

Louvain School of Management

Short Sea Shipping replacing road freight in the Baltic Region?

An analysis of the potential for a sustainable freight transport network

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Abstract

The objective of this study is twofold: firstly, it aims to develop a many-to-many freight transport model to represent the exchange of goods in the Baltic Sea region. Secondly, it will study the social, environmental, and economic impacts that would result from an incentive to switch from road to short sea shipping for the transport of goods in the Baltic Sea.

A literature review has been conducted to better understand the theory surrounding short sea shipping and freight transport modelling. A model representing the transportation network in the Baltic Sea region has been developed. By modifying parameters or the objective function, this model can simulate several scenarios with different types of incentives. The conclusions reached by reviewing the theory aids in interpreting the model's results and ultimately influences this thesis' principal question.

The key results of the thesis are as follows. The introduction of incentives is not only crucial in the task of convincing to switch parts of the goods transported by road to short sea shipping, but it has also increased the total distance travelled by the different vehicles while ensuring the same level of exchange. Economically, the investment made in the maritime sector could have positive fallouts on the European GDP, but the total costs of transport are increasing with the introduction of incentives. Environmentally, the decrease in road transportation helps to reduce the negative externalities caused by this transport mode, but the additional ton-kilometres of goods transported by short sea shipping have a negative impact on the air pollution level. Socially, the reduction of externalities linked with road transport is positive, and the investment in the maritime sector will create wealth and employment, but the total increase in cost will make the price of goods more expensive and the additional air pollution from ships is a health concern.

The results from this thesis suggest that the introduction of an incentive to shift part of the quantity transported in the Baltic Sea region from road to short sea shipping will indeed have some positive fallouts on economic, environmental, and social aspects. Therefore, it might be advisable to introduce an incentive to force the internalization of external costs which will help to reduce these externalities. On the contrary, the introduction of an incentive will also have negatives outcomes and some improvements in technology and regulations are needed further promoting this mode of transport. Neither truck transport nor short sea shipping can currently be considered a sustainable way of shifting goods.

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List of acronyms

BSR: Baltic Sea Region

CO₂: Carbon dioxide

DE: Germany

DK: Denmark

EC: Externalities costs

ECA: Emissions Control Area

EE: Estonia

EEA: European Economic Area

FI: Finland

GHG: Greenhouse gas

GTL: gas-to-liquid

HDV: Heavy Duty Vehicle

HELCOM: Helsinki Commission

HFO: Heavy fuel oil

IC: Inventory costs

IMO: International Maritime Organization

LNG: Liquefied natural gas

lo-lo: lift-on/lift-off

LT: Lithuania

LV: Latvia

MDO: Marine diesel oil

MGO: Marine gas oil

NECA: Nitrogen Emission Control Area

NO_x: Nitrogen oxide

OC: Opening costs

PL: Poland

PM: Particle matter

ro-ro: roll-on/roll-off

SCR: Selective catalytic reduction

SE: Sweden

SECA: Sulphur Emission Control Area

SO₂: Sulphur dioxide

SSS: Short Sea Shipping

TC: Transport Costs

1. Introduction

1.1 Motivation

During the last decades, the international trade activity has become increasingly easy thanks to the advanced technology reducing the constraint that represents the distance separating the different regions willing to trade together. Consequently, and with the help of some initiatives like the European single market, the total amount of goods transported grows bigger and bigger each year. Following (European Commission, n.d.-a), this increase in the demand for transportation is far from its peak and will continue to grow in a foreseeable future.

In Europe, transportation is crucial for the economy. The correlation between the level of transportation and the European GDP has already been proven. The majority of the international trade on the continent is provided by trucks. The advantages of this mode outperform the others which explains its large share in the modal split. However, transportation by trucks is not the best option regarding the environmental issues link with it. This mode is responsible for a large proportion of negative externalities like air pollution, accidents, congestion, noise pollution. All this led the transport activities to represent 5% of the European GDP and yet accounts for 24% of emissions of ozone precursors (Eurostat, 2019).

For several decades, the European Commission has promoted the multimodal solution over the unimodal in order to reduce the level of negative externalities. The aim is to shift part of the goods transported by trucks to other modes like train or ship that are considered as cleaner means of transportation. At the same time, it will reduce the congestion on the European network which also represents serious social and environmental issues. This solution is called multimodal because, in most cases, there is still a need for truck transport to provide a door-to-door service by bringing goods to/from the nearest port or station. The European Commission's objective is to shift 30 % of road freight over 300 km to other modes by 2030 and 50% by 2050 (European Environment Agency [EEA], 2018).

To reach this objective, short sea shipping is often considered as the solution. The term short sea shipping includes roughly all the domestic and international maritime transport along the coast between the Member States and their neighbours (European Community Shipowners' Associations [ECSA], 2016). For the transportation of containers and cargos on short and medium distances, short sea shipping is able to compete with the transport by truck. But for now, several features of this mode still made the still the best option and therefore, wins the highest market share thanks to its flexibility, its speed and the relatively low cost related to this mode.

To cause this shift of road freight to other modes, the European Commission develops programmes and establishes policies in order to make the multimodal solution more attractive. These efforts were joined by national initiatives. All this reflexion about which decisions must be taken in order to reach the objective results into a need for tools to assess the network and its modification resulting from a new programme, regulation, investment, or policy. The use of operation research is a good way to develop such a tool. Developing as close as possible to the reality models can help decision makers asses the effectiveness of what they are looking to implement.

1.2 Research question

The objectives of the thesis are to explore the literature for what has been written over the subject, the freight transportation network in Europe, the use of short sea shipping to compete with road transport, the international trade in the Baltic Sea Region (BSR), and the utilisation of freight transport model to analyse these exchanges. The aim of all this is to develop a many-to-many freight transport model with the region surrounding the Baltic Sea. The purpose of this paper is twofold. Firstly, it is to provide a model to enlarge the set of solutions brought to respond to the need for tools to analyse the transportation network and bring help in the process of decision making. Secondly, it aims to give an answer to the following research question.

Would an implementation of incentives for the shift from road to short sea shipping for the transport of goods in the Baltic Sea have positive social, environmental, and economic impacts?

This issue will be approached with the help of the exploration of the literature and with the many-to-many freight transport model. The study will only consider the BSR, but the results aim at being usable for other sea regions in Europe. Several scenarios will be introduced and used in order to analyse the consequences of one or several modifications in the European transportation network. These scenarios will help answer the research question but also the following sub questions.

Which measure will be the most helpful regarding the objectives set by the European Commission on the modal shift level by 2030 and by 2050?

Which type of incentive can reach the desired objectives while remaining fair for every stakeholder of the transportation network?

1.3 Limitations

This paper has some important limitations that may negatively impact the results of this thesis and therefore must be acknowledged before going further. These limitations are related to the three following issues: the data retrieval method, the lack of documentation, and the scope of the discussion.

The construction of a model comes with a need for inputs and consequently for data. To come as close as possible to the reality of the transportation network, real life data were used. Several issues appear in this data retrieval process. Most of them were secondhanded and came from a large panel of different papers. Moreover, some data coming from national statistic websites were subject to modifications before being utilized as inputs for the model. This may have led to some biases in the results.

While the interest in alternatives to road transport for the European freight exchange is a growing focus in literature, it still remains rather novel. Several papers contradict each other in their conclusions and thus, some of the issues addressed in this paper are not subject to a unanimous opinion in the literature. Additionally, the development of freight transport models is also a relatively new subject - some parts of the transportation network are not documented well enough and therefore prevent the modelling from being entirely accurate.

Lastly, my personal experience in conducting research and writing academic papers of this size might have compromised this paper on many levels regarding the depth and the scope of discussion.

1.4. Outline

Chapter 1 addressed the motivations for writing this thesis and the objectives of it. It introduces the research question as well as the different limitations on the paper. *Chapter 2* provides a summary of the current state of short sea shipping literature. It also reviews the theory regarding truck transportation, the different fuels used in the maritime sector, and the freight transport in the BSR. *Chapter 3* proposes the construction of a model to represent the freight transport network in the Baltic Sea, including the theory behind it and how it is applied within this thesis. *Chapter 4* provides information on how the model has been constructed. It explains its establishment and the extension created for the two scenarios. *Chapter 5* shows the different results used as inputs for the model. *Chapter 6* presents the results issued from the model and its scenarios. *Chapter 7* briefly discusses these results and attempts to construct answers for the research questions and sub-questions. *Chapter 8* concludes this thesis by suggesting recommendations, highlighting the contribution of this thesis within literature and acknowledging the

potential impacts of the limitations over the presented results. Finally, *chapter 9* consists of the references used throughout this thesis.

2. Literature Review

This chapter is a review of what has been said in the literature about the European freight transport and short sea shipping (SSS). Its role is to help gain a better understanding of the role of SSS inside the European network. This review will help identify the different issues linked to the transportation of goods and will highlight the different areas the model must explore.

The literature review is separated in 6 sections. It will start with a brief introduction of the actual goods repartition on the two different modes chosen for the model creation. Then, it will approach the strengths and weaknesses of SSS. Next, it will present the maritime transport regarding the three pillars of sustainability. The fourth section will address the different incentives set in place for the utilisation of the maritime transport but also the regulations this mode is subjected to, as for the road transportation. Then, a section will be dedicated to the presentation of the fuels used for the different operations. Finally, the last section will focus on the freight transport in BSR and the regulations specific to this area.

2.1 Introduction

This first section is about introducing the European freight transport network. To do so, the first subsection presents the different possibilities to shift goods on the continent, the second is about transportation by road, and the last addresses transportation by sea. Only these two modes will be kept for the construction of the model.

2.1.1 Modal Split

Europe offers a lot of different possibilities for the transportation of goods. Three surfaces are used for freight transport – land (road, rail and pipelines), water (inland waterways, SSS) and air. Each mode has its own characteristics, with strengths and weaknesses, and they require some specific infrastructures. These modes can compete or, in the case of intermodality, they can complement each other. That is often the case for rail and maritime transport, as both start from a terminal and most of the time need another mode to carry the goods during the beginning and the end of the total journey (Rodrigue, Comptois, & Slack, 2017).

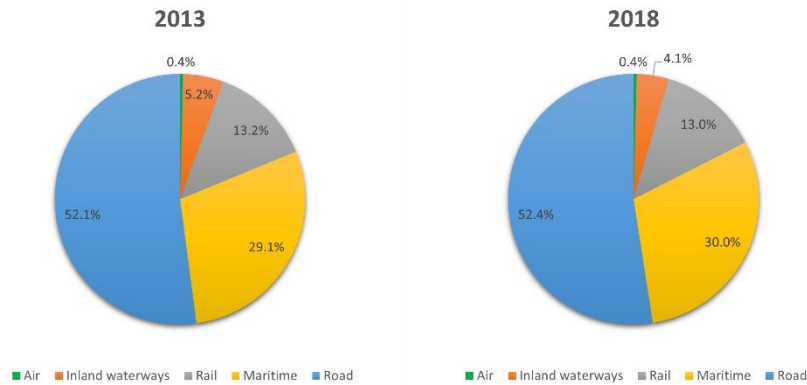


Figure 1: Modal split of freight transport in EU-27 in 2013 and 2018 (% share in ton-kilometres). Source: (Eurostat, 2021-c)

The modal split for intra-European transportation is given in *figure 1*. Road owns the biggest market share with 52.4% of the total tonne-kilometres of goods transported, this figure is steady over the years as it has increased by only 0.3% between 2013 and 2018. Road transport is followed by maritime transport with 30.0% in 2018, and rail transport has 13% of the market. From 2013 to 2018, freight transport increased by 12%, which was equally split between the five modes except inland waterways, it explains the steadiness of the figures and the decrease in market share of the latest (Eurostat, 2021-c).

2.1.2 Transportation by Road

This mode is the most accessible thanks to the large network existing in Europe and the low level of physical constraints needed to operate. Trucks are often chosen over the other modes on short and medium distance for their flexibility as they can carry almost every type of merchandise, their low price, and their rapidity. However, the economies of scale are small with this mode as there are several constraints limiting the weight and the length of vehicles enforced by governments and also because of the limit derived from the engine (Rodrigue et al., 2017).

Transportation by road is accompanied by several negative externalities – air pollution, global warming, noise pollution, accidents, and congestion. There are a lot of regulations forcing new trucks to conform to standards and consequently lower the air emissions. However, a large split of the external cost resulting from all the negative externalities cited above is not internalized and therefore, is not supported by the trucking industry (Santos & Soares, 2017).

In Europe, congestion on the road network has increased for three decades and it will continue to do so in the future. With this congestion come some logistics issues, costs and externalities. It is estimated

than 10% of the European road network suffers daily from traffic jam (Medda & Trujillo, 2010). This is estimated to cost €100 billion, which corresponds to 1% of the European GDP (European Commission, n.d.-a). Moreover, it is assumed that congestion makes every other externality linked with road transport even stronger and acts as a multiplier on the other external cost like noise pollution, accidents, infrastructure usage, air pollution or climate change (Medda & Trujillo, 2010).

2.1.3 Transportation by Sea

This mode of transport is largely dominant on long distances where there is no relevant alternative. On medium distances, sea transport competes with land-based modes as long as there is an access to maritime infrastructures in the area. Despite this competition, maritime transport also needs other modes to bring the freight to the gateway and deliver it to the destination. Maritime transport must operate with intermodality to provide a door-to-door service (Rodrigue et al., 2017).

In the maritime sector, Europe recognises SSS as a relevant alternative to road-based transport. This mode of transport serves intra-European trade and exchange with Europe's neighbours; it owns a large panel of strengths and weaknesses presented in the next section. SSS utilization helps creating synergies between modes via multimodality, permitting economies of scale, reducing congestion on the European network and therefore, reducing the external costs. This mode of transport proposes a very large capacity; it is possible to shift an important part of goods transported from the road to the sea, due to the unused space. It is widely recognized as a mode which has not reached its full potential yet (ECSA, 2016).

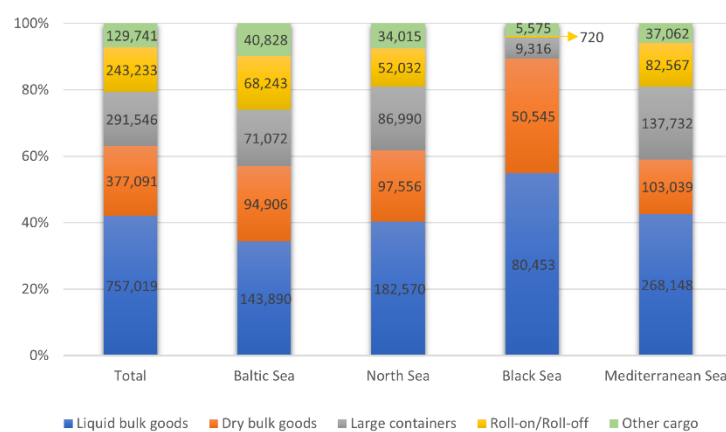


Figure 2: Gross weight of goods transported to/from main ports, by type of cargo for each sea region (2019). Source: (Eurostat, 2021-g)

The term short sea shipping encompasses different types of vessels with their own characteristics – length, size, type of merchandise transported, operating speed, average deadweight tons, etc. (Rodrigue et al., 2017). The main vessel types are the general cargo ships, the bulk carriers, the container ship also called Lift-on/Lift-off (lo-lo), and the Roll-on/Roll-off (ro-ro) ships. The repartition by the type of vessel of the goods transported through SSS in 2019 is given in *figure 2*.

General cargo ship is the most represented type of vessel on the Baltic Sea, but they are rather small in comparison with other vessels. They have a 6990 average gross tonnage. They transport general, bulk, and other cargo. Most of their trip is between a Baltic Sea country and another outside of the region. Consequently, the share of the total number of port visits compare to other vessel is rather small despite the large number of general cargo ships in the fleet. (HELCOM, 2018)

The second main type of vessel is the bulk carrier, also called tanker. These vessels are designed to transport liquid and dry bulk cargos. They have a large average gross tonnage of 25 500 GT (HELCOM, 2018). They typically transport unpacked dry and liquid bulk like mineral oil product, chemicals, liquefied petroleum gas, coal, iron ore, grain, etc. (Paixão & Marlow, 2002). The nature of the products transported allows these vessels to operate at low speed and with a high loading factor. Consequently, these vessel's emissions to air are very low. Bulk carriers do not suffer from competition, they represent the most economic and environmentally friendly alternative (Rodrigue et al., 2017).

Lift-on/Lift-off (lo-lo) are designed for the transport of containers. These ships are in competition with land-based transport on long-distance. They can operate only in ports where the infrastructures allow it, and the handling of cargo must be efficient in order to reduce the dwell time (Medda & Trujillo, 2010). This category also includes feeder vessels, which are small ships carrying containers from different ports to large container terminals providing a link for deep sea shipping. This kind of vessels is also engaged in SSS operations all over Europe by operating in Baltic Sea, Mediterranean Sea, English Channel and Atlantic coast (Paixão & Marlow, 2002). In the Baltic Sea, the average gross tonnage of this type of vessel is about 36 100 GT (HELCOM, 2018).

The last kind of vessels is the roll-on/roll-off (ro-ro) cargo. These vessels are designed to load on board directly the vehicles carrying the cargo. They compete with local alternatives on near sea and short sea distances. As the vehicles go directly on the vessels through a ramp, it has the big advantage of short loading and unloading times, which reduces a lot the total transit time. These types of vessels are optimal

to combined road and sea transport in an efficient way and therefore, are often considered as the optimal vessels to make SSS a true competitor to road transport on small and medium distances (Santos & Soares, 2017).

2.2 Strengths and Weaknesses of Short Sea Shipping

The literature is not always unanimous concerning the use of SSS. Ones describe it as the perfect alternative to transport efficiently goods in a greener way, others are expressing doubts about this green label awarded to SSS. As all other modes, it has its own strengths and weaknesses. Those are consecutively presented in the two following subsections.

2.2.1. Strengths

The potential of SSS to receive additional demand is enormous. Geographically, SSS has an important advantage over the other modes. With a coastline of 67,000 km, a large inland waterways network, between 60% and 70% of the industry located within 150-200 km of the coast (Paixão & Marlow, 2002), and 40.8% of the European population living in a coastal region (Eurostat, 2017). The potential market is huge and the road and rail networks, despite the competition between them, help increase it.

The carrying capacity of this mode is unbounded. Thanks to the unlimited capacity of the sea, SSS can carry as many additional tonnages as possible. Moreover, navigation on sea is not constraint; vessels can use the ocean twenty-four hours a day, seven days a week during the whole year (Paixão & Marlow, 2007). Trucking industry does not enjoy this. According to the country trucks are operating in, driving during the weekend, the night or the holidays is not always authorised. This and other legislative pressures decrease the attractiveness of road transport (Santos & Soares, 2017).

This mode of transport is presented as environmental friendlier than the traditional freight transport by truck. When a vessel sails with a sufficient loading factor, the level of emissions produced by the trip is considered lower regarding the emissions by tonne of good (Paixão & Marlow, 2002). But not everyone agrees with this statement, and consider that most of the time SSS, when speaking about ro-ro vessel, does not deserve this green image (Harlad & Fridell, 2012; Hjelle, 2011). Additionally, a shift from road to sea will decrease the congestion on the European road network and will also benefit the environment, as it will decrease the negative externalities related to road transport such as global warming, noise pollution and accidents.

From an economic point of view, shipping has advantages on several points. The high capacity of cargo allows economy of scale and therefore lower freight cost. Investments or maintenance costs are low compared to the ones linked to road or rail transport. The service expansion requires few land-areas; in comparison, to increase road or rail network, there is a need for space and a lot of costs related to the construction of the road surface or the new tracks. Additionally, there is also the cost for the infrastructures like tunnel or bridge and all the expenditure for their maintenance. The shipping industry only needs ports as land area to operate (Paixão & Marlow, 2002).

