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TRANSPORTATION PROBLEMS: APPLICATIONS

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ABSTRACT

Nowadays, the transaction of goods assumes a great importance on the daily life of both individual and collective entities. Their transportation within Europe relies mainly on road transport. The use of railways for cargo transportation is relatively low, however, during the last few years, the European Union has been implementing ideas and policies, aiming to standardize and facilitate the interoperability of international rail transportation, as this mode of transportation offers more advantages for long distance trips. To complement the relative benefits of the various transportation modes, namely the road and rail ones, it is necessary to ensure intermodal conditions. Programs like "Portugal Logístico", dating back from 2006, focus precisely on these concerns.

Just as with the planning and development of infrastructures, it is important to optimize their usage, i.e. get the highest possible profit out of them, reducing their usage costs, whether they are money, environment or time-related. Part of this optimization requires making the best decisions in terms of the allocation of transportation means to the different load requests.

Operations Research (OR) tools are useful to optimize transportation problems. Route planning is one of the practical applications for some OR methods, namely the Travelling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP).

TSP is a simple formulation model that aims to minimize the costs to travel around a given network, passing through all the nodes exactly once and closing the circuit by returning to the departure node, provided that the costs associated with travelling between every two nodes are well defined.

VRP is more complex as it allows costs to be minimized, taking into account a larger number of variables and allowing the existence of more circuits. This method is used, for instance, in fleet management applications.

In this work, both methods are explored and applied to several fictitious problems, in order to identify their eventual limitations and possible proposals, such as the inclusion of additional factors that could prove more relevant to attend to real transportation systems. More specifically, this thesis includes simulations about the reduction of distances and tonne·kilometer, occasionally based upon quite realistic data from road and rail networks that could actually be considered for real problems. The comparison between the optimal routes, for each transportation mode to achieve the same task, is a starting point to select between using one, the other or a combination of both methods.

KEYWORDS: Freight transport; Transeuropean transport networks; Logistics platforms; Network optimization.

RESUMO

Actualmente, a transação de bens assume grande importância no quotidiano de entidades individuais e colectivas. O transporte destes na Europa é maioritariamente feito por meios rodoviários. A utilização da ferrovia para o transporte de mercadorias é relativamente reduzida, no entanto, nos últimos anos, a União Europeia tem vindo a implementar ideias e políticas no sentido de uniformizar e facilitar a interoperabilidade do transporte ferroviário a nível internacional, visto que este meio de transporte é mais vantajoso para viagens de longas distâncias. Para complementar as vantagens relativas dos vários modos de transporte, nomeadamente rodoviário e ferroviário, é necessário garantir condições de intermodalidade. Planos como o "Portugal Logístico", de 2006, focam precisamente essas preocupações.

Tal como o planeamento e o desenvolvimento de infra-estruturas, é importante optimizar o seu uso, isto é, tirar o maior proveito possível das mesmas, minimizando os custos da sua utilização, quer sejam de foro monetário, ambiental ou "temporal". Esta optimização passa em parte por tomar as melhores decisões ao nível da afectação de meios de transporte às diversas solicitações de carga.

Para optimizar problemas de transporte, são úteis ferramentas de Invesitgação Operacional (IO). A definição de rotas é uma das aplicações práticas de alguns métodos de IO, nomeadamente o Travelling Salesman Problem (TSP) e o Vehicle Routing Problem (VRP).

O TSP é um modelo de formulação simples que tem como objectivo minizar custos para percorrer uma determinada rede, passando por todos os nós exactamente uma vez e fechando o circuito com o regresso ao nó inicial, assumindo que os custos de cada arco entre nós estão bem definidos.

O VRP é mais complexo, pois permite minimizar custos tendo em conta maior número de variáveis, possibilitando a existência de mais circuitos. É aplicado, por exemplo, para a gestão de frotas.

Neste trabalho são explorados estes dois métodos, aplicando-os em vários problemas fictícios, com o objectivo de identificar eventuais insuficiências dos mesmos e possíveis modificações, tal como a inclusão de factores mais relevantes para atender a sistemas de transporte reais. Mais concretamente, nesta tese foram simulados casos de minimização de distâncias e de tonelada·quilómetro, baseando-se algumas vezes em dados próximos da realidade de redes rodoviárias e ferroviárias que poderiam ser problemas reais. A comparação entre as rotas óptimas calculadas para cada meio de transporte para cumprir uma mesma tarefa é um ponto de partida para selecionar entre a utilização de um, de outro, ou da combinação de ambos.

PALAVRAS-CHAVE: Transporte de mercadorias; Redes transeuopeias de transporte; Plataformas logísticas; Optimização de redes.

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1
INTRODUCTION

1.1. MOTIVATION

In the last years, the concerns about the maintenance and efficiency of utilization of infrastructures have been assuming more and more importance in several areas of engineering.

Regarding transport infrastructures, namely roads and railways, the optimization of their use includes the minimization of distances travelled and loads applied by the vehicles in the whole network of roads and rails. Such optimization is even more important when considering environmental concerns and management of energy resources. The topic of this thesis arose from the general interest in the conservation of infrastructures, environment and energy resources.

Basic freight transport activities consist on delivering a certain amount of goods in a certain space and time limit, in order to satisfy the customers' demands, within respect to the restrictions or limits from the suppliers.

To plan transportation activities it is necessary to study and make some decisions, for instance, about the transport modes to use, the packing conditions and the vehicle routing.

The optimization of routes in networks is a subject that has been thought over for many years, thus there are already several known models that, with more or less modifications, can be used for specific problems. The Travelling Salesman Problem and the Vehicle Routing Problem are two well known models to find optimal routes, minimizing costs within respect for restrictions that represent a certain transport system.

The Travelling Salesman Problem, TSP, is the most fundamental and best known of the node-covering-problems. Its aim is to find the sequence of visiting the nodes that minimizes the total cost of the route, starting from the origin node, passing across the whole network and returning to the origin, visiting each node only once [1].

The Vehicle Routing Problem, VRP, also a node-covering-problem, is a combinatorial optimization problem that aims to define an optimal set of routes to be used by a fleet of vehicles to serve a set of customers [1].

An aim of this thesis is to experiment with those models to optimize transport networks, doing proper proposals and validating them in order for them to fit better to real transport network problems. In fact, the existent models are prepared to solve standard networks in general, so they do not take into account variables and/or restrictions related to each specific transport problem.

1.2. OBJECTIVES

This thesis discusses the freight transport by road and rail. It can be a widespread theme, because there are several issues related to it.

The main objectives of the thesis are:

1. Characterization of the actual reality of freight transport by road and rail in Europe.
2. Presentation of the transeuropean transport networks, focused on road and railways, together with the identification of intermodal platforms.
3. Reference of optimization models and algorithms for transportation problems based on existing literature.
4. Testing of mathematical models to optimize transportation problems.
5. Considerations of some particularities of transport problems.

1.3. STRUCTURE

This thesis is organized into six chapters, including this "Introduction" chapter, with a brief description of the motivation for this work, enumeration of the main objectives and description of its organization.

Each chapter (except for the first one) includes an introductory text containing the intent of the chapter and a final summary containing the most important information or conclusions taken from it.

Chapter 2, *Freight transport*, starts with the comparison between the main transport modes for freight transport. Next it presents several statistical data of freight transport in European Union, Portugal and Czech Republic. For the two aforementioned countries the statistics focus on road and rail transport.

Chapter 3, *Transeuropean networks and intermodal logistic platforms*, gives a brief description of the transeuropean networks, namely about the transport network, focusing the main goals, supports and concerns of the European Union on that matter. Next, the road and rail networks are analyzed and there is a small reference to the priority axis defined by the European Commission.

Next there is a reference to some basic concepts about intermodal logistic platforms and intermodality and the locations of the main intermodal logistic platforms in European Union are indicated. Finally, the importance of the logistics system in Portugal is described, referring to the actual situation of the intermodal platforms considered as fundamental.

Chapter 4, *Transportation optimization problems*, refers the importance of optimizing transport and logistics activities together. There is a description of the representation of real transport systems by graphical or mathematical models. Finally, the main part of the chapter presents and explains the following models for transport networks: Shortest Path, Travelling Salesman Problem and Vehicle Routing Problem.

Chapter 5, *Case studies*, is the most extensive chapter in this paper. The main goal of it is to show practical applications of the TSP and VRP. It starts with several different cases to exploring the operation of TSP in finding the shortest routes, identifying insufficiencies of it and detecting possible ways to improve it. Some cases are completely fictitious while some others are based on real networks. Then are explained and tested the proposals made to TSP.

After, the minimizing of tonne·kilometer measured in transportation problems is shown. To solve such problem one model based on VRP is presented, explained and tested then in some cases. Finally, a problem based on real networks is built. The main goal of it is to compare the option to use trucks or trains to respond to that problem.

Chapter 6, *Conclusions and future work*, refers the main conclusions of the work, as a summary of the conclusions of each chapter, and suggests some objectives to achieve in eventual future works.

2
FREIGHT TRANSPORT

2.1. INTRODUCTION

In this chapter the differences between the main transport modes for freight transportation are discussed, emphasizing the advantages and disadvantages of each transport mode.

Then general statistical data about freight transport in EU is presented, and, more specific, information regarding Portugal and Czech Republic is described. The comparison between these two countries is made because they have similar geographical area and population size, but a very different geographical location, which is an influent factor in the transport politics.

2.2. MODAL SPLIT OF THE EUROPEAN FREIGHT TRANSPORT

The six main modes of transport types that contribute for the transport of goods from a place to another are road, rail, inland water-ways, pipelines, sea and air transport. Each one of the transport mode has advantages and disadvantages, possibilities and restrictions. Some of them are enumerated in Table 1.

Table 1 - Advantages and disadvantages of different modes of transport [2] [3] [4] [5].

Transport mode	Advantages	Disadvantages
Road	High velocity of delivery; Mobility (door-to-door service); Easy access to individual entities.	Low carrying capacity; High energy and area use; Noise and toxic emissions; Possible traffic delays.
Rail	High carrying capacity; Fast delivery; Low energy use;	Restricted timetables and routes; Low density of track's use; Expensive for short distances;
Inland water-ways	High carrying capacity; Economically and ecologically sustainable; Existence of natural routes already.	Limited geographical reach; Low speed; High dependence on environmental and weather conditions; Risks of accidents with dangerous environmental effects;
Sea	Very high carrying capacity; Economic for bulky and heavy goods; Existence of natural routes already.	Long delivery times; Dependence of weather conditions; Risks of accidents with dangerous environmental effects; Suitable only for coastal regions
Pipelines	Large volumes; Safety; Unaffected by weather; No driver.	Limited type of cargo; Easy target to vandalism or terrorist acts.
Air	Very high speed; No physical barrier; Existence of natural routes already.	Very costly; Dependence of weather conditions; Low carrying capacity; Heavy losses in case of accident.

By analyzing Table 1, some comments about each transport mode are presented next.

The mobility and the door-to-door service by road vehicles is the most important reason to make this type of transport mode the most used one. The road infrastructures are not routes of natural existence, however there are already so many built roads prepared and projected to support heavy loads, that the freight transportation companies do not have the responsibility of the investment on the construction and the maintenance of such infrastructures. In recent years, as the concerns about environment quality are increasing, legal and politics entities are establishing goals and new rules in order to reduce emissions of toxic pollutants into the atmosphere. These kinds of policies are a threat to the use of road vehicles as we see them in the present [2] [3] [4].

Following those environmental policies, the developed countries are increasing efforts to develop railway transportations in order to take advantage of the low and non-toxic energy consumption of the electrified railways lines. Since there are so few railways in comparison of roads, it is very important to create facilities in intermodal freight villages, places where take place activities of loading, unloading, modal changing, storage and identification of freight, in order to promote an easy and quick trading of cargo between trains and trucks. Only then it is possible to take advantage of the door-to-door service provided by road vehicles [2] [3] [4].

The transport by pipeline is common used in water distribution systems in developed regions. This kind of transport is also used for longer distances, namely to transport high volumes of liquids or gases (only some solid capsules can be transported using compressed gas) between places distanced by thousands of kilometers. Petroleum and gas are the best examples of products lead by pipelines in long distances [5].

Regarding the water transportation in Europe, both inland water-ways and sea transport use existing natural routes. When referring to the transport of perishable goods, the low speed of inland water-ways may be a disadvantage, comparing with the higher speed of road and rail ways on land territories, near the rivers. The sea transportation is the most important mode for the intercontinental trading of bulk and heavy goods in high amounts [2] [3] [4].

Finally, the air transport is obviously the fastest way to transport goods between long distances and the most interesting mode to trade perishable goods. However, when comparing the air transport with the intercontinental ships, the carrying capacity of the former is significantly lower. As the water transports, for the air transportation there is no need to build routes infrastructures, because planes can travel through the air without physical obstacles. However, this type of transportation demands costly and big infrastructures in land, such as airports and aerodromes [2] [3] [4].

In order to understand the importance of each transport mode in the transportation of goods, an analysis of Eurostat statistical data is presented in continuation [7].

In general, the amount of goods transported in the last years has been increasing, as well as the distance traveled by goods, measured by tkm. This evolution can be observed in Figure 1, which shows the evolution of all traffic in European Union 27, where the unit of measuring is tonne·kilometer (tonne·km or tkm). One tkm represents one tonne of cargo moved per one kilometer distance.

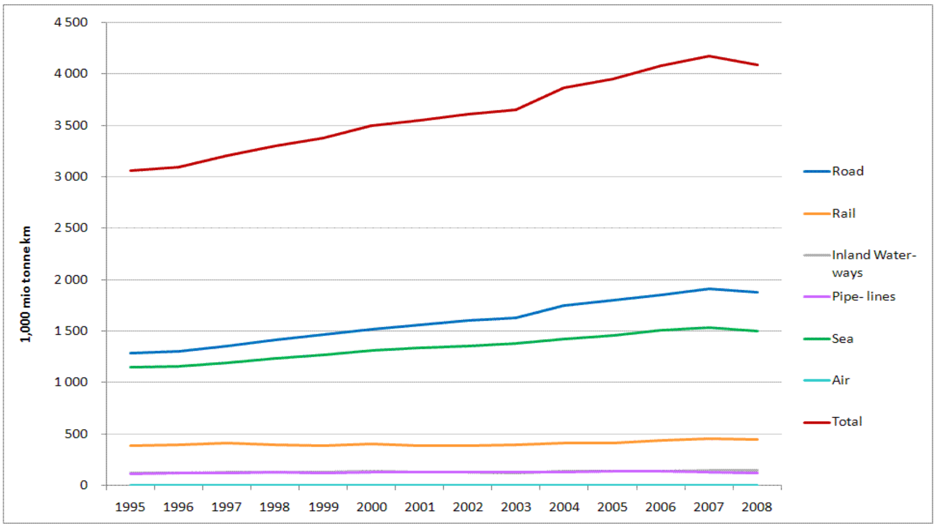

Figure 1 - Evolution of the freight transport mode in EU27 [6].

By analyzing Figure 1, it is noticeable a significant increase of road and sea transport. According to the characteristics of those transport modes, it is reasonable to say that the high value of tkm transported by road happens because there are a lot of road vehicles going with low weights on medium distances and the high tkm verified in sea transport is explained by the very high weight carried by ships for long distances.

2.3. INLAND TRANSPORTATION

In this section the inland freight transport is described, with mention to roads, railways and inland water-ways, either national or international transport. The air and sea transport is not included because, "due to their predominantly international nature, there are conceptual difficulties in dealing with these modes in a manner consistent with the inland modes" [8]. Figure 2 presents the percentage of each mode in total inland freight transport performance, measured in tonne·kilometer in 2009.

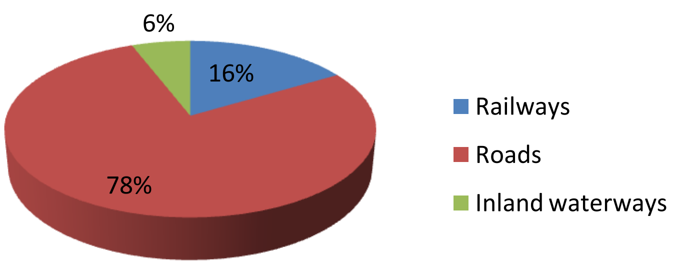

Figure 2 – Inland modal split in EU27, 2009, in tonne·km. Drawn from [7].

As expected, the transportation by roads is the preferred way to transport goods, with a quota of 78%, railways are responsible for 16% of the transportation and only 6% of tonne·km belong to inland waterways.

2.3.1. Transportation of goods by road and rail

2.3.1.1. European Union

According to the classification of goods adopted in Europe after 2007 ("Standard goods classification for transport statistics 2007", known as NST2007), there are 20 distinct groups of goods [7]:

Table 2 – NST2007 commodity classification [7].

1	Products of agriculture, hunting, and forestry; fish and other fishing products
2	Coal and lignite; crude petroleum and natural gas
3	Metal ores and other mining and quarrying products; peat; uranium and thorium
4	Food products, beverages and tobacco
5	Textiles and textile products; leather and leather products
6	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials; pulp, paper and paper products; printed matter and recorded media
7	Coke and refined petroleum products
8	Chemicals, chemical products, and man-made fibers; rubber and plastic products ; nuclear fuel
9	Other non metallic mineral products
10	Basic metals; fabricated metal products, except machinery and equipment
11	Machinery and equipment n.e.c.; office machinery and computers; electrical machinery and apparatus n.e.c.; radio, television and communication equipment and apparatus; medical, precision and optical instruments; watches and clocks
12	Transport equipment
13	Furniture; other manufactured goods n.e.c.
14	Secondary raw materials; municipal wastes and other wastes
15	Mail, parcels
16	Equipment and material utilized in the transport of goods
17	Goods moved in the course of household and office removals; baggage and articles accompanying travellers; motor vehicles being moved for repair; other non market goods n.e.c.
18	Grouped goods: a mixture of types of goods which are transported together
19	Unidentifiable goods: goods which for any reason cannot be identified and therefore cannot be assigned to groups 01-16.
20	Other goods n.e.c.

This table is useful to identify the distribution of transported goods by road and rail in European Union, according with the type of goods. Such distribution is presented for the year 2010 in Figure 3 and Figure 4 respectively.

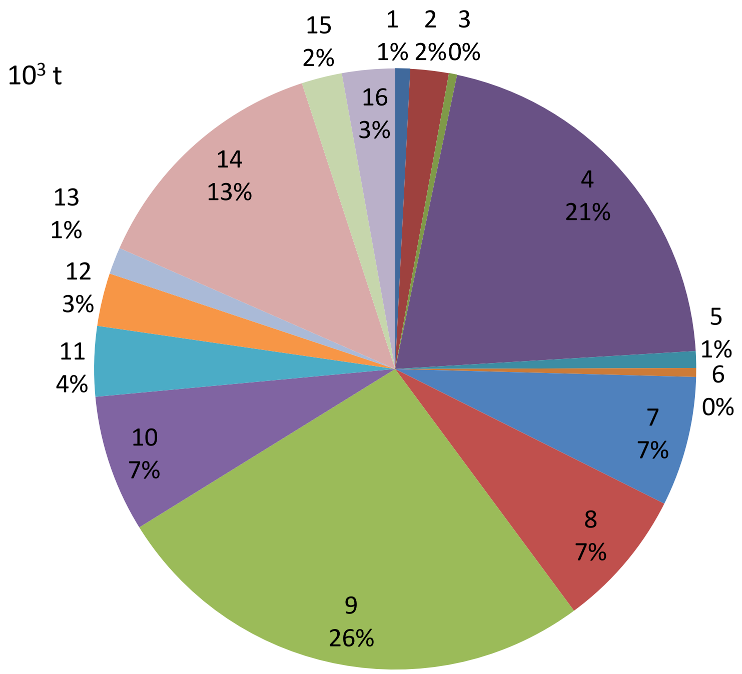

Figure 3 - Tonnes of goods (from group 1 to 16) carried in European Union by road, in 2010. Drawn from [7].

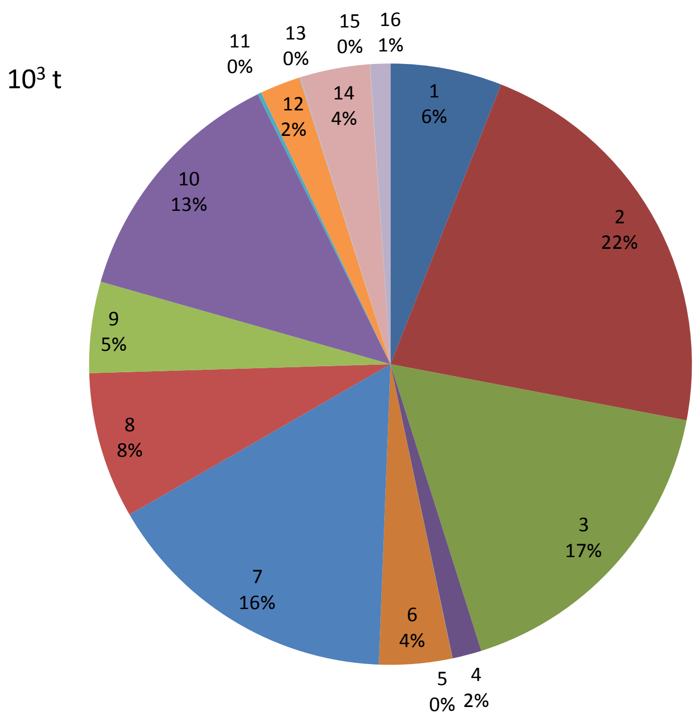

Figure 4 - Tonnes of goods (from group 1 to 16) carried in European Union by rail, in 2010. Drawn from [7].

It is noticeable that the "Other non metallic mineral products" and the "Food products, beverage and tobacco" were the type of goods with more tonnes transported by road, with 2 067 227 000 and 1 630 309 000 tonnes, respectively. By railway, the "Coal and lignite; crude petroleum and natural gas", the "Metal ores and other mining and quarrying products; peat; uranium and thorium" and the "Coke and refined petroleum products" are the ones with more tonnes carried with 259 931, 202 404 and 189 578 tonnes, respectively.

Despite these products being the most transported in weight, they are not necessarily carried for longer distances. The Figure 5 and Figure 6 show the overall transportation of the same groups of goods, using the unity tkm.

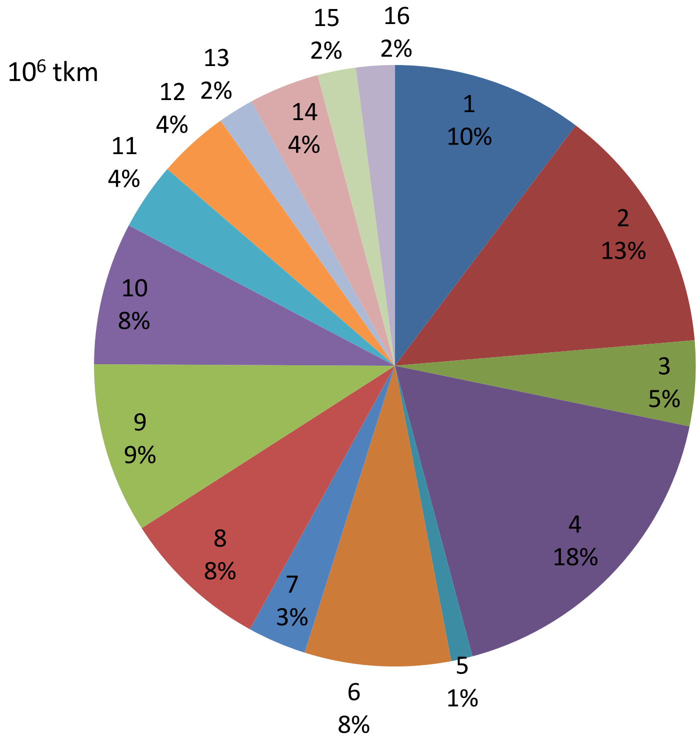

Figure 5 - Tonne km of goods (from group 1 to 16) carried in European Union by road, in 2010. Drawn from [7].

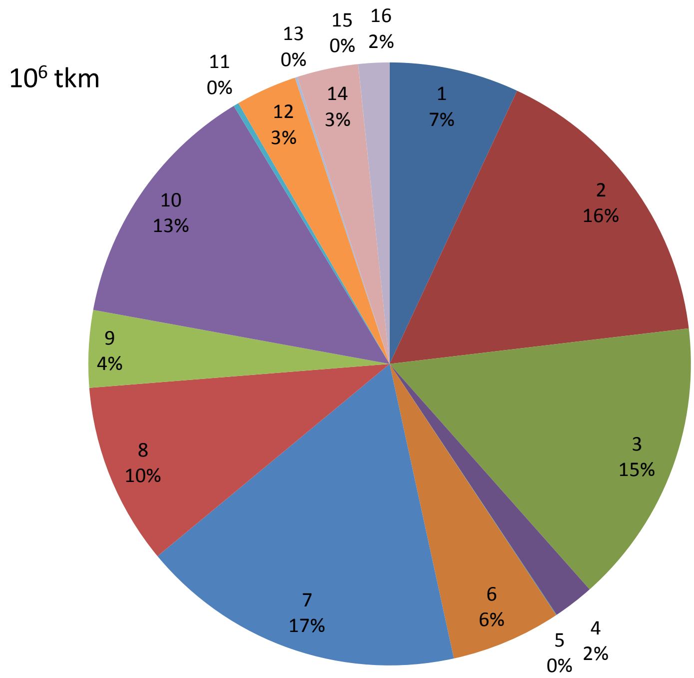

Figure 6 - Tonne km of goods (from group 1 to 16) carried in European Union by rail, in 2010. Drawn from [7].

According to this unity of measure, the "Food products, beverages and tobacco", the "Coal and lignite; crude petroleum and natural gas" and the "Products of agriculture, hunting, and forestry; fish and other fishing products" are the most carried by road, with 293 914, 223 247 and 171 227 tkm. By railways, the most carried goods are the "Chemicals, chemical products, and man-made fibers; rubber and plastic products; nuclear fuel", the "Metal ores and other mining and quarrying products; peat; uranium and thorium" and the "Food products, beverages and tobacco", counting with 49 677, 46 113 and 43 715 tkm.

Looking simultaneously to Figure 3 and Figure 4, in tonnes and Figure 5 and Figure 6, in tonne·kilometer, we can see that in road transport, the ranking of the most transported goods, measured in tonnes is not similar to the one in tonne·kilometer. Contrariwise, in rail transport, the rankings are similar for measures in tonnes and in tonne·kilometer.

Because each country in European Union have different transport behaviors, in Figure 7 and Figure 8 are shown some comparisons between Portugal and Czech Republic. These countries have similar geographical area and population size, but a very different geographical location, since Portugal is a peripheral country and Czech Republic is a central country, so it is interesting to compare the transport statistics among them.

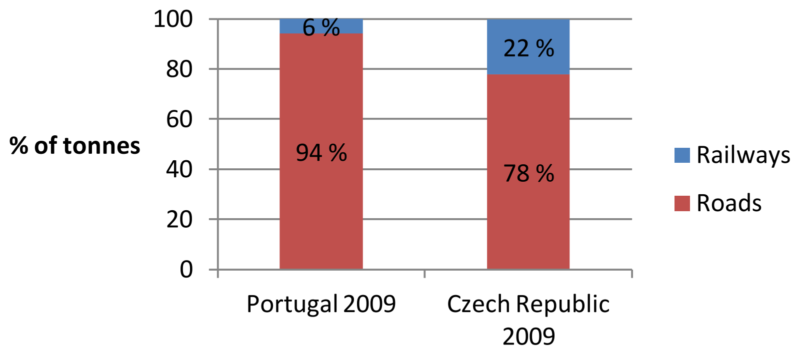

Figure 7 – Modal split of inland transportation In Portugal and Czech Republic, 2009. Drawn from [7].

Transport by inland waterways has a negligible freight transport in Portugal and in Czech Republic, so, Figure 7 only shows the road and rail transport. In Portugal, road transportation has a huge quota in freight transport. In Czech Republic, road transportation also has the highest part in transportation. Rail transport has more importance in Czech Republic than in Portugal with a percentage of 22% against 6% respectively.

Comparing these two countries with the average in EU27, in Portugal the roads are more used than the average in EU27, in opposite to the railways. In Czech Republic, freight transport in railways is more frequent than the average in EU27. Figure 8 shows these aspects.

