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Operations Research as a tool to decrease the environmental impact of freight transport in Norway

Maxime Petit

Supervisors: Stein Ivar Steinshamn & Per Agrell

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Abstract

Over the past decades, the volume of freight transported over the world has increased a lot. It has allowed the freight transport sector to develop itself. Transporting commodities has become very efficient thanks to the use of multimodal containers. And these volumes are expected to continue to grow in the future. Despite it, transporting such high volumes has external costs. The most important one concerns the environment. The transport sector emits huge amounts of CO_2. This Greenhouse Gas is the biggest cause of the greenhouse gas effect which is itself the cause of global warming. The concerns around global warming are rising faster than ever and the transport industry must also deal with it. There will be a need for new and less consuming technologies, but these improvements cannot help a sufficient decrease of CO_2 emissions. That is why there is a need for structural changes of the transport sector. And more specifically, the transport industry needs the less consuming transport modes to be more competitive.

The aim of this thesis is to analyze and demonstrate how Operations Research can be a useful tool to help decreasing the CO_2 emissions of the transport sector. In fact, planning models are very effective to analyze and assess policies or other improvements that have an impact on the decisions made in the transport sector. In order to decrease the emissions, the external environmental cost has to receive more attention in the decision process of transport companies. The impact of strategic decisions on the distribution over the different modes can therefore be assessed with the help of tactical models.

In this thesis, a tactical planning model is built and adapted to national freight transport planning in Norway. This model is then used to assess multiple strategic policies. The conclusions of the different policies tested are drawn at the end of the document. The model can easily be adapted to multiple different situations and the mechanisms used in this paper are adaptable beyond the Norwegian example.

Keywords – Freight Transport, Modelling, Operations Research, Environment

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1 Introduction

With the recent globalization that has taken place, transport all around the world has become a very important activity. Both passenger and freight transport have known an impressive surge in the last decades. And this surge is not meant to stop in the near future. However it is always difficult to predict the exact growth of these markets more than ten years ahead, the only certainty is that the number of people and the amount of commodity transported over the world will continue to grow.

This enormous increase in connections between all the parts of the world and the enormous progress made in the transport industry have had a lot of social and economic benefits over the year. But while these benefits are undeniable, other more negative counterparts have been brought to light since the end of the 20^{th} century. Probably the most important one being the emission of greenhouse gases that are produced by the transport industry. While the share of total GDP is equal to 5% for the transport sector in Europe, it causes around 25% of the greenhouse gas (GHG) emissions (OECD, 2018a).

Up to now, the driving factor for the organization of transport has always been maximization of the profit. Operations research have helped a lot in order to reach this objective. Through the years, models have been developed and become more complex including precise forecasts of the demand until the final allocation of travelers or commodities on different transport modes. A lot of aspects have been added to the very first basic models. In fact, inventory costs, congestion costs, expected costs of accidents are now all taken into account when countries or regions make their own models up. Regarding this, there should be a way to take the environment into account.

In this thesis, the objective is to show how Operations Research can help taking decisions in order to minimize the environmental issues of freight transport. A deeper focus will be put on strategic decisions on regional/national level. It will be illustrated with a concrete example of transport in Norway. Therefore, a self-made model based on models of the literature will be presented with data gathered from different sources and treated to fit for the model. Results and sensitivity analyses will be presented and linked to potential investments decisions, policies and how to help coordinating financial and environmental objectives.

The general context will first be described. It contains the most important information about freight transport and the environmental issues caused by this industry. The different steps for the allocation of freight transport will also be described. A literature review containing some existing models has also been made. After this, the model and its data are going to be broadly presented with all its potential uses. The results will be analysed and some conclusions made thanks to these.

2 Context

2.1 Environmental issues in freight transport

With the surge in population of the last century and the continuity in growth happening this century, the need for energy consumption and other natural resources has increased a lot. Some of the natural resources like water and oil are even considered as marginal goods. But at the same time, demand continues to grow and countries continue to develop and generate wealth. Creation of wealth also means creation of new needs for consumer goods. This is a quite obvious spiral affecting the world since last century (Böhm, 2012). In 2017, the world trade volume increased by 3.6 % (OECD, 2018b). And in the last decade, freight transport grew by more than 30%. All these goods are transported either by standardized containers or bulk tankers. The main transport mode is also the cheapest one, namely sea transport. In 2016, sea transport accounted for just over half of all goods imported into the EU (Eurostat, 2017). The remaining freight transport is handled mainly by road, rail and air. It is undeniable that this increase in international connections and in transport has helped a lot to develop new technologies and increase the social welfare. But freight transport also brings some negative aspects with it. In Norway, transport consumed 27,2 % of the energy in 2015 and 86 % of this energy came from oil products (Energy Facts Norway, 2019a). Knowing the importance of petroleum as a natural good and knowing the emissions produced by this kind of energy, it is easy to already imagine one of the biggest issue of transport.

The environmental impact caused by transport consists of different aspects. The first and the most known one is air pollution. The Greenhouse Gas emissions of transport are very important. As already mentioned, it causes around 25% of the greenhouse gas (GHG) emissions in the world (OECD, 2018a). The most important gas emitted is CO_2 by far. But other gases are also emitted like carbon monoxide (CO), nitrogen oxides (NO_x) or Hydrocarbons (HC). Theses gases are the main responsibles for the greenhouse effect and i.e. of the climate warming. Besides the warming of the earth, each of these gases pollute the air and affect human health, biodiversity and the materials themselves (OECD, 1997).

Besides this, transport also pollutes water, makes noise and causes accidents.

2.2 Transport planning: a useful tool to reduce emissions

In order to reach the new emission targets set by different agreements and organizations, the transport sector needs some significant change. Of course, big investments have to be made in new more environmental-friendly technologies. A lot of small improvements are made every year in order to make cars, trucks or planes that have lower environmental impacts. But these improvements of the technology on their own will not allow to reach the target. Indeed, the freight transport sector is expected to continue to grow constantly over the next years and even decades (European Commission, 2018). Not only the total freight transport market is continuing to grow, but also transport by plane or truck which are the most polluting transport means. In Europe, road freight transport increased by 4.5% in 2017 (Fleet Speak, 2019). Therefore, new technologies can difficultly compensate this growth and reach the emission reduction targets on their own and there is a need for a change in the actual structure of the transport market.

If people want to continue to increase the transported volumes around the world, it seems clear that there is a need for a modal shift on the market. This modal shift should transfer some transport volumes from the most consuming transport modes to less consuming ones. To do so, new policies and improvements are needed in order to influence the choice of transport companies towards greener transport modes.

The actual main decision factor for the transport mode of common goods is the financial cost of transport. And, regarding the actual share around different modes, the actual cost structure is poorly influenced by environmental concerns. Indeed, the environmental damage is an externality for the principal decision makers and the cost of it is supported by the whole population. It results in an often too large utilization of transport modes that have high greenhouse gases emissions. There is no doubt that the financial costs will stay the most important decision factor in the next decades. It is therefore highly needed to give much more importance to environmental costs in the cost functions of the decision makers or to increase the competitiveness of transport modes that are in line with the emission reduction targets. To reach such results, strategic decisions have to be taken on a large scale.