SSS takes advantage from the promotion conducted by Europe to increase its market share. EU is willing to decrease the congestion of its road network and shift the freight transport from road to sea. The different measures helping to move in this direction are presented further in the paper (cf. section 2.4).

2.2.2 Weaknesses

The very nature of maritime transport prevents this mode, in most cases, to ensure a door-to-door service. Only the bulk carriers are often able to directly make the delivery to a terminal. SSS is part of a broken chain; it constitutes a big disadvantage in the eyes of the client. The use of SSS requires the help of road and/or rail transport to take in charge the start and the end of the total journey (Kuhnimhof et al., 2012). Shipper facing a choice between unimodal or intermodal transport will usually choose the first one and avoid additional inventory cost linked to a longer trip. Studies shown than shippers would shift to the intermodal choice if the saving was big. The inventory cost due to the longer trip with an intermodal transport solution can be covered if the transportation cost for ship is 35% less than the one for road transport (Paixão & Marlow, 2002).

Ro-ro shipping, the most relevant alternative for intra-European transports, suffers from problems related to total transit time. This mode cannot provide as many departures as land-based transport. The ship's volume provides economies of scale but the small and numerous vehicles trucking industry owns is good for economy of scope. This lack of flexibility in departures causes non-added value action like double-handling or additional storage resulting in unnecessary costs (Paixão & Marlow, 2002). The operating speed on sea also constitutes a problem. When the speed is doubled, the fuel consumption is quadrupled. This relation between speed and environmental performance forces ro-ro ships to limit the timeliness of its operations (Hjelle, 2011). In SSS, a lot of complex and repetitive procedures are required to make freights transit from one location to another. This represents a disadvantage for the shipping industry since such amount of paperwork is not demanded for road transportation. For the same origin-destination transit, SSS needs documentation on navigation control, ship safety, cargo

declaration, etc. But if the same cargo is transported by truck, it only requires a CMR letter which represents a proof of the contract of carriage by road. To improve the competitiveness of SSS, goods carried by ship should be treated in the same way as goods carried by road (ECSA, 2016 ; Paixão & Marlow, 2002). Some of the ships used in SSS rely on ports infrastructures for the loading and unloading. Consequently, efficiency of ports to carry out these operations will have a great influence on the dwell time. An inefficient service inside the port will increase the transit time, the cost of handling goods and the unreliability of the maritime-based mode. This statement gives a clear idea of why the ro-ro ship is put under the highlight when speaking about a concrete alternative to road transport, its short time to load and unload the vessel and the low need in terminal space to do it being a real advantage for this type of ship (Medda & Trujillo, 2010).

The other issue is the loading during a journey. Thanks to economy of scale, a fully loaded vessel will minimize the energy used. The capacity utilization rate is an important factor to estimate the real consumption of a vessel, and this rate varies a lot depending on the type of vessel used. The bulk carriers are often loaded at full capacity thanks to the nature of the product transported. This is not the case for ro-ro and container ships. In SSS, these vessels have difficulties to working with a full capacity; this can be due to the low and inconstant demand. A lack of cargo density can conduct to a multi-port call approach, but this type of operations increases the transit time and works with an inefficient average loading factor (Hjelle, 2014). Moreover, the ro-ro ships suffer from the double load problem. Under normal operations, only a fraction of the available space will be occupied by trailers and those trailers are themselves not always loaded, as a lot of them have to return empty. When on average, half of the ro-ro vessel is loaded and among the trucks loaded only half is fully loaded, it gives a relevant loading factor of 25% (Hjelle, 2011). SSS with ro-ro operations between regions with small traffic is not competitive. SSS needs a high concentration of cargo to act as a true competitor to road transport (Kuhnimhof et al., 2012).

2.3 Sustainability

In order to study the research question, it's important to know the characteristics of maritime transport regarding the three pillars of sustainability. This section will introduce the economic aspects of freight transportation as well as the environmental aspects and finally, the social aspects.

2.3.1 Economic

Transportation is a pillar of each economy. It helps for the development of society by improving the human capital (income, health, education) or the physical capital (infrastructures, utilities, transport).

There is a clear relationship between level of transportation and economic development. In the developed countries, transportation accounts for 6 – 12% of the GDP. Transport development regardless of the mode, improves intermodality and lower the transportation cost. The constraint of distance decreases with each improvement in the sector; goods are conveyed with a smaller delay and in a more reliable way. Access to different market is more and more facilitated by the developed means of transportation. It triggers several opportunities like the possibility to have economy of scale, more choice in the raw materials, a cheaper workforce or produce more outputs (Rodrigue et al., 2017).

SSS makes no exception and also contributes a lot to economic development in Europe and increases its economic competitiveness (Kuhnimhof et al., 2012). When €1 million is invested by the shipping industry directly in the European GDP, €1.6 million is created elsewhere on the continent. Additionally, most of the ships destined for SSS operations are built in Europe and contribute to the economy (ECSA, 2016).

2.3.2 Environment

Sea transport also contributes to global warming through the large air emissions this sector is accountable for. In 2015 in Europe, 13% of the greenhouse gas (GHG) emissions were caused by transportation on sea (European Commission, n.d.-b). Among all the pollutions emitted, the main ones are emissions of carbon dioxide (CO₂), sulphur dioxide (SO₂), nitrogen oxide (NO_x) and particle matter (PM). In the literature, figures related to these emissions are usually expressed as a mass of emitted substances per amount of goods transport and distance (g/tonne-km). These emissions are often considered with respect to their scale of impact, which can be global, regional, or local. At the global level, all the GHG at the origin of the global warming is considered. For the regional level, the major issues are related to emissions of NO_x and SO₂. They participate in acidification and are therefore harmful for the environment, human and animal health. On a local perspective, the major issues are a consequence of poor air quality (Hjelle, 2014).

The maritime sector is accountable for the bad air quality related to the diverse emissions to air due to the vessels and the ports during operations and all the essentials' activities to run the operations smoothly (Mohesni, van Hassel, Sys, & Vanelslander, 2019). The emission of sulphur can result in acid rain, which are harmful for the crops, forests, aquatic species and contribute to the acidification of the ocean (International Maritime Organization [IMO], 2019). The quality of water is also impacted by the oil spilt inside the sea (Rodrigue et al., 2017).

However, the utilization of sea transport rather than land-based alternatives reduces the number of trucks on the road network as well as the congestion they are partly responsible for. Consequently, it alleviates some negative externalities – noise pollution, number of accidents and the cost of wear and tear (Vierth, Sowa, & Cullinane, 2019). It also reduces the pollution due to land take. Transport by sea is not a big consumer of land space as it, roughly, only requires ports infrastructures for their operations (Rodrigue et al., 2017).

2.3.3 Social

As far as the social dimension is concerned, the shipping industry has some positive impacts. This mode of transport is still developing as large capacities are still available on sea. This expansion creates a lot of employment, either directly with the operations inside the infrastructures or the shipping itself, or indirectly with all the auxiliary activities necessary for the shipping industry (Galati et al., 2016). SSS helping relieving congestion on the European road network, it results in a reduction of the negative externalities impacts linked with road transport (Medda & Trujillo, 2010). Moreover, transportation in general, gives an access to goods and services for as many people as possible (Rodrigue et al., 2017).

Despite all those benefits, SSS also contributes to several negative externalities. The most severe one is air pollution (Medda & Trujillo, 2010). Due to emission of SO₂, NO_x and PM, the maritime sector is a large contributor of air emissions and all related problems. Emissions of SO₂ and NO_x contribute to the acidification of ocean and the development of acid rains, which cause lots of health issues (Hjelle, 2014). The shipping sector significantly decreases the quality of air and is, according to recent studies, accountable for 400,000 premature deaths a year worldwide (Transport & environment, 2021). Infrastructures like ports situated near cities contribute locally to a high level of air pollution and possible noise pollution (Hjelle, 2014).

2.4 Incentives and regulations

At the end of the 20th century, the European Union began to promote intermodality and SSS as a competitive and sustainable alternative to road transport. The main objective was to reduce the environmental damage connected with the current transportation model in Europe. This promotion had been realised for three decades with several programs presented in the following section (Suarez-Alemán, 2016). Through the years and thanks to the numerous studies over the subject, SSS has appeared not as sustainable as initially presented. It has been shown that shipping is in fact a large contributor of NO_x and SO₂ emissions. Consequently, since 2006, European commission had to slow down their promotion by implementing new regulations to introduce some constraints on the level of emissions linked with maritime

transport (Mohseni et al., 2019). Transport by sea is not the only one being restraint by regulations, the trucking industry has also its own set of constraints. Transport by truck is subject to fees, tariffs, measures, and policies (Santos & Soares, 2017). All these incentives and regulations are presented in this section.

2.4.1 Incentives for the Maritime Sector

In 1992 the Pilot Action for Combined Transport (PACT) programme was launched to encourage intermodality. The aim was to give incentive to use intermodal transport rather than unimodal transport by road and minimize the total length covered by truck to complete the door-to-door service. During the whole programme, 167 projects were funded, each of them were cost effective and environment friendly (Suarez-Alemán, 2016).

In 1996, the European Union developed the Trans-European Networks which englobes the TEN-T programme. The aim was to promote intra-European exchange by improving long-distance communication and the basic infrastructures useful for the exchange of goods, persons and information considering the expected growth in the future (Suarez-Alemán, 2016). The TEN-T projects exists to improve the capacity of the bottleneck present on the European network and develop intermodality. The European Commission gives the following definition: "The TEN-T programme consists of hundreds of projects – defined as studies or works – whose ultimate purpose is to ensure the cohesion, interconnection and interoperability of the trans-European transport network, as well as access to it." (European Commission, 2015). Initially, the focus was on road and rail network development, but the integration of ports inside the TEN-T and the development of the project called "Motorway of the Sea" modifies this situation and gives opportunities to SSS development (Paixão & Marlow, 2007).

In 2003, the Marco Polo I programme was launched aiming to extend the view of the PACT. The program was implemented in two stages, the second begin in 2007 with Marco Polo II. The aim was to shift the growth in demand for freight transport from road to alternative modes such as rail or SSS (Suarez-Alemán, 2016). The European Commission targeted a 20 billion ton-km shift per year, which represents 700 000 trucks on a 1000 km journey removed from the road. Such a shift would imply some societal and environmental benefits (Eurostat, 2020). To do so they launched 125 projects involving more than 500 companies, each project making an economic and ecologic sense. The projects were multiple, some addressed directly the issue of modal shift and traffic avoidance, others aimed to provide supporting services.

Some regional initiatives may also be highlighted like the Italian eco-bonus, which is a rebate on the freight cost given by the Italian government to the companies using SSS rather than road transport. This program was established in 2007. The Italian government used a 3-years budget of €240 million. Another example of regional initiatives can be demonstrated with the Basque country and the *Ecobono*. In order to promote the utilisation of SSS, a refund of 15-30% of the freight cost was given to companies registered in the region and using a motorway of the sea between Belgium and Spain. In 2012, France also created an incentive to shift the freight from road to non-road modes by taxing the road haulers but was forced to remove this tax two years later after receiving some pressure from the trucking industry (Suarez-Alemán, 2016).

2.4.2 Motorways of the Sea

To improve the competitiveness of SSS, European Commission tries to promote a project called Motorways of the Sea (MoS). Its aim is to imitate the rail and road network on the water and develop intermodality based on maritime transport. Following Baindur & Viegas (2012), MoS can be understood as: "a high frequency, regular door-to-door intermodal services where the main haulage is done by SSS and last mile connectivity by road transport. These services would link ports and markets located in at least 2 European Member States." EU funds the development of this project through their programmes. With Marco Polo I, Marco Polo II and Ten-T project, Europe helps the development of intermodality with 1,152 million of euros (Baindur & Viegas, 2012).

To be efficient economically and environmentally and to play as a real concurrent towards the land-based transport, motorways of the sea need some improvements. The policy from one country to another need to be smoothened to avoid unnecessary procedures. SSS operations are too fragmented, there is a need for harmonisation. Ports should strive to reduce the time a ship spend inside their infrastructures. With less time idle, the vessels would be able to decrease their operating speed and improve their environmental performance without increasing the total time of the journey. In short, the motorways of the sea project need collaboration between the different stakeholders to increase its competitiveness and improve its environmental performance (Paixão & Marlow, 2007).

2.4.3 Maritime Freight Sector Regulations

The major regulations for the shipping industry are related to Annex VI of the MARPOL protocol. It was first adopted in 1997 to limit the air pollutant during the fuel combustion and then revised in 2005 to be strengthened. These regulations are developed by the International Maritime Organization (IMO), Annex VI of MARPOL defines areas in which stricter regulations and control exist to minimize the

emissions to air from ships. These zones are called Emissions Control Areas (ECA's) and exist all over the world. In Europe, the North Sea, the English Channel, and the Baltic Sea are under these regulations. (Mohseni et al., 2019). ECA's will help controlling and constraining emissions of SO₂, NO_x and PM with a progressive reduction. The first step was a limit of 3.5% sulphur in the fuel oil used by the vessels and was reduced to 0.5% the first January 2020 for the ship operating outside the ECA's. The regulation is even stricter for the ECA's zone where the emissions of sulphur cannot exceed 0.1% (Eurostat, 2021-g). The operators can comply to these regulations by low-sulphur fuel or with technologies to remove the sulphur created during combustion (Vierth et al., 2019).

As for the reduction of NO_x emissions, the IMO creates several regulations called "Tier". Tier 0, 1, 2 and nowadays Tier 3 are requirements that the engine of a ship built after a specific date must meet (Vierth et al., 2019). The IMO Tier 3 NO_x regulation applies for all vessels build after 2021 and operating in Nitrogen Emission Control Area (NECA's). In Europe three zones are concerned: the North Sea, the Baltic Sea and the English Channel. The ships affected by this Tier 3 regulation can emit a maximum of 2-3.4 g of NO_x /kWh (Transport & environment, 2021).

2.4.4 Road Freight Transport Regulations

As already mentioned, the trucking industry is also subject to regulations. A truck must legally meet several constraints on the engine type and the fuel used. The trucker is also under lot of regulations. Through the years, truck emissions have been successively constraint by the Euro-standard regulations. The trucking industry was forced to follow a continuous improvement in its environmental performance. Nowadays, new vehicles allow for a very low emissions level (cf. figure 3). The fuel efficiency used by the Heavy Goods Vehicle (HGV) had been improved too, but this improvement is less impressive than the one concerning emission to air (Hjelle, 2011).

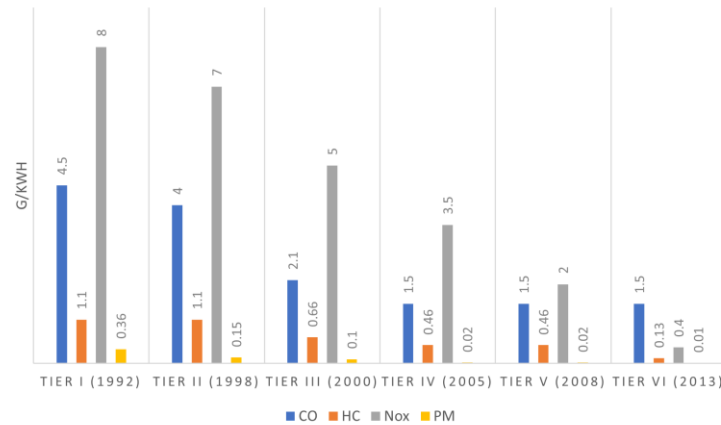


Figure 3: EU emission standards for HDV diesel engines. Source: (TransportPolicy, 2018).

Measures adding constraint on transportation by road are numerous and diverse. The number of driving hours a truck performs during a day is highly regulated. Moreover, from one country to another, circulation is sometimes forbidden during the night, the weekend, or the holidays. Trucks are sometimes not allowed on specific roads because there is an alternative motorway in the region or because it reduces the congestion on this section (Santos & Soares, 2017).

There are also tariffs and fees to internalize part of the costs related to negative externalities. Some countries charge foreign truck with a special tariff to make them contribute to the maintenance of the road network (Santos & Soares, 2017). The eurovignette, a tax for road freight transportation, also contribute to the internalization of external cost on the user or the infrastructure (Morales-Fusco, Sauri, & Lago, 2012).

2.4.5 Effectiveness of the promotion led by the European Commission

As presented in subsection 2.1.1, even with all these incentives and regulations, the modal split remains quite similar through the years. There are many reasons explaining the difficulties encountered by the shipping industry to gain market share in the transport industry. The efforts to make SSS a real alternative to road-based transport are sometimes killed by other national or European initiatives. It sends a mixed signal decreasing the attractiveness of SSS in the eyes of shareholders. There is a need for a harmonisation of all the policies developed on the European and the national levels (Baindur & Viegas, 2012).

One issue is the unfairness in infrastructure investments. Public investments on the road network or in necessary infrastructures are not fully supported by the end users. This is not the case for the shipping industry. The acquisitions of new assets (ships), the construction of new infrastructures are supported fully by the shipper and will cascade down to the end users through an increase in transportation costs (Santos & Soares, 2017).

Another reason to explain the steadiness in the modal split is the unexpected distribution of European investments between the different modes and the measures taken that decrease the attractiveness of SSS. While European commission was promoting a more sustainable transport model, most of the investments in transport infrastructure was made on the road network (cf. figure 4). Furthermore, the total amount of money invested in the road network increases between 2001 and 2008. The expansion of the road network has just increased the total demand in freight transport by road. Therefore, the congestion wasn't solved but just moved from one place to another, which explains the decline in the total investments since 2009 (EEA, 2018).

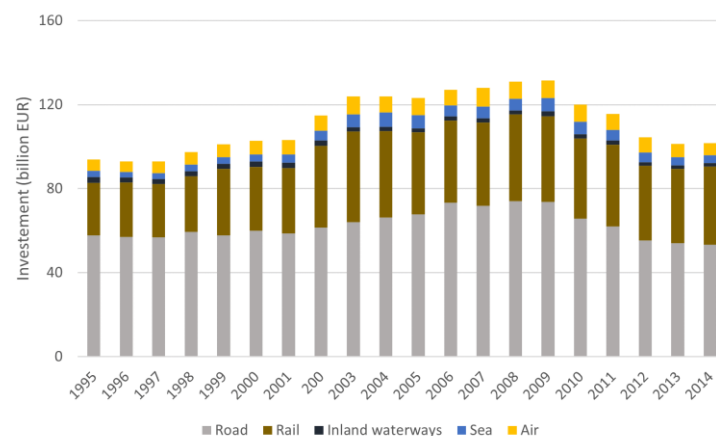


Figure 4: Investment in transport infrastructure in EEA-33 (from 1995 to 2014). Source: (EEA, 2018)

Additional examples of measures making SSS unattractive are the following. Transportation by road inside Europe is fully liberalised thanks to the European single market but this facilitation was not transferred to the ship industry, where a lot of report and inspection still remain in European ports. Another example is the European environmental policy Birds Habitats and Water Directives which limits the expansion of port infrastructures (Baindur & Viegas, 2012).

2.5 Fuel Emission

The fuel consumption of a ship is determined mainly by its size, type, speed, and load. The emissions caused by a vessel are influenced by its fuel consumption, the type of engine, the presence of abatements technology and the fuel type (Kabashkin, 2012). The figures for emissions of CO₂ will follow the fuel efficiency and can be found if the fuel consumption of the vessel is known. As the emissions of SO₂ increase with the quantity of sulphur present in the fuel, the quantity emitted can also be known with the fuel consumption. NO_x is developed inside the engine; the level of emission will depend on the engine type and the presence of a NO_x after treatment system. The term PM includes a lot of different particles with a rate relying on the engine type, the fuel quality and the after-treatment systems (Harlad & Fridell, 2012). This section will first address the issues related to the fuel used in SSS, then present the different options available for the carrier in order to comply with the regulations.