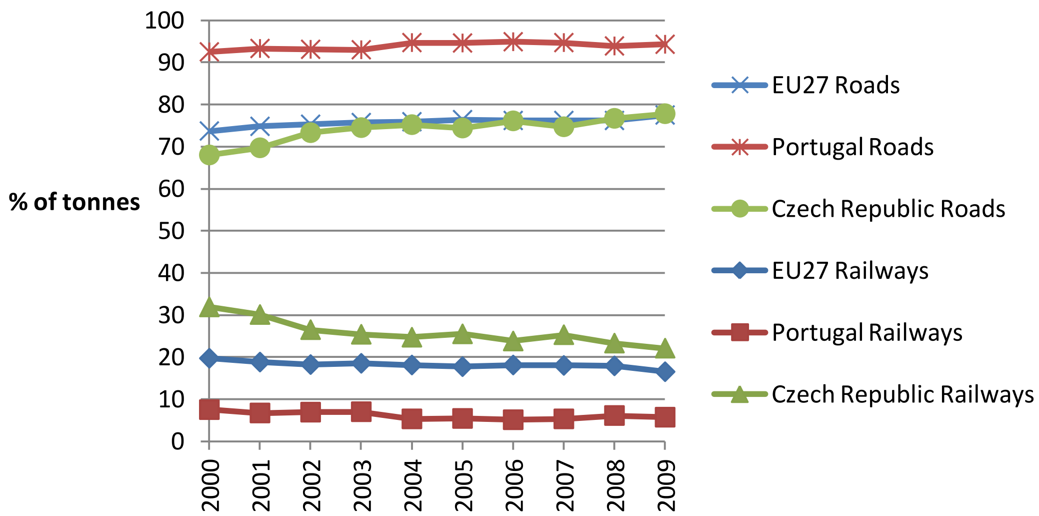

Figure 8 – Evolution of freight road and rail traffic in EU27, Czech Republic and Portugal. Drawn from [7].

2.3.1.2. Portugal

National and international traffic of goods

In this section, some comparisons between road and rail traffic, measured in carried tonnes, either referring to national traffic as to international traffic are present for Portugal.

The Figure 9 and Figure 10 below show the evolution of road and rail traffic since 2001 until 2010 [9]:

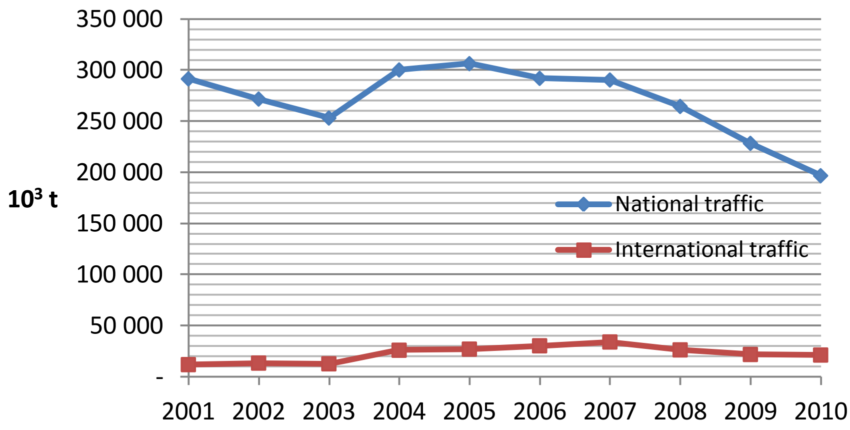

Figure 9 – Evolution of national and international freight road traffic in Portugal. Drawn from [7].

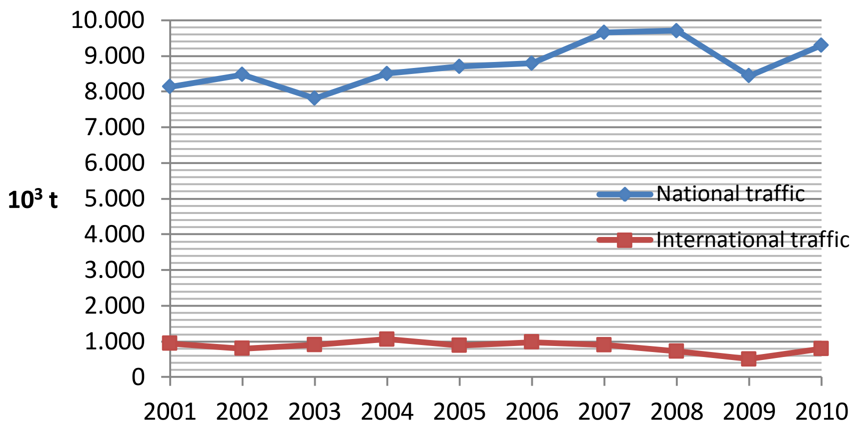

Figure 10 - Evolution of national and international freight rail traffic in Portugal. Drawn from [7].

The national traffic, measured in tonnes, is much higher than the international one. The international road traffic is increasing relatively to the national traffic, achieving 10% of the total amount carried in 2010. In the railway transport there is no notice of such modification. The international rail traffic corresponds to 8% of the total amount carried in 2010.

Class of distance

An interesting analysis consists of understanding the transportation of goods by rail and road, according to classes of distance.

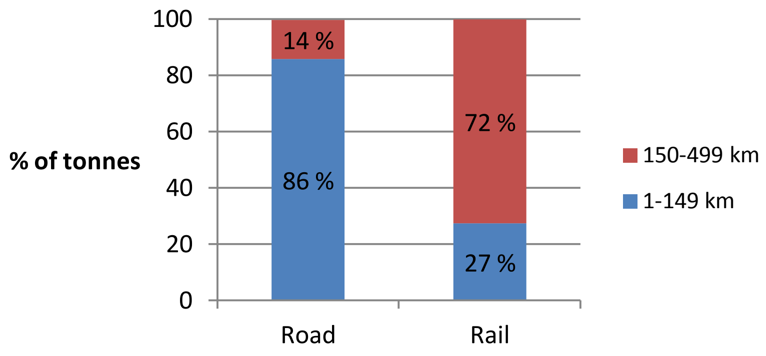

Figure 11 - Percentage of national traffic, according to class of distance, in Portugal, in 2010. Drawn from [9].

Figure 11 shows the evidence that road transport is more often used for shorter distances than longer distances, on the contrary to the railway transport. In the national territory, goods transported for more than 500 km have an negligible amount, which is explained by the limited area and dimension of the country.

Refering to internatinal traffic, Figure 12 shows the importance of european countries in imports and exports of Portugal, by rail and road transport.

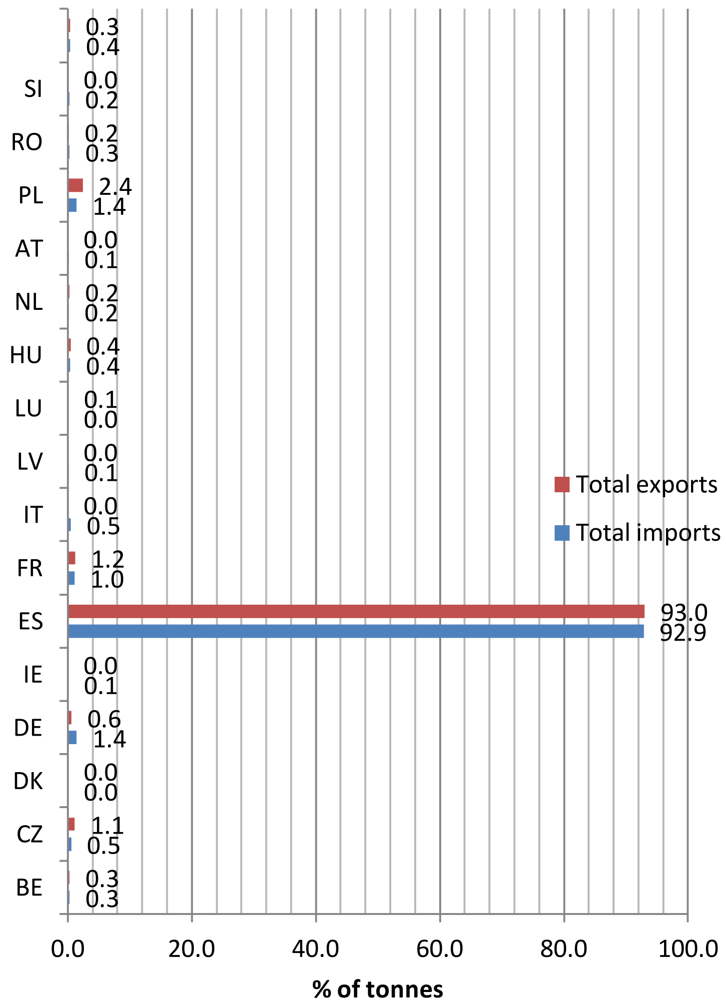

Figure 12 - Portugal imports and exports of goods by rail and road. Drawn from [7].

Only Spain has a relevant importance in internation traffic, achieving more than 90% of total imports and exports of goods. No other country represents more than 3% of imports or exports.

Rail Wagons

One of the indicators of the railways transportation efficiency is related to the empty or not filled wagons carried by a train. In Portugal, the not filled wagons have been reducing, from 19% of 312 000, in 2001, to 12% of 373 000 in 2010. However, the average weight for wagon is decreasing since 2001, according to Table 3 [9].

Table 3 - Evolution of the average weight of wagon.

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Average weight (t)	36	37	37	36	36	35	36	32	27	27

Dangerous goods

The transportation of dangerous goods requires distinct attention comparing to another type of goods, because they need more restrictive rules of packaging and carriage. As all the other types of goods, the road type of transportation is the most used one. However, in the last years, the number of tonne·kilometer carried by trucks has been decreasing, as it is shown in Figure 13:

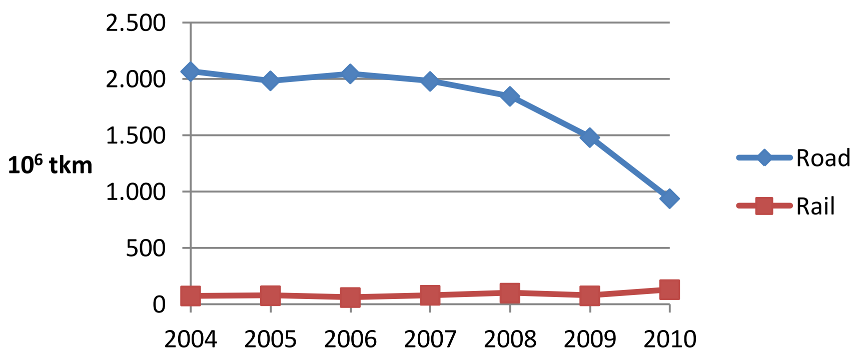

Figure 13 - Evolution of transportation of dangerous goods in Portugal. Drawn from [7].

The evolution of tkm transported by road vehicles shows a decreasing of 58%, from approximately 2 030 000 000 tkm in 2004 to 860 000 000 tkm in 2010, while in railways transport an increase of 77 %, from 74 tkm in 2004 to 131 tkm in 2010 is reckon.

The amount of tonnes of dangerous goods accounted in national ports decrease, in the same period, from 34 000 000 to 29 500 000. It is concluded that the total freight of dangerous goods has been reduced.

2.3.1.3. Czech Republic

Similar analysis on the national and international traffic of goods has been done for Czech Republic.

The Figure 14 and Figure 15 show the evolution of road and rail traffic since 2001 until 2010:

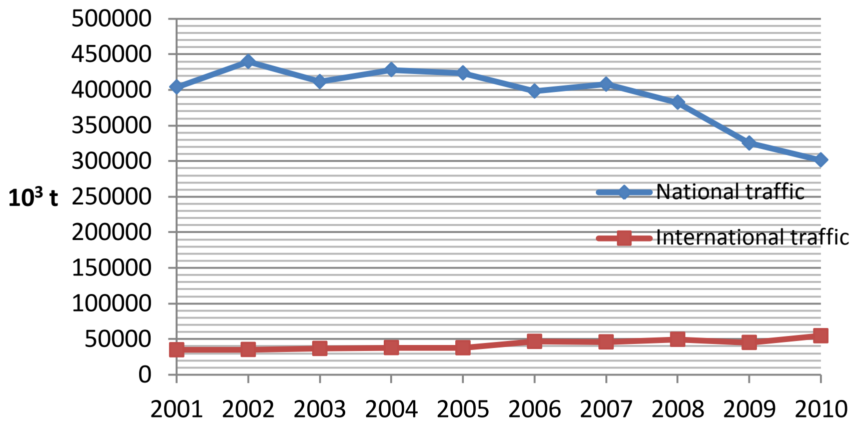

Figure 14 - Evolution of national and international freight road traffic in Czech Republic. Drawn from [7].

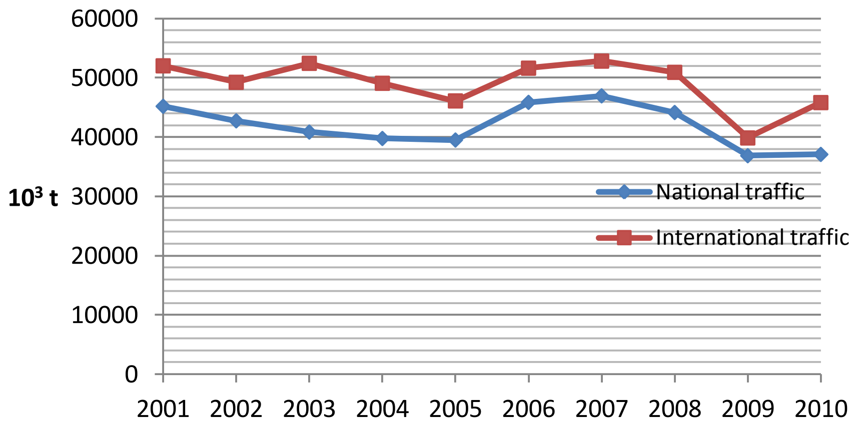

Figure 15 - Evolution of national and international freight rail traffic in Czech Republic. Drawn from [7].

In Czech Republic the national road transportation of goods is much higher than the international transportation, as in Portugal. However an increase of the international traffic and a decrease of national traffic are reckoned. The international rail traffic is higher than the national one, achieving a quota of 55% of the whole freight transported by railways in 2010.

Class of distance

Figure 16 refers to the transportation of goods by rail and road, according to classes of distance.

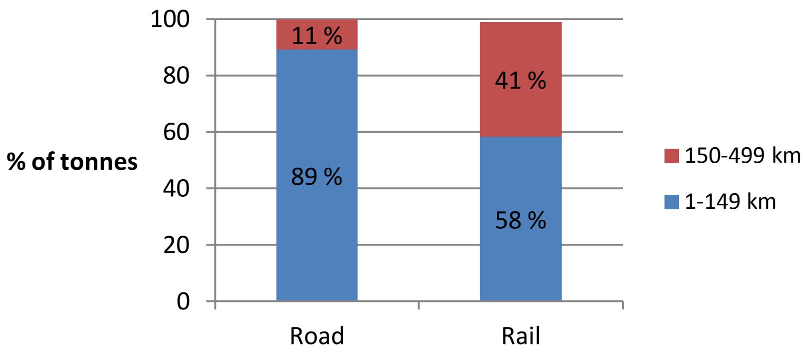

Figure 16 - Percentage of national traffic according to class of distance, in Czech Republic, in 2010. Drawn from [10].

As in Portugal, the national freight road traffic is more used for shorter distances and the rail transport traffic is used to shorter distances as well as to longer distances. For more than 500km, the national traffic is negligible because of the limited geographical area of the country.

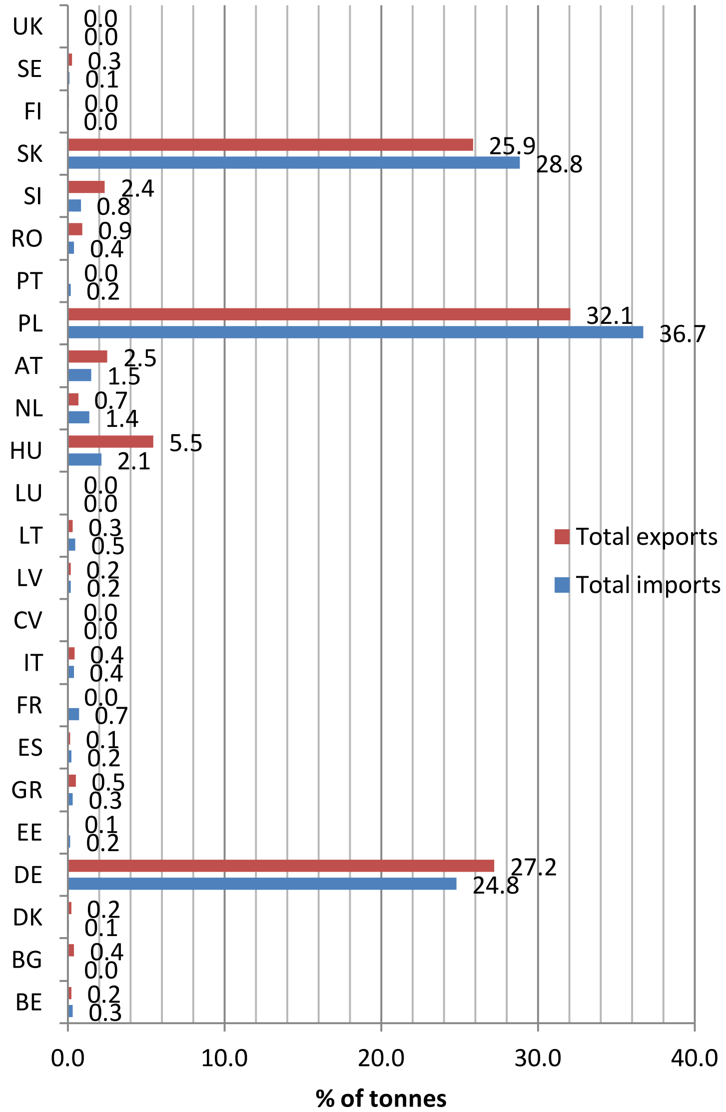

Figure 17 – Czech Republic imports and exports of goods by rail and road. Drawn from [7].

The country with the most freight trading with Czech Republic is Poland, representing 37% of imports and 32% of exports, by rail and road transport. Slovakia and Germany are also important countries in international trading with Czech Republic.

The majority of international interaction of Czech Republic is made with neighboring countries. Because of the geographical location in central Europe, Czech Republic has a relevant freight trading with more countries than Portugal.

Rail Wagons

In 2010, the quota of not filled wagons going on freight trains in Czech Republic was around 27%, 188 000 non-full wagons in a total of 706 000. In the last years, the percentage of not filled wagons has been similar [10].

In 2010, the percentage of not filled wagons in Czech Republic is higher than the percentage of the same in Portugal (27% against 12%), indicating that the rail freight transport in Portugal is, in this aspect, more efficient.

Dangerous goods

Figure 18 shows the evolution of transportation (measured in tkm) of dangerous goods in Czech Republic by road and rail.

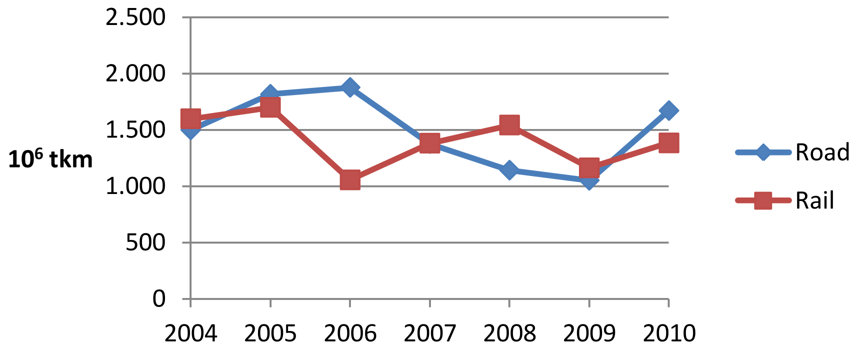

Figure 18 - Evolution of transportation of dangerous goods in Czech Republic. Drawn from [7].

From Figure 18, some fluctuations are observed in the total tkm measured. The transport by road was already the most used one, namely in 2006, with a total of 1875 000 000 tkm, but the transport by rail was also the most used one, in 2008, with a total of 1541 000 000 tkm. In 2010, the road transport was responsible for 55% of the dangerous goods transportation.

Considering this two transport modes, the road transport in Portugal has a quota of 87 % (Figure 13), while in Czech Republic this one is 55 %. The rail transport is much more used in Czech Republic (45%), than in Portugal (13%) for transportation of dangerous goods.

2.4. SUMMARY

This chapter starts with the identification of the main transport modes used for freight, highlighting the comparative advantages of each one, namely the mobility for road transport, the low energy use for railways, the high load capacity of ships, the high-speed of airplanes and the high volume capacity of pipelines.

Also statistics about the types and quantities of goods transported around European Union and about the transport modes used for it are presented, especially focusing on the road and rail transport, comparing the trends between the European Union, Portugal and Czech Republic.

Road transport is clearly the most used one in all Europe. The rail transport has more importance in Czech Republic and in the EU in general than in Portugal, contrariwise to road transport. The international traffic has more relative importance in Czech Republic than in Portugal, especially regarding the rail transport which may be justified by its central location in Europe and by the lack of technical facilities in Portugal. For instance, the difference of the Portuguese gauge in comparison to the European gauge size is a barrier to the international traffic.

3

TRANSEUROPEAN NETWORKS AND LOGISTIC PLATFORMS

3.1. INTRODUCTION

The development of economies, technologies and the implementation of new policies in the last decades leaded to a more open and global market, in which the operations of the freight trade have a lot of importance in the world. The development of infrastructures for long distances transport and of multimodal infrastructures has been an important factor in facing the needs of global trade [11]. With the same purpose, it makes sense that the principal transport corridors are compatibles with the locations of the main logistic centers.

In this chapter, a brief description of the concept of transeuropean networks and a more extensive analysis of the transport network is presented, with special attention paid to the road and rail networks, showing the main objectives and plans according to the European Union. To attend to some technical particularities of the rail network, it is done a comparison between the high-speed and the conventional railways, covering technical aspects with direct interference in transportation of passengers and goods in Europe.

Then, a small reference to the priority axis defined by the European Commission for the transport network is done. Also, a comparison between the transport networks in Portugal with the ones in Czech Republic is shown. This comparison is interesting because these two countries have similar geographical area and population size, but a very different geographical location, which is an influent factor in the transport politics.

After, some concepts about logistic platforms and intermodality are presented and an extensive list of locations of the main intermodal logistic centers in 25 countries of European Union is shown.

Finally it is described the importance of the logistics system in Portugal, referring to the actual situation of the intermodal platforms considered as fundamental.

3.2. CONCEPT OF TRANSEUROPEAN NETWORKS

The concept of transeuropean networks can be understood by the meaning of the two words separately: "transeuropean" refers to something that evolves or it is common for some of the European countries; "network" is, generically, a system that contains nodes or points connected between each other. So, transeuropean networks consist on a network through European countries.

According to the European Commission, this concept "emerged by the end of the 1980s in conjunction with the proposed Single Market" [12]. In fact, the idea of globalization, or "big market" is reasonable only if the nations and regions are connected with properly infrastructures, namely related to transport, energy and telecommunications, to support the movement of persons, goods and services. So, the creation and development of the transeuropean networks are essential to reinforce the Economic and Social Cohesion in European Union [12].

3.3. TRANSPORT NETWORKS

The transport networks, which include transport infrastructures (roads, railways, inland waterways, maritime ways, ports and airports) and systems of traffic management, positioning and navigation [14], are a very important part of the transeuropean networks.

The growing of freight transport noticed in the last years in European Union is responsible for the growing of traffic congestion, accidents, noise, air pollution, of dependence of fossil fuels and wasting of energy. To reduce these problems and to avoid eventual economical and social negative consequences due to the limited capacity of transport networks, it is necessary to develop and to optimize networks, integrated with logistic solutions to take as much advantage as possible of each transport mode and their combinations [13].

In European Union, the Commission has the duty to be aware and to define the major guidelines for the management of the transeuropean networks of transport, or TEN-T, which can be simply defined as a group of locations connected by transportation systems.

The main goals established by the EU are [14]:

- To ensure the sustainable mobility of persons and goods;
- To offer users high-quality infrastructures;
- To include all modes of transport, taking account of their comparative advantages;
- To allow the optimal use of existing capacities;
- To be, insofar as possible, economically viable;
- To cover the whole territory of the Member States of Community;
- To be capable of being connected to the networks of the European Free Trade Association (EFTA) States, the countries of Central and Eastern Europe and the Mediterranean countries.

To promote as much as possible the multimodal transport, it is essential to connect important freight points such as maritime ports, inland waterways ports and intermodal centers. In order to follow the environmental requirements, the priority should be given to the less environmental aggressive transport modes, namely the railways, maritime transport for short distance and inland waterways.

To support the European Commission and TEN-T project managers and promoters, in 2006 it was created the Trans-European Transport Network Executive Agency, TEN-T EA, which is responsible for managing the technical and financial implementation of TEN-T programme. Figure 19 and Figure 20 gives an idea of the number of projects and the monetary funds involved, by transport mode [19].

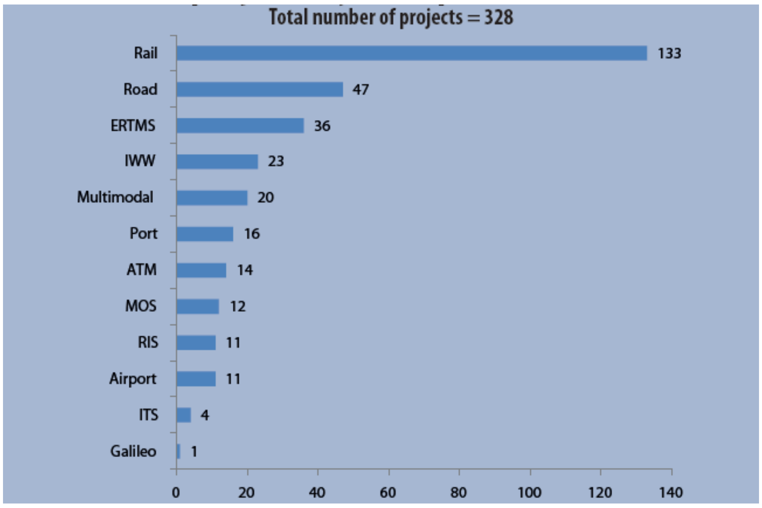

Figure 19 – Number of ongoing and completed projects by transport mode. [19].

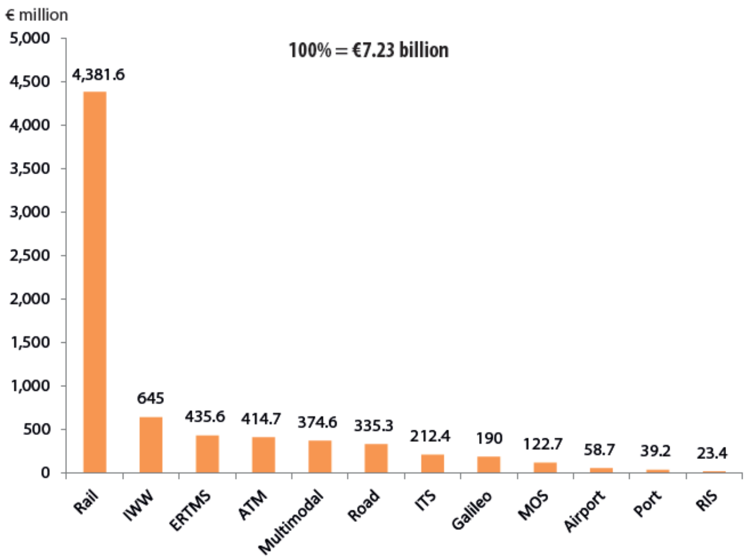

Figure 20 – Total TEN-T contribution (initially awarded) by transport mode. [19].

Legend:

ATM – Air Traffic Management;

ERTMS – European Rail Traffic Management System;

ITS – Intelligent Transport Systems and Services;

IWW – Inland Waterways;

MOS – Motorways of the Sea

RIS – River Information Services

From Figure 19 and Figure 20, some observations are made. Rail infrastructures are responsible for the highest part of the investment, representing 41% of the number of projects and 61% of the overall TEN-T funding. Although the road projects represent 35% of the overall number of projects, it only costs 5% of the total funding. These numbers shows that it lefts much more and complex work to do with railways infrastructures than with road infrastructures.

3.3.1. Road network

The transeuropean road network for freight transport includes existing or new highways and high quality roads and should verify one of the following topics [14]:

a) To "play an important role in long-distance traffic";
b) To "bypass the main urban centres on the routes identified by the network";
c) To "provide interconnection with other modes of transport";
d) To "link landlocked and peripheral regions to central regions of the Union".

The roads defined as part of transeuropean network are identified with the letter E and one number in a European scale, so there is no distinction of it between countries. For instance, the road E55 starts in Helsingborg (Sweden) and passes through several cities from different countries such as Copenhagen (Denmark), Berlin (Germany), Prague (Czech Republic), Salzburg (Austria), Pescara (Italy) and finishes in Kalamata (Greece) [15].

