Network Routing Applied to Intermodal Transportation

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ABSTRACT: The concept of Intermodality has had a great impact in most of the existent transportation chains worldwide, by addressing the problem of mode selection: selecting the best mode of transportation when more than one can be used, allowing a better integrated connection between all available resources for transportation. The use of different available resources such as railways, inland waterways and sea routes has an enormous potential to decrease the use of road haulages in cargo transportation, reducing traffic and emissions per cargo handled as well as increasing economy of scale and reducing costs. In this thesis, a numerical algorithm was developed in order to identify possible routes between a pair origin/destination in an intermodal transportation network by using the “Shortest Path Problem”, allowing the tracking of optimum paths between two nodes in terms of distance, transportation time, total transportation time and distance. To validate the numerical model and show the practical applications that the algorithm is capable of, it was applied in an intermodal transportation network which comprises a series of European countries and the north of Morocco, as well as including Portuguese, Spanish and Italian Islands. Different case studies were performed along some strategical cities embraced by the network, making it possible to draw conclusions concerning the use of intermodal transportation when compared to road-only transportation: the combination of modes is usually more cost effective, specially concerning longer distances. Nevertheless, it is important to point that the obtained optimum paths in terms of time were, in many cases, constituted by road legs, which means that optimizations in intermodal terminals infrastructures are to be performed in order to increase their competitivity. The algorithm is, therefore, an useful tool for cargo carriers, city councils and governments by pointing out alternative routes and determining whether a city terminal has a potential to grow should more investments are made.

1. INTRODUCTION

The movement of goods has been an important concern since ancient history, when cities started to develop and realize that they could acquire goods produced in other cities where natural resources, climate and even different human skills allowed the production of important different goods that are eventually necessary for the population. Historians believe that the first long-distance trade occurred around 3000 BC, when high value-added goods like spices and precious metals were traded between Mesopotamia (located in the middle east region) and the Indus Valley in Pakistan, going through a distance of more less 3000 km. With the advance of civilization, the network of trades started to grow more and more complex, leading to a use of more than one transportation mode to carry a good from one point to another. However, the lack of unitization between cargoes was a serious problem when shifting boxes, barrels and bags from a modal to another, being a slow, laborious and extremely inefficient process that was only changed by the mid-1950s, when the concept of modern containerization started to be introduced, and so, the idea of intermodality.

The intermodal transport, according to Bontekoning and Macharis [1], is defined as the combination of at least two modes of transportation in a single transport chain and under the same freight contract, without change of container for the goods when changing the mode of transportation. The containerization has already taken part in the transportation history as a great revolution, as most of the general cargo transported today moving between continents is allocated in containers and the percentage of other types of cargo are increasing steadily. Intermodality addresses the problem of selecting the best mode of transportation when more than one mode can be utilized, dealing also with the capacity of transferring the cargo from one mode to another. The wrong choice of transportation modes may greatly affect the total cost of transportation, implying in a high freight rate and reducing the competitivity of the carrier. This shows the importance of methods to select the best routes: the vast and complex network created by the idea of Intermodality started to require more sophisticated optimization methods that started to be better developed in the middle of the 20th century.

The most common method of network route planning is defined by the Shortest Path Problem (SPP), which is widely used in transportation problems as it allows the detection of an optimum path between two nodes in a graph (set of connected objects). Various types of algorithms related to the SPP have been developed, with more than 2000 scientific works being published by the end of the 1950's (Pallottino and Scutellà (1991) [2]), the most famous of those being the Dijkstra's method, the Bellman-ford's method and the Dantzig's method.

The methods aforementioned were studied and used as a basis to develop a code in a Fortran-based programming language that is capable of identifying optimum routes across an European intermodal transportation network, where initiatives have been launched to promote the use of Intermodality by the Combined Transport Directive or CT (Council Directive 92/106/EEC). This directive is promoted within the European Union (EU) and its goal is to stimulate combined transport operations in response to the growth of road freight transportation, which is projected to increase by around 40% by 2030 and has been taking part of more than 75% of the total inland freight transport in Europe since 2015 (Figure 1 - Modal split of inland freight transport in Europe between 2012 and 2017. Source: Eurostat). The CT directive, therefore, aims at cutting down road transportation towards less polluting and more efficient modes of transportation, by proposing a series of measures that should be followed by the EU, such as a further internalisation of external costs, ensuring a higher competitiveness of other modes in relation to the road transport.

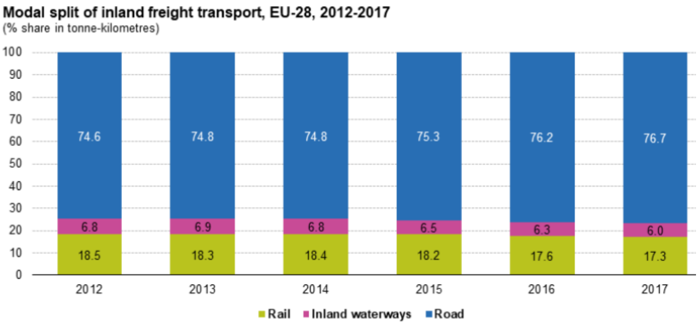


Figure 1 - Modal split of inland freight transport in Europe between 2012 and 2017. Source: Eurostat

2. LITERATURE REVIEW

Transport, undoubtedly, has negative consequences in the whole world in terms of pollution, congestion, climate change, noise and accidents. These externalities of transport create cost for society estimated at around 4% of the total European Union GDP and are mainly caused by the road sector, which dominates the freight transport in the EU [3].This topic will discuss measures taken by governments, in special the European Union, in order to encourage the use of combined transportation. Furthermore, theoretical methods for the analysis of transportation network chains will be discussed, as well as the methods used for network routing.

2.1. Intermodal Freight Transportation in Europe

In 1993, the European Conference of Ministers of Transport defined intermodal transportation as "the movement of goods in one and the same loading unit or vehicle, which uses successive, various modes of transportation (road, rail, water) without any handling of the goods themselves during transfers between modes". This definition is, nonetheless, too restrictive, as goods might be transported by using various combinations of transport and still handle the freight in the connection between the modes (Crainic and Kim (2005) [4]). Therefore, the definition of intermodality that better fits nowadays is the transportation of freight (or people) from their origin to their destination by a sequence of at least two transportation modes (Bektas and Crainic (2007) [5]).

