Mercitalia Rail [45]). In order to determine the average number of wagons composing a train and the average number of TEUs (or ITUs) loaded on each train, four main MTOs (Hupac, Cemat, Kombiverkehr, and Lineas Intermodal), operating between Italy and northern Europe, have been interviewed.

The average number of wagons composing each train has resulted in the following:

(i) 1st MTO: 25–26 wagons,

(ii) 2nd MTO: 23–24 wagons,

(iii) 3rd MTO: 25–26 wagons,

(iv) 4th MTO: 21–22 wagons.

The average number of Intermodal Transport Units (ITU) transported on each train has resulted in the following:

(i) 1st MTO: 35–38 ITUs, 63–68 TEUs,

(ii) 2nd MTO: 32–38 ITUs, 58–68 TEUs,

(iii) 3rd MTO: 35–38 ITUs, 63–68 TEUs,

(iv) 4th MTO: 30–33 ITUs, 54–59 TEUs.

For the first three MTOs, the conversion factor between TEUs and ITUs, as proposed in the UIR report (Unione Interporti Riuniti [46] p. 6), has been used. Therefore, 1 ITU = 1.79 TEUs. The 4th MTO instead provided both the number of ITUs and of TEUs transported on each train.

Therefore, it can be considered as an "average train" of 24 wagons and 62.5 TEUs (35 ITUs) per train, which is 2.6 TEUs per wagon. The average weight of each TEU in railways is generally 13.04 t/TEU (source: RFI). Maritime containers, however, weigh less at approximately 11 tonnes/TEU (source: elaboration from Assoporti [47]). This is because container ships also carry empty containers. Therefore, in this research, 13.04 t/TEU has been included.

The total weight of the train (in tonnes) was calculated as follows:

$$\mathrm{W}\,[\mathrm{t}] = n_L \bullet W_L + n_W \bullet \left(W_W + n_{TEU} \bullet W_{TEU}\right) \qquad (7)$$

where,

(i) n_L = number of locomotives of the train;

(ii) W_L = weight of each locomotive, i.e., 87 tonnes in case of the E189;

(iii) n_W = average number of flat wagons on each train, i.e., 24 wagons;

(iv) W_W = average unladen weight of a flat wagon = 17.5 tonnes/wagon;

(v) n_{TEU} = average number of TEUs loaded on each wagon = 2.6 TEUs/wagon;

(vi) W_{TEU} = average weight in tonnes of each TEU, i.e., 13.04 tonne/TEU.

The total weight of the train is therefore 1,321 tonnes when only one locomotive is used and 1,408 tonnes when two locomotives are used. The towed weight is 1,234 tonnes.

Resistances to motion, and, consequently, the cost of traction for a train in €/km, depend on several factors, particularly the speed on the gradient and on the curvature radius of each portion of the line. For example, in Italy (cost of electricity = 0.0813 €/kWh), for an average speed of 60 km/h, the values of traction cost for a train are the following:

(i) if the line's gradient is 0 ‰ (1 locomotive), the traction cost is around 0.60 €/km;

(ii) if the line's gradient is 5 ‰ (1 locomotive), the traction cost is 1.01 €/km;

(iii) if the line's gradient is 10 ‰ (1 locomotive), the traction cost is 1.41 €/km;

(iv) if the line's gradient is 15 ‰ (2 locomotives), the traction cost is 1.82 €/km;

(v) if the line's gradient is 20 ‰ (2 locomotives), the traction cost is 2.23 €/km.

In our research, the speed along a link has been calculated based on Equations (4) and (5). For the calculation of resistances to motion, the speed in rank A has been used. For the calculation of the link travel time (on which the staff cost depends), the average speed V_m has been used.

3.2.2. Maximum Towable Weight on a Rail Line Section and Lines with Special Operation Characteristics. There are two main constraints related to the maximum towable weight on a rail line:

(i) The maximum towable weight due to the resistance of train couplers, which depends on the geometrical characteristics of the rail line, in particular on the sum of the grade and curve resistances of each line section. In Table 4, the maximum towable weight, fulfilling the resistance of train couplers, according to RFI, is reported. The towed weight of the train considered in this study is 1,234 tonnes (Section 3.2.1). From Table 4, the maximum value of the sum of grade and curve resistances fulfilling the resistance of train couplers for the towable weight of the train taken into account is 20 N/kN.

(ii) The maximum weight that can be towed by the chosen locomotive. It depends not only on the geometry of the line but also on the type of locomotive used, because each typology of locomotive can tow a

Table 4: Maximum towable weight, fulfilling the resistance of train couplers according to RFI (Italian) rules, expressed in tens of tonnes, versus the sum of grade and curve resistances, expressed in N/kN.

Sum of grade and curve resistances (N/kN)															
4.5	5.0	5.5	6.0	6.5	7.0	7.7	8.4	9.2	10.0	11.0	12.0	12.9	13.8	14.6	15.8
Maximum towable weight (tens of tonnes)															
250	250	250	250	244	235	224	214	203	194	183	173	166	158	152	145
Sum of grade and curve resistances (N/kN)															
17.0	18.4	19.8	20.9	21.9	22.7	24.6	25.7	27.8	29.3	30.8	32.5	34.2	37.5	40.5	
Maximum towable weight (tens of tonnes)															
137	130	123	118	114	111	104	101	95	90	87	83	80	74	69	

different weight. For example, the E655 (six axles) is capable of towing a greater weight than the E189 (four axles) on the same line. The maximum weight that a locomotive can tow on each section of a line is reported in "Operating Rules" ("Norme di Esercizio") [31]. This type of document is available online publicly only in Italy. If this towed weight value is overcome, the train is allowed to travel on the line, but more than one locomotive it is necessary. For the towed weight of 1,234 tonnes and an E189 locomotive (this type of locomotive is widely used by rail transport companies in Europe because it is multitension), the maximum sum of grade and curve resistances allowable for one locomotive is 12 N/kN.

Therefore,

(i) if the sum of the grade and curve resistances is less than 12 N/kN, only one locomotive has been used;

(ii) if the sum of the grade and curve resistances is more than 12 and less than 20 N/kN, two locomotives (E189) have been used;

(iii) if the limit of 20 N/kN has been overcome on a secondary line, this line was not included in the modelized rail network. If the limit of 20 N/kN has been overcome on a main line, information on the operation of trains on this line was collected.

The Disposition n° 18 of 19/11/2015, published by RFI [48], has removed the limit (seen in Table 4) on the maximum towable weight, which fulfils the resistance of train couplers, to satisfy the requirements of rail transport companies which aim at improving their productivity operating longer trains. The Disposition states that the maximum towable weight is determined by the rail transport companies according to specific analyses based on factors including rail infrastructure characteristics.

In brief, as far as the modelled rail network is concerned, the sum of grade and curve resistances could be greater than 20:

(i) on secondary lines, which could be domestic Italian lines, such as the Parma–La Spezia and the Savona–Altare, or non-Italian lines, such as the Grenchenberg line in Switzerland, where only local freight trains travel. Therefore, they have been neglected in our study;

(ii) on some main lines, often those crossing the Alps, and often belonging to the Trans-European Transport Networks (TEN-T) corridors. In the following sections, a line of this type is called "*line with special operation characteristics*". For the area of interest (circled in red) in Figure 1, these lines are described in detail in Section 4.2. On these lines, the same operation rules as used by the rail transport companies, which effectively operate the services, apply.

3.2.3. Remarks on Proposed Cost Function. The proposed cost function has two main advantages:

(i) it takes into account, in detail, all the cost components incurred by a rail transport company;

(ii) it takes into account the geometry of the line, in particular the gradient, to determine the traction power needed and the number of necessary locomotives.

Indeed, the costs related to locomotives, i.e., amortisation/leasing/rent and maintenance, occupy a significant quota of the overall monetary cost of a train journey between an O/D pair. On the other hand, also the cost of traction is relevant, but it is less relevant than the cost because of the locomotives.

The proposed cost function does not consider the number of tracks of the line section. Indeed, on single-track lines, the travel time increases significantly because of the train-crossing manoeuvres at stations. The travel time in this case depends not only on the number of stations along a line where trains can cross each other, but also on the degree of congestion of the line. However, it must be noted that

(i) RFI usually allocates paths for freight trains in specific time slots to avoid crossing operations as much as possible. In addition, single-track lines usually register gradients too large for international freight trains or, in any case, heavy national/international freight trains to handle. These lines are used at most by light local freight trains. Therefore, only a few single-track lines have been considered in Italy.

(ii) In other European countries considered in this analysis, single-track lines have been excluded, except for Slovenia and Croatia where several important rail lines still have only one track.

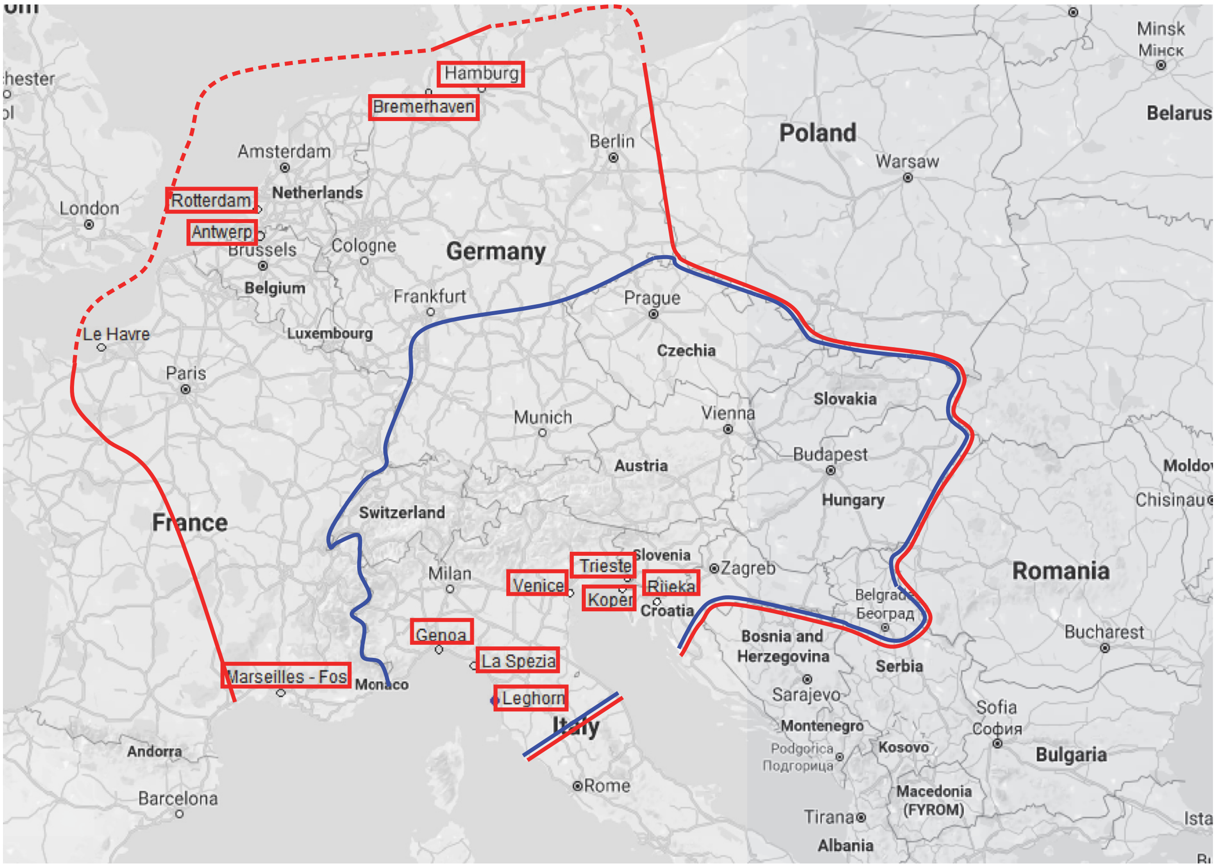

FIGURE 1: Potential hinterland (circled in blue) of the future container terminal of Leghorn and the European region whose rail network has been modelized (circled in red).

4. The Application of the Cost Function to the European Rail Network and the Problems of Data Collection

4.1. The European Regions under Study. Several European regions have been excluded from the potential hinterland of the "Europe Platform" of Leghorn because of their localisation. Therefore, Russia, Belarus, and Ukraine are excluded because they are too far to be considered within the hinterland of Leghorn port. Additionally, Northern Germany and Poland have been excluded because the ports in the northern range are far more accessible than the port of Leghorn from these regions. France has been excluded because, although it is not far from Leghorn, the position of the northern European ports of Antwerp and Le Havre and of the Mediterranean port of Marseilles-Fos is clearly more favourable than that of Leghorn. Finally, Spain, Greece, Bulgaria, and Romania have been excluded because they are close to some important ports with deep sea services: Valencia, Algeciras, Barcelona, and Piraeus.

Consequently, the following European regions can, potentially, be comprised into the hinterland of Leghorn (fundamental hinterland and competition margin): central and northern Italy; Switzerland (entire country); southern Germany; Austria (entire country); Slovenia (entire country); northern Croatia (Zagreb, in particular); northern Serbia (Belgrade, in particular); Hungary (entire country); Czech Republic (entire country); and Slovakia (entire country). In Figure 1, the potential hinterland of Leghorn is encircled in blue (hereinafter called "blue area"), which comprises some of the most contestable regions in Europe.

Although aimed at determining the potential hinterland of the port of Leghorn, this research actually analyses travel times and monetary costs to reach some of the most contestable destinations in Europe (marked by the blue area) from major European, Mediterranean, and Northern Range ports. The ports which are competing to serve the blue area are the Ligurian ports of Genoa, La Spezia, and Leghorn and the northern Adriatic ports. Northern Adriatic ports, particularly Venice, Trieste, Koper, and Rijeka, are in a more favourable position than Ligurian ports for destinations in north-eastern Italy and Central-Eastern Europe. However, Ligurian ports (as Leghorn) are in a much favourable position when the sea side is concerned. In fact, the Adriatic ports are currently crossed mainly by feeder routes to/from the Far East and are thus disadvantaged when compared to Ligurian ports for the routes from/to the American continent. Therefore, the blue area also comprises north-eastern Italy and Central-Eastern Europe. As far as some Central-Southern European markets are concerned (south Germany, particularly

Munich), the Ligurian and Adriatic ports are in competition with northern European ports as well, especially Antwerp, Rotterdam, Hamburg, Zeebrugge, and Bremerhaven.