Figure 21 shows the transeuropean road network, defined in 2010 for the horizon to 2020:

Figure 21 – Transeuropean road network [14].

Through a simple observation of Figure 21, a higher density of roads in the central zones of European Union is noticeable.

In annexes, the network maps of each country of EU are presented.

3.3.2. RAIL NETWORK

The transeuropean rail network, part of the TEN-T, refers to railways services of passengers and goods. It shall fulfill at least one of the following functions [14]:

a) To "play an important role in long-distance passenger traffic";

b) To “permit interconnection with airports, where appropriate”;
c) To “permit access to regional and local rail networks”;
d) To “facilitate freight transport by means of the identification and development of trunk routes dedicated to freight or routes on which freight trains have priority”;
e) To “play an important role in combined transport”;
f) To “permit interconnection via ports of common interest with short sea shipping and inland waterways”.

It is noticeable that the EU is making efforts to promote the combined transport. This concept is used when the major part of a freight travel is done by train or by maritime transport, using the road transport only in the beginning and/or ending journey [25]. Regarding the freight transport, the development of routes with priority for freight trains and the interconnection of sea ports are clearly aspects to increase the importance of freight rail transport.

One of the main purposes of developing the transeuropean rail network is to join all the railways services into a single market, passing from a national management to an international management “without boundaries”. In practical terms, the main goal is to allow, provide and facilitate the movement of rail units between countries unhindered in technical, logistic and administrative problems. To achieve such objective, it is needed a lot of technical, economic and political work, definition and application of standardization measures and interoperability specifications [16]. These specifications serve to eliminate structural and functional differences in the railway systems that cause obstacles in the passage of trains between countries with distinct characteristics. Such specifications are related to [17]:

- Structural areas:
  - Infrastructure
  - Energy
  - Control-command and signaling
  - Rolling stock
- Functional areas:
  - Traffic operation and management;
  - Maintenance;
  - Telematics applications for passenger and freight services.

The rail network includes high-speed and conventional lines, thus, the mentioned specifications are applied to both of them.

Figure 22 shows the map of transeuropean rail network:

Figure 22 – Transeuropean rail network [14].

Like in the road network, a higher density of lines in central zones of European Union is noticeable.

In annexes, the network maps of each country of EU are presented.

3.3.2.1. High-speed vs conventional railways

At this point, some technical characteristics and comparisons between high-speed and conventional lines are presented, in order to understand the restrictions of each one when being used to the transport of freight, in terms of velocity, maximum permissible load and train lengths. This characterization is useful to help in the definition of case studies based on real transport problems.

High-speed railways consist of lines specially built for that, prepared to velocities higher than 250 km/h, or on lines specially adapted, prepared to velocities around 200 km/h. These lines are especially focused on passenger transport, although they can also be used to freight transport, respecting the maximum static weights per axle indicated in Table 5. Those limits are defined looking forward the security and technical compatibility, depending on the class and velocity of the trains, identified in Table 4.

Table 4 – Class definition of high-speed trains. Adapted from [18].

Maximum service speed V		Details
Class 1	V ≥ 250	Self-propelled trainsets with driver's cab at each end of train, capable to bi-directional operation.
Class 2	190 ≤ V ≤ 250	Trainsets, or trains of variable formation with or without bi-directional capabilities

Table 5 – Static axle load to high-speed railways [18].

	V: Velocidade máxima de serviço, em Km/h				
	190 ≤ V ≤ 200	200 < V ≤ 230	230 < V < 250	V = 250	V > 250
Class 1				≤ 18t	≤ 17t
Class 2 locomotives and powerheads	≤ 22,5t		≤ 18t	n/a	n/a
Class 2 multiple units	≤ 20t	≤ 18t		n/a	n/a
Class 2 locomotive hauled coaches	≤ 18t			n/a	n/a

The total weight of train cannot be higher than 1000 t, and the maximum length must be 400 m [18].

Because of the highest speeds and the lowest axle loads, high-speed lines are more useful, but not exclusive, to achieve the functions a), b) and c), mentioned in section 3.3.2, relevant to the passenger transport.

The conventional railways network is, nowadays, the most extensive one, used for passenger and freight transport. The velocities are lower, but the axle load allowed is higher, so this network is more important to achieve the functions d), e) and f) also mentioned in section 3.3.2, relevant to the freight transport.

There are various categories of lines according to type of traffic, maximum speed, axle load and train length allowed, as it is shown in Table 16.

Table 6 – Performance parameters for freight and mixed traffic on conventional lines. Adapted from [24].

Types of traffic	TSI categories of line	Line speed (km/h)	Axle load (t)	Train length (m)
Freight traffic	New core TEN line	140	25	750
	Upgraded core TEN line	100	22.5	600
	New other TEN line	100	25	500
	Upgraded other TEN line	100	20	500
Mixed traffic	New core TEN line	200	25	750
	Upgraded core TEN line	160	22.5	600
	New other TEN line	140	25	500
	Upgraded other TEN line	120	20	500

It is observed that the lines exclusively for freight traffic have lower speeds that the ones who also are prepared for passenger traffic (mixed traffic).

Comparing with high-speed trains, the conventional ones can be longer and heavier, which makes it the preferred ones to freight transport in general.

3.3.3. Priority axis

In the whole TEN-T there are several planed projects, some with more importance than others.

Currently, the European Union has defined 30 priority projects to develop the transport network. These projects have the following main goals [14]:

- To "Eliminate bottlenecks or complete missing links on a major route of the trans-European network";
- To present socio-economic benefits;
- To improve significantly the mobility of goods and persons and thus also contribute to the interoperability of national networks;
- To improve connections with the peripheral and island regions;

In these thirty priority projects, eighteen are focus on railways, three on road projects, three on mix (road and rail) projects, three on waterways and one related to air transport. There is also one project involving intermodal transport in Iberian Peninsula, with investment in rail, road, maritime and air routes. The high amount of priority projects related to railways, waterways and related to mix (road and rail) transport reflect a high priority to the use of more environmentally friendly transport modes [20].

In the annexed maps of each country are written the priority axis ascribed to the respective country. To study it with more detail it is recommended to look at the properly references [21].

3.3.4. PORTUGAL AND CZECH REPUBLIC NETWORKS

Following the idea to compare the transportation systems of Portugal with Czech Republic, in this section are compared the road and rail networks of each country, illustrated in maps 7, 8, 38 and 51 annexed. In that maps are already included some identified red points representing the intermodal logistic platforms referred in section 3.5.

Relatively to the road network, the considered roads are only the ones defined on the transeuropean network, including the planned high-speed lines. The lengths were measured using Google software such as Google Earth and Google Maps, consistent with the maps 8 and 38 annexed. The use of Google tools to measure distances were useful to estimate with good approach the roads lengths, however, it is expected some difference between the measured values and the reality ones.

Relatively to the rail network, the information about the lengths of Portuguese railways were calculated based on a document from REFER, known as IET 50, provided to the author by IMTT, where there is included a national map of the rail network with identification of the lines and one table with lengths of sections for each line. The calculation was made by summing the sections lengths of each line. Looking towards some objectives of this work, only the conventional lines, existent and planned, were considered because they are the most appropriated to freight transport. Also, it was considered one existent connection between *Torre das Vargas* and *Caia*, designed in the annexed map 51 with a green straight and continuous line, because such omission would increase too much the distances between the northern platforms and Caia and take the simulation of case 5 in section 5.3 with an unrealistic character.

The information on the lengths of Czech railways was provided by Mrº Vladimir Kyncl, from the Ministry of Transport, and complemented with approximate measurements on Google Earth.

Table 8 present the total lengths of the referred networks and its relations with the area and population size for Portugal and Czech Republic. The area and population sizes are presented in Table 7.

Table 7 – Area and population size of Portugal and Czech Republic [22] [23].

	Area (km^2)	Population (inhabitants)
Portugal	92090	10561614
Czech Republic	78866	10562214

Table 8 – Total lengths, in kilometers, of road and rail transeuropean networks in Portugal and Czech Republic and its relation with area and population.

			Relation with area (km/km^2)	Relation with population (km/inhabitants)
Portugal	Road	2800	0.0304	0.000265
	Rail	1860	0.0202	0.000176
Czech Republic	Road	1774	0.0193	0.000168
	Rail	2190	0.0238	0.000207

From this table it is observed that:

- In Portugal, the transeuropean road network is longer than the rail one, while in Czech Republic is the opposite;
- The transeuropean road network in Portugal is longer than the transeuropean road network in Czech Republic. In Portugal, there are 30m of road length for each km^2 of territory, while in Czech Republic there are only 19m. For each habitant in Portugal there are 26cm of road, while in Czech Republic there are 17cm.
- The transeuropean rail network in Portugal is shorter than the transeuropean rail network in Czech Republic. In Portugal, there are 20m of rail length for each km^2 of territory, while in Czech Republic there are only 24m. For each habitant in Portugal there are 18cm of rail, while in Czech Republic there are 21cm.

These numbers are coherent with the statistics of chapter 2.3, which shows that the freight rail transport assumes more importance in Czech Republic than in Portugal. Such fact can be related with the central location of Czech Republic, making this country a transit point for international traffic between other countries.

3.4. LOGISTICS AND INTERMODALITY CONCEPTS

The concept of logistics refers to an activity related to the planning and management of the flow of goods in a certain space and time [25].

A logistic platform or centre or a freight village can be defined as a physical delimitated place where take place activities of loading, unloading, modal changing, storage and identification of freight. It is supposed to be a center where various cargo operators can work at the same time [25]. When a logistic platform is equipped to proceed to the modal changing without handling the freight, it is considered to be an intermodal logistic platform.

Maritime ports are a typical example of an intermodal platform, where the freight, usually carried in containers, is transferred from ships to trucks or trains and contrariwise. To the platforms located in the countryside with direct connections to maritime ports are given the name of “dry ports” [25].

The modal changing without handling the freight demands the compatibility between the various transport modes and the goods packages or containers. So, to carry the freight, intermodal containers are often used. They have standard specifications according to the International Organization for Standardization, ISO. The main goal is to oblige all the members of the organization to produce and use containers with the same dimensions and support characteristics so they can easily be moved from one transport mode to another, fitting good either in trucks, trains and ships, in a big range of countries.

There are several types of ISO containers, classified according to the packaging characteristics and the size. The most common types are [26] [27]:

- Dry Freight ISO containers
- Refrigerated ISO containers
- Insulated ISO containers
- Open Top ISO containers

Sizes and weights are indicated in Table 9.

Table 9 – ISO containers [27].

Container size		Weight (kg)		
Feet	Meters	Maximum gross weight	Tare	Maximum Payload
20’ x 8’ x 8’6”	6.096 x 2.438 x 2.591	30 480	2 300	28 180
40’ x 8’ x 8’6”	12.192 x 2.438 x 2.591	30 480	3 890	26 590
40’ x 8’ x 9’6”	12.192 x 2.438 x 2.896	30 480	4 170	26 310

* The tare and maximum payload differs from container to container depending on the material and on the function of each one. The maximum gross weight is the same for every types.

The information about dimensions and weights of containers are useful to define case studies of transport problems.

3.5. LOCATIONS OF INTERMODAL LOGISTIC PLATFORMS

The location of logistic platforms is a very important factor with consequences in the benefit taken from each platform. Following points present some important reasons to explain the location of logistics centers:

- Proximity to industrial and urban areas, where the markets, labour conditions and financial incentives are better [28];
- Existence of good transport infrastructures connected with the main national and international corridors;
- Proximity to coast side of territories, where it’s possible to take advantage of maritime transport;
- Proximity to a navigable river that allow the connection with other platforms near big urban areas;

It is important to note that not only the existing conditions influence the location of logistic centers, but also these centers influence the growing and expansion of the respective regions.

3.5.1. LOCATIONS BY COUNTRY

At this point, the locations names of the intermodal logistic platforms in 25 countries of European Union are presented. In order to have coherence between the transeuropean road and rail networks with the logistic platforms, of all the 27 countries of EU, Malta and Cyprus are not included, because there are no transeuropean rail networks defined for these countries.

For identifying the platform locations, several sources were considered and in some cases, some inconsistent information was found. For instance, in some big countries with a lot of intermodal platforms, such as France or Germany, different information sources consider different platforms as the principles ones. Also, the less information found about the freight villages in some other countries, such as Estonia and Latvia for example, makes it difficult to identify the localization of the platforms. Due to these reasons, the locations picked by the author, written in Table 10, might not represent all the most important logistic platforms in a consistent way. All the indicated platforms are located near the defined transeuropean transport networks.

Table 10 – Intermodal logistic platforms per country.

Country	Locations
Austria	Graz; Hall in Tirol; Linz; Salzburg; St. Michael; Villach; Wels; Wien; Wolfurt [29].
Belgium	Antwerp; Athus; Brussels; Charleroi; Liège; Mouscron; Muizen [29].
Bulgaria	Bourgas; Ruse; Sofia; Stara Zagora; Varna [30].
Czech Republic	Brno; Decin; Lovosice; Melnik; Nyrany; Praha; Prerov; Usti nad Labem.
Denmark	Aalborg; Aarhus; Esbjerg; Kobenhavn [31] [32] [33] [34].
Estonia	Muuga [35].
Finland	Helsinki; Oulu; Turku [36] [37] [38].
France	Agen; Aude; Bordeaux; Brest; Caen; Calais; Chalon sur Saone; Cherbourg; La Rochelle; Le Havre; Lille; Lyon; Mâcon; Marseille; Mulhouse; Nancy; Nantes; Paris; Sète; Strassbourg; Val-De-Marne; Vallenciennes [39].
Germany	Berlin; Cuxhaven; Dorpen; Duisburg; Emden; Erfurt; Frankfurt am Main; Frankfurt an der Oder; Halle; Hamburg; Hannover; Hof; Kassel; Kiel; Koln; Leipzing; Magdeburg; Munchen; Nurnberg; Regensburg; Rheine; Riesa; Rostock; Stuttgart; Trier [39].
Greece	Athens; Patras; Thessaloniki [39] [40].
Hungary	Budapest; Debrecen; Gyor; Miskolc; Szekesfehervar; Szolnok; Szombathely; Zahony [30].
Ireland	Cork; Dublin; Limerick; Sligo; Tralee [39].
Italy	Ancona; Bari; Brindisi; Cagliari; Civitavecchia; Genoa; Gioia Tauro; La Spezia; Livorno; Mantova; Messina; Napoli; Palermo; Piombino; Ravenna; Taranto; Trieste; Venice; Verona [39] [41] [42].
Latvia	Liepaja; Riga [43] [44].
Lithuania	Kaunas; Klaipeda; Vilnius [45] [46].
Luxembourg	Luxembourg.
Netherlands	Amsterdam; Born; Eindhoven; Moerdijk; Tilburg; Venlo [39] [47].
Poland	Gdynia; Gliwice; Krakow; Kutno; Mlawa; Poznan; Sosnowiec; Warszawa; Wroclaw [29].
Portugal	Bobadela; Caia; Entroncamento; Guarda; Leixões; Maia/Trofa; Poceirão; porto de Aveiro; Sines; Tunes; Valença [49] [50].
Romania	Bacau; Brasov; Bucaresti; Cluj; Constanta; Sibiu; Timissoara [39].
Slovakia	Bratislava; Kosice; Sladkovicovo; Vel'ka Ida; Zilina [30].
Slovenia	Celje; Koper; Ljubjana; Maribor [30].

Country	Locations
Spain	Algeciras; Alicante; Barcelona; Bilbao; Cadiz; Cordoba; Gijon; Jundiz; La Coruña; León; Linares; Lugo; Madrid; Málaga; Murcia; Salamanca; Santander; Sevilla; Tarragona; Valencia; Vigo; Zaragoza [39] [48].
Sweden	Gavle; Goteborg; Helsinborg; Malmo; Nassjo; Stockholm; Sunsvall; Vasteras [29].
United Kingdom	Aberdeen; Belfast; Birmingham; Bristol; Cardiff; Crewe; Daventry; Harwich; Holyhead; Hull; Larne; Liverpool; London; Manchester; Mossend; Newcastle; Plymouth; Portsmouth; Ramsgate; Southampton; Stranraer [39].

3.6. INTERMODAL LOGISTIC PLATFORMS IN PORTUGAL

The Portuguese logistic platforms have been an important matter in the last years, in which some entities have been working and studying, releasing policies and projects. The main goal is to improve the importance of Portugal in the international trade of goods coming through the Atlantic sea to Europe.

In 2006, the Ministry of Public Works defined the logistic network in order to foment the intermodality transport of freight, to be more environmental friendly, to contribute to national economic growth, develop some territories and to be more competitive in the European logistics by turning the disadvantage of being a peripheral country into an advantage of having a long coast in Atlantic sea. The platforms were selected based on existing infrastructures, locations, intermodality facilities, costs and dimension. Table 11 indicates the main characteristics of such platforms [50].

Table 11 – National network of intermodal logistic platforms defined in “Portugal Logístico” program [50].

Location	Transport types	Expected demand per year (10^3 tonnes)	Transeuropeans Connections
Maia/Trofa (Suspended)	Road and rail	1600	**Road:** E01 **Rail:** Conventional line of Minho.
Poceirão (not operating yet)	Road and rail	3000	**Road:** E01 and E90. **Rail:** Conventional line of Alentejo / South; Conventional line Lisboa-Évora; Future high-speed line Lisboa-Madrid.

Location	Transport types	Expected demand per year (10^3 tonnes)	Transeuropeans Connections
Leixões	Road, rail and maritime	900	**Road:** E01 and E90. **Rail:** Conventional line of Minho; Conventional line of Leixões.
Porto de Aveiro e Cacia	Road, rail and maritime	1000	**Road:** E80 **Rail:** Conventional line of Norte
Bobadela	Road, rail and maritime	800	**Road:** E80 **Rail:** Conventional line of Norte.
Sines	Road, rail and maritime	400	**Road:** IP8. **Rail:** Conventional line of Sines.
Valença (not operating yet)	Road and rail	800	**Road**: E 01. **Rail**: Conventional line of Minho; Future high-speed line Porto-Vigo.
Guarda (stills without railway connection)	Road and rail	300	**Road:** E80 and E802. **Rail:** Conventional line of Beira Baixa/ Beira Alta.
Caia (stills without railway connection)	Road and rail	1100	**Road:** E90. **Rail:** Future conventional line Elvas-Caia; Future high-speed line Lisboa-Madrid.
Tunes (not constructed yet)	Road and rail	600	**Road:** E01. **Rail:** Conventional line of South/Algarve.

Besides the platforms mentioned above which are included in the program “Portugal Logístico”, it is also important to refer the intermodal centre in Entroncamento because it is well located in the center of Portugal in an important node of railways lines [51].

It should be mentioned that not all the indicated platforms are already constructed or in operation, however they are considered for the application/study of the transport problem presented in sections 5.3.4, 5.3.5 and 5.4.3.7.

3.7. SUMMARY

As a summary some annotations are made:

- Roadways had always had more international character than the railways, mostly because of technical aspects. For instance, while a truck can easily travel around a lot of different types of roads, one train has to be supported by a specific railway with similar characteristics in the whole line.
- The interoperability desired to the rail network demands complex works and agreements within all the countries involved.
- The European Union, concerned with environmental policies, is providing more resources to the development of the rail network, especially to the construction of new high-speed lines and to the implementation of the necessary modifications in conventional lines looking towards the interoperability.
- All the main logistic platforms identified are located near to the some transeuropean transport corridor.

The development of the TEN-T by thinking together in the road and rail infrastructures is an important aspect in order to promote the intermodality for the movement of passengers and goods.

4

TRANSPORTATION OPTIMIZATION PROBLEMS

4.1. INTRODUCTION

The previous chapters have focused on some statistical data that demonstrate the importance of freight transport in Europe and on some policies and concepts showing the European Union concerns and actions in order to improve the transportation system in the community.

In fact, regarding logistic subjects and trading of goods, the transportation is an important matter, because it represents costs and plays an important role in the performance of logistic systems [1]. It is natural that individuals are always looking for the best decision to move from a place to another. In the same way, the decision makers in transportation subjects are always looking for the optimal use of their resources and constrainers.

To achieve the best way how to operate logistics and transportation systems it is essential to control and manage them in a good way. To do so, basic steps have to be taken:

- Recognition of the system and its characteristics;
- Definition of objectives and criteria to be optimized;
- Building a model system;
- Experimentations on the model to find the best way how to control the system in order to achieve the objectives with the optimum criteria value;
- Application of the model into real situations.

A system should be understood as a set of elements with relations among them. It can represent a certain part of a real world. The whole system and each of its elements have attributes or parameters that characterize its state. A transportation system basically consists on the transportation infrastructures, transportation flows and the actors on transport activities. A system can be classified according three main topics:

- Dynamic or static, if it changes with time or if it is time independent, respectively;
- Discrete or continuous. Discrete if the attributes consists only in discrete values and the system state may change only by jumps between states. Continuous if the attributes can assume values in a feasible interval, so it can change continuously;
- Deterministic or stochastic. Deterministic if its behavior is always the same under the same input conditions. Stochastic if it is influenced by the stochastic inputs and/or parameters [52].

A model is a representation of a system in such way so it is suitable for experimenting. Mathematical formulations and graphical representations are very often used for models [52].

This chapter begins with describing how a model can be representative of a transportation system, making references to the processes that occur in each part of the model (nodes, arcs and networks). Next presented and explained are the mathematical models usually used to solve transport problems: Shortest Path, Travelling Salesman Problem, Vehicle Routing Problem.

4.2. MODEL OF A TRANSPORTATION SYSTEM

A transportation system generically consists of:

- Transportation infrastructure;
- Vehicles or transportation flows;
- A control subsystem.

Basically, the infrastructure is like a network with nodes and arcs through where the vehicles move along. For instance, nodes can represent locations, and arcs can represent roads. In this case, the cost of the edge could be the distance between the adjacent nodes. A group of nodes and arcs form a graph, which can be directed, if arcs are unidirectional or have different costs for the two directions, or undirected if the arcs have the same costs for both sides. In general, all the graphs can be managed as directed graphs with the particularity that in some cases the costs of arcs are equal in both directions

The control subsystem controls and co-ordinates the activities in the system [52].

Transportation systems can be represented by several different models, with different levels of detail, depending on the application or optimization problem in question. In general, two types of models can be distinguished: macroscopic and microscopic.

- Macroscopic model: defines a transportation system by a network and its basic attributes, usually by assigning costs to the arcs linking the nodes, which can represent distances, monetary costs or other variables used to measure or characterize the connection. In this case, the system is considered to be static and the corresponding model is frequently designed as a graph or it is formulated as a mathematical programming model, suitable to be solved using methods of operations research.
  Macroscopic models are useful for solving optimization tasks like finding paths in a network, usually using data obtained with simple measures like distances between nodes.
  Examples of these models are mentioned in section 4.3.
- Microscopic model deals with individual vehicles or with detailed description of transportation flows described by dynamic characteristics, in which the time assumes an important role. This kind of model is usually formulated as a system of differential equations.
  Microscopic models are useful to estimate variable data such as, for instance, travel time, energy consumption, loading and manipulation time, because these variables always depend of real traffic situations. For instance, there are models to characterize transportation flows by considering the interaction among the vehicles as for example [53]:

  - Multi-regime models: Greenshields, Greenberg, Underwood, Drew.

  - Waiting line models.

  - Shock-wave models

The results of microscopic models can be used as input data to optimize problems on a macroscopic level and vice versa, so they can be used in co-operation. For instance, if it is intended to find an optimal path by minimizing the travelling time, a microscopic model can be used to estimate travel times, and then, a macroscopic model uses the estimated times as an input to find the best path [52]. In this thesis, only the macroscopic models are discussed.

4.2.1. Transportation processes

Transportation processes are activities taking place in a transportation system and can be classified as: processes in arcs, processes in nodes and processes in networks.

Processes in arcs refer to the motion of vehicles along the arcs, taking into account, for instance, the travel time or energy consumption.

Processes in nodes are related to the activities occurring in the nodes of a transportation network, namely the accumulation of elements and the sorting of elements. The sorting is especially important and complex in railway transports when a sequencing is to be attained, because the wagons cannon change their succession on a track, so it is important to order the elements according to the order of exit of the train.

Processes in networks represent management and optimization of activities on a network as a whole, comprising basic problems as: shortest path; transportation problem; travelling salesman problem and routing; location problem and network design. To solve them, macroscopic models and methods of the graph theory are the proper tools [52].

In this paper, the optimization of transport problems are focus only on the processes in networks, so the arcs and the nodes have already defined parameters.

4.3. Models for transport networks

Many optimization problems of transport are only defined on a macroscopic level. Such problems include [52]:

- Location problem – to decide the optimal location and capacity allocation of production, storage or loading/unloading facilities in a network;
- Network design problem – to make an optimal choice of links in a network to serve transportation demands. Important to define the roads or railways to be built or transportation services to be operated;
- Transportation/transshipment problem – to estimate a commodity amount to be transported between sources and sinks in a network;
- Scheduling – to optimize the time planning of transportations services;
- Shortest paths problem – to minimize distance routes among nodes of a network.
- Routing – to find an optimal path for vehicles serving several places;

Next on this chapter there are present and explained the Shortest path problem and two Routing problems (Travelling Salesman Problem; Vehicle Routing Problem), because the main goals of this thesis are related with optimization of routes in existent transport networks, not in the planning of new adds to a network.

In chapter 5 are experimented and discussed the mentioned Routing problems.

4.3.1. Shortest paths

The shortest paths problem is one of the basic optimization problem, which aims to find paths and determinate distances between nodes in a network.

Optimization problems like routing, transportation problem, location problem or network design often require distances as input data, so before solving the problem it is needed to know the distances.

In a network, a path consists of a succession of nodes and arcs, beginning with an origin node and ending with a destination node, that can be or not the same as the origin node. A mathematical formulation uses binary variables ($x_{ij} \in \{0,1\}$) to decide if an edge(i,j) between node i and j is used ($x_{ij} = 1$) in a path or is not used ($x_{ij} = 0$). The flow conservation in each node of a network is a basic condition of a path solution. Considering a network with a set of nodes V, such condition can be defined by the following system of equations:

$$\sum_{(i,k)\in V} x_{ik} - \sum_{(i,k)\in V} x_{kj} = \begin{cases} -1\ for\ k = r \\ 1\ for\ k = s \\ 0\ for\ k \neq r\ and\ k \neq s \end{cases} \quad (1)$$

This formulations means that every node with incoming flows has to have outgoing flows, except i) the origin node ($k = r$) that only has an outgoing edge and ii) the destination node ($k = s$) that only has an incoming edge. In fact, if the origin node is the same as the destination one, it has simultaneously outgoing and incoming flows, so equation (1) is changed for (2):

$$\sum_{(i,k)\in V} x_{ik} - \sum_{(i,k)\in V} x_{kj} = 0 \quad (2)$$

The length of a path from origin to destination node (T_{rs}) can be calculated by summing the distances (c_{ij}) of all the used arcs.

$$d(T_{rs}) = \sum_{(i,j)\in V} x_{ij} * c_{ij} \quad (3)$$

Then, a distance (d_{rs}) is defined as a length of the shortest path according to equation (4) and restrictions mentioned above:

$$minimize \quad d_{rs} = \sum_{(i,j)\in V} x_{ij} * c_{ij} \quad (4)$$

The shortest path problem can be formulated to find:

- the shortest path between 2 nodes (single number);
- the shortest paths from one node to all other nodes (vector of numbers);
- the shortest paths among all pairs of nodes in a network (matrix of numbers or distance matrix).

A distance vector can be build by a repeated search of the shortest paths between two nodes and a distance matrix can be build by a repeated calculation of a distance vector. The opposite calculation can also be done.

The distance matrix is a necessary input in many network optimization problems, so the shortest distances between every pairs of nodes have to be known. There are some algorithms to determinate the distances matrix, namely [52]:

- Floyd algorithm;
- Dantzig algorithm;
- Tabourrier algorithm.

The distance matrix obtained consists on a set of values representing the shortest paths between all pair of nodes, even if in the real network some pairs are not directly connected, i.e., they have an intermediate node between. It is to say that the distance matrix represents a network as if it there are arcs linking directly all pairs of nodes with the shortest distance possible.

None of these algorithms is used in this paper, so no further explanation is done.

4.3.2. ROUTING PROBLEM

Routing problems have been extensively studied by experts, not only because its complexity, but also because it can be applied in a lot of real life situations [1].

There are two main different types of routing problems:

- Node-covering-problems;
- Edge-covering-problems.

Node-covering-problem refers to a situation where the vertices represent customers, and the arcs represent the "costs" of travelling between the vertices. The word "costs" can have several meanings, such as monetary costs; distances; time and other data, depending on the problem to solve. The basic assumption requires that the customers demand is satisfied all at once, so every node is visited only once. This kind of problem is used, for example, to make decisions about the routing of buses or about the distribution of newspapers to kiosks.