The strategic decision-level concerns decision with effects on the long term. Such decisions have big impacts and always have influence on a lot of stakeholders. The impacts of strategic decisions such as policies or investments on the present infrastructures (Steadieseifi et al., 2014) can really involve big changes and huge emission reductions, but these decisions are also the ones that need to be thoroughly analysed before being implemented. One way to analyse strategic decisions, is to test the consequences of them at the tactical planning-level (de Jong et al., 2013b). Indeed, freight transport models are very useful as a tool to analyse the impacts of policies or measures. The tactical planning is assigning commodity flows to different transport modes and links. As this planning-level is directly influenced by the strategic decisions, it is often used to assess policies.

2.3 Problematic

As stated before, this thesis focuses on freight transport and on the environmental issues of the sector. As the environmental concerns will need more and more focus in the next years, it is important to develop strong and effective policies in order to reduce CO_2 emissions drastically. To be efficient, these measures need to be thoroughly developed and analysed. In this thesis, a freight transport model is used to analyze and develop policies reducing emissions in Norway.

On a theoretical part, this paper tries to give answers on how Operations Research can help reaching the emission reduction targets of the next decades. The aim is to demonstrate how freight transport planning models can be helpful tools to find the best measures and how to assess them. Even though a practical example is used to demonstrate the usefulness of tactical planning, the methodology used in this paper can be broadened to other situations.

On a more practical aspect, the model is applied to the Norwegian freight transport market. The objective of this application is, first of all, to demonstrate how tactical models can be used and how to interpret these measures. The aim is to assess future potential policies in Norway, but also to find the most efficient way of implementing them.

To sum up, the problematic tackled here is the development of tools to assess environmental measures. This thesis aims to answer to the question *How can tactical planning be used as a tool to assess environmental policies and develop efficient measures in order to reduce greenhouse gas emissions from freight transport?*. The answer to this question is given through an example which is the Norwegian national freight transport market. The model and conclusions are kept as general as possible so that the methodology can be easily transferred to other cases.

3 Literature Review

In this chapter, all the theoretical framework of this thesis will be provided. The literature is mainly composed of scientific articles. University papers, encyclopedias, peer reviewed articles, websites etc. were also used in order to diversify the sources.

This review will be introduced by some information about freight transport in general. It will include a brief historical perspective and some actual trends. Further on, the focus will be made on the environmental aspects of this activity. A special attention will be put on freight transport in Norway. Once the basics are put in place and all the aspects of freight transport are clear, the review will be focused on the link with Operations Research. It will begin with a very broad review of all the aspects Operations Research take care of when it comes to the planning and assignment of freight transport to types of mode and routes. Afterwards, the representation method of transport networks will be described. Finally, the review talks more specifically about tactical planning for strategic decisions and the modelling at this decision level.

3.1 Freight Transport

3.1.1 Freight Transport in general

According to the website Freightquote (2018), freight transport or shipping *"is the process of transporting commodities, goods and cargo by land, sea or air"*. The freight are the goods or commodities that are transported. As stated in the definition, this activity consists of 3 main transport areas. The first one is the transport on the ground. It can be divided in two categories, namely trucks and trains. Trucks usually transport one or two containers while a train can carry more containers. Secondly, transport on sea is carried by ships. Usually, the ships are huge container ships that can transport more than 20,000 containers for the biggest ships. 90% of the total tonnes.km transported in the world are done by ship (International Chamber of Shipping, 2018). Thirdly, transport by air is also a possibility. Freight is then carried by aircraft. This mean of transport is clearly the most expensive one, but also the quickest one over long distance. A fourth mode is also often used, namely pipelines. It consists of exclusively bulk that is transported in special pipes above or under the ground. This type is out of the scope of this thesis and therefore it will not be considered in the literature and further analysis.

Nowadays, it is very usual for a commodity to be transported from its origin to final destination by different means of transport. This is called intermodal freight transport. The main invention that has made intermodal transport that easy is the invention of the standardized container. The shipping containers are steel boxes of standard sizes. They can be transported on ships, trucks, trains and even in some aircraft. Its invention in the 1950's has had an enormous impact on the shipping industry, but also on local development and global economy (Thomlinson, 2009). The use of this container has reduced a lot the cost of time and money in the handling of freight. Containers are easily transferred from one to another transport mean. The standard size of a container is 8 feet (2.44 m) wide by 8 ft 6 (2.59 m) high. The length is usually either 20 or 40 ft. The size of a container is often expressed in Twenty-foot equivalent units (TEU) which is the capacity of one 20-feet standard container (Wikipedia, 2019). The invention of the standardized container and the rapid spread of its utilization around the world have been a driver of the globalization that has taken place the last decades. The strong increase in population and new trade agreements have pushed this globalization a bit further and the number of goods traded has increased significantly since then. It has become normal to outsource in different parts of the world and to transport materials from anywhere in the world thanks to the really strong decrease in the costs of transporting goods. The number of goods transported around the world has exploded and freight transport has become a very important industry. This important increase of transport around the world has also strengthened the importance of cost-efficient decisions in terms of commodity transport.

3.1.2 Competition between modes

The modal split is the partition of all the flows into the different modes. In most of the cases, the transport of a product does not give any additional value to its final product and therefore the objective when deciding about the transport mode is to minimize costs. Transportation costs are often accounting for around 10% of the total costs of a product (Rodrigue, 2017). The competitiveness of transport companies is mainly based on costs and it has pushed the costs of transportation to extremely low levels compared to a few decades earlier. Of course, these huge improvements in cost-efficiency of transport have helped a lot in the enormous increase of goods transported over the world. In fact, if transport costs double, the total flow of goods in the world would decrease by 80% (Rodrigue, 2017). The most costly parts of a journey are the first and last parts, known as first and last miles.

A lot of factors have to be taken into consideration when the costs have to be calculated. The book *Transport Systems* written by Rodrigue (2017) goes through all these factors. A first important factor is geography. It impacts both distance and accessibility. Distance is the main influence for the costs. A good that needs to be transported over a long distance will obviously have bigger transportation costs than a good transported over a shorter distance. Accessibility is also very important. The less accessible are the origin and destination points, the less possible modes and vehicles can reach them. Of course, places with poor accessibility need more expensive and very specific vehicles to be reached. Transport costs can also vary a lot depending on the type of product. Some products need special storage conditions during transport, need to be transported quickly or need a careful handling. Of course, the more constraints added on the transportation conditions, the more expensive the transportation becomes. In parallel with the type of products, the value of the product is also very important. As the products are investments waiting to be sold, they have a certain capital cost. A product in the transportation process is capital immobilized. The more value a product has, the more important is the time factor in the transportation costs. Also, the value of products broken or lost are very obviously more expensive for products of high value. The yield of a transportation mode and its handlings become more important for high-value goods. Economies of scale are another influence of the transportation costs. These economies of scale are favoring large transportation modes and vehicles. Bigger trucks, longer trains, taller containerships lead to lower costs per tonne transported. Energy is also important and will become more important in the future. The fuel costs are not to neglect when choosing the type of transport. These fuel costs are also influenced by another important factor which is the taxes. Taxes can be added on almost any cost type. From road or fuel taxes to environmental taxes or taxes on the wages, they influence very importantly the transport decisions. All these factors are only the major ones, but a lot of other more specific factors are also part of the cost structure of the transport sector.

