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.

Keywords:

Intermodality, Shortest Path Problem, Route Optimization, Maritime, Transportation Network

RESUMO:

O conceito de Intermodalidade teve um grande impacto na maioria das cadeias de transporte existentes ao redor do mundo, ao abordar o problema da seleção modal: selecionar o melhor meio de transporte quando mais de um puder ser usado, permitindo uma melhor conexão integrada entre todos os recursos disponíveis para o transporte. A utilização dos diversos recursos disponíveis, como ferrovias, hidrovias e vias marítimas, tem um enorme potencial para diminuir a utilização do transporte rodoviário no transporte de cargas, reduzindo o tráfego e as emissões por carga movimentada, além de aumentar a economia de escala e então reduzir custos. Nesta tese, um algoritmo numérico foi desenvolvido a fim de identificar possíveis rotas entre um par origem / destino em uma rede de transporte intermodal por meio do "*Problema do Caminho Mais Curto*", permitindo o rastreamento de caminhos ótimos entre dois nós em termos de distância, tempo de transporte, tempo total de transporte e distância. Para validar o modelo numérico e mostrar as aplicações práticas de que o algoritmo é capaz, uma aplicação foi realizada em uma rede de transporte intermodal que engloba uma série de países europeus e o norte de Marrocos, assim como as ilhas portuguesas, espanholas e italianas. Diferentes estudos de caso foram realizados ao longo de cidades estratégicas abrangidas pela rede, permitindo tirar conclusões sobre o uso do transporte intermodal quando comparado ao rodoviário: a combinação dos modais costuma ser mais econômica, principalmente no que diz respeito a distâncias maiores. No entanto, é importante salientar que os percursos ótimos obtidos em termos de tempo foram, em muitos casos, constituídos por trechos rodoviários, o que significa que a otimização das infraestruturas dos terminais intermodais é de vital importância para aumentar a competitividade. O algoritmo é, portanto, uma ferramenta útil para transportadores de carga, prefeituras e governos, apontando rotas alternativas e determinando se um terminal tem potencial de crescimento caso investimentos sejam feitos.

Palavras-chave:

Intermodalidade, Problema do Caminho Mais Curto, Optimização de Rotas, Marítimo, Rede de Transportes.

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ACRONYMS:

CFS: Container Freight Station

CT: Combined Transport Directive (Council Directive 92/106/EEC)

DOTs: US State Departments of Transportations

DVR: Dynamic Vector Routing Protocol

EU: European Union

Eurostat: Statistical Office of the European Union

FEU: Forty-Foot Equivalent Unit

GDP: Gross Domestic Product

GIS: Geographical Information System

LSR: Link State Routing Protocol

NUTS: Nomenclature of Territorial Units for Statistics

RP: Routing Protocol

SPP: Shortest Path Problem

TEN-T: Trans-European Transport Network

TEU: Twenty-Foot Equivalent Unit

UNCTAD: United Nations Conference on Trade and Development

US CFS: US Commodity Flow Survey

VOT: Value of Time

1. INTRODUCTION

1.1 Background and Motivation

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 (2004) [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.

The use of containers has changed a lot the concept of transportation: the movement of cargo from origin to its very final destination is now emphasized, not the movement of goods by a series of independent modal carriers. Figure 1 shows an example of an intermodal transport chain from a rail specialized company that provides supply chain services applied to intermodality. Shippers and transportation companies no longer think of themselves as a single mode company, always aiming for the product to be transported in the most optimal way possible, with the integration of all modes of transportation available. This results in what Capineri and Leinbach (2006) [2] called the seamlessness of freight transportation services, in which impediments for the integration of the modes are dissipated in order to create a smooth freight flow between regions.

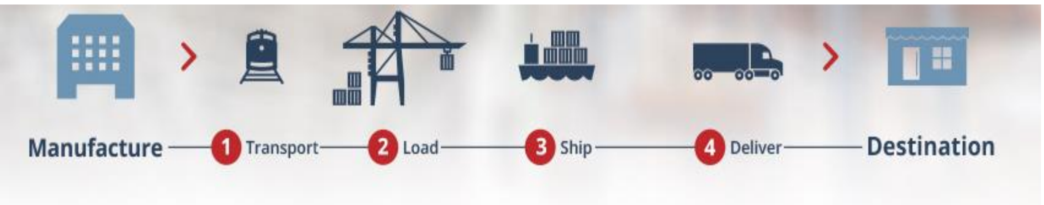


Figure 1- Example of an intermodal transport chain. *Source:* Canadian National Railway (CN)

The intermodality, according to Donovan (2000) [3] 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, showing the importance of methods to select the best routes. Nevertheless, 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.

There are mainly two criteria that are used as an objective function when optimizing routes in a transportation network chain: cost and time. Mainly, the cost is preferred as the predominant criterion, however, it's reasonable to adopt time as one important constraint due to contract related questions. 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) [4]), the most famous of those being the Dijkstra's method, the Bellman-ford's method and the Dantzig's method, whose descriptions and peculiarities will be further developed in this work.

Since it's impossible to cover all the SPP algorithms that might be applied to the study of this thesis and since no best algorithm exists for each kind of transportation problem, the methods aforementioned shall be 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 2). 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.

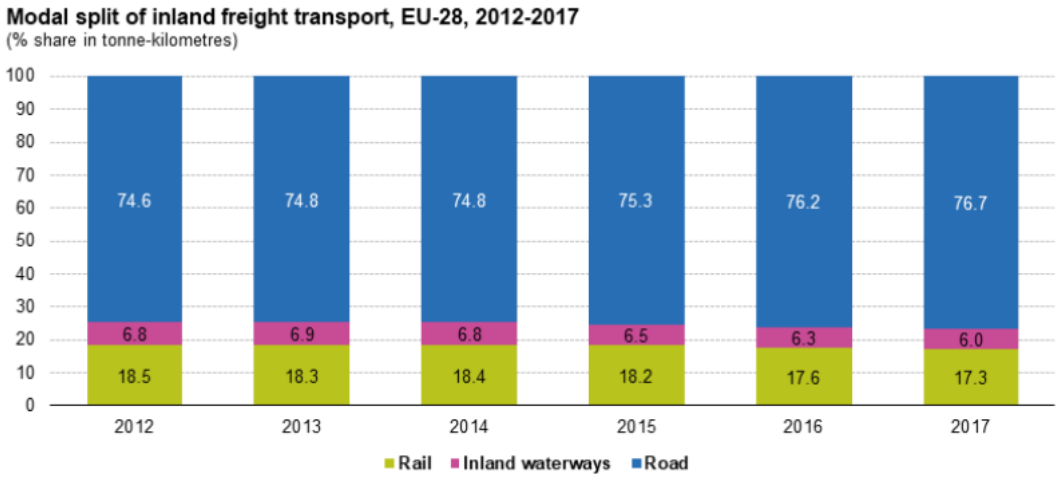


Figure 2 - Modal split of inland freight transport in Europe between 2012 and 2017. *Source:* Eurostat

1.2 Objectives

The objective of this thesis is to develop a numerical module which identifies possible routes between a pair origin/destination in an intermodal transportation network by using the Shortest Path Problem, considering the results of the review of the existing numerical models that can be applied to this problem. The algorithm is to be developed in a computational tool that determines routes given an input of origin/destination which minimizes the distance, transportation cost, transit time, generalized transportation cost, external costs and emissions, as well as identifying non-optimal transport solutions which might be susceptible of being used by shippers given its overall positive parameters, even though not optimal. The code is to be tested and implemented in the software Intermodal Analyst (IA), developed by Santos (2016) in the research unit CENTEC of IST. The modelled transport network consists in a series of European countries and the north of Morocco, as well as the Portuguese, Spanish and Italian Islands.

1.3 Structure of the Thesis

The structure of this thesis is divided so that the reader can have a better understanding of the performed study and the background in which it is inserted. The thesis is divided into five chapters:

Chapter 1: Introduction section of the thesis. Contains some background information regarding the definition and status of the intermodal transportation and the methods used for analysis of a network.

Chapter 2: Literature review. It's divided in basically two topics: the intermodal freight transportation and the network models that are commonly used. The first section basically deals with information related to the intermodal transport, with an emphasis to intermodal terminals and also the initiatives being taken in Europe to support intermodal transport. The second section consists in a briefing of the existing models used in transportation networks and a description of the developed optimization algorithms for network routing.

Chapter 3: Network Routing. This chapter deals with detailing the methodology applied, focusing on the development of the Shortest Path algorithm used for the network optimization. The section describes the principles of network routing and existing types of algorithms for this kind of study. The last part of the section focuses is in describing the used algorithm ("*Dijkstra's Algorithm*") numerical implementation and its application in the intermodal network structure.

Chapter 4: Case Study. This section focuses on the practical applications of the algorithm along a series of strategical cities and terminals comprised by the European intermodal structure. The first case study describes optimum routes from Portuguese cities to main container terminals in its continental territory. The second and third case studies focus on routes involving maritime and rail transportation, with a higher emphasis in the connection between Portuguese cities and other strategic locations in the European Union. The fourth case study focus on optimum routes involving the Port of Rotterdam and NUTS 2 cities in Northern Europe, allowing a better understanding of the intermodal alternatives that the port possesses. The final case study is related to the investigation of the competitiveness of River-Sea transportation in the Tagus river region, studying mainly the alternatives to transportation from different Portuguese municipalities to the port of Sines using intermodal terminals in the navigable areas of the river. Furthermore, rail intermodal terminals in Guarda and Lousado were studied to verify their efficiency when transporting cargo from their neighboring municipalities to the Port of Sines.

Chapter 5: Conclusions. This section summarizes the most important results from the performed case studies and gives recommendations for further possible works in the area.

2. LITERATURE REVIEW

This section is reserved to the discussion and definition of some important topics that will be approached by this thesis.

2.1 Intermodal Freight Transportation

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) [5]). 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) [6]).

In order to allow a smooth flow in an intermodal freight network, the unitization of cargo is imperative, which explains why the container transportation is a major component of intermodal transportation, being the most used unitization method due to its standardization among almost all kinds of transportation modes. According to the United Nations Conference on Trade and Development report of 2019 (UNCTAD) [7] , the number of containers being handled in ports worldwide has been increasing year after year (Figure 3), with a growth of 4.7% between 2017 and 2018 and is not showing any sign of slowing down. This is indeed a foment for the intermodality, as the standardization of transportation and reduced cargo handling results in cost efficiency, boosting the growth of the economy.

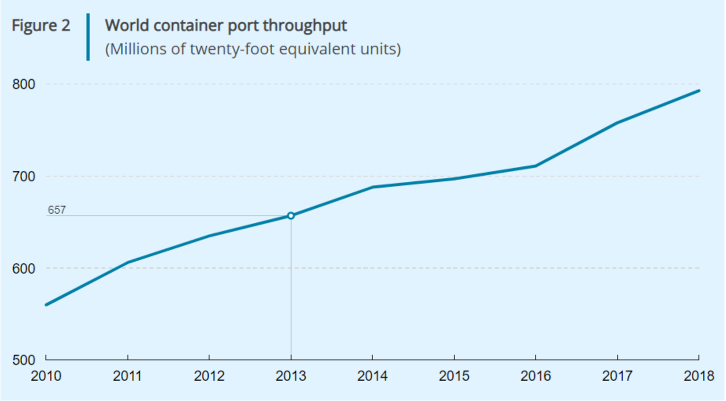


Figure 3 - World container port throughput in millions of TEUs (Twenty-foot equivalent units). *Source:* UNCTAD

The impact of containerized trade in all modes of transportation, from rail to water, has been extremely significant, as terminal equipment and operational procedures must always be enhanced in order to keep the competitivity among other terminals.

2.1.1. Intermodal Terminals

An intermodal system, be it directed to cargo or people, is constituted basically by three subsystems: vehicles, routes and terminals. Terminals fulfil the necessity of entrance/exit of goods or passengers from one mode of transportation to another, being as simples as a bus stop or as complex as the huge ports in Asia (Gualda (1995) [8]), working as nodes in the system network. It's imperative that they are planned, designed, operated and implemented in order to contribute to the desired economic performance of the systems in which they are inserted.

In order to efficiently wield its function of transferring cargo from a mode to another, intermodal terminals should possess the following services:

- Loading and unloading of full and empty containers from trucks, railway wagons, barges and ships.
- Cleaning, inspection and repair of containers.
- Storage area for both full and empty containers.
- Container Freight Station (CFS), where freight shipments are consolidated or deconsolidated.
- Custom services.

Three main intermodal terminals will be approached in this section due to its relevance to the project: Port terminals, rail terminals and distribution centres (Figure 4).

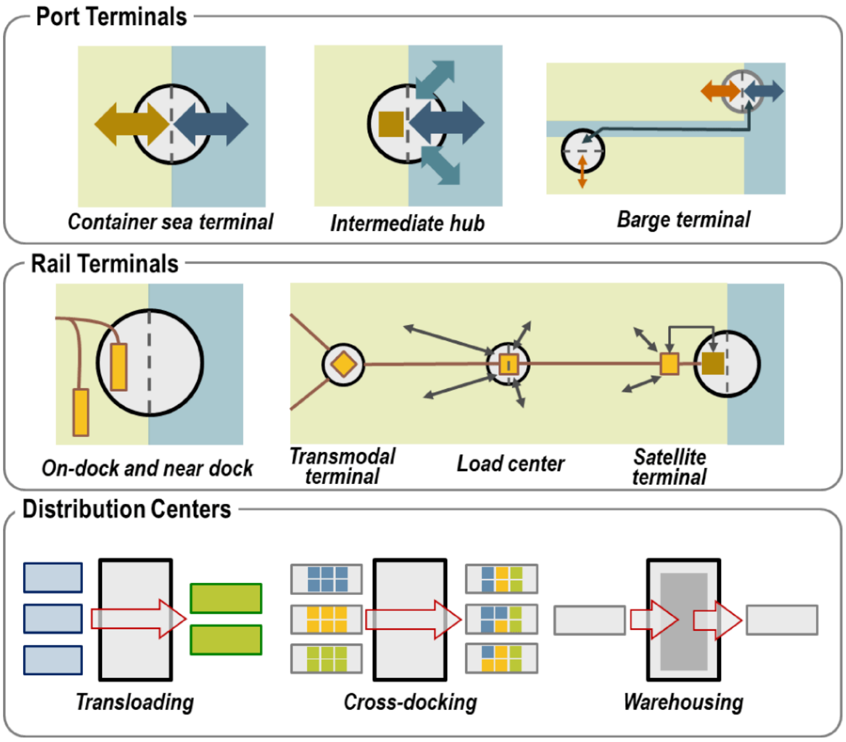


Figure 4 - Main intermodal terminals. Source: Rodrigue and Hatch (2009)

2.1.1.1. Port Terminals

Port terminals are the busiest of intermodal terminals, requiring a lot of space and capital to operate efficiently. This requirement has been growing steadily mainly due to the increase of the capacity of containerships, with the existence of ships capable of carrying over 20000 TEUs. Such growth in the size of the ships stimulated the growth of hub ports, where super-ships stop at a series of small major seaports and then the cargo is transhipped to smaller ships for the distribution to smaller ports whose physical restrictions prevent the entrance of the super-ships.

In order to provide transfer facilities for the arriving containers, port container terminals are usually composed of (Rodrigue (2011) [9]):

- Docking Area: berths where ships are allocated in order to be loaded/unloaded.
- Apron: Adjacent to berths, it’s the zone of interaction between the cranes and the storage areas where containers are brought in.
- Yard: Temporary buffer zone where containers are left while waiting for the transfer into the ship or the opposite.
- Gates: Access for trucks to enter/exit the container port terminal.

- Chassis Storage: Area where empty chassis are stored while waiting to be repaired or to be allocated to a truck.
- Repair/maintenance Area: Area where the maintenance activities of the terminal's equipment occur.
- Rail and/or Barge Terminal: Terminals adjacent to the container port terminal.
- Administration: Management facility, where logistics functions and bureaucracy are performed.

Container terminals, as Voss and Stahlbock (2004) [10] propose, might be described as open systems of material flow with two external surfaces: the quayside with loading and unloading of ships; and the landside where containers are loaded and unloaded off trucks, trains and even barges, depending on where the terminal is located (Figure 5).The existence of these two very different interfaces between water and land transportation leads to a very complex operation, as the flow of containers in these kind of terminals are usually big.

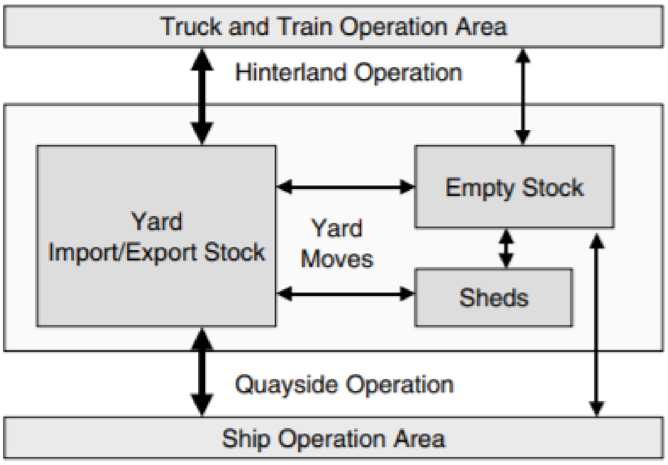


Figure 5 - Operation areas of a container port terminal. *Source:* Voss and Stahlbock (2004)

The handling equipment used in the terminals must be as efficient as possible, depending on the throughput of containers in the port. Ship-to-shore Gantry Cranes (STS) are the most used equipment at quays at container terminals due to its high productivity, theoretically being capable of carrying around 30~40 boxes per hours, whereas Mobile Harbour Cranes (MHC) have a theoretical productivity of only 15~20 boxes per hour, being usually used in smaller ports. Figure 6 shows these two types of quay cranes.

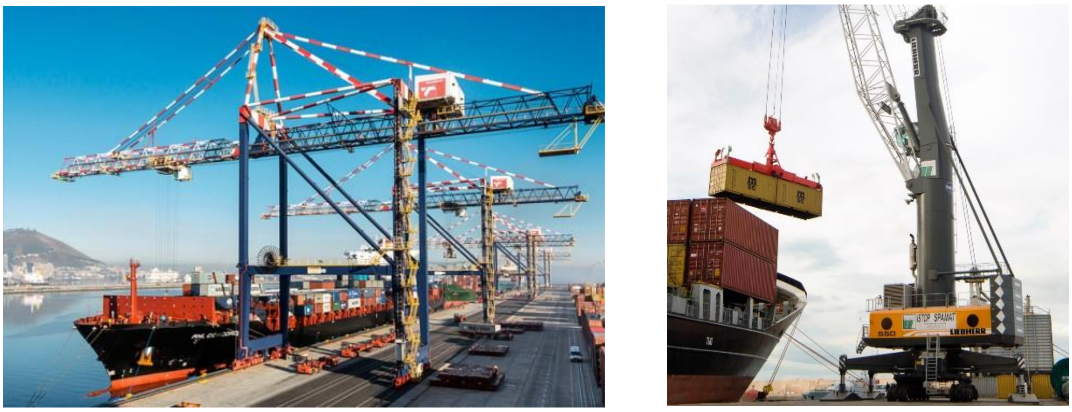


Figure 6 - STS Gantry Crane (left) and Mobile Harbour Crane (Right)

The transportation of the containers moved from ships to other intermodal terminals, yard and stacking areas is usually given by passive and active horizontal transport means (Voss and Stahlbock (2004) [10]). The former is classified as passive as vehicles are not capable of lifting the containers themselves (trucks with trailers or multi-trailers and Automatic Guided Vehicles [AGV]), while the latter is classified as active due to its ability of lifting containers themselves, such as straddle carriers, forklifts and reach stackers.