In edge-covering-problem, customers are along the arcs which represent sections of the way. This is the kind of problem applied to solve questions like the cleaning of the streets, the delivery of mail to residences or the plowing of snow.

Figure 23 shows the referred problems of routing:

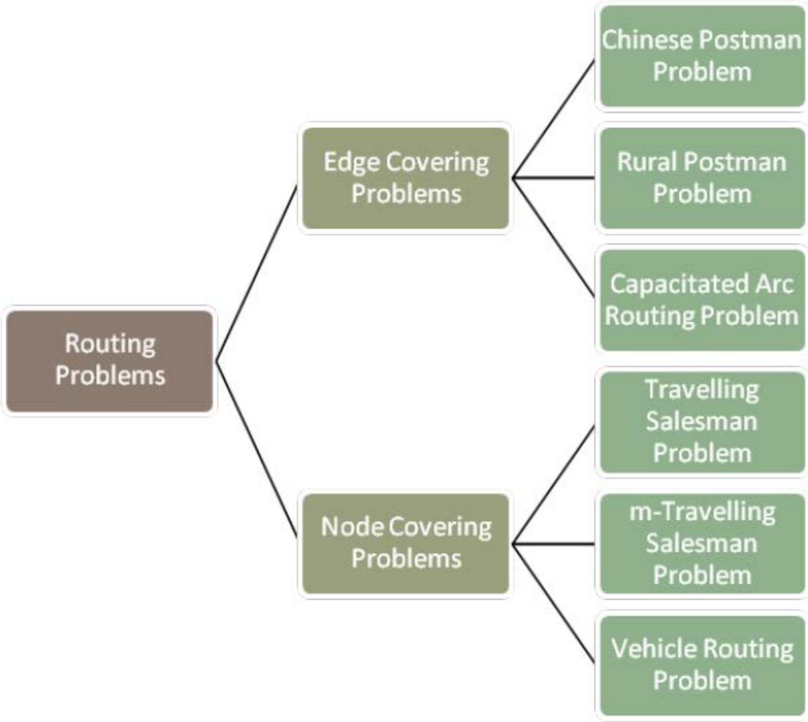

Figure 23 – Routing Problems [1].

In the present thesis the node covering problems are the important ones, because the transport problems discussed, the nodes represent customers, which are connected by arcs with a certain allocated cost. In the next points are discussed the Travelling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP). These are the ones that are going to be applied to the simulated cases in chapter (5).

4.3.2.1. Travelling Salesman Problem

Travelling Salesman Problem, or TSP, is a fundamental node-covering-problem. In this problem, the request is to go from a given beginning node, passing through a set of defined nodes and return to the first node, minimizing the total cost of the route. As the main characteristics, the following points are enumerated:

- Deterministic demands of the same type (only delivery or only collection);
- One vehicle without a capacity limit and without any time limits;
- One depot;
- The objective function minimizes the total cost (e.g. distances) of a route.

The problem can be divided in symmetric version and in asymmetric version. In the first version, the costs of all arcs are the same in both directions (from node i to node j the edge value is the same as from node j to node i), which does not happen on asymmetric version.

The TSP is defined as a direct graph $G = (V, A)$, where $V = \{1, \dots, n\}$ is the node set to be considered, $A = \{(i, j): i, j \in V\}$ is the arc set. The cost of each arc (c_{ij}) is defined on A. The main idea of the resolution is to define which arcs will be used and which are not. So it is used the binary variables x_{ij} equal to 1 if and only if the edge (i, j) (from node i to j) is part of the solution.

There are several models to solve the TSP that can be divided in exact, heuristic and metaheuristic models. In this paper it is just referred and used an exact one.

The following equations show one formulation of TSP.

Objective function:

$$minimize \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} c_{ij} x_{ij} \tag{5}$$

Constraints:

$$\sum_{i=1}^{n} x_{ij} = 1 \tag{6}$$

$$\sum_{j=1}^{n} x_{ij} = 1 \tag{7}$$

$$\sum_{v_i \in S} \sum_{v_j \in S} x_{ij} \leq \mid S \mid -1 \tag{8}$$

$$x_{ij} \in \{0,1\} \qquad i,j = 1, \dots, n \tag{9}$$

with $i,j \in \{1, \dots, n\}$, $i \neq j$ and $S \subseteq \{2, \dots, n\}$; $2 \leq \mid S \mid \leq n-1$

As already mentioned before, variable x only can assume the values 0 or 1. The restrictions (6) and (7) ensure that in each node there is only one incoming arc and one outgoing arc.

Equivalent to equation (8), there can be used the following polynomial constraints:

$$u_i - u_j + (n-1)x_{ij} \leq n-2 \tag{10}$$

$$1 \leq u_i \leq n-1 \tag{11}$$

with $i,j \in \{2, \dots, n\}$ and $i \neq j$

The new variable u_i define the order in which node i is visited on a tour.

Imagining a six node network, let us imagine that the tour of the travelling postman was done in the following order, by node numbers:

$$1 \rightarrow 3 \rightarrow 4 \rightarrow 6 \rightarrow 5 \rightarrow 2 \rightarrow 1$$

In this case, the variable u would take the values as follows:

$$u_2 = 5; u_3 = 1; u_4 = 2; u_5 = 4; u_6 = 3$$

The beginning node, which is also in this case the last one, does not have any variable u affected, respecting the constraint (11).

The constraints about the order of visit, equation (8) or (10) and (11) are essential to guarantee that the solution forms a single tour so there are no interruptions between the origin node and some other one [1].

This model is applied in the case studies in section 5.3.

4.3.2.2. Vehicle Routing Problem

The Vehicle Routing Problem (VRP) consists in defining an optimal set of vehicle routes in order to minimize the overall cost of a transportation problem. As the main characteristics, the following points are enumerated:

- Deterministic or stochastic demands of the operation type (only deliver, only collection or combined) with or without service limits;
- Homogeneous or heterogeneous fleet of vehicles with equal or different capacities;
- One or more depots;
- With or without total time restrictions, that can vary from vehicle to vehicle;
- Costs can be fixed or function of the route length (transportation costs);
- The objective function minimizes the fixed costs or transportation costs or both together.

In spite of all the variety of parameters able to consider in VRP, enumerated above, the formulation presented in this paper respect the next ones:

- Each costumer is visited exactly once by exactly one vehicle;
- All vehicles routes start and end in the same single depot, denominated v_1 in the next paragraphs;
- The vehicle capacity is not exceeded.

The VRP is defined as a graph $G = (V, A, C)$, where V is the set of nodes, A is the set of arcs and C is the set of vehicles. As additional input data includes the demand, b_i attached to each node (except to v_1) and the vehicle (k) capacity, (B_k), larger than any individual demand.

One possible formulation to the VRP is presented next [52].

Objective function:

$$\text{minimize} \quad \sum_{k=1}^{n_v} \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} c_{ij}\, x_{kij} \tag{12}$$

where (Nv) is the number of vehicles available and the variable x_{kij} is a binary one, equal to 1 if vehicle k goes directly from node i to node j, otherwise it is equal to 0.

Constraints:

$$\sum_{k=1}^{n_v} \sum_{\substack{i=1 \\ i \neq j}}^{n} x_{kij} = 1 \qquad j = 2, \dots, n \tag{13}$$

$$\sum_{\substack{j=1\\j\neq i}}^{n} x_{kij} = \sum_{\substack{j=1\\j\neq i}}^{n} x_{kji} \qquad i = 1,\dots,n \quad k = 1,\dots,n_v \tag{14}$$

$$\sum_{i\in S}\sum_{j\in S} x_{kij} \leq \mid S \mid -1 \qquad S \subseteq \{2,\dots,n\},\ k = 1,\dots,n_v \tag{15}$$

$$\sum_{i=1}^{n}\sum_{\substack{j=2\\i\neq j}}^{n} b_j\, x_{kij} \leq B \qquad \forall\, k = 1,\dots,n_v \tag{16}$$

$$x_{kij} \in \{0,1\} \qquad i,j = 1,\dots,n, \quad i \neq j, \quad k = 1,\dots,n_v$$

Constraints (13) and (14) ensure that every node is visited only once by one vehicle only and if a certain vehicle goes to some node, it also has to leave it. Constraint (15) is the sub tour elimination constraint to guarantee that every route consists of a unique circuit. Constraint (16) takes into account the vehicle capacity.

In this paper, a formulation similar to the VRP, with some targeted arrangements, is presented and applied in the section 5.4.3.

4.4. SUMMARY

Several aspects may be referred as a summary of this chapter:

1. A basic transport system consists of the infrastructure in which the vehicles flow to achieve a certain objective and is generically represented by nodes representing locations and arcs representing the connections between locations.

2. To optimize transport network problems there are several mathematical models, depending on the question to optimize and the variables included on it, distinguishing essentially the macroscopic problems from the microscopic ones.

The shortest path problem and two routing problems, the travelling salesman problem both node-covering routing problems are described in this chapter. The three models are macroscopic as defined.

The TSP contains simple restrictions and limited input data to optimize when comparing to the VRP.

To solve in an optimal way the routing problems, it is recommended to have arcs among all the pairs of nodes (even if it is just virtual arc) characterized by the shortest paths.

Forward in this paper, the TSP and VRP are tested and some modifications are also tested to attend some specific goals of transport problems.

5

CASE STUDIES

5.1. INTRODUCTION

After the discussion about the optimization of transport problems and the explanation of the Travelling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP), some simulations of network optimizations are now presented.

In this thesis, all the models were implemented in the calculation program, Xpress. A brief description of it is done in section 5.2, before the presentation of the simulated cases.

Next the TSP is being explored, applying it to several different cases to test it, identifying limitations and detecting possible ways to improve it in order to fit better with transportation problems. Some of the cases are theoretical while some others are based on estimated distances between platforms in the transeuropean network (sections 3.3 and 3.5). Then, some modifications to the original TSP are proposed and tested. One of the suggestions refers to the possibility of minimizing the tonne·kilometer travelled which leads to a VRP.

Also in this chapter (section 5.4.3) the model used to find the best routes by minimizing the tkm travelled is presented. Finally, it is exemplified one case, based on real values of the Portuguese transport network, with the purpose of comparing the road option with the rail option to respond to a concrete transport problem.

5.2. CALCULATION SOFTWARE

To run the mathematical model, the software Xpress, from FICO, is used after programmed by the Portuguese supervisors with the equations and restrictions exposed in 4.3.2.1. The required input data is a matrix with the distances between the pairs of the logistic platforms considered in each case. Xpress gives information about what arcs are crossed, indicating the origin and destination node, and the order of visit of each node.

In the student version of Xpress, available for free use in http://optimization.fico.com/student-version-of-fico-xpress.html, it is possible to solve problems up to 400 constraints. It means that the maximum nodes as input data can be only 20. In section 5.3, in case 1 some aspects of the program are shown.

5.3. SIMULATED CASES

In this section some theoretical examples of network optimization are shown in order to achieve the goals enunciated in section 5.1. The costs of the arcs refer to distances and every edge is bidirectional with the same cost in both directions.

To illustrate and to explain each case, some tables and graphs are presented. The graphs are designed in another software of network optimization with a very friendly graphic environment, GIDEN. In all the illustrated examples, the origin of the network is the node number 1.

The cases in study are summarized in Table 12.

Table 12 – Simulated cases for minimizing distances.

Case	Purpose / Identification
1	To show the software and understand the influence of the origin node.
2	To understand if the model has some criteria to choose the direction of solution.
2A	Simple network to be easy to visualize the shortest path.
2B	Similar to 2A with switched arc lengths.
3	To observe the differences of adding one node to a network.
3A	Original five nodes network with an added node (6^{th} node) represented.
3B	Network with the 6^{th} spaced to all the other of 30 units.
3C	Network with the 6^{th} spaced to all the other of 1 unit.
3D	Network with the 6^{th} connected to all the others with random lengths.
4	Road network of Portugal and its sub-division
4A	Considering all the logistic platforms.
4B	Network divided in three zones.
4C	Network divided in three zones.
4D	Network divided in three zones.
4E	Network divided in three zones.
4F	Network divided in two zones.
5	Rail network of Portugal.
6	Rail network of Czech Republic.

5.3.1. CASE 1 – SOFTWARE DEMONSTRATION AND INFLUENCE OF THE FIRST NODE

The purpose of this first case is to show the graphical environment of the software and to illustrate the graphical style and the common aspects which are going to be considered in the next cases. Case 1 is also useful to verify the importance of choosing the origin node to find the shortest route in a given network.

Consider the following theoretical network, Figure 24, with five nodes all connected by arcs with random distances. All the arcs have one arrow in each direction, meaning that it can be travelled in both directions.

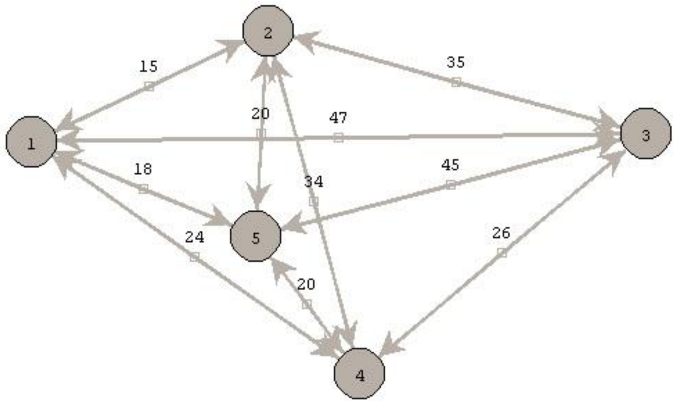

Figure 24 – Case 1, network.

The input data required by Xpress is the symmetric matrix of distances with the following aspect, Figure 25.

```
costs:
[ 0 15  47  24  18
15  0   35  34  20
47  35  0   26  45
24  34  26  0   20
18  20  45  20  0]
```

Figure 25 – Case 1, aspect of input matrix in Xpress.

The first row and first column refers to the distances between the node number one and the others. This node is considered by the model to be the origin of the network, simultaneously the beginning and the ending node of the trips.

After running the program, the solution is given in three parts, explained after Figure 26.

```
Total cost: 114

 journey(1,5) = 1
 journey(2,1) = 1
 journey(3,2) = 1
 journey(4,3) = 1
 journey(5,4) = 1

 order(2) = 4
 order(3) = 3
 order(4) = 2
 order(5) = 1
```

Figure 26 – Case 1, solution aspect in Xpress.

1) Total distance is the sum of the distances of the arcs that form the solution. In this case, total cost is 114.
2) Journey(i,j), where *i* and *j* are the numbers of the nodes, are variables that represent the "existence" of the arc between node *i* and *j*, and only can assume binary values, equal to 0 or equal to 1. The visible journeys are the ones part of the solution.

In this case, the arcs that are going to be travelled are the ones between the following nodes: (1,5), (2,1), (3,2), (4,3) and (5,4).

3) Order(i) indicates the order of visit of node *i*.
In case 1A, node 2 is the 4th to be visited while node 5 is the 1st to be visited.

Observing the solution from Xpress, it is identified the shortest route, illustrated in Figure 27 with black arrows.

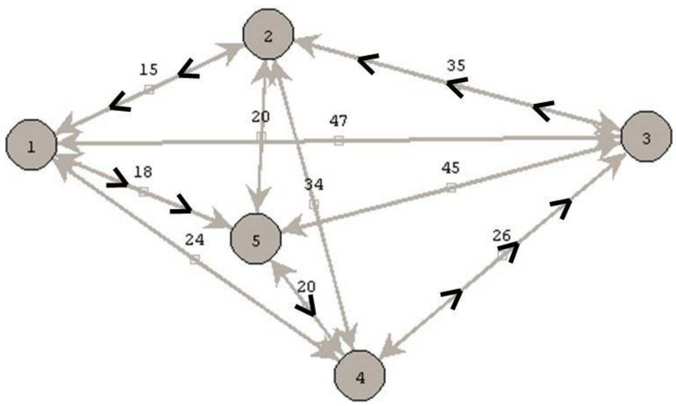

Figure 27 – Case 1, solution.

In this case, the sequence of the visited nodes is: 1-5-4-3-2-1.

This solution represents the less costly combination of arcs to connect all the nodes, which is independent from the origin node. For instance, choosing the node number 4 as the origin, the solution will be: 4-3-2-1-5-4, with the same total distance.

5.3.2. CASE 2 – CHOOSING THE DIRECTION

In all the networks that can be represented by undirected graphs or by directed graphs with equal distances in both directions, the same shortest route can be travelled in two directions with the same length.

The main goal of case 2 is to understand if the model follows some criteria to choose the direction of the trip taking into account the distance of the first edge. It is divided in two versions with different purposes, like related in Table 13.

Table 13 – Purposes of case 2A and 2B.

Case	Purposes of the networks
2A	To be easy to visualize the shortest route.
2B	To check what happens when the length of the first arc from the solution 2A is switched by the length of the last arc.

In network of case 2A, illustrated in Figure 28, the lengths were chosen in such a way that it is easy to visualize the route with lower distance.

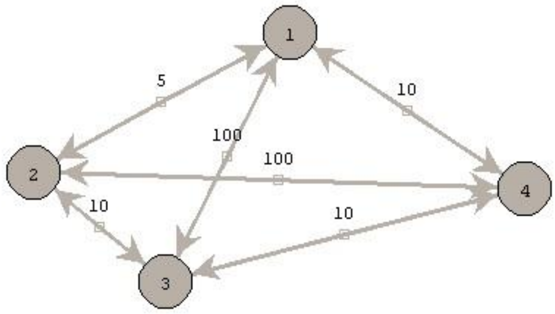

Figure 28 – Case 2A, network.

Intentionally, the journeys 1-3 and 2-4 have much higher length when compared to the others, so these connections are not going to be used and it is obvious that the best route would be 1-2-3-4-1, or 1-4-3-2-1.

The solution given by Xpress is represented in Figure 29.

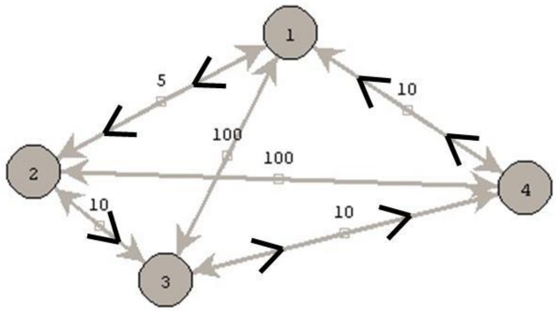

Figure 29 – Case 2A, solution.

From network 2A to network of case 2B it is switched the length of arc(1,2) with the length of arc(1,4). The solution is the same as the case 2A, with the same distance and the same direction (Figure 30).

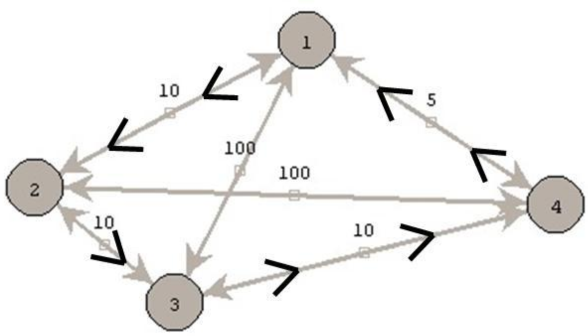

Figure 30 – Case 2B, network and solution.

Comparing case 2A with case 2B, it is concluded that the program does not care if the first journey is longer than the last journey. Notice that the same solution in the opposite direction would have the same total distance.

In some transport problems it can be useful to define the direction of the trip taking into account the lengths of the first travelled arcs. For instance, in some freight truck, it can be advantageous to start with short journeys than with the longer ones in order to travel less distances fully loaded. This comment is on the basis of the minimization of tonne·kilometer problem presented further in section 5.4.3.

5.3.3. CASE 3 – ADDING ONE NODE TO THE NETWORK

This case serves to see how the solution can modify when one more node is included in the network.

Consider the initial network with five nodes (1,2,3,4,5), in which it is added one node (6th node) in the center, connected to all the other nodes with the same distance *x* (Figure 31). In this section (5.3.3), this node is called a "central node".

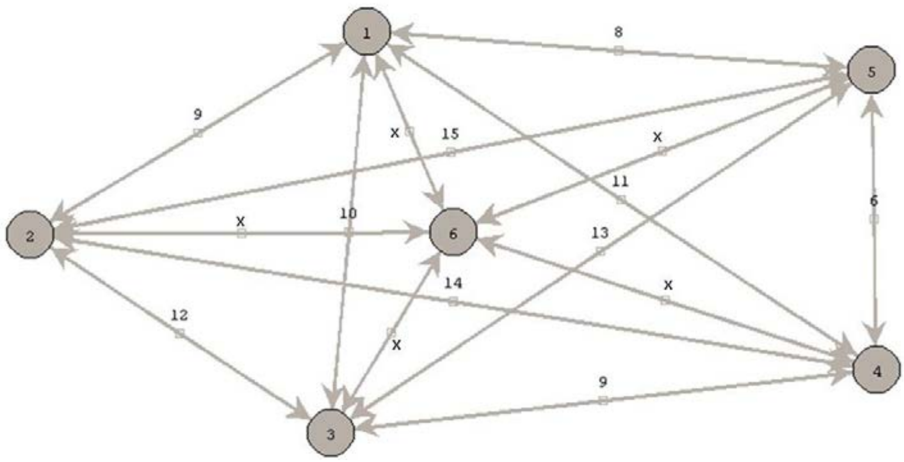

Figure 31 – Case 3A, network.

From the original network (case 3A), two versions are made: case 3B and case 3C. The difference between 3B and 3C is the distance from the central node to all the others, signed as *x* in Figure 31. The information and the results are written in Table 14.

Table 14 – Case 3, distinctions between case A,B and C.

Case	Nº nodes	Distance from 6th node to the others	Shortest way (bidirectional)	Total cost
Case 3A	5 nodes(original)	----	1-5-4-3-2-1	44
Case 3B	6 nodes	30	1-5-4-3-6-2-1	92
Case 3C	6 nodes	1	1-5-4-3-6-2-1	34

Cases 3B and 3C assume the same shortest route, even with different distances. The 6th node interrupts the sequence of the solution of case 3A between the nodes connected with the longer arc. Basically, the longer arc is changed by two arcs with length equal to *x*.

In case 3D, Figure 32, different values are given to the arcs between the central node and all the others.

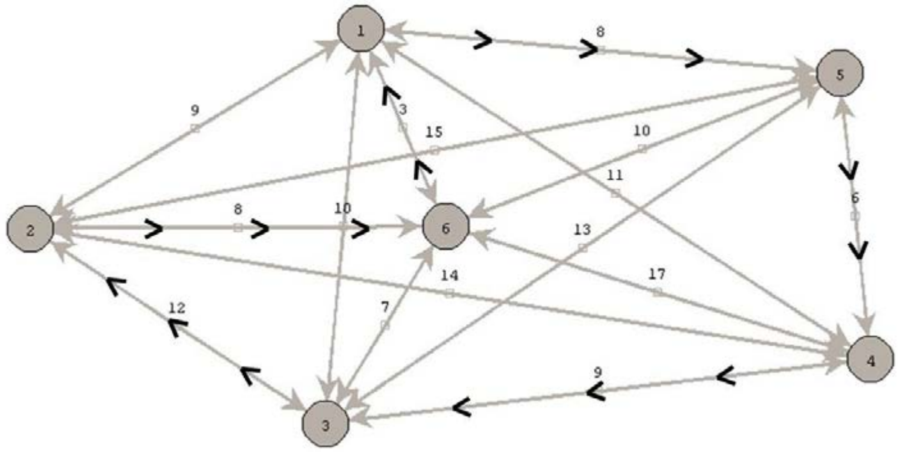

Figure 32 – Case 3D, network and solution.

Again, two arcs connected with node 6 replace one other arc that belonged to the solution of five nodes. Those possibilities are:

Figure 33 – Case 3D, modification of the total distance.

New used arcs and lengths	Old used arc and length	Modification of total distance
(1,6)+(6,2)=3+8=11	(1,2)=9	11-9=+2
(2,6)+(6,3)=15	(2,3)=12	+3
(3,6)+(6,4)=24	(3,4)=9	+15
(4,6)+(6,5)=27	(4,5)=6	+21
(5,6)+(6,1)=13	(5,1)=8	+5

The change which leads to the less increase of total distance or, even better, to the most decrease of it, is the one to be included in the new solution.

By analyzing the cases in this section, one important conclusion can be drawn about the input matrix of distances to solve the TSP: the shortest routes calculated after adding the 6th node are not the shortest possible ones to pass in all the nodes if it is considered the possibility to pass more than once in the nodes. Demonstration of that is illustrated in Table 15, regarding the case 3C.

Table 15 – Demonstration of the shortest route to case 3C, by allowing the passage on nodes more than once.

Passing each node only once 1-5-4-3-6-2-1		Possibility to cross the nodes more than once 1-6-5-6-4-6-3-6-2-6-1	
Path	Length	Path	Length
(1,5)	8	(1,6,5)	2
(5,4)	6	(5,6,4)	2
(4,3)	9	(4,6,3)	2
(3,6)	1	(3,6)	1
(6,2)	1	(6,2)	1
(2,1)	9	(2,6,1)	2
Total	**34**	**Total**	**10**

It is noticeable that the shortest route occurs when it passes on the node 6 several times. In all sub-examples of case 3, the initial network (before adding the 6th node) is defined by the shortest paths among all pairs of nodes. After adding the 6th node, such situation is no longer true. So, to respect the constraint of TSP of visiting one node only once, the solution is found by changing one "old arc" by two "new arcs" as already mentioned above.

Regarding real transport networks, when a new location becomes part of an existent network as an obligatory visiting point, it is more common to have an increase to the total distance of the previous route, rather than a decrease of it. For instance, considering the road and rail networks, generally, those are already defined for some geographical area, where every single part or section of the network is available to be used for indefinite times.

In order to obtain more realistic results from the TSP it is necessary to have the input distance matrix filled with the shortest paths between all pairs of nodes, even if that path is not a direct connection (have to pass for another node). Notice that the objective of the TSP is not to define the best "physical" paths between nodes, but to define the sequence of visiting nodes that leads to the shortest route. So, to use the TSP in an optimal way to transport problems, it is necessary to find the shortest paths by using other algorithms, like the ones mentioned in section 4.3.1.

As a particularity of transport networks, it is impossible to decrease the total distance travelled by defining an obligatory node in the existent network, because all the paths are already considered on the definition of the arcs' distance. The only possibility to decrease the total distance travelled is by building new ways on the network to connect with the new node, with less length than the existent ones.

5.3.4. CASE 4 – LOGISTIC PLATFORMS AND ROAD NETWORK OF PORTUGAL

In this example, a case based on real values of distances between the logistic platforms in Portugal is simulated. The platforms are mentioned in the section 3.5.1, located and connected according to the annexed map 38 and the explanation in the section 3.3.4.

In this case, because of the high number of nodes it would be hard to visualize all the arcs in a graph like in the previous examples, so it is presented the symmetric matrix that indicates the shortest distances between all pairs of logistic platforms in Portugal, Table 16.

Table 16 – Road distances between logistic platforms in Portugal.

km by road	Valença	Maia /Trofa	Leixões	Porto de Aveiro	Guarda	Entroncamento	Bobadela	Poceirão	Caia	Sines	Tunes
Valença		101	115	189	309	335	412	451	558	548	631
Maia/Trofa			29	99	218	245	321	361	467	458	541
Leixões				87	205	236	308	348	454	445	527
Porto de Aveiro					163	180	254	294	400	391	473
Guarda						202	303	343	295	440	523
Entroncamento							109	148	228	246	328
Bobadela								47	221	167	249
Poceirão									174	119	201
Caia										259	287
Sines											163
Tunes											

In this case it is considered the theoretical situation in which a truck from Valença needs to pass through all the platforms to deliver some goods. It is considered such situation in order to understand how it would be the best sequence of visited nodes to pass in all the platforms in Portugal, by road. Applying the described model, the solution shown schematically in Figure 34 is obtained. Each node is identified with the location name and with the number respective to the row and column of the matrix.