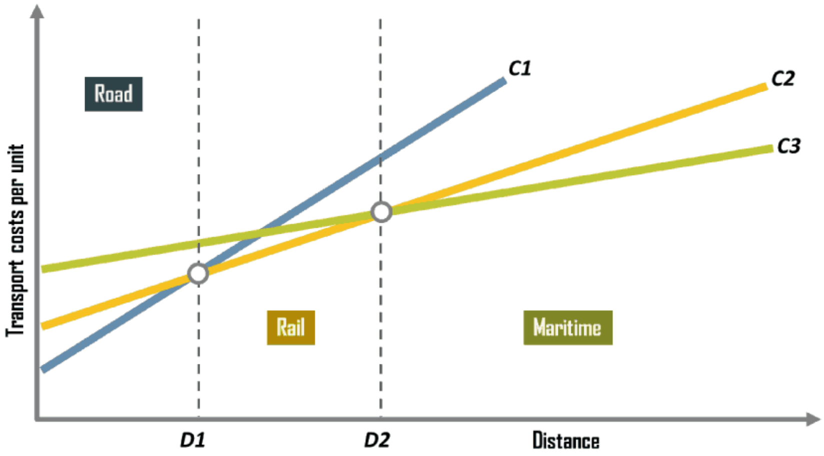
Still according to Rodrigue (2017), there are three main types of costs. The first type is often the first cited and is here called 'linehaul costs'. These costs are proportional to the distance and contain the fuel costs, labor costs and basically all the operational costs that take place during the transport itself. The second type of costs are the terminal costs. These costs occur at the loading or unloading and at the transshipment of the goods. Each good has to be loaded and unloaded once at origin and end destinations. During its journey, a good can be transshipped from one vehicle to another. The terminal costs can variate very importantly in function of the types of mode. These costs include the cost of handling the products, the docking fees, eventual intermediate transport or even tariffs. The third important category of costs are the capital costs. The capital costs are as well the costs of the goods themselves that are fixed assets during the duration of the transport as the costs of the equipment needed to assure the transportation of the goods.

Looking at the three main transport modes which are rail, road and maritime freight transport, their cost structure is quite different. Road transport is the most expensive one when looking at the distance-related costs. Road transport consumes more fuel than the two other modes and it is difficult to transport big quantities at the same time with truck transport. Economies of scale are difficultly made because of the very limited capacity of a truck. On the other side, trucks have the best ability to access any place without much supplementary costs. Thanks to the small capacities they transport, trucks are also very flexible and the overal terminal costs are very low. For rail transport, the linehaul costs are much lower. But rail transport is much less flexible and needs a lot more infrastructure. Rail transport is not fitted to deliver the first and last miles and it needs therefore to be part of combined chains with truck transport before and after rail transport in order to achieve a whole journey. This leads to enormous loading and transshipment costs. The infrastructures of rail transport are also very costly and it is costly to maintain them.

Maritime transport faces a quite similar cost structure as rail transport. But maritime transport can achieve much bigger economies of scale than rail transport. This also leads to huge handling costs. The very low flexibility and accessibility of boats are important cost factors of maritime transport. Maritime transport is also very slow compared to other transport modes. This causes high capital costs for the goods that are transported.

The graph here below provides the general cost structure of different transport modes. Each transport mode's cost structure is a trade-off between distance-independent and -dependent costs. Of course, high distances favor low distance-dependent costs and vice-versa. Road transport, in blue, has the lowest fixed costs and is therefore the most competitive transport mode over short distances. Train and boats incur higher fixed transfer costs and need therefore more distance in order to be competitive and to compensate these high fixed costs with their lower distance-related costs.

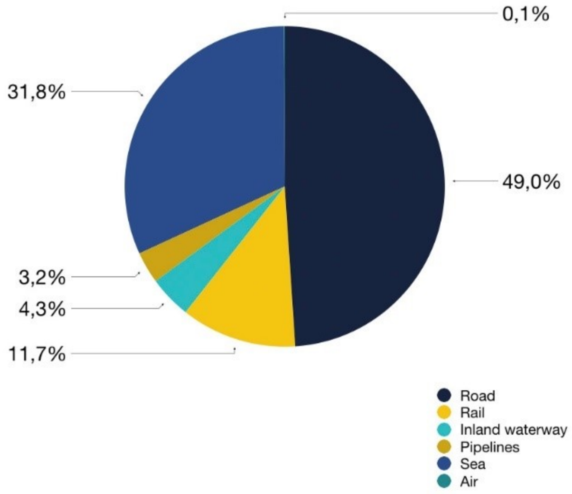
Figure 3.1: Cost structures of different modes in function of distance



Source: Rodrigue (2017)

Overall, different modes do not compete that much between each other. Each mode has its own competitive advantage that makes it lead some parts of the transport market. The different types of transport are complementary on their respective geographical markets. Long-distance modes are used for doing the biggest part of the transport and the shortest distance at the beginning and end is made by another mode. They also complement each other on different transport markets. Road transport for freight and rail transport for passengers, for example. The difference in levels of services can also be retained as a complementary aspect of the different modes (Rodrigue, 2017). Transport by ship is often the less expensive option for long distance carriage of bulk or commodities that do not need specific storage conditions. Trucks are more interesting when the commodity is transported in small quantities and over shorter distances. Rail is a good and often cheaper mean of transport for bulk over longer distances, but it needs much more infrastructure than trucks and is less flexible. Air transport is very expensive and is therefore only used for small quantities of high-value that need to be transported quickly or to remote locations.

Figure 3.2: Different modes used between European countries in 2014 in % of total tonne.km



Source: European Union of Road Transport (2018)

The graph does only include freight traded between European countries. On a worldwide-scale, the part of tonne.km processed by ship is way higher due to the long distances.

Inland freight transportation in Europe is composed of 75% transportation by truck, 18% by rail and 7% by inland waterways approximately (Eurostat, 2018). Inland freight transportation does not include transportation on sea or by air.

3.1.3 Freight Transport in Norway

Norway has a particular geography that makes the freight transport in this country even more strategic. The total surface of the mainland is 323,781 km^2 for 5,258,317 habitants. It makes it a country with a very low population density compared to the other countries of the European continent. It counts 17.3 inhabitants/km^2 on average, but more than 80% of the population lives in urban areas. Indeed, more than 80% of the country is covered by mountains or forests. The Norwegian transport network is also influenced by its enormous coastline. When taking all the fjords into account, Norway has a coastline of 28,953 km long (Norwegian Ministry of Transport and Communications, 2017). These specificities represent a lot of constraints for the development of the transportation network of Norway. Different urban areas are the home of almost all the industrial activities and end consumers. These different areas are separated by very long distances. The actual infrastructures of the transportation network are the following. There are 94,600 km of public roads and 4,208 km of railway in the country. There are also 49 airports, 32 seaports and 700 small fishing ports (Norwegian Ministry of Transport and Communications, 2017).