In the yard and stacking areas, usually two types of cranes are used: Rail Mounted Cranes (RMG), which possess a high productivity and are more stable; and Rubber Tired Gantries (RTG), which are more flexible in operation even though having a lower productivity. Figure 7 shows the two types of gantries. These cranes can also be used in the rail terminals for the loading/unloading of trains depending on the demand.

Figure 7 - RMG (left) and RTG (right)

2.1.1.2. Rail Terminals

In intermodal network chains, rail terminals are often connected with container terminals. There are mainly two classifications regarding the location of the rail terminal: on-dock and near-dock facility (Asaf and Swigart (2007) [11]). On-dock facilities are those where containers can be moved directly from a maritime terminal using its own equipments, whereas a near-dock facility requires other means to transport the container from the port to the rail terminal, usually being transported by trucks. Near-dock facilities tend to have more storage space available as it's disconnected from the port, however, the use of the local road system might cause congestions and the terminal clearance shall cause delays in the delivery of containers.

Rail terminals are usually composed of the following elements, each of them performing a specific function (Rodrigue (2011) [9]):

- Intermodal Yard: Area where unit trains are loaded by RMGs, RTGs or side-loaders such as reach stackers or forklift trucks.
- Storage Area: Act as a buffer between the road system and the intermodal yard, by storing containers which are waiting to be transferred.
- Classification Yard: Responsible for the assembly and break down of freight trains which are carrying different types of cargo.
- Gates: Access for trucks to enter/exit the rail terminal
- Chassis Storage: Area where empty chassis are stored while waiting to be repaired or to be allocated to a truck.
- Repair/maintenance Area: Area where the maintenance activities of the terminal’s equipment occur.

2.1.1.3. Distribution centers

Distribution centers perform mainly value-added functions, being supported mainly by trucking and located preferably in suburban locations with good road (or rail) accessibility and land availability (Rodrigue (2011) [9]). Three main activities occur in distribution centers:

- Transloading: Transfer of goods of incoming containers into domestic containers or truckloads (and vice-versa).
- Cross-docking: Transfer of goods from an incoming container to a set of different containers direct to each one’s final destination.
- Warehousing: Same for the container port and rail terminal.

2.1.2. Intermodality in Europe

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, as aforementioned in Figure 2. (European Commission, 2011).

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 CO2 emissions, being expected to decrease in about 30% due to the reduction of road transportation. [12]

To see the importance of the shift of road transportation to other lower-emission modes, Wagener (2014) [13] 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 CO2 emission (Wagener, 2014) [13].

The definition of combined transport is however different from the definition of intermodality according to the directive, with some restrictions and specifications imposed. For the purpose of the directive, "combined transport" means the transport of goods:

- Between member states where the transportation unit uses the road on the initial or final leg of the journey and, on the other leg, rail, inland waterway or maritime services where this section exceeds 100 km as the crow flies and make the initial or final road transport leg of the journey.

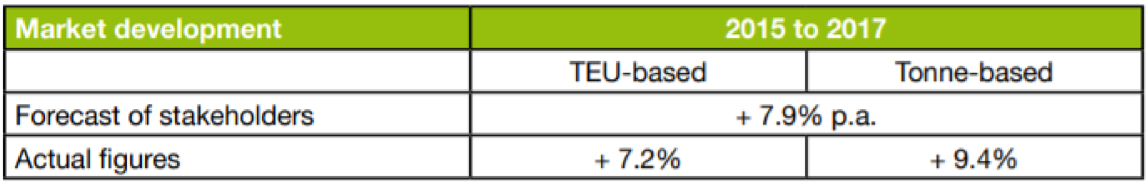
- Between the point where goods are loaded and the nearest available loading intermodal station for the initial leg; and Between the nearest unloading intermodal station and the point where the goods are unloaded for the final leg.

- Within a radius not exceeding 150 km as the crow flies from the inland waterway port or seaport of loading and unloading.

It's important to say that the CT Directive does not impose obligations to the use of combined transportation, but establishes criteria for support measures, leaving operators free to decide if they can use it. The directive guarantees the freedom to provide cross-border services without the need to concern about national restrictions such as tariffs, quotas and authorisations. It also allows vehicles used on CT road legs to carry heavier loads than road-only transport, encouraging the use of more modes of transportation, supported also by the Weights and Dimensions Directive (Directive (EU) 2015/719). Furthermore, road vehicles used in CT are exempt from road taxes, to balance the user fee paid in the other modes' infrastructure.

According to a public consultation, respondents brought out several advantages created by the CT Directive. Fiscal incentives for example were considered one of the most critical points for CT operations, allowing it to compete with road transportation on a price basis. Nonetheless, most correspondents considered the definition imposed too restrictive, in relation to both road leg limits and load units. It was also stated that the financial incentives in the Directive were not efficient and that some parts of the Directive became obsolete for today's world, 28 years after its first implementation, with a need to change the implementation and monitoring.

The last report on combined transport in the EU performed in 2018 showed the positivity of the market participants regarding the growth expectations for combined transportation. This is given mainly due to the results expected between 2015 and 2017, proving the forecast model for the increase of CT fairly accurate, as seen in Figure 8. The average expected growth rate for the market between the years pf 2018 and 2020 was calculated as a weighted average between the stakeholders and, although the expectations varied significantly between different market sectors (-20% to 50% p.a.), the results showed a steady growth (Figure 9).



Market development	2015 to 2017	
	TEU-based	Tonne-based
Forecast of stakeholders	+ 7.9% p.a.	
Actual figures	+ 7.2%	+ 9.4%

Figure 8 - Expected vs Real market development in combined transport between 2015 to 2017. *Source*: BRS Analysis

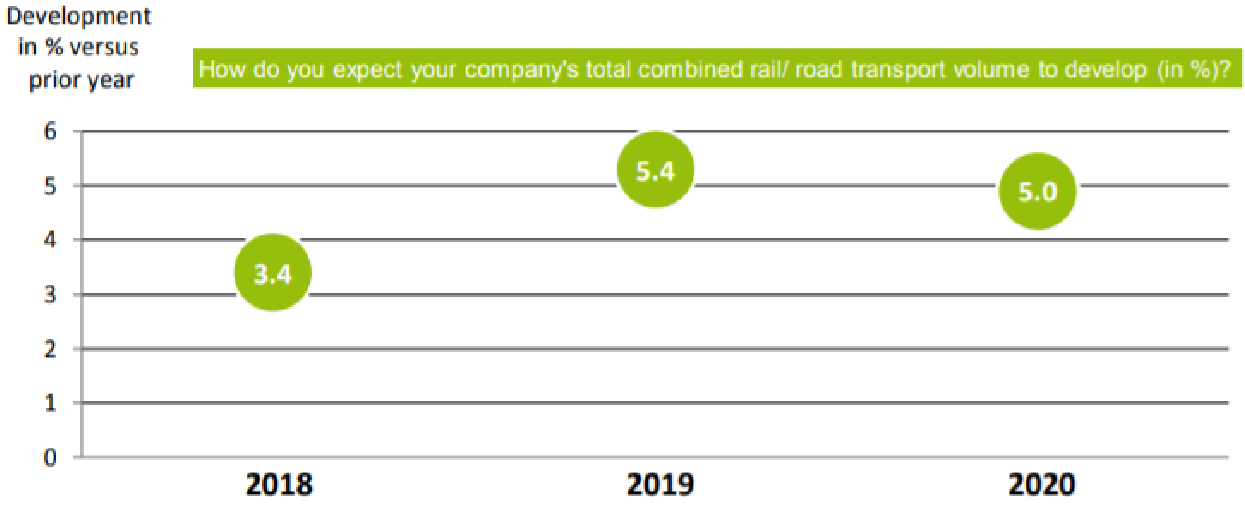


Figure 9 - Average expected volume growth of the total combined transport market between 2018 to 2020.

2.1.3. Nomenclature of Territorial Units for Statistics (NUTS)

The Nomenclature of Territorial Units for Statistics (NUTS) was created by Eurostat (Statistical Office of the European Union) more than 30 years ago in order to provide a single uniform breakdown of territorial units for the production of regional statistics for the European Union. The NUTS classification has been used in EU legislation since 1988, but it was only in 2003 that a European Parliament and Council Regulation on NUTS was adopted. The main objective of this nomenclature is to try to reduce the impact of changes in the national administrative structures of EU countries on the availability of comparable regional statistics, allowing the harmonization of the European Union's regional statistics.

The NUTS nomenclature was developed in order to favor institutional subdivisions currently in force in the member states, following a normative criteria: limits are fixed according to the tasks allocated to the territorial communities, population size and social/historical/cultural factors, among others. This is done mainly due to practical reasons regarding data availability and the implementation of regional policies, nonetheless, NUTS might divide territorial units depending on the fields of activity. Rail traffic regions, farming regions, labor-market regions, for instance, might be used in certain EU member states.

Regarding internal subdivisions, NUTS subdivides each member state into a number of NUTS 1 regions, each of which is in turn subdivided into a number of NUTS 2 regions and so on. At a regional level, the administrative structure of the Member States usually comprises two main regional levels. The grouping together of comparable units at each NUTS level involves establishing, for each Member State, another regional level in addition to the two main levels referred to above. This additional level corresponds to a less important or even non-existent administrative structure, and its classification level varies within the 3 levels of NUTS, depending entirely on the Member State. For example, NUTS 1 is used for France, Italy, Poland, Romania, and Spain; whereas NUTS 2 is usually used for Germany and NUTS 3 are used for smaller countries like Belgium, etc.

The nomenclature, apart from establishing correlations between regions in terms of size, provides as well analytical capacity levels. For instance, The 1961 Brussels Conference on Regional Economies, organized by the Commission, found that NUTS 2 (basic regions) was the framework generally used by Member States to apply their regional policies and is therefore the appropriate level for analyzing regional/ national problems. NUTS 1 (major socio-economic regions grouping together basic regions), however, should be used for analyzing regional problems within the EU, such as the effect of the customs union and economic integration on member state's areas. NUTS 3, which comprises regions which are too small for complex economic analyses, may be used to pinpoint where regional measures need to be taken.

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 [14]). In many of the operations research literature (Hillier and Lieberman, Arenales and Armentano, Bazara et al), 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.

Even though there are attempts to develop continuum models for describing mathematically a network transportation chain, the graph theory remains until these days the most efficient way to represent it in a sufficient detail. Nonetheless, Geographic Information Systems for Transportation (GIS-T) have received a lot of attention in transportation issues given its capacity to capture, store, analyse and manage all types of geographical data whilst providing visualization of the data in a spatial environment (Rodrigue [15]).

2.2.1. Graph Theory

The applications of the graph theory are extensive, being useful from the modelling of message transmissions in a data communication network to the transportation of cargo in an intermodal transportation network. (Arenales and Armentano [16])

2.2.1.1. Definition and Terminology

A transport network described by a graph is represented by a set of links and a set of nodes (Figure 10). 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.

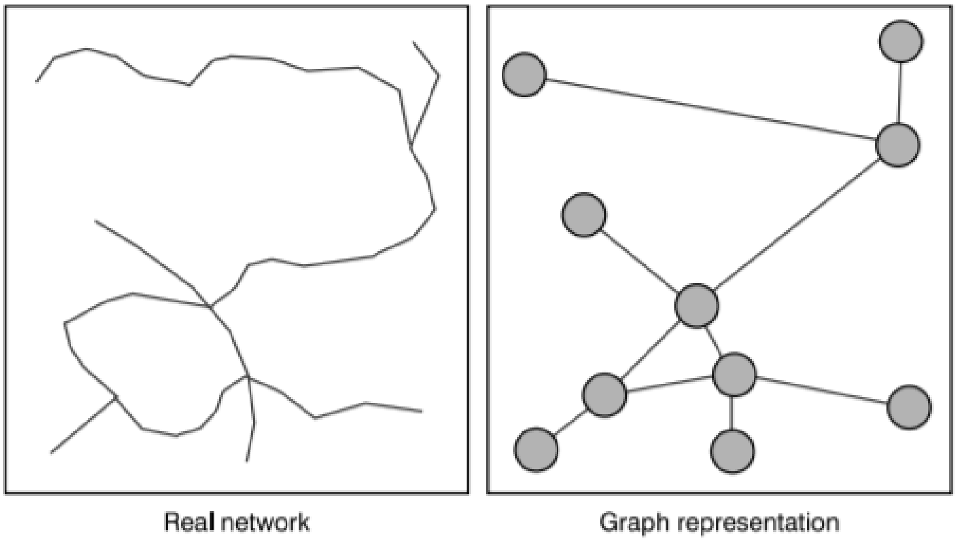


Figure 10 - Graph representation of a transportation network

The links might be either directed or undirected. In the first case, a link is considered directed whenever the direction of the movement is specified (in this case it's referred as an arc) while in the other case the direction is irrelevant, for example the case of a two-way trafficway. In this case, the link is referred as an edge, nonetheless, the terminology varies depending on the studied literature. Regarding link's characteristics, three are of major importance (Bell and Lida [14]);

- Link Length: the length of the link in metres.
- Link Cost: the cost taken to transport the cargo through the path or the transportation variable chosen (such as travel time). It's important for weighted graphs, in which each

branch is given by a numerical weight, therefore being imperative for optimization purposes.

- Link Capacity: Maximum flow allowed.

In the case of one origin and one destination, the node in which they are represented is denominated as a centroid. Each centroid is connected to one or more internal nodes, being referred to as a centroid connector, representing the multiple entrance or exits available to reach the centroid. The connectors allow the link of the centroid with adjacent nodes, allowing the creation of paths, which is a sequence of distinct nodes connected in one direction by a series of links (Arenales and Armentano [16]). This is important to the study proposed by this thesis since the optimization procedure will be related to finding the minimal path that connect a pair origin/destination.

Other useful terms for graphs that are commonly used are: a cycle, which is a path that connects the node to itself at the ends; a tree, which is a network is visited only one time (important for the Travelling Salesman Problem); a cut set, which is a minimal collection of links whose removal would split the network with no links between the resulting sub-networks. Regarding trees, a common concept is the spanning tree, which is a connected network (network where every pair of nodes might be connected by a path) of n nodes that contains no undirected cycles, having exactly n-1 arcs, the minimum number of links needed to have a connected network and the maximum number possible without having undirected cycles (Hillier and Lieberman [17]). The spanning tree gives origin to a common network optimization model called The Spanning Tree Problem, which represents the shortest route connecting all nodes in the network.

2.2.1.2. Indices and Measures

To analyse a network efficiency, several measures and indices are used. Most of them were developed by Kansky (1989) [18] and can be used to compare different transportation networks at a specific point in time or even compare the evolution of a transport network at different points in time (Rodrigue [15]).

Regarding measures, two are often used: the diameter of the network and the number of cycles. The diameter is the length of the shortest path that connects the two farther nodes of a graph. This measure allows an observation of the connectivity of the network: the higher the diameter, the less linked the network tends to be. The number of cycles is intuitively the maximum number of independent cycles in a network. It allows the verification of the complexity of a network, indicating the level of development of a transport system.

Regarding Indices, many methods have been developed to represent the structural properties of a graph and are relatively more complex due to the comparison of a measure over another. Four main indices were developed by Kansky, the alpha, beta, theta and Pi indices.

The alpha and beta indices evaluate the connectivity of a network. The first one is done by comparing the existing number of cycles to the maximum number of cycles possible, meaning that the higher the alpha index, the more connected is the network. The beta index, nonetheless, is expressed by the ratio between the number of inks and the number of nodes. The theta index measures the average amount of traffic per node (or intersection), meaning that the higher theta is, the higher is the load of the network. Finally, the Pi index represents the relationship between the total length of the graph and its diameter. The greater the Pi index, the more developed is the network.

2.2.2. Geographical Information System (GIS)

A Geographical Information System (GIS) is a system specialized in the input, management, analysis and reporting of geographical information. The applications of the GIS are wide and have received attention in transportation issues, with a specific branch commonly labelled as GIS-T (Geographical Information System applied to transportation problems).

Rodrigue [15] describes mainly four major components of a GIS: encoding, management, analysis and reporting (Figure 11). The encoding deals with the representation of the transport system and its spatial elements. Usually, the transportation system is encoded by composing nodes and links, adding also elements relevant to transportation such as qualitative and quantitative data to their respective components. The management deals with the organization of the large amount of heterogenous data in order to facilitate the access the encoded information in the GIS, allowing the organization along spatial (region, country etc), thematic (for highway, railway, terminals etc) or temporal (by year, month, hour etc). The analysis is responsible for the investigation of the relationships that can be performed in the network, by using a vast possibility of methodologies and tools to analyse these relationships (For example shortest path and routing algorithms). Finally, the reporting is one of the differentials in a GIS, since it offers interactive tools to convey complex information into a visual format. This allows the observation of hidden patterns and relationships in the network, representing a useful and ultimately cost-effective tool for the collection, storage, analysis and reporting of data (Lewis (1997) [19]).

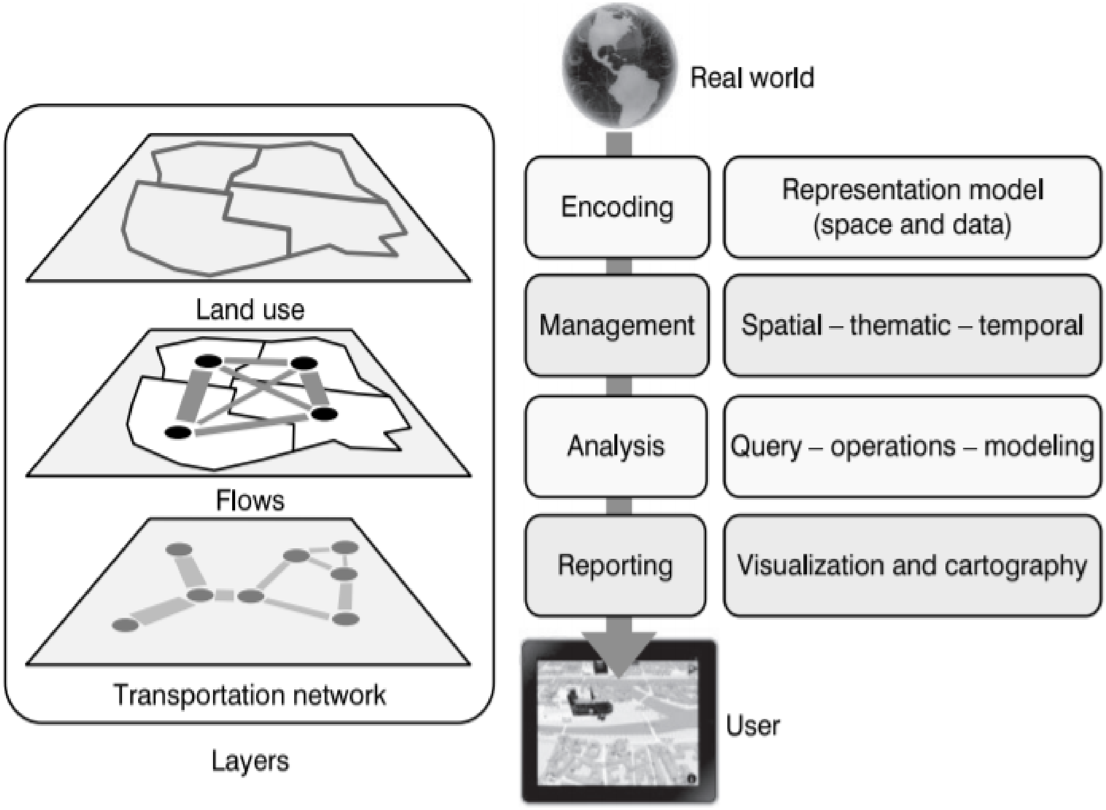


Figure 11 - Representation of GIS-T

The applications of this technology have been used by several governments in their transport departments since its first stages of development. Simkowitz (1988) [20] provides a series of case studies in the US State Departments of Transportations (DOTs) and how they have deployed GIS-T. For instance, Alaska has developed a Highway Analysis System (HAS), which is mainframe database of the relevant information regarding highways (such as highway inventory, traffic, accidents, project history, performance etc) and a collection of codes responsible to process and analyse the data to produce reports. Moyer and Danielson (1996) [21] discuss a case in which GPS technology had been used by the State DOTs of Virginia and Tennessee, in which photolog technology was used to record images of the highway systems in order to integrate the data into a GIS-T.