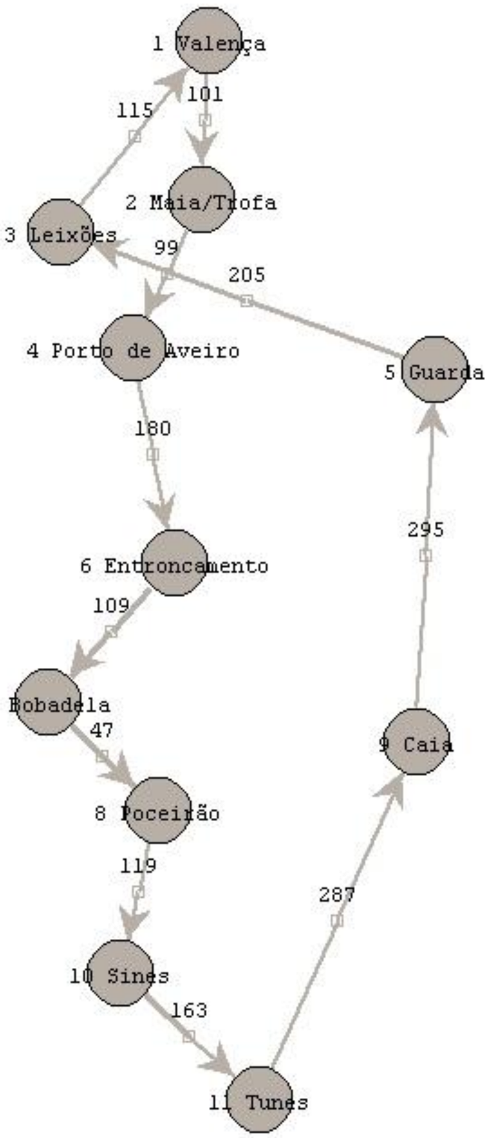

Figure 34 – Case 4, solution.

The total distance travelled is 1720 km, in a total length of network of approximately 2800 km (mentioned in section 3.3.4), so it is only necessary to use 60% of the road network to visit all the logistic platforms.

This example has an unrealistic character because it is not usual for a truck to travel around the whole country stopping in so many logistic platforms. Having limited freight capacity, there is no meaning in delivering goods, loaded only in the origin place, through the whole country; otherwise it would unload a very little amount in each platform and travel for long distances carrying a few percentage of the load capacity.

In a possible real situation, the truck does not need to pass in all the platforms, so, in a given network, it is reasonable to impose only the cross of the necessary nodes, excluding the obligation to go through all of them.

The standard travelling salesman problem, does not predict such an option for a given network, unless it is build a new smaller network only with the necessary nodes and respective arcs, ensuring that those arcs are the shortest ways between nodes. So, to improve the model it would be interesting to add the possibility of, in a given network, making the distinction between obligatory nodes and non-obligatory nodes to cross. Such improvement is referred in section 5.4.1.

Taking into account the Portuguese transport statistics presented in section 2.3.1.2., namely in Figure 11, the most part of freight (86% in 2010) carried by road transport is transported for less than 150 km. That suggests that it is not usual for a truck to travel all the country with a certain freight. So, the division of the network into geographical zones seems to be reasonable to represent the real transport of goods by road.

Five different divisions were made, forming cases 4B, 4C, 4D, 4E and 4F. Each case represents a sub-network, in which the truck visits all the platforms. For each sub-network the distance travelled is determined and then, the total distance to visit all the platforms in the country is calculated by summing those distances.

In case B and C, Portugal is divided into three zones: North, Center and South. In case B is given more area to the South part (5 platforms) while in case C is given more area to the North part (5 platforms). Case D is also divided into three zones, but this time into: Littoral North, Littoral South and Interior Center. Case E is divided in an incoherent way because it joins in the same group platforms very distant between each other. Finally, case F is divided only into two zones, North and South. In Table 17 are identified the locations of each case.

Table 17 – Case 4, division in sub-networks.

Case	Sub-networks	Locations	Distance	Total distance
4A	1	ALL.	1720	1720
4B	3	Valença; Maia/Trofa; Leixões.	245	1627
		Porto de Aveiro; Guarda; Entroncamento.	545	
		Bobadela; Poceirão; Caia; Sines; Tunes.	837	
4C	3	Valença; Maia/Trofa; Leixões; Porto de Aveiro; Entroncamento.	683	1696
		Entroncamento; Bobadela; Poceirão.	304	
		Caia; Sines; Tunes.	709	
4D	3	Valença; Maia/Trofa; Leixões; Porto de Aveiro.	402	1705
		Guarda; Entroncamento; Caia.	725	
		Bobadela; Poceirão; Sines; Tunes.	578	
4E	3	Valença; Maia/Trofa; Leixões.	245	2059
		Porto de Aveiro; Entroncamento; Bobadela; Poceirão.	629	
		Guarda; Caia; Sines; Tunes.	1185	
4F	2	Valença; Maia/Trofa; Leixões; Porto de Aveiro; Guarda.	683	1636
		Entroncamento; Bobadela; Poceirão; Caia; Sines; Tunes.	953	

Two main observations can be drawn:

- Case 4F (2 sub-networks) is longer than case 4B (3 sub-networks) and shorter than case 4C and 4D (3 sub-networks);
- Case 4E is much longer than the others.

From the results, it can be concluded that there is no direct relation between the number of sub-networks and the total distance travelled. Also, when the division is made in a sensibility way, the total distance tends to be lower than the total distance without divisions. For instance, the divided zones in case 4E are not so coherent because they includes in the same zone platforms very distant from each other, like Guarda and Tunes, so the total distance increase a lot, comparing to the original network.

5.3.5. Case 5 – Logistic platforms and rail network of Portugal

Similar to the case 4, it is simulated one case based on the logistic platforms in Portugal, this time connected by railways according to the annexed map 51 and the explanation in 3.3.4..

In Table 18 the shortest distances between platforms are indicated.

Table 18 – Railway distances between logistic platforms in Portugal.

Km by rail	Valença	Maia /Trofa	Leixões	Porto de Aveiro	Guarda	Entroncamento	Bobadela	Poceirão	Caia	Sines	Tunes
Valença		113	138	199	387	356	450	501	527	645	713
Maia/Trofa			25	86	274	243	337	388	414	532	600
Leixões				93	281	250	344	395	421	539	607
Porto de Aveiro					206	175	269	320	346	464	532
Guarda						240	334	385	353	529	597
Entroncamento							94	145	171	289	357
Bobadela								67	235	211	279
Poceirão									168	144	212
Caia										312	380
Sines											170
Tunes											

In case 5 is considered the theoretical situation that one train, starting the trip in Valença, needs to pass through all the logistic platforms. The shortest route is indicated schematically in Figure 35. The whole trip is characterized in detail in Table 19, identifying the names of the railway lines used and the distances travelled in each one.

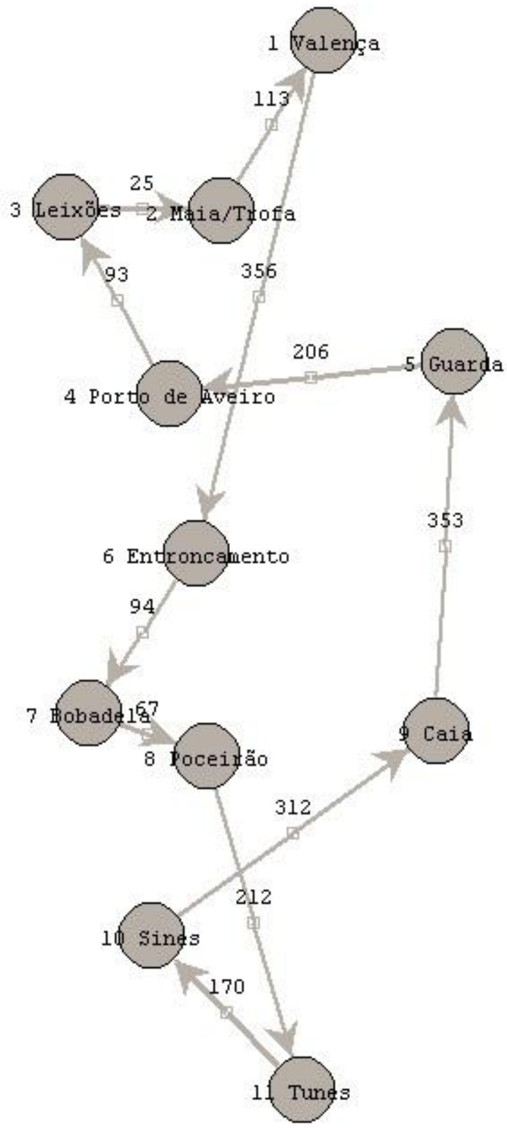

Figure 35 – Case 5, solution.

Table 19 – Case 5, Identification of travelled railway lines.

Journey	Line	Origin	Destiny	Km's
1	Linha do Minho	Valença	Porto-Campanhã	128
	Linha do Norte	Porto-Campanhã	Entroncamento	228
2	Linha do Norte	Entroncamento	Bobadela	94
3	Linha do Norte	Bobadela	Braço da Prata	7
	Linha de Cintura	Braço da Prata	Campolide	8
	Linha do Sul	Campolide	Pinhal Novo	37
	Linha do Alentejo	Pinhal Novo	Poceirão	15
4	Concordância de Poceirão Concordância de Águas de Moura	Poceirão	Águas de Moura	6
	Linha do Sul	Águas de Moura	Tunes	206
5	Linha do Sul	Tunes	Ermidas-Sado	119
	Linha de Sines	Ermidas-Sado	Sines	51
6	Linha de Sines	Sines	Ermidas-Sado	51
	Linha do Sul	Ermidas-Sado	Águas de Moura	87
	Concordância de Águas de Moura Concordância do Poceirão	Águas de Moura	Poceirão	6
	Linha do Alentejo	Poceirão	Casa Branca	60
	Linha de Évora	Casa Branca	Évora	26
	New planned line	Évora	Caia	82
7	Linha do Leste	Caia	Abrantes	142
	Linha da Beira Baixa	Abrantes	Guarda	211
8	Linha da Beira Alta	Guarda	Pampilhosa	156
	Linha do Norte	Pampilhosa	Plataforma de Cacia	41
	Ramal do Porto de Aveiro	Plataforma de Cacia	Porto de Aveiro	9
9	Ramal do Porto de Aveiro	Porto de Aveiro	Plataforma de Cacia	9
	Linha do Norte	Plataforma de Cacia	Porto-Campanhã	62
	Linha do Minho	Porto-Campanhã	Contumil	3
	Linha de Leixões	Contumil	Leixões	19
10	Linha de Leixões	Leixões	São Gemil	15
	Concordância de São Gemil	São Gemil	Ermesinde	4
	Linha do Minho	Ermesinde	Maia/Trofa	6
11	Linha do Minho	Maia/Trofa	Valença	113

The total distance travelled is 2001 km, in a total length of network of approximately of 1860 km (mentioned in section 3.3.4.).

The shortest way to visit all the platforms is longer than the overall length of the network, which is possible because there are some sections of the line that are passed more than once and because almost the whole network is used. This last fact denotes that the logistic platforms are located in extremes or "corners" of the rail network.

In opposition to case 4A, the possibility of some train deliver freight in all the platforms can be more realistic because it can carry much bigger quantities of goods loaded in one place, to be unloaded in all the other places in reasonable amounts. Also, railway transport is more used to transport goods for long distances than short distances, as it is suggested by Figure 11, in which it is indicated that more than 72% of all tonnes carried by train in 2010 were moved to distances higher than 150 km.

5.3.6. CASE 6 – LOGISTIC PLATFORMS AND RAIL NETWORK OF CZECH REPUBLIC

Case 6 refers to a network of logistic platforms in Czech Republic connected by railways. The annexed map 7 illustrates the network based on the rail transeuropean network in Czech Republic, from where it was built a matrix with distances between all pairs of platforms, Table 20. (distances provided by Mr. Vladimir Kyncl from Ministry of Transport of Czech Republic).

Table 20 – Railway distances between logistic platforms in Czech Republic.

Km by rail	Brno	Prerov	Nyrany	Praha	Melnik	Lovosice	Usti nad Labem	Decin
Brno		86	390	264	267	337	365	388
Prerov			411	285	288	358	386	409
Nyrany				141	182	211	193	218
Praha					62	103	131	154
Melnik						70	88	92
Lovosice							28	53
Usti nad Labem								28
Decin								

Considering the situation that one train from Brno needs to pass in all platforms, the shortest way is to follow the sequence: Brno – Prerov – Praha – Nyrany – Decin – Usti nad Labem – Lovosice – Melnik – Brno (Figure 36).

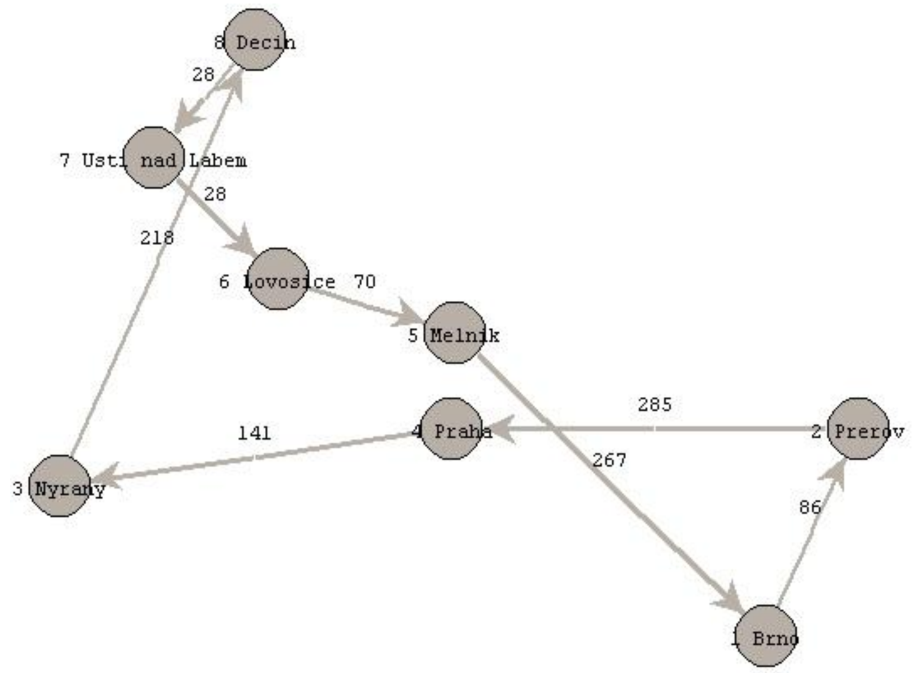

Figure 36 – Case 6, solution.

The total distance travelled is 1123 km, in a total length of network of 2190 km approximately (mentioned in section 3.3.4.).

The length of the shortest route to visit all the platforms is approximately half of the overall lengths of the networks, which denotes the central location of the platforms, so that a lot of lines near the borders are not used to connect the national platforms between them, but to link with other countries. In fact, as verified in Figure 15 in section 2.3.1.3, the international traffic is higher than the national one (measured in transported tonnes).

5.4. PROPOSALS TO THE MODEL AND INPUT DATA

After testing the aforementioned cases, some limitations were detected in the usage of the TSP applied to transport problems. At this point, some proposals are made for the model to be used in transportation problems.

5.4.1. CHOOSING OBLIGATORY NODES

In case 4 was noticed that for a given network with a matrix of costs, the model does not allow the user to choose only some obligatory nodes to cross. To solve a problem in which it is not required to pass in all the nodes, two options can be considered:

5.4.1.1. Option 1: changing distances matrix (limited).

In section 5.3.3 it was concluded that to use the TSP in an optimal way, the distances matrix has to be completely filled with the shortest paths among all pairs of nodes. If so, it can be build a sub-matrix only with the rows and columns associated to the obligatory nodes. This sub-matrix, coming from the original networks' matrix can be easily obtained by removing the rows and columns respective to all of the other nodes.

To demonstrate this, one application of the proposed model is done, using the network from case 4 (Table 16).

Considering the situation that one truck loaded in Leixões has to deliver goods in Guarda, Entroncamento and Caia, from the original matrix it is picked up a smaller one with only four rows and columns, like shown in Table 21, in which the origin node is the one in the first row.

Table 21 – Sub-matrix of case 4.

Km_road	Leixões	Guarda	Entroncamento	Caia
Leixões		205	236	454
Guarda			202	295
Entroncamento				228
Caia				

With this data, the travelling salesman problem can be used in the standard way, like on cases of section 5.3. The shortest route calculated is: Leixões – Guarda – Caia – Entroncamento, like illustrated in Figure 37, with a total travelled distance equal to 964 km.

Figure 37 – Case 4, solution to pass in obligatory nodes only.

In summary, this improvement to the model is done by changing the input data rather than the mathematical algorithmic.

5.4.1.2. Option 2: changing the model.

This option is recommended to use on networks in which:

- All pairs of nodes are connected, but it is not ensured that such connection is the shortest path;
- It is no possible to pass more than once by the nodes.

This modification consists in changing and adding some constraints to the mathematical model explained in 4.3.2.1.

The objective function stills equal to the original TSP:

$$minimize \sum_{i=1}^{n}\sum_{\substack{j=1\\ j\neq i}}^{n} c_{ij}x_{ij} \tag{17}$$

The first step is to make the distinction between the required and the optional nodes, by creating two vectors, "R" and "O", with the numbers of the required and optional nodes, respectively.

Then, the constraints are:

$$\sum_{i=1}^{n} x_{ij} = 1 \quad \forall\, j \in R, \quad j \neq i \tag{18}$$

$$\sum_{i=1}^{n} x_{ij} \leq 1 \quad \forall\, j \in O, \quad j \neq i \tag{19}$$

Constraint number (18) ensures that in each obligatory node there is only one incoming arc. Constraint number (19) gives the possibility for some optional nodes to be connected by one incoming arc.

All the nodes that get an incoming arc have to get an outgoing arc. Equation (20) imposes that condition.

$$\sum_{j=1}^{n} x_{ij} = \sum_{j=1}^{n} x_{ji} \quad \forall\, i = 1, \dots, n, \quad i \neq j \tag{20}$$

After upgrading the model, equivalent modifications were made to the Xpress software in order to run some examples to test the improvements. In the following tests, the red nodes require to be visited and the green ones are optional.

5.4.1.3. Test 1 – Shortest way includes optional node

Figure 38 represents a network with five nodes, in which four are an obligatory passage and one is optional. On purpose, the costs of arcs were provided in order to include the optional node in the shortest way, regarding further developments of this model where those options are relevant.

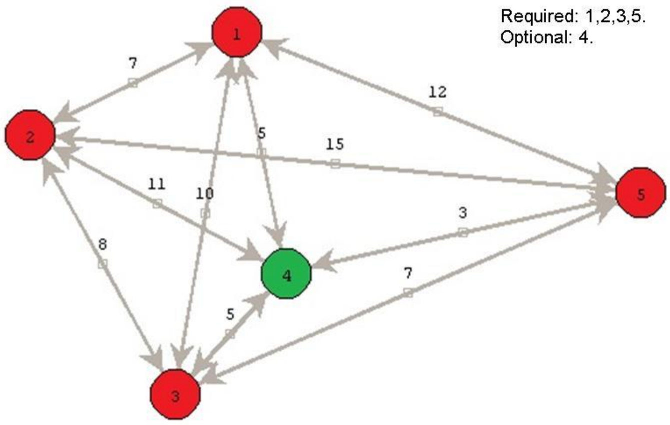

Figure 38 – Test 1, network.

Xpress gives the solution with the same graphical aspect as before the improvement:

```
Total cost:  30

journey(1,4)  = 1
journey(2,1)  = 1
journey(3,2)  = 1
journey(4,5)  = 1
journey(5,3)  = 1

order(2)  = 4
order(3)  = 3
order(4)  = 1
order(5)  = 2
```

Figure 39 – Test 1, solution given by Xpress.

The total cost is equal to 30, and, as pretended, the shortest way includes the optional node number 4, because to go from node 1 to node 5 it is shorter to pass through it than to go through the direct arc. See Figure 40.

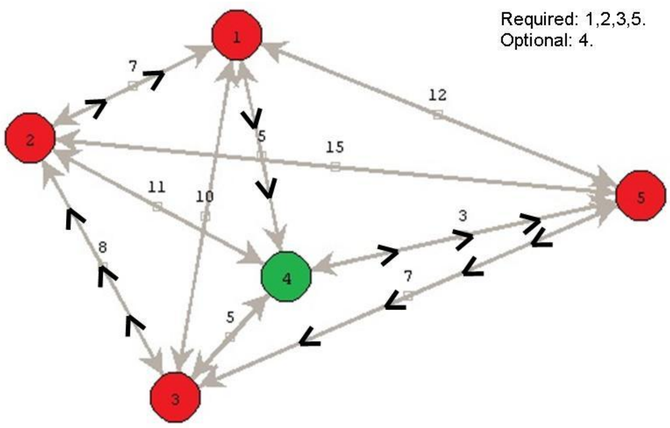

Figure 40 – Test 1, solution.

If it was not considered the possibility to pass in the optional node 4, by changing the matrix as suggested in Option 1 in 5.4.1.1, the solution would be 1→5→3→2→1, with a total cost of 34 units, which is not the optimal one.

5.4.1.4. Test 2 – Shortest way does not pass through optional nodes

In this test the road network of Portugal is considered, as in case 4, defining the same obligatory nodes as in section 5.4.1.1, Leixões, Guarda, Entroncamento and Caia, while all the others are optional. So, the input matrix is like the original one for the road network in Portugal but with Leixões referred in the first row and column to be the origin node.

Figure 41 shows the network with the solution already included.

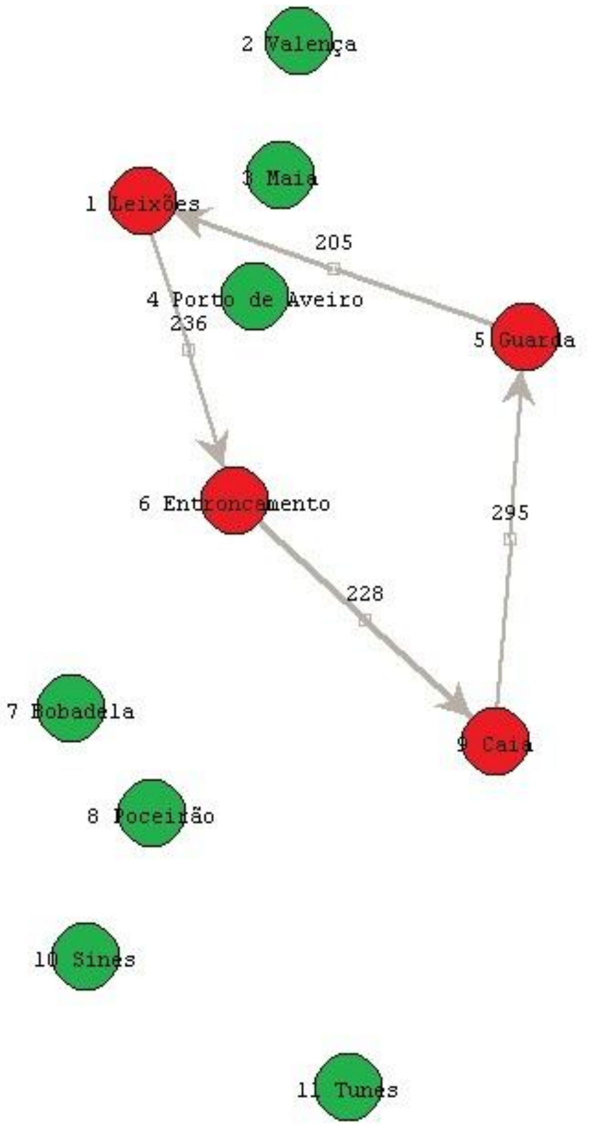

Figure 41 – Test 2, network and solution.

Because all the pairs of nodes are connected by the shortest paths, as expected, none of the optional nodes are crossed, because all the "shortcuts" through those nodes are longer than the direct way. The solution has the same total distance as the one calculated with option 1 in 5.4.1.1.

5.4.2. CHOOSING THE DIRECTION OF A TRIP

As mentioned in Case 2, the model does not have restrictions to define the direction to travel through the network, because sometimes it starts with the shortest arcs and other times with the longest arcs.

As a transport optimization problem, it is important to care about some aspects to choose the best direction of the trip:

1) Minimization of consumption of energy;
2) Minimization of CO_2 emissions;
3) Minimization of the damage to road pavements or rail lines.

These three points are related with the gross weight of truck or train and the distance travelled with such weight. In general, to the same transport mode, the bigger is the weight carried and the distance travelled, the bigger is the consumption of energy, CO_2 emissions and the worst is the damage to the infrastructure. To take into account these factors, there is an important freight transport unit of measure: the tonne·kilometer (tkm) that can be considered in the problem formulation.

Therefore, to define the direction of the route through a network, it is useful to minimize the total tkm measured. This criterion aims to maximize the distance travelled with the less weight and minimize the distance travelled with the more weight.

The difficulty to minimize the tkm by using the TSP is to know the input matrix with the values of tkm between nodes. Such matrix is obtained by scalar multiplication of the distances matrix with the matrix of tonnes carried from one location to another. However, in networks with more than two nodes, the amount of freight carried between some locations depends on the visiting order of such locations and the respective change of tonnes carried in each one.

Section 5.4.3 is dedicated to the problem of minimizing the tonne·kilometer measured.

5.4.3. MINIMIZATION OF TONNE·KILOMETER

This point aims to understand the difficulties to consider the variable tkm and to show and test a different mathematical formulation taking into account such variable.

In this chapter, to consider the variable tkm in a consistent way, it is necessary to define the freight vehicles in terms of self-weight and load capacity, which is done in section 5.4.3.1.

After that, some transport problems are calculated in order to show that the using of the original TSP to minimize tkm can be a complicated way to solve the problem.

Then is presented a model based on Vehicle Routing Problem and several cases are tested. Finally it is done a simulation based on real networks of Portugal in order to compare the rail solution with the road solution. The simulated cases are enumerated in Table 22.

Table 22 – Simulated cases for minimizing tkm.

Case	Purpose / Identification
7	To demonstrate the importance of considering the vehicle self-weight.
7A	Considering the vehicle self-weight.
7B	Ignoring the vehicle self-weight.
8	Application and demonstration of the new model.
9	To compare the options of using one and two vehicles.
10	To show the importance of a carefully distribution of demands of nodes.
10A	Incompatible distribution of demands.
10B	Compatible distribution of demands.
11	To compare the road with the rail solution in the Portuguese network.

5.4.3.1. Capacity of the considered vehicles

In the cases simulated below, two different types of vehicles can be considered, a truck or a train, with the characteristics indicated in Table 24 and Table 25. The goods are supposed to be wrapped in 40’ ISO containers, characterized in Table 23.

Table 23 – Basic technical details of ISO 40’ container.

40’ ISO containers	
Self-weight	3.8 t
Load capacity	26.7 t
Maximum weight	30.5 t
Dimensions	12.2*2.5*2.6

Table 24 – Basic technical details of trucks available [54].

Trucks	
Self-weight	14 t
Maximum weight	40 t
Load capacity	26 t
40’ ISO containers capacity	1

The maximum gross weight of the truck selected is normally the maximum limit in European Countries [54].

The train was selected based on the available fleet of “CP Carga”.

Locomotive: Universal Locomotive LE 4700 [55].

Wagon: Serie Lgnss 22 94 443 3 001/100 - wagon platform for transportation of containers and mobile plates [56].

Table 25 – Basic technical details of trains available.

Trains	
Locomotive self-weight	87 t
Wagon self-weight	13.5 t
Wagon load capacity	31.5 t
Maximum number of wagons	30
Maximum train load capacity	780 t
40' ISO containers capacity	1

In each case it is mentioned which transport mode is used.

5.4.3.2. Case 7 – The importance to consider the self-weight of the vehicle

In this case it is used one truck that has to deliver equals amounts of goods in three locations, separated by different distances. It starts the trip with 38 tonnes of gross weight and unloads 8 tonnes in each node.

Figure 42 represents the network with the indication of unloaded tonnes next to each node. There is also identified the shortest route, with black arrows.

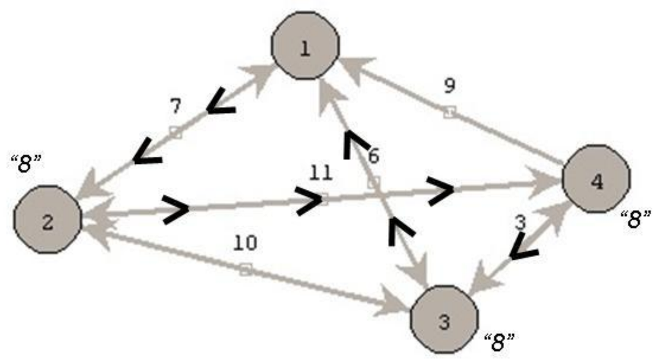

Figure 42 – Case 7, network and shortest path.

This case is also divided into two versions:

- Case 7A: it is considered the gross weight of the truck (weight of empty truck plus the freight weight);
- Case 7B: as academic test it is only considered the freight weight.

Table 26 and Table 27 present all the hypotheses to cross the network for both cases. The total tkm are compared in Table 28.

Table 26 – Case 7A, characteristics of the six hypotheses.