In Figure 1, the potential competitor ports to serve the blue area are encircled in red. Some of these ports are external to the blue area, and therefore it was necessary to model the rail network of a wider area. The European region, whose rail network was modelled, is made up of not only the blue area but also the remaining part of Germany, Belgium, the Netherlands and Luxembourg, and the northern and eastern regions of France. This region is encircled in red in Figure 1 (hereinafter the “red area”).

The rail network of the red area has been modelled through 571 nodes and 753 links. Among these links, 701 are bidirectional and 52 are unidirectional. Bidirectional links have been used for plains or almost flat terrains, while unidirectional links have been used for mountainous terrains because the energy consumption and travel time in the two directions are different.

4.2. Data Collection. In order to apply the proposed cost function and calculate travel times and monetary costs for each line section, the following information was deemed necessary:

(i) the maximum speed allowed in rank A on each line section,

(ii) the length of the line section,

(iii) the grade and curve resistances of the line section or, at least, the slope and the curve radius.

The first two pieces of information are needed to determine the travel time on each link. The average speed has been calculated from the maximum speed in rank A according to (4) in Section 3.1. The maximum speed in rank A, if not explicitly stated, was calculated according to (5) from the maximum speed in rank C. All three sets of data are needed to calculate the monetary cost. The third information, in particular, is necessary to determine the number of locomotives to be used and the electric traction cost.

In Italy, this information is publicly available in the route books where, for each line section, the maximum allowed speed, for each speed rank (A, B and C; freight trains belong to rank A), the length of the section, and the sum of grade and curve resistances (this sum is called “degree of performance” in Italy) are given. From the route books, we also determined the rail lines to be excluded from the model because the maximum towable weight is incompatible with the weight of the train considered in Section 3.2.1.

In the other European countries, however, this information is not made public.

Only in Slovenia and Czech Republic some sort of route books are made available to the public. These books report for each line section the length of the section and the maximum permissible speed in the ranks A, B, and C. In other countries, to the best of our knowledge, the so-called “network statements” that provide the general characteristics of the lines are made available to the public. These documents report only the length of the section and the maximum speed in rank C of each line section. To calculate the speed in rank A from the speed value in rank C, the Equation (5) (Section 3.1) has been used.

The network statements and the other documentation on rail lines are available for each country under study at the following websites: Austria [49], Belgium [50], France [51], The Netherlands [52], Germany [53], Croatia [54], Czech Republic [55], Slovakia [56], Slovenia [57], Hungary [58], and Switzerland [59]. While conducting our study, we found that route books in Switzerland only revealed distances. Therefore, in order to collect full information on the speeds, it was necessary to interview the railway network manager and some MTOs.

Germany, Croatia, and Slovenia, on the other hand, provided the slopes of lines in the network statements. In all the other cases, it was necessary to calculate the slopes manually through “Openstreetmap”. The curve resistance of the lines was not available in any other European country besides Italy, and it has been again calculated manually. For this, the curve radius was taken from “Openstreetmap” and, given the curve radius, the curve resistance was calculated through the Von Röckl formula.

As far as the lines with special operation characteristics are concerned, those in the red area of Figure 1 are described in detail in the following. In our model, we consider the same number of locomotives as used by the MTOs in real operations to tow a weight of 1,234 tonnes. MTOs generally use locomotives similar to the E189 considered in this paper.

On the Brenner line (Italy–Austria border), the maximum sum of grade and curve resistances equals 26 N/kN on the Italian side from Bressanone to the Brenner Pass (51 km) and 28 N/kN on the Austrian side from Steinach to the Brenner Pass, (13 km). On the Italian side, from Bressanone to the Brenner Pass, double traction (both locomotives pulling the wagons) was used; on the Austrian side, double traction (both locomotives pulling the wagons) from Innsbruck to Steinach (26 km) and triple traction (two locomotives pulling and one pushing) from Steinach to the Pass (13 km) were used. The information on the number of locomotives was taken from Zurlo [60] and Schmittner [61]. On the Brenner line, a maximum towable weight of 1,500 tonnes on the Italian side and 1,560 tonnes on the Austrian side is allowable (as reported in Schmittner [61]).

The maximum sum of grade and curve resistances on the Frejus line, on the Italian side, is equal to 28 N/kN from Bussoleno to Salbertrand (22 km) and 31 N/kN for only 3 km between Bardonecchia and the beginning of the Frejus tunnel. From Salbertrand to Bardonecchia, the sum of grade and curve resistances is less than 22 N/kN. On the French side, between Modane and the end of the Frejus tunnel, which is 11 km long, the maximum sum of grade and curve resistances is 31 N/kN (also along the Frejus tunnel). Between Modane (France) and Bussoleno (Italy) and vice versa, the maximum towable weight of 1,150 tonnes with double traction and 1,600 tonnes with triple traction is allowed (Osservatorio [62], in Ferrari [63]). The line on the French side from St Michel de Maurienne to Modane shows a lower maximum sum of grade and curve resistances equal to 22 N/kN. This part of the line is operated by double traction with a maximum towable weight of 1,600 tonnes (source: interviews to Novatrans, one of the most important French MTOs that operates on this line).

As far as the Sempione line is concerned, the section with a sum of grade and curve resistances above 20 N/kN and equal to 24 N/kN is very short (2 km) and is close to Iselle station. The line is operated with double traction between Domodossola (Italy) and Brig (Switzerland).

As for the Loetschberg line, thanks to the new Loetschberg tunnel, the maximum sum of grade and curve resistances, which occurred in the north ramp, has been reduced from 29 to 14 N/KN. Single or double traction trains ply on this line, depending on the towed weight and the performance of the locomotive, while the resistance values completely fulfil the resistance of the train couplers of Table 4 [64].

With regard to the Gotthard line, thanks to the opening of the new Gotthard Base tunnel, the maximum sum of grade and curve resistances that occurred in the south ramp has been reduced from 27 to 13 N/kN [65, 66]. The new Gotthard line is operated in single traction except for the Ceneri Pass north ramp, whose sum of grade and curve resistances is 26 N/kN, which is operated in triple traction, and the Ceneri Pass south ramp, whose sum of grade and curve resistances is 21 N/kN, which is operated in double traction (source: interviews to the Hupac MTO). However, the Ceneri Base tunnel is still under construction.

As far as the Tarvisio line is concerned, it does not face the problems of grade and curve resistances. However, it is a part of the international path connecting Italy with Vienna, a portion of which is the Semmering rail line. While the Semmering west ramp (on the side of Mürzzuschlag) does not show high slope, the east ramp (on the side of Gloggnitz) shows a grade resistance of 25 N/kN and a maximum curve resistance of 5.5 N/kN. Some curves have a radius of even 150 metres. The maximum sum of grade and curve resistances is 28 N/kN. This line is operated with triple traction between Gloggnitz and Mürzzuschlag [67] (Mürzzuschlag is close to Bruck an der Mur) and double traction for the rest of the line between Carnia in Italy and Mürzzuschlag, while the rail between Gloggnitz and Vienna is flat and operated with only one locomotive (source: interviews to Alpe Adria, one of the main MTOs operating on this line). It should be noted that the Semmering line has high slope for only 40 km. To mitigate this, a new Semmering base tunnel is currently under construction.

The last lines "with special operation characteristics" are those running from the ports of Trieste, Koper, and Rijeka to the internal Karst plateau. In particular, we have the following:

(i) The rail from Trieste Campo Marzio to Villa Opicina (Italy–Slovenia border, 15 km) shows a sum of grade and curve resistances of 25 N/kN. This rail is part of the Trieste–Ljubljana path and is operated with triple traction trains from Trieste Campo Marzio to Villa Opicina (Source: interviews to Alpe Adria, the main MTO operating rail connections to/from the Trieste Campo Marzio rail terminal). Between Villa Opicina and Ljubljana, instead, the sum of grade and curve resistances is below 20 N/kN and the line is operated with double traction.

(ii) A portion of about 18 km of the line from Koper to Ljubljana, comprised in the rail line Koper–Pivka, shows a maximum sum of grade and curve resistances of 23 N/kN. This line is operated in double traction (source: interviews to Metrans, the main MTO operating on this line).

(iii) A portion of 15 km of the line from Rijeka to Ljubljana, close to the Rijeka port, shows a sum of grade and curve resistances of 27 N/kN. This line portion is operated with triple traction while the rest of the line is operated with double traction (source: interviews to Metrans).

(iv) A portion of approximately 25 km of the line from Rijeka to Zagreb shows a sum of grade and curve resistances of 28 N/kN. This line portion is operated with triple traction while the rest of the line is operated with double traction (source: interviews to Metrans).

5. Optimal Paths and Comparison of the Results

5.1. Optimal Paths between Each O/D Pair. The optimal paths between each O/D pair have been calculated through the Dijkstra algorithm. Origins of paths are the ports marked in red in Figure 1. Destinations are the main rail terminals in northern Italy and some important rail terminals near the main cities in Central-Southern and Central-Eastern Europe. The destinations considered are: the Italian terminals of Prato (near Florence), Bologna, Milan Segrate/Milan Smistamento (the two terminals are adjacent), Novara, Busto Arsizio–Gallarate (near Milan), Turin, Verona, and Padua; the Central-Southern European terminals of Basel (Switzerland), Zurich (Switzerland), Munich (Germany), Nuremberg (Germany), Stuttgart (Germany), and Vienna (Austria); and the Central-Eastern European terminals of Zagreb (Croatia), Ljubljana (Slovania), Budapest (Hungary), Prague (Czech Republic), Bratislava (Slovakia) and Belgrade (Serbia).

Because of the high variability in the monetary value of time, as highlighted in Section 2.3, three distinct optimisations have been carried out: a first optimisation which minimises travel times; a second optimisation which minimises monetary costs; and a third optimisation which optimises generalised costs. For each optimisation (based on travel times, monetary costs or generalised costs), the optimal paths and the related travel times, monetary costs and generalised costs have been calculated.

5.2. Comparison between the Results of the Two Optimisations. The problem which can arise in such calculations is that the optimisation based on, for example, monetary costs (the optimal path obtained), is very different from that obtained based on travel times or generalised costs. Consequently, all the comparisons among optimal paths obtained based on monetary costs, travel times, and generalised costs (from the point of view of monetary costs, travel time and generalised

Table 5: Monetary costs (in €) per train, from each origin port (shown in the columns) to each destination city (shown in the rows) resulting from the optimisation by monetary costs.

	Leghorn	Genoa	La Spezia	Venice	Trieste	Koper	Rijeka	Marseilles	Le Havre	Antwerp	Rotterdam	Hamburg	Bremer-haven
Prato	5654	8038	6554	7517	9769	10801	11517	13505	25128	23847	25499	30395	29449
Parma	7944	6933	8159	7389	9642	10674	11390	12400	22553	21272	22924	28063	27096
Bologna	6900	8338	7801	5985	8237	9269	9985	13805	23958	22677	24329	29224	28278
Milan	8867	6403	7629	7666	9918	10951	11667	11870	20922	19527	21179	26318	25351
Novara	8597	6133	7359	8657	10909	11941	12657	11600	20538	19281	20933	26072	25105
Busto A. Gallarate	9653	7189	8415	8573	10825	11857	12573	12656	20430	19035	20687	25826	24860
Padua	8480	9391	9380	4564	6816	7848	8564	14858	24182	22788	24440	28738	27792
Verona	8254	8163	9154	5634	7886	8918	9634	13630	22954	21559	23212	27510	26564
Turin	9010	6546	7772	10131	12383	13415	14131	11701	19181	20158	21810	27546	26579
Vienna	18497	19408	19397	13821	13315	13617	13544	24876	28422	24312	24415	22872	23209
Basel	14538	12074	13300	13910	16162	17194	17910	15645	14719	13324	14976	20115	19149
Zurich	13431	10967	12193	12802	15054	16087	16803	16435	16208	14813	16465	21604	20637
Munich	16743	16651	17643	13294	12788	13775	13702	22119	21314	18095	19164	19268	18322
Nuremberg	19717	18452	19677	16269	15762	16749	16676	22494	20196	16086	16189	16293	15347
Stuttgart	17817	15353	16578	17188	17005	17992	17919	19395	17097	13878	15040	17561	16615
Zagreb	15292	16203	16192	10616	8663	8845	7889	21671	30925	27706	28774	28878	27932
Ljubljana	12856	13767	13756	8180	6227	6410	6337	19235	28489	25270	26338	26443	25496
Budapest	19281	20193	20182	14606	12653	12835	12585	25660	32141	28031	28134	26052	26389
Prague	24191	24574	25091	19515	19009	19996	19923	29060	26761	21359	19899	16007	16344
Bratislava	19866	20777	20766	15190	14684	14986	14913	26245	29792	25681	25784	23364	23702
Belgrade	20806	21717	21706	16130	14177	14359	13402	27184	36225	32115	32218	30136	30473

costs achieved) have been carried out. Due to manuscript constraints, only some of these comparisons can be reported. As for the other comparisons, similar results have been obtained.

In Tables 5–7, the comparison regarding monetary costs between the optimisations based on monetary costs with respect to the optimisations based on travel times and generalised costs is shown. Generalised costs were determined assuming a value of time of 0.96 €/ (t·h), as proposed in De Jong [28]. For further details,

(i) in Table 5, the monetary costs obtained from the optimisation based on monetary costs are shown;

(ii) in Table 6, the differences in percentage of monetary costs between the optimisations based on monetary costs and travel times are shown (the optimisation based on monetary costs is taken as reference);

(iii) in Table 7, the differences in percentage of monetary costs between the optimisations based on monetary costs and generalised costs are shown (the optimisation based on monetary costs is taken as reference). In this table, it can be noticed that differences are less pronounced than in the preceding comparison (Table 6).

For each O/D pair, the best path according to travel times may be different from the best path according to monetary costs.