2.2.3. Intermodal Transportation Networks

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) [22] provided a study in the development and construction of an intermodal transportation network as part of the US Commodity Flow Survey (US 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) [23] 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) [2] 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) [24] 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) [25] 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) [26] develop 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. 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 generalized 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) [27] 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.

2.2.4. Optimization 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 [17]).

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) [28]). In transportation, Glover et al. (1985) [29] 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 SPP is an attractive topic to researches worldwide due to its capability to offer efficient solutions to real world problems, determining in a fast and economical way the best approach to follow a determined activity. Nonetheless, as the studies in this field are relatively new, much remains to be studied. Compared with other optimization problems such as the spanning tree, transportation and assignment problems, researches in SPP started relatively late (Schrijver (2012) [30]). 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) [31] 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) [32], Luce and Perry (1949) [33] and Shimbel (1951) [34]. 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) [35] and Dijkstra (1959) [36], who developed an efficient algorithm for the SPP. Shimbel (1955) [34], Bellman (1958) [37] and Moore (1959) [38] started the development of algorithms with arbitrary weights for the links in a graph (including negative weights).

Nowadays, there are a great number of algorithms to solve find the shortest path in a network, however, as Dreyfus (1969) [39] 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

3.1 Principles of Network Routing

With main applications in computer science, telecommunications and transportation, routing consists in finding a path between two points in a network. Despite seeming a complex subject, routing is actually part of everyone's daily life: whenever someone wants to move from a place to another, its brain automatically creates a path and it will most likely try to find the shortest one. It is also present in every computer network we use, for instance, every phone call that is made must establish a connection between two points in a phone network and remain static until the end of the conversation.

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 this definitions are often used in computer science, the applications for transportation networks are equally the same.

The Static Routing Protocol consists in entering manually the addresses of individual locations, filling manually the routing table. This process is usually more advantageous when working with small networks, since it requires a lot of work in the initial stages of the network configuration. This method also reduces memory cycles and is not affected by possible deformations caused by the loss of dynamic routing on neighboring points, however, it is not able to react to failures of individual paths.

Dynamic Routing Protocols, on the other hand, are much more adequate to large networks as it can use the changing parameters of the network and update the routes according to the modifications. There are two subdivisions for this kind of routing protocol: internal and external routing. The latter will not be discussed in this project since the external protocol consists in finding the path information using outside autonomous systems, which is not the case being studied. The former, however, suits better to main focus of this thesis, since it creates a path using only the information provided by an owned autonomous system. They keep track of the paths used to move the data (weighted arcs, in the case of transportation) from one point to another inside a network or a set of interconnected networks. There are basically two types of routing algorithms when considering Internal Dynamic Routing Protocols: Distance Vector Routing and Link State Routing. These two methods will be discussed in the next section.

3.2 Algorithms for Network Routing

As discussed in Section 3.1., there are two kinds of Interior Dynamic Routing Protocols: Distance Vector Routing (DVR) and Link State Routing (LSR).

3.2.1. Link State Routing Protocol (LSR)

Link State Routing 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 (Perlman 1999). 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 need 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.

The best-known and most used LSR algorithm is Dijkstra's algorithm, named after its inventor Edsger Dijkstra. The algorithm is iterative and is able to compute the shortest path between any nodes in a non-negative weighted graph such that $G = (V, E)$, besides having the property that after k^{th} iteration of the algorithm, the least cost paths are known to k destination nodes. The notation used for this algorithm is:

- $c(i, j)$: link weight from node i to node j. When two pair of nodes are not directly connected, the weight is considered to be infinite. When links between i and j are two-way directed, then $c(i, j) = c(j, i)$.
- $D(v)$: labeled weight of the path from origin node to node v that contains the least weight.
- $p(v)$: previous node along the current least weight from source to v.
- $S(v)$: process parameter that verifies whether node v has been swept in the iteration (1 to processed and 0 to not processed).

The link state algorithm is consisted by basically two steps: initialization and loop. The initialization step basically defines initial condition values in order to make the algorithm run, whereas the loop step sweeps all the *k* nodes and finds a node *w* that has not yet been processed and update the weight of the path according to the equation:

$$D(v) = \min\ (\ D(v)\ ;\ D(k) + c(k, v)\ )$$

After that, the algorithm sweeps the updated values and searches for the node which contains the smallest weight of the path and sets it as the new current node and then the iteration continues until the searched node is the destination node. When the LSR algorithm terminates, there is a predecessor node for each node along the least cost path from the source node, allowing the construction of the shortest path.

3.2.2. Distance Vector Routing Protocol (DVR)

Distance Vector Routing, also known as a decentralized routing algorithm, performs the calculation of the shortest path in an iterative, distributed and asynchronous manner. Differently from LSR algorithms, the nodes do not possess information about link's weights in the network. Instead, each node begins with only the knowledge of the costs of its own directly attached links and then, through an iterative process of calculation and exchange of information with its neighboring nodes, it gradually calculates the least cost path to a destination, or set of destinations. Moreover, differently from LSR, DVR can work with links whose weights are negative.

Also known as Bellman-Ford algorithms, DVR algorithms operate in basically two stages. At the beginning, a routing table is created and information regarding the node's immediate neighbors and weights is added to it. Later, the algorithm sends the table to the node's neighbors who complete their routing tables with the information they have obtained from the routing table that has just been sent.

Each node's routing table has a row for each possible destination in the network and a column for each of its directly attached neighbors. Considering a node *x* that might be linked through a minimum path in the network to node *y* via its directly attached neighbor *z*. Node *x*'s routing table entry, $D^x(y, z)$, is the sum of the weight of the direct link between *x* and *z*, $c(x, z)$; and the neighbor *z*'s currently known minimum weight path from itself to *y*, taking it from *z*'s directly attached neighbors *w*. The equation below suggests the neighbor-to-neighbor communication that will be performed by the algorithm: each one of the nodes must know the weight of each of its neighbors' minimum weight path to each destination.

$$D^x(y, z) = c(x, z) + \min_{\mathrm{w}}\{D^z(y, w)\}$$

The initialization of the algorithm starts with attributing the weight for all adjacent nodes z to origin x. Therefore, in this first step, the weights of the directly attached nodes are computed and, for the non-directly attached nodes, the infinite value is attributed. For a destination y, the algorithm sends the minimum value from its attached neighbors w. Then, the iteration procedure starts with a loop when it receives a link change to neighbor z or until it is updated. If there is a change of weight to the destination via neighbor z by a node whose weight is d, then the routing table entry is updated.

$$D^x(y,z) = D^x(y,z) + d$$

Followed to that, the algorithm verifies whether the shortest path from z to y has changed and then the routing table is once again update with the new value, the minimum weight path from a neighbor w to z. If there is a new minimum value $D^x(z,w)$, this information is passed to all its neighbors. The iterative procedure continues on until no more information is exchanged between neighbors, which means that the algorithm is self-terminating: there is no "signal" that the computation should stop.

3.2.3. Comparison Between Routing Protocols

To better study the best routing protocol to be applied in this thesis, three main attributes were chosen in order to verify the advantages and drawbacks of each RP: Message complexity, speed of convergence and robustness.

- Message Complexity: LSR algorithms require that each node knows the weight of each link in the network, requiring O(VE) messages to be sent, where V is the number of nodes in the network and E is the number of links. The DV algorithm, on the other hand, requires message exchanges between directly connected neighbors at each iteration, which can result in a large packet flow for large networks.
- Speed of Convergence: LSR algorithms are $O(n^2)$ algorithms requiring O(nE) messages, and potentially suffering from oscillations. The DV algorithm can converge slowly (depending on the relative path weights) and can have routing loops while the algorithm is converging. DVR also suffers from the count to infinity problem, which does not happen in LSR.
- Robustness: In case a router fails or misbehaves, under LSR algorithms, a router could broadcast an incorrect weight for one of its attached links (but not to others). A node

could also corrupt or drop any Link State Broadcast packets it receives. However, an LSR node is only computing its own routing tables while other nodes are performing similar calculations but for themselves. This means route calculations are separated under LSR algorithms, providing a degree of robustness. Under DVR algorithms, however, a node can advertise incorrect least path costs to the destination. More generally, we note that at each iteration, when a calculation is performed in one of the nodes, the error propagates to its neighbor and then indirectly to its neighbor's neighbor on the next iteration. In this sense, an incorrect node calculation can be diffused through the entire network. To illustrate this, there is a famous example: the AS 7007 incident. In 1997, a malfunctioning router in a small Internet Service Provider (ISP) in the US provided national backbone routers with huge routing tables with erroneous data. This caused other routers to spread the malfunctioning router with traffic and caused large portions of the Internet to become disconnected for up to several hours, creating a routing black hole (Neumann 1997 "Internet Routing Black Hole").

With the qualitative analysis of both LSR and DRV protocols, as well as considering an intermodal transportation network used for this project, Link State Routing protocols were found to be the best match for the problem. The functioning of Dijkstra's algorithm will be further detailed in the next sections.

3.3 Functioning of 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. The notations used in this section are based on the ones described in Section 3.2.1.

The 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 (Equation 3.1).

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

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

$$u = o \tag{3.1.}$$

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 (Equation 3.2).

$$if \quad \{ D(u) + c(u,v) < D(v) \} \ then$$

$$D(v) = D(u) + c(u,v)$$

$$p(v) = u \tag{3.2.}$$

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 described in Equation 3.3.

$$if \quad \{ D(v) < SD \} \quad then$$

$$SD = D(v)$$
$$u = v \qquad 3.3.$$

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.

In order to verify the complexity of the algorithm, one must analyse the nodes selection. In a node selection operation, for a graph with *n* nodes, the operation is performed in *n* nodes and after the first iteration it is performed *n-1* times. As the operation is not performed for permanently labelled nodes, from the k^{th} selected node, the algorithm will study *n-k* nodes. The update loop, on the other hand, analyses each node for $|A(i)|$ times, meaning the algorithm will perform the operations *m* times. Therefore, the operation complexity, which is the time that the algorithm will take to run, is described by Equation 3.4.

$$\begin{cases} n + (n-1) + (n-2) + k + 1 = O(n^2) \\ \sum_{i \in N} |A(i)| = m = O(m) \end{cases} \qquad 3.4.$$

As $m < n^2$, the algorithm will have a complexity of $O(n^2)$. However, with optimization methods developed throughout the years for the Dijkstra's algorithm, researchers found out that the use of *heaps* and *Fibonacci heaps*, the running times started to follow a more logarithmic shape: O(*m* log(*n*)) and O(*m* + *n* log(*n*)), respectively.

3.4 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 12 shows the map with the network's geographical locations.

An important note to be made is that the degree of detail Portugal's road network is higher than in the other countries, fully connecting each municipality to main ports and other countries. Moreover, the region in Spain that comprises the provinces of Zamora, Salamanca, Caceres and Badajoz have a road network degree of detail equal to the one in Portugal, however, the rest of the country is modelled so that the main capital cities of provinces are fully connected to the network. The rest of the covered EU countries, the main road network in included in the model and all NUTS 2 capitals are fully connected.

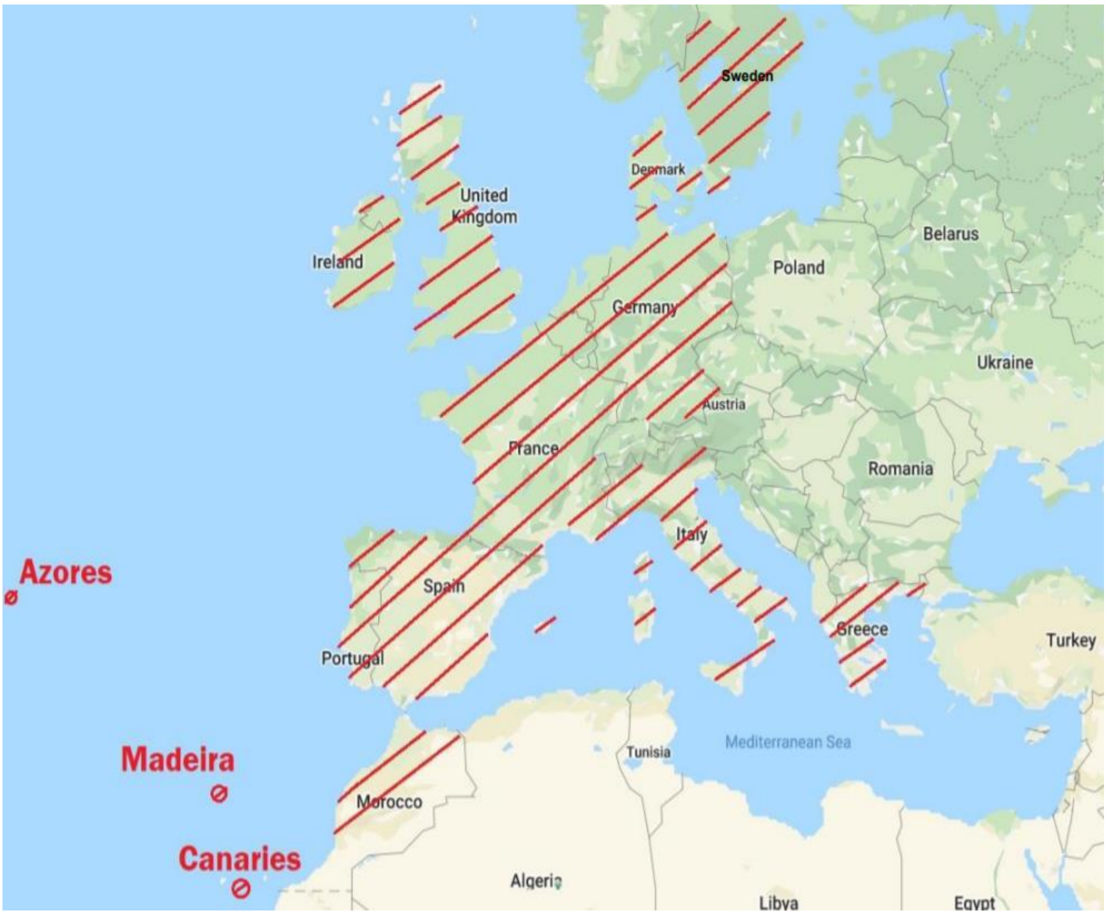


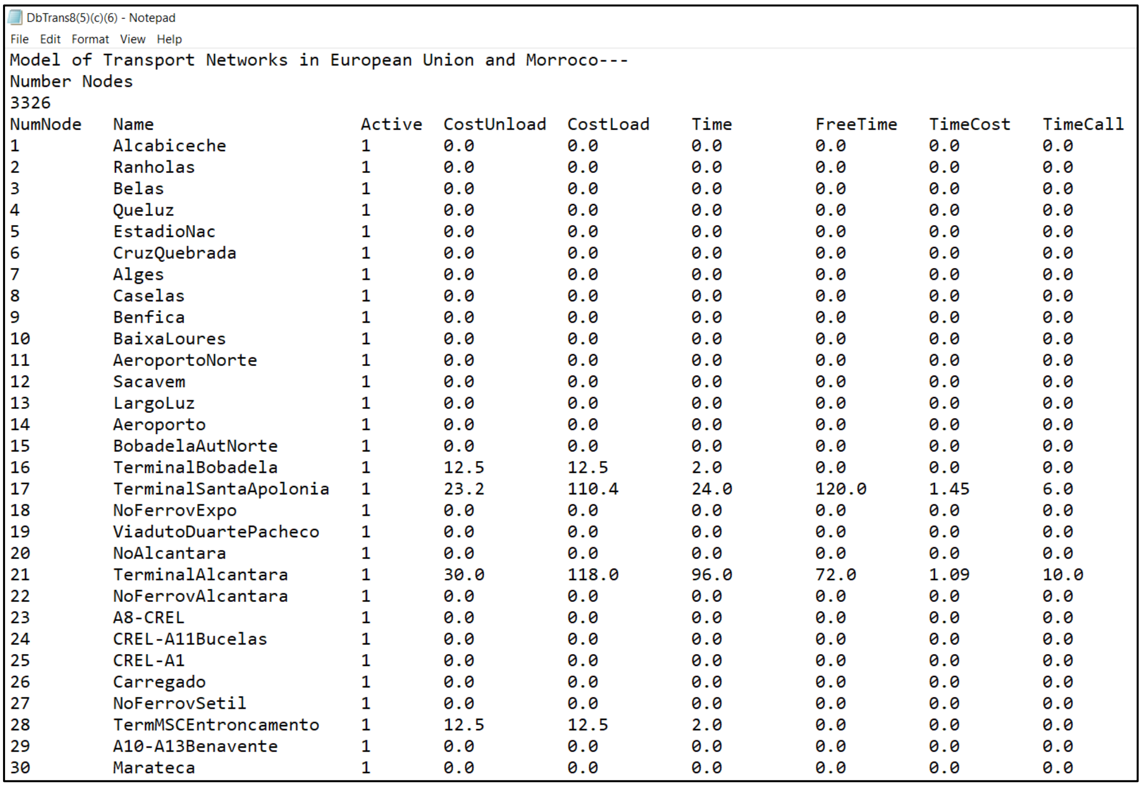
Figure 12 - Map with the geographical location of places comprised by the transportation network (Source: Intermodal Analyst Manual – Tiago Santos)

3.4.1. Data Structure

The database in which the intermodal network's information is inserted is basically divided in two parts: information regarding *n* nodes and information regarding *l* links (G(*n*,*l*)). The database is contained in a *.txt* file.

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 nodes possess the following characteristics (Figure 13).