Edge	Distance (km)	Hyp. A		Hyp. B		Hyp. C		Hyp. D		Hyp. E		Hyp. F	
		t	tkm	t	tkm	t	tkm	t	tkm	t	tkm	t	tkm
(1,2)	7	38	266	38	266	...	...	14	98	...	...	14	98
(1,3)	6	...	...	14	84	38	228	38	228	14	84	...	...
(1,4)	9	14	126	...	...	14	126	...	...	38	342	38	342
(2,3)	10	30	300	...	...	30	300	...	...	22	220	22	220
(2,4)	11	...	...	30	330	22	242	22	242	30	330	...	...
(3,4)	3	22	66	22	66	...	...	30	90	...	...	30	90
Total			**758**		**746**		**896**		**658**		**976**		**750**

Table 27 – Case 7B, characteristics of the six hypotheses.

Edge	Distance (km)	Hyp. A		Hyp. B		Hyp. C		Hyp. D		Hyp. E		Hyp. F	
		t	tkm	t	tkm	t	tkm	t	tkm	t	tkm	t	tkm
(1,2)	7	24	168	24	168	...	...	0	0	...	...	0	0
(1,3)	6	...	...	0	0	24	144	24	144	0	0	...	...
(1,4)	9	0	0	...	...	0	0	...	...	24	216	24	216
(2,3)	10	16	160	...	...	16	160	...	...	8	80	8	80
(2,4)	11	...	...	16	176	8	88	8	88	16	176	...	...
(3,4)	3	8	24	8	24	...	...	16	48	...	...	16	48
Total			**352**		**368**		**392**		**280**		**472**		**344**

Table 28 – Differences of tkm between case 7A and 7B.

	Hyp.A	Hyp.B	Hyp.C	Hyp.D	Hyp.E	Hyp.F
Case 7A	758	746	896	658	976	750
Case 7B	352	368	392	280	472	344
Difference	406	378	504	378	504	406

The difference of total cost for each hypothesis between case 7A and case 7B is not equal for all the hypotheses as expected. In this case, the solution to minimize the tkm is the same either considering or not considering the self-weight of truck. However, such fact is not necessarily true for the general situations. It is to say that optimizing a route while considering the self-weight of truck is different than if it is ignored.

A demonstration of that conclusion is present in Table 29. For the same network of Figure 42, the distance of arc (3,4) was changed from 3 km to 10.5 km the solution was calculated to minimize the tkm, with the following results.

Table 29 – Case 7, influence of consider the self-weight of truck.

	Edge (3,4) = 3 km	Edge (3,4) = 10.5 km
Considering self-weight	Hyp.D = 658 tkm	Hyp.D = 883 tkm
Ignoring self-weight	Hyp.D = 280 tkm	Hyp.C = 392 tkm

It is observed that the solutions can be different when it is considered the self-weight and when it is not.

Looking forward to the reasons to minimize the tkm, mentioned in the beginning of this section, it is more reasonable to consider the self-weight of truck when minimizing the tkm, because this weight also influences on the energy consumption, CO_2 emissions and on the damage of pavements.

Figure 43 illustrate all the hypothesis of case 7A.

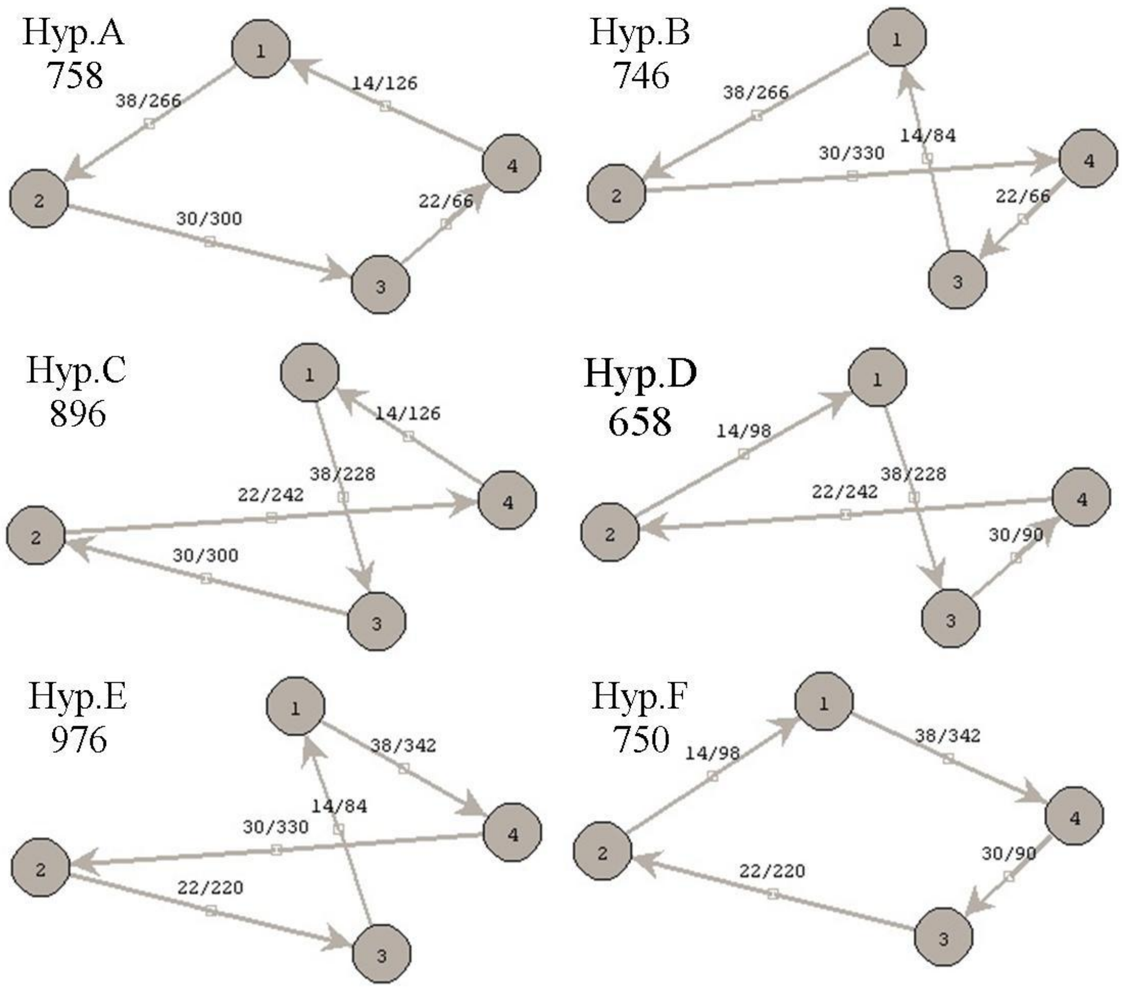

Figure 43 – Case 7A, hypothesis to cross the network with respective costs (tkm).

It is observed that the less costly solution, in terms of tkm, is the hypothesis D, with a total of tkm measured equal to 658. It coincides with the solution for the shortest distance travelled (Hyp. D or Hyp. B). In Table 30 it is done a small analysis, comparing all the hypotheses with

Hyp.D, in terms of distances and tonne·kilometer, to understand how the difference in the travelled distance relates to the difference of tkm.

Table 30 – Case 7, comparison of hypotheses against Hyp.D.

Hypotheses	Total km	Difference to the km of Hyp.D	Total tkm	Difference to the tkm of Hyp.D
Hyp.A	29	+2 (7.4 %)	758	+100 (15.2 %)
Hyp.B	27	0	746	+88 (13.4 %)
Hyp.C	36	+9 (33.3 %)	896	+238 (36.2 %)
Hyp.D	27	0	658	0
Hyp.E	36	+9 (33.3 %)	976	+318 (48.3 %)
Hyp.F	29	+2 (7.4 %)	750	+92 (14.0 %)

By observing the values it is concluded that no coherent relation can be made between the distances travelled and the tkm measured. For instance, to travel 9 km more can signify an increase of 36.2 % (Hyp.C) on total tkm or of 48.3 % (Hyp.E). This unit always depends heavily of the tonnes carried in each journey.

As a summary, the presented case was useful to:

- Explain the utility of including the minimization of tkm in freight transport problems;
- Illustrate the differences between considering or not the self-weight of the truck and concluding that it is important to consider it;
- Test all the possible ways to cross the given network of 4 nodes, demonstrating that the shortest route might not be the one with the minimum amount of tkm and concluding that no coherent relation can be made between the distances travelled and the tkm measured.

5.4.3.3. Formulation of mathematical model to minimize tonne·kilometer

At this point a mathematical formulation is presented, based on Vehicle Routing Problem, in order to minimize the tonne·kilometer measured in a freight transport problem. In this model there is the option to choose obligatory and optional nodes to cross and it is allowed to have more than one vehicle affected.

Below it is written the formulation of the model, where the parameters and variables have the meanings mentioned in Table 31 and Table 32, respectively. When appropriated, the restrictions are accompanied with a brief explanation under the equation.

Table 31 – Meanings of the parameters.

N	Total number of nodes.
R	Total number of obligatory nodes.
O	Total number of optional nodes.
Nv	Total number of available vehicles.
c_{ij}	Cost of the journey between node *i* and *j.*
Q_k	Maximum capacity, in tonnes, of vehicle *k.*
qn_j	Demand, in tonnes, in node *j.*
$tara_k$	Self-weight of vehicle *k.*

Table 32 – Meanings of the variables.

t_{kij}	Gross weight, in tonnes, of the truck *k* when passing the journey from node *i* to *j.*
x_{kij}	Binary variable equal to 1 if the vehicle *k* makes the journey from node *i* to *j.*
$load_{ki}$	Weight of freight carried by vehicle *k* when leaving the node *i.*

Objective function:

$$minimize \sum_{k=1}^{Nv} \sum_{i=1}^{N} \sum_{j=1}^{N} c_{ij} t_{kij} \tag{21}$$

Respecting the following restrictions:

$$\sum_{k=1}^{Nv} \sum_{\substack{i=1 \\ i \neq j}}^{N} x_{kij} = 1 \qquad \forall j \ \in R \backslash \{1\} \tag{22}$$

The exception to this restriction to the first node is necessary because it is allowed to have more than one vehicle in the solution, so, eventually more than one vehicle leaving and arriving to node 1.

$$\sum_{k=1}^{Nv} \sum_{\substack{i=1 \\ i \neq j}}^{N} x_{kij} \leq 1 \qquad \forall j \ \in O \tag{23}$$

$$\sum_{\substack{j=1 \\ j \neq i}}^{N} x_{kij} = \sum_{\substack{j=1 \\ j \neq i}}^{N} x_{kji} \qquad \forall i \ \in N, \forall k \ \in Nv \tag{24}$$

Restrictions (23) and (24) allow the visiting of optional nodes and ensure that if a certain vehicle goes to some node, it also has to leave that node.

$$\sum_{j=2}^{N} x_{k1j} \leq 1 \qquad \forall k \in Nv \tag{25}$$

It is ensured that if some vehicle k is needed in the solution, it only can go from node 1 to one node j.

$$load_{kj} - load_{ki} + Q_k x_{kij} \leq Q_k - qn_j \;\; \forall k = 1, \dots, Nv, \forall i, j = 2, \dots, N, i \neq j \tag{26}$$

It is ensured that for an arc (i,j) that is part of the solution, the unloaded amount in node j is equal to its demand.

$$load_{k1} = \sum_{l=2}^{N} qn_l \sum_{\substack{j=1 \\ j \neq l}}^{N} x_{klj} \qquad \forall k = 1, \dots, Nv \tag{27}$$

$$0 \leq load_{ki} \leq load_{\,k1} \;\; \forall k = 1, \dots, Nv, \forall i = 2, \dots, N \tag{28}$$

The total freight carried after leaving node i cannot be bigger than the amount after leaving the origin node.

Constraints (26) and (28) are the subtour elimination constraints, so each vehicle does one single tour well connected, ensuring that all the nodes are linked to the origin one.

$$load_{k1} \leq Q_k \qquad \forall k = 1, \dots, Nv \tag{29}$$

$$\sum_{\substack{j=1 \\ j \neq i}}^{N} t_{kij} = load_{ki} + tara_k \sum_{\substack{j=1 \\ j \neq i}}^{N} x_{kij} \qquad \forall k = 1, \dots, Nv, \forall i = 1, \dots, N \tag{30}$$

$$t_{kij} \leq (Q_k + tara_k)\, x_{kij} \qquad \forall k = 1, \dots, Nv \forall i, j = 1, \dots, N, i \neq j \tag{31}$$

About restrictions (30) and (31), the gross weight for vehicle k, travelling between node i and j is equal to the freight carried plus the self-weight of vehicle. In the non passed arcs, the total weight passed there is equal to 0.

$$x_{kij} \in \{0,1\} \quad \forall k = 1, \dots, Nv, \forall i, j = 1, \dots, N, i \neq j \tag{32}$$

After showing the model, now there are presented some examples to test it, using the Xpress software.

5.4.3.4. Case 8 – Using the new formulation

To case 8 is considered the same network as in case 7, as well as the same conditions about obligatory nodes to visit, number and type of vehicles used and unloaded freight in each node, so it is possible to compare the solution given by this formulation with the best one calculated before.

Table 33 shows the values for the freight carried and the gross weight in each arc crossed, according to the solution given by Xpress

Table 33 – Variables values.

$load_{11} = 24$
$load_{13} = 16$
$load_{14} = 8$
$t_{113} = 38$
$t_{121} = 14$
$t_{134} = 30$
$t_{142} = 22$

The solution calculated is the same as the one calculated in case 7A for Hyp.D, as illustrated in Figure 44, representing in each arc the vehicle gross weight and the tonne·kilometer (t/tkm). The total cost is, like in Hyp.D, 658 tkm.

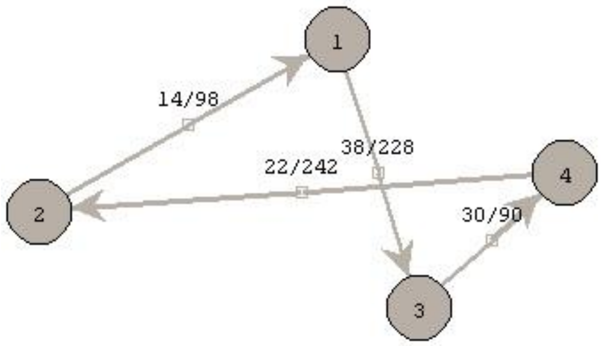

Figure 44 – Case 8, solution.

5.4.3.5. Case 9 – Using more than one vehicle

In this case is considered the network of case 7, with the same unloaded freight in each node, but this time there are two trucks available with the characteristics mentioned in Table 24. Besides being a transport problem, it is also a logistic problem.

Figure 45 illustrate the solution with less tkm measured, representing in two different colors the arrows referred to each vehicle. Table 34 compares the best solutions by using one vehicle and two vehicles.

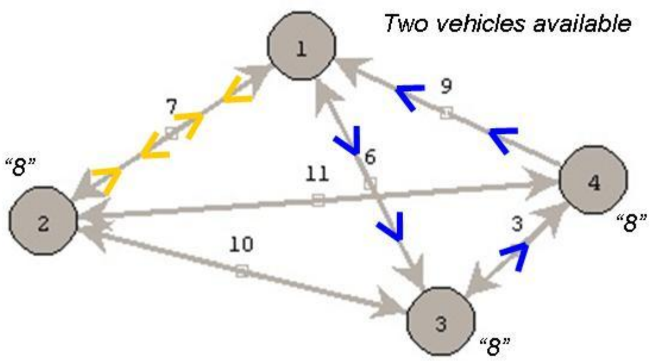

Figure 45 – Case 9, solution with two vehicles.

Table 34 – Case 9, comparison between using 1 vehicle and 2 vehicles.

With 1 vehicle				With 2 vehicles			
Arcs	Distance (km)	Gross weight (t)	tkm	Arcs	Distance (km)	Gross weight (t)	tkm
arc (1,3)	6	38	228	arc (1,2)	7	22	154
arc (3,4)	3	30	90	arc (2,1)	7	14	98
arc (4,2)	11	22	242	arc (1,3)	6	30	180
arc (2,1)	7	14	98	arc (3,4)	3	22	66
				arc (4,1)	9	14	126
Total	**27**	**104**	**658**	**Total**	**32**	**102**	**624**

It is concluded that is less costly in terms of tkm to solve the problem with two vehicles than only with one. With two vehicles the total distance travelled is 5 km longer and none of the trucks is completely full.

Notice that in real situations, regarding only the minimization of tkm, an equivalent solution would be to have only one vehicle doing the trips of both, with the same load through the same arcs.

5.4.3.6. Case 10 – Importance of the distribution of demands

To this case, also related with transport and logistics problems, the node demands are distributed in such a way that is required the use of two trucks at least. A few different versions are presented in order to understand some aspects of the model. In all of them, the nodes are linked by the shortest paths (Figure 46).

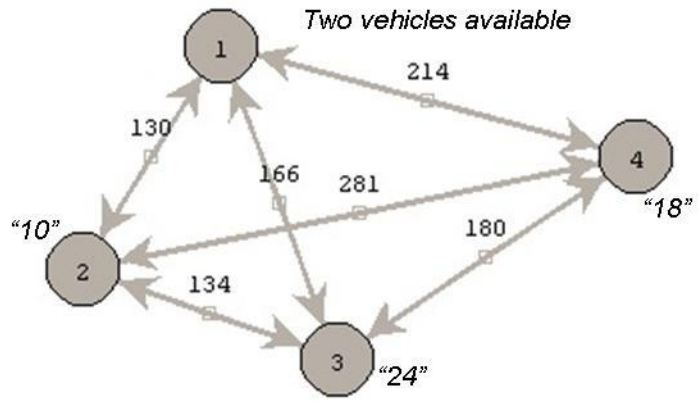

Figure 46 – Case 10A, network and node demands.

The total demand is equal to the capacity of two trucks together, 52 tonnes, so it is possible to satisfy all the customers. In this concrete example, none of the trucks have enough capacity to carry the required amount to deliver to two nodes, thus, it is necessary for one node to be visited by both trucks.

One of the model constraints imposes for each node to be visited once and only once, so it is impossible to calculate an optimal solution to this example. To make it possible, it would be necessary to change some constraints. Such changes are not discussed in this thesis, but it is left as an open path to future works.

To apply the model is then necessary to define carefully the amount to unload in each node according to the number of vehicles available. Also, it does not make sense to consider more available vehicles than nodes. For instance, case 10A would be solved if there were three vehicles available.

In network of Figure 47 is shown the same network with a different distribution of demands, acceptable to run the mathematical model. It is already included the solution, where the routes are represented by yellow and blue narrows.

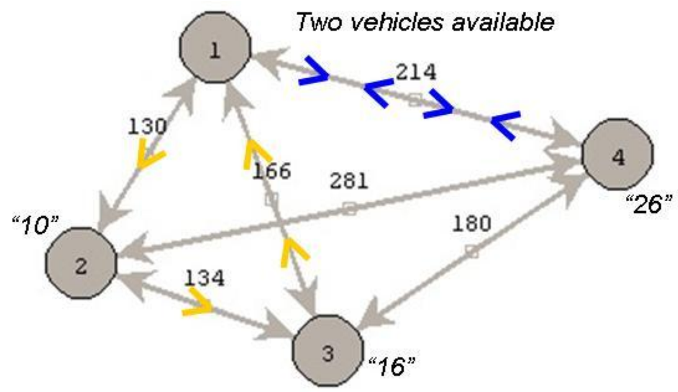

Figure 47 – Case 10B, network and solution.

All the customers' demands are satisfied by a visit of one only vehicle. The minimum tkm measured is 24038 in a total distance travelled of 644 km.

5.4.3.7. Case 11 – Rail and road solutions in the Portuguese network

This case simulates a transport problem based on real road and rail networks of Portugal and serves to compare the optimal solutions in terms of tonne·kilometer, considering the gross weight transported.

The simulation represents a situation in which it is supposed to transport containerized goods from Porto de Aveiro to Maia/Trofa, Guarda, Entroncamento and Bobadela, according to the demands indicated in Table 35, using the trucks, trains and containers mentioned in section 5.4.3.1.

Table 35 – Demands (including containers weight) of each platform.

	Demand (including containers weight)	
	Containers	Tonnes
Maia	5	130
Guarda	4	104
Entroncamento	12	312
Bobadela	9	234

The gross weight of containers is 26 tonnes. The self-weight of container is also included on the demand values.

Let us considerer at first the railway network, defined with the shortest paths among all pairs of nodes like indicated in Table 36.

Table 36 – Distances matrix for railway network.

km by rail	Aveiro	Maia	Guarda	Entroncamento	Bobadela
Aveiro		86	206	175	269
Maia			274	243	337
Guarda				240	334
Entroncamento					94
Bobadela					

To find the optimal route(s) to minimize the tkm measured, it is supposed that are available for use four trains with 30 wagons each one.

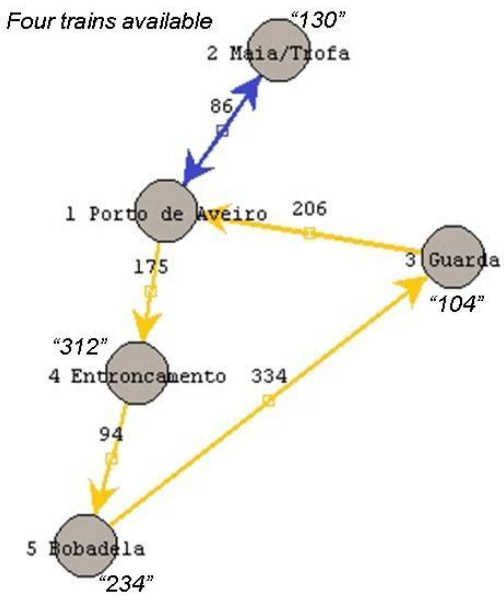

Figure 48 – Rail network, solution for the demands including the containers weight.

The solution calculated includes the use of two trains with a total cost of 674090 tkm.

On purpose, the capacity of each train is equal to the sum of demands, so, if it is used more than one train it means that there are some empty wagons travelling, thus, the calculated tkm is higher than the necessary one, as demonstrated in Table 37:

Table 37 – Necessary tkm to the routes of Figure 48.

		Freight carried		Self-weight (including locomotive)		tkm
Edge	Distance	Containers	Tonnes	Wagons	Tonnes	
(1,2)	86	5	130	5	154.5	24467.0
(2,1)	86	0	0	5	154.5	13287.0
(1,4)	175	25	650	25	424.5	188037.5
(4,5)	94	13	338	25	424.5	71675.0
(5,3)	334	4	104	25	424.5	176519.0
(3,1)	206	0	0	25	424.5	87447.0
Total	**981.0**	**47.0**	**1222.0**			**561432.5**

As it is observed, by considering only the necessary wagons for each route, removing the empty ones, the total cost is 561432.5 tkm, 83 % of the previous cost.

Regarding the mathematical formulation, the removal of the empty wagons change the tare of each vehicle. The tare is an input data for solve the problem, thus it influences the calculation of the shortest route. But the definition of the shortest route also influences the necessary number of wagons for each train, so the input tare has to be change again. This fact leads us to a problem that can consist in a lot of iterations, because the solution and the tare values depend on each other.

To get around that problem, it is assumed that in every platform the wagons are unloaded together with the containers, so there are never empty wagons travelling. In fact, this assumption is an approach to what happens in reality, since the Portuguese statistics indicates that only 12% of the wagons moved in 2010 were non-filled (section 2.3.1.2.).

Therefore, let us consider the new demands, in which it is included the weight of one wagon for each container:

Table 38 – Demands (including containers and wagons weight) of each platform.

	Demand (including containers & wagons weight)	
	Containers & wagons	Tonnes
Maia	5	197.5
Guarda	4	158
Entroncamento	12	474
Bobadela	9	355.5

To this demands another solution is obtained. Notice that the vehicle tare now is only the self-weight of the locomotive, 87 tonnes.

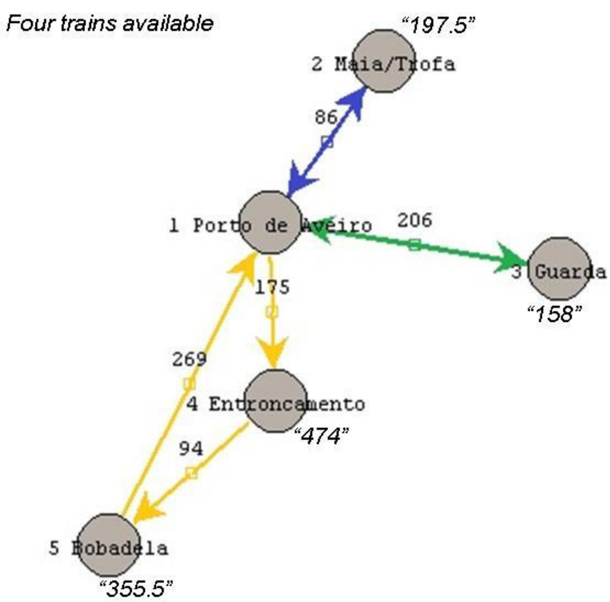

Figure 49 – Rail network, solution for the demands including the containers and wagons weight.

The calculated solution contains three routes with a total cost of 325727 tkm, much less costly than the one considering the circulation of empty wagons.

Now it is calculated the optimal route(s) to the road network.

For that, some aspects about the mathematical formulation and the characteristics of the used trucks must be taken:

- The maximum number of used vehicles is four, because there are only four nodes to visit;
- The fleet capacity is lower than the total demand;
- The demand values are multiples of the containers gross weight;

- Each truck can take only one container.

With the last points it is concluded that every truck goes for a node with a net weight equal to the container gross weight. So, the network and the routes can be represented like in Figure 50.

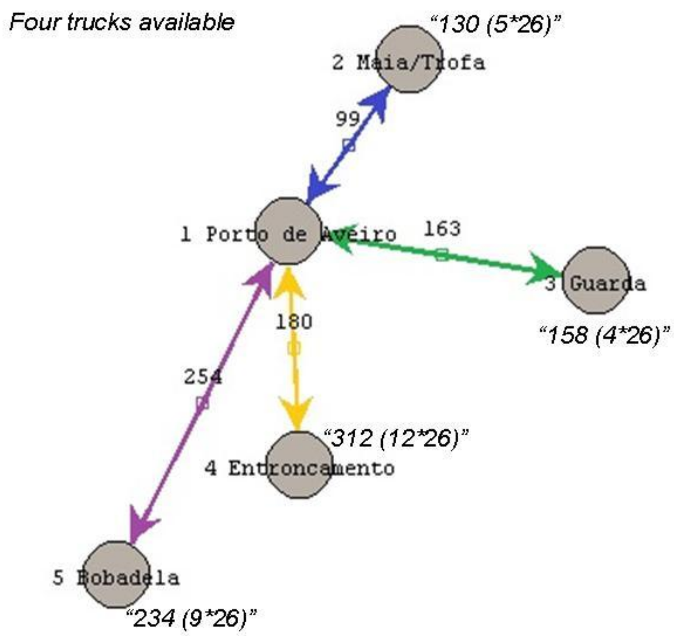

Figure 50 – Road network, demands and optimal routes.

Because of the limited capacity of each truck, the only possibility to satisfy the platforms demands is to do single journeys between the origin and each platform. On Table 39 is calculated the total cost of that possibility, taking into account the number of times that each edge is passed:

Table 39 – Road network, calculation of the total cost.

Edge	Tonnes	Distance	Repetitions	tkm
(1,2)	40	99	5	19800
(2,1)	14	99	5	6930
(1,3)	40	163	4	26080
(3,1)	14	163	4	9128
(1,4)	40	180	12	86400
(4,1)	14	180	12	30240
(1,5)	40	254	9	91440
(5,1)	14	254	9	32004
			Total	**302022**

The total cost is 302022 tkm, of which 26 % refer to empty trips.

The road option is less costly in terms of tkm than the rail one.

5.5. SUMMARY

This final section of chapter aims to be a summary of conclusions taken along the study cases above. Those are divided in five parts:

A. Conclusions about the operation of the original model, TSP;
B. Observations to the proposals implemented to the model;
C. Conclusions about the model based on VRP used to minimize tonne·kilometer;
D. Transport networks in general.
E. Suggestions about important input data to optimize transportation problems.

A. Conclusions about the operation of the original TSP:

- Given a certain network, the solution does not depend of the origin node, so the sequence of visiting is always the same.
- The shortest routes to networks represented by indirect graphs or symmetric direct graphs can be travelled in opposite directions with the same cost. The model does not predict any restriction to choose one or another.
- It imposes that the shortest route has to include all the network nodes, visiting each one once and only once. Two consequences for the solution may arise:

  - The passage in unnecessary nodes, implying an increase or decrease of the total distance travelled;

  - When a network is not defined by the shortest paths among all pairs of nodes, the total distance calculated can achieve higher values than necessary because it is not allowed to use more than once the same arc.

  - To use the TSP in an optimal way it is necessary to characterize the network with the shortest paths among all pairs of nodes.