Firstly, the average speed is different from a rail link to another; therefore, a longer path could show a lower travel time than a shorter path. However, the monetary cost has several components proportional to the operative distance.

On the other hand, the monetary cost per unit of distance could be very different from a link to another, for the following reasons:

(i) The traction cost (in €/km) is different from one link to another because it is the product of the electric energy price, which changes from one country to another, and the power consumption, which depends on the resistances to motion of each link. Therefore, it is different from one link to another in terms of unit of distance.

(ii) The number of locomotives, which heavily impacts the monetary cost of the link, is also different from one rail link to another

(iii) The rail track cost (in €/km) is different from one rail line to another (and from one country to another). The differences of rail track cost sometimes are highly relevant.

Therefore a longer path could have a lower monetary cost than a shorter path because, for example, it would need fewer locomotives or incur a lower track cost.

However, the best path according to monetary costs coincides with the shortest path by distance more frequently

Table 6: Differences, in percentage, of monetary costs, between the optimisation by monetary costs and the optimisation by travel times (the optimisation by monetary costs is taken as reference).

	Leghorn	Genoa	La Spezia	Venice	Trieste	Koper	Rijeka	Marseil-les	Le Havre	Antwerp	Rotterdam	Hamburg	Bremer-haven
Prato	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	1.0%	8.0%	0.0%	0.0%
Parma	0.0%	0.0%	8.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	1.1%	8.9%	0.0%	0.1%
Bologna	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	1.1%	8.4%	0.0%	0.0%
Milan Smistamento	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.2%	9.6%	0.0%	0.1%
Novara	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	1.3%	9.7%	0.0%	0.1%
Busto A. - Gallarate	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	1.4%	10.0%	0.1%	0.2%
Padua	0.0%	2.9%	0.0%	0.0%	0.0%	0.0%	0.0%	1.8%	0.0%	1.1%	8.3%	0.8%	0.9%
Verona Q. E.	0.0%	3.3%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	0.0%	1.1%	8.8%	0.0%	0.0%
Turin	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.2%	12.1%	0.0%	0.1%
Vienna	0.0%	1.4%	0.0%	0.0%	0.0%	5.4%	5.1%	1.1%	0.0%	0.0%	0.0%	2.4%	2.4%
Basel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	0.0%	1.8%	13.6%	0.0%	0.1%
Zurich	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	12.4%	0.0%	0.1%
Munich	0.0%	1.6%	0.0%	0.0%	0.0%	0.3%	0.0%	1.2%	0.0%	5.3%	0.0%	0.0%	0.0%
Nuremberg	0.0%	0.0%	4.8%	0.0%	0.0%	0.3%	0.0%	2.4%	0.0%	0.0%	0.0%	0.0%	0.0%
Stuttgart	0.0%	0.0%	0.0%	1.9%	0.0%	0.3%	0.0%	2.7%	0.0%	9.1%	1.3%	4.4%	4.7%
Zagreb	0.0%	1.7%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%	0.0%	3.5%	0.0%	0.0%	0.0%
Ljubljana	0.0%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	0.0%	3.8%	0.0%	0.0%	0.0%
Budapest	9.4%	10.3%	9.0%	12.4%	25.7%	5.7%	0.2%	8.1%	0.0%	0.0%	0.0%	2.1%	2.1%
Prague	2.0%	1.1%	1.9%	0.0%	0.0%	0.2%	0.0%	1.8%	0.0%	0.0%	0.0%	0.0%	0.0%
Bratislava	0.0%	1.3%	0.0%	0.0%	0.0%	4.9%	4.6%	1.0%	0.0%	0.0%	0.0%	2.3%	2.3%
Belgrade	0.0%	1.3%	0.0%	0.0%	0.0%	0.0%	0.0%	1.0%	0.0%	0.0%	0.0%	1.8%	1.8%

than the best path according to travel times. In the monetary cost function, only one cost component is proportional to the travel time, which is the driver cost. All the other components, namely the traction cost, the rail track cost, and the amortisation, maintenance, and insurance costs of locomotives and wagons, are proportional to the distance.

Very often, the best paths obtained from the three optimisations coincide with one another or have only minor differences. This is clear not only from the comparison of monetary costs (reported in Tables 5–7) obtained from the three optimisations, but also from that of travel times and generalised costs, which have not been reported due to the scope of this paper.

The highest differences between the results of the optimisations based on monetary costs and travel times occur for the destination of Budapest and for all Italian origin ports (Genoa, La Spezia, Leghorn, Venice, and Trieste) and for non-Italian origin ports of Marseilles and Koper. Therefore, the best path according to monetary costs goes through the Slovenian line from the Adriatic Sea to Ljubljana and Ormoz. Similarly, the best path according to travel time passes through Austria and in particular the Tarvisio and Semmering Passes. The Slovenian path is tortuous and characterised by low speeds, while the Austrian path, apart from the Semmering section (which is long only 40 km on a total path length of over 300 km), is characterised by higher speeds. On the other hand, the rail track cost of the Austrian lines is much higher than the Slovenian one, and similarly, the price of electric energy is higher in Austria than in Slovenia. As far as the optimisation by generalised costs is concerned, the highest differences occur with the optimisation by monetary costs, and again for the destination of Budapest and for all Italian origin ports (Genoa, La Spezia, Leghorn, Venice and Trieste) and for non-Italian origin ports of Marseilles and Koper. The paths chosen in the optimisation based on generalised cost for the above-mentioned O/D pairs are the same as the paths chosen in the optimisation based on travel times.

Other remarkable differences concern the origin port of Rotterdam and destinations Basel, Zurich, Turin and Busto Arsizio–Gallarate (and consequently other destinations in Italy). For Turin, the optimal path according to travel times passes through Germany and the Loetschberg and Sempione lines, while the optimal path according to both monetary and generalised costs passes through Belgium and France and the Frejus tunnel that connects France and Italy. For the other three destinations, the optimal path according to travel times passes through Germany, while the optimal path according to both monetary and generalised costs passes through Belgium and France. These paths join in Basel. The rail track cost in France is 1.96 €/km on average, while in Germany it is 2.65 €/km, in Belgium 3.94 €/km, and in Switzerland 5.21 €/km.

Table 7: Differences, in percentage, of monetary costs, between the optimisation by monetary costs and the optimisation by generalised costs (the optimisation by monetary costs is taken as reference).

	Leghorn	Genoa	La Spezia	Venice	Trieste	Koper	Rijeka	Marseilles	Le Havre	Antwerp	Rotterdam	Hamburg	Bremer-haven
Prato	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%
Parma	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.1%
Bologna	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%
Milan Smistamento	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Novara	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.1%
Busto A. - Gallarate	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	0.2%	0.1%	0.2%
Padua	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%	0.9%
Verona Q. E.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Turin	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Vienna	0.0%	0.0%	0.0%	0.0%	0.0%	5.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Basel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Zurich	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Munich	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Nuremberg	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Stuttgart	0.0%	0.0%	0.0%	1.9%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Zagreb	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ljubljana	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Budapest	9.4%	9.0%	9.0%	12.4%	0.0%	0.0%	0.2%	7.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Prague	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Bratislava	0.0%	0.0%	0.0%	0.0%	0.0%	4.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Belgrade	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Adding to this, the electric energy price in France is 0.09 €/kWh, in Germany 0.15 €/kWh, in Belgium 0.08 €/kWh, and in Switzerland 0.1 €/kWh. Although the track cost in Belgium is higher than in Germany, it is lower in France. In addition, the electric energy price is much higher in Germany than in the other mentioned countries.

5.3. Railway Lines Crossing the Alps Used to Connect the Considered O/D Pairs. In the past, nearly all railway lines across the Alps had high grade and curve resistances. Therefore, they all would be comprised among the lines "with special operation characteristics". Currently, two base tunnels have been constructed along the Loetschberg and Gotthard lines. As a result, the geometry of these two railway lines has improved considerably. The railway lines across the Frejus, Brenner, and Semmering passes are among those "with special operation characteristics". However, new base tunnels are being planned or are already under construction.

In this section, the importance of each railway line crossing the Alps (through a pass or a base tunnel) is pointed out in terms of their usage by the optimal paths connecting O/D pairs (only O/D pairs which require crossing the Alps have been considered). The results of this analysis are displayed in Table 8. The main lines across the Alps are schematically represented in Figure 2.

From Table 8, it could be observed that the most used line is the Gotthard line. This line, owing to its geographical position, is the main railway axis between the Padan Plain and northern Europe. This line ends at Milan, but its branches across Varese and Luino rapidly connect this line to all destinations in the western Padan Plain (Novara, Turin, and the main Italian intermodal centre of Busto Arsizio–Gallarate) and to the ports of Genoa and La Spezia. The Loetschberg–Sempione rail line is less used and provides an alternative path to the Gotthard line for the Italian terminals located in Piedmont region (administrative centre Turin). The Gotthard and Loetschberg lines join in the south of Basel.

The Semmering route between Villach and Vienna is crucial for the connections from Italian ports to Vienna and to several Central-Eastern European destinations. It is the only alternative to the path across Ljubljana, Ormoz, and Hungary, which is tortuous and has low speeds for a long distance (the Semmering route is tortuous for only a portion of 40 km on a total route length of 340 km). In addition, Villach is connected to Italy through the Tarvisio line, which has been modernised recently. In addition, the Tauern line in Austria between Villach and Salzburg is widely used from the origin ports of Trieste, Koper, and Rijeka to the destinations in southern Germany. The path across Villa Opicina and Slovenia is used from the Italian ports to the destinations of Zagreb, Ljubljana, and Belgrade and from the origin ports of

Table 8: Railway lines crossing the Alps used to connect the considered O/D pairs. Only O/D pairs which require the crossing of Alpine passes have been taken into account.

Origin	Destination	Pass - optimization by travel times	Pass – optimization by monetary costs	Pass – optimization by generalized costs
Leghorn	Vienna	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio - Semmering
Leghorn	Basel	Chiasso – Gotthard	Luino – Gotthard	Luino - Gotthard
Leghorn	Zurich	Chiasso – Gotthard	Luino – Gotthard	Luino - Gotthard
Leghorn	Munich	Brenner	Brenner	Brenner
Leghorn	Nuremberg	Brenner	Brenner	Brenner
Leghorn	Stuttgart	Chiasso – Gotthard	Luino – Gotthard	Luino - Gotthard
Leghorn	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Leghorn	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina
Leghorn	Budapest	Tarvisio – Semmering	Villa Opicina – Ormoz	Tarvisio – Semmering
Leghorn	Prague	Brenner	Tarvisio – Tauern	Tarvisio - Tauern
Leghorn	Bratislava	Tarvisio – Semmering	Tarvisio – Semmering	Tarvisio - Semmering
Leghorn	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Genoa	Vienna	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio – Semmering
Genoa	Basel	Luino – Gotthard	Luino – Gotthard	Luino – Gotthard
Genoa	Zurich	Luino – Gotthard	Luino - Gotthard	Luino – Gotthard
Genoa	Munich	Brenner	Brenner	Brenner
Genoa	Nuremberg	Luino – Gotthard	Luino – Gotthard	Luino – Gotthard
Genoa	Stuttgart	Luino – Gotthard	Luino – Gotthard	Luino – Gotthard
Genoa	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Genoa	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina
Genoa	Budapest	Tarvisio – Semmering	Villa Opicina – Ormoz	Tarvisio – Semmering
Genoa	Prague	Brenner	Brenner	Brenner
Genoa	Bratislava	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio – Semmering
Genoa	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
La Spezia	Vienna	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio – Semmering
La Spezia	Basel	Luino – Gotthard	Luino - Gotthard	Luino – Gotthard
La Spezia	Zurich	Luino – Gotthard	Luino - Gotthard	Luino – Gotthard
La Spezia	Munich	Brenner	Brenner	Brenner
La Spezia	Nuremberg	Brenner	Luino – Gotthard	Luino – Gotthard
La Spezia	Stuttgart	Luino – Gotthard	Luino - Gotthard	Luino – Gotthard
La Spezia	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
La Spezia	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina
La Spezia	Budapest	Tarvisio – Semmering	Villa Opicina – Ormoz	Tarvisio – Semmering
La Spezia	Prague	Tarvisio – Tauern	Tarvisio - Tauern	Tarvisio - Tauern
La Spezia	Bratislava	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio - Semmering
La Spezia	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Venice	Vienna	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio - Semmering
Venice	Basel	Chiasso – Gotthard	Chiasso - Gotthard	Chiasso - Gotthard
Venice	Zurich	Chiasso – Gotthard	Chiasso - Gotthard	Chiasso - Gotthard
Venice	Munich	Tarvisio – Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Venice	Nuremberg	Tarvisio – Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Venice	Stuttgart	Tarvisio – Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Venice	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Venice	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina
Venice	Budapest	Tarvisio – Semmering	Villa Opicina – Ormoz	Tarvisio – Semmering
Venice	Prague	Tarvisio – Tauern	Tarvisio - Tauern	Tarvisio - Tauern

Table 8: Continued.

Origin	Destination	Pass - optimization by travel times	Pass – optimization by monetary costs	Pass – optimization by generalized costs
Venice	Bratislava	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio - Semmering
Venice	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Trieste	Vienna	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio - Semmering
Trieste	Basel	Chiasso – Gotthard	Chiasso - Gotthard	Chiasso - Gotthard
Trieste	Zurich	Chiasso – Gotthard	Chiasso - Gotthard	Chiasso - Gotthard
Trieste	Munich	Tarvisio – Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Trieste	Nuremberg	Tarvisio – Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Trieste	Stuttgart	Tarvisio – Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Trieste	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Trieste	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina
Trieste	Budapest	Tarvisio – Semmering	Villa Opicina – Ormoz	Tarvisio – Semmering
Trieste	Prague	Tarvisio – Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Trieste	Bratislava	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio - Semmering
Trieste	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Rotterdam	Prato	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Parma	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Bologna	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Rotterdam	Busto A. - Gallarate	Gotthard – Varese	Gotthard - Varese	Gotthard - Varese
Rotterdam	Padua	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Verona Q.E	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Turin	Sempione - Loetschberg	Frejus	Frejus
Antwerp	Prato	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Parma	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Bologna	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Antwerp	Busto A. - Gallarate	Gotthard – Varese	Gotthard - Varese	Gotthard - Varese
Antwerp	Padua	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Verona Q.E	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Turin	Frejus	Frejus	Frejus
Hamburg	Prato	Brenner	Brenner	Brenner
Hamburg	Parma	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Hamburg	Bologna	Brenner	Brenner	Brenner
Hamburg	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Hamburg	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Hamburg	Busto A. - Gallarate	Gotthard – Varese	Gotthard - Varese	Gotthard - Varese
Hamburg	Padua	Brenner	Brenner	Brenner
Hamburg	Verona Q.E	Brenner	Brenner	Brenner
Hamburg	Turin	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Bremerhaven	Prato	Brenner	Brenner	Brenner
Bremerhaven	Parma	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Bremerhaven	Bologna	Brenner	Brenner	Brenner
Bremerhaven	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Bremerhaven	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Bremerhaven	Busto A. - Gallarate	Gotthard – Varese	Gotthard - Varese	Gotthard - Varese

Table 8: Continued.