- NumNode: Node's number. $-(i)$
- Name: Node's name.
- Active: Identify whether nodes are active or not. (1 for active nodes and 0 for inactive nodes).
- CostUnload: Cost of unloading cargo in the node [€/TEU]. $-UC(i)$
- CostLoad: Cost of loading cargo in the node [€/TEU]. $-LC(i)$
- Time: Average time spent on node [h]. $-TA(i)$
- FreeTime: Free storage time allowed on the node [h] $-FT(i)$
- TimeCost: Cost of storage in case cargo is still stored on node passed the free time [€/h]. $-CS(i)$
- TimeCall: Transit time in the node [h]. $-TC(i)$



```
Model of Transport Networks in European Union and Morroco---
Number Nodes
3326
NumNode   Name                    Active  CostUnload  CostLoad    Time        FreeTime   TimeCost   TimeCall
1         Alcabiceche             1       0.0         0.0         0.0         0.0        0.0        0.0
2         Ranholas                1       0.0         0.0         0.0         0.0        0.0        0.0
3         Belas                   1       0.0         0.0         0.0         0.0        0.0        0.0
4         Queluz                  1       0.0         0.0         0.0         0.0        0.0        0.0
5         EstadioNac              1       0.0         0.0         0.0         0.0        0.0        0.0
6         CruzQuebrada            1       0.0         0.0         0.0         0.0        0.0        0.0
7         Alges                   1       0.0         0.0         0.0         0.0        0.0        0.0
8         Caselas                 1       0.0         0.0         0.0         0.0        0.0        0.0
9         Benfica                 1       0.0         0.0         0.0         0.0        0.0        0.0
10        BaixaLoures             1       0.0         0.0         0.0         0.0        0.0        0.0
11        AeroportoNorte          1       0.0         0.0         0.0         0.0        0.0        0.0
12        Sacavem                 1       0.0         0.0         0.0         0.0        0.0        0.0
13        LargoLuz                1       0.0         0.0         0.0         0.0        0.0        0.0
14        Aeroporto               1       0.0         0.0         0.0         0.0        0.0        0.0
15        BobadelaAutNorte        1       0.0         0.0         0.0         0.0        0.0        0.0
16        TerminalBobadela        1       12.5        12.5        2.0         0.0        0.0        0.0
17        TerminalSantaApolonia   1       23.2        110.4       24.0        120.0      1.45       6.0
18        NoFerrovExpo            1       0.0         0.0         0.0         0.0        0.0        0.0
19        ViadutoDuartePacheco    1       0.0         0.0         0.0         0.0        0.0        0.0
20        NoAlcantara             1       0.0         0.0         0.0         0.0        0.0        0.0
21        TerminalAlcantara       1       30.0        118.0       96.0        72.0       1.09       10.0
22        NoFerrovAlcantara       1       0.0         0.0         0.0         0.0        0.0        0.0
23        A8-CREL                 1       0.0         0.0         0.0         0.0        0.0        0.0
24        CREL-A11Bucelas         1       0.0         0.0         0.0         0.0        0.0        0.0
25        CREL-A1                 1       0.0         0.0         0.0         0.0        0.0        0.0
26        Carregado               1       0.0         0.0         0.0         0.0        0.0        0.0
27        NoFerrovSetil           1       0.0         0.0         0.0         0.0        0.0        0.0
28        TermMSCEntroncamento    1       12.5        12.5        2.0         0.0        0.0        0.0
29        A10-A13Benavente        1       0.0         0.0         0.0         0.0        0.0        0.0
30        Marateca                1       0.0         0.0         0.0         0.0        0.0        0.0
```

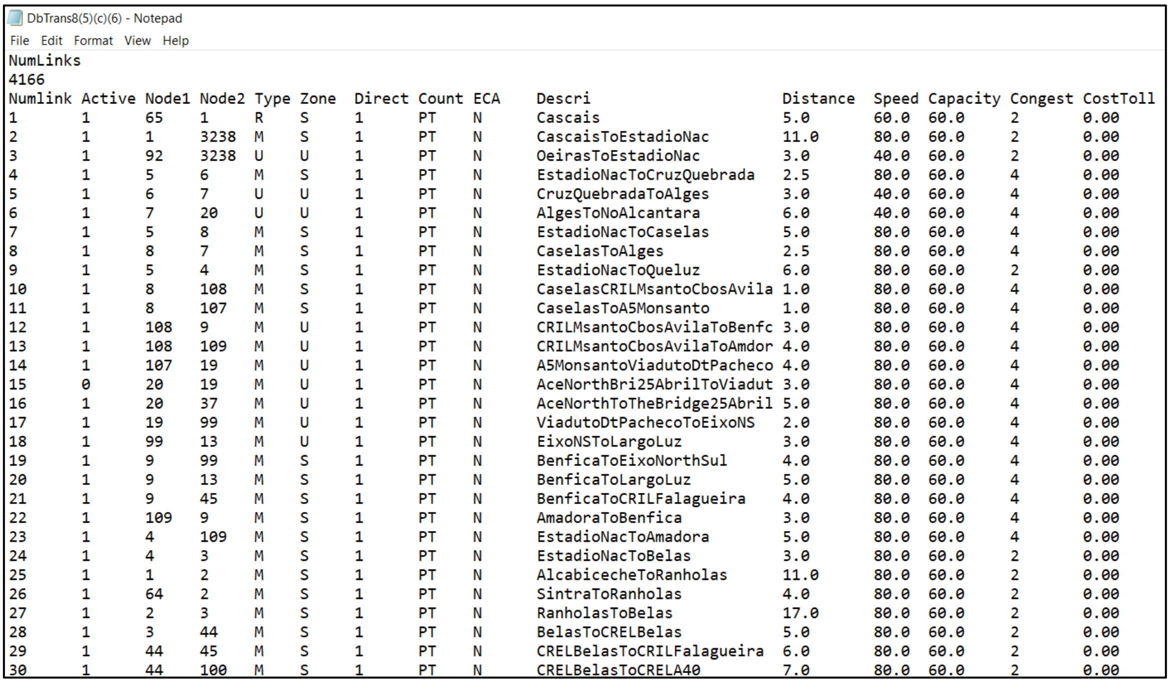
Figure 13 - Database structure for nodes information

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. The links possess the following characteristics (Figure 14).

- NumLink: Link's number. $-(j)$
- Active: Identify whether links are active or not. (1 for active nodes and 0 for inactive links).
- Node1: Link's node nº 1. $-a(j)$
- Node2: Link's node nº 2. $-b(j)$
- Type: Type of the link in terms of modal type. $M_{type}(a(j), b(j))$
    - Road Transportation: R (road), M (motorway) and U (urban).
    - Rail Transportation: F (railway).
    - IWW Transportation: I (Inland waterway).
    - Maritime Transportation: C (containership) and S (Ro-Ro ship).
- Zone: Zone where link is located.

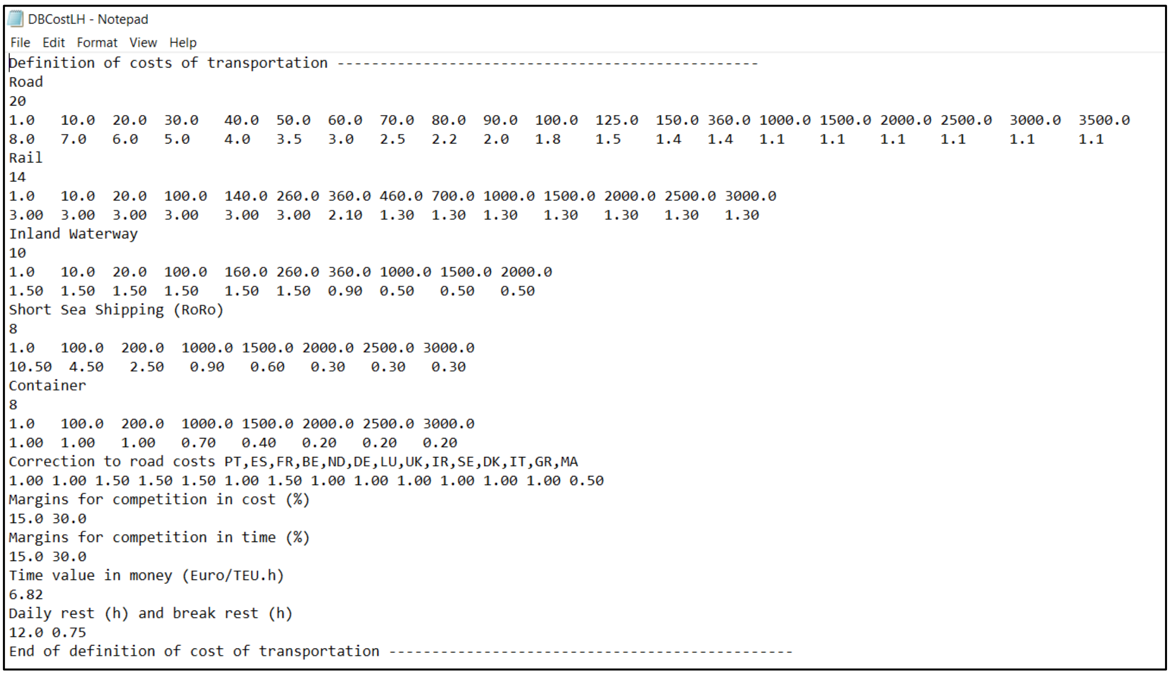
- Direct: Verify whether traffic can be directed in both ways (1 for yes and 0 for no).
- Count: Country in which link is located.
- ECA: ECA zone in which the link is located (for sea routes).
- Descri: Description of the link.
- Distance: Total distance of the link [km]. $- d(j)$
- Speed: Average speed in link [km/h]. $- V(j)$
- Capacity: Capacity of the link.
- Congest: Congestion in link.
- CostToll: Tolls in link [€]. – $tc(j)$

Another important database structure is the cost database, which returns the cost function for each type of modality. The cost function allows the interpolation of the distances to estimate the cost of transportation in a given distance in any type of mode transportation. The structure can be seen in Figure 14, and the units are in [km] for distances and [€/TEU.km].r The database also provides correction factors for road modality depending on the country where the link is located, as well as some other parameters that are not in the scope of this project. The values, although not extremely accurate to reality, provide a good estimative of costs in a given path, allowing the comparison of different routes.



```
NumLinks
4166
Numlink Active Node1 Node2 Type Zone  Direct Count ECA    Descri                     Distance  Speed Capacity Congest CostToll
1       1      65    1     R    S     1      PT    N      Cascais                    5.0       60.0  60.0     2       0.00
2       1      1     3238  M    S     1      PT    N      CascaisToEstadioNac        11.0      80.0  60.0     2       0.00
3       1      92    3238  U    U     1      PT    N      OeirasToEstadioNac         3.0       40.0  60.0     2       0.00
4       1      5     6     M    S     1      PT    N      EstadioNacToCruzQuebrada   2.5       80.0  60.0     4       0.00
5       1      6     7     U    U     1      PT    N      CruzQuebradaToAlges        3.0       40.0  60.0     4       0.00
6       1      7     20    U    U     1      PT    N      AlgesToNoAlcantara         6.0       40.0  60.0     4       0.00
7       1      5     8     M    S     1      PT    N      EstadioNacToCaselas        5.0       80.0  60.0     4       0.00
8       1      8     7     M    S     1      PT    N      CaselasToAlges             2.5       80.0  60.0     4       0.00
9       1      5     4     M    S     1      PT    N      EstadioNacToQueluz         6.0       80.0  60.0     2       0.00
10      1      8     108   M    S     1      PT    N      CaselasCRILMsantoCbosAvila 1.0       80.0  60.0     4       0.00
11      1      8     107   M    S     1      PT    N      CaselasToA5Monsanto        1.0       80.0  60.0     4       0.00
12      1      108   9     M    U     1      PT    N      CRILMsantoCbosAvilaToBenfc 3.0       80.0  60.0     4       0.00
13      1      108   109   M    U     1      PT    N      CRILMsantoCbosAvilaToAmdor 4.0       80.0  60.0     4       0.00
14      1      107   19    M    U     1      PT    N      A5MonsantoViadutoDtPacheco 4.0       80.0  60.0     4       0.00
15      0      20    19    M    U     1      PT    N      AceNorthBri25AbrilToViadut 3.0       80.0  60.0     4       0.00
16      1      20    37    M    U     1      PT    N      AceNorthToTheBridge25Abril 5.0       80.0  60.0     4       0.00
17      1      19    99    M    U     1      PT    N      ViadutoDtPachecoToEixoNS   2.0       80.0  60.0     4       0.00
18      1      99    13    M    U     1      PT    N      EixoNSToLargoLuz           3.0       80.0  60.0     4       0.00
19      1      9     99    M    S     1      PT    N      BenficaToEixoNorthSul      4.0       80.0  60.0     4       0.00
20      1      9     13    M    S     1      PT    N      BenficaToLargoLuz          5.0       80.0  60.0     4       0.00
21      1      9     45    M    S     1      PT    N      BenficaToCRILFalagueira    4.0       80.0  60.0     4       0.00
22      1      109   9     M    S     1      PT    N      AmadoraToBenfica           3.0       80.0  60.0     4       0.00
23      1      4     109   M    S     1      PT    N      EstadioNacToAmadora        5.0       80.0  60.0     4       0.00
24      1      4     3     M    S     1      PT    N      EstadioNacToBelas          3.0       80.0  60.0     2       0.00
25      1      1     2     M    S     1      PT    N      AlcabicecheToRanholas      11.0      80.0  60.0     2       0.00
26      1      64    2     M    S     1      PT    N      SintraToRanholas           4.0       80.0  60.0     2       0.00
27      1      2     3     M    S     1      PT    N      RanholasToBelas            17.0      80.0  60.0     2       0.00
28      1      3     44    M    S     1      PT    N      BelasToCRELBelas           5.0       80.0  60.0     2       0.00
29      1      44    45    M    S     1      PT    N      CRELBelasToCRILFalagueira  6.0       80.0  60.0     2       0.00
30      1      44    100   M    S     1      PT    N      CRELBelasToCRELA40         7.0       80.0  60.0     2       0.00
```

Figure 14 - Database structure for links information



```
Definition of costs of transportation -------------------------------------------------
Road
20
1.0    10.0   20.0   30.0    40.0   50.0   60.0   70.0   80.0   90.0   100.0   125.0   150.0  360.0  1000.0 1500.0 2000.0 2500.0   3000.0   3500.0
8.0    7.0    6.0    5.0     4.0    3.5    3.0    2.5    2.2    2.0    1.8     1.5     1.4    1.4    1.1     1.1    1.1    1.1      1.1      1.1
Rail
14
1.0    10.0   20.0   100.0   140.0  260.0  360.0  460.0  700.0  1000.0 1500.0 2000.0 2500.0 3000.0
3.00   3.00   3.00   3.00    3.00   3.00   2.10   1.30   1.30   1.30    1.30    1.30    1.30    1.30
Inland Waterway
10
1.0    10.0   20.0   100.0   160.0  260.0  360.0  1000.0 1500.0 2000.0
1.50   1.50   1.50   1.50    1.50   1.50   0.90   0.50    0.50    0.50
Short Sea Shipping (RoRo)
8
1.0    100.0   200.0   1000.0 1500.0 2000.0 2500.0 3000.0
10.50  4.50    2.50    0.90    0.60    0.30    0.30    0.30
Container
8
1.0    100.0   200.0   1000.0 1500.0 2000.0 2500.0 3000.0
1.00   1.00    1.00    0.70    0.40    0.20    0.20    0.20
Correction to road costs PT,ES,FR,BE,ND,DE,LU,UK,IR,SE,DK,IT,GR,MA
1.00 1.00 1.50 1.50 1.50 1.00 1.50 1.00 1.00 1.00 1.00 1.00 1.00 0.50
Margins for competition in cost (%)
15.0 30.0
Margins for competition in time (%)
15.0 30.0
Time value in money (Euro/TEU.h)
6.82
Daily rest (h) and break rest (h)
12.0 0.75
End of definition of cost of transportation -----------------------------------------------
```

Figure 15 - Database structure for cost information

3.4.2. Computation of Transport and Total Time, Distance and Generalized Costs

The developed algorithm for this project must return the shortest path routes in the intermodal network in relation to four main parameters: distance, transportation time, total time of transportation and generalized costs.

First, the distance 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 $TIME(a,b)$. Formulation 3.5. describes the procedure.

$$
\begin{array}{l}
for\ \{link\ j\} \in G(n,l) \\
\quad if\ j\ \rightarrow active \\
\quad\quad DIST(\,a(j), b(j)\,) = d(j) \\
\quad\quad TIME(\,a(j), b(j)\,) = \dfrac{d(j)}{V(j)}
\end{array}
\tag{3.5.}
$$

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, the calculation can be performed (Equation 3.6).

$$
\begin{array}{c}
if\ \left\{\, D(u) + TIME(u,v) + TC(v) < D(v)\ and\ MT(v) = MT\big(p(u)\big)\ \right\} then \\
TOTALTIME(v) = D(v) = D(u) + TIME(u,v) + TC(v)
\end{array}
\tag{3.6.}
$$

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

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. Formulations in 3.7 shows the procedure.

$$
\begin{aligned}
&if\ \{\ D(u) + C_{trans}(u,v) + toll(u,v) < D(v)\ and\ MT(v) = MT\big(p(u)\big)\ \}\ then \\
&\qquad D(v) = D(u) + C_{trans}(u,v)
\end{aligned}
\tag{3.7.}
$$

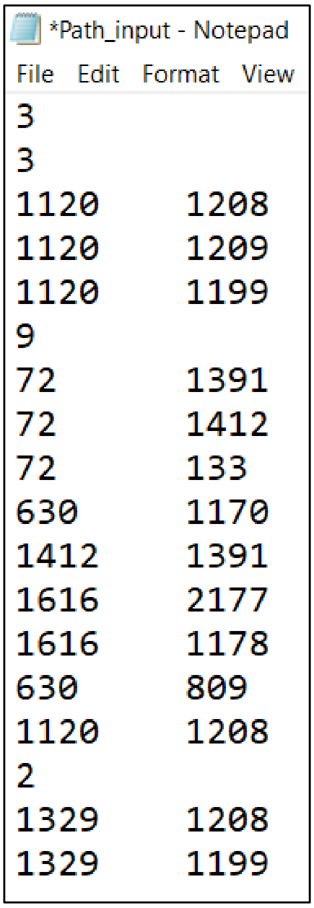
$$
\begin{aligned}
&if\ \{\ D(u) + C_{trans}(u,v) + LC(v) + UL\big(p(u)\big) + CS\ (v) * \big(TA(v) - FT(v)\big) + toll(u,v) \\
&\qquad < D(v)\ \ and\ MT(v) \neq MT\big(p(u)\big)\ \}\ then \\
&\qquad D(v) = D(u) + C_{trans}(u,v) + LC(v) + UL\big(p(u)\big) + CS\ (v) * \big(TA(v) - FT(v)\big) \\
&\qquad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

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 $(toll(a,b))$.

3.5 Implementation of Dijkstra’s Algorithm in the Network Model

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.

The program first step is input files reading and require a defined structured database, as defined previously (Figure 13, Figure 14 and Figure 15). In addition to the network and cost functions database, the program will require a path input file with the set of nodes of interest for calculation. The first line of the file must contain the number of desired group of nodes for study and from it, the number of nodes in the group and their definition according to a (destination – origin) organization. Figure 16 shows the structure of an example file for input in the program.



```
3
3
1120    1208
1120    1209
1120    1199
9
72      1391
72      1412
72      133
630     1170
1412    1391
1616    2177
1616    1178
630     809
1120    1208
2
1329    1208
1329    1199
```

Figure 16 - Input structure for desired nodes of study

After allocation of the required data and end of the file reading, the program starts to perform calculations of the transportation time and costs of the network links and store them into suitable arrays for the performance of the shortest path problem operation.