B. Observations to the proposals implemented to the model.

- The possibility to identify the required nodes is useful to adapt certain network to real situations with different groups of customers. It can be done by changing the original matrix or the original TSP.
- When it is not ensured that all the nodes are connected by the shortest paths, it can be beneficial to admit the passage in optional nodes.
- To choose the direction of a trip is necessary to define new criteria, such as the minimization of tonne·kilometer.

C. Conclusions about the model used to minimize tonne·kilometer.

- The consideration of this variable approach the model to a Vehicle Routing Problem.
- Looking forward to real problems, it is convenient to take into account with the vehicles weight.
- The demand values have to be carefully allocated to each customer due to the model impossibility to have more than one vehicle visiting the same node.
- Regarding to the rail networks, if it is considered the self-weight of wagons, the definition of the number of wagons to a certain train depends on the route to be traveled, which in turn depends on the train self-weight. If the wagons are delivered together with the goods in each node, then the self-weight of the train refers only to the locomotive, so an optimal solution can be calculated by the model.

D. Transport networks in general.

- Given a certain network in which all the ways between nodes are identified, the addition of one node in an existent way (arc) never leads to a decrease of the total distance travelled. However, if the new node is inserted in such a place that requires the implementation of new ways, the total distance travelled to cross the whole network can be longer or shorter than before the addition.
- On railway networks, where the amount of different ways is reduced, the percentage of the total net length travelled to pass in all logistic platforms can be an indicator about the location of such centers. High percentages of use suggest that the platforms are located in extremes, boundaries or “corners” of the network, like it happens in the Portugal case. Lower percentages of use suggest that the platforms are located in central areas, dismissing the use of the lines in boundaries of the network, like it happens in the Czech Republic case. Comparison between these two countries is summarized in Table 40 (case 5 and case 6).
- Generally, on road networks, when comparing to the rail ones, the percentage used of it to go through the same platforms is much lower because there are more alternative ways to go to the same places. Comparison between road and rail network of Portugal is summarized in Table 40 (case 4 and case 5).

Table 40 – Comparison between cases 4, 5 and 6.

	Case 4	Case 5	Case 6
Distance travelled (km)	1720	2001	1123
Network length (km)	2800	1860	2190
% of network length travelled (%)	61	108	51
Number of platforms	11	11	8

- The minimization of transportation of empty wagons reduces significantly the total amount of tkm measured, so the indicator of non-empty wagons transported is an efficiency measure to the rail transport.

E. Suggestions about important input data to optimize transportation problems.

Besides the distances and the tonne·kilometer, there are some other decision factors that should be considered to optimize freight transportation, such as:

- Consumption of energy.
- Emissions of pollutants.
- Duration of journeys and total trip.
- Monetary costs of operation.
- Definition of different priorities for costumers to respect deadlines.

These and other factors can be considered individually or together, with different importance according to the main goal to achieve in each case.

6

CONCLUSIONS AND FUTURE WORK

6.1. CONCLUSIONS

In this section the main conclusions taken along the paper are presented.

In chapter 2 and chapter 3 some information was presented about freight transport in Europe, and the main aspects to refer are:

- The road transport is clearly the most used one to the freight transport in Europe. The main reason for that has to be with the existent infrastructures and the mobility of road vehicles.
- In spite of the increasing of the freight transport in general, the rail transport has maintained the same importance in the last years.
- Due to the high carrying capacity and the low energy use of the rail transport, this transport mode is more beneficial for long distances trips. In fact, for long distance trips, the mobility aspect is relatively less important than the economy and efficiency aspects of transport. These facts makes the rail transport important for international transportation, namely in central countries of Europe, like Czech Republic.
- Looking towards social, economical and environmental concerns, the European Union defined transeuropean networks of transports, mainly focused on road and railways. From the proposed maps, it is observed the higher density of these networks in central areas of the community. However, some efforts are being done to connect the peripheral counties, as it can be demonstrated by the definition of transport corridors planned for Portugal, for instance, defined as priority axis.
- The networks are defined by taking into account the location of big urban centers and intermodal logistic platforms, promoting the intermodality on the freight transportation in order to complement the advantages of each transport mode together.

In chapter 4, the existent network optimization methods are presented, focused on transport problems, noting that:

- Transport systems are suitable to be modeled as a network of nodes and arcs where some transportation processes occur.
- For transportation problems there are some existent models, of which it were highlighted the Shortest Path Problem and two Routing problems: the Travelling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP).
- The TSP is a mathematical formulation with simple restrictions and limited input data, useful to find shortest routes on basic transport problems by minimizing only one variable.

- The VRP is more complex because it allows to be considered at the same time more decision variables and input data

Finally, in chapter 5, several cases of transport problems were analyzed. The main conclusions taken from this analysis are:

Regarding the TSP, it is observed that it does not has any criteria to choose the direction of the trip. Because of the impossibility of visiting a node more than once, all the nodes should be connected by the shortest paths possible, so the routes are calculated in an optimal way. Finally, given a certain network, the TSP demands the cross of all of nodes, even if it is not necessary to a concrete transport problem to cross them. An improvement for choosing the obligatory and optional nodes was successfully done and demonstrated.

The model based on VRP was implemented in order to take into account another decision variable into transport problems: the minimization of tonne·kilometer, because this variable and the chosen route depend on each other. In this model it is allowed to use more than one vehicle up to a maximum equal to the number of existent nodes, excluding the origin one. Its formulation imposes that each node can be visited only once, which is a problem when a customer demands more freight that the capacity of one vehicle, even if there are more vehicles available.

6.2. FUTURE WORK

In the next point are enumerated some aspects that can be done in future to give continuity to the work presented in this thesis.

Regarding to the transeuropean networks of transport and intermodal logistic platforms:

- To obtain more detailed data in order to achieve a better characterization of the networks in each country;
- To assess the progress of the priority axles;
- To characterize the logistic platforms in terms of storage capacity and cargo handling, road and rail accessibilities.

Regarding to the optimization of transport problems:

- To include more decision variables for each transport mode, such as:
  - Microscopic variables: time of the trip; consumption of energy; emission of pollutants to the environment; associated costs to these factors. These variables can be assumed as macroscopic by doing estimations or analyzing statistical data.
  - Macroscopic variables: costs associated with staff engaged in the activity; delivery deadlines in order to create different priorities of visit to each customer;
- To include data about the time and cost involved to transfer the freight from a transport mode to another.
- To apply the models, considering the variables individually and together, to real transport problems associated with companies or state entities.
- To study and implement the possibility for a node to be visited more than once.

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ANNEXES

In these annexes, the transeuropean transport networks for twenty five countries of European Union are presented. The maps of Malta and Cyprus are not present because there was no information about the rail network in those countries. So, the author decided to not include those road networks in order to have the same number of countries in rail and road networks.

Table of Maps

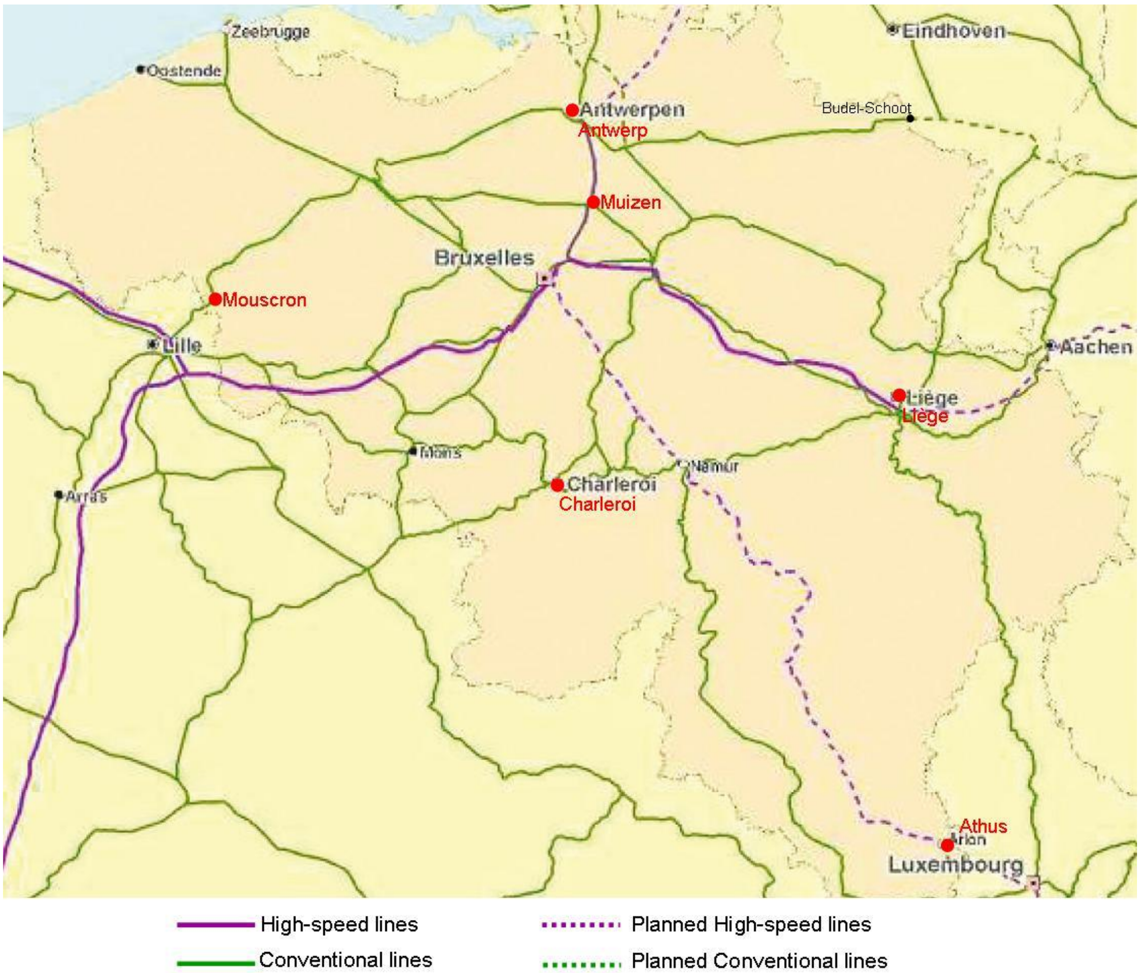
Map 1: Transeuropean rail network in Austria.

Priority axis 1:
Munchen - Kufstein - Innsbruck - Brennero.
Priority axis 17:
Salzburg - Linz - Wien.
Priority axis 22:
Ceske Budejovice - Linz;
Breclav - Wien - Gyor (Hungary).
Priority axis 23:
Breclav - Wien.

Map 2: Transeuropean road network in Austria.

Priority axis 25:
Brno (Czech Republic) - Wien.

Map 3: Transeuropean rail network in Belgium.

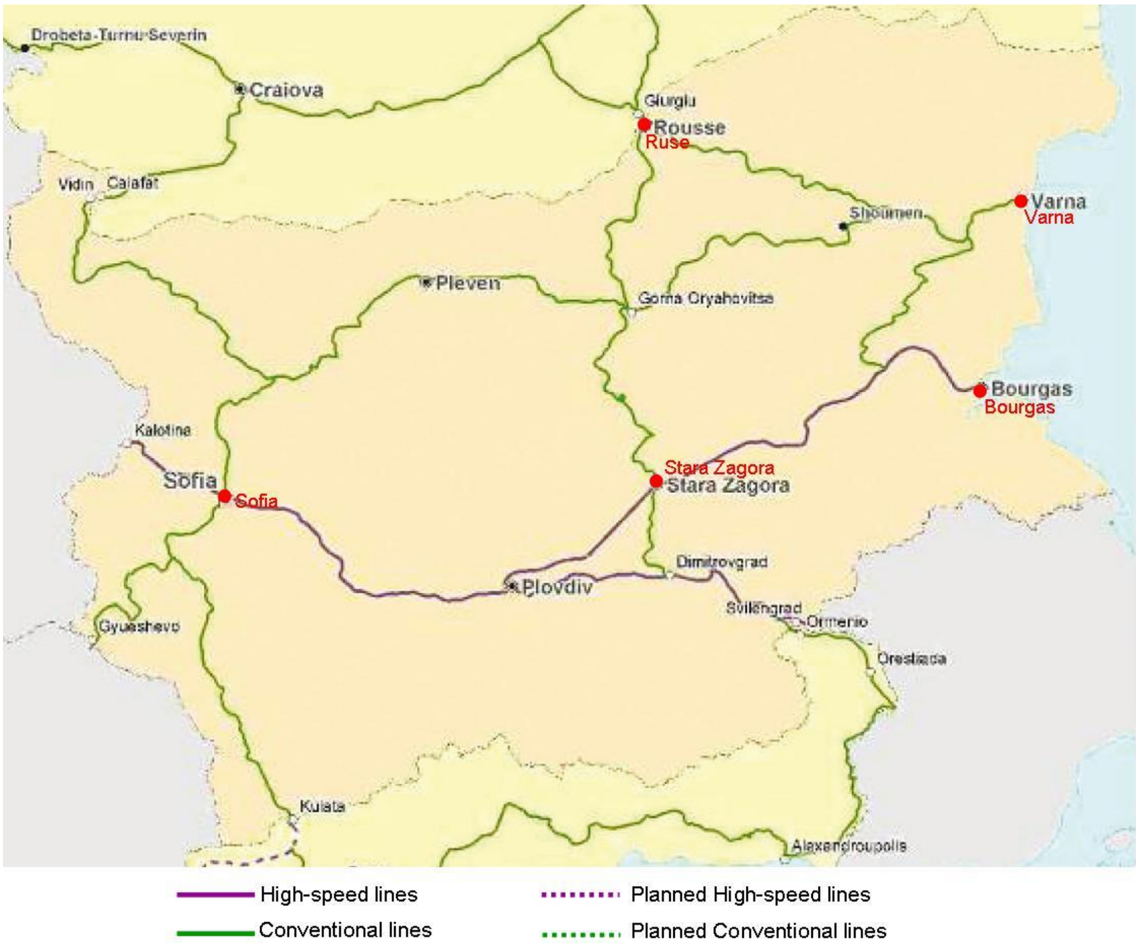


Priority axis 2:
Rotterdam - Antwerp - Brussels - Liège - Aachen;
Brussels - Lille.
Priority axis 24:
Antwerp - Budel-Schoot.
Priority axis 28:
Brussels - Namur - Arlon.

Map 4: Transeuropean road network in Belgium.

High-speed lines   Planned High-speed lines

Map 5: Transeuropean rail network in Bulgaria.

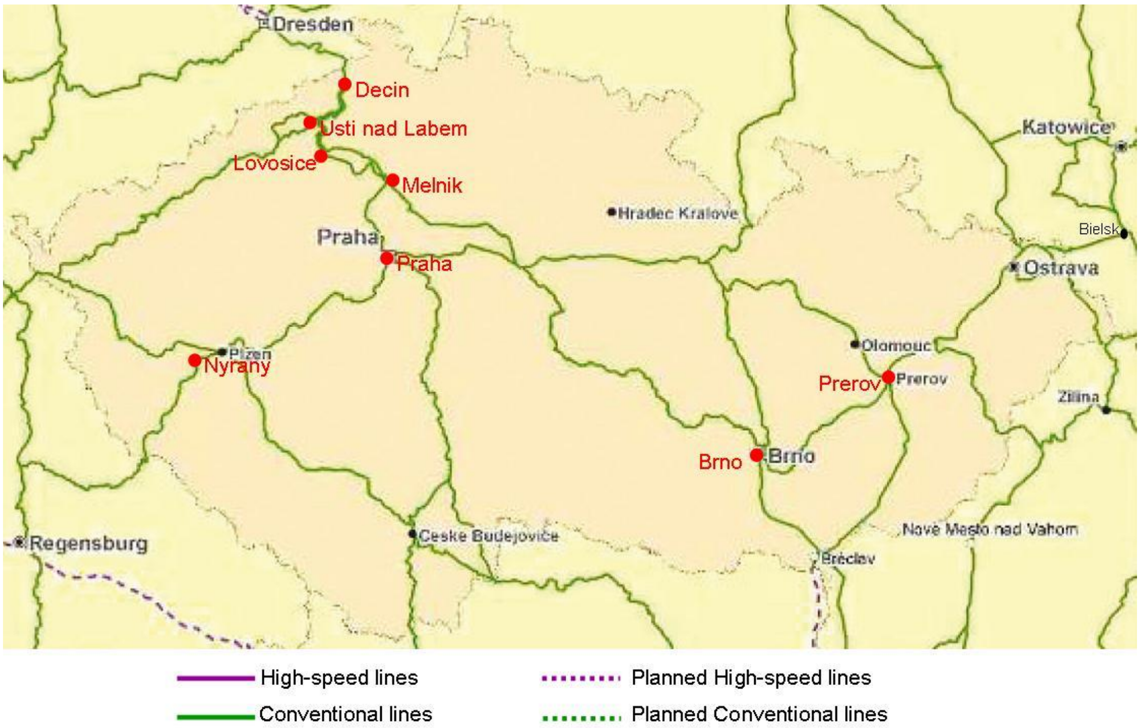


Priority axis 22:
Calafat - Sofia - Kulata.

Map 6: Transeuropean road network in Bulgaria.

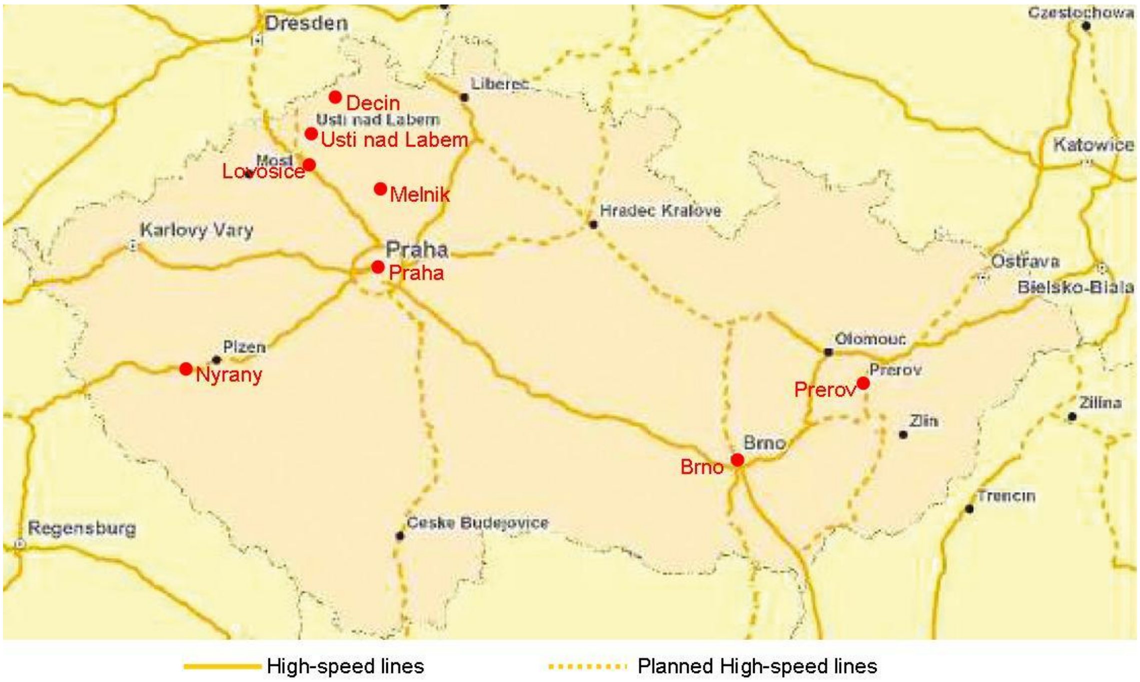
Priority axis 7:
Calafat - Sofia - Kulata.

Map 7: Transeuropean rail network in Czech Republic.



Priority axis 22:
Nurnberg - Plzen - Praha - Brno - Breclav;
Praha - Ceske Budejovice - Linz (Austria).
Priority axis 23:
Bielsk - Ostrava - Brno - Breclav.

Map 8: Transeuropean road network in Czech Republic.



Priority axis 25:
Bielsko-Biala - Olomouc - Brno - Wien (Austria).

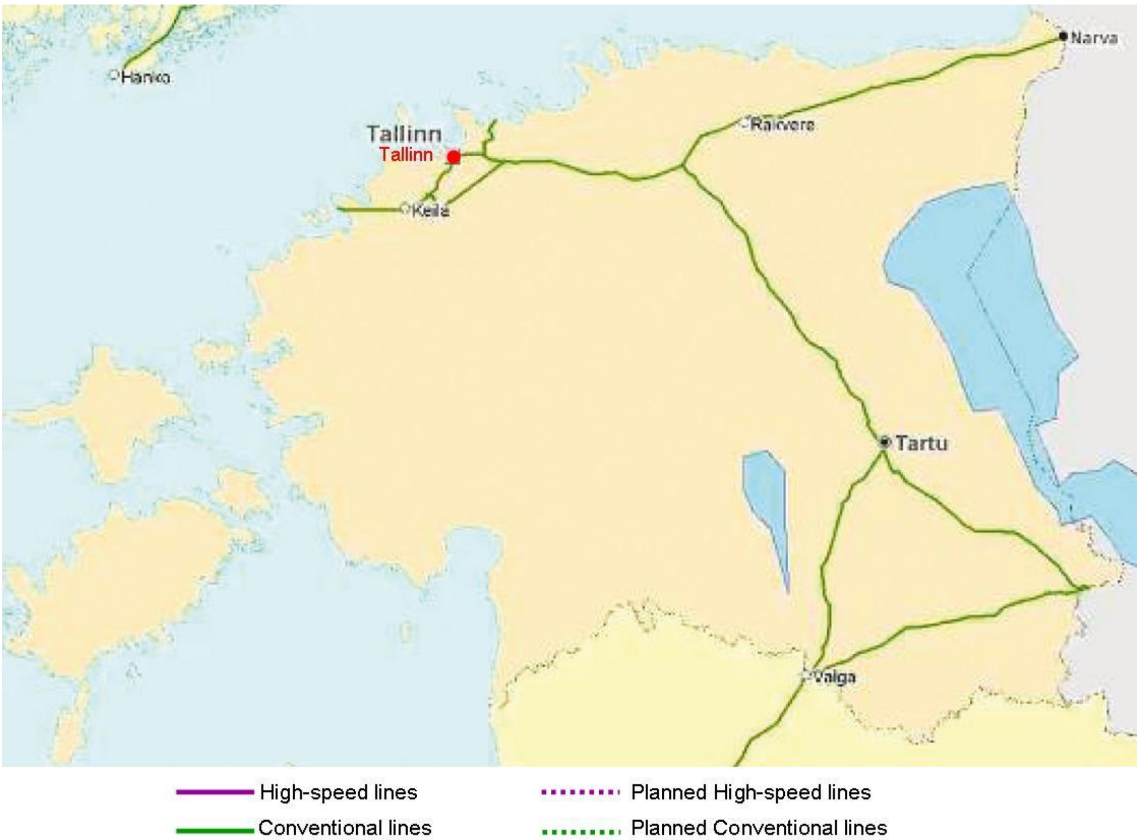
Map 9: Transeuropean rail network in Denmark.

Priority axis 11:
Malmo - Kobenhavn.
Priority axis 20:
Kobenhavn - Rodby - Lubeck (Germany).

Map 10: Transeuropean road network in Denmark.

Priority axis 11:
Malmo - Kobenhavn.
Priority axis 20:
Rodby - Fehmarn (Germany).

Map 11 Transeuropean rail network in Estonia.



Priority axis 27:
Tallinn - Tartu - Valga.

Map 12: Transeuropean road network in Estonia.

Map 13: Transeuropean rail network in Finland.

Priority axis 12:
Vainikkala - Lahti - Kerava - Helsinki - Turku.
Priority axis 27:
Helsinki.

Map 14: Transeuropean road network in Finland.

Priority axis 12:
Vaalima - Helsinki - Turko.

Map 15: Transeuropean rail network in France.

Priority axis 2:
Calais - Lille - Paris;
Brussels - Lille.
Priority axis 3:
Paris - Tours - Bordeaux - San Sebastián;
Lyon - Nimes - Perpignan.
Priority axis 4:
Paris - Reims - Baudrecourt - Strasbourg;
Luxembourg - Metz - Baudrecourt;
Saarbrucken - Baudrecourt.

Priority axis 6:
Lyon - St Jean de Maurienne - Torino.
Priority axis 17:
Paris - Reims - Braudecourt - Strasbourg.
Priority axis 24:
Mulhouse/Mulheim - Lyon.
Priority axis 28:
Luxembourg - Baudecourt - Strasbourg.

Map 16: Transeuropean road network in France.

High-speed lines   Planned High-speed lines

Map 17: Transeuropean rail network in Germany.

Priority axis 1:
Berlin/Leipzig - Halle - Erfut - Nurnberg -
- Munchen - Kufstein
Priority Axis 2:
Aachen - Koln.
Priority axis 4:
Mannheim - Saarbrucken - Baudrecourt.
Priority axis 17:
Strasbourg - Karlsruhe - Stuttgart - Ulm -
- Munchen - Salzburg.

Priority axis 20:
Rodby - Ludbeck - Hamburg - Bremen;
Bremen - Hannover.
Priority axis 22:
Nurnberg - Plzen;
Dresden - Praha.
Priority axis 24:
Emmerich - Duisburg - Koln - Frankfurt am Main -
- Mannheim - Karlsruhe - Mulhouse/Mulheim;
Rheidt - Koln.

Map 18: Transeuropean road network in Germany.

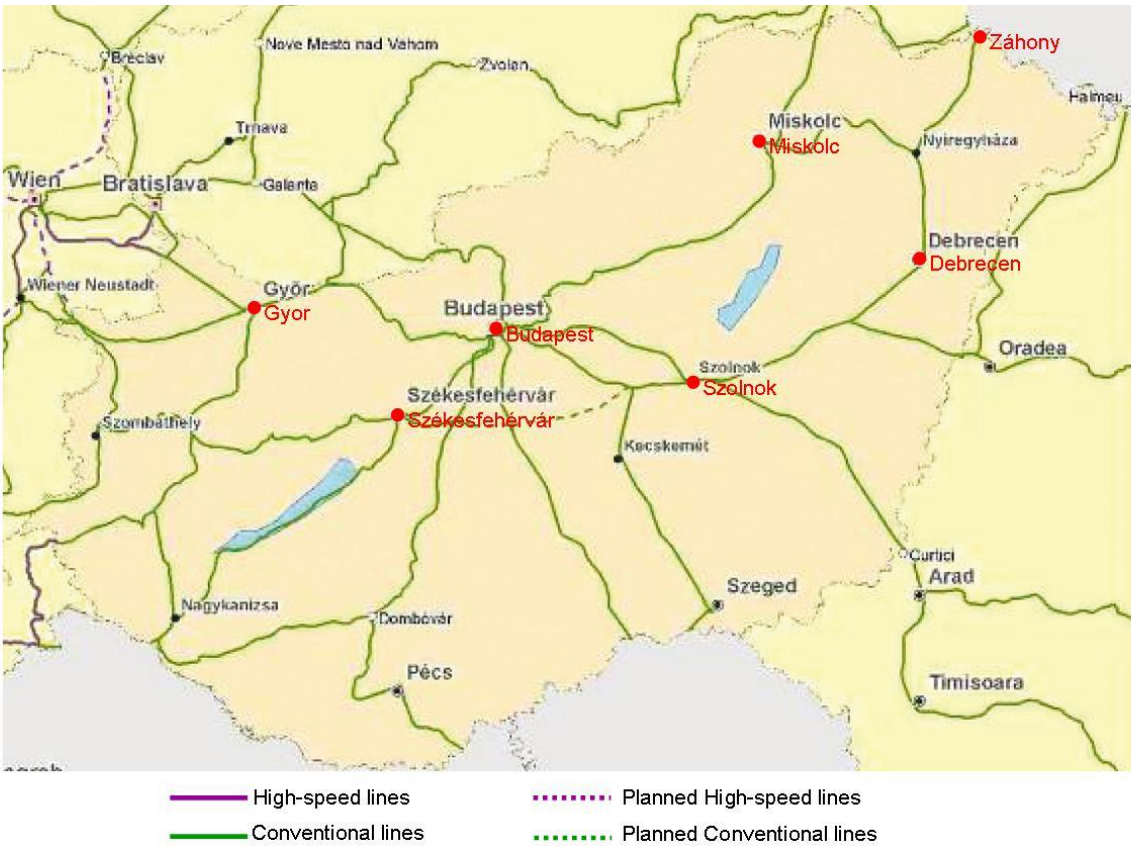
Map 19: Transeuropean rail network in Greece.

Priority axis 22:
Kulata - Thessaloniki - Larissa - Athina.
Priority axis 29:
Kozani - Kalamba - Ioannina - Igoumenitsa;
Ioannina - Antirrio;
Rio - Patra - Kalamata.

Map 20: Transeuropean road network in Greece.