In an initiative that aims the reduction of negative impacts of road freight transport, the European Union created in 1992 the Combined Transport Directive (Council Directive 92/106/EEC), which aims the better use of more environment friendly modes of transportation (maritime, inland waterways, rail etc) in the carriage of cargo, reducing the participation of road transportation and internalising the external costs.

Another initiative with great impact in the boosting of intermodality in the EU is the Marco Polo Programme, which was proposed in 2003 following the 2001 White Paper on Transport to support intermodal freight transport initiatives and alternatives to road only transport in the early stages of implementation until they become commercially viable by providing grants. The Programme had a second version, the Marco Polo II 2007-2013, with a larger budget and with new actions to promote the shift to other modes of transportation, such as the motorway of the seas (MoS), an initiative that aims to shift freight from long road distances to a combination of short sea shipping (SSS) and other modes of transport; and traffic avoidance measures, aiming to integrate transport into production logistics, leading to a reduced demand by road with a direct impact on emissions. The last Marco Polo II call of the 2007-2013 financial period deemed eligible 27 projects to receive EU support for five distinct types of actions: modal shift, catalyst actions, common learning actions, traffic avoidance and motorway of the seas. The support varied form a maximum of €4.2 million to a minimum of around €280,000 for projects aiming to these actions: the development of a motorway of the seas between the Spanish port of Vigo and the French port of Nantes - St. Nazaire, for example, received over €3 million in order to develop the infrastructure capacity and upgrade the interface between terminals and hinterland connections.

Apart from the Marco Polo Programme, the European Commission also established the Trans-European Transport Network (TEN-T) to foment the development and construction of transport infrastructure across the European Union, creating an executive agency in 2006 to provide support for the completion of the TEN-T network, guaranteeing the execution of the TEN-T budget and financial management of projects under the programme from start to finish. Its projects offer prime examples of how EU co-funding positively contributes to mobility by improving transport infrastructure in an area or region, in addition to providing well economic and social advantages. Since its conception, the TEN-T programme has benefitted a series of EU Member States regarding all modes of transport – air, sea, inland waterway, rail, and road, besides logistics and intelligent transport systems.

One of the main projects regarding the connection of transportation modes by TEN-T are is the Atlantic Corridor, which has an important strategic goal to increase modal integration in Europe mainly in terms of exploiting maritime connectivity and railway interoperability. The Atlantic Corridor’s project list for 2017 included more than 250 projects with an investment of €43.6 billion, where rail investments represented about more than half of the budget. Furthermore, the project list includes a further 63 projects that correspond to branches connected to the Atlantic Corridor with relevant influence for the it. Their implementation, besides expected to lead an increase of GDP in the EU member states, also does well when comparing CO_2 emissions, being expected to decrease in about 30% due to the reduction of road transportation [3].

To see the importance of the shift of road transportation to other lower-emission modes, Wagener (2014) [6] takes the example of the "Rail Baltica", a greenfield rail transport infrastructure project with a goal to integrate the Baltic States in the European rail network, connecting Tallinn, Riga, Kaunas and the North-Eastern Poland. A model calculation shows that the transportation of one container via the combination of railways and trucks would require almost the same transit time as in pure road transport, however it would reduce in about 56% the CO_2 emission (Wagener, 2014) [6].

2.2. Transport Network Models

In a vast transportation infrastructure, it is necessary to represent the agents involved in the transportation chain in some formal, simple but sufficiently detailed way (Bell and Lida [7]). In many of the operations research literature (Hillier and Lieberman [8], Arenales and Armentano, Bazara et al [9]), the problem to describe the network topology is approached by using a special structure named graph, represented by a set of links and a set of nodes.

A transport network described by a graph is represented by a set of links and a set of nodes (Figure 2). Links, in an intermodal transportation problem, represent some process reality, as for instance physical trafficways such as highways, railways, waterways etc; whereas the nodes represent the terminals in which the shipment is allocated or the distribution centre facility.

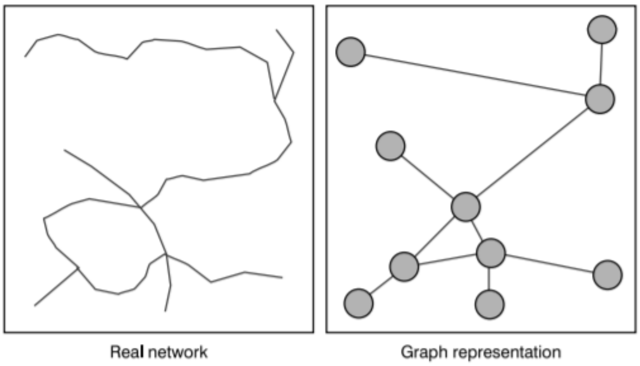


Figure 2 - Graph representation of a transportation network.

The construction of an intermodal network database involves the merging of mode-specific transportation networks into a single, integrated multimodal network that is able to provide single and intermodal routing between a pair a nodes. Southwork and Peterson (2000) [10] provided a study in the development and construction of an intermodal transportation network as part of the US Commodity Flow Survey (CFS), showing also the needs of adjustment of the various network parameter settings in order to accommodate specific route selections where empirical data suggested its feasibility. This is a common issue when merging networks: previously, a study of Southwork et al. (1997) [11] showed that a transportation network represented within a GIS database may not be useful for traffic routing analysis as separate modal networks must be integrated in order to form a single database, with the need of appropriate representation of intermodal transfer terminals and intra-modal carrier transfer.

In the US, Capineri and Leinbach (2006) [12] pointed that accessibility gap between central and peripherical regions has been reduced with the advance of intermodals, however, no further studies had been made in the ability of regions to position themselves more effectively in the economy in a national and global basis. This changed when Lim and Thill started to develop researches in this field. The impact of an intermodal network in the accessibility measures of a region have been assessed by Thill and Lim (2010) [13] in the US, by the use of a GIS, different modes of transportation were modelled and integrated allowing the observation of the need to develop better connections to container ports in order to decrease the gap of accessibility among different regions.