As the program will perform the calculations for the shortest path in relation to distance, transportation time, total time and generalized costs, the program requires an entry for the kind of calculation desired by the user: distance only or all four parameters. Then, another entry is required to verify the minimum paths using road-only transportation or an intermodal option, allowing to make use of all possible modes of transportation available in the network.

The initialization of Dijkstra’s algorithm defines some initial boundary conditions, as described in the section 3.3 Functioning of Dijkstra’s Algorithm. Figure 17 and Figure 18 shows the code’s flowchart.

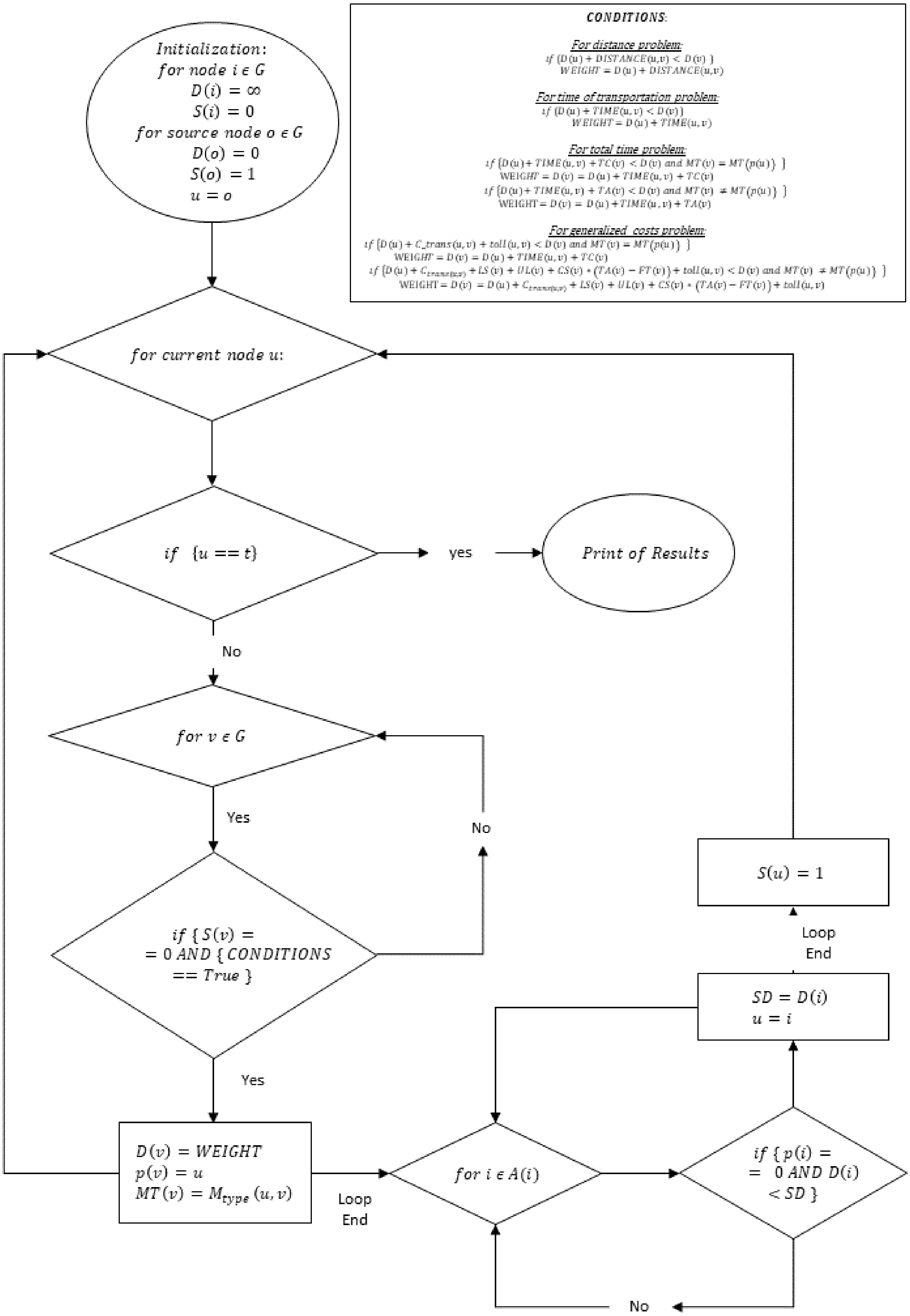
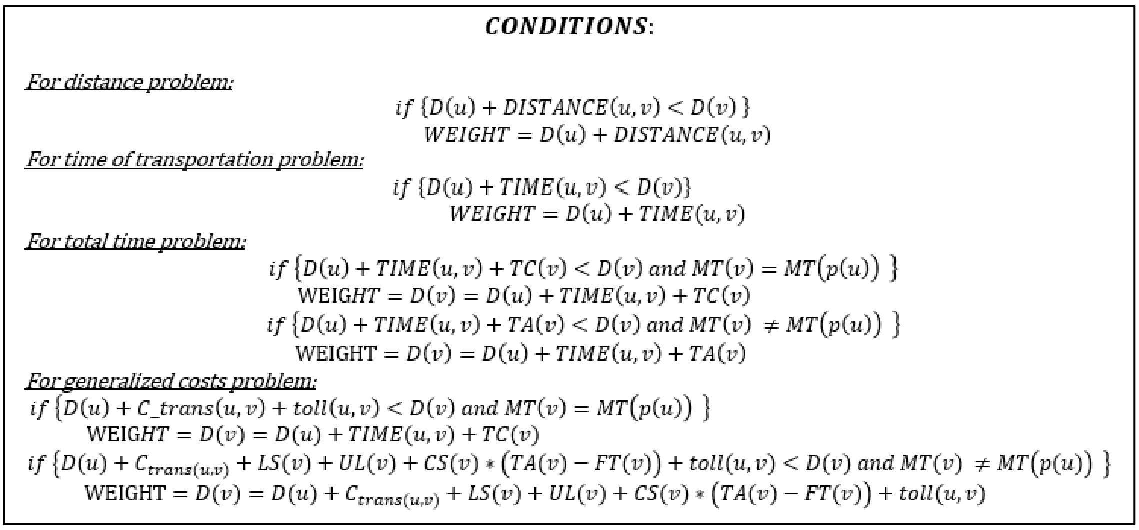


Figure 17 - Program's algorithm fluxogram

The algorithm for the search of the minimum path starts by sweeping all nodes and verifying whether they have not been processed yet and a determined set of conditions is true. Since the main SPP algorithm was coded as a *Fortran95* function, this set of conditions will depend on the optimization type (distance, transportation time etc). Some other secondary conditions appear in some of the algorithm's block, such as a verification of whether the storage costs will be taken into consideration by comparing the average time spent on node and the free storage time of it. However, most of them are created to the only finality of assisting a smooth run for program.



***CONDITIONS*:**

For distance problem:

$$if\ \{D(u) + DISTANCE(u,v) < D(v)\}$$
$$WEIGHT = D(u) + DISTANCE(u,v)$$

For time of transportation problem:

$$if\ \{D(u) + TIME(u,v) < D(v)\}$$
$$WEIGHT = D(u) + TIME(u,v)$$

For total time problem:

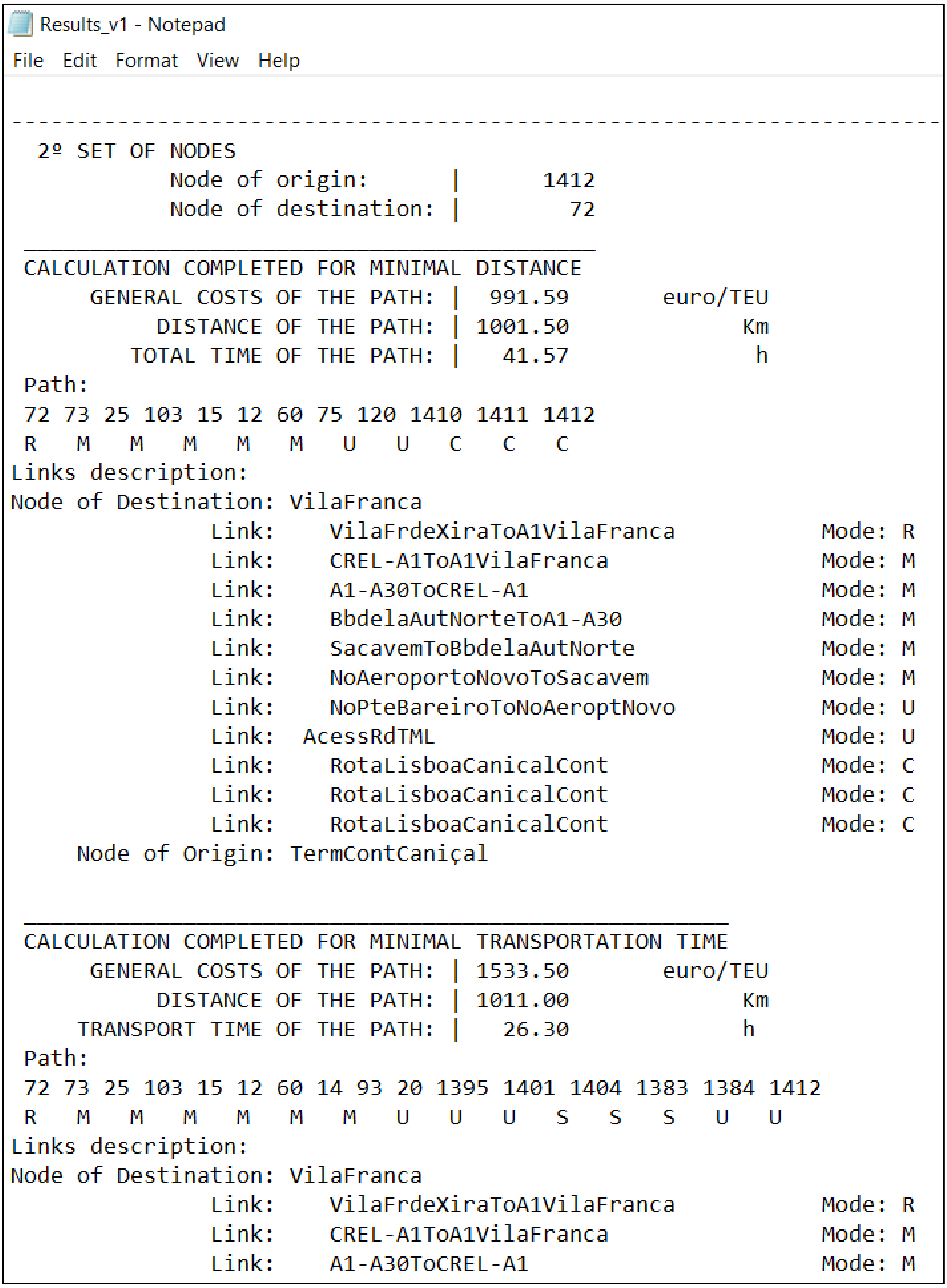
$$if\ \{D(u) + TIME(u,v) + TC(v) < D(v)\ and\ MT(v) = MT(p(u))\ \}$$
$$\text{WEIGHT} = D(v) = D(u) + TIME(u,v) + TC(v)$$
$$if\ \{D(u) + TIME(u,v) + TA(v) < D(v)\ and\ MT(v)\ \neq MT(p(u))\ \}$$
$$\text{WEIGHT} = D(v) = D(u) + TIME(u,v) + TA(v)$$

For generalized costs problem:

$$if\ \{D(u) + C\_trans(u,v) + toll(u,v) < D(v)\ and\ MT(v) = MT(p(u))\ \}$$
$$\text{WEIGHT} = D(v) = D(u) + TIME(u,v) + TC(v)$$
$$if\ \{D(u) + C_{trans(u,v)} + LS(v) + UL(v) + CS(v) * (TA(v) - FT(v)) + toll(u,v) < D(v)\ and\ MT(v)\ \neq MT(p(u))\ \}$$
$$\text{WEIGHT} = D(v) = D(u) + C_{trans(u,v)} + LS(v) + UL(v) + CS(v) * (TA(v) - FT(v)) + toll(u,v)$$

Figure 18 - Algorithm's calculations

After the amount of necessary iterations, the program returns the calculated results. Regardless of the SPP optimization type, the program will return the generalized costs of transportation, time of transportation, total time of transportation and total distance of the shortest path found, as well as the nodes through which the optimum goes and the type of modal used by the links. This allows a better visualization of results and also provides a higher analysis capacity.



```
----------------------------------------------------------------------
  2º SET OF NODES
            Node of origin:      |      1412
            Node of destination: |        72
 ___________________________________________
 CALCULATION COMPLETED FOR MINIMAL DISTANCE
      GENERAL COSTS OF THE PATH: |  991.59       euro/TEU
           DISTANCE OF THE PATH: | 1001.50             Km
         TOTAL TIME OF THE PATH: |   41.57              h
 Path:
 72 73 25 103 15 12 60 75 120 1410 1411 1412
 R   M   M   M   M   M   U   U   C   C   C
Links description:
Node of Destination: VilaFranca
               Link:    VilaFrdeXiraToA1VilaFranca           Mode: R
               Link:    CREL-A1ToA1VilaFranca                Mode: M
               Link:    A1-A30ToCREL-A1                      Mode: M
               Link:    BbdelaAutNorteToA1-A30               Mode: M
               Link:    SacavemToBbdelaAutNorte              Mode: M
               Link:    NoAeroportoNovoToSacavem             Mode: M
               Link:    NoPteBareiroToNoAeroptNovo           Mode: U
               Link:  AcessRdTML                             Mode: U
               Link:    RotaLisboaCanicalCont                Mode: C
               Link:    RotaLisboaCanicalCont                Mode: C
               Link:    RotaLisboaCanicalCont                Mode: C
     Node of Origin: TermContCaniçal


 _____________________________________________________
 CALCULATION COMPLETED FOR MINIMAL TRANSPORTATION TIME
      GENERAL COSTS OF THE PATH: | 1533.50       euro/TEU
           DISTANCE OF THE PATH: | 1011.00             Km
     TRANSPORT TIME OF THE PATH: |   26.30             h
 Path:
 72 73 25 103 15 12 60 14 93 20 1395 1401 1404 1383 1384 1412
 R   M   M   M   M   M   M   U   U   U   S   S   S   U   U
Links description:
Node of Destination: VilaFranca
               Link:    VilaFrdeXiraToA1VilaFranca           Mode: R
               Link:    CREL-A1ToA1VilaFranca                Mode: M
               Link:    A1-A30ToCREL-A1                      Mode: M
```

Figure 19 - Output file structure (Example: Shortest path from Caniçal container terminal to Vila Franca)

4. NUMERICAL STUDIES

A number of numerical studies are presented in this chapter 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 [40]. On the other hand, Portugal's geographical position is also extremely strategic due to its long extension of the Atlantic coastline and its seaports characteristics, positioning the country in a privileged entry point for cargo coming from the rest of the World into Europe: in terms of maritime traffic, the Portuguese EEZ (Economic Exclusive Zone), which is up to 200 nautical miles from the Portuguese territories coasts, is crossed by some of the main shipping lanes transporting goods throughout the world, passing through major players in the global trade in the Mediterranean, northern Europe, Africa and America. Much of the worldwide freight carried by sea passes along the Portuguese coast.

Portugal has 22 seaports available, of which the most significant, in terms of commercial shipping, are Lisbon, Sines, Leixões, Setubal and Funchal. The rest of them are smaller and are designated as secondary in the Portuguese port system (regarding the continent). Together, these 5 seaports handle the majority of vessels coming to Portugal each year [41], meaning that the access to them is imperative to the Portuguese economy. The Port of Sines, the biggest in the country, has registered a cargo movement of 46.473 million tons in 2017 and was ranked among the TOP20 largest ports of the EU.

4.1.1. Optimum Route from Lisbon to XXI Terminal in Sines

The Port of Sines is the first artificial port of Portugal, created to be a deep water port with natural depths down to 17 m ZH and also with specialized terminals which allow the port to handle different types of cargos. Being Portugal’s largest port in relation to moved goods, it requires a good connection to other Portuguese municipalities, specially related to containerized cargo. The terminal XXI, Port of Sines’ container terminal, can receive the biggest and most modern container carriers performing intercontinental routes, making the port the main entry to foreign goods and the principal gateway for exportation.

The connection of the Port of Sines to the Lisbon is of imperative importance due to the Portuguese capital’s importance in the global scenario. In what concerns the Port of Sines’ hinterland, there are good direct connections to the national road and rail network, both integrated on Atlantic Corridor of the Trans European Transport Network.

The optimization of the routes linking these two locations is, therefore, often needed in the Portuguese transportation scenario. The implementation of the developed code can help find alternatives for transportation of cargo between the cities, including intermodal alternatives that can decrease the number of trucks used for road transportation, relieving road congestion, reducing costs of transportation and increasing competitivity.

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 20 (Route’s sketch). 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.The results of the program (Table 1), show that although there’s 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.

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	*

Figure 20 – Sketch of optimum routes between Lisbon and Sines

It’s also possible to observe a high dependency on both main bridges in Lisbon (25 de Abril and Vasco da Gama) to transport cargo to the cities in the south of Portugal. This, combined to daily regular traffic, causes congestions that can influence on the total time of transportation. By setting as inactive the links to these bridges, one can observe some changes in routes: for total time optimization, the shortest path will be the one that goes to Vila Franca, northeast of Lisbon, and then goes down all the way to Sines by motorway. The results in Table 3 show that the total time is slightly increased by going to Vila Franca whereas the generalized costs do not change significantly when compared to the routes using the bridges, meaning that the route is a good alternative for road-only transportation to avoid congestion.

Table 3 - Results for optimum routes between Lisbon and Sines without using Lisbon bridges

Route Lisbon - Term. XXI (Sines) Bridge Links Inactive	**Total Time optimization - all modes transportation**
Distance (km)	190.50
Total Time of Transportation (h)	2.65
Generalized Costs (€/TEU)	1174.92
Modes of Transportation	R

4.1.2. Optimum Route from Guarda to the Port of Leixões

The Port of Leixões is the biggest port in the northern region of Portugal and handles a great amount of the Portuguese international trade, given the location in the region of Porto and with a hinterland rich of industries. This, however, might also be seen as a drawback since the densely populated region surrounded by the port hinders its expansion possibilities, affecting the growth of the Port.

A possible alternative to contour this situation is the connection with dry ports, which did not have a proper regimentation until 2019, when the Decree-Law n.º 53/2019 has been approved by the Portuguese government. Dry ports are viable solutions since they act as interior nodes for the concentration of goods, empty container warehouses and other value-added logistics services. The Decree-Law regulated the procedures for the circulation of goods and their introduction into the national territory, as well as the procedures for the movement of goods to be removed from the national territory. According to the document, "the implementation of the dry port concept has numerous benefits in terms of increasing the capacity of the competent authorities to act on the execution of transport processes, given the greater visibility of the entire logistics chain, the optimization of multimodal operations, through the sharing of information and the reduction of contextual costs, namely the global number of empty trips and waiting times and congestion when goods leave".

Although in Portugal there are already interior platforms and terminals, which can now become dry ports and which already addressed this need, allowing the concentration of cargo for direct intermodal connections with ports or other intermodal terminals, "Brexit" accelerated the need for rapid implementation of this measure. According to specialists in the sector [42], "Brexit" might introduce additional bureaucratic effort in national maritime terminals, with consequences that might affect cargo clearance and thus creating congestions in the ports. The dry port model will allow quick transfer between maritime terminals and dry ports, ensuring that domestic ports are not strangled.