2.5.1 Issues with fuel used in Short Sea Shipping

In the literature, maritime transport is seen as the best transport solution regarding the CO₂ emission and is promoted as the solution to reach a sustainable transport model in Europe. This statement is true when considering the energy consumed per deadweight tonne (Harlad & Fridell, 2012). With this type of calculation, the figures obtained will show that maritime transport performs 10 or 20 times better than road transport. In fact, not all types of vessels are able to reach their deadweight tonnage, these are typically figures corresponding to the real performance of a bulk vessel and it explains the low competition between modes when cargos are liquid or dry bulk products. On the opposite, the container market, represented by the ro-ro and lo-lo vessels has very different environmental performance results due to the low loading rate of the vessels and reach figures similar to the other modes of transport. Three reasons explain this low performance for the container market. Firstly, the payload capacity compared to the size of the vessels is lower than the one of the bulk vessels. Secondly, the vessels dedicated to container transportation operate with a higher speed, less environment friendly, than the bulk vessels. Thirdly, the load factor is in average lower with container than with bulk products due to low cargo density, multiple port call approach or double-loading problem (Harlad & Fridell, 2012).

The European Commission promoting for SSS, invests a lot of money to increase its market share. However, the various policies implemented to promote this mode of transport led to an increase in air pollution (Serrano, González-Cancelas, & Soler-Flores, 2018). Shipping industry was far less constraint than the trucking industry for the use of fuels. Therefore, CO₂ emissions were quite similar between the two modes but with regard to other emissions like SO₂, NO_x and PM, shipping industry had higher results (Harlad & Fridell, 2012). It led the IMO to address this issue with stronger regulations on the

ECA's in order to decrease the various emissions caused by the different vessels (IMO, 2019 ; Vierth et al., 2019).

2.5.2 Way of Complying with the Regulations

The type of fuel used for the operations of a ship will heavily influence the emissions related to shipping activities. Therefore, switch of fuel is a largely discussed topic when looking for solutions to reduce air emissions. It is important to note that the quality of a certain fuel cannot be assessed on the basis of the emissions from the combustion phase. To have a good understanding of the environmental impact of each fuel, a total life cycle analysis is far more relevant. All the required steps to provide the fuel needed for a ship are also polluting. The cradle-to-grave perspective considers two main parts. The first is the well-to-tank phase with extraction of raw material, fuel production, transportation and storage, and bunkering. The second is the tank-to-propeller phase with the operation of the vessel (Bengtsson, Andersson, & Fridell, 2011).

Several fossil fuels are available for the maritime sector. The crude-oil-based fuels include residuals fuels with the heavy fuel oil (HFO) and two different distillate fuels with marine gas oil (MGO) and marine diesel oil (MDO), which is a mixture of HFO and MGO. There are also gas-based fuels with Liquefied natural gas (LNG) and gas-to-liquid (GTL) fuel which is a process to convert natural gas in liquid fuel (Bengtsson et al., 2011).

MGO and MDO require more steps in the refineries and are considered cleaner during the operations of the vessel. The large reduction in nitrogen and sulphur emission is clear but the additional time in refining increases the emissions of GHG on a total fuel cycle basis. Consequently, when considering switching fuel for the maritime industry, there is a trade-off between the different levels of emissions (Corbett & Winebrake, 2008). LNG has a similar problem. Using this fuel helps to fulfil the Tier III and the SECA regulations, but fails at reducing significantly the level of GHGs on a life cycle point of view (Bengtsson et al., 2011). To decrease both sides of this trade-off, the additional operations needed in the refineries for these cleaner fuels should be more efficient. It would reduce the related GHG emissions and make the fuel switch worth it (Corbett & Winebrake, 2008).

To reach the level of emissions expected by the authorities in the SECA and NECA, the owner of the ship can choose to install abatement technologies. Those technologies allow to reduce emissions during the operations of the vessel thanks to chemical reactions with the pollutants. With regard to the emission

of sulphur, the reduction can be made with a scrubber. It will make the SO_2 react in water and be transformed into sulphate. It can be used on a vessel, but this technology is expensive for the owner, and is space and resource consuming. However, it allows the vessel to run with cheap fuel like HFO (Bengtsson et al., 2011). To comply with Tier III regulation where emission of NO_x must be below 2-3.4 g of NO_x /kWh, there is also an abatement technology with a selective catalytic reduction (SCR) process (Transport & environment, 2021). This process combines NO_x and urea and creates a reaction with the presence of a solid catalyser; this combination results in nitrogen and water. It has the potential to decrease the emissions of NO_x up to 90%. This technology can be implemented in any type of vessels but is less effective when the loading factor is small or on a two-stroke engine (Bengtsson et al., 2011).

Another way to reduce the emissions to air is to adapt the speed of the vessel. Indeed, the relation between speed and fuel consumption is not linear. When the speed doubles, the fuel consumption quadruples. Reducing the operating speed is therefore a good decision to reduce the emission of pollutants, but it will negatively impact the demand for maritime transport. As the transit time should not be modified, the idle time spent by ships in ports must be reduced to allow ships to travel more slowly. Port operations must be efficient (Hjelle, 2011).

2.6 Short Sea Shipping in the Baltic Sea

The previous sections were about the European freight transport network and its different characteristics. This section will focus on the area studied in this paper, which is the BSR. It will first introduce the importance of the BSR regarding the global European trade. Then it will introduce the use of SSS in this sea and finally, the different regulations that constraint the transportation in this area.

2.6.1 Importance of BSR in Global trade and in Europe

The Baltic Sea can nearly be considered as an EU inland sea thanks to the high proportion of EU members surrounding it. Among them are Denmark, Germany, Estonia, Latvia, Lithuania, Poland, Finland, and Sweden. To this list we can add Norway which is not a member of the European Union but is part of the European Economic Area (EEA), and Russia which also trades a lot with all the listed countries. Those ten countries form what is called the BSR and have developed strong trade relations between each other (Liuhto, 2017).

Imports and exports of the BSR countries compared to the global world trade are really impressive but are often overstated due to the importance of trade activities of some BSR countries with non-BSR

countries. Among the ten nations, Germany, Russia and Poland contribute a lot to this overstatement. For example, Germany's export represents more than 50% of the BSR's export. When considering only the exchange intra BSR, the figures are far lower. To reevaluate the figure according to the real participation of each country in the BSR trade, some correction scheme can be applied to the figures. With this correction, the share of the BSR in the global trade decreases from 13.6% to less than 4% for the exports and from 11.5% to also less than 4% for the imports. These figures show BSR as a small economic area with a limited importance in the global GDP (Liuhto, 2017).

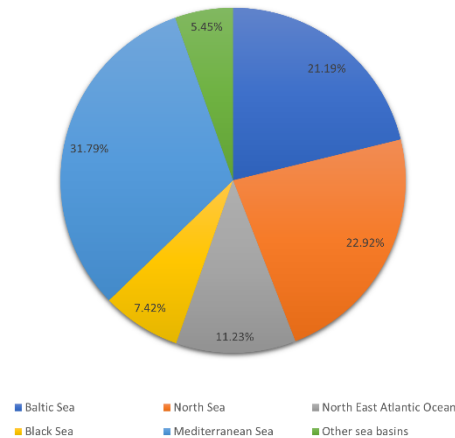


Figure 5: Share by Sea region of the total quantity of goods transported by SSS in EU-27 (2019). Source: (Eurostat, 2021-g)

In Europe, 21.19% of all SSS operations are located in the Baltic Sea (cf. figure 5). The countries operating through the Baltic Sea are often trading with countries located in the same sea region. Between 2017 and 2018, six European countries have registered impressive increase in the use of SSS. Among them, three of the BSR, namely Poland, Lithuania, and Finland, show an increase of 19.5%, 15.9% and 10.1% respectively. The eight countries which are both part of the BSR and the EU-27 represent 83% of the total weight of goods transported through SSS in the Baltic Sea. The share of each is given in figure 6.

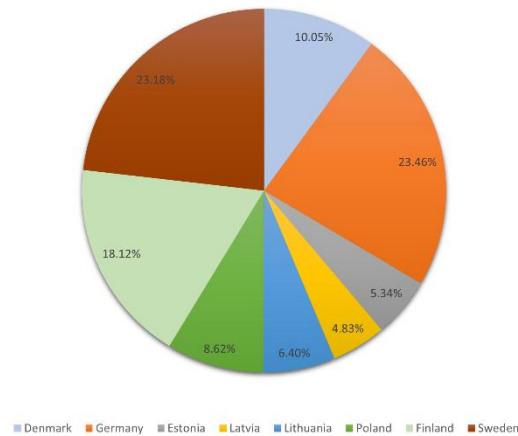


Figure 6: Share of the total quantity of goods transported by SSS in BSR by country (2019). Source: (Eurostat, 2021-g)

2.6.2 Incentives and Regulations in BSR

Regarding incentives and regulations. The marine environment of the Baltic Sea is regulated by different authorities. Most of the countries on the Baltic Sea rim are in the European Union and therefore are under its regulations. Additionally, the Baltic Sea environment is protected by the Helsinki Convention developed by the Helsinki Commission (HELCOM). Finally, the shipping operations inside the Baltic Sea are regulated by the IMO (Hilmola, 2015).

Inside the BSR, the two majors handling container ports are Gothenburg (Sweden) and St-Petersburg, their opposite positions on the Baltic Sea making them act as a true link between two hubs for the freight transport. This explains why the Baltic Sea is concerned with only two of the projects financed in Europe in the TEN-T programme. The priority is more on the development of inland maritime feeder connections. The first project is Motorway of the Baltic, which aims at increasing the maritime-based door-to-door service thanks to intermodality. The second is a project called "Rail Baltica" and aims at developing the rail network between Lithuania, Latvia, Estonia, and Central Europe (Kabashkin, 2012).

HELCOM works with BONUS, a cooperative whose goals are to help the policymaking with a science support and to develop the Baltic Sea Action Plan (BSAP). This plan wants to improve the environmental status of the Baltic Sea, and is created around 4 pillars, eutrophication, hazardous substances, biodiversity and nature conservation, and maritime activities. Each qualitative goal is translated into clear, precise and scientific objectives, and the measures utilized are also concrete and based on the best scientific knowledge (Kononen, Andrusaitis & Sirola, 2014).

As far as IMO regulations are concerned, the Baltic Sea is a Sulphur Emission Control Area (SECA). The vessels shipping on it must satisfy strict level of sulphur emission, they cannot use fuel with more than 0.1% of sulphur. The Baltic Sea is also a NECA, which means that each vessel built after 2021 and sailing in the Baltic must answer strict regulation on the NO_x emissions (Transport & environment, 2021).

3. Modelling Freight Transport

This chapter is about the creation of models to study a freight transportation network. This type of model is a derivation of the models used to study passengers transportation network. Therefore, the first section will address the reasons behind the needs for transition from passenger towards merchandise and presents the classic way of doing it. Then, the differences brought by the freight transport model in the structure of the model will be addressed. The following section presents each step out of the four-step method used and the different ways of achieving it. Finally, the last section is a synthesis of what has been done for the development of the model used to study the research question with the assumptions and the different method used to complete each of the four steps.

3.1. Introduction to transport modelling

The use of mathematical models to analyse transportation is a relatively new subject gaining in popularity over the years. Considering the correlation between transportation and negatives externalities like global warming, local air deterioration or noise pollution, some transport policies took place everywhere in Europe. With new policies came a demand for tools to analyse the impacts of the different programmes. Nowadays a lot of models exist. Some are designed for public authorities and aim at assessing the impact of different types of policies measures. Others are designed for the private sector and help some industries pursuing logistics planning or help company minimizing the cost of transportation throughout their whole supply chain (De Jong, Vierth, Travasszy, & Ben-avika, 2013). For that reason, models do not always have the same focus. The ones dedicated to the private sector are most of the time concentrate on cost performance while the ones developed for the public authorities have various purposes. They are built to measure emissions rate, safety, congestion, noise, etc. (De Jong, Gunn, & Walker, 2004).

Most of the first models were designed for passenger transportation. The basic method was the four-step modelling structure (De Jong et al., 2004). This method consists of four modules, namely production and attraction, distribution, modal split, and assignment. For each of these modules one or several models have been developed. De Jong et al. (2004) in its overview of the existing models confirm that the four-step modelling structure can be applied for freight transport even if significant differences exist. A description of each step in a freight transport model system context is given.

Generation: In this step, the volume of goods that a specific area produce to the benefit of destination areas and receive from origin areas is determined. This is the need for export and import of each zone. The volume is evaluated in tonnes of goods but can also be in monetary units.

Distribution: This step is the filling of the origin/destination matrix. The total flow of goods calculated in the previous step must now be distributed between all the possible areas.

Modal split: For each flow of goods between two areas, a mode of transport is defined to ensure transit.

Assignment: The volume transported must be changed from tonnes to unit of vehicle and this number of vehicles must be assigned to a network.

This paper focusses on the models designed for the analysis of multi-modal freight transport. In the following section, an overview of the existing models designed for the four-steps method will be given.

3.2. Comparison between passenger and freight transport models

As said in the previous section, the four-step modelling structure initially used for passenger transport can also be used for the analysis of freight transport. The models are obviously not the same, large differences exist between them. When using a four-step modelling structure to analyse freight transport, one must be careful to the diversity of decision makers involved in the transportation of goods, the variation in the nature of goods being transported, the extended cost function that considered inventory costs for instance, and the scarcity of data for freight transportation (De Jong et al., 2004 ; Jourquin, 2017).

3.2.1. The diversity of decision makers

To promote SSS successfully, some knowledge on how the variables impact the decision for the modal choice is essential. The first complexity to study the competition between modes for freight transportation is that different actors take part in it. They have different objectives and are sensitive to different factors. In the literature, the main actors considered are the shipper, the carrier, and the public authorities (Jourquin, 2017).

The shipper can be associated to the producer of goods. He wants to transport a certain quantity of goods from one location, the origin, to another location, the destination. It is called a door-to-door service. To do so, he has several transport solutions to transfer the cargo. His choice will be based on several transport characteristics but mainly on the costs and the time taken by the different solutions. Competition between modes exists thanks to the fluctuation in offer and demand (Santos & Soares, 2017).

The carrier is the entity owning the transport solutions. It can be a shipping company for example. The carrier is an economic agent looking to maximize its own profit. He delivers a service, the transportation of cargos, with a certain level of quality and charged at a certain price. His concern will be over the freight rate acceptable for its client, the costs he is facing to operate, the uncertainties linked to those costs and its revenues (Santos & Soares, 2017).

The third agent, the public authorities, are concerned with the social and environmental impacts of transportation. For them, it is important to consider the externalities of the activity. A lot of externalities do exist, but the main ones are costs related to global warming, air pollution, noise pollution, accidents, congestion, impact on nature and landscape (Santos & Soares, 2017). They can impact the modal split through taxes, subsidies, infrastructures development and regulations (Jourquin, 2017).

3.2.2. The diversity in the nature of the transported goods

For passenger transport, the nature of goods is ignored as the vessels will always transport humans and therefore, they will be very similar. For freight transport, the product varies, so the time taken to transport one category has a different importance from one product type to another and consequently will be valued differently. Following the nature of the product, the vessel will be adapted and so will the price for an hour of transportation. Five different categories of products can be highlighted, namely, raw materials and low value semi-finished products, raw materials and high value semi-finished products, perishable final products, imperishable final products, and containers. Following the type of commodities being transported, the shipper will value differently the time spent in transportation (García-Menéndez & Feo-Valero, 2009).

3.2.3. The extended cost functions

Freight transports have multiple operation costs. When creating an objective function, based on cost, the more the model is complete, the more accurate and closer to reality he will be. Moreover, the point of view chosen between all the possible actors in the transportation will greatly modify the cost function, while the public authorities are interested in the total cost of the trip, considering the external costs. Most of the time, the private sector will be only interested in the cost charged for the transit. Traditional costs that might arise in a cost function are the following.

Cost of transportation (TC): The road haulage company will charge the transit from origin to destination or, for intermodal transport, from origin to the initial port and from the final port to destination. As far as transit by vessels is concerned, the shipping company will charge a freight rate (FR), which will cover every cost including port costs. The price of fuel is included in the

FR but, as it represents a large proportion of the shipping cost, and can be very fluctuant, a bunker adjustment factor (BAF) is charged separately (Santos & Soares, 2017).

Handling cost (WC): For maritime transport, there is a charge for the handling of cargos at the origin and at the destination ports. This handling can be directly integrated in the FR. This cost is not always proportional to the quantity of goods to be transported (Santos & Soares, 2017).

Inventory cost (IC): During the whole transportation, the cargos are considered in stock and their holding induces IC. Its value depends on the type of cargo and the total transit time. In an intermodal solution, it arises from the time spent in the trucks, in the ports and on the vessel (Santos & Soares, 2017).

Externalities costs (EC): One parameter regularly left out of the equation is the external cost caused by all the negatives externalities that transportation is accountable for. They vary a lot, but among the most strongly linked to freight transport are wear and tear, accidents, noise, air pollution which is evaluated with emissions of NO_x, SO₂ and PM, climate change which can be assessed with the level of CO₂ emissions (Vierth et al., 2019).

These costs vary mainly with the quantities transported and/or the distance covered. The two parameters time and cost appear to be the main ones in the choice made by the shipper to decide between unimodal or intermodal transportation (Santos & Soares, 2017). Nevertheless, other quantitative or qualitative parameters are often taken into account when considering the nature of the goods and the transporter's business structure. A shipper can sometimes give more importance to parameters like safety of the cargo, reliability, quality of the service, frequency, etc. (Kuhnimhof et al., 2012).

3.2.4. The scarcity of data

The lack of publicly available data for SSS analysis limits the development of a model able to predict the future of freight transport or to optimize the flows of goods. The quantity used often came from the total transport volume going through the main European ports (inward and outward). Consequently, there might be a problem of double counting. Such a problem occurs when a cargo is declared by both, origin, and destination ports. This double counting issue might be avoided by only looking at the inwards movements from each port (Van Den Bos & Wiegman, 2018).

3.3. Four Step Model

The four-step model is the classical model used for the analysis of freight transportation network. Each step has several different ways of being complete following the type of network studied, the data used,

the degree of precision, the desired outcomes, etc. This section addresses each one out of the four steps and presents the different methods that can be used to complete it.

3.3.1. Generation

After determining which nodes will be considered in the model, the first out of the four steps is to determine what comes and goes to and from each node in term of tonnes of goods. The basic concept is to classify the flow through each node according to categories (e.g., types of goods) and to determine which factors will influence this flow (e.g., population in the area, level of income, types of goods, etc.) To do so, three types of models have been used in the literature (De Jong et al., 2004).

- Trend and time series models.
- System dynamics models.
- I/O and related models.

Trend models use historical data to extrapolate them into the future. It can be through simple growth factor models or with more complex models like autoregressive moving average models. Time series models will use an explanatory variable to estimate the current total flow. This explanatory variable can be the GDP for instance (De Jong et al., 2004).

System dynamics models are more complete and can be used to perform directly the first three steps of the four-step method. They model the change on the total flows over time and the impacts it has on the economy. With it, an estimated growth in the GDP helps get the necessary data for the generation step (De Jong et al., 2004).