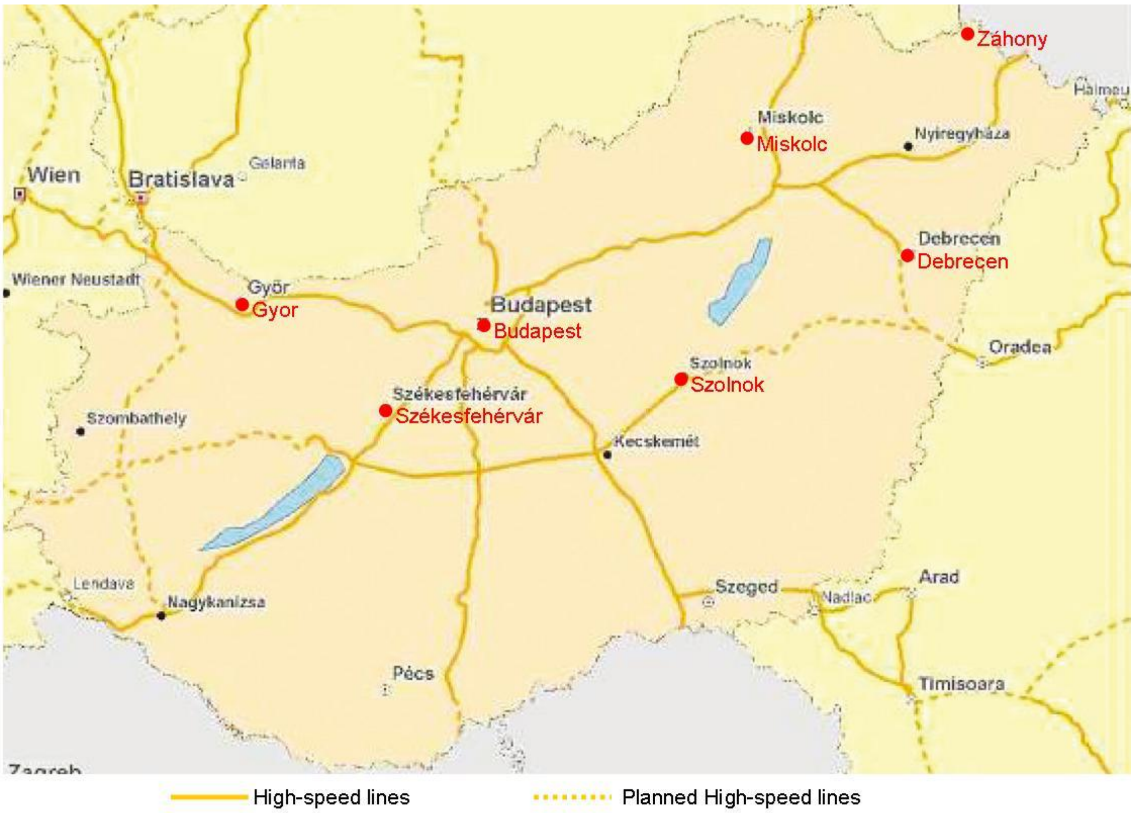
Priority axis 7:
Kulata - Thessaloniki;
Ormenio - Alexandroupolis - Thessaloniki - Kozani - Ioannina - Igoumenitsa;
Thessaloniki - Larissa - Volos - Athina - Korinthos - Patras.

Map 21: Transeuropean rail network in Hungary.



Priority axis 6:
Pragersko (Slovenia) - Székesfehérvár - Budapest - Miskolc - Záhony.
Priority axis 22:
Wien - Gyor - Budapest - Curtici.

Map 22: Transeuropean road network in Hungary.



Priority axis 7:
Budapest - Nadlac.

Map 23: Transeuropean rail network in Ireland.

Priority axis 9 and 26:
Belfast - Dublin - Cork.

Map 24: Transeuropean road network in Ireland.

Priority axis 13:
Dundalk - Dublin - Portlaoise - Cahir - Cork.

Map 25: Transeuropean rail network in Italy.

Priority axis 1:
Innsbruck - Brennero - Verona - Bologna - Roma - Napoli - Messina - Palermo;
Milan - Bologna.
Priority axis 6:
Torino - Verona - Venezia - Trieste - Divaca.
Priority axis 24:
Domodóssala - Novara - Genoa;
Chiasso - Milano - Genoa.

Map 26: Transeuropean road network in Italy.

High-speed lines
Planned High-speed lines

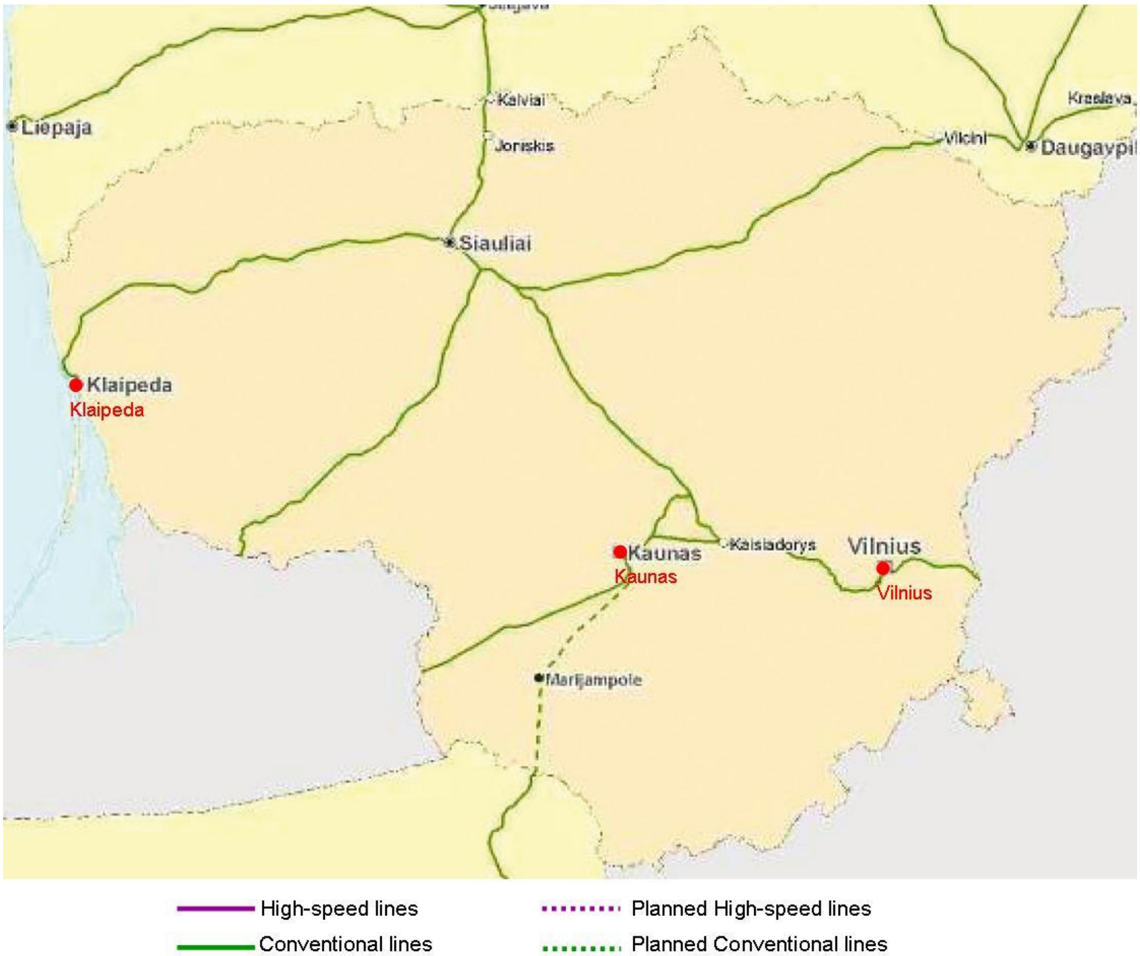
Map 27: Transeuropean rail network in Latvia.

High-speed lines
Planned High-speed lines
Conventional lines
Planned Conventional lines

Priority axis 27:
Valga - Riga - Kalviai.

Map 28: Transeuropean road network in Latvia.

Map 29: Transeuropean rail network in Lithuania.



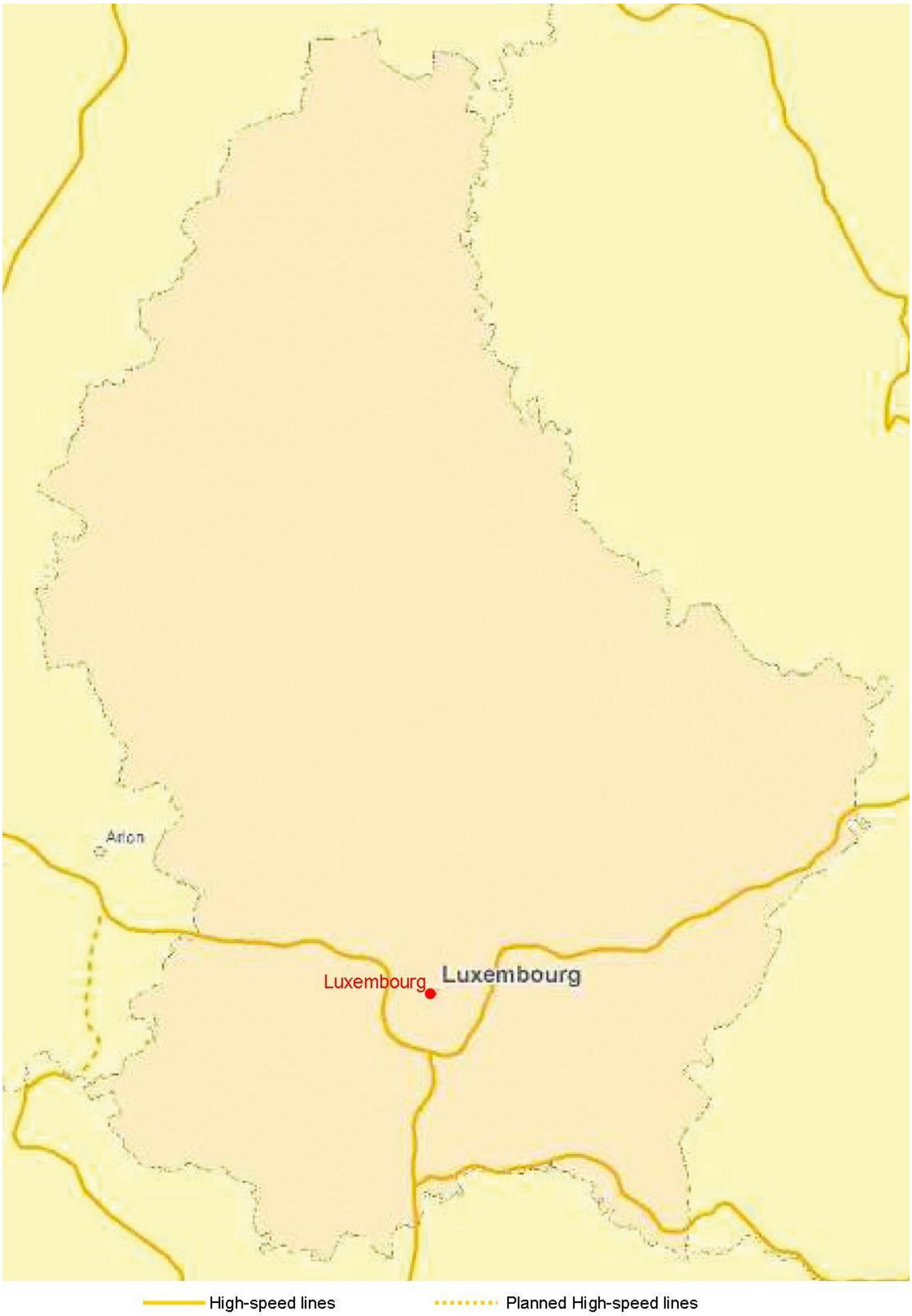
Priority axis 27:
Kalviai - Kaunas - Bialystok (Poland).

Map 30: Transeuropean road network in Lithuania.

Map 31: Transeuropean rail network in Luxembourg.

Priority axis 4:
Luxembourg - Metz (France).
Priority axis 28:
Arlon - Luxembourg - Braudecourt (France).

Map 32: Transeuropean road network in Luxembourg.



Map 33: Transeuropean rail network in Netherlands.

Priority axis 2:
Amsterdam - Rotterdam - Antwerp.
Priority axis 5:
Europort - Emmerich.
Priority axis 24:
Amsterdam - Rotterdam - Emmerich;
Budel-Schoot - Rheidt.

Map 34: Transeuropean road network in Netherlands.

Map 35: Transeuropean rail network in Poland.

Priority axis 23:
Gdansk - Warszawa - Katowice - Bielski - Ostrava;
Bielski - Zilina.
Priority 27:
Kaunas (Lithuania) - Bialystoko - Warszawa.

Map 36: Transeuropean road network in Poland.

High-speed lines   Planned High-speed lines

Priority axis 25:
Gdansk - Lodz - Sosnowiec - Bielsko-Biala.

Map 37: Transeuropean rail network in Portugal.

Priority axis 3:
Salamanca - Aveiro;
Porto - Aveiro - Lisboa;
Badajoz - Évora - Poceirão - Lisboa.

Priority axis 16:
Badajoz - Évora - Sines.

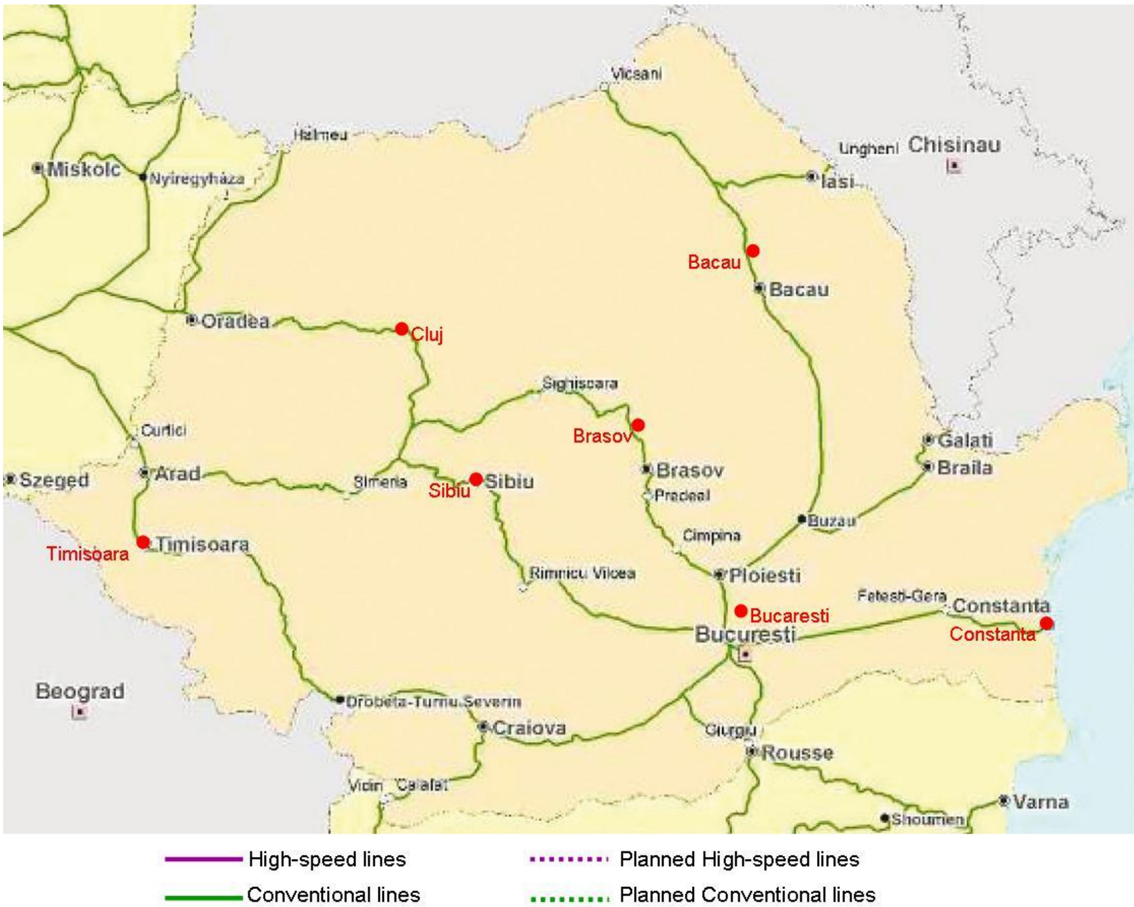
Priority axis 8:
Vigo - Valença - Porto - Aveiro - Coimbra -
- Entroncamento - Lisboa - Poceirão - Ermidas - Sines;
Ermidas - Tunes - Faro;
Guarda - Coimbra;
Guarda - Entroncamento.

Map 38: Transeuropean road network in Portugal.

Priority axis 8:

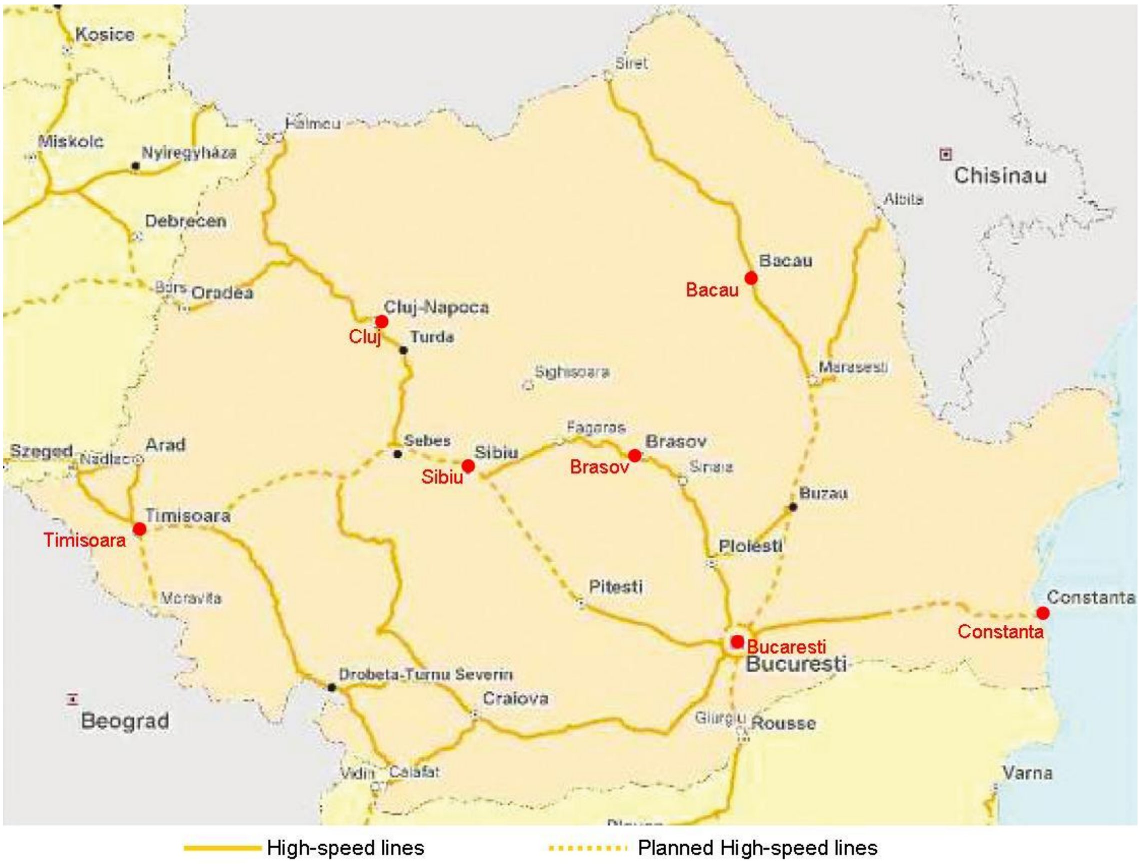
Vigo - Porto - Aveiro - Entroncamento - Vila Franca de Xira - Poceirão - Tunes - Faro;
Vila Franca de Xira - Lisboa;
Guarda - Aveiro;
Guarda - Entroncamento;
Chaves - Vila Real - Porto;
Huelva - Faro.

Map 39: Transeuropean rail network in Romania.



Priority axis 22:
Curtici - Arad - Brasov - Bucaresti - Constanta;
Arad - Timisoara - Craiova - Calafat.

Map 40: Transeuropean road network in Romania.

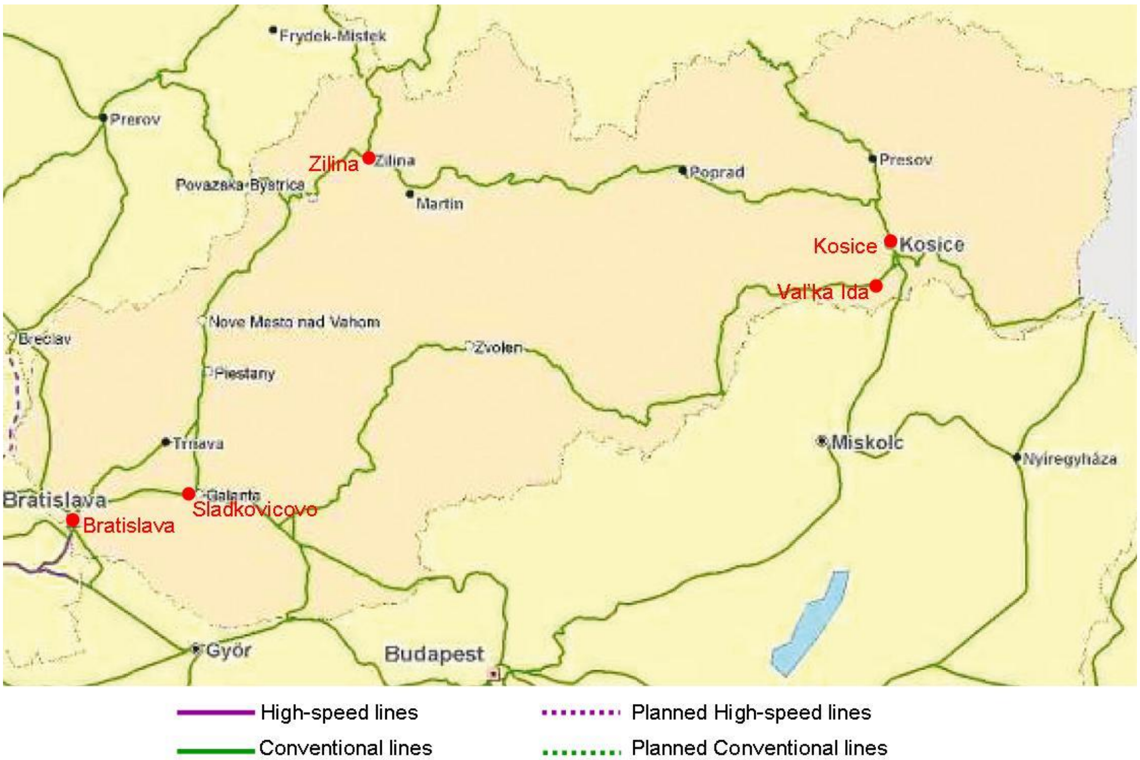


Priority axis 7:

Nadlac - Arad - Sibiu - Pitesti - Bucaresti - Constanta;

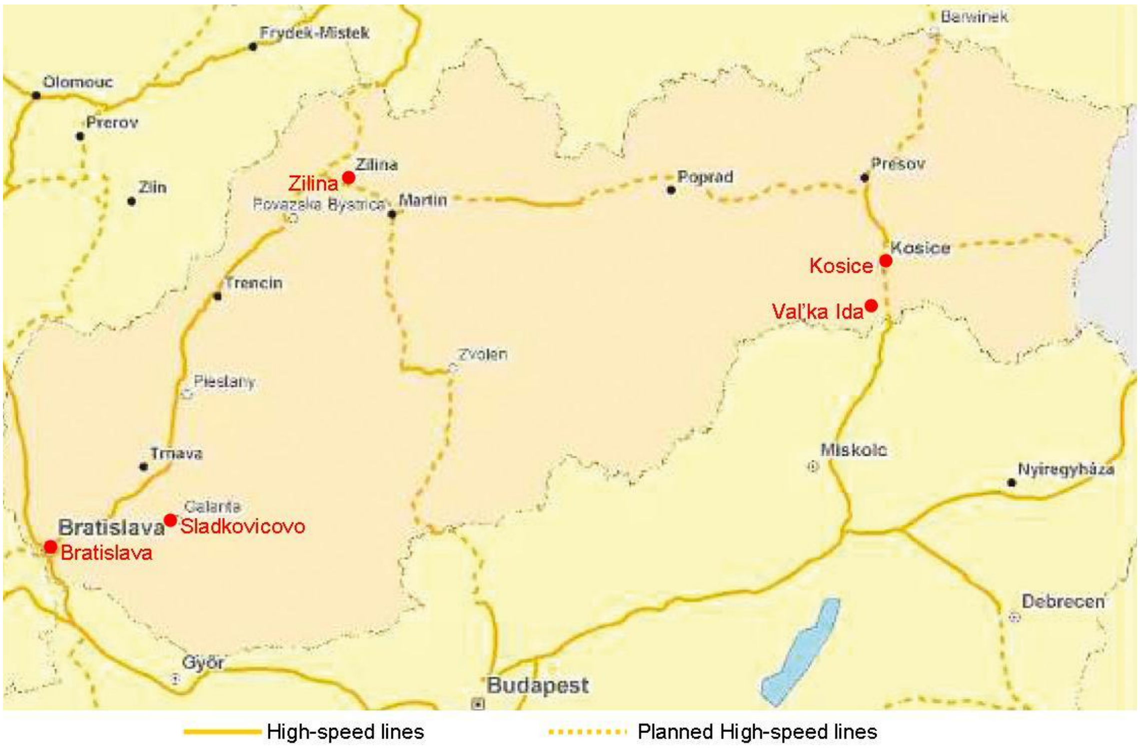
Nadlac - Timisoara - Calafat.

Map 41: Transeuropean rail network in Slovakia.



Priority axis 17:
Wien - Bratislava.
Priority axis 23:
Bielski (Poland) - Zilina - Bratislava.

Map 42: Transeuropean road network in Slovakia.



Priority axis 25:
Bielsko-Biala (Poland) - Zilina - Bratislava..

Map 43: Transeuropean rail network in Slovenia.

Priority axis 6:
Trieste - Divaca;
Koper - Divaca - Ljubjana - Pragersko - Székesfehérvár (Hungary)

Map 44: Transeuropean road network in Slovenia.

Map 45: Transeuropean rail network in Spain.

Priority axis 3:
San Sebastián - Bilbao;
San Sebastián - Vitoria - Valladolid - Madrid - Cáceres - Badajoz;
Perpignan - Barcelona - Tarragona - Zaragoza - Madrid;
Salamanca - Aveiro.

Priority axis 8:
La Coruña - Vigo;
Valladolid - Salamanca - Guarda;
Sevilla - Huelva - Faro.

Priority axis 16:
Zaragoza - Madrid - Manzanares - Ciudad Real - Badajoz;
Manzanares - Linares - Cordoba - Algeciras.

Map 46: Transeuropean road network in Spain.

Priority axis 8:
San Sebastián - Vitoria - Burgos - Valladolid - Salamanca - Guarda;
Valladolid - Chaves;
La Coruña - Vigo;
Sevilla - Huelva - Faro.

Map 47: Transeuropean rail network in Sweden.

High-speed lines — Planned High-speed lines

Conventional lines — Planned Conventional lines

Priority axis 11:
Malmo - Kobenhavn.
Priority axis 12:
Charlottenberg - Stockholm - Nassjo - Malmo - Goteborg - Skottan.

Map 48: Transeuropean road network in Sweden.

High-speed lines   Planned High-speed lines

Priority axis 11:
Malmo - Kobenhavn.
Priority axis 12:
Tocksfors - Stockholm - Jonkoping - Helsinborg - Malmo;
Svinesund - Goteborg - Helsinborg.

Map 49: Transeuropean rail network in United Kingdom.

Priority axis 2:
London - Calais.

Priority axis 9 and 26:
Larne - Belfast - Dublin.

Priority axis 14:
Glasgow - Carstairs - Crewe - Birmingham -
- Daventry - London.
Stranraer.

Priority axis 26:
Holyhead - Crewe;
Liverpool - Leeds - Kingson upon Hull;
Nuneaton - Felixstowe;
Stranraer.

Map 50: Transeuropean road network in United Kingdom.

Priority axis 13:
Larne - Belfast - Dundalk;
Stranraer - Winwick - Holyhead;
Winwick - Birmingham - Felixstowe.

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Map 51: Transeuropean rail network in Portugal, considering the line between Torre das Vargas and Caia.