Researches on the competitiveness of the intermodal transportation have also been made in the past few years. Lupi et al (2016) [14] assess the monetary costs and travel times of intermodal transport based on MoS and road only transport connecting Italy's mainland with Sicily. With the intermodal network model, it was stated that unaccompanied intermodal transport (in which only the loading units are carried) provided lower costs for a great majority of origin/destination pairs (considering also generalized costs) but registering higher travel times than all-road transport. Furthermore, it allowed the observation of a need for improvement on the Italian Adriatic side, since trucking companies also deemed important several other parameters apart from costs and time, such as reliability, frequency and availability. Santos et al (2019) [15] develops a numerical model for the calculation of costs and transit times over complex networks of transportation that is capable of evaluating the competitiveness of different transport solutions in Europe (*Intermodal Analyst*). The study applied on routes connecting the north of Portugal and Northern France showed that chain using SSS presented cost and time competitive results depending on the type of ship used, as well as showing that the consideration of generalized costs might affect greatly the transport solutions.

Accounting external costs presented an important role in the study of the competitiveness of intermodal transportation, as non-monetary costs might have a considerable participation. Pekin and Macharis (2013) [16] analysed the impact of Value of Time (VOT) in a location analysis model for intermodal terminals (LAMBIT) in Belgium, showing that the VOT impacts in the importance of the type of good to be transported. High value-added goods are usually transported by road while low value added goods are transported via rail or even barge, consisting in a better market for intermodal transportation.

2.3. Optimization Methods in Transportation Networks

One of the most important challenges when considering a complex network is to find the optimal route between a set of points in terms of cost, time and also some other parameters. One of the most imperative optimization problems is the Shortest Path Problem (SPP), which started to be further developed in the mid 1950's, with more than 2000 articles being written in that period. It consists in finding a path between two nodes in a weighted graph so that the sum of the arc's weights is minimized. The SPP is one of the most important topics in linear programming (Hillier and Lieberman [8]).

The applications of the SPP are related to the optimization of several activities in different fields of knowledge, for instance in power transmission lines, network connections routing, planning of movements of a robot and even molecular biology (Eppstein (1994) [17]). In transportation, Glover et al. (1985) [18] mentions that SPP algorithms have already solved many practical applications, such as the planning of routes and travel times, planning of capacity and expansion of transport networks. They also quote some linear programming problems that were solved with the SPP criteria, such as the travelling salesman problem.

The first studies started to be developed in the 1950's, with the idea of finding an alternative route when a path is blocked. Trueblood (1952) [19] was one of the pioneers by developing an algorithm to find best routes in a freeway when some kind of blockage occurred, with possible applications also in telephone calls routing. From 1946 to 1953 some studies on developing matrices methods to determine the shortest path have been performed mainly by Landahl and Rounge (1946) [20], Luce and Perry (1949) [21] and Shimbel (1951) [22]. However, the methods proposed were not directed to transportation networks but to applications in communication nets, neural networks and animal sociology. Further research on SPP algorithms that could be implemented in transportation networks started to be developed after 1955. The main SPP algorithms to find an optimum between a pair of nodes in graphs with non-negative weights were developed by Leyzoreck et al. (1957) [23] and Dijkstra (1959) [24], who developed an efficient algorithm for the SPP. Shimbel (1955) [22], Bellman (1958) [25] and Moore (1959) [26] started the development of algorithms with arbitrary weights for the links in a graph (including negative weights).

Nowadays, there is a great amount of algorithms to solve find the shortest path in a network, however, as Dreyfus (1969) [27] states, many algorithms might have been omitted or unknown due to the intense search of algorithms by many researchers. He also advises a serious and detailed search when choosing SPP algorithms, as due to the great quantity of algorithms that exists in the literature, some of them do not have their efficiency verified and might even have errors.

3. NETWORK ROUTING

With main applications in computer science, telecommunications and transportation, routing consists in finding a path between two points in a network. In a routing protocol (RP), often a routing table is created, containing information regarding the possible paths and its weights. Regarding the way data is filled into them, routing is divided into static and dynamic routing protocols. In spite of the fact that these definitions are often used in computer science, the applications for transportation networks are equally the same.

Link State Routing is a dynamic routing protocol which finds the shortest path in a network by using a complete and global knowledge about the network, hence being often called as a global routing algorithm. The algorithm requires as an input the connectivity between all the nodes and all link's weights (cost, distance, time etc), therefore the user must know the entire network topology in order to perform the calculations. In reality, this is achieved by having each node broadcast the identities and weights of the links attached to them, in a Link State Broadcast. This link state broadcast can be accomplished without the nodes having to initially know the identities of all other nodes in the network: for the algorithm to work, a node only needs to know the identities and costs to its directly attached neighbors, and it will then learn about the topology of the rest of the network by receiving information from other nodes.

3.1. Dijkstra's Algorithm

In 1959, a Dutch computer scientist named Edsger W. Dijkstra presented a new method to find shortest paths in oriented or non-oriented graphs in his article "A Note on Two Problems in Connection with Graphs", giving thus origin to Dijkstra's Algorithm. Dijkstra's algorithm finds the shortest path from a source node to any of the other nodes in the network, given they are non-negative. The algorithm works based in a labeling method and keeps the labeled weight $D(v)$ for each node *v* and contains the upper limit of the shortest path to node *v*. The algorithm divides the nodes in two groups: permanently (PL) and temporarily (TL) labeled. The labeled weight of PL nodes represents the shortest distance from the source node *o* to node *v*, whereas the labeled weight of TL nodes represents the upper limit of the weight of the shortest distance to the node *v*. This way, the algorithm verifies all the nodes in the network and permanently labels them, assuring the determination of the shortest path in the network.

The algorithm starts after the initialization of some initial conditions: setting the labeled weight of the source node to zero and all others to infinite; setting the value of 1 to the process parameter to permanently label the source *o* and zero to all others; set the current node *u* for iteration to origin node.

$$\begin{cases} D(o) = 0 & , \quad o \in G \\ D(i) = \infty & \forall \quad i \in G \end{cases}$$

$$\begin{cases} S(o) = 1 & , \quad o \in G \\ S(i) = 0 & \forall \quad i \in G \end{cases}$$

$$u = o$$

In each iteration, the algorithm sweeps all possible nodes attached to it and performs an operation of shortest labeled weight selection, which verifies the labeled weights of current node *u* of the iteration and its *v* neighboring nodes that satisfy the following condition: if the sum of the link's weight from current node *u* to visited node *v* ($c(u,v)$) plus the labeled weight of u ($D(u)$) is smaller than the labeled weight of *v* ($D(v)$), $D(v)$ is updated by this new sum and the previous parameter $p(v)$ takes the value of the current node, allowing the creation of the path after the algorithm's performance conclusion.