Origin	Destination	Pass - optimization by travel times	Pass – optimization by monetary costs	Pass – optimization by generalized costs
Bremerhaven	Padua	Brenner	Brenner	Brenner
Bremerhaven	Verona Q.E	Brenner	Brenner	Brenner
Bremerhaven	Turin	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Le Havre	Prato	Gotthard- Chiasso	Frejus	Gotthard- Chiasso
Le Havre	Parma	Gotthard- Chiasso	Frejus	Gotthard- Chiasso
Le Havre	Bologna	Gotthard- Chiasso	Frejus	Gotthard- Chiasso
Le Havre	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Le Havre	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Le Havre	Busto A. - Gallarate	Gotthard – Varese	Gotthard - Varese	Gotthard - Varese
Le Havre	Padua	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Le Havre	Verona Q.E	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Le Havre	Turin	Frejus	Frejus	Frejus
Marseilles	All Italian destinations	Ventimiglia	Ventimiglia	Ventimiglia
Rijeka	All Italian destinations	Villa Opicina (Ilirska Bistrica)	Villa Opicina (Ilirska Bistrica)	Villa Opicina (Ilirska Bistrica)
Rijeka	Vienna	Maribor - Semmering	Maribor - Semmering	Maribor - Semmering
Rijeka	Basel	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard
Rijeka	Zurich	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard
Rijeka	Munich	Karavanke - Tauern	Karavanke - Tauern	Karavanke - Tauern
Rijeka	Nuremberg	Karavanke - Tauern	Karavanke - Tauern	Karavanke - Tauern
Rijeka	Stuttgart	Karavanke - Tauern	Karavanke - Tauern	Karavanke - Tauern
Koper	All Italian destinations	Villa Opicina (Presnica)	Villa Opicina (Presnica)	Villa Opicina (Presnica)
Koper	Vienna	Villa Opicina – Tarvisio – Semmering	Maribor - Semmering	Villa Opicina – Tarvisio – Semmering
Koper	Basel	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard
Koper	Zurich	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard
Koper	Munich	Villa Opicina – Tarvisio – Tauern	Karavanke - Tauern	Villa Opicina – Tarvisio – Tauern
Koper	Nuremberg	Villa Opicina – Tarvisio – Tauern	Karavanke - Tauern	Villa Opicina – Tarvisio – Tauern
Koper	Stuttgart	Villa Opicina – Tarvisio – Tauern	Karavanke - Tauern	Villa Opicina – Tarvisio – Tauern

Koper and Rijeka to all destinations in Italy and Switzerland. Although the path across Villa Opicina is tortuous, it is the only possibility of reaching these destinations.

The Brenner line is used for paths connecting the origin ports of Genoa, La Spezia, and Leghorn (Ligurian ports) with the destination cities of south-eastern Germany, Munich, and Nuremberg. Both the origin ports and the destinations connected through this rail line are of great importance.

The Ligurian coastal line across Ventimiglia is used by all the paths that originate in Marseilles and destinations in all the cities of northern Italy.

The Frejus line, on the other hand, is included only in the shortest paths connecting Rotterdam, Antwerp, and Le Havre with Turin. The most convenient route from these ports to the majority of northern Italian destinations crosses northern France, the cities of Strasbourg, Mulhouse, and Basel, and continues towards Italy through the Gotthard line. The path across the Frejus line is convenient, as far as the optimisation based on monetary costs is concerned, for the origin port of Le Havre and destinations Prato, Parma, and Bologna, although the shortest path by distance crosses the Gotthard line. While the Frejus line requires triple traction, which increases monetary costs, the rail track cost is, on an average, 1.5 €/km less in France than in Switzerland (in France, it is around 3.7 €/km, while in Switzerland it is 5.2 €/km).

This analysis has been performed taking into account the current situation of rail lines. It should be noted that several base tunnels are currently under construction or planned, such as those in Brenner, Ceneri, Frejus, and Semmering. All these tunnels will avoid the steepest and most tortuous line sections.

The construction of these tunnels will increase the competitiveness of all these lines. They will no longer be “with special operation characteristics”. As a result, some paths connecting O/D pairs will change. However, the construction

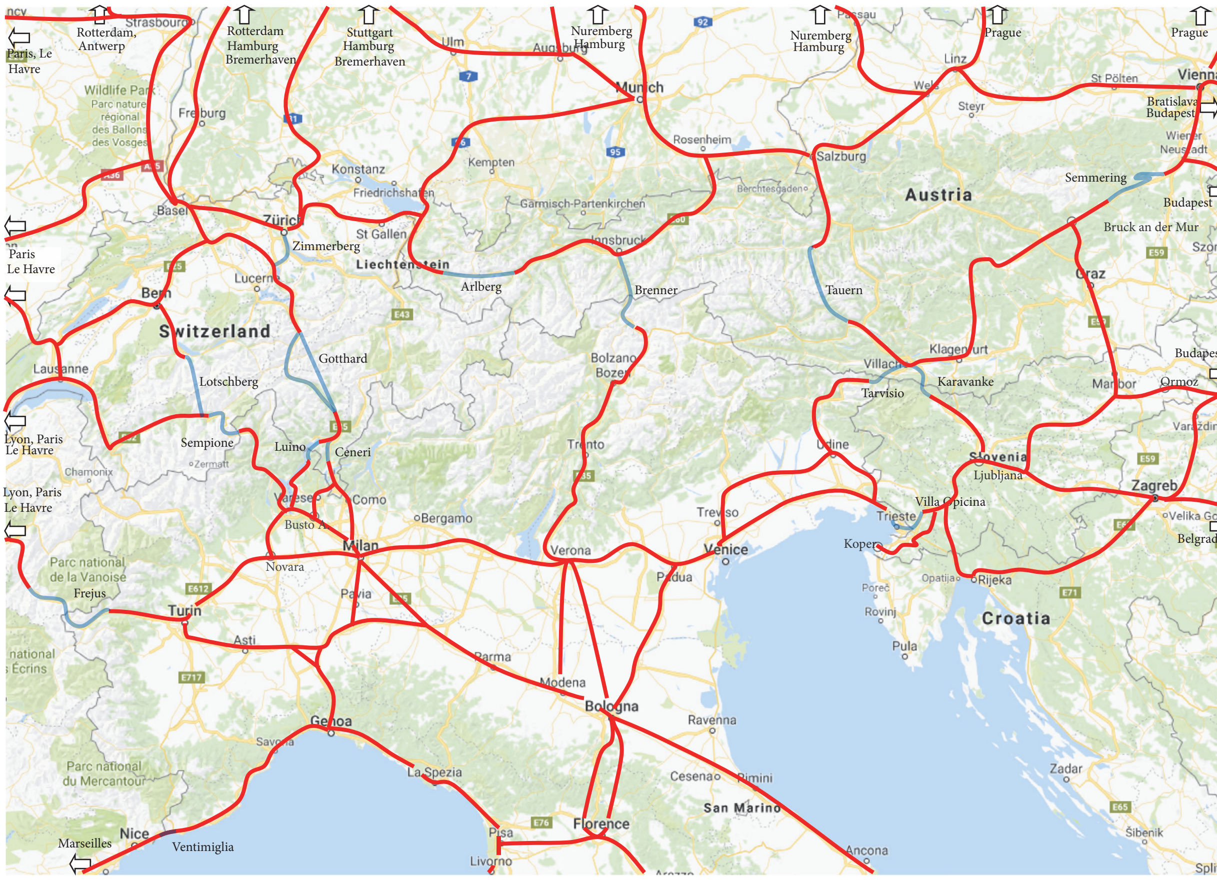

FIGURE 2: The main rail lines (represented in red) across Alpine passes (shown in blue).

of the new Ceneri Base tunnel will further increase the competitiveness of the Gotthard line.

In 16 O/D pairs, out of a total of 120, a different Alpine pass is chosen in the optimisations based on travel times and monetary costs. Among them, in five O/D pairs, the path chosen in the optimisation based on monetary costs is the same as in the optimisation by generalised costs, while in the rest of the 11 O/D pairs the path chosen in the optimisation based on travel times is the same as in the optimisation based on generalised costs. Among these 11 O/D pairs, five concern the destination of Budapest and the origin ports of Leghorn, Genoa, La Spezia, Venice, and Trieste. The path across Tarvisio and Semmering is more convenient than the path across Ljubljana and Ormoz (which is the best path according to monetary costs) not only with respect to travel times but also with respect to generalised costs. For the origin port of Koper and the destinations in southern Germany (Munich, Nurember, and Stuttgart), the path across Villa Opicina and Tarvisio is more convenient than the path across Ljubljana and Karavanke (which is the best path according to monetary costs) not only with respect to travel times but also with respect to generalised costs. All the other O/D pairs (among the 16 ones) concern origins in Italian ports and destinations in Central-Southern European terminals and origins in northern range ports and destinations in northern Italy. The paths across Gotthard or Loetschberg are chosen for the optimisation based on travel times in alternative to the paths across Frejus or Brenner passes, which are the most convenient ones in terms of monetary costs.

5.4. Competition among the Ports Considered (the Ports Signed in Red in Figure 1) for the Destinations in the "Blue Area". In Figures 3–11 the values of travel times, monetary costs, and generalised costs between the considered O/D pairs are reported:

(i) Italian destinations: Figure 3 (travel times), Figure 4 (monetary costs), Figure 5 (generalised costs);

(ii) Central-Southern European destinations: Figure 6 (travel times), Figure 7 (monetary costs), Figure 8 (generalised costs);

(iii) Central-Eastern European destinations: Figure 9 (travel times), Figure 10 (monetary costs), Figure 11 (generalised costs).

The reported travel times are those obtained from the optimisation based on travel times; the reported monetary costs are those obtained from the optimisation based on monetary costs; the reported generalised costs are those obtained from the optimisation based on generalised costs.

Regarding Italian destinations, travel times and monetary costs are reported for: Prato, Parma, Bologna, Milan Segrate/Smistamento, Novara, Busto Arsizio–Gallarate, Padua,

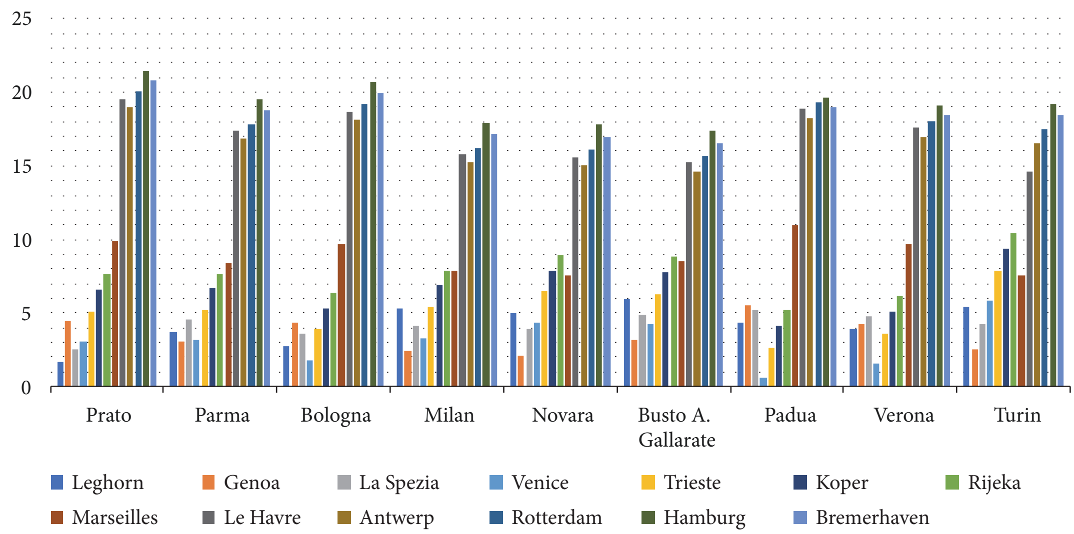

FIGURE 3: Travel times (h) from the ports considered in the analysis, towards Italian destinations. Optimisation by travel times.

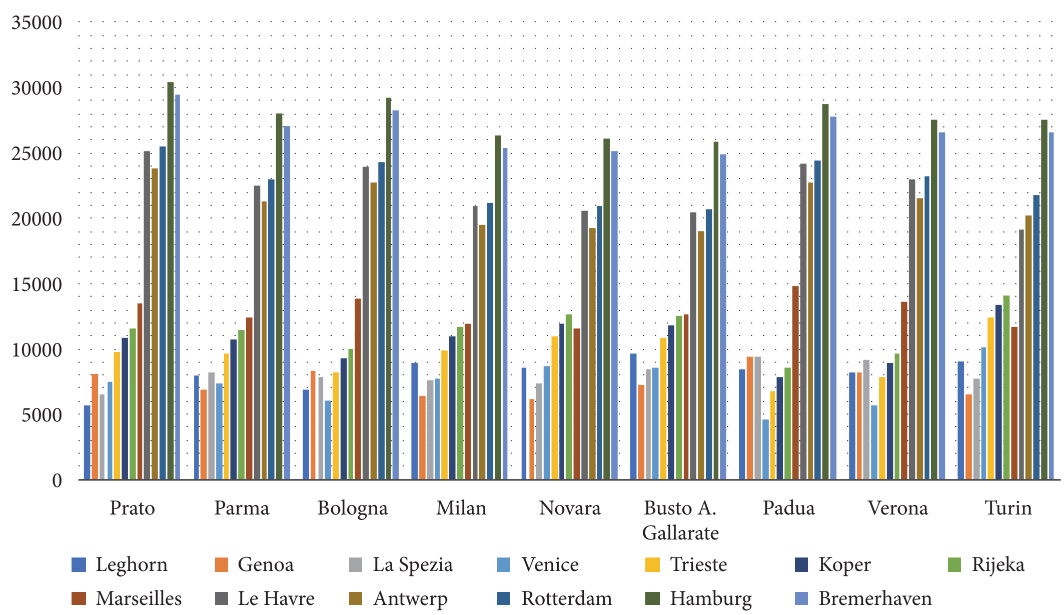

FIGURE 4: Monetary costs of a full train (€) from the ports considered in the analysis, towards Italian destinations. Optimisation by monetary costs.