The city of Guarda, in the northern-central region of Portugal, is a strategic location for the construction of a Dry Port, given its privileged conditions for logistics with two railway lines connected to the main Portuguese railways and two highways crossing the city. The installation of the dry port would allow greater competitiveness to this area and could become a gateway for goods from Europe to Portugal, as well as a gateway for goods that are manufactured in Portugal to Europe and the rest of the world.

When applying the developed algorithm to the route between Guarda and Port of Leixões, results (Table 4) show that the use of the railway lines are much more cost efficient than road-only routes, which is the case of the shortest paths regarding distance, transportation time and total transportation time, that shows optimum routes using trucks, going through highways that cross the municipalities of Viseu and Vila Nova de Gaia. Figure 21 illustrates a sketch of the routes between the two locations.

The increase in the amount of total time of transportation for the railway route, explained by the handling services at the rail terminal of Guarda, can be object of further study for the implementation of a dry port in the region as it can be optimized and thus increase competitiveness of the terminal to justify investments in the region.

Table 4 - 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	*

Figure 21 - Sketch of optimum routes between Guarda and the Port of Leixões

4.1.3. Optimum Route from Aveiro to the Port of Lisbon

The port of Lisbon is located at the mouth of the Tagus River, in an area where the river delta is quite wide, between the northern part, in the Lisbon area (being the metropolitan area of Lisbon the largest consumption center in the country) and the cities located to the north of the Setúbal Peninsula (south bank of the river). The Tagus estuary configures the port as natural and allows the operation on the two banks of the river, offering favorable conditions for the development of port in a densely populated area.

Being located in the center of Portugal’s economy, the Port of Lisbon possess connections to the Portuguese railway and road networks, besides having Tagus’ inland waterway which can be opportunities to further increase the connectivity of the port to the rest of the country.

To study the accessibility of the Port of Lisbon, the city of Aveiro, located in the central region of the country, was taken to be object of study given the presence of container terminal in the Port of Aveiro and due to the implementation of the ZALI (Zone of Logistics and Industrial Activities), located 9 km from the port in Cacia and with railway connections to the rest of the country (including one direct route to the northern line Porto – Lisbon).

When applying the optimization procedure, the routes varies significantly among the different optimization criteria adopted. Regarding optimum paths in relation to distance, the obtained route consists in a mixture between rail, road and IWW modes of transportation: the cargo leaves Aveiro by the railway to the rail terminal of Entroncamento and then performing a road haulage to the fluvial terminal of Golegã, being then transported through the Tagus river until the Alcantara terminal of the Port of Lisbon (Liscont). For transportation time optimization, the best route consists in taking the cargo by railway to the rail terminal in Cacia and then performing the rest of the route by road. As one can observe with the results in Table 5, the cost of transportation is greatly increased whereas the total distance is almost the same. Furthermore, it's important to remember that the total time of transportation for transportation time optimization does not considers the time spent in the terminal, which means that the total time of transportation is actually higher.

Regarding total time of transportation optimization, the optimum route uses a mixture of rail and road modes a bit similar to the transportation time optimization. The difference, however, lies on the extension of the railway until the rail terminal of Alfarelos, near Coimbra, and performing the rest of the route by trucks to Lisbon.

When the optimization for generalized costs is applied, the calculated route varies abruptly when compared to the other optimization criteria. The cargo is moved from Aveiro to the terminal container terminal in Leixões and then carried to Lisbon via the containership line between Leixões and Morocco, stopping in Santa Apolonia container terminal and moved through the Tagus river to Alcantara Terminal via IWW.

As one can see, even though the cost of transportation is reduced, the total transportation time is significantly higher than the other optimum routes. Furthermore, the distance optimization criteria provided similar results in terms of costs but with a significant smaller total time of transportation, meaning that the further investment for the development of the involved terminals - specially between Entroncamento and Golegã – shall provide better results in terms of cost and time.

Table 5 - 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	*

Figure 22 - Sketch of optimum routes between Aveiro and the Port of Lisbon

4.2 Optimum Routes Involving Maritime Transportation

In this section, the study will be directly related to the efficiency of maritime transportation among the European Union, with a focus on the Portuguese ports and the routes involving the exportation of goods from Ireland to the rest of Europe, especially since Brexit shall shift the exportation measures of the United Kingdom and thus involve Irish ports to flow British goods and avoid customs clearances.

4.2.1. Optimum Route Involving Portuguese Ports

As discussed in chapter 4.1., Portugal is located in a strategic position in Europe, providing natural conditions for the entry of cargo from the rest of the world.

The Port of Leixões, one of the biggest in the country, has exported more than 1M tons of goods in the first trimester of 2020 and plays an important role in the European maritime transportation. As the port continues to grow in relevance in the global scenario, expansion projects for the port, not only in terms of infrastructure, are topics of frequent discussion. In June 2020, for example, the Port of Leixões started to ensure a new connection to the port of Zeebrugge, in Belgium, with port calls in Sweden, Denmark and Ireland. The new connection is expected to increase the flow of goods through the port, especially related to Ro-Ro cargo, since the Port of Zeebrugge is one of the main references for Ro-Ro traffic in Europe.

The connection of the Port of Leixões to the rest of the EU is an important factor for the Portuguese economy to access international markets and the further development of the regions surrounded by it.

France is the second biggest consumer of Portugal’s exportation goods, representing about 13% in terms of financial volume of the country’s exports [43]. To verify the connection to France, it was decided to compare the optimum routes between the rail terminal of Valongo, in the region of Porto, to Rouen, a French city located about 80 km to the east of the Port of Le Havre.

The results for the optimum routes between these two locations can be seen in Table 6, for total time and general costs optimizations. It is interesting to observe that the minimal total time of transportation is given by road-only mode of transportation, taking about 20 hours to complete the trajectory, whereas the general costs optimization returns a path with the same order of magnitude in terms of distance but with general costs up to 65% more economic. As possible to see in the sketch of Figure 23, the former path consists in a truck transportation leaving Portugal through Bragança and then crossing northern Spanish motorways to get to France, concluding the last road leg to Rouen. The latter consists in using the rail terminal in Valongo to get to the terminal container of the Port of Leixões, using the container line between the Portuguese city and the Port of Le Havre, using then the Sena River to transport the cargo to Rouen in its IWW terminal.

Table 6 - Results for optimum routes between Valongo and Rouen

Route Valongo - Rouen	**Total Time optimization - all modes transportation**	**General Costs optimization - all modes transportation**	**Percentual Difference (%)**
Distance (km)	1579.4	1560.9	-1%
Total Time of Transportation (h)	20.05	82	309%
Generalized Costs (€/TEU)	5236.76	1853.33	-65%
Modes of Transportation	R	F - C - I	*

The path using intermodal transportation, although more cost efficient, loses its competitivity when analyzing its total time of transportation. The path takes about 82 hours to be completed, which is more than four times the shortest path regarding time. This difference, however, might be an object of study for the terminals involved in the transportation: the optimization of their infrastructure can decrease the lead time and thus increase competitivity of this parameter. For instance, the average total time in the Port of Leixões is of 24 hours, corresponding to almost 1/3 of the total time of transportation. Should the terminal invest on more efficient quay cranes or reduce the waiting time for bureaucracy, the port time decreases and the optimum path gains competitivity in all aspects.

Figure 23 - Sketch of optimum routes between Valongo and Rouen

Another important transportation route in Portugal is the supply chain logistics services to the Island of Madeira. Even though the main economic activities of the island are related to tourism, the exportation of goods from the island has been increasing significantly since 2012 according to the National Institute of Statistics (INE) [44], mainly due to wine and embroidery produced in the island. Furthermore, the region requires the importation of products which the island is unable to produce, thus demanding an efficient port system in order to allow a smooth flow of goods.

The main ports in Madeira are the port of Funchal and the port of Caniçal. The port of Funchal is one of the main ports in Portugal and is currently the Portuguese national port with the highest number of tourists and the 13th in Europe. It also represents an important port of call for transoceanic voyages, linked to the annual repositioning of ships between the United States and Europe. The port of Caniçal, on the other hand, was initially aimed at supporting the Madeira Free Trade Zone, as it was dedicated to the operation of containers and fishing, with two main areas, each one of them specialized in these types of cargos. Over the years, with difficulties regarding accumulation of a set of functions in the Port of Funchal, the Economic and Social Development Plan (PDES 2000-2006), declared that investments in port infrastructure should be aimed in the port of Caniçal (for the movement of goods and support to fisheries), in order to give it better operational conditions, providing better quality services and increasing the port’s competitivity [45].

To study the movement of cargo from continental Portugal to Madeira, the city of Vila Franca was chosen due to its proximity to the metropolitan region of Lisbon, strategic industries and the possibility of using Tagus IWW.

Results in Table 7 show that the use of the Port of Funchal is used when optimizing the route regarding distance, whereas the Port of Caniçal is used for the other optimum routes. This, however, does not show that Funchal loses competitivity in relation to Caniçal: by observing the optimum routes for distance and generalized costs optimization, one can see that there is a slight difference in the distance and total time of transportation, with a higher gap between the total costs of transportation of about 25%. This is given mainly due to the cargo handling costs at the Port of Funchal, which makes generalized costs go up when going through this port of call, however, the use of the IWW route via the Tagus river to connect Vila Franca to the Port of Lisbon is as well a good option for cost reduction. Therefore, using the IWW other than road might also reduce the cost of transportation when going to the Port of Funchal, allowing it a possible larger flow of goods.

Table 7 - Results for optimum routes between Vila Franca and Funchal

Route Vila Franca - Funchal	**Distance optimization - all modes transportation**	**Transportation Time optimization - all modes transportation**
Distance (km)	1027.4	1040.6
Total Time of Transportation (h)	46.72	26.67
Generalized Costs (€/TEU)	1496.62	1753.92
Modes of Transportation	R - S - R (Funchal)	R - S - R (Caniçal)

	Total Time optimization - all modes transportation	**General Costs optimization - all modes transportation**
Distance (km)	1226.2	1046.1
Total Time of Transportation (h)	41.96	49.6
Generalized Costs (€/TEU)	3188.67	1114.95
Modes of Transportation	R - S - R (Caniçal)	R - I - C - R (Caniçal)

Figure 24 - Sketch of optimum routes between Vila Franca and Funchal (Madeira Island is out of scale)

4.2.2. Optimum Routes Involving the Port of Dublin

Since the United Kingdom officially left the European Union in the beginning of 2020, Ireland gained an opportunity to become the bridge between the British goods to the rest of Europe, given its location on the British island and good relation with the UK. The Brexit, however, implies also further challenges for the emerald island ports in matters of customs clearance services, as it adds extra costs and inefficiency in the supply chain.

The port of Dublin, by far the busiest port of Ireland, handling approximately two-thirds of Ireland's port traffic travels, has already spent €30 million on primary and secondary inspection posts at the port in 2018, preparing for Britain's departure from the EU single market and customs union [46]. However, the port will still depend on third parties (State agencies, ferry companies etc) to complete preparations during 2020 to ensure the continued smooth flow of trade with the UK.

As aforementioned, Portugal has a good opportunity to become a gateway for British goods, specially now with the creation of the legislation for the legal definition of dry ports. As Brexit could introduce additional bureaucratic effort in national maritime terminals, the dry port model shall be able to allow quick transfer between maritime terminals and dry ports, ensuring that national ports are not strangled. Moreover, the creation of a new direct Ro-Ro commercial triangulation line of CLdN between the ports of Leixões, Liverpool and Dublin, announced in the middle of 2020, strengthens the Iberian link with the British islands and shows that the country is already taking measures to increase its competitiveness in face of the imposed challenge caused by Brexit.

To analyze the optimum routes from Dublin to Portugal, it was chosen to use the ferry terminal of Valongo, near Leixões, as reference. For distance optimization, the cargo leaves Dublin via its Ro-Ro terminal to Liverpool, taking then a large road transportation leg to Massvlatk, in the Netherlands, using again a Ro-Ro line to the terminal XXI in Sines. The cargo, once again, takes a large road portion (using a small railway line between Entrocamento and Alfarelos) to Valongo. This route is also the optimum path for minimal transportation time and total transportation time, with small differences in the path regarding the use of a small portion of railways. The main difference lies in the optimization of minimal transportation costs: the cargo leaves the Ro-Ro terminal in Dublin to Cherbourg in France and then uses a road portion to the container terminal in Le Havre. There, it goes to the container terminal of Leixões, where the cargo is transported via railway to Valongo.

Table 8 - Results for optimum routes between Dublin and Valongo

Route Dublin - Valongo	Distance optimization - all modes transportation	Transportation Time optimization - all modes transportation
Distance (km)	1011.8	1021.5
Total Time of Transportation (h)	123.81	13.8
Generalized Costs (€/TEU)	5462.81	5916.03
Modes of Transportation	R - F - S - F - R	R - S - R
	Total Time optimization - all modes transportation	**General Costs optimization - all modes transportation**
Distance (km)	1579.4	1560.9
Total Time of Transportation (h)	20.05	82
Generalized Costs (€/TEU)	5236.76	1853.33
Modes of Transportation	R – S – R – F – R – S – R - F	R – S – R – C - F

As one can see in Table 8, the difference in the generalized costs is about three times smaller when using the container route Leixões – Le Havre. However, to study the impact of costs with the new triangulation line, a link between the Ro-Ro terminal of Dublin and Leixões was created to simulate the cost impact of this new route. The results for the optimization algorithm did not change for distance, transportation time and total transportation time, but for generalized costs the outcome was clearly visible. The route uses the new Ro-Ro line and the railway line between Leixões and Valongo, with a reduction of cost of about 40% and even with a reduction in time (Table 9).

Table 9 - Results with addition of the direct Ro-Ro line between Dublin and Leixões

Route Dublin - Valongo	Generalized Costs optimization - all modes transportation
Distance (km)	1707.00
Total Time of Transportation (h)	78.11
Generalized Costs (€/TEU)	1126.76
Modes of Transportation	R - S - F

Another important route for the connection between the UK and continental Europe is the Ro-Ro line between Dublin and Cherbourg. To transport cargo to the city of Caen, for example, the algorithm was applied to verify the difference in costs when using the Ro-Ro line and when using the connection between Dublin and Liverpool. The results in Table 10 show that the Ro-Ro line Dublin – Cherbourg presents a generalized cost of about half the cost when using the Ro-Ro line Dublin – Liverpool.

Table 10 - Results for optimum routes between Dublin and Caen

Route Dublin - Caen	**Distance optimization - all modes transportation**	**Transportation Time optimization - all modes transportation**
Distance (km)	834.3	1106
Total Time of Transportation (h)	35.21	19.43
Generalized Costs (€/TEU)	2323.43	4399.72
Modes of Transportation	R – S - R	R – S -R – F - R
	Total Time optimization - all modes transportation	**General Costs optimization - all modes transportation**
Distance (km)	1106	834.3
Total Time of Transportation (h)	22.93	35.21
Generalized Costs (€/TEU)	4399.72	2323.43
Modes of Transportation	R – S -R – F - R	R – S – R – C - F

4.3 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 mentioned in 2.1.2. Intermodality in Europe, is a 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, as one can see in Figure 25. 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.

Figure 25 - Atlantic Rail Freight Corridor (Source: www.corridor4.eu)

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. 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 11 - 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%.

4.4 Optimum Routes to NUTS 2 in Northern Europe

This section will focus mainly on the routes used to connect NUTS 2 regions in northern Europe to the rest of the continent. The study will be directed to Netherlands and Germany as both countries play important roles in terms of transportation in Europe, with the ports of Rotterdam and Antwerp being the busiest ports in Europe in terms of container throughput.

Rotterdam has by far the biggest port in the European union and consequently in the Hamburg - Le Havre range (NUTS 2 Regions) and not only for bulk goods, but for containers well. The dominance of the port is a clear illustration of the fact that the city is located in a favorable geographical location within Western Europe, its location at the mouth of the River Rhine and its excellent connection with the North Sea. The port handles a large stream of containers via deep sea shipment originating from all over the world and is one of the major gateways of goods arriving from different countries, specially China and other Asiatic countries. The Port of Rotterdam’s area can be seen in Figure 26.

The container flow from the port to the hinterland proceeds via a variety of modes of transportation, with a considerable volume of container traffic being transported by inland waterways, with a major stream moving along the Rhine river to Germany. The importance of the hinterland connections has been a subject of frequent discussion in the port authority’s board of direction, with a constant need to improve and optimize the transport connection from Europe’s largest container hub. Plans have already been put in place to upgrade rail infrastructure in the region: the extension of the Betuweroute line between Oberhausen and Emmerich in North Rhine-Westphalia, the construction of an alternative route to the Middle Rhine Valley, seen as necessary for optimizing transportation; and also initiatives to expand the inland navigation corridor, with direct participation of the German government [47].

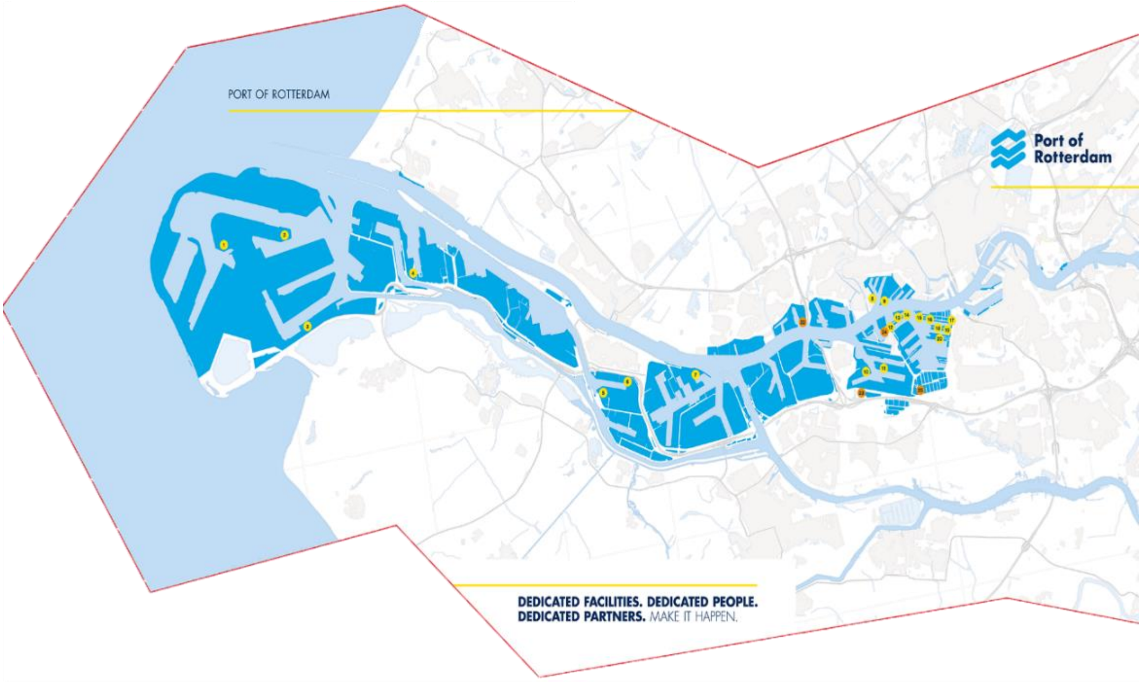


Figure 26 - Port of Rotterdam’s area

The optimization algorithm was applied to verify the port’s connection to some strategic locations in Germany: the rail terminal in Oberhausen and to Hamburg. Between Rotterdam and Oberhausen, the paths vary significantly depending on the used optimization method. For distance optimization, the route uses entirely rail transportation, whereas for transportation time and total transportation time there is a majority use of road transportation, with a small portion of rail transportation in the latter from Rotterdam to Betuwert. The generalized costs optimization, however, uses a significant portion of inland waterways from Rotterdam to Ruhrort in Germany, with the rest of the connection being performed by rail.