Input/output models are derived from the I/O tables of each industry in term of exports and transports. An I/O table represents the exchange between each sector of the economy and also includes the final demand by the consumer. These tables are often in monetary units. Many countries have developed national I/O tables and those tables are made available by the central statistical office. Old I/O table can also be updated with the sector growth rate. To derive these new tables into total flows of goods between areas, two techniques exist. First, by keeping the present production and exchange rates and applying them to the I/O table. Second, by using technical and trade coefficients. The second method allows to take in consideration the variation in transport cost and time (De Jong et al., 2004).

3.3.2. Distribution

This step is about filling the O/D matrix with respects to the total flows calculated in the generation phase. The classical solution used in the literature to fulfil this objective is the following (Jourquin, 2017).

- Growth rate methods
- The synthetic methods

The basic concept behind the growth rate methods is the utilization of an old O-D matrix and an adjustment factor to estimate a new matrix. Some methods use a steady growth rate for all matrix cells, others use a specific growth rate for each location. These methods are easy to reproduce, the difficulty lying in the need for a pre-existence O-D matrix. These methods are preferred for short-term prediction on stable networks (Jourquin, 2017).

The synthetic methods are used for less stable networks. Among all the existing methods, the gravity model is the most used for this step. With the gravity model, the trade flows between two areas are estimated thanks to a measure of the production and the attraction and a measure of the transport resistance, usually translated as a transport cost. The flow between the origin area and the destination area is a function of the product of the origin's production and the destination's attraction divided by some measure of the transport cost. The value of the attraction is impacted by the distance between two areas, but also by the factors that drive them to make exchange together like synergies or complementarity in their activities (Jourquin, 2017).

3.3.3. Modal Split

This step received the most attention from the literature these past years. Consequently, a lot of different models exist to determine the allocation of the flow between two areas on the different modes of transport. These models are usually divided in two categories in the literature, the aggregated models, and the disaggregated ones (De Jong et al., 2004 ; García-Menéndez & Feo-Valero, 2009 ; Jourquin, 2017). The difference lies in the degree the data used is aggregated. The first category of models is generally used for the analysis of transport modes' market shares at a regional or national level, while the disaggregated models are concerned with the mode choice at the individual level (García-Menéndez & Feo-Valero, 2009). De Jong et al. (2004) identify 7 different models present in the literature.

- Elasticity-based models.
- Aggregate modal split models.
- Neoclassical economic models.
- Econometric direct demand models.

- Disaggregate modal split models.
- Microsimulation approach.
- Multimodal networks models.

Elasticity-based models modify the value of a parameters, the cost of using a specific mode of transport for instance, and observe the effects induced by this modification. The values of the elasticities are derived from the literature. These models are used to gain a quick evaluation of the network movement and are often combined with other models to have a deeper analysis (De Jong et al., 2004).

Aggregate modal split models are binomial or multinomial logit models. They use a sample of the transportation between some zones to derive the probability to use one mode over another, or in other words the transport's market share. These models can be used with cost minimization but also with utility maximisation (De Jong et al., 2004).

Neoclassical models are the ones minimizing a cost function in order to derive a demand for transport mode. The shippers are supposed to minimize the total transportation cost while considering some technological constraints. It is difficult to implement these models in a larger picture like the four-step method. Moreover, these models are not suited for network with many links and nodes (De Jong et al., 2004).

Econometric direct demand models predict the number of trips, or the total travel distance, of all modes. But like the previous models, these ones are difficult to implement in a four-step structure (De Jong et al., 2004).

Disaggregate modal split models use data from individuals rather than national or regional ones. These data can be issued from surveys of shippers, commodity surveys, etc. These models assume that the shipper, or the firm, faces a utility function based on transportation cost and the quality. The factors considered by the decision makers when choosing between several modes are diverse. The most commonly used in these models are transit price, transit time, frequency, flexibility, and reliability of the service (De Jong et al., 2004).

Microsimulation approach mode is part of a bigger picture. It is used with the combination of an I/O model that estimates the flows between each zone in monetary terms. The microsimulation models use

the output of the I/O model to derive the pattern of urban vehicles. It provides the unit conversion from the monetary term to shipments and will allocate transshipment points, carrier types and vehicle types (De Jong et al., 2004).

Finally, multimodal network models are the ones combining the modal split step and the assignment to a network. The last two steps of the four-step method. It allows to use more than one mode to complete the desired door-to-door service. These models need links for each mode but also ports and terminals for transshipment. They are used for aggregated data as they are looking to OD combination (De Jong et al., 2004).

3.3.4. Assignment

Now that we have the quantity that each mode has to transport between each OD pair, the purpose of this step is to assign them a route to follow. Some of the freight models skip this step, most of them only do it for trucks traffic. The reason is that unlike other modes, most of the traffic on road network is not dedicated to freight transport (De Jong et al., 2004). Models for this step can be classified in four categories depending on whether or not capacity constraints are taken into account and if the objective function is linear or non-linear (Jourquin, 2017).

- All-Or-Nothing
- Equilibrium
- Multi-flow
- Multi-flow equilibrium

The All-Or-Nothing method is for models without capacity constraint and with a linear constraint. The model is said to be following a non-stochastic behaviour, meaning that the outcome of the variable does not involve randomness. In these models the different modes are not subject to capacity constraints, consequently they do not take congestion into account. Therefore, this method is better suited for networks not subject to congestion. However, it can be used with congestion considered as an additional cost added for going through a particular node (Jourquin, 2017).

The equilibrium methods enable the user to solve the constraint linked with the network capacity. Some algorithms offer the possibility to re-assign part of the flows on other routes. The idea is that the more a link is used, the more the cost to go through it increases, allowing other links to be more attractive after the first assignment (Jourquin, 2017).

The two other methods are concerned with non-stochastic behaviour. They take into consideration that the user may prefer a route over another for reasons that are not economic. These models run with the notion of utility. The users of the networks will choose the route that maximizes their own utility function. For that reason, these models are not adapted for multi-modal transportation on long distance and therefore, will not be considered in this study (Jourquin, 2017).

3.4. Synthesis

The purpose of this section is to describe the method used to study the BSR freight transport network. On the basis of what has been seen in the literature review and in this chapter about modelling. The first part of the section will present the different elements taken into consideration, those which have been left apart and all the assumptions made to simplify the reality of the transportation market. Then, a presentation of the method used to develop the model will be given in the second part.

3.4.1. Assumptions

Some assumptions on the transportation network of the Baltic Sea are made in order to simplify the reality and make the modelling easier. It helps also decreasing the scope of the model and improve the focus on this thesis research question. These assumptions are presented in this subsection.

Assumptions have been made on the geographic scope. Basing the division of regions on the NUTS 1 nomenclature, regions consider in this study meet the two following conditions, being part of the EU-27 and having a coastline on the Baltic Sea. This choice removes Norway, Russia, a part of Poland, and a part of Germany from the model.

Only two modes of transport will be considered inside the paper, transportation by road with trucks and maritime transport with ships. There are several reasons behind this choice. Firstly, these two modes carry the majority of the goods transported in Europe. In 2018, the share of good transported by road or maritime modes was about 82.4% of the totality of goods transported inside the EU-27 (Eurostat, 2021-c). The second reason is that in the literature, maritime transportation, and more precisely SSS, is largely considered as a true competitor for road transport, thanks to the numerous advantages related to the utilization of ships inside a multimodal solution as discussed in the subsection 2.2.1.

The commodities considered in this paper are those on which there is a real competition between maritime and road modes of transport. Those are the containers and other cargos. It seems logical to exclude raw materials, liquid, and dry bulk products out of the analysis as their transportation is mainly done with specific ships which face almost no competition thanks to their efficiency (cf. section 2.1.3). Furthermore, empty containers which are carried by the same vehicles, will be out of scope. As observed by Hjelle (2011), the double load factor made the emission figures often underestimated, which may result in the maritime transport being unattractive. To avoid this, empty containers will be assumed to be transported separately, leaving only filled containers on the different vehicles.

The merchandise will be exchanged between different locations thanks to three different types of vehicles. For road transportation, the selected vehicle is a truck following EURO VI regulations and therefore, driving with ultra-low sulphur diesel. The trucker will be subject to European legislation with regard to his driving hours (cf. subsection 2.4.4). For the maritime transport, given the commodities considered in this paper, two different types of vessels have been selected. Those are ro-ro and lo-lo vessels. Both vessels are suitable for the transport of containers and other cargos. Ro-ro vessels receive a lot of attention in the literature because of the short waiting time in port, these vessels are considered as serious competitors for the unimodal transport using only road transportation by truck. However, a fleet with only these types of vessels is not realistic, which explains the inclusion of lo-lo vessels in the model. Each vessel is assumed to be fuelled by MDO. As seen in the literature, the fuel choice is subject to a trade-off between different types of emissions, and it seems hard to find a unanimous answer for the right fuel to use when its total life cycle is considered. Nevertheless, each vessel will be assumed to be equipped with abatement technologies and to respect TIER III conditions. This assumption is made because the Baltic Sea is an ECA for both the sulphur and the NO_x. Consequently, the emissions must be lower than the standards presented previously (cf. subsection 2.5.2).

The main decision maker considered will be the shipper. The reason is that he has the final decision regarding the transport mode used and the purpose of the thesis is to study the variability of this decision. Nevertheless, the point of view of the other actors will not be put aside. The public authorities have other concerns and those will also receive some focus through the internalization of externalities.

3.4.2. Methods Deployed

The method used to study the transportation network in the Baltic Sea is a four-step method. As it has been seen, each step has different ways of being carried out. Therefore, this section will present how each of the four steps was realised. During the research, the border between the generation and the

distribution phase was not well differentiated. The same goes for the third and fourth steps, named modal split and assignment. Consequently, the two pairs of steps will be addressed together in this section.

The generation and the distribution steps aim to end up with the origin-destination matrix of the area studied. In other words, for each origin region, it will determine the quantity exchanged with every destination region. The generation phase is done with the input/output model and therefore, with data from the I/O tables developed at a European level. The methods presented for the distribution phase are not used. The filling of the OD matrix was done with specific calculation presented further on.

The first thing to be defined is therefore the area considered and the different origin and destination regions. The eight European countries present in the BSR are chosen, namely, Denmark, Germany, Estonia, Latvia, Lithuania, Poland, Finland, and Sweden. Some of these countries like Poland and Germany have a large part of their territory too far away from the Baltic Sea to consider any influence on the exchange of goods. To avoid any useless region to be considered, the European NUTS nomenclature is used. The NUTS 1 region with a coastline in the Baltic Sea is selected. These regions are then segmented into smaller ones following the NUTS 2 nomenclature. The reason behind the use of this level of segmentation is that, at a NUTS 2 level, regions are considered small enough to choose a geographical point inside each called centroid. From this centroid, one can assume that all regions exports will leave, and all regions imports will arrive. Such an assumption is not reasonable at a NUTS 1 level. For each region, the selection criterion for the centroid is the city with the largest population. It should more than likely coincide with the city with the most economic activities. To resume, the area considered is made of thirty different regions in eight different countries. In each of these regions, a centroid is chosen to represent the origin region and also the destination region (cf. figure 7) (cf. annex A, p.1).

The second pair of steps are the modal split and the assignment phase. The type of model used for the third and fourth steps of the method is a multimodal network model. For each pair of origin and destination, the transportation of goods can be done through two different ways. The first way is a unimodal transportation solution, where the cargo is taken from the origin directly to the destination region by truck. The second way is the multimodal transportation solution. The goods are taken by truck and sent to a port called port of origin. Then the merchandise is loaded on a vessel and is brought from the port of origin towards the port of destination. Once arrived in the port of destination, the last part of the journey between the port and the destination region is again done by truck.

To enable the model to attribute some exchange between regions through a multimodal solution, the network has to be extended in order to contain not only the thirty nodes already established but also the different ports. The port selection is made on the basis of the total quantity of goods loaded and unloaded between 2017 and 2019 for the intra-European exchange. Only the ports located in the considered area and with more than 1000 thousands of tonnes of goods in total during at least a year are selected to be part of the network. These criteria match 62 ports everywhere around the Baltic Sea (cf. figure 7) (cf. annex B, p. 2-3).

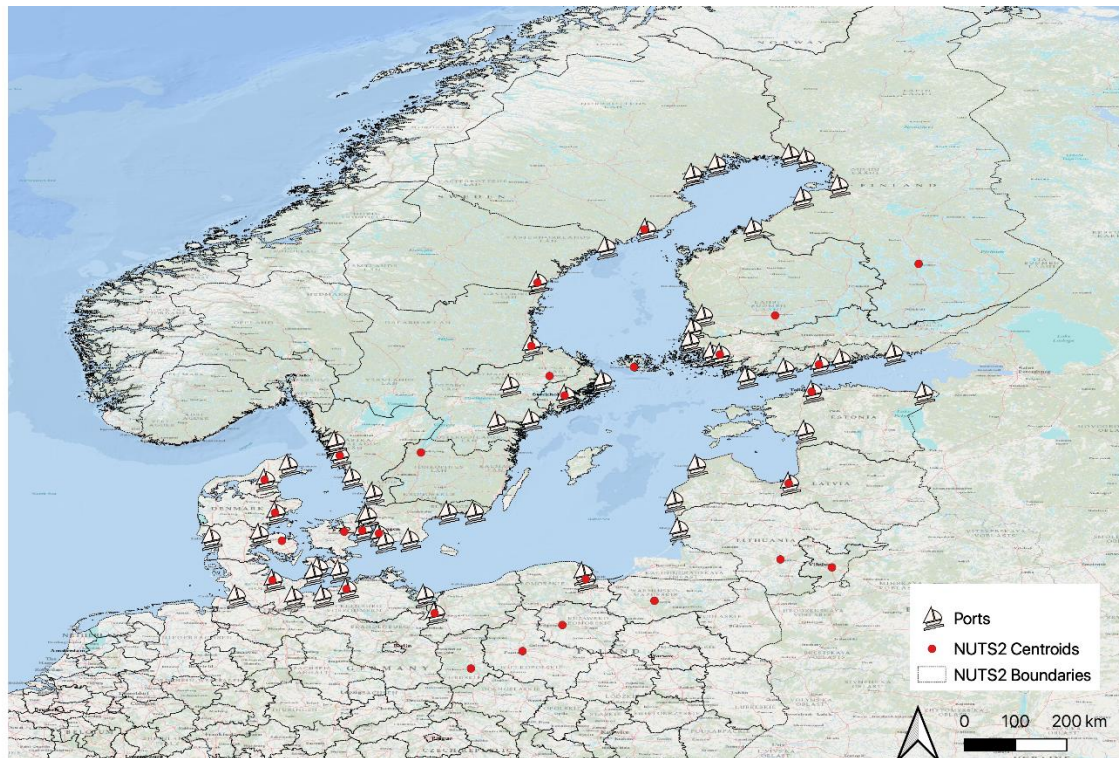


Figure 7: Centroids and ports considered in the model

The model is linear and without capacity constraint. Therefore, the assignment phase is done is an All-Or-Nothing method. Due to the large area considered in this study, adding the road sections affected by congestion seems a bit unrealistic.

4. Model Development

This chapter presents the building of the model which will be used to determine the modal split and the traffic assignment as explained in the previous part. After a brief description of the model, we will go through its formulations. Then, a complete description of the objective function will be given as well as the constraints that the model is subject to. Lastly, a fifth section will address the modifications needed on the model to put in place new scenarios.

4.1. Description of the model

As explained in the synthesis, the third and fourth steps, namely, modal split and assignment will be carried out through a multimodal network model. This sort of model is also called "*many to many model*". In this specific case, the reason is that every node representing a region willing to trade can exchange goods with all the other regions. To do so, this model is a set of 30 nodes acting as origin and destination regions, and 62 nodes acting simultaneously as port of origin and port of destination. It results into 92 nodes and 8372 links that represent the freight transport network in the BSR. For ease of understanding, the 870 links that connect directly the 30 centroids with each other will be referred to as the "*unimodal 1st link*". For the multimodal solution, the 1860 links that are used as to connect by road the origin region with the port of origin will be referred to as with "*multimodal 1st link*", the 3782 nautical links with "*multimodal 2nd link*", and the last 1860 links connecting the port of destination with the destination region as "*multimodal 3rd link*".

4.2 Model formulation

This section presents the model construction with first all the indexes used, then the list of parameters and finally the different variables. The model described hereafter will be referred to as the base case and will be as close as possible to the reality of the BSR transportation network. To do so, real data will be used to approach the correct modal split for the utilization of maritime transport over road transport. It should be noted that in this case we assume that the shipper does not pay for the externalities induced by the mode of transport chosen.

4.2.1 Indexes

Four different indexes will be used in the base case. Two are for the 30 centroids of the NUTS 2 region. The index origin region (i) is for the centroid when it acts as the sender of goods, the index destination region (j) is for when it acts as a receiver. The same logic is applied with the two indexes that represent the 62 ports selected.

Table 1: List of indexes

Index	Description	Set
i	Origin region (<i>Orig</i>)	$\epsilon \{1 \dots 30\}$
j	Destination region (<i>Dest</i>)	$\epsilon \{1 \dots 30\}$
p	Port of Origin (<i>Origport</i>)	$\epsilon \{1 \dots 62\}$
q	Port of Destination (<i>Destport</i>)	$\epsilon \{1 \dots 62\}$

4.2.2 Parameters

The parameters used in the base case are the following.

Table 2: List of parameters

Notation	Description	Unit
$D_{(i,j)}$	Quantity of goods to be transported from origin region (i) towards destination region (j)	t
$DistOrigDest_{(i,j)}$	Distance between the origin region (i) and the destination region (j)	Km
$DistOrigOrigport_{(i,p)}$	Distance between the origin region (i) and the port of origin (p)	Km
$DistOrigportDestport_{(p,q)}$	Distance between the port of origin (p) and the port of destination (q)	Km
$DistDestportDest_{(q,j)}$	Distance between the port of destination (q) and the destination region (j)	Km
ARS	Average road speed	Km/h
ANS	Average nautical speed	Km/h
$TTOrgDest_{(i,j)}$	Transit time between the origin region (i) and the destination region (j)	h
$TTOrgOrigport_{(i,p)}$	Transit time between the origin region (i) and the port of origin (p)	h
$TTOrgportDestport_{(p,q)}$	Transit time between the port of origin (p) and the port of destination (q)	h
$TTDestportDest_{(q,j)}$	Transit time between the port of destination (q) and the destination region (j)	h
$BKOrigDest_{(i,j)}$	Number of breaks the driver must take between the origin region (i) and the destination region (j)	#

Notation	Description	Unit
BKOrigOrigPort _(i, p)	Number of breaks the driver must take between the origin region (i) and the port of origin (p)	#
BKDestportDest _(q, j)	Number of breaks the driver must take between the port of destination (q) and the destination region (j)	#
Breaktime	Length of the mandatory breaktime for a truck driver	h
RoroShare	Share of ro-ro vessels in the fleet	%
LoloShare	Share of lo-lo vessels in the fleet	%
PTroro	Average port time spent by a ro-ro vessel in port	h
PTlolo	Average port time spent by a lo-lo vessel in port	h
FCopeningNav	Fixed cost to be paid to activate a maritime link	€
FCopeningRd	Fixed cost to be paid to activate a road link	€
FCroad	Freight cost for road transportation	€ / t * km
FCroro	Freight cost for maritime transportation with ro-ro vessel	€ / t * km
FClolo	Freight cost for maritime transportation with lo-lo vessel	€ / t * km
IC	Inventory cost	€ / t * h
WCroro	Waiting cost for the ro-ro vessels	€ / t * h
WClolo	Waiting cost for the lo-lo vessels	€ / t * h

The parameters "*FCroad*", "*FCroro*" and "*FClolo*" include a lot of different costs. The repartition of these costs is described in (Van Der Meulen, Grijspaardt, Mars, Roest-Crollius, & Kiel, 2020) and is as follows. The freight cost for road transportation is subdivided in 5 categories, the fixed costs, the variable costs (with the fuel costs), the staff costs, mode-specific costs, and general operating costs. These five categories are the same for the freight transport by ro-ro or lo-lo vessels, but what is included in each category varies. For example, the costs of tyres included in the variable cost for the truck transport, are obviously not in the cost function for the use of ship.