Verona, and Turin. Milan Segrate and Milan Smistamento are considered together because they are adjacent, and they are the closest terminals to Milan city. Similarly, Busto Arsizio–Gallarate is also taken into account because, as reported in Lupi et al. [68], it is the most important intermodal centre in Italy (it is quite near to Milan).

As far as Central-Southern European destinations are concerned, travel times, monetary costs, and generalised costs are reported for: Vienna, Basel, Zurich, Munich, Nuremberg, and Stuttgart.

As far as Central-Eastern European destinations are concerned, travel times, monetary costs, and generalised costs are reported for: Zagreb, Ljubljana, Budapest, Prague, Bratislava, and Belgrade.

For all destinations, the origin ports of Leghorn, Genoa, La Spezia, Venice, Trieste, Koper, Rijeka, Marseilles, Le Havre, Antwerp, Rotterdam, Hamburg, and Bremerhaven were considered.

As far as the Italian destinations are concerned, the following can be observed.

For the destinations located in the north-western part of the Padan Plain, namely Busto Arsizio–Gallarate (the main intermodal terminal in Italy), Milan Segrate/Smistamento, Turin, and Novara, the lowest travel times, monetary costs, and generalised costs are represented by Genoa. For the destinations located in the eastern part of the Padan Plain, namely Verona and Padua, the origin port of Venice shows the lowest travel times, monetary costs, and generalised costs.

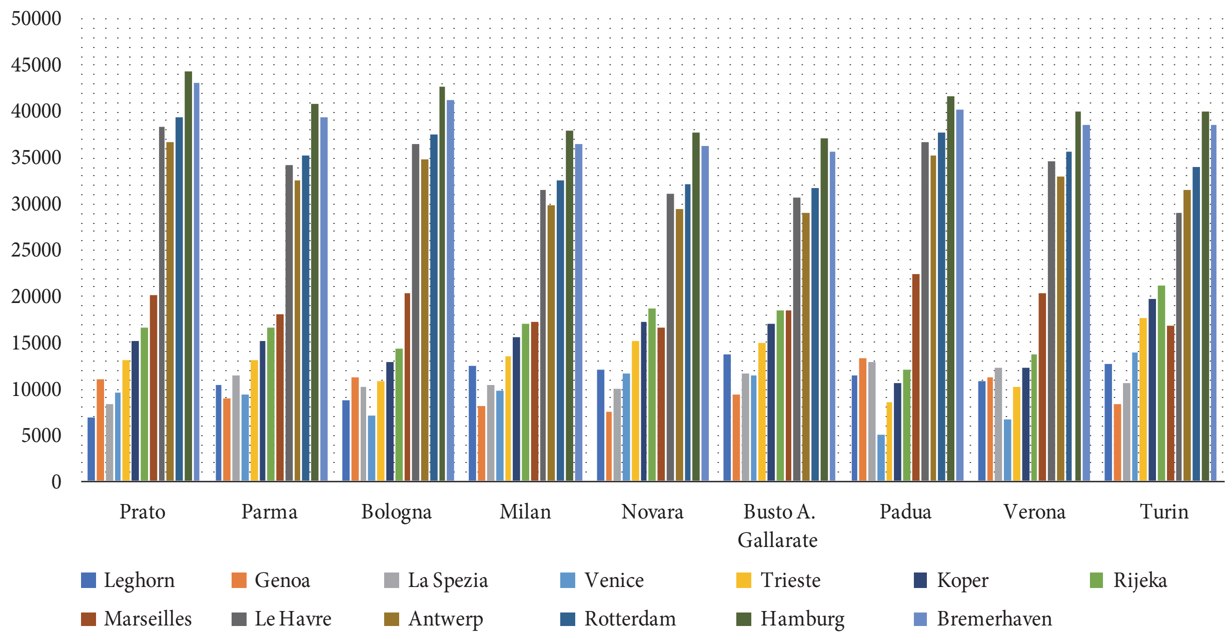

Figure 5: Generalised costs of a full train (€) from the ports considered in the analysis, towards Italian destinations. Optimisation by generalised costs.

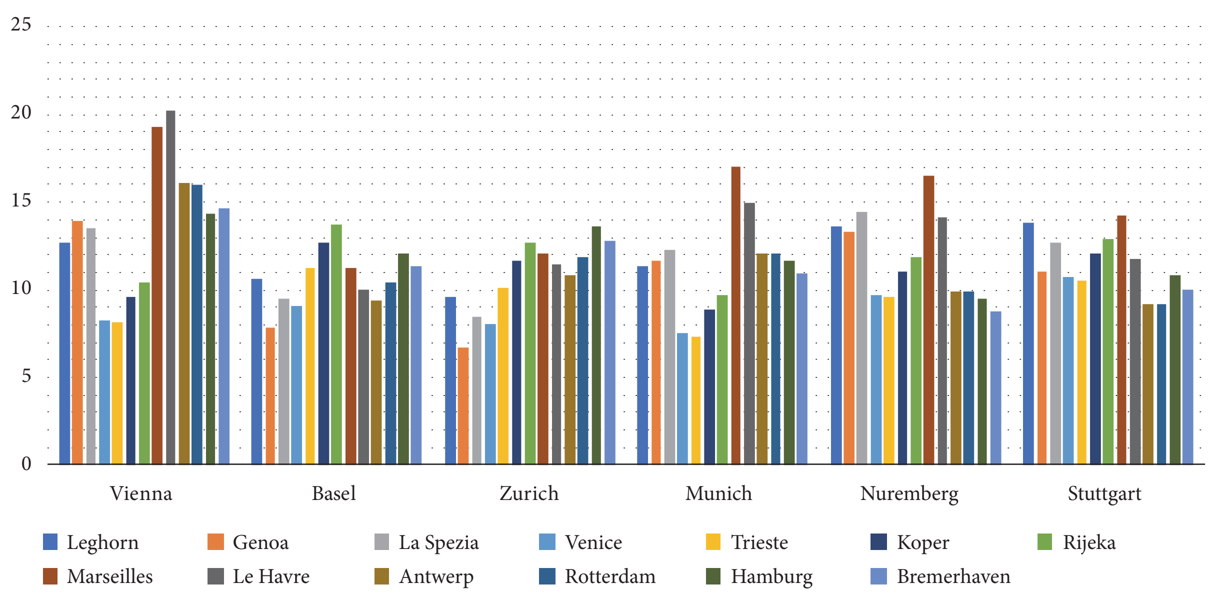

Figure 6: Travel times (h) from the ports considered in the analysis, towards Central-Southern European destinations. Optimisation by travel times.

For destinations located in the central part of the Padan Plain, namely Parma and Bologna, the lowest travel times, monetary costs, and generalised costs are shown by the origin port of Venice, but similar values are also shown by Genoa (for destination Parma; indeed a little less as far as travel time and generalised cost are concerned) and Leghorn (for destination Bologna). However, it should be noted that the position of Venice is not very favourable on the sea side (as for the other Adriatic ports) because, as shown in [9], it is crossed by only a few Deep Sea Shipping (DSS) container routes to/from Far East, and it does not connect to the Americas. Instead, Ligurian ports are crossed by several DSS routes, directed to Far East and to the Americas. Among Ligurian ports, Leghorn shows the lowest travel times and costs for all north-eastern Italian destinations (Verona, Padua, and Bologna). Therefore, Leghorn can be competitive given its favourable sea side position for the routes towards the American continent. Regarding the Europe–Far East route, Leghorn can be competitive given the small number of DSS routes (from Far East) calling at the Adriatic

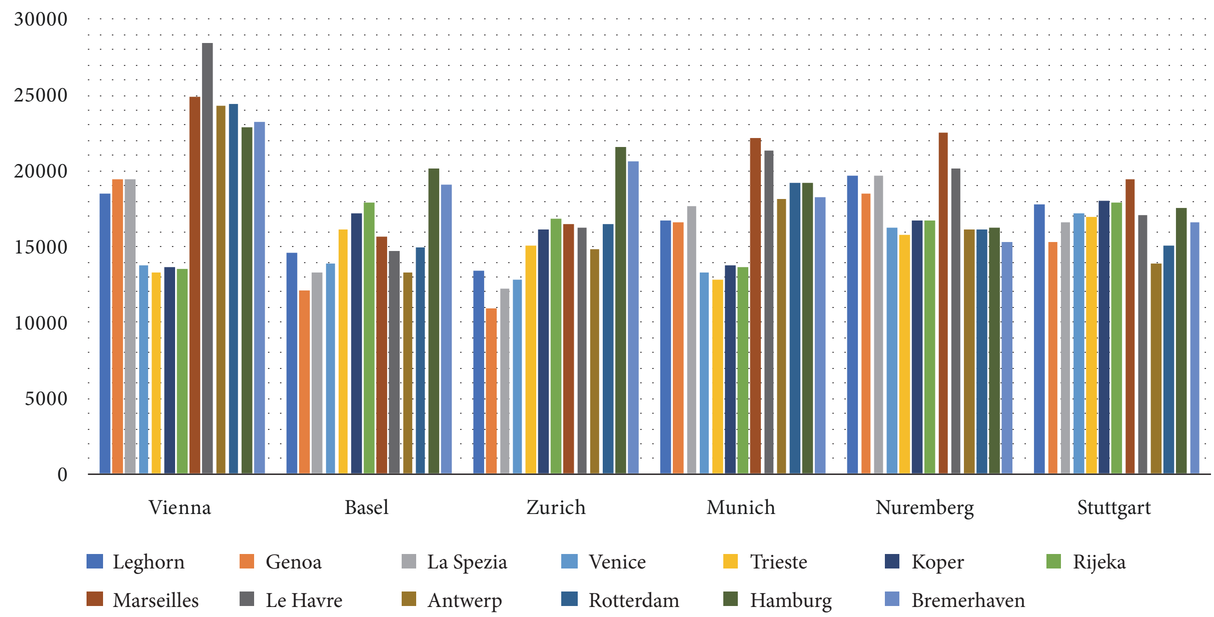

Figure 7: Monetary costs for a full train (€) from the ports considered in the analysis, towards Central-Southern European destinations. Optimisation by monetary costs.

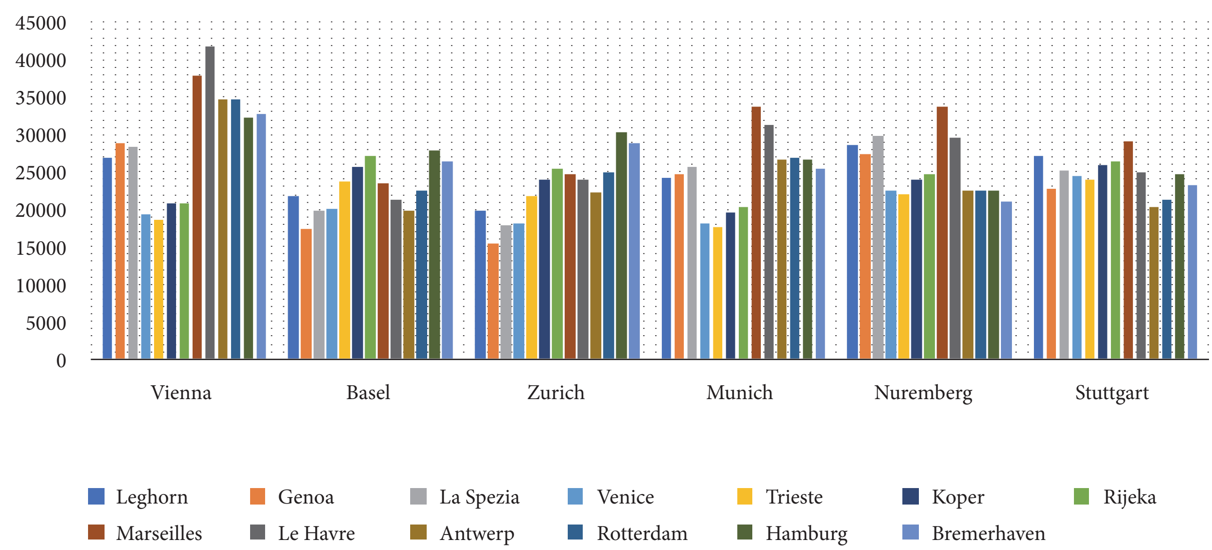

Figure 8: Generalised costs for a full train (€) from the ports considered in the analysis, towards Central-Southern European destinations. Optimisation by generalised costs.

ports of Venice and Trieste. Leghorn is the most favourable port for the Verona destination and the Brenner rail axis among all other Ligurian ports. This is particularly important because Germany is Italy's top trading partner (12.6% of total Italian exports and 16.3% of total Italian imports, in 2016) [69].

Northern Italian destinations appear in the fundamental hinterland (core market) of Italian ports. But it must be underlined that, in spite of the much higher travel times and monetary costs (and generalised costs), northern range ports unload/load a noticeable quantity of containers with destinations/origins in northern Italy. Musso et al. [70] point out the main variables affecting port competition, which are not very developed in Italian ports: price for port operations, freight rates of shipping companies, port capacity, productivity of port terminals (e.g., number of crane movements per hour), and competition among companies operating in the port. In addition, Dekker [71] points out that the idle times of a container at a northern European port are considerably less than those at Italian ports.