If one analyze the results in Table 12, however, it is possible to observe that the cost difference between general cost and distance optimization is in the magnitude of 20% whereas the time of transportation is almost eight times greater. This means that the rail corridor between this two cities is more competitive when compared to IWW transportation in the region even though the best cost related alternative is their use. Improvements in the infrastructure of the region for example might increase the potential of inland waterways when compared to both rail and road transportation, since the use of road-only transport also requires a much smaller transportation time.

Table 12 - Results for optimum routes between Rotterdam Ro-Ro terminal and Oberhausen rail terminal

Route Rotterdam Ro-Ro Terminal - Oberhausen Rail Terminal	**Distance optimization - all modes transportation**	**Transportation Time optimization - all modes transportation**
Distance (km)	225.7	242.9
Total Time of Transportation (h)	6.1	3.05
Generalized Costs (€/TEU)	677.1	1294.11
Modes of Transportation	F	R
	Total Time optimization - all modes transportation	**General Costs optimization - all modes transportation**
Distance (km)	245.9	265
Total Time of Transportation (h)	3.51	47
Generalized Costs (€/TEU)	1211.72	543.1
Modes of Transportation	F - R	F - I - F

From Rotterdam to Hamburg, the paths calculations are the same for distance, transportation time and total transportation time optimizations, using road-only transportation to move cargo. For generalized costs, however, the path takes mostly the inland waterway in the Rhine river to Ruhrort, using after that trucks to transport cargo. This path, however, as might be observed in Table 13, has a cost reduction in the order of 18% and a increase in time transportation in about 50 hours.

Once again, it is verified that the use of inland waterways can be a cost efficient and also eco-friendly solution for the flow of goods from the port of Rotterdam, however, improvements in its infrastructure and implementations of new technologies to reduce the time spent on terminals shall be a good way for this type of transportation to gain competitivity compared to road transportation.

Table 13 - Results for optimum routes between Rotterdam Ro-Ro terminal and Hamburg

Route Rotterdam Ro-Ro Terminal - Hamburg	**Distance optimization - all modes transportation**	**Transportation Time optimization - all modes transportation**
Distance (km)	481.4	481.4
Total Time of Transportation (h)	6.03	6.03
Generalized Costs (€/TEU)	2277.91	2277.91
Modes of Transportation	R	R
	Total Time optimization - all modes transportation	**General Costs optimization - all modes transportation**
Distance (km)	481.4	597.5
Total Time of Transportation (h)	6.03	57.06
Generalized Costs (€/TEU)	2277.91	1867.8
Modes of Transportation	R	R - I - F

4.5 Competitiveness of River-Sea Transportation from Golegã to Sines

4.5.1 General Outline of Case Study

The main objective of this case study is to observe the competitiveness of river-sea containerized cargo transportation using Tagus river and coastal waters to Sines. 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.

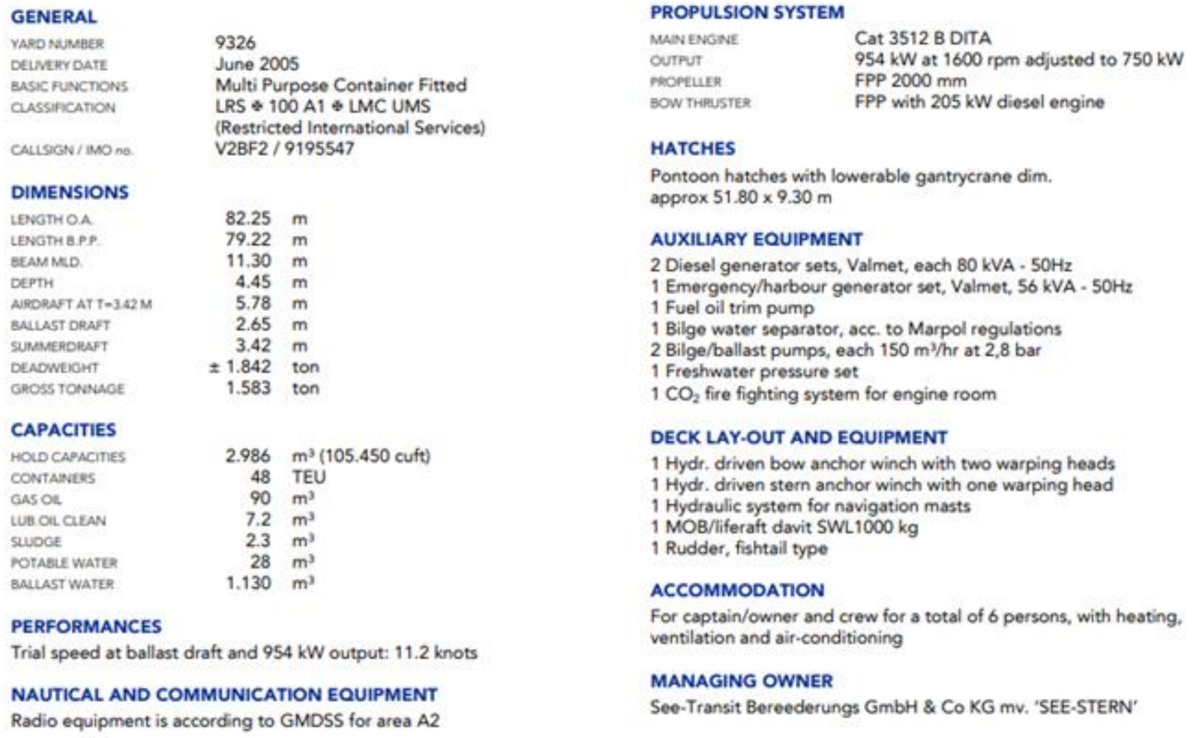
Furthermore, two other intermodal transport chains were studied to verify the competitiveness of rail transportation compared to road-only and river-sea transportation. These other transport chains use rail terminals in Guarda and Lousado. The two cities have got projects for the installation of intermodal terminals (as previously discussed about Guarda) and can boost Portugal’s intermodal traffic, allowing a greater shift from road transportation [48].

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 is analyzed to estimate the costs of transportation per unit of cargo in this river-sea part of the transport chain. These new paths will then be 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, road sections will be obtained using the algorithm and used for the analysis of railway transportation from terminals in Guarda and Lousado.

4.5.2 Transport costs from Golegã to Sines using a river-sea vessel

In order to study the transport costs between Golegã and Sines container terminal, the containership DAMEN COMBI COASTER 1700 was chosen. This is because its characteristics match with the requirements in river Tagus, mainly regarding draft and breadth. These are considered to be a maximum draft of 4m and a maximum breadth of 12m, values in line with current practice for inland ships in river Douro, for example. Furthermore, projects and studies are being developed to allow a better utilization of the hydric resources of the river, associated with flood control, draining and also making feasible the navigability in the region. “Projeto Tejo”, for example, proposes the implementation of small dams (fitted with locks) that should allow both the irrigation of agricultural fields in the Ribatejo and also turning the navigation possible [49].

The ship’s characteristics can be seen in Figure 27 and Figure 28 shows a vessel built according with the Combi Coaster project.



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	m^3 (105.450 cuft)
CONTAINERS	48	TEU
GAS OIL	90	m^3
LUB.OIL CLEAN	7.2	m^3
SLUDGE	2.3	m^3
POTABLE WATER	28	m^3
BALLAST WATER	1.130	m^3

PERFORMANCES

Trial speed at ballast draft and 954 kW output: 11.2 knots

NAUTICAL AND COMMUNICATION EQUIPMENT

Radio equipment is according to GMDSS for area A2

PROPULSION SYSTEM

MAIN ENGINE	Cat 3512 B DITA
OUTPUT	954 kW at 1600 rpm adjusted to 750 kW
PROPELLER	FPP 2000 mm
BOW THRUSTER	FPP with 205 kW diesel engine

HATCHES

Pontoon hatches with lowerable gantrycrane dim.
approx 51.80 x 9.30 m

AUXILIARY EQUIPMENT

2 Diesel generator sets, Valmet, each 80 kVA - 50Hz
1 Emergency/harbour generator set, Valmet, 56 kVA - 50Hz
1 Fuel oil trim pump
1 Bilge water separator, acc. to Marpol regulations
2 Bilge/ballast pumps, each 150 m^3/hr at 2,8 bar
1 Freshwater pressure set
1 CO_2 fire fighting system for engine room

DECK LAY-OUT AND EQUIPMENT

1 Hydr. driven bow anchor winch with two warping heads
1 Hydr. driven stern anchor winch with one warping head
1 Hydraulic system for navigation masts
1 MOB/liferaft davit SWL1000 kg
1 Rudder, fishtail type

ACCOMMODATION

For captain/owner and crew for a total of 6 persons, with heating, ventilation and air-conditioning

MANAGING OWNER

See-Transit Bereederungs GmbH & Co KG mv. ‘SEE-STERN’

Figure 27 - Technical characteristics of selected ship. Source: DAMEN

Figure 28 - River-sea ship of Combi coaster design.

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”) was taken into consideration (Figure 27), 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.

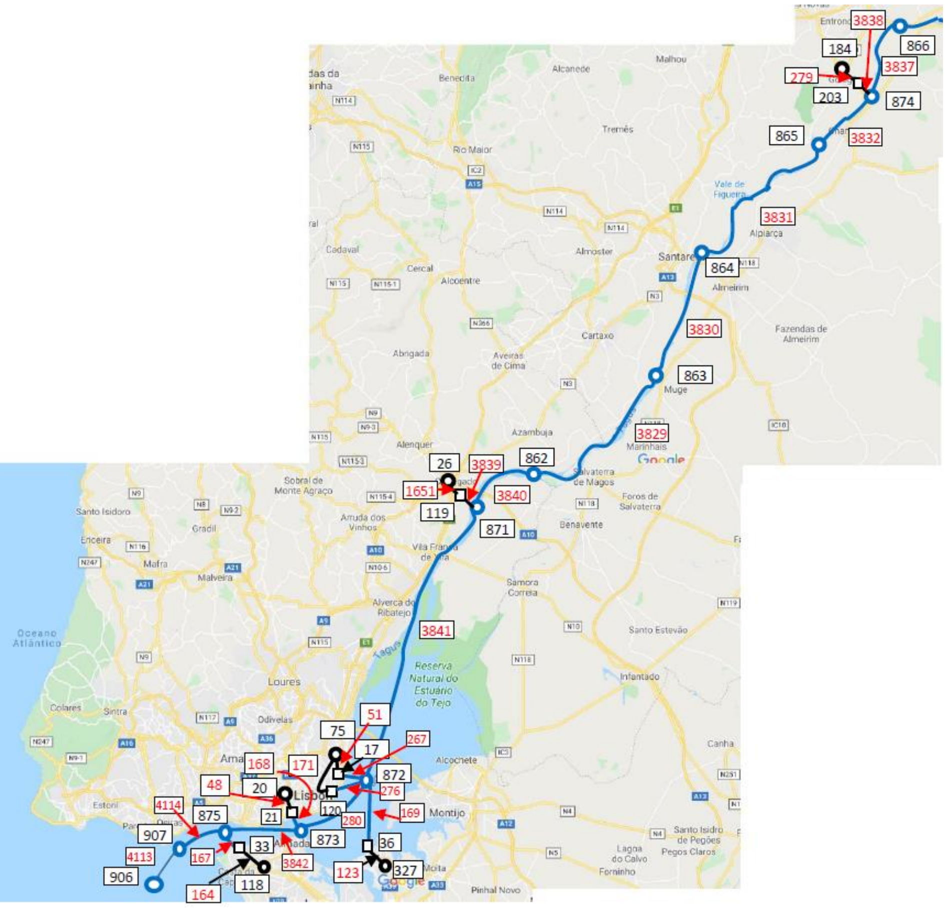


Figure 29 - Tagus river inland waterway (locks between Golegã and Lisbon are represented by nodes 862 to 865).

The handling of containers in the Golegã and Sines terminals is assumed to cost 25€ and 50€ respectively. It is possible that Lisbon Port Authority could also apply a fee for the transit through the river, but this has been neglected because this type of service would contribute to the general policy objective of decreasing emissions and reducing air pollution, so it is assumed that it would be exempted from additional fees.

The fuel costs are calculated considering the use of the main engines and the generators in two conditions: sailing and in port. It was assumed that the main engine will use HFO fuel when at sea (sulfur content restricted to 0.5%S) and LSMGO when in the river (0.1%S) and the generator will use MGO all the time. The percentage of load in the generators does not change significantly: 30% while sailing (p_{sail}) and 25% in ports (p_{port}). Table 14 shows the prices of HFO and MGO that were used in this analysis.

Table 14 - Prices of fuels on November 2020 (Source: www.shipandbunker.com).

VLSFO Price	$ 300	(USD$/ton)
LSMGO Price	$ 320	(USD$/ton)

The speed of the ship in the river is considered to be 8 knots and in the sea it is 10 knots. With these speeds, the navigation time is to be obtained using the Equation 4.1.

$$T_{nav} = \frac{D_{river}}{V_{river}} + \frac{D_{Sea}}{V_{Sea}} \qquad 4.1.$$

Where D_{river} is the total river distance, D_{Sea} is the total sea distance and V_{river} and V_{Sea} are the average speeds of the vessel in these two environments.

The time in port is given by Equation 4.2, considering two cranes loading/unloading the ship at 80% of capacity, at a rate of 15 moves per hour (LR) and an average waiting, queuing and mooring time ($T_{service}$) of about 4 hours:

$$T_{port} = 80\% * \frac{FEU}{LR} + T_{service} \qquad 4.2.$$

The round voyage time, including also the time spent in locks (one hour per lock), is given by Equation 4.3:

$$T_{RV} = T_{nav} + T_{port} + T_{locks} \qquad 4.3.$$

With this round voyage time, very near to 48 hours, it is assumed that the ship will be able to carry out 3 round voyages per week.

For the total fuel consumption in the round voyage time, the information in Table 15 for the specific fuel consumption of the main engine ($SFOC_{main}$) and generator ($SFOC_{gen}$) was used. Multiplying it by the main engine power obtained (HP_{main}) and the generators power (HP_{gen}) by the time used by the specific fuel consumption (SFOC) of each one, the fuel costs (F_{cost}) could be calculated, as shown in the Equation 4.4.

$$F_{cost} = SFOC_{main} * HP_{main} * T_{nav} * P_{VLSFO} + p_{sail} * SFOC_{gen} * HP_{gen} * T_{nav} * P_{LSMGO} + p_{port} * SFOC_{gen} * HP_{gen} * T_{port} * P_{LSMGO} \tag{4.4}$$

The main engine SFOC was calculated considering the MAN reports [50], allowing a more precise estimate of the specific fuel consumption.

Table 15 - Main Engine SFOC. Source: MAN report

PMCR (%)	*SFOC (g/kWh)*
43	176.00
47	174.10
52	172.00
59	170.10
70	168.00
80	167.40
90	168.20
100	170.40
108	173.00
Calculated SFOC (g/kWh)	
PMCR Percentage	100%
SFOC Main Engine	170.40
Percentage of Generator in Sailing	0.2
Percentage of Generator in Ports	0.35
SFOC Generator	200

Crew costs are considered, as shown in Table 16, with a base of 6 people in the crew of the vessel (N_{crew}).

Table 16 - Crew Costs – Source: https://www.seamanmemories.com/seamans-salary-per-month-on-international-ships/

Category	*Crew per vessel*	*Salary*	*Cost*
Master	1	$8,983	$8,983
Chief engineer	1	$8,784	$8,784
Able seamen	4	$1,190	$4,760
Total	6		$22,527

The repairs and maintenance costs are calculated by using D'Almeida, 2009, formulations [51], as given in Equation 4.5. The newbuilding price method of estimate can be seen in Appendix I and, for the chosen ship, was calculated to be a cost of around U$D 5.000.000,00.

$$C_{mr} = 0.0035 * \left(NB_{price}\right) + 105 * HP_{main}^{0.66} \tag{4.5}$$

The periodical maintenance is calculated by using Equation 4.6 (D'Almeida, 2009), considering statutory dockings:

$$C_{pm} = 0.006 * NB_{price} \tag{4.6}$$

The insurance is calculated by Equation 4.7, where GT is the ship's gross tonnage:

$$C_s = 0.01 * (Newbuilding\ Price) + 11.5 * GT \tag{4.7}$$

The stores and consumables are calculated by Equation 4.8:

$$C_{sc} = 3500 * N_{crew} + 4000 * CN^{0.25} + 200 * HP^{0.7} \tag{4.8}$$

Where CN is a number that depends on the vessel's geometric characteristics, as shown in Equation 4.9 [52].

$$CN = L_{pp} * B * T \tag{4.9}$$

The administration costs depend a lot on the management structure of the ship owner, size of the fleet and also from the accounting criteria adopted. However, typical values from coastal ships are in the range of USD$100.000,00 but given the small size of this ship it could be taken as half this value, USD$50.000,00.

For the capital costs, the concept of Capital Recovery Factor (CRF) was used, which is a function of the discount rate (j), to perform the calculation of the annual capital annuities (Pi). Using annuities, the estimation of the capital costs of the ship can be performed without many details regarding the different forms of payments. . It was considered a useful life, *n*, for the ship of 20 years and discount rate, j, of 8%. The newbuilding price of the ship was considered to be 5 million USD and the scrap price after 20 years was not considered. The formulation can be seen in Equation 4.10.

$$P_i = NB_{price} * \frac{j * (j + 1)^n}{(1 + j)^n - 1} \tag{4.10}$$

The cost structure may be summarized as shown in Table 17, calculated per voyage and per container box in FEU. A final one-way cost per FEU carried was estimated to be equal to $286.34. The costs distribution chart can be seen in Figure 30.

Table 17 - Costs estimate from Golegã to Sines.