According to Norway's National Transport Plan, the competition between the different transport modes is quite small. The different modes operate in different market segments and are therefore not directly in competition between each other. More than 90 percent of road transport volume occurs over short distances. This freight is mainly composed of materials for construction work and related to local distribution. 80 percent of the maritime transport is international bulk transport. And the rail transport has more than 80% of its total freight volume that is composed of ore or cast iron and other bulk goods. Air freight, as usually, is only used for very remote and inaccessible places or to open up new markets. It is important to notice that three quarters of the total Norwegian transport work is produced at sea. In terms of growth, road transport has managed to keep up a sensitive growth through the years. It is still the best option for many companies when it comes to the transport of fresh or high-value products. The increase in trade with Eastern Europe countries has also strengthened the position of truck transport. Air transport has also grown significantly thanks to the fresh fish market and to the fast delivery of mechanical parts. Actually, the conditions and the external value creation of a transport mode are almost as important as the cost itself. That is the reason why more expensive means like road and plane transport still hold the competition with the less expensive ships (Institute of Transport Economics of Norway, 2015).

When competition between different transport modes is not based on the value creation and therefore when competition is stronger, rail and maritime transport perform better thanks to the reduced costs. Rail and ship transport still have the problem that it usually needs more handling of the product which increases its cost. That is why the competitiveness of these transport modes is increasing a lot when there is no need for road transport to carry the freight to bring to or pick it up at a terminal. This is a reason why industrial areas are built around the ports. Especially for short-sea shipping, the problem of the many handlings is important. A transport over sea often needs two truck trips and two port terminal handlings. These are expensive, cost time and are big compared to the little gain in costs of transporting over sea rather than with only road transport. To have an idea of the importance of the handling at terminals, direct maritime transport (without any road transport) is competitive with direct road transport beyond 200 kilometers. A combined transport chain with two short truck trips and a longer distance covered by ships is competitive with direct road transport from around 500 km (Institute of Transport Economics of Norway, 2015).

The geography of Norway is quite particular for transport. At first sight, it seems suited for short-sea shipping since it has an enormous coast line. But this enormous coast line has a lot of fjords that can make transport along the coast more difficult. Another problem for short-sea shipping is the shape of the country. Road transport needs often a shorter distance than maritime transport. Especially when looking at the biggest city, Oslo. Transporting from the Oslo fjord to coastal cities on the western coast and more specifically north of Bergen has a longer distance than by road. Ships obviously need to navigate all around the south of the country to reach the western cities. Ships also need bigger volumes to be profitable and that is why they are often limited to weekly departures while trucks are much more flexible. These reasons make maritime transport and more specifically short-sea shipping less competitive in markets that need fast delivery or high frequencies of delivery for competitive prices (Institute of Transport Economics of Norway, 2015).

For the future, Norway has already brought forward an ambitious plan. The plan has been built together by the different transport agencies in Norway. This plan is applying to the transport network in Norway from 2019 until 2028. It concerns transport of commodity and transport of persons. The objective defined by the Ministry of Transport and Communications is to develop a *"A transport system that is safe, enhances value creation and contributes to a low-carbon society"*.

Concerning freight transport, this plan means a lot of big changes in the future. Norway wants to enhance value creation by modernizing its road network in order to ensure competitiveness for companies and industries. For the rail network, Norway wants to make it more reliable by adding more loops into the network. It is also important for them to have rail terminals near to transport-intensive businesses or industries. Sea routes will also be focused on. They will be made more accessible and safer. Since the objective is also to reinforce the value creation of the network, air transport will also be developed to ensure that fresh and fast-delivery products can benefit from good transport possibilities.

3.1.4 Environmental impact of freight transport

The transport sector is facing a kind of a paradox. Its growth in last decades has brought a lot of environmental benefits, but at the same time it has had a very bad impact on the environment (Rodrigue, 2017).

The impacts on environment are diverse. The direct impacts are the easiest to assess and to understand. Some direct impacts are noise or carbon monoxide (CO) emissions. CO is known to be very bad for human health and intoxication from CO is immediately harming the intoxicated bodies. Secondary impacts are less obvious at a first view, but are nevertheless also very important. Their impact is even more important than from source of direct impacts. As the negative effects are not directly visible, secondary impacts are more difficult to understand and to assess. For instance, particulates released in the air by fuel combustion are indirect causes of respiratory and cardiovascular problems are part of the factors to such conditions (Rodrigue, 2017). Finally, the impacts are also cumulative. With the enormous amount of goods transported every day, a lot of gases are accumulated in the atmosphere. And it is probably the most concerning aspect of transport. And this last environmental damage is also the main externality from transport that will be studied in this thesis.

It is known that climate change is mainly due to the greenhouse gas effect. This greenhouse gas effect is not surprisingly caused by greenhouse gases. These gases retain energy in the atmosphere and an increase in concentration also increases the temperature on the earth surface. The greenhouse gas emissions of transport are very important. As already mentioned, it causes around 25% of the greenhouse gas (GHG) emissions in the world (OECD, 2018a). The most important gas emitted is CO_2 by far. But other gases are also emitted like carbon monoxide (CO), nitrogen oxides (NO_x) or Hydrocarbons (HC). Theses gases are the main responsible of the greenhouse effect and i.e. of the climate warming. Besides the warming of the earth, each of these gases pollutes the air and affects human health, biodiversity and the materials themselves (OECD, 1997). In this thesis, the focus is put on CO_2 emissions.

It has already been proved that environmental damages were underestimated in the near past. But, in the actual more and more environmentally conscious society, the environmental issues have gained a lot of attention. In the transport sector, environmental externalities are nevertheless still not receiving enough importance regarding the huge amount of greenhouse gases produced by the sector. The economic considerations are the main drivers of transport choices. This is due to the fact that the environmental cost is not totally supported by the beneficiaries of transport. Therefore, environment is continuing to be hardly damaged by transport and the cost of this damage is paid by the whole population through air pollution and climate change (Rodrigue, 2017).

The influence on the environment is depending on the transport networks, modes used and traffic conditions. In order to reduce the environmental impact caused by the transport sector, there is of course a need for new less polluting technologies. But, solutions that rely only on the development of new technologies are not sufficient. A change in the actual transport trends is needed. Therefore, the environmental costs need to be supported by the beneficiaries and decision makers of the transport sectors. This can be done through a lot of different policies that can change the cost structure in order to fit with the environmental objectives (Rodrigue, 2017).

3.2 Operations Research

3.2.1 Operations Research in the transport sector

According to the Business Dictionary (2018), Operations Research (OR) is the *application of mathematical (quantitative) techniques to decision making.* The process used in OR is the following. *A problem is first clearly defined and represented (modeled) as a set of mathematical equations. It is then subjected to rigorous computer analysis to yield a solution (or a better solution) which is tested and re-tested against real-life situations until an optimum solution is found.* In OR, the mathematical formulations are modelling the real-life decisional environment. The more precise and complete the formulation, the better the solution will fit in real life. Once the problem is defined adequately, a solver is used to find a solution set that has the best objective function while respecting all the constraints that define the environment. Operations Research are therefore a rational and pragmatic tool that is very useful when it comes to the planning of industrial activities, supply chain and of course freight transport.