The parameters "*WCroro*" and "*WClolo*" are the waiting cost for the port operations. It represents the cost of loading and unloading the vessels, and of being idle.

4.2.3 Variables

The model uses eight different variables in the base case. Four of them are continuous and refer to the quantity transported on each of the four different links, for every trade between two regions. The last four are binary variables, each representing a particular link. This binary variable will take the value of 1 if the link it represents is used.

Table 3: List of variables

Notation	Description	Unit
$QtyUnimodal_{(i,j)}$	Quantity of goods transported between the origin region (i) and the destination region (j) through a unimodal solution.	t
$QtyOrigOrigport_{(i,j,p)}$	Quantity of goods exchanged between the origin region (i) and the destination region (j) transported by truck from the origin region (i) toward the port of origin (p)	t
$QtyOrigportDestport_{(i,j,p,q)}$	Quantity of goods exchanged between the origin region (i) and the destination region (j) transported by ship from the port of origin (p) toward the port destination (q)of	t
$QtyDestportDest_{(i,j,q)}$	Quantity of goods exchanged between the origin region (i) and the destination region (j) transported by truck from the port of destination (q) toward the destination region (j)	t
$yOrigDest_{(i,j)}$	Binary variable which equals: 1, if the link between the origin region (i) and the destination region (j) is used. 0, otherwise	{0,1}
$yOrigOrigport_{(i,p)}$	Binary variable which equals: 1, if the link between the origin region (i) and the port of origin (p) is used. 0, otherwise	{0,1}
$yOrigportDestport_{(p,q)}$	Binary variable which equals: 1, if the link between the port of origin (p) and the port of destination (q) is used. 0, otherwise	{0,1}
$yDestportDest_{(q,j)}$	Binary variable which equals: 1, if the link between the port of destination (q) and the destination region (j) is used. 0, otherwise	{0,1}

4.3. Objective function

The objective function summarizes all the different costs the shipper faces when sending a certain quantity of goods. The model is about minimizing the sum of all these costs supported by every centroid to send their merchandise. For the initial situation, three different types of costs are considered: the transportation costs, the inventory costs, and the opening costs. Three equations are presented below, one for each of these costs.

The objective function is therefore obtained by putting together these three equations. As said previously, the minimization of the objective function will result in a modal split and an assignment of the traffic in all-or-nothing manner. For every pair of nodes, the goods will be attributed to the unimodal or multimodal solution based on which option is the cheapest.

$$OF = TransportCost + InventoryCost + OpeningCost \quad (OF.1)$$

4.3.1. Transportation cost

The equation to evaluate the total cost of transportation in the base case is divided in 7 different lines. The cost link with the transportation is the one linked with the freight rate charge by the carrier to the shipper. The freight cost varies according to the mode used. The equation to calculate transport costs is the following.

$$\sum_{i \in I} \sum_{j \in J} QtyUnimodal_{(i,j)} * DistOrigDest_{(i,j)} * FCroad \quad (TC.1.1)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} QtyOrigOrigport_{(i,j,p)} * DistOrigOrigport_{(i,p)} * FCroad \quad (TC.1.2)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * DistOrigportDestport_{(p,q)} * RoroShare * FCroro \quad (TC.1.3)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * PTroro * RoroShare * WCroro * 2 \quad (TC.1.4)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * DistOrigportDestport_{(p,q)} * LoloShare * FClolo \quad (TC.1.5)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * PTlolo * LoloShare * WClolo * 2 \quad (TC.1.6)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{q \in Q} QtyDestportDest_{(i,j,q)} * DistDestportDest_{(q,j)} * FCroad \quad (TC.1.7)$$

The lines (TC.1.1), (TC.1.2), and (TC.1.7) represent the three different links where the goods are transported by trucks. The freight cost is given in [€/ton*km] and therefore, is multiplied by the distance and the quantity transported between two nodes. For the multimodal 2nd link, it is a bit different. The transportation cost related to the transportation by sea varies following the type of vessel. Furthermore, the cost is split in two. One part is for the freight rate charge by the carrier, the other part is for the waiting cost. The waiting cost includes all the charges resulting from loading and unloading operations, plus the waiting time in port. The two lines (TC.1.3) and (TC.1.5) are for the freight cost charge for the transportation by ro-ro vessel and by lo-lo vessel, respectively. The two remaining parts of the formula (TC.1.4) and (TC.1.6) are for these waiting costs.

4.3.2. Inventory cost

The inventory cost is for the shipper to pay. The goods he owns are temporarily unavailable. As long as the merchandise is being transported, the shipper must pay for it. The level of this cost varies with the quantity and the total transit time. The inventory cost equation is subdivided in 5 lines which are presented below.

$$\sum_{i \in I} \sum_{j \in J} QtyUnimodal_{(i,j)} * [TTOrigDest_{(i,j)} + (BKOrigDest_{(i,j)} * Breaktime)] * IC \quad (IC.1.1)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} QtyOrigOrigport_{(i,j,p)} * [TTOrigOrigport_{(i,p)} + (BKOrigOrigport * Breaktime)] * IC \quad (IC.1.2)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * [TTOrigportDestport + (PTroro * 2)] RoroShare * IC \quad (IC.1.3)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * [TTOrigportDestport + (PTlolo * 2)] * LoloShare * IC \quad (IC.1.4)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{q \in Q} QtyOrigOrigport_{(i,j,q)} * [TTDestportDest_{(q,j)} + (BKDestportDest * Breaktime)] * IC \quad (IC.1.5)$$

With regard with the transportation by truck, carriers are subject to strict European regulations and must therefore take breaks after a certain amount of driving hours. A certain link between two nodes has an integer amount of breaks to be taken. The unimodal 1st link is represented by the line (IC.1.1), and the multimodal 2nd and 3rd links by the lines (IC.1.2) and (IC.1.5). For the ship transport, there is no break to be taken but the goods are immobilized in the port of origin and in the port of destination. Additionally, the transit time of the vessel must be taken into consideration. As the ro-ro vessels have smaller lead time in port than lo-lo vessels, their respective cost are calculated in separate lines. The one for the ro-ro is (IC.1.3) and the last one, (IC.1.4), is for the lo-lo.

4.3.3. Opening costs

The opening costs are the fixed costs related to the opening of a link between two nodes. A difference is made between the opening of a road leg and a link connecting two ports. The first is assumed to be cheap and even more for the small trip made by truck in the multimodal solution where the road links are generally smaller. On the other hand, the fixed cost for opening a link between two ports is far more expensive. This prevents the model to exchange small quantity of goods between two ports which would not make sense in real life situations.

$$\sum_{i \in I} \sum_{j \in J} y_{OrigDest(i,j)} * FCopeningRd \quad (OC.1.1)$$

$$+ \sum_{i \in I} \sum_{p \in P} y_{OrigOrigport(i,p)} * FCopeningRd / 2 \quad (OC.1.2)$$

$$+ \sum_{p \in P} \sum_{q \in Q} y_{OrigportDestport(p,q)} * FCopeningNav \quad (OC.1.3)$$

$$+ \sum_{q \in Q} \sum_{j \in J} y_{DestportDest(q,j)} * FCopeningRd / 2 \quad (OC.1.4)$$

4.4. Constraints

The first constraint is called "*demand constraint*". It forces the model to deliver the quantity expected by the destination region (j) from the origin region (i). This exchange can be made through the unimodal solution with "*QtyUnimodal_(i,j)*" or through the multimodal solution with "*QtyDesportDest_(i,j,q)*". Only the third and last link in the multimodal solution are taken into consideration for this demand constraint.

$$QtyUnimodal_{(i,j)} + \sum_{q \in Q} QtyDesportDest_{(i,j,q)} \geq D_{(i,j)} \quad \forall i \in I, j \in J \quad (C.1)$$

Since only the multimodal 3rd link appears in the previous constraint, the model needs flow constraints to ensure that merchandise present on this link comes from one of the numerous multimodal 2nd links. This is enforced by the constraint (C.2.1). The same goes for the merchandise going from one port to another. A constraint is needed to ensure that the merchandise leaving the port of origin (p) is equal to the quantity transferred from the origin region (i) to this very same port, and this is done with the constraint (C.2.2).

$$\sum_{p \in P} QtyOrigportDestport_{(i,j,p,q)} \geq QtyDesportDest_{(i,j,q)} \quad \forall i \in I, j \in J, \quad q \in Q \quad (C.2.1)$$

$$QtyOrigOrigport_{(i,j,p)} \geq \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} \quad \forall i \in I, j \in J, \quad p \in P \quad (C.2.2)$$

All the following constraints aim at activating a binary variable. There are four constraints, (C.3.1) is for the unimodal 1st link, (C.3.2) for the unimodal 1st link, (C.3.3) for the multimodal 2nd link, and (C.3.4) for the multimodal 3rd link. The quantity going through a link can be larger than 0 only if the binary variable corresponding to this link is activated. In each constraint, the binary variable is multiplied by a very large number. This number represents the largest quantity of goods that can go through one of the links.

$$QtyUnimodal_{(i,j)} \leq yOrigDest_{(i,j)} * M \quad \forall i \in I, j \in J \quad (C.3.1)$$

$$\sum_{j \in J} QtyOrigOrigport_{(i,j,p)} \leq yOrigOrigport_{(i,p)} * M \quad \forall i \in I, p \in P \quad (C.3.2)$$

$$\sum_{i \in I} \sum_{j \in J} QtyOrigportDestport_{(i,j,p,q)} \leq yOrigportDestport_{(p,q)} * M \quad \forall p \in P, q \in Q \quad (C.3.3)$$

$$\sum_{i \in I} QtyDestportDest_{(i,j,q)} \leq yDestportDest_{(q,j)} * M \quad \forall q \in Q, j \in J \quad (C.3.4)$$

4.5. Model scenarios

To answer the research question, a modification in the actual network is needed to analyse the results that come off it. These modifications are achieved through two different scenarios implemented in the model with new indexes or parameters that will reshape the objective function and, therefore, bring change in the optimization of the network.

4.5.1 Scenario 1: Internalisation of externalities

For this first scenario, the model used for the "*base case*" will be extended to include the emissions costs in the objective function. Inside this scenario, the emissions of NO_x, SO₂, PM and CO₂ emitted by the different modes will be considered. Furthermore, some externalities involving only the transportation by truck will also be added to the model. These externalities include wear and tear, noise, and accidents.

Consequently, the introduction of new indexes and new parameters is required. Two additional indexes will be used, one for the four different pollutants emitted by both truck and ship (identified by "e"), another for the externalities involving road transport only (identified by "f").

Table 4: List of additional indexes needed for scenario 1

Index	Description	Set
e	Emissions from both modes	$e \in \{1 \dots 4\}$
f	Externalities from road transport	$e \in \{1 \dots 3\}$

To assess the level of the pollution from each mode, some parameters must be added to the model. The following table lists all the new parameters used in the extension of the basic model.

Table 5: List of additional parameters needed for scenario 1

Notation	Description	Unit
$EQ_{road(e)}$	Quantity of emissions from road transport by truck	g / t * km
$EQ_{roro(e)}$	Quantity of emissions from maritime transport by ro-ro	g / t * km
$EQ_{lolo(e)}$	Quantity of emissions from maritime transport by lo-lo	g / t * km
$EC_{road(e)}$	Cost of emissions from road transport by truck	€ / g
$EC_{roro(e)}$	Cost of emissions from maritime transport by ro-ro	€ / g
$EC_{lolo(e)}$	Cost of emissions from maritime transport by lo-lo	€ / g
$EConly_{road(f)}$	Cost of externalities from road transport by truck	€ / t * km

The different costs related to the externalities resulting from transportation activity must now appear in the objective function. Here is the detailed equation subdivided in 8 lines.

$$\sum_{i \in I} \sum_{j \in J} \sum_{e \in E} QtyUnimodal_{(i,j)} * DistOrigDest_{(i,j)} * EQ_{road(e)} * EC_{road(e)} \quad (EC.1.1)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{f \in F} QtyUnimodal_{(i,j)} * DistOrigDest_{(i,j)} * EConly_{road(f)} \quad (EC.1.2)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{e \in E} QtyOrigOrigport_{(i,j,p)} * DistOrigOrigport_{(i,p)} * EQ_{road(e)} * EC_{road(e)} \quad (EC.1.3)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{f \in F} QtyOrigOrigport_{(i,j,p)} * DistOrigOrigport_{(i,p)} * EConly_{road(f)} \quad (EC.1.4)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} \sum_{e \in E} QtyOrigportDestport_{(i,j,p,q)} * DistOrigportDestport_{(p,q)} * EQ_{roro(e)} * EC_{roro(e)} * RoroShare \quad (EC.1.5)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} \sum_{e \in E} QtyOrigportDestport_{(i,j,p,q)} * DistOrigportDestport_{(p,q)} * EQ_{lolo(e)} * EC_{lolo(e)} * LoloShare \quad (EC.1.6)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{q \in Q} \sum_{e \in E} QtyDestportDest_{(i,j,q)} * DistDestportDest_{(q,j)} * EQ_{road(e)} * EC_{road(e)} \quad (EC.1.7)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{q \in Q} \sum_{f \in F} QtyDestportDest_{(i,j,q)} * DistDestportDest_{(q,j)} * EConly_{road(f)} \quad (EC.1.8)$$

The first two lines (EC.1.1) and (EC.1.2) are for the externalities for which the unimodal transport by truck is accountable. One is for the emissions to air, the other is for the only-truck externalities. Similar lines are used for the multimodal 1st link with (EC.1.3) and (EC.1.4), and the multimodal 3rd link with (EC.1.7) and (EC.1.8). For the multimodal 2nd link, where containers are carried by ships, the only-truck externalities are not necessary in the equation because vessels are not concerned with those. Therefore,

two lines are needed, one for each type of vessel, (EC.1.5) is for the emissions to air resulting from transport by ro-ro vessel, the last one, (EC.1.6) is for the emissions to air from lo-lo vessels.

Finally, the objective function is extended to consider these new costs.

$$OF = TransportCost + InventoryCost + OpeningCost + ExternalitiesCost \quad (OF.2)$$

4.5.2. Scenario 2: Incentive introduction

For the second scenario, a kilometre tax is introduced for the use of truck in freight transportation. The objective is to drastically reduce the ton-kilometre transported by truck. To make the tax fair, an index is also applied. This index will vary following the average externalities cost paid by country in the base case, the number of inhabitants in the parts of the countries considered with the NUTS 2 regions, and the GDP per capita by country.

Table 6: List of additional parameters needed for scenario 2

Notation	Description	Unit
Tax	Tax for the utilization of truck.	€ / t * km
TaxIndex	Index applied on the tax	#

Both parameters are added in the lines which calculate the cost of shifting goods by truck. It will modify the equation for transport costs. This concerns the line (TC.2.1) with the unimodal transportation and the lines (TC.2.2) and (TC.2.7) which represent the links from multimodal 1st and 3rd link.

$$\sum_{i \in I} \sum_{j \in J} QtyUnimodal_{(i,j)} * DistOrigDest_{(i,j)} * [FCroad + (Tax * TaxIndex)] \quad (TC.2.1)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} QtyOrigOrigport_{(i,j,p)} * DistOrigOrigport_{(i,p)} * [FCroad + (Tax * TaxIndex)] \quad (TC.2.2)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * DistOrigportDestport_{(p,q)} * RoroShare * FCroro \quad (TC.2.3)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * PTroro * RoroShare * WCroro \quad (TC.2.4)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * DistOrigportDestport_{(p,q)} * LoloShare * FClolo \quad (TC.2.5)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{q \in Q} QtyOrigportDestport_{(i,j,p,q)} * PTlolo * LoloShare * WClolo \quad (TC.2.6)$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{q \in Q} QtyDestportDest_{(i,j,q)} * DistDestportDest_{(q,j)} * [FCroad + (Tax * TaxIndex)] \quad (TC.2.7)$$

5. Data

To approach as much as possible the reality of the distribution network in the BSR, data were mainly taken from the literature and from national or European statistic databases. As explained in the literature review, scarcity of data is sometimes a problem. There is a lack of publicly available data for SSS, which explains the large panel of different sources to gather all the data needed and sometimes the numerous transformations they are subject to in order to have relevant information for this paper.

5.1. Demand parameters

In order to develop the OD matrix which will be incorporated in the parameter " $D_{(i,j)}$ ", two smaller OD matrices are developed. One with the total amount of exchange by road and another with the total amount of maritime trade between all the regions. The OD matrix that will be used in the model is simply the sum of both the road OD matrix and the maritime OD matrix. (cf. annex E, p. 8-9)

For the first sub-table, the one concerned with the total amount of merchandise exchange by truck between each pair of regions, the table is constructed in the following way. The start was with a table describing the total amount of exchange by truck between each of the eight countries considered in this paper, given by (Eurostat, 2021-b). To derive the amount of exchange for each NUTS 2 region, this table was multiplied by the share of the population living in the origin NUTS 2 region and the share of the population living in the destination NUTS 2 region (Eurostat, 2021-a). (cf. annex C, p. 4-5)

For the second sub-table, the construction of the table is different. The matrix is created by starting with the total quantity loaded in each origin NUTS 2 region (Eurostat, 2021-e). Taking only the loaded merchandise allows to avoid problems with double counting. These quantities are multiplied with the share of merchandise that belongs to the type of commodity considered in this work, which are containers and other cargos. The share of relevant commodity varies by country, the figures are from (Eurostat, 2021-d). Then, the total quantity of relevant commodities loaded in each country is multiplied by the percentage of exchange between the origin country and the destination region (Observatory of Economic Complexity, 2021). This helps exclude the merchandise that wasn't for one of the eight chosen countries. Finally, the remaining quantity is multiplied by that of the population living in the NUTS 2 region (Eurostat, 2021-a). All these transformations result in the obtention of an origin-destination matrix for maritime transport.

It should be noted that every NUTS 1 region selected for this paper has a coastline in the Baltic Sea. But this is not the case for every NUTS 2 region. For the destination region without a coastline, the share of population living in it was added to the share of the closest region having access to the sea. So, the merchandise intended for the region without sea access would arrive in the nearest port. (cf. annex D, p. 6-7)

5.2 Distance parameters

For the unimodal 1st link category, the 870 links connecting every centroid with each other, the distance was retrieved with the tool (Google Maps Platform, n.d.). The same goes for the 1860 links belonging to the category multimodal 1st link and the 1860 links from multimodal 3rd link. As far as the links between ports are concerned, the category multimodal 2nd link contains 3782 links. They were all calculated with the tool (Seamatrix, 2020).

From these four tables giving the distance between every link, four other matrixes can be derived. These are dedicated to the length of the trip in hours. To calculate it, the distance in km is divided by the average speed on the link. For the road link, an average speed of 65 km/h was chosen following what was done by Santos & Soares (2017). The same paper is recommending very low speed for the maritime transport in order to be really competitive regarding the emissions of pollutants. So, an average nautical speed (ANS) of 14 knots was chosen. It equals to 25.928 km/h.