Concerning Central-Southern European destinations of Basel and Zurich, the port in the most advantageous position in terms of travel times, monetary costs, and generalised costs is Genoa.

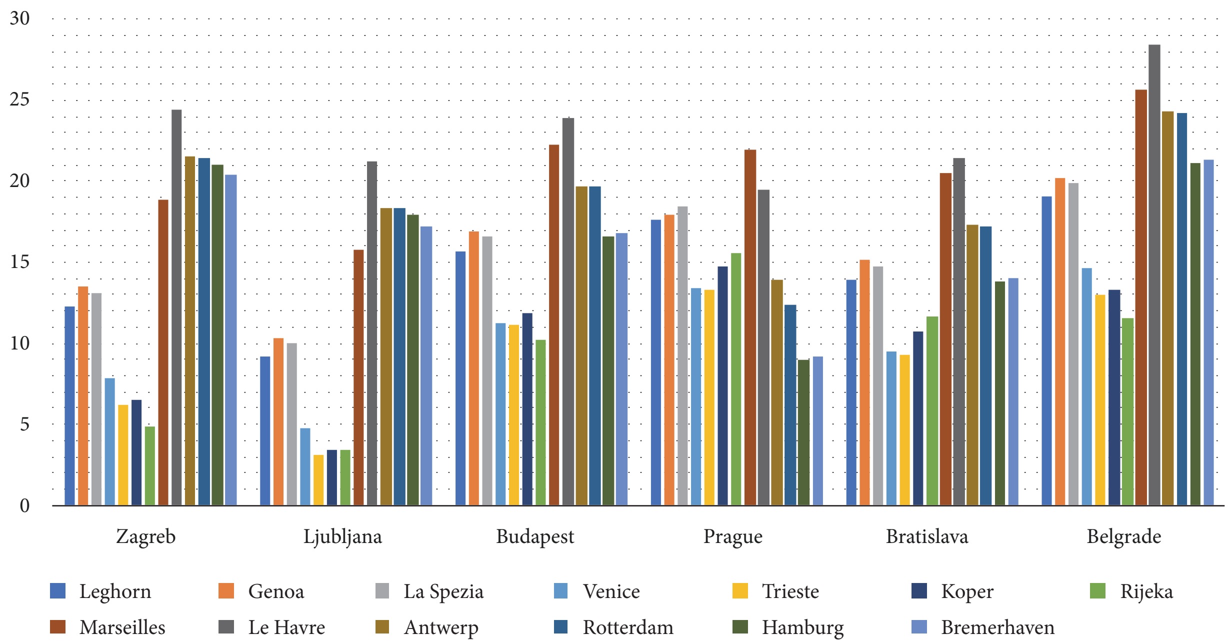

Figure 9: Travel times (h) from the ports considered in the analysis, towards Central-Eastern European destinations. Optimisation by travel times.

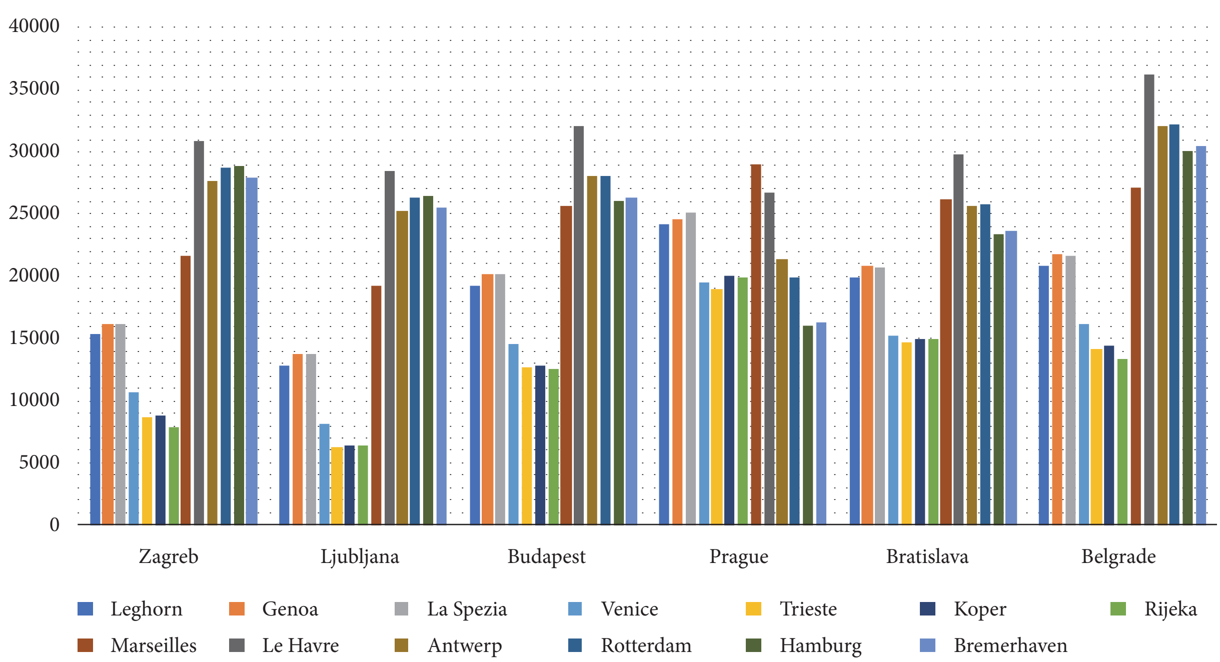

Figure 10: Monetary costs for a full train (€) from the ports considered in the analysis, towards Central-Eastern European destinations. Optimisation by monetary costs.

Among Italian ports, the Adriatic ports of Venice and Trieste are the most favourable when it comes to the important destination of Munich (southern Germany). However, as observed before, Ligurian ports can be competitive for this destination given their more favourable seaside position than Adriatic ports for the routes towards the Americas and the Far East. Among Ligurian ports, Leghorn is the most competitive. Among northern European ports, the German ports of Hamburg, and in particular of Bremerhaven, are in the most advantageous positions for the destination of Munich (Antwerp is advantageous as far as monetary costs are concerned). However, the German ports are farther than northern Adriatic ports. The distance from Trieste to Munich is 536 km, while the distance from Bremerhaven to Munich is 825 km. Travel times from Trieste to Munich are slightly less than those from Venice to Munich, although Venice is

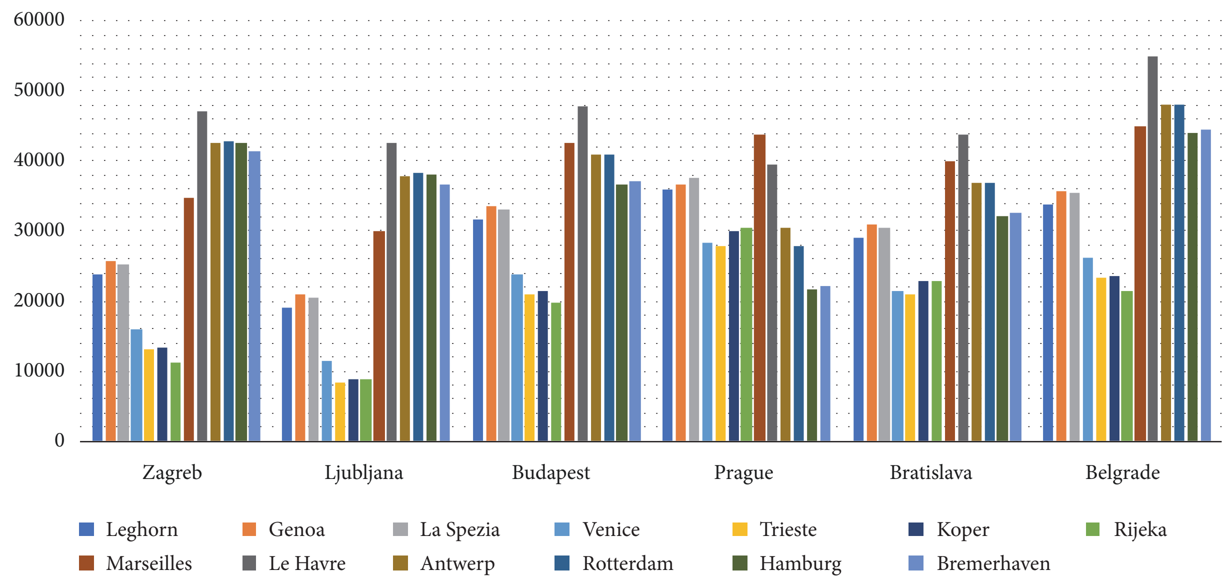

FIGURE 11: Generalised costs for a full train (€) from the ports considered in the analysis, towards Central-Eastern European destinations. Optimisation by generalised costs.

closer to the Brenner rail axis than Trieste. The best path from Trieste to Munich crosses the Tarvisio and Tauern lines, which are shorter than the Brenner line and are not "with special operation characteristics". The best paths connecting all other Italian ports to Munich cross the Brenner rail axis.

As for the German destinations of Nuremberg and Stuttgart, the ports in the most advantageous position are the northern range ports (these two cities are closer to the North Sea than Munich), in particular, Bremerhaven and Hamburg for Nuremberg (Antwerp and Rotterdam have very similar costs) and Antwerp and Rotterdam for Stuttgart. Finally, for the destination of Vienna, the most favourable origin port is Trieste in terms of travel times, monetary costs, and generalised costs; however, Venice is in a very similar situation, and, from the point of view of monetary costs, all northern Adriatic ports are in a similar situation.

In regard to Central-Eastern European destinations (Zagreb, Ljubljana, Budapest, Prague, Bratislava, and Belgrade), the ports in the most advantageous position (in terms of travel times, monetary costs, and generalised costs) for all destinations apart from Prague are the Adriatic ports. Prague is located more in the north than all the other Central-Eastern European destinations; therefore, the most favourable ports for this destination are the German ports of Hamburg and Bremerhaven.

To calibrate the model and validate the calculus, the results, in terms of monetary costs, have been compared with the prices practiced by a few MTOs. In particular, an MTO transporting almost exclusively "maritime" containers applies the following prices:

(i) transport of 1 TEU by rail from La Spezia to Milan Melzo (10 km to Milan Segrate / Smistamento): 140 €;

(ii) transport of 1 TEU from Rotterdam to Milan Melzo: 380 €.

The total monetary costs resulting from our model on these O/D pairs are as follows:

(i) from La Spezia to Milan Segrate/Smistamento (close to Milan Melzo): 7629 € per train. Considering that each train carries, on the average, 62.5 TEUs, the cost per TEU is 122 €;

(ii) from Rotterdam to Milan Segrate/Smistamento: 21179 € per train, therefore, considering 62.5 TEUs carried on each train, they result in 339 €/TEU.

6. Sensitivity Analysis

In the sensitivity analysis, two different scenarios (hereinafter 1st and 2nd sensitivity scenarios) have been studied. Both scenarios concern only changes in monetary costs and not in travel time.

In the 1st sensitivity scenario, the number of drivers is set to 1 in both Italy and the rest of Europe. Indeed only in Italy two drivers are needed by railway regulations to operate freight trains, which results in an increase in the monetary costs. This scenario has been studied in order to quantify the impact of the staff cost on the overall monetary cost of the links.

The second sensitivity scenario has been chosen in order to study the impact of the geometrical characteristics of rail lines, in particular of grades and curves, on the monetary cost of links. In order to "isolate" the effect of line geometry, all the other components that heavily influence the monetary cost have been standardised. Therefore, the number of drivers has been taken as 1 in Italy and the rest of Europe, and the same value for the rail track cost and for the energy price has been taken for the whole red area.

The rail track cost heavily influences the monetary cost of a link, and it is very different (in terms of €/km) not only from

Table 9: Differences, in percentage of monetary costs, between monetary costs of the first sensitivity scenario and monetary costs of the current scenario (the current scenario is taken as reference).

	Leghorn	Genoa	La Spezia	Venice	Trieste	Koper	Rijeka	Marseilles	Le Havre	Antwerp	Rotterdam	Hamburg	Bremer-haven
Prato	-1.6%	-3.0%	-2.1%	-2.1%	-2.8%	-2.5%	-2.3%	-2.4%	-1.5%	-1.1%	-1.0%	-1.3%	-1.3%
Parma	-2.5%	-2.3%	-3.1%	-2.2%	-2.9%	-2.5%	-2.4%	-2.0%	-1.2%	-0.7%	-0.6%	-0.5%	-0.5%
Bologna	-2.1%	-2.8%	-2.5%	-1.6%	-2.5%	-2.1%	-2.0%	-2.3%	-1.4%	-0.9%	-0.9%	-1.2%	-1.2%
Milan Smistamento	-3.2%	-2.1%	-2.9%	-2.3%	-2.9%	-2.6%	-2.4%	-1.9%	-0.3%	-0.3%	-0.3%	-0.2%	-0.2%
Novara	-3.1%	-1.9%	-2.8%	-2.7%	-3.1%	-2.8%	-2.7%	-1.8%	-0.8%	-0.3%	-0.3%	-0.2%	-0.2%
Busto A. - Gallarate	-3.3%	-2.4%	-3.1%	-2.6%	-3.1%	-2.8%	-2.6%	-2.1%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%
Padua	-2.7%	-3.2%	-2.9%	-0.7%	-2.1%	-1.7%	-1.6%	-2.7%	-0.9%	-1.0%	-0.9%	-1.1%	-1.2%
Verona Q. E.	-2.6%	-2.9%	-2.8%	-1.4%	-2.4%	-2.1%	-1.9%	-2.4%	-0.7%	-0.7%	-0.7%	-0.9%	-1.0%
Turin	-3.2%	-2.1%	-2.9%	-3.1%	-3.4%	-3.1%	-2.9%	-1.8%	-0.5%	-0.5%	-0.4%	-0.5%	-0.5%
Vienna	-2.1%	-2.4%	-2.2%	-1.1%	-1.1%	0.0%	0.0%	-2.2%	0.0%	0.0%	0.0%	0.0%	0.0%
Basel	-2.3%	-1.5%	-2.0%	-1.7%	-2.1%	-2.0%	-1.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Zurich	-2.4%	-1.6%	-2.2%	-1.8%	-2.3%	-2.1%	-2.0%	-1.6%	0.0%	0.0%	0.0%	0.0%	0.0%
Munich	-2.8%	-3.0%	-2.9%	-1.1%	-1.1%	-0.6%	0.0%	-2.6%	0.0%	0.0%	0.0%	0.0%	0.0%
Nuremberg	-2.4%	-1.0%	-1.4%	-0.9%	-0.9%	-0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Stuttgart	-1.8%	-1.2%	-1.6%	-1.3%	-0.8%	-0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Zagreb	-2.3%	-2.6%	-2.4%	-1.0%	-0.3%	0.0%	0.0%	-2.4%	-0.9%	0.0%	0.0%	0.0%	0.0%
Ljubljana	-2.7%	-3.1%	-2.8%	-1.4%	-0.4%	0.0%	0.0%	-2.7%	-0.9%	0.0%	0.0%	0.0%	0.0%
Budapest	-1.8%	-2.1%	-1.9%	-0.8%	-0.2%	0.0%	0.0%	-2.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Prague	-1.6%	-2.0%	-1.7%	-0.8%	-0.7%	-0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Bratislava	-1.9%	-2.2%	-2.1%	-1.0%	-1.0%	0.0%	0.0%	-2.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Belgrade	-1.7%	-1.9%	-1.8%	-0.7%	-0.2%	0.0%	0.0%	-1.9%	-0.1%	0.0%	0.0%	0.0%	0.0%

one country to another, but also from one line to another. For example, the rail track cost in Switzerland is very high, especially when compared to France. In this 2nd sensitivity scenario, the same rail track cost, equal to 3.284 €/km, has been considered for the whole red area; this cost has been calculated as a weighted average of track costs of all lines in the red area.