$$\begin{aligned} & if \quad \{D(u) + c(u,v) < D(v)\} \ then \\ & \quad D(v) = D(u) + c(u,v) \\ & \quad p(v) = u \end{aligned}$$

The algorithm then performs a new loop, but this time sweeping the nodes that have not yet been permanently labeled. The selection of the minimum labeled weight of node i represents the shortest path from the source node to destination *t* containing the intermediate nodes. The algorithm then chooses the node $i \in A(i)$, where $A(i)$ is the adjacent list of the nodes *j* that are adjacent to *i*, whose temporary labeled weight is the smallest one and then sets it as permanently labeled. The algorithm then ends when *i* is the destination node and all nodes have been processed (permanently labeled). The mathematical formulation for this loop is:

$$\begin{aligned} & if \quad \{D(v) < SD\} \ then \\ & \quad SD = D(v) \\ & \quad u = v \end{aligned}$$

After the search for the node whose labelled weight represents the smallest temporary distance (SD, set as infinite at the beginning of every iteration) to node *u*, SD is updated and the current node is updated to router *v*. After the end of the loop, the process parameter of the updated node u is set as 1 to show that this node has been permanently labelled.

3.2. Network Model

The intermodal network model that will be used in this project was created by the research center CENTEC (Centro de Engenharia e Tecnologia Naval e Oceânica) of IST – UL (Instituto Superior Técnico da Universidade de Lisboa), led by Professor Tiago Santos.

The intermodal transportation network comprises links of different types: road, motorway and urban (truck transportation); inland waterway -IWW- (fluvial transportation); train (rail transportation) and sea route containership and Ro-Ro ship (maritime transportation). Its main geographical scope comprises the regions of Portugal (including Madeira and Açores), Spain (including Canarias and Baleares), France (including Córsega), Italy (including Sardegna and Sicilia), Germany, Netherlands, Belgium, Luxembourg, Denmark, Sweden (south of Stockholm), Greece and Morocco (north of Atlas Mountains). Figure 3 shows the map with the network's geographical locations.

Figure 3 - Map with the geographical location of places comprised by the transportation network (Source: Intermodal Analyst Manual – Tiago Santos)

The first part of the database contains information regarding the network's nodes, which may represent cities; intermodal and seaport terminals; road, rail and IWW junctions. Furthermore, borders between countries are also represented by nodes and some strategic nodes in sea routes were inserted. The second part of the database contains information regarding links of different types between nodes. As aforementioned, links might be of different types: road, motorway and urban; inland waterway; railway or sea route containership and Ro-Ro ship.

3.3. Algorithm Implementation

The algorithm developed to track the shortest path between two nodes in the described network model was coded in *Fortran95*, using Dijkstra's algorithm as base theory.

As the program will perform the calculations for the shortest path in relation to distance, transportation time, total time and generalized costs, the following procedure was applied.

First, the distance of the n x n matrix $DIST(a,b)$ is created containing the distance to get to node b from node a. The table is filled with the information available in the database and the rest of it is filled by infinite in case $a \neq b$ and 0 in case $a = b$. The total transportation time can be calculated by a simple division between the arc's distance and its average speed, hence also being stored in a n x n matrix $TIME(a,b)$.

$$
\begin{aligned}
& for\ \{link\ j\} \in G(n,l) \\
& \quad if\ j \rightarrow active \\
& \qquad DIST(\,a(j), b(j)\,) = d(j) \\
& \qquad TIME(\,a(j), b(j)\,) = \frac{d(j)}{V(j)}
\end{aligned}
$$

To compute the total time of transportation $TOTALTIME(i)$, matrix $TIME(a,b)$ is used once again. However, as the total time of transportation will consider the time spent in nodes (average time and time call), those will be required to be implemented during the algorithm's routine. The use of the average time or time call will depend on whether there is a modal change or not. When the cargo is shifted from one mode of transportation to another, loading and unloading operations will be required, thus spending more time in the terminal. When the mode of transportation is kept, on the other hand, handling services will not be necessary, and the time spent on the node will be only regarding to transit time at the node. The implementation of these times is dynamic and thus inside the Dijkstra's algorithm loop.

As the calculation of the total time depends on the modal type, a new parameter was created to verify whether there must be a cargo shift or not. The parameter $MT(i)$ will then store the type of modal used to get to node and it will be used to verify the mode of transportation will change or not. Therefore, in terms of the parameter of minimum weight label recorder $D(i)$ inside the algorithm's loop:

$$
\begin{aligned}
& if\ \{D(u) + TIME(u,v) + TC(v) < D(v)\ and\ MT(v) \\
& \qquad = MT\big(p(u)\big)\ \}\ then \\
& \quad TOTALTIME(v) = D(v) \\
& \qquad = D(u) + TIME(u,v) + TC(v)
\end{aligned}
$$

$$
\begin{aligned}
& if\ \{D(u) + TIME(u,v) + TA(v) < D(v)\ and\ MT(v) \\
& \qquad \neq MT\big(p(u)\big)\ \}\ then \\
& \quad TOTALTIME(v) = D(v) \\
& \qquad = D(u) + TIME(u,v) + TA(v)
\end{aligned}
$$

The calculation of the generalized costs $GC(i)$ follows the same principle as for total time of transportation, using the minimum weight label recorder $D(i)$. The difference now, however, lies on the loading and unloading costs to be considered, as well as storage costs if the free storage time is higher than the average time spent on node.

$$
\begin{aligned}
& if\ \{D(u) + C_{trans}(u,v) + toll(u,v) < D(v)\ and\ MT(v) \\
& \qquad = MT\big(p(u)\big)\,\}\ then \\
& \quad D(v) = D(u) + C_{trans}(u,v)
\end{aligned}
$$

$$if\ \{D(u) + C_{trans}(u,v) + LC(v) + UL(p(u)) + CS\ (v) * (TA(v) - FT(v)) + toll(u,v) < D(v)\ \ and\ MT(v) \neq MT(p(u))\ \}\ then$$
$$D(v) = D(u) + C_{trans}(u,v) + LC(v) + UL(p(u)) + CS\ (v) * (TA(v) - FT(v)) + toll(u,v)$$

The computation of the transportation costs $C_{Trans}(a,b)$ consists in using the cost function for each mode of transportation and linear interpolating it to the distance from node a to node b. Furthermore, the cost tolls are added in case there are tolls included in any kind of link $(toll(a,b))$.