Finally, the transport by truck is also impacted by the breaks that the driver must take. Based on the European guidelines, the repartition of driving hours and breaks chosen is the following. The driver must take 11,75h break every 9,33h driving (European Commission, n.d.-a). The tables giving the time needed to connect two nodes are divided by 9.33h and rounded downwards. It results in three new tables giving the number of breaks to be taken for each road link. Maritime transport is not impacted by breaks but rather by waiting time in port when the vessels are loaded or unloaded. The ro-ro vessels are assumed to have short waiting time due to the easiness of the loading/unloading operations. The waiting time used by Morales-Fusco et al. (2012) is 4 hours in each port. The lo-lo vessels have much longer idle time during port operations. The average loading/unloading time of one container is equal to 1.52 min (Serry, 2020). With the characteristics of the lo-lo vessels considered in this paper, it results in 23.92 h waiting in each port to be completely (un)loaded. These waiting times are represented by the parameters "*PTroro*" and "*PTlolo*", respectively.

5.3. Vehicle description

Three different vehicles are considered in the model. Road segment will be made by truck and sea segment will be assumed with ro-ro or lo-lo vessels.

Based on the data used by Vierth et al. (2019), the truck has the following characteristics: a gross weight of 40 tons, a maximum load capacity of 28 tons and an average utilization rate of 86%. This gives an average load capacity of 24 tons for every truck. Every container will be assumed to have this weight, regardless of mode of transport.

The type of ro-ro vessel used has a dwt of 24,485 tons, a loading capacity of 342 trailers with a utilization rate of 80%, which results in an average loading capacity of 273.6 trailers loaded with 24 tons of merchandise each, for an average loading capacity of 6,566.4 tons. These data were taken from the paper of Vierth et al. (2019) and the website Vessel Tracking (2021). The ro-ro vessels are assumed to transport 48.98% of the total quantity transiting by SSS (Eurostat, 2021-g), this share is represented by the parameter "*RoroShare*".

The lo-lo vessel is assumed to be very large and have a dwt of 83,122 tons and an average GT of 36,100 tons. Coupled with a utilization rate of 68%, it results in an average loading of 22,071 tons or 920 trailers equivalent. These data were taken from (Jankowski, 2021 ; Van Der Meulen et al., 2020). The lo-lo vessels are assumed to transport 51.02% of the total quantity transiting by SSS (Eurostat, 2021-g), this share is represented by the parameter "*LoloShare*".

5.4. Emission parameters

Emissions also vary following the mode of transport. As in the paper of Vierth et al. (2019), the website NTM was used to compute the emission from each mode (Network for Transport Measures [NTM], 2021). For the truck, a reference route is chosen between Copenhagen and Stockholm and the emissions are calculated as if a truck like described in the previous section was doing the trip. The same origin and destination are chosen for the reference maritime route, and the emissions are calculated in the same way. These emissions are then adapted to the assumptions made for this model. As a reminder, the truck is assumed to be a Euro VI vehicles and then to be running with ultra-low sulphur diesel. As for the vessels, they are assumed to be under tier III regulations and to respect the emissions limits of the SECA and the NECA zone.

Table 7: Consumption and emissions from each mode of transport

Emissions	Unit	Truck	Ro-ro	Lo-lo
Fuel consumption	[L/100 km]	44.40	50.18	141.78
NO _x emissions	[g/ton*km]	0.03211	0.13621	0.12048
SO ₂ emissions	[g/ton*km]	0.00042 (*)	0.00075 (*)	0.00063 (*)
PM emissions	[g/ton*km]	0.00104	0.00512	0.00386
CO ₂ emissions	[g/ton*km]	53.45	31.20	22.64

The data related to emissions of SO₂ is not the one from NTM, the different values were attributed following the assumptions made on the mode. For the truck, it is assumed to be running with ultra-low sulphur diesel with no more than 10 ppm of sulphur content, which represents 0.010 g per liter of fuel. For the vessel, the SECA regulations prevent the ships to emit more than 0.1% of sulphur by mass of fuel. The level of emissions is therefore derived from the fuel consumption given by NTM (NTM, 2021).

5.5. Cost parameters

For the transportation cost, the values of the freight transport for the three modes are the ones used in Vierth et al. (2019). The cost allocation is derived from the paper of Van Der Meulen et al. (2020) like the waiting cost. With regard to the inventory cost, the value used by Santos & Soares (2017) was used and applied all the same for the three different modes. The opening costs were set to this level to be more realistic and to reach a modal split in the base case that approaches the reality as much as possible. Finally, all the costs linked with externalities come from the European guidelines as presented in Vierth et al. (2019).

Table 8: Cost value by type of vehicles

Costs	Unit	Truck	Ro-ro	Lo-lo
Transport costs	[€/ton*km]	0.0511	0.022	0.022
• Fixed costs	[%]	8.06%	27.18%	27.18%
• Variable costs	[%]	37.43%	45.03%	45.03%
• Staff costs	[%]	44.56%	11.11%	11.11%
• Mode-specific costs	[%]	0.58%	13.35%	13.35%
• General operating cost	[%]	9.37%	3.33%	3.33%
Waiting costs	[€/ton*h]	-	0.0846	0.0252
Inventory costs	[€/ton.h]	0.007	0.007	0.007

Costs	Unit	Truck	Ro-ro	Lo-lo
Opening Costs	[€]	0.1	1,000,000	1,000,000
Externalities Costs				
• Wear and tear	[€/km]	0.068	-	-
• Accidents	[€/km]	0.011	-	-
• Noise	[€/km]	0.045	-	-
• NO _x	[€/g]	0.00525	0.00521	0.00521
• SO ₂	[€/g]	0.00539	0.00544	0.00544
• PM	[€/g]	0.01458	0.0145	0.0145
• CO ₂	[€/g]	0.00011	0.00009	0.00009

5.6. Additional data for scenarios

All data for scenario 1 has already been presented. In this scenario, only the objective function is modified.

As far as scenario 2 is concerned, two new parameters are introduced, "*Tax*" and "*TaxIndex*". The first parameter ranges from 0 to 0.040 €/ton.km in increment of 0.005. This way, tax is first very small and with a relative impact and then increases to reach nearly the same cost per ton-kilometer as the freight cost from the trucking industry. When the tax is zero, this case will be the same as the one studied in the base case. For the second parameter, "*TaxIndex*", it is the result of the following calculation: the average externalities cost per ton of goods imported for each country calculated in the base case is divided by the population of this country (Eurostat, 2021-a) to result in the externalities cost per capita, then is multiplied by the GNP per capita (Eurostat, 2021-f) to make the tax equal for every country. These tax indexes are the following.

Table 9: Tax index by country

	DK	DE	EE	LV	LT	PL	FI	SE
TaxIndex	0.811	0.976	1.000	0.594	0.618	0.137	0.916	0.478

6. Results

This chapter submits the different results collected after running the model and its extensions with the two scenarios. It is logically divided into three different sections. The first section is dedicated to the base case and its results. The second presents scenario 1 and the difference between this and the initial base case. The third section does the same with scenario 2.

6.1. Base case

The results of the base case are presented in this section. As for the two following sections, it will be divided into four different subsections to respectively analyze the modal split and the economic, environmental and social aspects.

6.1.1. Base case - modal split

Three different modal splits can be taken from the results of the model. The first is a "*classic modal split*" that gives the share of goods in tons handled by the unimodal solution, and the share handled through the multimodal solution. The second: a "*statistic modal split*", like the one that can be calculated using the road OD matrix and the maritime OD matrix. This statistic modal split will take the amount of goods transported between every country. This means that the goods transported through the unimodal solution will be included as the goods transported by truck internationally during their multimodal journey. The last modal split will be referred to as the "*real modal split*" and will give the quantity of goods in ton-kilometer transported by each mode.

After running the model for the base case, the results for these modal splits are given in the following two tables.

Table 10: Modal split between the unimodal and the multimodal solution in the base case

Modal split	Unit	Unimodal solution	Multimodal solution
Classic modal split	[ton]	18.15%	81.85%
Real modal split	[ton*km]	8.02%	91.98%

Table 11: Modal split between road and maritime transportation in the base case

Modal split	Unit	Road transport	Maritime transport
Statistic modal split	[ton]	30.15%	69.85%
Real modal split	[ton*km]	38.26%	61.74%

As the construction of the OD matrix has been done in two steps, with the road OD matrix first and then the maritime OD matrix, the proper modal split that the model should approach can be calculated. Following the two OD matrixes, the share for the road should be about 35.31% and the remaining 64.69% are for maritime transport. These figures can be compared to the "statistic modal split" and can be interpreted as a measure of the model's accuracy.

The low share attributed to unimodal transport is not a trend repeated in every country of the BSR. The share in the mode used for transportation of goods in each country is given in *figure 8*.

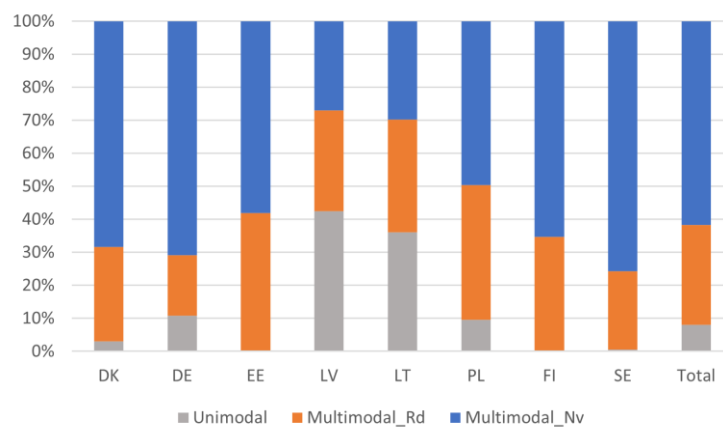


Figure 8: Share of quantity transported (in ton-kilometre) on each mode of transport by country for the base case

It should be noted that these modal splits are based on the import at each stage of the transportation. The quantity import by one country for the multimodal 1st link will be transferred to another country and will not be consumed by the inhabitants of the first country, but it will be included in its share of goods transported through the multimodal solution. In this base case, there are not enough maritime links open to enable each centroid to import and export from their own ports. This explains the high share of ton-kilometers attributed to the multimodal transport by road. Each centroid must send their export to the adequate port with a maritime link opened towards the destination they want to reach; this port cannot always be in the surrounding with only 84 maritime links opened.

Figure 8 shows the important shares that Lithuania, Latvia, and Poland have for road utilization (Unimodal + Multimodal_Rd). For Poland and Lithuania, one explanation is the absence of coastline for some of their NUTS 2 regions included in this report. Truck utilization is therefore an obligation and not a choice, unlike other regions. Latvia has the greatest share of road utilization even though its unique centroid is situated alongside the port of Riga. The proximity between Riga and the two centroids of Lithuania explains this: more than 2.5M tons is transferred using the unimodal solution from Lithuania

to Latvia. Additionally, the distance between Vilnius (one of two centroids in Lithuania) and Lithuania's coastline is similar to the distance between Vilnius and Latvia's coastline. Consequently, part of Lithuania's export is loaded into the port situated in Latvia, which increases the quantity of ton-kilometers of goods going into Latvia by road.

6.1.2. Base case - economic aspects

Three different costs appear in the base case: transport costs, inventory costs, and opening costs. The weight of each of these costs relies on the mode used for transportation. In terms of transport costs, maritime transport holds the advantage, however transportation by truck is cheaper for the two other cost types.

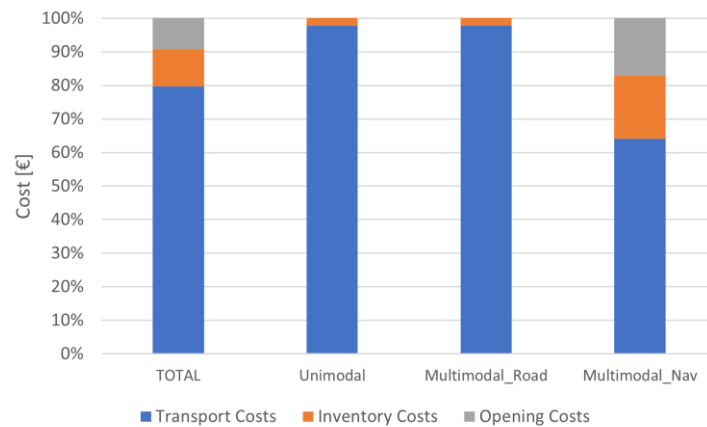


Figure 9: Cost repartition following the mode of transport used for the base case

Transportation by road is much faster than SSS and it results in very few inventory costs incurred by the shipper. With the low ANS in addition to the loading and unloading time, goods remain in the pipeline stock for a long period with the multimodal solution. This is translated into larger inventory costs. Costs linked to externalities are not represented in this *figure 9* as they are not internalized in the base case.

With only 84 maritime links opened out of the 3782 available, truck transport plays a crucial role in the transportation of merchandise between centroids and appropriate ports. But this large employment of trucks comes with a great amount of costs. The sum of transport and inventory costs for the road legs of the multimodal solution represents 36.6% of the total cost. However only 30.2% of the total amount of ton-kilometers are transported through this mode.

6.1.3. Base case - environmental aspects

The costs resulting from the externalities are not in the objective function but nevertheless exist. Their distribution according to each type of mode is given in the following figure.

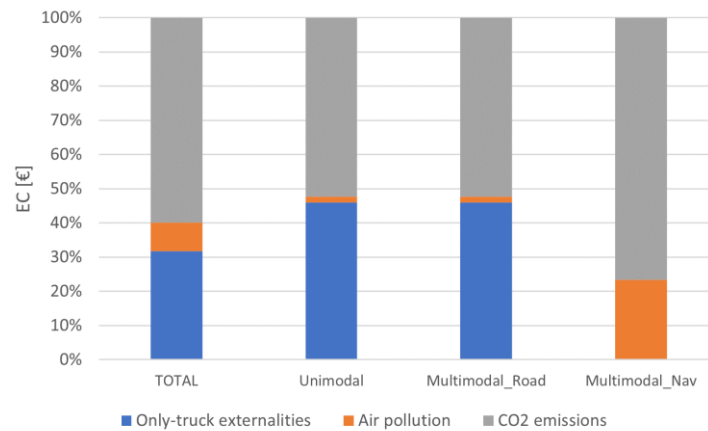


Figure 10: EC repartition by each mode of transport in the base case

The three main categories of externalities are represented in *figure 10*. Transportation by truck is accountable for 68.8% of the total amount of EC. This large amount is a consequence of the additional externalities trucking is accountable for and the slightly larger fees for every negative externality. The EC linked with air pollution is largely issued from the maritime transport as the trucking industry shows a low emissions factor. Still, the share of air pollution costs is minor compared to the two other types of externalities. Finally, CO₂ emissions are the most expensive external cost in this base case. Maritime transport has an advantage over road regarding its lower emissions rate but remains a great contributor due to the large quantity transported.

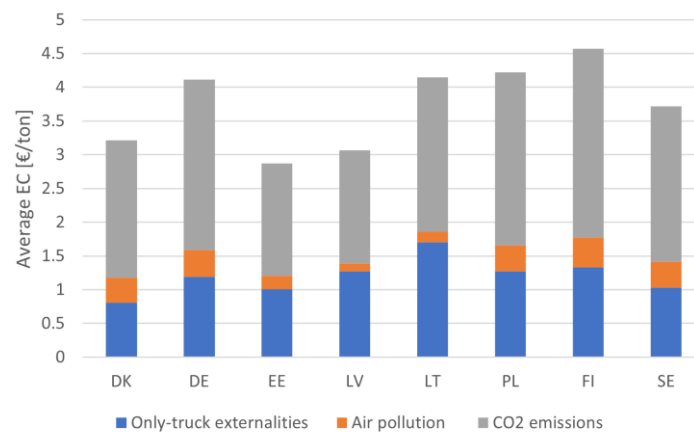


Figure 11: Average EC paid to import 1 ton of goods by each country

The average EC caused by each country is based on the externalities linked with the transport of merchandise imported by the country. Externalities that result from the transportation on one of the multi-modal 1st links will be the responsibility of the country at the end of the chain. Lithuania and Poland reach a high average due to their lack of sea access. Sweden and Finland have two issues that increase their average EC: some of their NUTS 2 regions in the north are farther away from the rest of the economic area so they have a longer trip distance regardless of which mode is chosen, and the landscape makes the on-land trip longer for trucks. For Germany, which also incurs a high average EC, the reasons involve the use of the unimodal solution with its two neighbors and the lack of an opened maritime link, which forces the use of long multimodal legs to connect centroids with ports.

6.1.4. Base case - social aspects

As seen in the literature, transportation can have socially impact in several ways. An overview of these impacts is represented through the figures in *table 12*. The costs resulting from the transport of merchandise will ultimately be supported by the end user - the people. The externalities that transportation is accountable for leads to negative social impacts such as the high number of accidents linked with road transportation, or the air pollution produced from maritime transport. Finally, the number of links open and the number of vehicles used are good indicators for both the activity level and the need for employment in the different sectors.

Table 12: Figures representing the social impact of freight transport in the base case

Name	Unit	Value
Total cost of transportation	[€]	919 M
Total cost of only-truck externalities	[€]	42 M
Total cost of air pollution	[€]	11M
Total cost of CO ₂ emissions	[€]	80M
Number of link open	[#]	84
Number of trucks	[#]	2,705,291
Number of vessels (ro-ro – lo-lo)	[#]	2,855 (2180 – 675)

6.2. Scenario 1

Scenario 1 is about internalizing all the costs linked with only-truck externalities (wear and tear, accidents, and noise pollution), air pollution (emissions of NO_x, SO₂ and PM) and CO₂ emissions. Integrating them into the objective function forced the model to adapt the modal split calculated in the base case into a solution that minimizes the total cost. Results from scenario 1 will be presented in a similar way to the results from the base case, with four identical subsections. In addition, each sub-section will also outline some comparisons between the base case and its extensions with the elements of scenario 1.

6.2.1 Scenario 1 - modal split

This integration of externalities costs makes the operations of the three modes of transport more expensive. This cost augmentation is even higher for truck transport, which is responsible for externalities not found in maritime transport. In this scenario, 10 additional maritime links are opened; these new connections allow for shorter distances in the transit of goods. This results in a decrease of the quantity of goods transported through the unimodal solution and on the 1st and 3rd links of the multimodal solution.

Table 13: Modal split between the unimodal and the multimodal solution in the scenario 1

Modal split	Unit	Unimodal solution	Multimodal solution
Classic modal split	[ton]	18.03% (- 0.12%)	81.87% (+ 0.12%)
Real modal split	[ton*km]	7.85% (- 0.17%)	92.15% (+ 0.17%)

Table 13 shows this slight decrease in the total quantity of goods transported through the unimodal solution. It represents 43 thousand tons of merchandise that switch from only road transportation toward a multimodal solution.

Table 14: Modal split between road and maritime transportation in the scenario 1

Modal split	Unit	Road transport	Maritime transport
Statistic modal split	[ton]	29.04% (- 1.11%)	70.96% (+ 1.11%)
Real modal split	[ton*km]	36.03% (- 2.23%)	63.97% (+ 2.23%)

The reduction of 2.23% in the real modal split for road transportation in comparison to the reduction of 0,17% in the same modal split for the unimodal solution highlights that most of the shift is made inside the multimodal solution. A large number of ton-kilometres transported on road during the multimodal transport in the base case is carried out by vessels and transported through SSS in the first scenario.

Figure 12 shows this decrease for the case where trucks are utilized in freight transport. This reduction is even more pronounced for the road legs of multimodal transport. The opening of supplementary maritime links creates a shorter path to connect the centroids and the ports. It should be noted that the total quantity of goods in ton-kilometre is slightly increasing. As the total amount of merchandise is steady, it meant that the total amount of kilometres must have increased.