Moreover, the electric energy cost (in €/km) is equal to the energy consumption (in kWh/km) multiplied by the price of electricity (in €/kWh); the energy cost also affects the monetary cost of a link. The electric energy consumption (in kWh/km) depends on the line geometry. However, the price of electricity is very different from one country to another. For example, it is 0.079 €/kWh in Slovenia and Hungary, 0.142 €/kWh in Italy, and 0.15 €/kWh in Germany. As a result, a line in Slovenia with worse geometrical characteristics may show a lower energy cost than a line in Germany or Italy with better geometrical characteristics. Therefore, a single electric energy price for the whole red area has been taken into account. The reference electricity price proposed in Baumgartner, which is equal to 0.1 €/kWh, has been considered.

As a result, in the 2nd sensitivity scenario, the cost of a link in €/km is different from one rail link to another only because of the quantities that depend on the geometrical characteristics of the link, the number of locomotives and the power consumption. Both these quantities depend only on the grade and curve resistances of each line section.

As far as the first sensitivity scenario is concerned, monetary costs of the 1st sensitivity scenario are compared with monetary costs of the current scenario. In Table 9, the differences, in percentage of monetary costs, between monetary costs of the first sensitivity scenario and monetary costs of the current scenario, are displayed. Only the comparison of monetary costs has been performed because, as stated at the beginning of this section, both sensitivity scenarios involve only changes in the calculation of monetary costs, and not of travel times.

As far as the second sensitivity scenario is concerned, monetary costs of the 2nd sensitivity scenario are compared with monetary costs of the current scenario. Differences, in percentage of monetary costs, between monetary costs of the 2nd sensitivity scenario and monetary costs of the current scenario, are displayed in Table 10.

The comparison between the 1st sensitivity scenario and the current scenario shows that the driver cost does not have a significant impact on the overall cost function. The maximum decrease in monetary costs, which occurs for O/D pairs where both the origin and the destination are located in Italy, is slightly above 3%. However, competition in freight transportation is very strong; the profit margins are low and the price is often the deciding factor on the market. Therefore,

Table 10: Differences, in percentage, of monetary costs, between monetary costs of the second sensitivity scenario and monetary costs of the current scenario (the current scenario is taken as reference).

	Leghorn	Genoa	La Spezia	Venice	Trieste	Koper	Rijeka	Marseilles	Le Havre	Antwerp	Rotterdam	Hamburg	Bremer-haven
Prato	-0.6%	-1.3%	-0.8%	-0.9%	-1.3%	0.6%	1.5%	3.4%	3.7%	-2.0%	-2.0%	-6.4%	-6.4%
Parma	-0.9%	-1.0%	-1.5%	-0.7%	-1.1%	0.8%	1.7%	4.0%	4.4%	-1.9%	-2.0%	-7.6%	-7.6%
Bologna	-0.8%	-1.1%	-0.9%	-0.5%	-1.0%	1.2%	2.2%	3.4%	4.0%	-1.9%	-2.0%	-6.5%	-6.5%
Milan Smistamento	-1.5%	-1.0%	-1.5%	-0.9%	-1.2%	0.6%	1.5%	4.2%	4.3%	-2.0%	-2.0%	-8.0%	-8.0%
Novara	-1.3%	-0.6%	-1.2%	-1.1%	-1.4%	0.4%	1.2%	4.5%	5.4%	-1.7%	-1.8%	-7.8%	-7.8%
Busto A. - Gallarate	-1.6%	-1.2%	-1.7%	-1.1%	-1.4%	0.3%	1.2%	3.8%	4.6%	-1.8%	-1.9%	-8.0%	-8.0%
Padua	-1.0%	-1.4%	-1.1%	-0.3%	-1.0%	1.6%	2.7%	2.9%	3.5%	-2.0%	-2.0%	-5.5%	-5.4%
Verona Q. E.	-0.9%	-1.3%	-0.9%	-0.5%	-1.0%	1.3%	2.3%	3.4%	3.8%	-2.0%	-2.0%	-5.7%	-5.6%
Turin	-1.3%	-0.7%	-1.2%	-1.2%	-1.4%	0.1%	0.9%	4.4%	11.1%	1.2%	0.9%	-7.5%	-7.5%
Vienna	-2.5%	-2.6%	-2.4%	-2.7%	-2.9%	3.9%	5.2%	0.2%	2.5%	-5.6%	-5.6%	-9.2%	-9.1%
Basel	-5.8%	-6.4%	-6.2%	-6.2%	-5.7%	-4.2%	-3.4%	10.8%	11.6%	3.1%	2.5%	-6.5%	-6.4%
Zurich	-5.0%	-5.5%	-5.4%	-5.4%	-5.0%	-3.4%	-2.6%	-0.2%	9.1%	1.2%	0.8%	-7.1%	-7.1%
Munich	-2.5%	-4.8%	-3.5%	-3.2%	-3.4%	-1.4%	2.0%	-1.0%	5.5%	-1.1%	-5.5%	-6.4%	-6.3%
Nuremberg	-3.4%	-7.6%	-7.3%	-4.1%	-4.3%	-2.6%	0.2%	2.6%	6.3%	-5.0%	-5.0%	-6.1%	-5.9%
Stuttgart	-6.8%	-7.4%	-7.2%	-7.1%	-4.6%	-3.0%	-0.4%	4.4%	8.9%	1.1%	-4.7%	-6.2%	-6.1%
Zagreb	4.9%	4.3%	4.5%	7.8%	9.9%	11.1%	8.2%	5.8%	4.8%	0.4%	-2.6%	-3.2%	-3.0%
Ljubljana	1.8%	1.3%	1.6%	3.8%	5.5%	7.2%	6.7%	3.9%	3.4%	-1.6%	-4.8%	-5.4%	-5.3%
Budapest	9.0%	8.4%	8.5%	12.4%	14.6%	15.3%	14.4%	8.8%	4.2%	-2.6%	-2.7%	-9.2%	-9.1%
Prague	-5.6%	-7.1%	-5.4%	-6.5%	-6.7%	-5.2%	-2.9%	-0.7%	1.8%	-6.5%	-6.8%	-7.4%	-7.4%
Bratislava	-3.3%	-3.4%	-3.2%	-3.8%	-4.0%	2.3%	3.4%	-0.5%	1.7%	-6.0%	-6.0%	-11.6%	-11.6%
Belgrade	9.1%	8.5%	8.7%	12.2%	14.1%	14.8%	13.4%	8.9%	6.4%	0.8%	0.7%	-4.7%	-4.7%

a decrease by 3% does not change the situation, but it may help rail freight companies in intermodal competition.

Comparing the 2nd sensitivity scenario with the current scenario (Table 10), it can be observed that the impact of different rail track costs and energy prices is significant; the changes of monetary costs are quite high. The maximum increase between 12 and 15%, from the current scenario to the 2nd sensitivity scenario, concerns the destination of Budapest and the origins of Trieste, Venice, Rijeka, and Koper. Both the rail track costs and energy prices in Slovenia, Croatia, and Hungary are far lower than the European average; the rail track cost in Slovenia is 1.9 €/km, in Croatia 1.59 €/km, and in Hungary 1.54 €/km, while the European average rail track cost (taken into account in the 2nd sensitivity scenario) is 3.3 €/km; the energy price in Slovenia and Hungary is 0.079 €/kWh and in Croatia 0.09 €/kWh, while the European average energy price taken into account in the 2nd sensitivity scenario is 0.1 €/kWh.

Another relevant increase in monetary costs from the current scenario to the 2nd sensitivity scenario concerns the origin port of Le Havre and the destinations of Turin and Basel, because the rail track costs in France are far below the average values; the average rail track cost in France is about 1.96 €/km while the European average rail track cost is 3.3 €/km; the energy price in France is 0.09 €/kWh, which is almost equal to the European average (reference).

The highest decreases of monetary costs occur for the origin ports of Hamburg and Bremerhaven and the destination Bratislava; the two paths between these O/D pairs cross Germany, Czech Republic, and a small part of Slovakia, which shows high track costs and energy prices in the current scenario. It is true that the track cost in Germany is 2.646 €/km, which is below the European average. In Czech Republic, the same cost is very high (6.55 €/km, the average track cost is 3.3 €/km) and, in Slovakia, it is even higher (9.24 €/km). On the other hand, the electric energy price in Germany is 0.15 €/kWh, far above the average value, while in Czech Republic it is 0.079 €/kWh and in Slovakia 0.11 €/kWh. Apart from Czech Republic, also the electricity price is above the average one.

In Table 11, the Alpine pass crossings in the 2nd sensitivity scenario for each O/D pair are compared with the current situation. The comparison involves both optimisations by monetary costs and by generalised costs. Indeed, in Section 5 it was shown that sometimes the best path according to monetary costs crosses a different pass from the best path according to generalised costs. The choices of Alpine passes according to the optimisation by travel times are not reported in Table 11, because they are the same in the current scenario

Table 11: Railway lines crossing the Alps used to connect the considered O/D pairs. The 2nd sensitivity scenario (called in the table briefly "2nd scenario") is compared with the current one. Only O/D pairs which require the crossing of Alpine passes have been taken into account.

Origin	Destination	Pass – optimization by monetary costs		Pass – optimization by generalized costs	
		Current scenario	2nd scenario	Current scenario	2nd scenario
Leghorn	Vienna	Tarvisio – Semmering	Tarvisio – Semmering	Tarvisio – Semmering	Tarvisio – Semmering
Leghorn	Basel	Luino – Gotthard	Luino – Gotthard	Luino - Gotthard	Luino - Gotthard
Leghorn	Zurich	Luino – Gotthard	Luino – Gotthard	Luino - Gotthard	Luino - Gotthard
Leghorn	Munich	Brenner	Brenner	Brenner	Brenner
Leghorn	Nuremberg	Brenner	Brenner	Brenner	Brenner
Leghorn	Stuttgart	Luino – Gotthard	Luino – Gotthard	Luino - Gotthard	Luino - Gotthard
Leghorn	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Leghorn	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina	Villa Opicina
Leghorn	Budapest	Villa Opicina – Ormoz	Villa Opicina – Ormoz	Tarvisio – Semmering	Tarvisio – Semmering
Leghorn	Prague	Tarvisio – Tauern	Tarvisio – Tauern	Tarvisio – Tauern	Tarvisio –Tauern
Leghorn	Bratislava	Tarvisio – Semmering	Tarvisio – Semmering	Tarvisio – Semmering	Tarvisio – Semmering
Leghorn	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Genoa	Vienna	Tarvisio – Semmering	Tarvisio – Semmering	Tarvisio – Semmering	Tarvisio – Semmering
Genoa	Basel	Luino – Gotthard	Luino – Gotthard	Luino – Gotthard	Luino – Gotthard
Genoa	Zurich	Luino - Gotthard	Luino - Gotthard	Luino - Gotthard	Luino - Gotthard
Genoa	Munich	Brenner	Luino - Gotthard	Brenner	Luino - Gotthard
Genoa	Nuremberg	Luino – Gotthard	Luino – Gotthard	Luino – Gotthard	Luino – Gotthard
Genoa	Stuttgart	Luino – Gotthard	Luino – Gotthard	Luino – Gotthard	Luino – Gotthard
Genoa	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Genoa	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina	Villa Opicina
Genoa	Budapest	Villa Opicina – Ormoz	Villa Opicina – Ormoz	Tarvisio – Semmering	Tarvisio – Semmering
Genoa	Prague	Brenner	Luino – Gotthard – St. Gallen	Brenner	Luino – Gotthard – St. Gallen
Genoa	Bratislava	Tarvisio - Semmering	Tarvisio – Semmering	Tarvisio - Semmering	Tarvisio – Semmering
Genoa	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
La Spezia	Vienna	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering
La Spezia	Basel	Luino - Gotthard	Luino - Gotthard	Luino - Gotthard	Luino - Gotthard
La Spezia	Zurich	Luino - Gotthard	Luino - Gotthard	Luino - Gotthard	Luino - Gotthard
La Spezia	Munich	Brenner	Luino - Gotthard	Brenner	Luino - Gotthard
La Spezia	Nuremberg	Luino – Gotthard	Luino - Gotthard	Luino – Gotthard	Luino - Gotthard
La Spezia	Stuttgart	Luino - Gotthard	Luino - Gotthard	Luino - Gotthard	Luino - Gotthard
La Spezia	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
La Spezia	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina	Villa Opicina
La Spezia	Budapest	Villa Opicina – Ormoz	Villa Opicina – Ormoz	Tarvisio – Semmering	Tarvisio – Semmering
La Spezia	Prague	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern
La Spezia	Bratislava	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering
La Spezia	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Venice	Vienna	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering
Venice	Basel	Chiasso - Gotthard	Chiasso - Gotthard	Chiasso - Gotthard	Chiasso - Gotthard
Venice	Zurich	Chiasso - Gotthard	Chiasso - Gotthard	Chiasso - Gotthard	Chiasso - Gotthard

Table 11: Continued.