4. CASE STUDIES

Several numerical studies are performed in order to thoroughly test the developed algorithm for the calculation of the optimum routes between two nodes in the European intermodal transportation network. These studies are performed for some strategic points across Europe and countries covered by the network database, with a higher emphasis to Portuguese municipalities given its higher degree of detailing in the database compared to other countries. A final application of the results of this algorithm is carried out to verify the competitiveness of intermodal terminals and thus provide a basis to encourage companies to shift from road transportation to other modes of transportation.

4.1. Optimum Routes to Container Terminals in Portugal

Portugal has a particular geographical location in Europe, which might be seen as both an advantage and a disadvantage. On the one hand, being located in Europe's periphery makes Portugal totally dependent on the relationship with the Spanish transport infrastructure to reach the rest of Europe by land. Therefore, cross-border projects such as the TEN-T priority projects have a particularly significant role in Portugal's development: for the 2014-2020 transport grants by the EU, Spanish beneficiaries participated in 115 projects with a total budget of 843.7 million, mainly funding projects related to rail infrastructure [28].

This section is composed by the study of three routes involving the main seaports in Portugal: Sines, Leixões and Lisbon. The routes were chosen in order to study the effectiveness of the developed algorithm and to draw some conclusions regarding the competitiveness of intermodal transportation in Portugal.

The first analysis was related to the connection of the Port of Sines to the Lisbon, given its imperative importance due to the Portuguese capital's importance in the global scenario and Terminal XXI's magnitude in terms of moved goods.

The distance tool optimization for both road-only and intermodal paths was applied to verify the shortest routes between Lisbon and the Port of Sines. Regarding the road-only path, the cargo leaves Lisbon from the bridge *25 de Abril* and cross Setúbal to reach Alcácer do Sal, then arriving in the Port of Sines, as one can see in Figure 4. When optimizing for all modes of transportation, the algorithm was able to find a route using the inland waterway routes to cross Lisbon from the terminals of Santa Apolonia to Barreiro and then from Setubal to Troia using a ferry, with the rest and major part of the path being constituted by road links.

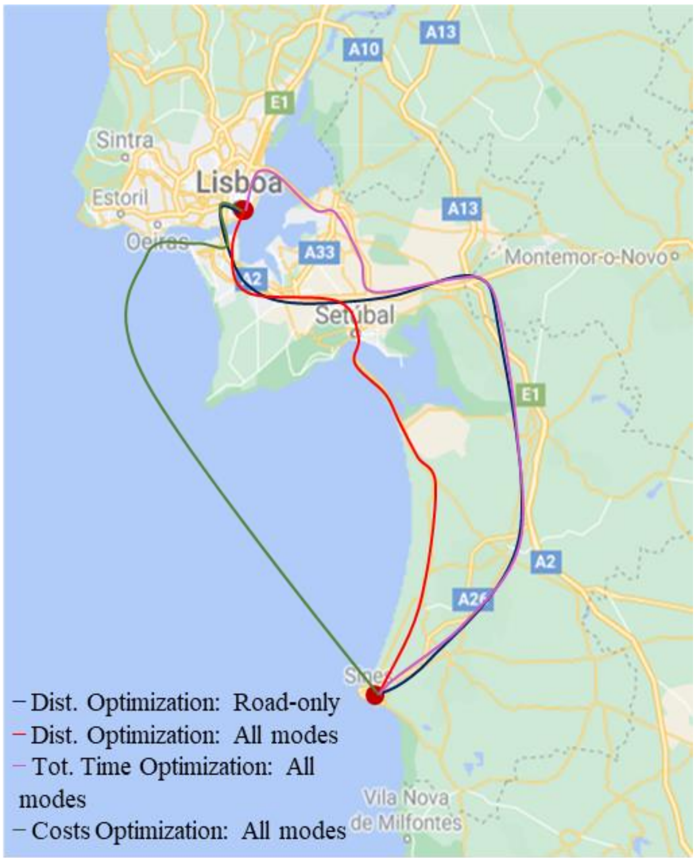


Figure 4 – Sketch of optimum routes between Lisbon and Sines

The results of the program (Table 1), show that although there is a significant reduction in the distance when allowing the program to explore routes with various modes of transportation, the difference in generalized costs is not perceived. In addition to that, the total time of transportation increased more than 50 times, mainly due to cargo handling and waiting time at terminals without covering a significant portion of the total distance.

Table 1 - Results for optimum routes between Lisbon and Sines regarding distance

Route Lisbon - Term. XXI (Sines)	Distance optimization - road transportation	Distance optimization - all modes transportation	Percentual Difference (%)
Distance (km)	174.00	119.30	-31%
Total Time of Transportation (h)	2.36	123.52	5134%
Generalized Costs (€/TEU)	1107.07	1075.29	-3%
Modes of Transportation	R	R - I - R - S - R	*

When performing the optimization procedure for generalized costs and total time of transportation, however, results change. For total time of transportation, road-only transportation is still best alternative, but instead of crossing the bridge *25 de Abril*, it crosses the bridge *Vasco da Gama* and goes all the way down in motorway to Sines. In generalized costs, nevertheless, the route takes a whole different format: it crosses the bridge *25 de Abril* and then goes to the terminal of Trafaria to take the sea route connection (characterized as IWW). This optimum path is about 60% more cost efficient than road-only paths and takes a acceptable amount of time of transportation (Table 2), which means that the navigability of the Tagus river in Lisbon has a great potential to be explored for inland waterway alternatives, at least in the estuary area of the river.

Table 2 - Results for optimum routes between Lisbon and Sines regarding total time of transportation and general costs

Route Lisbon - Term. XXI (Sines)	Total Time optimization - all modes transportation	General Costs optimization - all modes transportation	Percentual Difference (%)
Distance (km)	176.00	136.00	-23%
Total Time of Transportation (h)	2.36	16.64	605%
Generalized Costs (€/TEU)	1072.10	378.44	-65%
Modes of Transportation	R	R - I	*

Other studies have been performed, namely the routes between Guarda and Leixões and Aveiro to the Port of Lisbon. Results obtained by the algorithm (Table 3 and Table 4) has shown that intermodal alternatives are also the best choices to transport cargo in financial terms, however, the total time of transportation still remains a significant handicap.