Freight transport models are part of a whole planning process and this whole process often consists of different models. The first transport models were basically created for passenger transport. These models were adapted afterwards for freight transport. To adapt models, some huge differences had to be taken into account. These differences contain a.o. the diversity of the decision-makers in freight transport and the diversity of the items being transported (de Jong et al., 2004). In most of the models, these two issues are tackled by simplifying assumptions and the use of aggregate data (de Jong et al., 2013b). But, the overall process is more or less the same and consists of four different steps. In the article written by de Jong et al. (2004), these steps are listed as follows :

1. Production and attraction. In this step, the input and output quantities are forecasted for each zone and each type of item. It results in tonnes of goods that need to be shipped from and to each zone.
2. Distribution. Here, the quantities are transformed into flows between supply and demand destinations. In other words, origin and destination are linked by certain quantities of each product.
3. Modal split. After the distribution of the different flows, these flows are distributed across the different modes.
4. Assignment. Finally, all the goods are assigned to vehicles and the flow of vehicles can then be planned.

Of course, these four steps are only the general framework of transport planning. A number of other transformations and reworking of the data are needed to form a complete freight transport model system. Also, the four steps are not always occuring separately. Some of them are processed together through one model while some steps need multiple models to be achieved.

The geographical level of such a transport planning system can also vary. Some models are concerning a regional level, inter-regional, national or even international level. Some much more precise systems take care of the planning of one and only one company for example. In function of the size and precision of the geographical level, the aims of the models can be very different. At a national level, transport planning is used to make policy simulations or evaluate projects, for example (de Jong et al., 2004).

3.2.2 The different planning levels

As explained by Bektas et al. (2018) and Crainic (2000), it is important to define the decision level of a model. There are three different decision levels than can be classified from long term to short term as follow.

- Strategic and systemic: This decision level is the long term decision level. Strategic decisions have impacts on the whole transport sector. It concerns the design of the transportation network itself. Decisions to invest in new infrastructure or to implement new taxes are strategic decisions. Strategic models are used to find the best facility location, to centralize warehouses or to consolidate flows. The aim here is to build a transportation network and cost structures that maximize the social welfare of all the people concerned by the transport market targeted.
- Tactical: The tactical decision level is the intermediate level of decision. On this level, the choice of the fleet or the global distribution of the flows over the links and modes is decided. Backhauling can for example be optimized at a tactical level. At a tactical level, the network built at the strategic level is given and the aim is to minimize the costs with all the constraints fixed at the higher level.
- Operational: This is the lowest level of decisions. Optimization here is performed at local levels and by small decision-makers. At this level, the daily planning is built. Goods are assigned to vehicles and vehicles have their pick-up places and customers assigned. The aim of this last level is to optimize the daily planning in function of the parameters and constraints defined at the higher decision levels.

These three decision levels are obviously strongly linked between each other. The decision flow goes from strategic to operational level. Strategic decisions set policies and other rules for the tactical planning. Tactical planning then fixes other rules and flows for the operational planning level that is finally responsible for the effective flow of vehicles and the precise planning of it (Crainic, 2000). The data flow follows the route in the other direction. Each decision level provides information that is useful to make decisions at the above level. For example, tactical planning is dependent of the transport network and other regulations decided at a strategic level. But, on the other side, the distribution of the flows decided at the tactical level is useful for strategic decision makers in order to influence the tactical planning in the right way (Crainic, 2000).

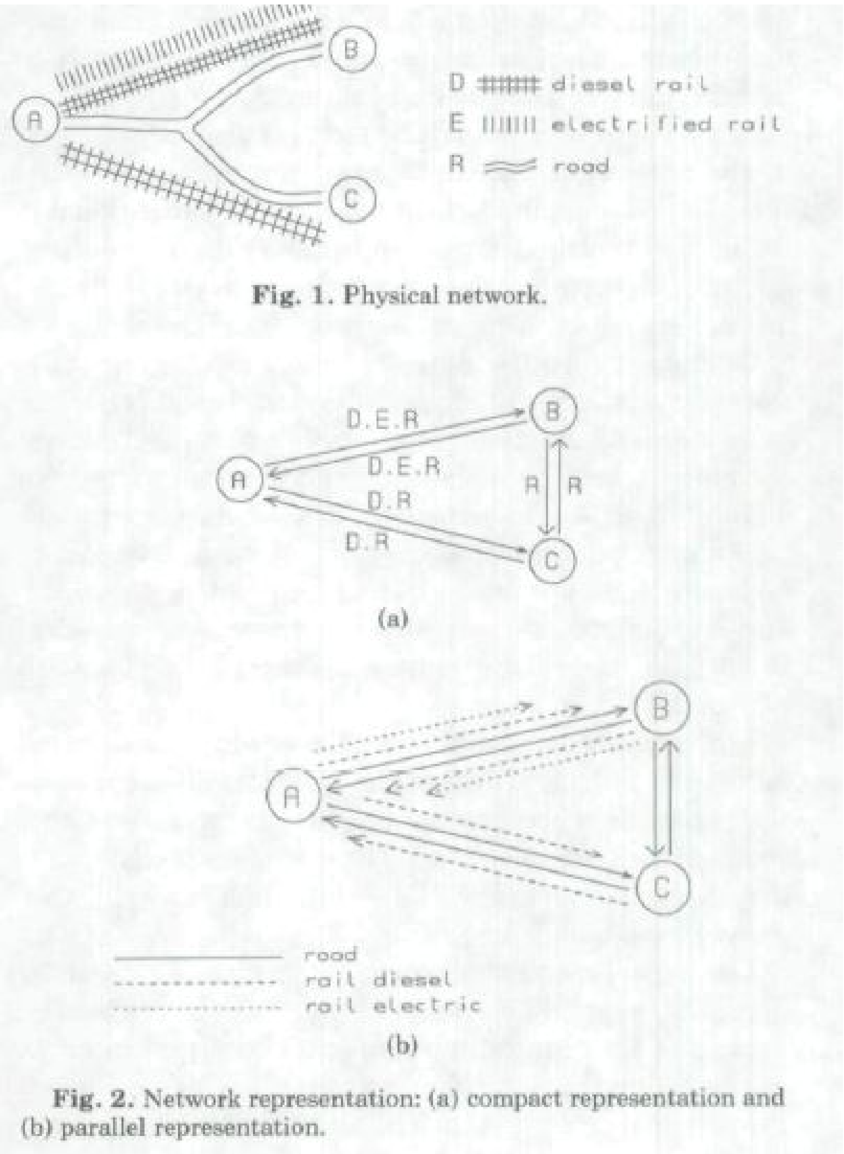
3.2.3 Representation of a transport network

In the thesis, the physical transport infrastructures of Norway are represented by a network model. This network is composed of nodes and links between the nodes. The chosen representation of a transport network is one by Guélat et al. (1990). The network consists of nodes, links and modes. The nodes are the different terminals or cities of the network. The modes are different types of transportation means. The modes can be differentiated on the basis of their different transport areas (air, sea, road), but can also vary in function of the capacity and other characteristics in more precise models. A link is defined by different parameters (i, j, m). The parameters i and j define the origin and destination nodes that are linked by this link. The parameter m defines the mode of the link.

In order to better understand the network, the figure below shows an example with three nodes A,B and C. The three modes are electric or diesel train and road transport.

In this thesis, the parallel representation (2b) is used. It requires a slightly more complex formulation, but the advantage of this representation is that it is possible to assign flows specific to each mode and not only aggregated for each link.