Type	Costs	Unit	Cost per FEU
Total Fuel Cost	$1,482	(U$D/voyage)	$62
Wages	$1,429	(U$D/voyage)	$60
Maintenance Cost per voyage	$160	(U$D/voyage)	$7
Insurance cost per voyage	$333	(U$D/voyage)	$14
Administrations cost per voyage	$264	(U$D/voyage)	$11
Docking costs per Voyage	$156	(U$D/voyage)	$7
Stores and Consumables Cost per Voyage	$397	(U$D/voyage)	$17
Capital Cost per Voyage	$2,651	(U$D/voyage)	$110
Total Costs	**$6,872**	**(U$D/voyage)**	**$286**

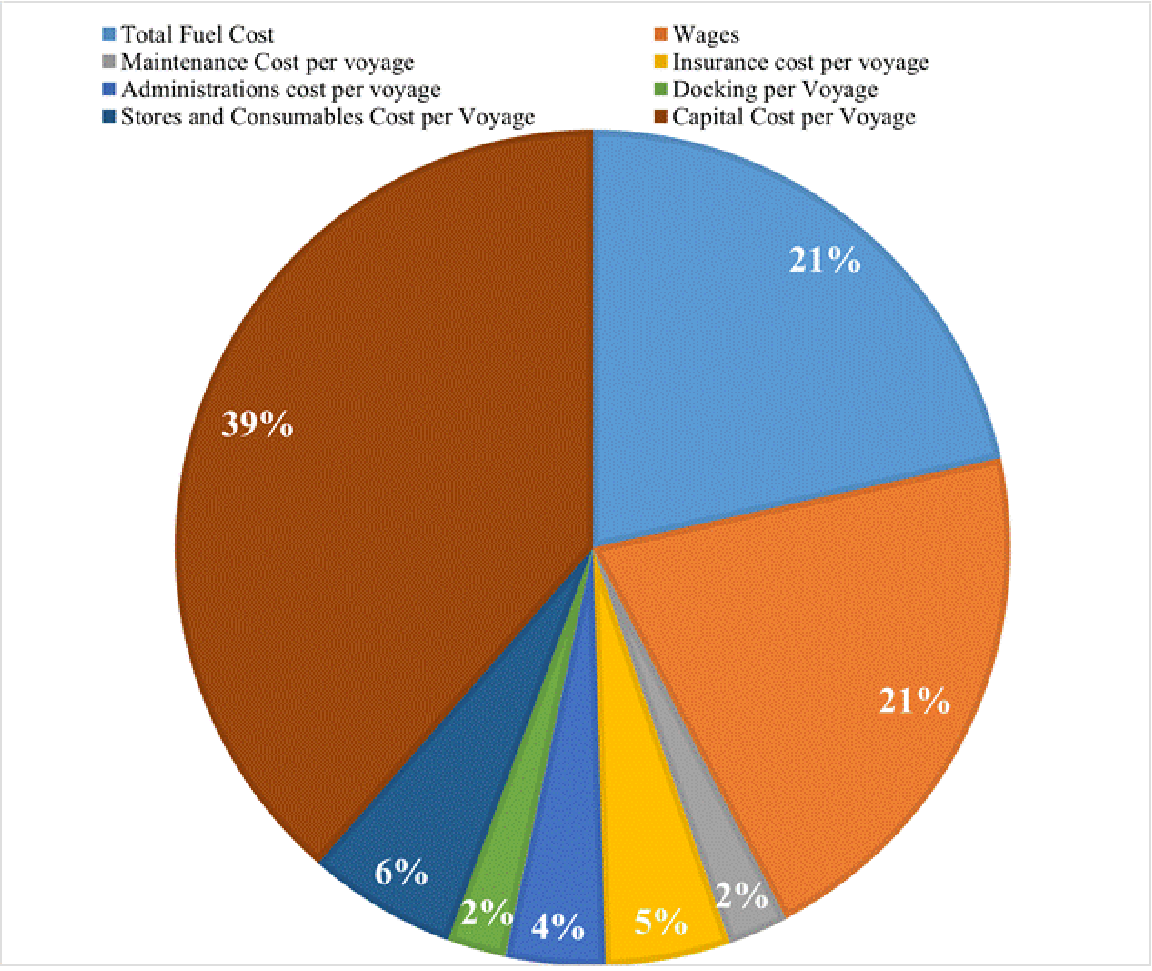


Figure 30 - Costs distribution.

4.5.3 Results regarding relative competitiveness of transport chains

The set of municipalities chosen for this case study can be seen in Table 18. From each municipality in each region, three different paths are considered: road-only, railway+road and river-sea + road. In the western region, there is one optimum (in terms of distance) road-only route directly from the municipality to Sines, one route from the municipality to the rail terminal in Entrocamento by truck and a final leg to Sines by train and a road route from the municipality to Golegã and a final IWW leg to Sines. The same idea is applied to other regions, with only one difference regarding rail transportation, using the intermodal terminals of Guarda and Lousado in the Beira and Northern regions, respectively.

Table 18 - List of municipalities for case study

Western Region		**Beira Region**	**Northern Region**	
Alenquer	Pombal	Fundão	Vila Nova de Gaia	Amarante
Torres Vedras	Entroncamento	Covilhã	Gondomar	Felgueiras
Lourinhã	Alcanena	Manteigas	Valongo	Vizela
Peniche	Vila Nova da Barquinha	Seia	Porto	Vila Nova de Famalicão
Bombarral	Sardoal	Gouveia	Matosinhos	Guimarães
Óbidos	Tomar	Guarda	Maia	Fafe
Caldas da Rainha	Ourém	Celorico da Beira	Santo Tirso	Cabeceiras de Basto
Alcobaça	Benavente	Fornos de Algodres	Trofa	Mondim de Basto
Nazaré	Coruche	Almeida	Vila do Conde	Póvoa de Lanhoso
Porto de Mós	Salvaterra de Magos	Pinhel	Póvoa de Varzim	Vieira do Minho
Batalha	Azambuja	Trancoso	Paços de Ferreira	Braga
Marinha Grande	Cartaxo	Mêda	Lousada	Barcelos
Leiria	Almeirim	Figueira de Castelo Rodrigo	Penafiel	Esposende
Santarém	Alpiarça		Marco de Canaveses	Vila Verde
Golegã	Rio Maior		Baião	Amares
Chamusca				Terras de Bouro

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.

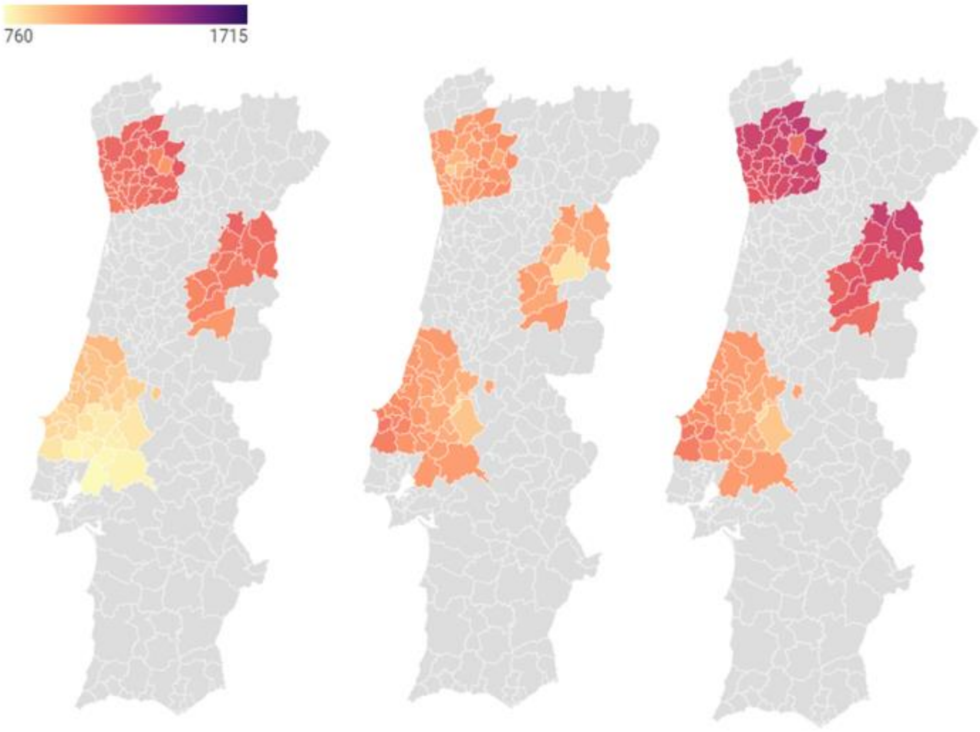
The results for generalized costs and time of transportation can be seen in Figure 31 and Figure 32, respectively, and some conclusions are possible to be drawn. First, analyzing the western region, it is possible to observe a clear advantage of road-only transportation regarding both costs and time in comparison to combined transportation. The huge difference related to both of these 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.

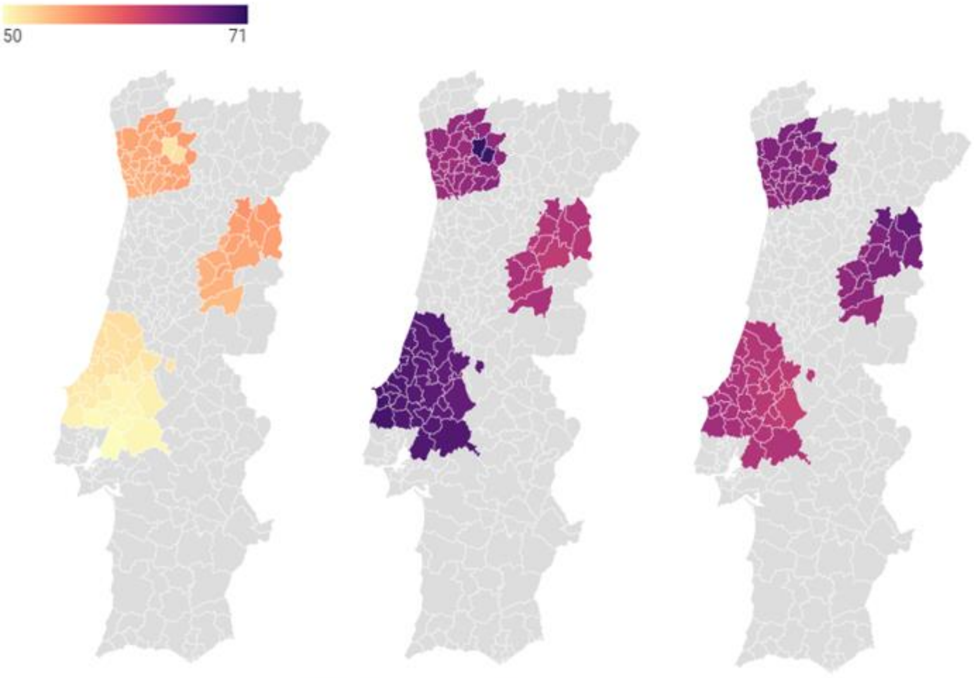
The main reason for that mainly relies on two factors. The first is related to the time spent on the terminal for the modal shift, which increases an amount of time that does not exist in road-transportation. Therefore, the same optimization analysis should be valid for the terminal, which must seek for ways of making the technical aspects of shifting cargo as efficient as possible.

The main problem, however, is given by the low economy of scale that the small size of the ship presents. 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” are extremely important so that the river gains competitiveness against other modes of transportation, but it needs to allow slightly larger ships.



Map: Vitor Victal Teixeira • Source: Author • Get the data • Created with Datawrapper

Figure 31 – Generalized transport cost to Sines (€/FEU). Left: road-only transportation / Centre: road+rail transportation / right: road+IWW transportation



Map: Vitor Victal Teixeira • Source: Author • Get the data • Created with Datawrapper

Figure 32 -Time of transportation to Sines (hours). Left: road-only transportation / Centre: road+rail transportation / right: road+IWW transportation

4.6 Computation time

To analyze the computation time taken by the algorithm to perform the calculation for the optimum routes between two nodes in the network, 22 pairs of nodes origin/destination were chosen to be analyzed. These pairs are quite the same of the pairs analyzed during this project, which means that they vary greatly amongst them in terms of distance and separation in the studied network.

The time analysis was taken into consideration the optimization method used for path's mapping. As one can see in Table 19, the optimization method (using Dijkstra's method) has proved to be efficient to analyze a network of this magnitude, with calculation times in the average of less than 1 second per method.

Table 19 – Algorithm computation times in seconds

	Node of Origin	**Node of Destination**	**Distance Optimization Time (s)**	**Transportation Time Optimization Time (s)**	**Total Transportation Time Optimization Time (s)**	**Generalized Cost Optimization Time (s)**
1	544	382	0.23	0.19	1.59	0.31
2	21	640	0.40	0.42	0.89	0.38
3	133	93	0.13	0.14	0.83	0.17
4	1390	72	1.17	1.32	1.62	0.92
5	1170	630	0.96	0.92	1.11	1.45
6	2177	1617	0.29	0.28	0.39	1.39
7	1178	1617	0.20	0.50	0.36	1.23
8	1029	1617	1.18	1.17	1.23	1.76
9	630	1617	1.00	0.95	1.65	0.10
10	630	809	0.98	1.03	1.71	0.73
11	1208	1120	0.13	0.13	0.16	0.32
12	2379	1329	0.15	0.17	0.78	0.11
13	2375	2379	0.69	0.56	0.34	1.55
14	133	1029	0.70	0.64	1.30	1.23
15	203	1029	0.45	0.52	0.59	0.77
16	28	1029	0.45	0.47	0.56	0.67
17	133	382	0.58	0.58	0.92	0.80
18	203	382	0.34	0.36	0.43	0.40
19	28	382	0.33	0.34	0.39	0.30
20	133	630	0.52	0.50	0.89	0.45
21	203	630	0.31	0.30	0.38	0.39
22	28	630	0.30	0.28	0.52	0.48
Average			0.522	0.534	0.847	0.723
St. Dev			0.340	0.342	0.488	0.504

It is interesting to observe, however, that the biggest calculation times are involved when calculating the total transportation time and the generalized costs, due to the need of performing more calculations with different conditions involving modal shift, tolls passage etc. For a bigger network, however, this calculation time is more likely to increase significantly, which might affect the analysis of multiple pairs. Therefore, optimizations in the algorithm can be performed in order to make it more efficient.

5. CONCLUSIONS AND RECOMMENDATIONS

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.

5.1. Discussion

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. Furthermore, analysis based on political decisions, such as the BREXIT, could be performed, verifying alternatives for example for Ireland to become a gateway of flow of goods from the United Kingdom to Europe.

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.

5.2. Recommendations

The next steps for this project consist mainly in improving the algorithm in order to consider more parameters included in the network, such as considering emissions of CO2 and sulfurous gases into the environment. External costs shall be better applied, with the development of more precise methods to compute these parameters into a more reliable cost parameter, allowing a better analysis from the developed tool.

Furthermore, programming techniques shall be applied to the algorithm in order to make it more time efficient. As the network grows in complexity, the algorithm should keep up to it and therefore modifications must be made. The use of *heaps* and *Fibonacci heaps*, as previously mentioned, reduce the running times for the algorithm, making it follow a more logarithmic shape and therefore with smaller running times.

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APPENDIX 1 – METHODOLOGY FOR NEWBUILDING PRICE ESTIMATE

The methodology for the estimate of the newbuilding price for a ship was proposed by D'Almeida 2009 [51]. The methodology depends on the knowledge of ship type and its main dimensions, propulsion system, equipment fitted in the hull and cargo area and other relevant parameters, however, might give some good estimates in the construction price of a vessel.

The methodology consists in dividing the construction price in basically three parts: cost of hull, cost of equipment and cost of machinery.

The hull cost (C_h)can be estimate, considering a steel construction, by the following formula:

$$C_h = k_{hull1} * W_h^{k_{hull2}} * C_b^{k_{hull3}} \qquad A.1$$

The coefficients k_{hulln} are characteristic of each ship type obtained from statistical regression analysis, C_b is the vessel's block coefficient and W_h is an estimate of the hull's weight, also proposed by a statistical analysis regression by D'Almeida, where:

$$W_h = k_{hull1"} * L_{pp}^{k_{hull2"}} * B^{k_{hull3"}} * D^{k_{hull4"}} \qquad A.2$$

The coefficients values can be seen in Table 20 and Table 21

Table 20 - Coefficients for hull cost estimate

	k1	k2	k3
Oil Tankers	2,523	0.8864	-0.2380
Bulk Carriers	2,666	0.8837	-0.2336
Container Carriers	3,167	0.8802	-0.2217
General Cargo	2,925	0.8815	-0.2285

Table 21 - Coefficients for hull weight estimate

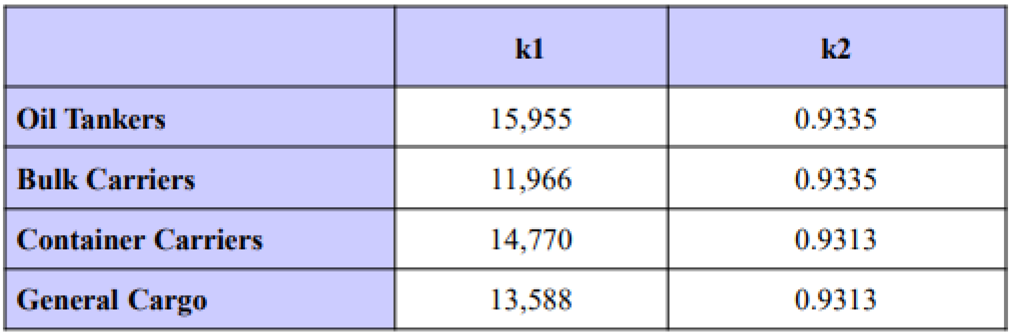
	k1	k2	k3	k4
Oil Tankers	0.0361	1.600	1.000	0.220
Bulk Carriers	0.0328	1.600	1.000	0.220
Container Carriers	0.0293	1.760	0.712	0.374
General Cargo	0.0313	1.675	0.850	0.280

The equipment cost can be described as a function of the equipment weight (W_E). The coefficients for its calculation can be seen in Table 22 and Table 23.

$$C_E = k_{equi1} * W_E^{k_{equi2}} \qquad A.3$$

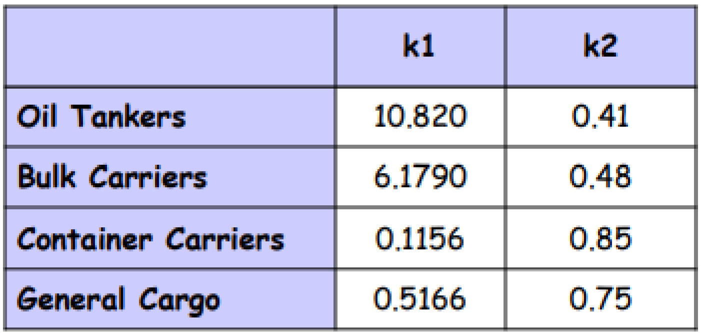
$$C_E = k_{equi1"} * \left(L_{pp} * B * D\right)^{k_{equi2}} \qquad A.4.$$

Table 22 - Coefficients for equipment cost estimate



	k1	**k2**
Oil Tankers	15,955	0.9335
Bulk Carriers	11,966	0.9335
Container Carriers	14,770	0.9313
General Cargo	13,588	0.9313

Table 23 - Coefficients for equipment weight estimate



	k1	**k2**
Oil Tankers	10.820	0.41
Bulk Carriers	6.1790	0.48
Container Carriers	0.1156	0.85
General Cargo	0.5166	0.75

The machinery cost (C_M) can be described as a function of the vessel's main propulsive power, with the coefficients (Table 24), differently from the hull and equipment costs, depending on the type of propulsive plant:

$$C_M = k_{mach1} * HP_{main}^{k_{mach2}} \qquad A.5$$

Table 24 - Coefficients for machinery cost estimate

	k1	k2
Diesel (2 stroke)	19,877	0.620
Diesel (4 stroke)	12,507	0.647
2 x Diesel (2 stroke)	14,141	0.650
Steam Turbine	38,480	0.540

Finally, the total construction cost NB_{price} is expressed by the sum of the above parcels multiplied by the shipyard's profit margin k_a, considered to be 10% in this project:

$$NB_{price} = (C_h + C_E + C_M) * (1 + k_a) \qquad A.6.$$