Table 3 - Results for optimum routes between Guarda and the Port of Leixões

Route Guarda - Port of Leixões (Porto)	Distance optimization - all modes transportation	Transportation Time optimization - all modes transportation	Percentual Difference (%)
Distance (km)	200.20	200.40	0.1%
Total Time of Transportation (h)	2.53	2.53	0.0%
Generalized Costs (€/TEU)	1462.40	1466.37	0.3%
Modes of Transportation	R	R	*
	Total Time optimization - all modes transportation	General Costs optimization - all modes transportation	Percentual Difference (%)
Distance (km)	200.40	277.30	38%
Total Time of Transportation (h)	2.53	7.49	196%
Generalized Costs (€/TEU)	1466.37	836.90	-43%
Modes of Transportation	R	R - F	*

Table 4 - Results for optimum routes between Aveiro and the Port of Lisbon

Route Aveiro - Liscont (Port of Lisbon)	Distance optimization - all modes transportation	Transportation Time optimization - all modes transportation	Percentual Difference (%)
Distance (km)	287.90	294.60	2.3%
Total Time of Transportation (h)	11.36	3.92	*
Generalized Costs (€/TEU)	763.78	1837.11	140.5%
Modes of Transportation	F - R - I	F - R	*
	Total Time optimization - all modes transportation	General Costs optimization - all modes transportation	Percentual Difference (%)
Distance (km)	302.10	429.30	42%
Total Time of Transportation (h)	5.07	27.08	434%
Generalized Costs (€/TEU)	1616.23	615.53	-62%
Modes of Transportation	F - R	F - C - I	*

4.2. Optimum Routes Involving Rail Transportation

Rail transportation is frequently defined as a factor to determine the degree of economy of a country, being an efficient and reliable mode of transportation. The Atlantic Rail Freight Corridor (RFC), part of the Atlantic Corridor, is one of the main players in enhancing the efficiency of rail freight services along it and the inland backbone the corridor delivering transport efficiency and sustainability. RFC connects with the Mediterranean Corridor in Madrid and Zaragoza, with the North Sea-Mediterranean Corridor through Paris, Metz and Strasbourg. With the extension of the Atlantic Corridor to Mannheim in Germany, it was enabled a direct articulation with two other corridors: The Rhine-Alpine and the future Rhine-Danube, thus increasing outreach of the Atlantic Corridor.

To study the effectiveness of the RFC, the route between Valongo and Mannheim was decided to be studied. Mannheim is the third-largest city in the German federal state of Baden-Württemberg, and it is one of the twenty largest cities in Germany. Three corridors run through the urban node of Mannheim: the Rhine-Alpine, Atlantic and Rhine-Danube Corridors. The motorway A6, passing next to the node, as well as many corridor rail lines are part of the Rhine-Danube network while the Rhine and the Neckar, that flow together in Mannheim, belong to the Rhine-Alpine core network. Two rail-road terminals and three trimodal terminals characterize the urban node area of Mannheim, which has good connections for intermodal transportation.

When running the algorithm for this pair of cities, some interesting conclusions can be drawn (results in Table 5). For the minimal distance optimization, the cargo leaves Valongo via truck to the terminal XXI in Sines, with a small railway transportation between Alfarelos and Entroncamento. From Sines, the cargo takes the Ro-Ro line until Maasvlatke, in the Netherlands, where it takes a small railway path and then shifts the modal to road transportation to Paris. There, the cargo takes the Paris – Mannheim section of the Atlantic rail freight corridor to perform the final leg of the path. This path is almost similar to the path calculated for minimal transportation time, with differences regarding the small utilization of rail in Portugal and Netherlands, but still using the Atlantic rail freight corridor to transport the cargo from Paris to Mannheim. For the total time of transportation optimization, the difference mostly relies on the use of maritime transportation: instead of using cargo ships to transport the cargo across Portugal and Spain, the cargo takes a road portion leg to Paris, where it takes the Paris – Mannheim section of the Atlantic rail freight corridor one more time.

Table 5 - Results for optimum routes between Valongo and Mannheim

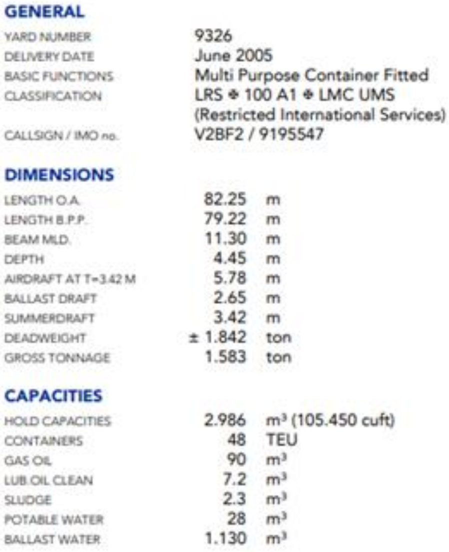
Route Valongo - Mannheim	Distance optimization - all modes transportation	Transportation Time optimization - all modes transportation
Distance (km)	1526.9	1536.6
Total Time of Transportation (h)	50.38	28.37
Generalized Costs (€/TEU)	6633.34	7023.16
Modes of Transportation	R - F - M - S - F - M	R - S - M – R - F
	Total Time optimization - all modes transportation	General Costs optimization - all modes transportation
Distance (km)	2218.7	2170.5
Total Time of Transportation (h)	46.76	105.1
Generalized Costs (€/TEU)	7632.96	3746.61
Modes of Transportation	F - R -F	F - C - F

For these three optimization methods one can see the importance of the freight corridor to transport the cargo, however, this importance is better noticed for the minimal transportation costs. The cargo uses the rail portion to the container terminal of Leixões, where it takes the maritime route to Le Havre, in France. There, it directly takes a bigger portion of the Atlantic rail freight corridor to Mannheim, consisting in a route that do not use road transportation. Besides being a greener alternative to the other possible paths, the route also implies in a total reduction of generalized costs in the order of 50%.

4.3. Competitiveness of River-Sea Transportation from Golegã to Sines

The main objective of this case study is to observe the competitiveness of river-sea cargo transportation of the Tagus river. To study this, a set of municipalities in the northern and western regions of Portugal were chosen to observe the competitiveness of combined transportation to the container terminal XXI in Sines. Furthermore, two other intermodal facilities were studied to verify the competitiveness of rail transportation compared to road-only and river-sea transportation through the Tagus river: Guarda and Lousado. The two cities have got projects for the installation of intermodal terminals and can boost Portugal's intermodal traffic, allowing a greater shift from road transportation.