Figure 3.3: Network representation



Source: Guélat et al. (1990)

3.2.4 Classifications of planning models

According to different literature reviews written by de Jong et al. (2013b), de Jong et al. (2004) and Steadieseifi et al. (2014), a lot of different models have already been developed. A lot of countries and regions have their own transport planning models. These models are systems with different models used from the forecasting of the flow demand to the final allocation on each link and for each mode (de Jong et al., 2004). Systems become more and more complicated and take very detailed factors into account. These models are answers to the growing need of new policy analysis tools concerning climate change, noise or air pollution (de Jong et al., 2013b).

Steadieseifi et al. (2014) made an interesting review of recent developments of tactical planning models. First of all, the tactical models can be separated into two main types. The first one is the Network Flow Planning (NFP) which is concretely assigning flows of commodity throughout the network. The second one, Service Network Design (SND) involves decisions about the type of services included in the transportation services and modes. SND can further be separated into static and dynamic types. Static types are giving solutions that are fixed in time while dynamic models are optimizing multiple periods.

Another important distinction highlighted by Steadieseifi et al. (2014) concerns the variables. These can be either arc-based or path-based. When variables are arc-based, commodity flows are assigned to each arc (=link). The goods usually are assigned to multiple consecutive arc in order to satisfy the demand constraints of the model. For path-based variables, the data need a first pre-processing phase. In this phase, all the possible paths for each origin-destination pair are sorted out. The main model then assigns each tonne of commodity to one and only one path in order to satisfy all the demand constraints of the model. In NFP problems, arc-based variables are mostly used, but path-based models are also very interesting to study. Once the paths are enumerated, a path-based model is often able to reach better solutions in a same amount of time. The drawback of the paths relies in the pre-processing phase. Indeed, when the number of nodes and arc increases, the number of potential paths increases exponentially.

4 Model formulation

4.1 Description of the model

The problem is a typical network flow model. The network is here represented by a set of nodes N, a set of transportation modes M and a set of products P. Each node can be reached from several other nodes by the use of a link. Each link has some specific parameters like its length or its mode of transport. The aim of the model is to distribute all the goods according to the given origin-destination demand matrices while minimizing the total costs of the transport of all the goods. The variables are arc-based. This means that data are assigned to each arc (=link) (more information can be found at Section 3.2.4). The model is suited for tactical planning of freight transport. This means that the demand data are aggregated. In order to be nearer to the reality, the assumption is made that the demand is given per product in the format of an origin-destination matrix. These data can, for example, be forecasted by a demand forecasting model. The model is static and concerns the demand for a certain period that has to be assigned to specific links and transport modes. The outcomes of such a model can then be used in a more precise and dynamic operational planning model where smaller players optimize their own freight transport needs. Some parameters of the model are strategic choices. The optimization of the model with such parameters can therefore be a good tool to assess the impact of strategic decisions.

4.2 Mathematical notations

4.2.1 Indexes

As already stated in the last paragraph, indexes are the following.

Table 4.1: Indexes of the model

Notation	Description
N	Set of nodes in the network
M	Set of modes used in the network
P	Set of products

In order to make the model easier to understand, the indexes $i \in N$ and $j \in N$ are used when referring to a link of nodes. i being the origin node and j the destination node.

4.2.2 Parameters

The parameters are the following.

Table 4.2: Parameters of the model

Notation	Description
$L_{i,j,m}$	Length of the link of mode m between i and j
$A_{i,j,m}$	$= 1$ if the link of mode m between i and j exists. 0 otherwise.
C_m	Cost of a vehicle of mode m over one unit of distance
H_m	Cost of handling one ton from any mode to mode m
E_m	Emission output for transporting one ton over one unit of distance with transport mode
G_m	Emission output for handling one ton from any mode to mode mode m
K_m	Capacity of one vehicle of mode m
$B_{p,m}$	$=1$ if product p can be transported on mode m. 0 otherwise
$F_{n,p}$	Demand in node n for product p
$I_{n,p}$	Initial stock of product p at node n
V	Cost of emitting one unit of emissions

In this configuration, there is no difference made between products of different origins. However, if there is a need to plan the transport of the products between specific pairs of origin and destination nodes, an origin index can easily be added in combination with the index p. In the variables and parameters containing the index p, the index $o \in N$ is added. The number of different products considered by the model becomes then $P * N$. This means that the demand parameter becomes $F_{j,p,o}$ and is then the demand in node j for product p of origin $o \in N$. The initial stock parameter becomes $I_{i,p,o}$ and is the initial stock at node i of product p from origin o which initially is a diagonal matrix for each product.

4.2.3 Variables

For this model, two decision variables are created.

Table 4.3: Variables of the model

Notation	Description
$x_{i,j,m,p}$	Quantity of product p transported by mode m from node i to node j
$y_{i,j,m}$	Quantity of vehicles of mode m used from node i to j

4.3 Objective function

Quite logically, the usual objective when assigning transport flows to modes and links for freight transport is to minimize the total costs. Since the objective of this model is to assess environmental policies, environmental costs need to be included separately. There are therefore two important types of cost. The first, financial ones, are impacting directly actors responsible for the transport of the freight. Indeed, they are spending money to transport goods and aim to spend the least possible money while assuring the required service level. The second type of costs are the environmental costs. These costs have an impact on the whole society and are way more difficult to estimate in monetary terms.

The first part mentioned above are the direct financial costs of transport. These can be divided into costs of transporting over a long distance by one mode of transport (expressed in NOK/vehicle.km) and in costs of transfer between two modes of transport (expressed in NOK/tonne). The direct costs of transport are fuel costs, crew costs, overhead costs, administration costs, etc. (Qu et al., 2014). Concerning the costs of transfer or intermodal costs, they are mainly due to the cost of handling the goods. In this model, a different cost is used for each different transport mode, not per combination of transport mode. The assumption is made that transfer costs do not depend on the combination of the modes, but only on the transport mode it is transferred to. The costs include the loading at the beginning of the journey and unloading at the end of it. When calculating the handling costs like this, it seems obvious that the costs do not depend on the previous mean of transport as the cost of unloading this mean of transport has already been included before in the model. Another main reason of modelling transfer costs like this, is to avoid a combinatorial explosion for big amounts of different transport modes. This part of the costs can be written as following.

Financial costs :

$$FC = \sum_{i \in N} \sum_{j \in N} \sum_{m \in M} y_{i,j,m} * L_{i,j,m} * C_m + 1/2 * \sum_{n \in N} \sum_{p \in P} \sum_{m \in M} \mid \sum_{i \in N} x_{i,n,m,p} - \sum_{j \in N} x_{n,j,m,p} \mid * H_m \tag{4.1}$$

In this equation, the first term clearly expresses the costs that are proportional to the number of vehicles and the number of kilometers travelled. The second term has to be divided by half because the absolute value counts every change of mode twice (at the beginning and at the end of the journey). It is important to note that the transfer towards the first mode of transport at the beginning of the journey is also accounted for in the objective function. As the goods always need to be gathered from somewhere and handled to bigger units of transport at central hubs, it is correct to include this cost in the objective function.