Origin	Destination	Pass – optimization by monetary costs		Pass – optimization by generalized costs	
		Current scenario	2nd scenario	Current scenario	2nd scenario
Venice	Munich	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio – Tauern
Venice	Nuremberg	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio – Tauern
Venice	Stuttgart	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Venice	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Venice	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina	Villa Opicina
Venice	Budapest	Villa Opicina – Ormoz	Villa Opicina – Ormoz	Tarvisio – Semmering	Tarvisio – Semmering
Venice	Prague	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Venice	Bratislava	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering
Venice	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Trieste	Vienna	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering
Trieste	Basel	Chiasso - Gotthard	Chiasso - Gotthard	Chiasso - Gotthard	Chiasso - Gotthard
Trieste	Zurich	Chiasso - Gotthard	Chiasso - Gotthard	Chiasso - Gotthard	Chiasso - Gotthard
Trieste	Munich	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Trieste	Nuremberg	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Trieste	Stuttgart	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Trieste	Zagreb	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Trieste	Ljubljana	Villa Opicina	Villa Opicina	Villa Opicina	Villa Opicina
Trieste	Budapest	Villa Opicina – Ormoz	Villa Opicina – Ormoz	Villa Opicina – Ormoz	Villa Opicina – Ormoz
Trieste	Prague	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern	Tarvisio - Tauern
Trieste	Bratislava	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering	Tarvisio - Semmering
Trieste	Belgrade	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova	Villa Opicina – Dobova
Rotterdam	Prato	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Parma	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Bologna	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Rotterdam	Busto A. - Gallarate	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese
Rotterdam	Padua	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Verona Q.E	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Rotterdam	Turin	Frejus	Sempione - Loetschberg	Frejus	Sempione - Loetschberg
Antwerp	Prato	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Parma	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Bologna	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Antwerp	Busto A. - Gallarate	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese
Antwerp	Padua	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso

Table 11: Continued.

Origin	Destination	Pass – optimization by monetary costs		Pass – optimization by generalized costs	
		Current scenario	2nd scenario	Current scenario	2nd scenario
Antwerp	Verona Q.E	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Antwerp	Turin	Frejus	Sempione - Loetschberg	Frejus	Sempione - Loetschberg
Hamburg	Prato	Brenner	Gotthard- Chiasso	Brenner	Gotthard- Chiasso
Hamburg	Parma	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Hamburg	Bologna	Brenner	Gotthard- Chiasso	Brenner	Gotthard- Chiasso
Hamburg	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Hamburg	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Hamburg	Busto A. - Gallarate	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese
Hamburg	Padua	Brenner	Brenner	Brenner	Brenner
Hamburg	Verona Q.E	Brenner	Brenner	Brenner	Brenner
Hamburg	Turin	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Bremerhaven	Prato	Brenner	Gotthard- Chiasso	Brenner	Gotthard- Chiasso
Bremerhaven	Parma	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Bremerhaven	Bologna	Brenner	Gotthard- Chiasso	Brenner	Gotthard- Chiasso
Bremerhaven	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Bremerhaven	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Bremerhaven	Busto A. - Gallarate	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese
Bremerhaven	Padua	Brenner	Brenner	Brenner	Brenner
Bremerhaven	Verona Q.E	Brenner	Brenner	Brenner	Brenner
Bremerhaven	Turin	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Le Havre	Prato	Frejus	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Le Havre	Parma	Frejus	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Le Havre	Bologna	Frejus	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Le Havre	Milan Segrate / Smistamento	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Le Havre	Novara	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg	Sempione - Loetschberg
Le Havre	Busto A. - Gallarate	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese	Gotthard - Varese
Le Havre	Padua	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Le Havre	Verona Q.E	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso	Gotthard- Chiasso
Le Havre	Turin	Frejus	Frejus	Frejus	Frejus
Marseilles	All Italian destinations	Ventimiglia	Ventimiglia	Ventimiglia	Ventimiglia
Rijeka	All Italian destinations	Villa Opicina (Ilirska Bistrica)	Villa Opicina (Ilirska Bistrica)	Villa Opicina (Illirska Bistrica)	Villa Opicina (Ilirska Bistrica)
Rijeka	Vienna	Maribor - Semmering	Maribor - Semmering	Maribor - Semmering	Maribor - Semmering
Rijeka	Basel	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard
Rijeka	Zurich	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard
Rijeka	Munich	Karavanke - Tauern	Karavanke - Tauern	Karavanke - Tauern	Karavanke - Tauern

Table 11: Continued.

Origin	Destination	Pass – optimization by monetary costs		Pass – optimization by generalized costs	
		Current scenario	2^{nd} scenario	Current scenario	2^{nd} scenario
Rijeka	Nuremberg	Karavanke - Tauern	Karavanke - Tauern	Karavanke - Tauern	Karavanke - Tauern
Rijeka	Stuttgart	Karavanke - Tauern	Karavanke - Tauern	Karavanke - Tauern	Karavanke - Tauern
Koper	All Italian destinations	Villa Opicina (Presnica)	Villa Opicina (Presnica)	Villa Opicina (Presnica)	Villa Opicina (Presnica)
Koper	Vienna	Maribor - Semmering	Villa Opicina – Tarvisio – Semmering	Villa Opicina – Tarvisio – Semmering	Villa Opicina – Tarvisio – Semmering
Koper	Basel	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard
Koper	Zurich	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard	Villa Opicina - Gotthard
Koper	Munich	Karavanke - Tauern	Villa Opicina – Tarvisio – Tauern	Villa Opicina – Tarvisio – Tauern	Villa Opicina – Tarvisio – Tauern
Koper	Nuremberg	Karavanke - Tauern	Villa Opicina – Tarvisio – Tauern	Villa Opicina – Tarvisio – Tauern	Villa Opicina – Tarvisio – Tauern
Koper	Stuttgart	Karavanke - Tauern	Villa Opicina – Tarvisio – Tauern	Villa Opicina – Tarvisio – Tauern	Villa Opicina – Tarvisio – Tauern

and in the 2^{nd} sensitivity scenario. The methodology for the calculation of link travel times was not changed.

In Table 11, it is clearly shown that the lines passing through Switzerland are chosen more frequently, especially for the origin port of Genoa in the 2^{nd} sensitivity scenario. Indeed, the cost of rail track of Swiss lines is very high, far above the European average. The usage of the Brenner line and, in particular, the Frejus line, decreases significantly. The Frejus line in the 2^{nd} sensitivity scenario is used only for the origin port of Le Havre and the destination of Turin; instead of the Frejus line, the lines through Switzerland are chosen, especially the Gotthard and the Sempione–Loetschberg ones.

Other differences between the current scenario and the 2^{nd} sensitivity concern the origin port of Koper and destinations in Austria and southern Germany. In the current scenario, for the destinations Munich, Nuremberg, and Stuttgart, the path across Ljubljana and Karavanke is chosen, while in the 2^{nd} sensitivity scenario the path across Villa Opicina and Tarvisio is the best one. In the current scenario, the path across Ljubljana, Maribor, and Semmering is chosen for the destination of Vienna, while in the 2^{nd} sensitivity scenario, the path across Villa Opicina, Tarvisio, and Semmering lines is chosen. This occurs because the electricity price is much higher in Italy than in Slovenia (in Italy it is 0.142 €/kWh while in Slovenia it is 0.079 €/kWh). Therefore, if the same energy price of 0.1 €/kWh is taken, the lines across Italy see a reduction in their monetary cost, while the lines through Slovenia see an increase in monetary cost. In addition, the track cost is higher in Italy than in Slovenia: 2.3 €/km against 1.9 €/km; therefore, in the 2^{nd} sensitivity scenario the track cost of Italian lines increases less than the track cost of Slovenian lines. The lines through Slovenia show greater grade and curve resistances than the line across Tarvisio, which has been renewed completely in two steps in 1995 and 2000.

In brief, taking a single value of rail track costs and electric energy prices for the whole red area has shown which would be the most chosen lines because of their geographical position and performance. The line across Gotthard, and in particular its branches through Chiasso and Luino, is the most important line for connections between Italian and northern European terminals. This line has a favourable position as it is on the way to the ports of Antwerp, Rotterdam, Hamburg, Bremerhaven, and Le Havre. Most importantly, it also shows good geometrical characteristics. The new Gotthard Base tunnel has been constructed with low slopes; therefore, double traction is necessary only for a small portion of the line across the Ceneri Pass where a new base tunnel is currently under construction. On the other hand, the Brenner line requires double traction and, partially, triple traction, while in the Frejus line trains are operated with three locomotives. The construction of the new Brenner and Frejus base tunnels would increase the choice of these lines: the Brenner line is crucial for Italian economy because Germany is Italy's top trading partner. As far as Central-Eastern European lines are concerned, the most used line crosses the Tarvisio pass because it shows better geometrical characteristics than the path across Ljubljana and Ormoz and the line of Karavanke. The Tarvisio line will further increase its importance when the new Semmering base tunnel, which is currently under construction, will be opened because it is a part of an alternative path to the one across Ljubljana and Ormoz.

7. Conclusions

In this paper, the potential hinterland (competition margin) of the new container terminal of the port of Leghorn was analysed. The study also analyses the competitiveness of major Mediterranean and northern European ports to serve some of the most contestable regions in Europe, which include Switzerland, southern Germany, Austria, the Padan

Plain in Italy, and some other important destinations in Central-Eastern European countries.

The optimal rail paths from the origin ports to the destination cities have been determined. The rail network of a large part of Europe has been modelled through a graph. For the computation of the monetary costs of rail links, only a few cost functions exist in literature and, generally, are not very detailed. Therefore, in this paper, a new cost function for rail transport has been developed. The new cost function takes into account: staff cost; amortisation, maintenance, and insurance costs of locomotives and wagons; rail track usage cost; and traction cost. All these costs have been calculated in detail for each line. In particular, the traction cost has been determined precisely from all the resistances to motion. In order to calculate these resistances, in particular the grade and curve resistances, and the number of locomotives necessary to operate the train, detailed information on the geometry of each rail line has been collected, with special concern for the lines crossing the Alps (for which the operation rules used by the rail transport companies have been assumed).

The monetary value of time in freight transport registers high variability; therefore, three different optimisations of the paths between each O/D pair have been carried out. These include generalised cost, travel time, and monetary cost optimisations. The comparison of the optimisation results has shown that the differences in monetary costs, travel times, and generalised costs obtained from the three optimisations are not relevant—the most marked differences concern the destination of Budapest and the optimisations based on travel times and monetary costs, because each optimisation is given a completely different path.

Moreover, the railway lines crossing Alpine passes used to connect each O/D pair have been determined. This analysis has pointed out that the most used lines are the Gotthard line, the Brenner line, and the lines across Tarvisio, Semmering, and Tauern passes. In addition, the path across Villa Opicina and Ljubljana is used for several Central-Eastern European destinations.

A sensitivity analysis was performed on parameters that influence the monetary cost of a link, namely: staff cost, rail track cost, and price of electric energy.

The first sensitivity analysis aimed at understanding the importance of the staff cost has shown that this quantity does not influence the monetary costs of the O/D paths significantly.

The second sensitivity analysis has shown that the rail track cost and the electric energy price heavily influence the overall monetary costs of the O/D paths. The Swiss lines, which register a high rail track cost (5.2 €/km), much higher than the European average (3.3 €/km), would be used to connect a greater number of O/D pairs if the same rail track cost was taken for entire Europe. In addition, the Tarvisio line would be used to connect a greater number of O/D pairs if the same energy price for the whole Europe was considered. The electric energy price in Italy (0.142 €/kWh) is much higher than the average European price (0.1 €/kWh), which was taken into account in the 2nd sensitivity analysis.

In general, the most favourable rail lines across Alpine passes, because of their geographical position and of their geometric characteristics (reduced slopes), are the Gotthard line for Central-Southern European destinations and the Tarvisio line for Central-Eastern Europe. The Brenner line is also in a very favourable position. However, it still has disadvantages in terms of geometric characteristics, as double (on the Italian side) and triple (on the Austrian side) traction are required. This could be mitigated by the new base tunnel that is coming up on the Brenner line.

As far as the competitiveness of the port of Leghorn is concerned, after the construction of the new container terminal, the following has resulted from the analysis performed in this paper.

The port of Leghorn will become competitive beyond its fundamental hinterland (some regions of Central Italy), not only for north-eastern Italian destinations but also for some Central-Southern and Central-Eastern European ones.

In regard to north-eastern Italy, the research has shown that Leghorn has good possibilities to attract into its hinterland Verona and other destinations on the Brenner rail axis, and particularly the German city of Munich. Indeed, for these destinations, Trieste and Venice are in a more favourable position as far as the landside is concerned; however, the Ligurian ports are crossed regularly by DSS direct services to/from Far East, while Adriatic ports are mainly crossed by feeder routes. Among the Ligurian ports, Leghorn is in the best position. Moreover, the geographic position of Leghorn, and of the other Ligurian ports, is certainly favourable to the connections to/from the Americas. In any case, Munich (Figures 6–8) is one of the most contestable destinations in Europe (practically from almost all ports considered in the research).

It is important to notice that northern Adriatic ports, based on the results of Figures 6–11, are in a very good position on the land side to serve several destinations in Central-Southern and Central-Eastern Europe once they will open up to direct DSS routes to the Far East.

Leghorn also has the possibility of attracting into its hinterland some regions of Central-Eastern Europe. For all these regions, the most favourable unloading/loading ports are clearly the northern Adriatic ones. However, based on the results of the research, Leghorn can be competitive, especially for routes to/from the Americas.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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