First, the developed algorithm will be used to obtain the shortest paths in terms of distance for road transportation between municipalities and the Golegã Terminal. These road haulage sections will be added to a river-sea route to Sines. The cost structure of the operation of a river-sea vessel of 50 TEU (respecting geometric restrictions imposed by the river) is analyzed to estimate the costs of transportation per unit of cargo in this river-sea part of the transport chain. The required values for the calculations were taken from a DAMEN ship project, the "Combi Coaster" (Figure 5).



GENERAL

YARD NUMBER	9326	
DELIVERY DATE	June 2005	
BASIC FUNCTIONS	Multi Purpose Container Fitted	
CLASSIFICATION	LRS ✠ 100 A1 ✠ LMC UMS (Restricted International Services)	
CALLSIGN / IMO no.	V2BF2 / 9195547	

DIMENSIONS

LENGTH O.A.	82.25	m
LENGTH B.P.P.	79.22	m
BEAM MLD.	11.30	m
DEPTH	4.45	m
AIRDRAFT AT T=3.42 M	5.78	m
BALLAST DRAFT	2.65	m
SUMMERDRAFT	3.42	m
DEADWEIGHT	± 1.842	ton
GROSS TONNAGE	1.583	ton

CAPACITIES

HOLD CAPACITIES	2.986	m³ (105.450 cuft)
CONTAINERS	48	TEU
GAS OIL	90	m³
LUB OIL CLEAN	7.2	m³
SLUDGE	2.3	m³
POTABLE WATER	28	m³
BALLAST WATER	1.130	m³

Figure 5 - Technical characteristics of selected ship. Source: DAMEN

The distance between the two cities using inland waterways (river Tagus) and a maritime leg in the coast of Portugal was estimated to be about 230 km, allowing the calculation of the total voyage time to complete the path. Moreover, the time for passing through four canal locks (nodes 862, 863, 864, 865, located in accordance with "Projeto Tejo" [29]) was taken into consideration (Figure 6), adding four more hours to the total voyage time (one hour per canal lock). It was also considered that the ship will perform this route twice a week, being an important parameter since some operating costs are calculated per year. The costs distribution in percentage of the ship can be seen in Figure 7 and as one can see, capital costs represent the highest percentages for the total costs of the ship in the described route.

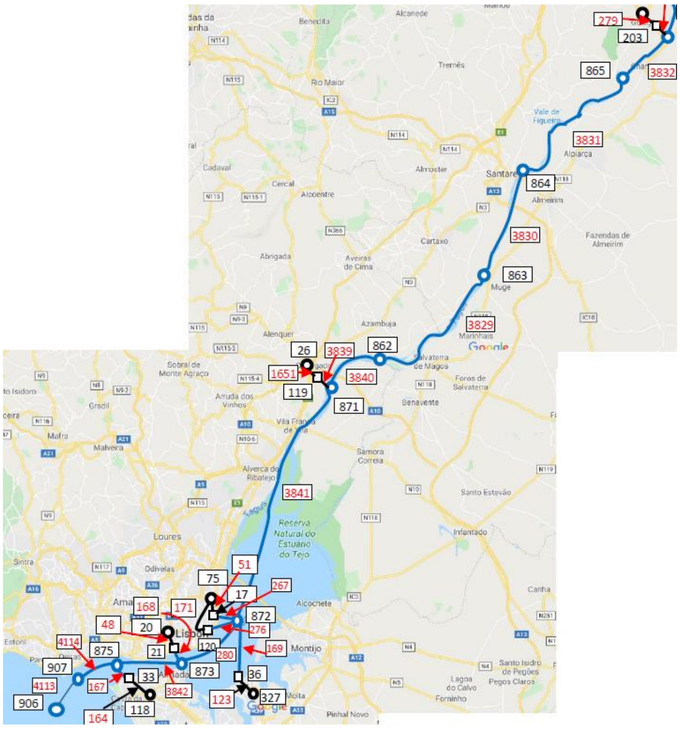


Figure 6 - Tagus river inland waterway (locks between Golegã and Lisbon are represented by nodes 862 to 865).

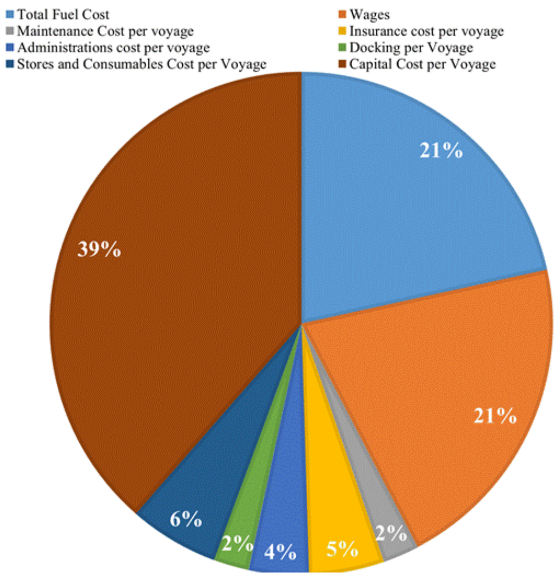


Figure 7 - Ship's cost distribution from Golegã to Sines

These new paths were then compared to the road transportation between the municipalities and Sines, for a further comparison of the competitiveness of the intermodal transportation in relation to a road-only solution. Additionally, these road sections will be used for the analysis of railway transportation regarding the municipalities of Guarda (Beira region), Lousado (Northern region) and Entroncamento (Western region), since they add impacts in the Portuguese railway infrastructure.

Using the developed algorithm to obtain the optimum routes in terms of distance, it was possible to run the *Intermodal Analyst* software in order to obtain more precise calculations in each path. The data was then plotted in a map with Portuguese municipalities, allowing a better analysis of generalized costs and time of transportation per municipality to Sines, for different combinations of modes of transportation.