The second part of the total costs concerns the external costs of emissions caused by the transport of the goods. For the calculation of the emissions, an interesting formula has been developed by McKinnon and Piecyk (2011). Qu et al. (2014) also use this formula to build a resembling tactical model. The formula states this:

$$EmissionCosts = l * d * e \tag{4.2}$$

where l is the load carried over a distance d and e represents the average emission factor for a given transport mode in g/tonne.km. In this model, the same formula is used. The reasons for the use of this calculation are its ease of use, but also the fact that it is not relevant to make more precise calculations on a tactical level. Effectively, more detailed models can make the use of microscopic data in order to build more precise cost functions. This formula is activity-based which means that the costs directly depend on the importance of the activity. The emission cost function is therefore the following.

Emission costs:

$$EC = V * (\sum_{i,j,m,p} x_{i,j,m,p} * L_{i,j,m} * E_m + 1/2 * \sum_{n \in N} \sum_{p \in P} \sum_{m \in M} \mid \sum_{i \in N} x_{i,n,m,p} - \sum_{j \in N} x_{n,j,m,p} \mid * G_m) \tag{4.3}$$

However the emissions occurring during the handling of the goods are often very small and quite insignificant compared to the financial costs of handling goods, they are accounted in this objective function. As the data and the variables allow us to easily calculate the costs of the handled goods, it seems more complete to still add the emission costs of transferring goods to a transport mode.

The addition of these two types of costs into a unique function give the following objective function.
Minimize Total Costs:

$$\begin{aligned} TC = & \sum_{i \in N} \sum_{j \in N} \sum_{m \in M} y_{i,j,m} * L_{i,j,m} * C_m + 1/2 * \sum_{n \in N} \sum_{p \in P} \sum_{m \in M} \mid \sum_{i \in N} x_{i,n,m,p} - \sum_{j \in N} x_{n,j,m,p} \mid * H_m \\ & + V * \left(\sum_{i,j,m,p} x_{i,j,m,p} * L_{i,j,m} * E_m + 1/2 * \sum_{n \in N} \sum_{p \in P} \sum_{m \in M} \mid \sum_{i \in N} x_{i,n,m,p} - \sum_{j \in N} x_{n,j,m,p} \mid * G_m \right) \end{aligned} \tag{4.4}$$

4.4 Constraints

With the notations from Tables 4.1, 4.2 and 4.3, the constraints of the mathematical model are the next ones:

$$\sum_{i \in N} \sum_{m \in M} x_{i,n,m,p} - \sum_{j \in N} \sum_{m \in M} x_{n,j,m,p} + I_{n,p} \geq F_{n,p} \qquad \forall n \in N, \forall p \in P \tag{4.5}$$

$$x_{i,j,m,p} \leq \sum_{n \in N} I_{n,p} * B_{p,m} \qquad \forall i \in N, \forall j \in N, \forall m \in M, \forall p \in P \tag{4.6}$$

$$\sum_{p \in P} x_{i,j,m,p} \leq K_m * y_{i,j,m} * A_{i,j,m} \qquad \forall i \in N, \forall j \in N, \forall m \in M, \forall p \in P \tag{4.7}$$

$$x_{i,j,m,p} \geq 0 \qquad \forall i \in N, \forall j \in N, \forall m \in M \tag{4.8}$$

$$y_{i,j,m} \in \{0, 1, 2, ...\} \qquad \forall i \in N, \forall j \in N, \forall m \in M \tag{4.9}$$

Constraint 4.5 is a typical flow constraint. It is also forcing the model to serve all the demand. For this model, the demand is considered to be forecasted previously and therefore it assumes that all the demand is served. The second constraint concerns the availability of the transport modes for each product. Some products can not be transported by specific modes and it is given in the parameter $B_{p,m}$. $\sum_{n \in N} I_{n,p}$ is the maximum amount of a product that exists on the whole network and thus is an upper limit on x. Constraint 4.7 is defining the number of vehicles needed on each link for each mode. The model will automatically count the minimum number of vehicles needed to transport the quantities x of each product. This quantity is summed on all the products p as the assumption is made that a vehicle can transport different types of product. This assumption might seem questionable for truck transport, but it clearly makes sens for bigger transport modes like trains and boats. The two last constraints are defining the two variables x and y. x can be any positive continuous quantity of goods and y is a discrete positive quantity of vehicles needed for each mode on each link.

4.5 Linearization of the model

Due to the absolute value in the objective function (4.4), the model is a mixed integer non-linear program. This makes it much more difficult to solve and need more complicated solvers to solve it than a linear one. In order to make from the objective function a linear objective function, Qu, Bektas and Bennell (2014) have brought a solution. To linearize, they use a new variable $z_{n,p,m}$ defined for each $n \in N$, $p \in P$ and $m \in M$. This new variable represents the amount of product p transferred to and from mode m at node n.

Proposition 1 *The component* $\mid \sum_{i\in N} x_{i,n,m,p} - \sum_{j\in N} x_{n,j,m,p} \mid$ *for* $\forall n \in N$, $\forall p \in P$, $\forall m \in M$ *can be linearized using the following constraints:*

$$\sum_{i\in N} x_{i,n,m,p} - \sum_{j\in N} x_{n,j,m,p} \leq z_{n,p,m} \qquad \forall n \in N, \forall p \in P, \forall m \in M \tag{4.10}$$

$$\sum_{j\in N} x_{n,j,m,p} - \sum_{i\in N} x_{i,n,m,p} \leq z_{n,p,m} \qquad \forall n \in N, \forall p \in P, \forall m \in M \tag{4.11}$$

where $z_{n,p,m} = \mid \sum_{i\in N} x_{i,n,m,p} - \sum_{j\in N} x_{n,j,m,p} \mid$

Source: (Qu et al., 2014)

With this new variable and constraints, the objective function becomes:
Minimize

$$\begin{aligned} TC = &\sum_{i\in N}\sum_{j\in N}\sum_{m\in M} y_{i,j,m} * L_{i,j,m} * C_m + 1/2 * \sum_{n\in N}\sum_{p\in P}\sum_{m\in M} z_{n,p,m} * H_m \\ &+V * \left(\sum_{i,j,m,p} x_{i,j,m,p} * L_{i,j,m} * E_m + 1/2 * \sum_{n\in N}\sum_{p\in P}\sum_{m\in M} z_{n,p,m} * G_m \right) \end{aligned} \tag{4.12}$$

The model is now a mixed integer linear program (MILP) and can be solved with any optimization solver. Now that the model is clearly defined and ready to be computed, the next section will present the data used for the experiment of this paper.