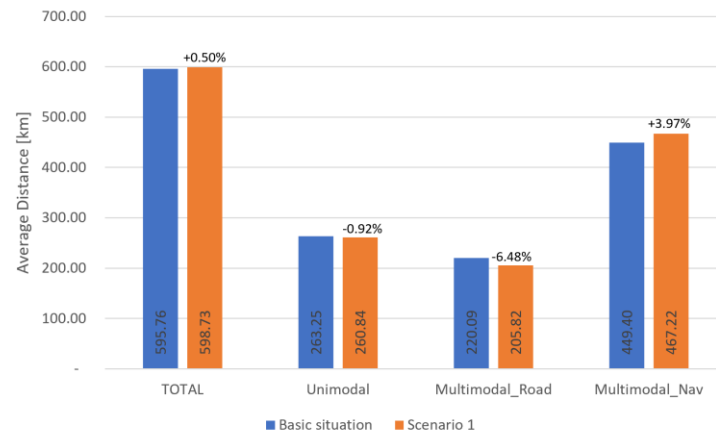


Figure 12: Average distance by mode in scenario 1

Figure 12 confirms that the distance has decreased for the links carried out by truck. Using road transport on long distances seems too costly with the externalities internalized. However, the average distance made by the vessels rises by nearly 4%. In general, the number of kilometres the different modes travelled in average is also going up. As the total quantity of goods transported in the base case has not been modified, this is a confirmation that the total number of kilometres has risen.

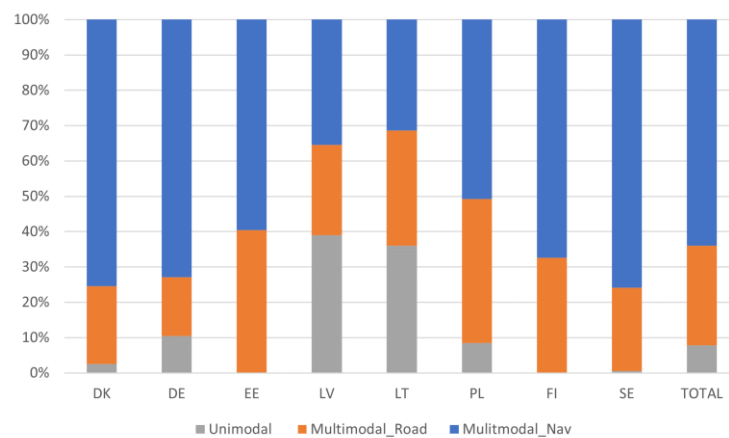


Figure 13: Share of each mode of transport by country in scenario 1

Each country seems to follow this general trend and reduce the amount of goods transported by truck whether it is through the unimodal or multimodal solution. With the opening of 10 maritime links, some countries can cut their quantity of goods transported by truck in the 1st or 3rd link of the multimodal solution. The connection between centroids and their most convenient port is now easier.

6.2.2. Scenario 1 - economic aspects

The modifications made in the modal split leads to some changes in the total amount of costs and the repartition of these costs for the different modes. *Table 15* compares each type of cost in the base case and scenario 1.

Table 15: Cost comparison between the base case and scenario 1

Type of cost	Unit	Base case	Scenario 1
Total transport cost (TC)	[€]	733.3 M	722.1 M
Total inventory cost (IC)	[€]	102.3 M	103.3 M
Total opening cost (OC)	[€]	84 M	94 M
Total externalities cost (EC)	[€]	132.7 M *	129.6 M
Total cost	[€]	929.6 M	1,049.1 M

* Externalities cost (EC) are not in the objective function of the base case and therefore, not included in the total.

Table 15 shows a drop of €11.2 M in the total transport cost. This is due to the growth in the total amount of goods transported by maritime modes. As the freight cost for trucks is the most expensive among the three different types of vehicles, the decrease in road transportation is correlated with the decrease in transport cost. This decline is slightly less pronounced since the total amount of kilometers has risen. The small increase in total inventory cost is a consequence of both the increase in quantity for maritime transport and the increase of average nautical distance. The total time of transit goes up, as the maritime vehicles are very slow in comparison with trucks, and this leads to a rise in the total cost of inventory. As the cost for opening a maritime link has been set to 1,000,000 €, the 10 new connections are inevitably increasing the total opening cost. Finally, externalities cost was not supported in the base case. These new costs are nevertheless optimized by the model and are, therefore, less important in scenario 1. Once again, the reduction in the use of trucks helps to diminish the total amount of externalities in monetary terms.

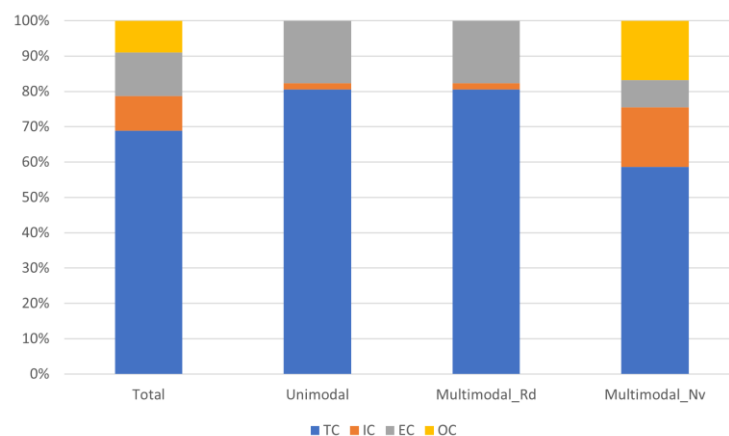


Figure 14: Cost repartition following the mode of transport used in scenario 1

The modes of transport using trucks (unimodal and multimodal_rd) had nearly 100% of their total costs from the transport cost in the base case. With the externalities finally internalized, the share of transport

cost inside the total cost is considerably reduced. Maritime transport has a smaller share of the total cost dedicated to these externalities as it does not have to pay as much. In general, the transport cost is decreasing but remains dominant while all three of the other costs are increasing. *Table 15* clearly shows that the sum of all these costs leads to a growth largely explained by the inclusion of EC in the objective function.

6.2.3. Scenario 1 - environmental aspects

The inclusion of externalities in this scenario forced the model to reduce the quantity of ton-kilometers attributed to truck transport. This led to several changes in the repartition of externalities costs and its total amount.

Table 16: EC level comparison between the base case and scenario 1

Externalities costs	Unit	Base case	Scenario 1
Only-truck externalities	[€]	42 M	39.8 M
Air pollution	[€]	11.2 M	11.5 M
CO ₂ emission	[€]	79.6 M	78.3 M
Total cost of externalities	[€]	132.8M	129.6 M

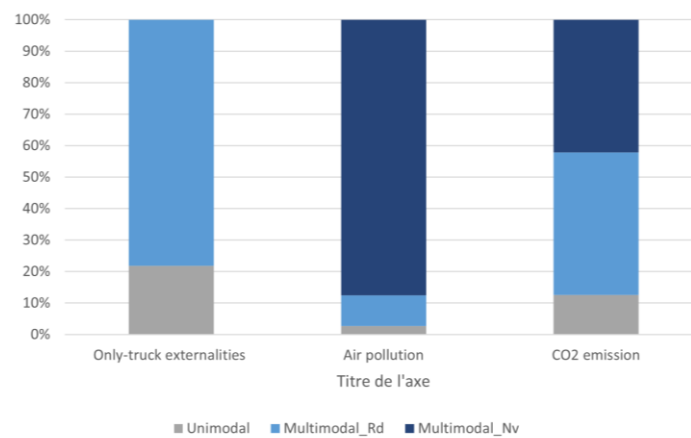


Figure 15: Share of EC each mode is accountable for by type of externalities.

The evolution in external costs to reimburse air pollution is subject to slight modification from the base case to scenario 1. The restrictions upon these emissions made them small in comparison to the CO₂ emissions. Trucking and the maritime industry both have small emission factors and therefore the switch from one to the other is of little consequence. Nevertheless, the maritime sector is less performant and is a major source of air pollution. Consequently, air pollution is marginally increasing in this scenario.

The switch towards SSS increases the total quantity of goods transported on sea and the average distance travelled by the vessels. Consequently, emissions of CO₂ go up for this mode. On the other hand, the reduction in truck utilization, which performs worse with regards to the CO₂ emission factor, enables the total balance to be negative. It results in a drop of 1.11% for the EC linked with CO₂.

This figure gives the share of externalities costs paid by each country. This is the repartition that results from scenario 1, but it is almost identical to that of the base case. Sweden, Finland, Denmark, and Latvia contribute to nearly three quarters of the total costs of externalities. As these four countries are also those that have the largest demand for goods, it seems logical.

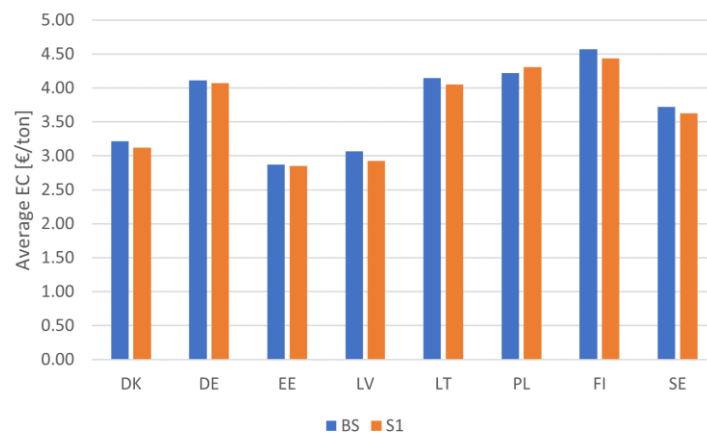


Figure 16: Average EC per ton by country

This figure gives the average externalities costs that each country must pay to import one ton of goods. Some of the countries around the BSR are not performing as well as Germany, Lithuania, Poland, and Finland. They are all above 4€/ton. This is the consequence of continuing to largely use truck transport despite the incentives for SSS. Poland and Lithuania have regions that do not have access to a coastline: truck transport is therefore not a choice but a necessity for them. Finland has a similar issue as some of their centroids are situated in the middle of the territory. Moreover, reaching the region in the north takes much longer and therefore results in additional externalities. Germany uses unimodal transport to exchange with its neighbors and it uses their ports. It consequently increases the length of the road legs in the multimodal solution.

6.2.4. Scenario 1 - social aspects

Table 12 can be used to enable a comparison between the base case and scenario 1 regarding the different figures representing the social impact from transportation.

Table 17: Figures representing the social impact of freight transport. Comparison between the base case and scenario 1.

Name	Unit	Base case	Scenario 1
Total cost of transportation	[€]	919.6 M	1,049.1 M
Total cost of only-truck externalities	[€]	42 M	39.8 M
Total cost of air pollution	[€]	11.2 M	11.5 M
Total cost of CO ₂ emissions	[€]	79.6. M	78.3 M
Number of link open	[#]	84	94
Number of trucks	[#]	2,705,291	2,707,115
Number of vessels (ro-ro – lo-lo)	[#]	2,855 (2180 – 675)	2,859 (2183 – 676)

On the positive side, the opening of ten maritime links will create direct and indirect employment that will surely benefit the people living around the concerned ports. Moreover, the number of trucks increases but the average distance travelled is going down. This decline is preferable due to the decrease of congestion and of the externalities linked with the trucking industry. Finally, the drop in CO₂ emissions is a positive outcome of this scenario with regards to how global warming affects people.

On the negative side, the global surge of total transport costs, which is mainly a consequence of internalization, will be supported by the end user of the merchandise. This will be translated as an increase in the price of goods coming from the BSR. Additionally, the increase in air pollution is harmful towards human health. SO₂ and NO_x emissions are contributing to the acidification of oceans, and it results in the formation of acid rain. Lastly, the diminution of truck transport utilization will go with a reduction of jobs in the trucking industry.

6.3. Scenario 2

Scenario 2 simulates the implementation of a kilometer-tax for road utilization. The value varies from 0 €/ton*km, which is the base case, to a tax level of 0.040 €/ton*km. The results from this scenario are given in this section with four different subsections. The base case will be included in the comparison thanks to the zero-tax.

6.3.1. Scenario 2 - modal split

The evolution of the statistical modal split according to the value of the tax is given in *table 18*. This evolution showed that with a kilometer tax of 0.010 €/ton*km the road share is already smaller than the one reached with scenario 1 (cf. table 14).

Table 18: Statistical modal split evolution following the tax level

Modal Split	BS	Tax level							
		0.005	0.010	0.015	0.020	0.025	0.030	0.035	0.040
Statistical modal split									
Road share [ton]	30.2%	29.4%	28.5%	28.1%	27.9%	27.0%	26.5%	25.5%	25.3%
Maritime share [ton]	69.8%	70.6%	71.5%	71.9%	72.1%	73.0%	73.5%	74.5%	74.7%
Real modal split									
Road share [ton*km]	38.26%	36.52%	34.83%	33.05%	29.89%	28.90%	26.73%	25.94%	25.83%
Maritime share [ton*km]	61.74%	63.48%	65.17%	66.95%	70.11%	71.10%	73.27%	74.06%	74.17%

Each increment in the tax is accompanied by a switch from road to SSS in the total quantity of goods in tons transported. This switch is even more pronounced in the total quantity of goods in ton-kilometer.

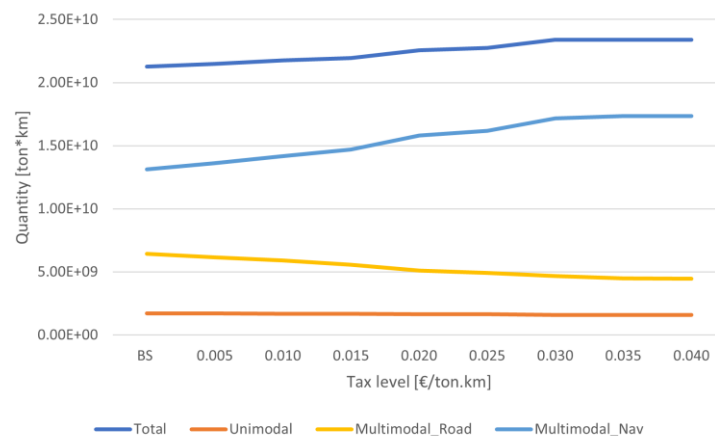


Figure 17: Merchandise repartition on the different modes following the tax level

Figure 17 shows that the quantity transported by the unimodal solution remained relatively steady despite the increases in the value of the tax. The real change is in the multimodal solution: the number of ton-kilometers transported by truck is lower when the tax is higher. This is compensated for by the large increase in the ton-kilometers carried out by maritime vehicles. In general, the quantity of goods to be transported is the same at each level of the tax, but the total amount of kilometers travelled to do it increases significantly as displayed in *figure 18*.

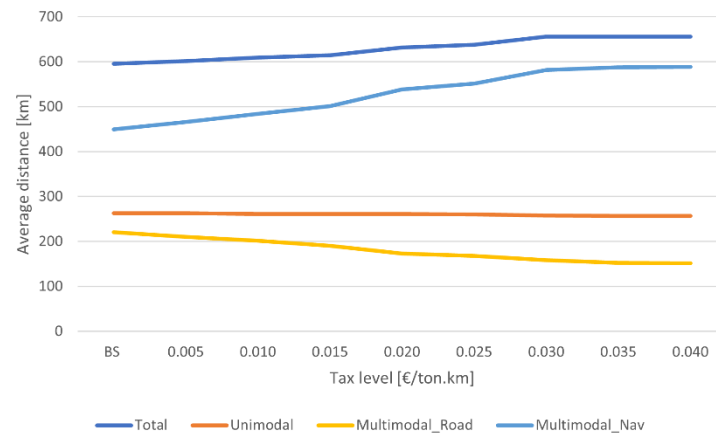


Figure 18: Average distance travelled by each mode following the tax level

For each reduction in the average distance travelled by truck in the multimodal solution, the equivalent increase in the average distance for ships is always greater. This results in an inevitable growth of the average distance for all freight transport in the BSR.

6.3.2. Scenario 2 - economic aspects

The evolution of global costs with tax level is presented in the following figure. The externalities costs are not included as they are not supported in this scenario.

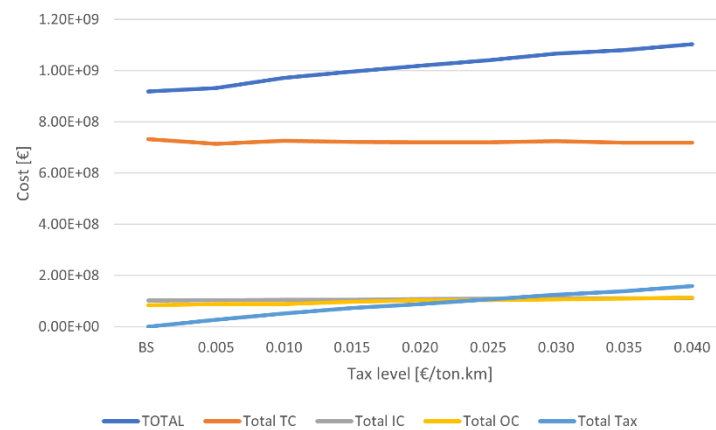


Figure 19: Total cost evolution following the tax level

As there are fewer truck transports, the transport cost decreases. However, the rise in the average distance travelled by the vessels increases the average transport cost for the maritime mode. Consequently, cost of transport is wavering but globally it tends to decrease with tax hikes. The two other costs, IC and OC, behave conversely and slightly increase at each new level of tax. They almost have the same level,

so the two lines representing these costs overlap (cf. figure 19). The last cost is link with the tax. The decrease in truck utilization is not strong enough to compensate the tax augmentation. Therefore, the total cost for tax is also increasing. This results in an augmentation in the total cost for the freight transport in BSR of nearly €200M with the highest level of the tax.

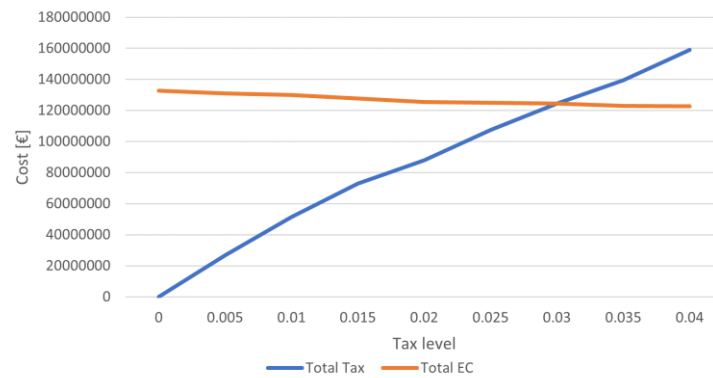


Figure 20: Evolution of the level of externalities costs and the total amount of tax in scenario 2

This figure shows the evolution of costs for reimbursing the externalities linked with freight transport. The tax is helpful on this point as the total level of externalities in monetary terms is indeed decreasing with the rising level of tax. Even if the quantity of goods shifted from road to maritime modes in scenario 1 was subject to a tax of 0.010 €/ton*km, the EC are far from internalizing at this level of taxation. The complete internalization of external costs is made around a tax level of 0.030 €/ton*km.

6.3.3. Scenario 2 - environmental aspects

Tax globally decreases the externalities costs as shown in *figure 20*, but each category, taken separately, does not evolve in the same direction. The modification of costs from only-truck externalities is displayed in the following *figure 21*.