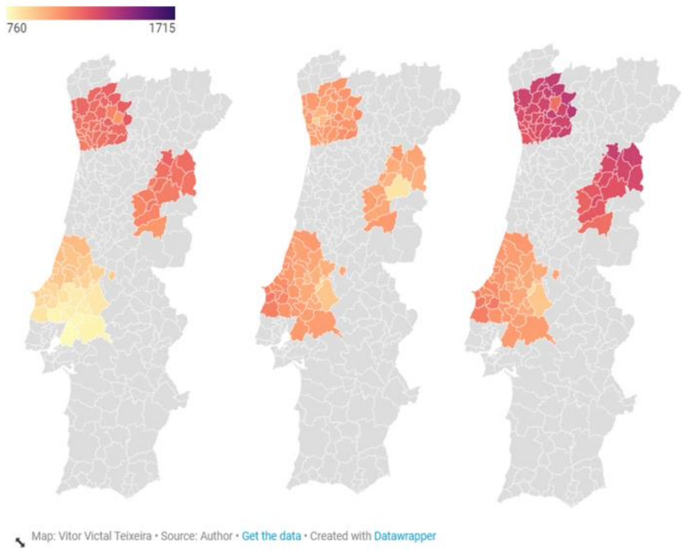


Figure 8 - Generalized transport cost to Sines (€/FEU)

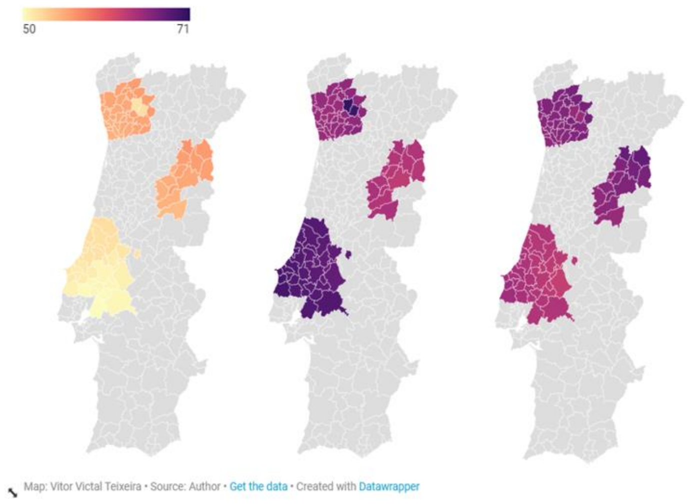


Figure 9 - Time of transportation to Sines (hours)

The results for generalized costs and time of transportation can be seen in Figure 8 and Figure 9, respectively, and some conclusions are possible to be drawn. The maps show the results for road-only transportation (left), road+rail transportation (centre) and road+IWW transportation (right). First, analyzing the western region, it is possible to observe a clear advantage of road-only transportation regarding both costs and time in comparison to combined transportation. The huge difference related to both parameters lies mainly in the existence of a terminal facility, which adds both time and cost to the whole transportation chain. Since this region is relatively close to Sines, there is a narrow margin for competitiveness of other modes of transportation, making the terminals of Entroncamento (rail terminal) and Golegã (IWW terminal) inefficient for the nearby municipalities.

In relation to northern municipalities and the Beira region, the results are different. In Beira, it is possible to observe that generalized costs in rail + road transportation from Guarda's intermodal terminal are smaller than road-only transportation. Nonetheless, transportation via Golegã (IWW terminal) is still not competitive, both in terms of time and cost. The main problem regarding rail+road transportation in this region is related to the time of transportation, having a difference in haulage to road transportation of about 15 hours, in average. This situation can be optimized should the terminal performs investments to increase its cargo handling efficiency and even reduce bureaucracy, allowing the reduction of time in the terminal, from where the biggest parcel of total time of transportation comes.

The results in northern municipalities are somehow similar to the ones in the Beira region, showing a high potential for the rail terminal of Lousado should total time spent in it is reduced. However, the competitiveness of IWW + road transportation is still far from optimal, with high costs and times of transportation in all three regions studied. The main reason for that mainly relies on two factors. The first is related to the time spent on the terminal for the modal shift, which increases an amount of time that does not exist in road-transportation. Therefore, the same optimization analysis should be valid for the terminal, which must seek for ways of making the technical aspects of shifting cargo as efficient as possible.

The main problem, however, is given by the loss of economy of scale that ships usually adds to transportation. Besides the route distance from Golegã to Sines being relatively small, because of the restrictions imposed by the navigability in the Tagus river, large ships cannot operate and therefore the cost of transportation per cargo unit increases significantly. Initiatives such as "Projeto Tejo", which proposes the implementation of weirs that should allow both the irrigation of agricultural fields in the Ribatejo and also turning the navigation possible, are extremely important so that the river gains competitiveness against other modes of transportation, by implementing solutions that can increase and surpass the geometric restrictions for ships to navigate in the river and even extend its navigable extension.

5. CONCLUSIONS

Intermodality has an enormous potential for further expansions, with governments and political unions taking concrete measures to encourage the use of combined transportation. The reduction of road transportation is imperative for a greater optimization of transportation chains, as traffic in urban regions and external costs are significantly reduced. The use of a Shortest Path Problem algorithm was verified as a good method for transportation networks, obtaining optimum paths in a small amount of time and requiring a relatively small computational power.

In order to better study the effects of Intermodality in transportation networks, a number of numerical studies were performed in order to test the developed algorithm for the calculation of the optimum routes between two nodes in the European intermodal transportation network. The numerical model based on Dijkstra's algorithm has shown results that were in accordance to reality and could therefore perform analysis with a small margin of error. The studies were performed for strategic points across Europe and countries covered by the network database, with a higher emphasis to Portuguese municipalities given its higher degree of detailing in the database compared to other countries.

The proposed study allowed an analysis on how cargo carriers and shippers can benefit from intermodal transportation, as many of the optimum paths' solutions between a pair of nodes in the network made use of more than one mode of transportation. However, the analysis also points out that some strategies and improvements must be performed by intermodal terminals in order to make combined transportation effective. The terminals of Guarda and Lousado, for example, had good results in terms of generalized costs when moving cargo from their neighboring municipalities to the XXI terminal in Sines, however, high cargo handling and waiting times ends up by reducing their competitiveness compared to road-only transportation.

The study could also verify the connection between Portuguese municipalities to rest of Europe by making use of intermodal projects that had been funded by the European Union throughout the years, such as the Atlantic Corridor, which is a viable alternative for transporting cargo across Europe without the use of road transportation.

All in all, one can observe that the algorithm developed in this study has applications in logistics and supply chains by allowing a better visualization of alternative routes making use of combined transportation, giving a higher analytical analysis capability for governments and shippers. Moreover, various simulations can be performed by adding terminals or new links between nodes in the transportation network to study the effects of the construction of a new terminal, investments, and improvements in an existing terminal and even the addition of a new route, for example.

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