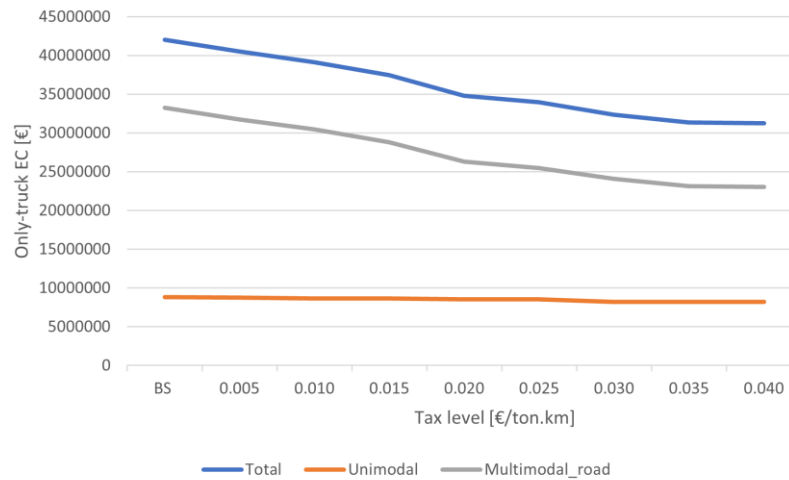


Figure 21: Evolution in the total cost for only-truck externalities by mode of transport, following the tax level.

Externalities that are only concerned by the trucking industry are obviously decreasing since the tax is on this type of vehicle and solely exists to discourage its use. The total cost for only-truck externalities in scenario 1 is equal to €39.8 M. In comparison, a greater EC reduction is reached with the second level of tax with a total of €39.2 M. The drop is even more evident at the tax level where externalities are totally internalized, with a total cost for only-truck externalities of €32.3 M.

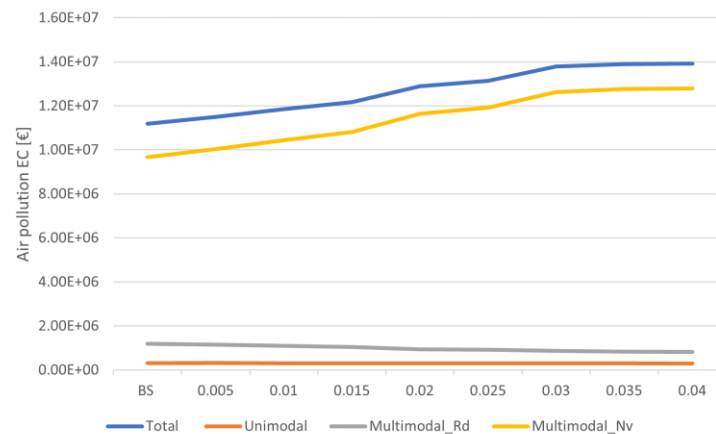


Figure 22: Evolution in the total cost for air pollution externalities by mode of transport, following the tax level.

The truck performs worse than both types of ship regarding air emissions. Therefore, it is not surprising to see the amount of pollutants emitted soaring with the rise in tax level. The increase in the quantity transported and the rise in the average distance for the maritime link are the two causes of these additional tons of pollutants.

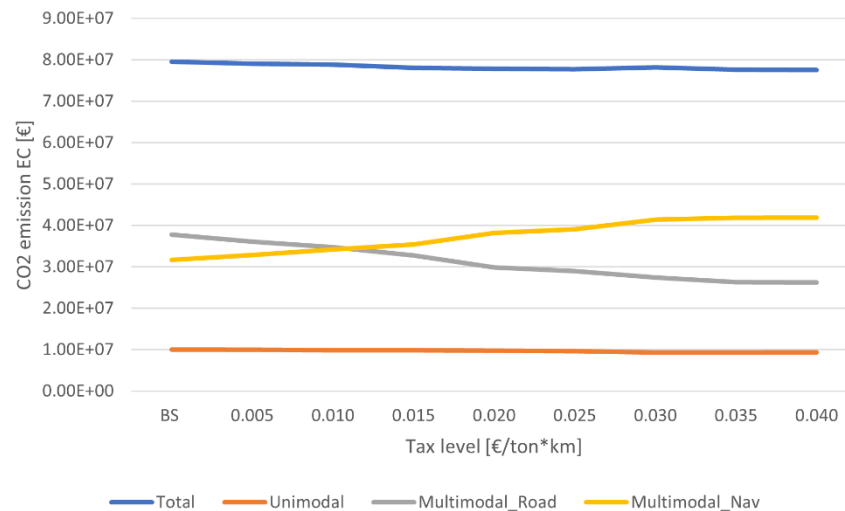


Figure 23: Evolution in the total cost for CO₂ emissions externalities by mode of transport, following the tax level.

Maritime modes of transport are cleaner than trucks in terms of CO₂ emissions. Nevertheless, as the average distance increases, the total amount of CO₂ emitted on every multimodal 2nd link is also going up. The opposite decline, thanks to the reduction of the average distance travelled by trucks on the multimodal 1st and 3rd links, made the total emissions of CO₂ variable. The total amount of CO₂ appears volatile and will sometimes increase with a more expensive tax. The total cost for CO₂ emissions was about €78.3 M. This total cost is smaller in scenario 2 where the tax exceeds 0.015€/ton*km.

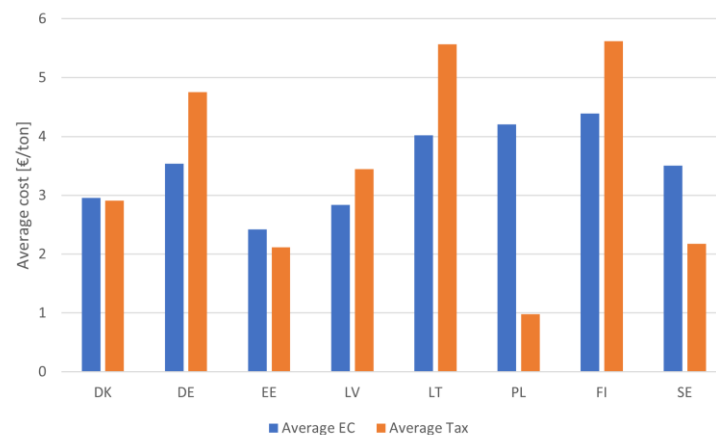


Figure 24: Comparison between the average EC and the average Tax for each country when the tax level is equal to 0.030€/ton*km

This figure represents the average value of the tax paid for the average EC each country is accountable for, regarding its import when tax is equal to 0.030€/ton*km. Tax is greater for countries still using a

large share of truck transportation like Finland, Lithuania, and Germany. This is true in all these cases except for Poland which has an abnormal level of tax for the level of EC it presents. These are the results of the "TaxIndex" parameter. Poland has a large population inside the 6 NUTS 2 regions considered and also has a low level of GDP per capita. This therefore results in it having the lowest index among the eight countries.

6.3.4. Scenario 2 - social aspects

On the negative side, the tax inevitably increased the total cost of transportation (cf. figure 19). This rise in costs will be sustained by the end user. Nevertheless, a small tax is more efficient than the internalization of goods - the results obtained in scenario 1 can be achieved with a smaller growth in the total cost. Another issue is air pollution: the increases in both the quantity transported by maritime transport and the average distance travelled by vessels is the cause of a significant rise in air emissions (cf. figure 22). These emissions have strong negative impacts on human health and are therefore a negative outcome of this tax. Finally, the level of CO₂ emitted does not seem to follow a particular trend with regards to the tax hike. The variations are not as clear as for the other externalities. The tax does not seem to act efficiently against the global warming linked with carbon emissions.

On the positive side, the tax is a significant boost for the maritime sector. It opens a lot of links between ports as exhibited in the *figure 25*. It therefore has a real potential to not only create direct employment with the transportation of cargos and business handling, but also indirect employment with the construction of new vessels, and perhaps even new terminals.

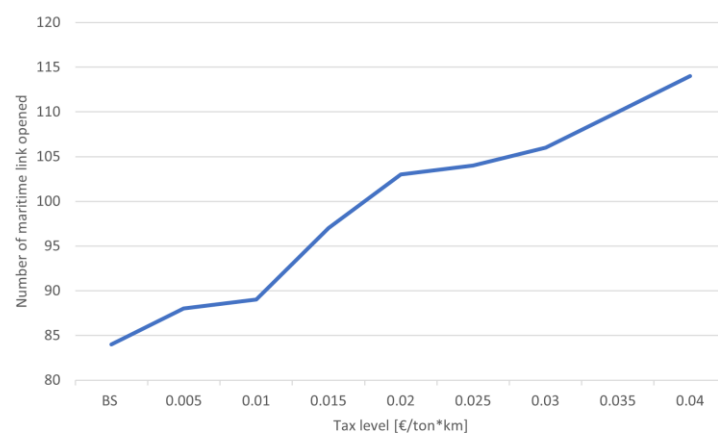


Figure 25: Number of maritime links opened following the tax level

Additionally, external costs from only-truck externalities drop with the rise in tax. This tax drastically reduced the average distance travelled by truck on the European road network. Thus, all externalities like wear and tear, accidents and noise pollution will follow this decline. Moreover, the lower levels of congestion on the network will boost this reduction in externalities.

7. Discussion

The objective of this chapter is to interpret the results of the different models in the aim of answering the principal research question: *"Would an implementation of incentives for the shift from road to short sea shipping for the transport of goods in the Baltic Sea have positive social, environmental, and economic impacts?"*

The principal research question is accompanied by two sub questions, which will also be addressed in this chapter. These two sub questions are as follows:

Which measure will be the most helpful regarding the objectives set by the European Commission on the modal shift level by 2030 and by 2050?

Which type of incentive can reach the desired objective while remaining fair for every stakeholder of the transportation network?

7.1. Results interpretation

In this section, the different results outlined in the previous chapter will be reviewed and used to answer the research question and the two sub questions. To do so, the four different subsections used in each section of chapter six will once again be employed.

7.1.1. The evolution in the modal split

In both scenarios, some of the quantity transported by truck is indeed shifted towards SSS. This shift is more important inside the multimodal solution where the average distance for road segments is decreasing and is being replaced by longer maritime trips. The longer trips made through the unimodal solution are also decreasing, as suggested by the data on average distances. But this decrease is far less pronounced seeing that most of the exchanges through the unimodal solution are made between neighboring countries. These types of exchanges are relatively fixed because shifting to SSS will mean travelling almost the same distance in the multimodal road segments than in the direct unimodal route.

Scenario 2 involves a kilometer-tax to enable a more aggressive switch from road to maritime transport. At a certain level, the tax occupied a large share of the total cost from trucking operations. In addition, the tax appears to be more helpful in moving towards the objectives set by the EC since only the road-based mode is targeted by it. As a reminder, these objectives are a shift of 30 % of road freight over 300 km to other modes by 2030 and 50% by 2050 (EEA, 2018). Results from both models indicate that an

incentive will indeed reduce the number of long-distance road transports and replace these with a multimodal solution. However, the results also suggest that this shift may considerably increase the average distance travelled by the maritime mode and increase the total number of kilometers needed to complete every exchange.

7.1.2. Economic changes

Results suggest an inevitable rising in the total amount of costs in the two applied scenarios. Even if both demonstrated a reduction in transport costs, the rise in both the other types of costs and the implementation of incentives still overcome this reduction. Upon considering the current environmental situation, leaving the external costs uninternalized seems irrational. Therefore, this increase in the total cost seems necessary. It should be noted, however, that the total cost might be overstated. The growth in the quantity transported by SSS should unlock synergies in the sector that are not considered by the model.

The growth in total cost is slower with the kilometer-tax from scenario 2 as it reaches similar results in term of modal split while being below scenario 1 in terms of cost. The reason for this is that scenario 1 made every type of mode pay for its own externalities while scenario 2 forces the trucking industry to pay for a percentage (depending on the tax level) of the total cost of externalities from the whole transportation activity in the BSR. Despite the index implemented, the incentives presented in the second scenario seem far from being fair. The maritime sector does not even have to pay for the externalities for which it is responsible. In addition, some countries have a significantly reduced access to a coastline in the Baltic Sea than others. For them, utilization of trucking is not a choice but a necessity.

The impact of an incentive on the economy seems unclear. On one hand the rise in the total cost will trickle down to the end user, who will face an increase in the price of final products. This may lower consumption levels and consequently, levels of importation. On the other hand, investment in the maritime sector is good for the GNP of a country. As developed in section 2.3 about sustainability, €1M investment in the European shipping industry will result in €1.6 million created elsewhere in the continent (ECSA, 2016).

7.1.3. Environmental changes

The results from both scenarios indicate that the environmental impact of these incentives on the different level of externalities is also balanced. The decrease in the use of road transport is inevitably accompanied by a reduction in the costs linked with only-truck externalities. Air pollution levels follow an

opposing behavior. As the progress in truck technologies enables the industry to show low factors for air pollutant emissions levels, the shift of merchandise towards SSS is increasing the total costs issued from the NO_x, SO₂ and PM emitted during transport. Regarding CO₂ emissions, the relevance of the incentives is not always clear. The emissions factors are smaller for the maritime modes but the increase in maritime distance comes with additional costs, which in several situations, overpowers the reductions made from the modal switch. To summarize, the implementation of incentives is helpful regarding the total cost of externalities but on a more detailed level, trade-offs do certainly exist. The decrease in road occupation allows for a decrease in wear and tear, accidents, and noise pollution, but will also cause more air pollution and have an uncertain impact on CO₂ emissions.

At this point it seems important to highlight some of the limitations and questions that will influence the effectiveness of an incentive on the level of externalities caused by transportation. First, some negative externalities have been excluded in this paper either in the aim of simplifying the model or because the impact of the externality was not documented well enough. Consequently, externalities like congestion, noise pollution from ports, air pollution from ports and noise pollution in the sea, have been defined as out of this model's scope. Furthermore, as presented in section 2.4, some measures already exist to help internalize part of the externalities caused by the trucking industry, for example, the Eurovignette and the occasional border tariff. According to the data, the transport cost attributed to road transport may have already considered these fees. If so, the level of externalities the trucking industry is accountable for may have been overstated in the model. Lastly, *sub-section 2.4.4* and *figure 3* demonstrate the potential of technology in reducing emissions in the trucking sector. Through the years, this evolution enables the truck to reach low emission factors and to perform better than SSS on air pollution externalities level. This technological progress may also be the answer for other types of externalities, such as the utilization of artificial intelligence inside trucks to avoid accidents. The shift from road-based transport to SSS induced by the presented incentives will slow down the development of such technologies.

Having considered all the above, it is clear that answering the question "*will an implementation of incentives to shift from road to SSS for the transport of goods in the Baltic Sea have a positive environmental impact*" is not so evident. Shifting part of the goods to SSS will indeed have positive environmental impacts but also negative ones. Neither road nor maritime transport can be defined as the perfect answer to environmental issues - the choice of one over the other is accompanied with a complex trade off.

7.1.4. Social changes

The results from the extended models with two scenarios implied similar conclusions. The social impact from the mode switch has some positive and negative aspects. As previously stated, the increase in the total cost will be supported by the end user with a rise in the price of goods coming from the BSR. It should be noted that for the same level of switching between modes, this total escalation in cost is less severe in scenario 2 than in scenario 1: the social impact is balanced. On one hand, the rise in prices will negatively impact the consumption of these goods and decrease the national level of import, and on the other hand, a reduction in consumption is necessary to decrease the level of externalities resulting from the transportation activity.

The results also reveal a rise in air pollution. Despite the ECA's zone, the maritime sector is still a much larger polluter regarding NO_x , SO_2 , and PM emissions. As outlined in the sustainability section of the literature review (section 2.3), NO_x and SO_2 emissions contribute to the acidification of oceans, resulting in acid rain that damages human health. On this matter, the social impact resulting from the modal switch of goods is clearly negative.

The final social impact caused by the introduction of incentives is the development of activity in the maritime industry. The growth in the total quantity handled, in the average distance travelled and in the number of SSS connections opened will have some positive social fallouts. Development in the industry will create direct employment with the transportation of merchandise and its handling, as well as indirect employment including the construction of vessels, the development of scrubber technology and the building of port infrastructures.

The introduction of incentives to shift part of the goods transported in the Baltic Sea from road to SSS will have some social positive impacts. But once again, these impacts are subject to a trade-off. The increase of the quantity of goods exchanged through maritime transportation is not desirable when considering the rise in total cost and in the air pollution level.

8. Conclusion

The purpose of this thesis was to investigate the economic, environmental, and social changes that an incentive to boost the utilization of short sea shipping over road for the transportation of merchandise will have. The evaluation of these modal changes between unimodal and multimodal solution was made through a many-to-many freight transport model. The model was applied to the Baltic Sea region and two separate scenarios were used to simulate two different incentive introductions.

According to the results, shifting part of the quantity transported in the Baltic Sea region from road to short sea shipping has some positive effects on economic, environmental, and social aspects. In this view, it can be suggested that public authorities introduce incentives to boost the utilization of maritime transportation. To do so, the internalization of external costs seems more appropriate than the introduction of a kilometer-tax for road utilization. Even if the tax can help in reaching similar results to internalization while achieving a lower amount of additional expenses in the total cost, forcing the trucking industry to pay for not only the externalities they have caused but also those from the maritime sector is unfair and would most likely be unrealistic.

This internalization of externalities costs seems necessary given the environmental and social issues known nowadays. It will indeed negatively impact the level of road-based transportation and the level of externalities correlated. The public authorities or the national organizations attempting to promote short sea shipping as a solid alternative to truck transport should also consider the negative fallouts of this switch. Maritime transport is not as green as it is sometimes portrayed. Certain evolutions in technology and additional regulations for the maritime sector are first advisable before considering it as the solution for a sustainable freight transport network and before promoting it further than the internalization of external costs. The two modes considered in this thesis, transportation by trucks through a unimodal solution and short sea shipping inside a multimodal solution, both have their strengths and their weaknesses, but for now, neither of them seems able to ensure a sustainable transport of merchandise.

This thesis aims at contributing to the literature covering the potential of short sea shipping in the European freight transport network in two ways: first, it provides a many-to many freights transport model which will enlarge the set of solutions available to analyze a transportation network, to study the modal split evolution in response to a change in parameters, and to shed some light over better decision-making processes. Secondly, it concludes the principal research question. Following the results obtained from the model, the implementation of incentives to shift from road to short sea shipping for the transport of goods in the Baltic Sea will indeed have positive impacts socially, environmentally, and economically.

Positive social impacts include the development of activity in the maritime sector that ultimately creates wealth and jobs, and the reduction in congestion and in the level of externalities linked with road transportation. Positive environmental impacts include the decrease in the total costs of externalities caused by transportation. Positive economic impacts include investments in the maritime sector that will positively affect the European GDP.

8.1. Limitations and further research

Before concluding this final chapter, it seems important to acknowledge some limitations faced by the thesis and how these may have impacted the quality of the research. These limitations are linked to the data retrieval, the lack of previous research, and the scope of the discussion. All the data used in the model are secondhanded and comes from a large set of different sources. Some faced significant modifications before being used as inputs such as the origin/destination matrix. This data retrieval method increases the risk of biases inside the model. Additionally, some limitations arise from the lack of documentation. To give an example, the level of externalities coming from port infrastructures and the share of externalities from trucking industries already internalized are difficult to determine within the current literature. This may have consequences on the model's accuracy, specifically regarding the level of external costs a mode is accountable for. Lastly, my young experience in research, in creation of complex freight transport model and in the writing of long academic paper may lead to limitations in the depth and the scope of the discussion.

Further research and discussion on this subject could broaden the area and the number of modes considered in the network. It could also explore the less documented externalities that concern the shipping industry. Finally, it would be interesting to discuss methods of improving both the sustainability of short sea shipping, but also, of transportation in general.

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