5 Data

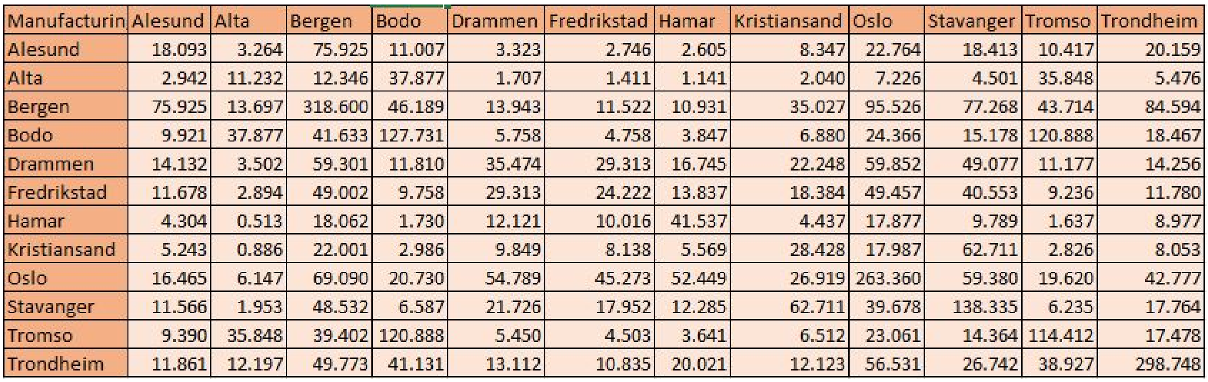
In this computational experiment, the aim is to distribute the previously forecasted transport demand over all the links of the network. The player that wants to minimize its cost here is Norway. Therefore, the network will contain the biggest cities over all Norway. Due to the limited acces to data and forecasting models, the data calculated here can contain a small bias compared to reality. However, the overall pattern should in principle be in line with the reality. In any case, the focus will be put on the general conclusions and on how to interpret results. The data of this research will be useful to show an example of how strategic decisions on the network flow can be made with this methodology and model.

5.1 Demand parameters

The first data gathered are the supply and demand from and to each city. These data are the first needed before constructing the whole network flow. The source used for these data is a commodity flow survey processed in 2014 by the Norwegian statistics Bureau (Statsbanken, 2014). The purpose of processing this survey is *"(...) to gain better knowledge of where the main trade flows is transported within Norway and between Norway and abroad. Commodity flow is measured primarily in terms of tonnes transported and trade value. The survey is important for planning and to prioritize investments, improvements and development of infrastructure that will benefit the industry."* (Statsbanken, 2014). The survey results contain different tables. Some of them contain the total flows between counties for main group of commodities. Another table contains the partition of supply from every county on a more detailed level of commodities. At the end, 9 pertinent groups of product were selected and the flow between counties was constituted thanks to the data gathered for the main group of commodities to which each product p belongs. Finally, the flow between counties was divided over the main cities of each county based on the population of the cities. So, 9 types of products p were obtained and each of them has its own demand matrix $F_{n,p,o}$ and supply matrix $I_{n,p,o}$. Indeed, to assure that the flow from supply to demand is kept, the index $o \in N$ has been added. The index o is therefore also added to the variable $x_{i,j,m,p,o}$. This allows the model to differentiate products from different origins. It will also be useful to remove this index later to show possible improvements due to coordination.

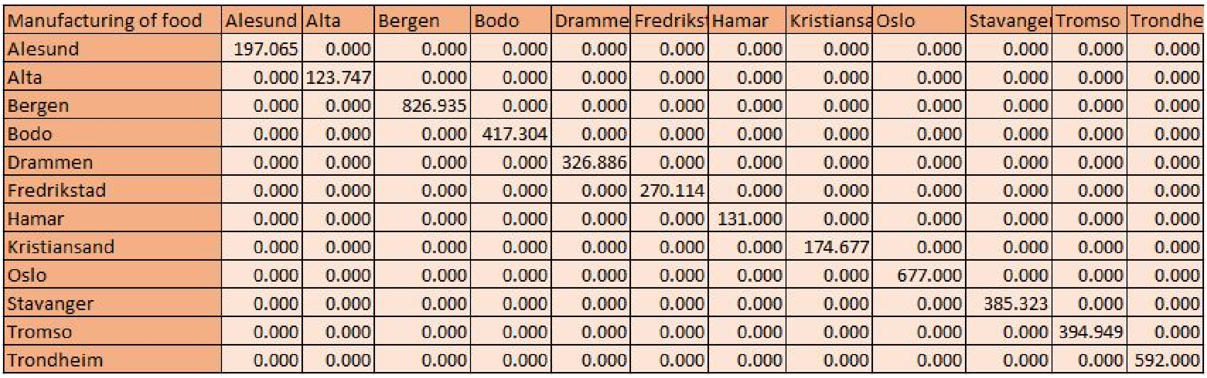
Here below, an example of the two matrices can be found for one product.

Figure 5.1: Demand $F_{n,p,o}$ in 1000 tonnes for manufacture of food



Manufacturin	Alesund	Alta	Bergen	Bodo	Drammen	Fredrikstad	Hamar	Kristiansand	Oslo	Stavanger	Tromso	Trondheim
Alesund	18.093	3.264	75.925	11.007	3.323	2.746	2.605	8.347	22.764	18.413	10.417	20.159
Alta	2.942	11.232	12.346	37.877	1.707	1.411	1.141	2.040	7.226	4.501	35.848	5.476
Bergen	75.925	13.697	318.600	46.189	13.943	11.522	10.931	35.027	95.526	77.268	43.714	84.594
Bodo	9.921	37.877	41.633	127.731	5.758	4.758	3.847	6.880	24.366	15.178	120.888	18.467
Drammen	14.132	3.502	59.301	11.810	35.474	29.313	16.745	22.248	59.852	49.077	11.177	14.256
Fredrikstad	11.678	2.894	49.002	9.758	29.313	24.222	13.837	18.384	49.457	40.553	9.236	11.780
Hamar	4.304	0.513	18.062	1.730	12.121	10.016	41.537	4.437	17.877	9.789	1.637	8.977
Kristiansand	5.243	0.886	22.001	2.986	9.849	8.138	5.569	28.428	17.987	62.711	2.826	8.053
Oslo	16.465	6.147	69.090	20.730	54.789	45.273	52.449	26.919	263.360	59.380	19.620	42.777
Stavanger	11.566	1.953	48.532	6.587	21.726	17.952	12.285	62.711	39.678	138.335	6.235	17.764
Tromso	9.390	35.848	39.402	120.888	5.450	4.503	3.641	6.512	23.061	14.364	114.412	17.478
Trondheim	11.861	12.197	49.773	41.131	13.112	10.835	20.021	12.123	56.531	26.742	38.927	298.748

Figure 5.2: Supply $I_{n,p,o}$ in 1000 tonnes for manufacture of food



Manufacturing of food	Alesund	Alta	Bergen	Bodo	Dramme	Fredrikst	Hamar	Kristiansa	Oslo	Stavange	Tromso	Trondhe
Alesund	197.065	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Alta	0.000	123.747	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Bergen	0.000	0.000	826.935	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Bodo	0.000	0.000	0.000	417.304	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Drammen	0.000	0.000	0.000	0.000	326.886	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fredrikstad	0.000	0.000	0.000	0.000	0.000	270.114	0.000	0.000	0.000	0.000	0.000	0.000
Hamar	0.000	0.000	0.000	0.000	0.000	0.000	131.000	0.000	0.000	0.000	0.000	0.000
Kristiansand	0.000	0.000	0.000	0.000	0.000	0.000	0.000	174.677	0.000	0.000	0.000	0.000
Oslo	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	677.000	0.000	0.000	0.000
Stavanger	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	385.323	0.000	0.000
Tromso	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	394.949	0.000
Trondheim	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	592.000

In this case, the I matrix is always a diagonal matrix as each city n supplies products from its own origin o.

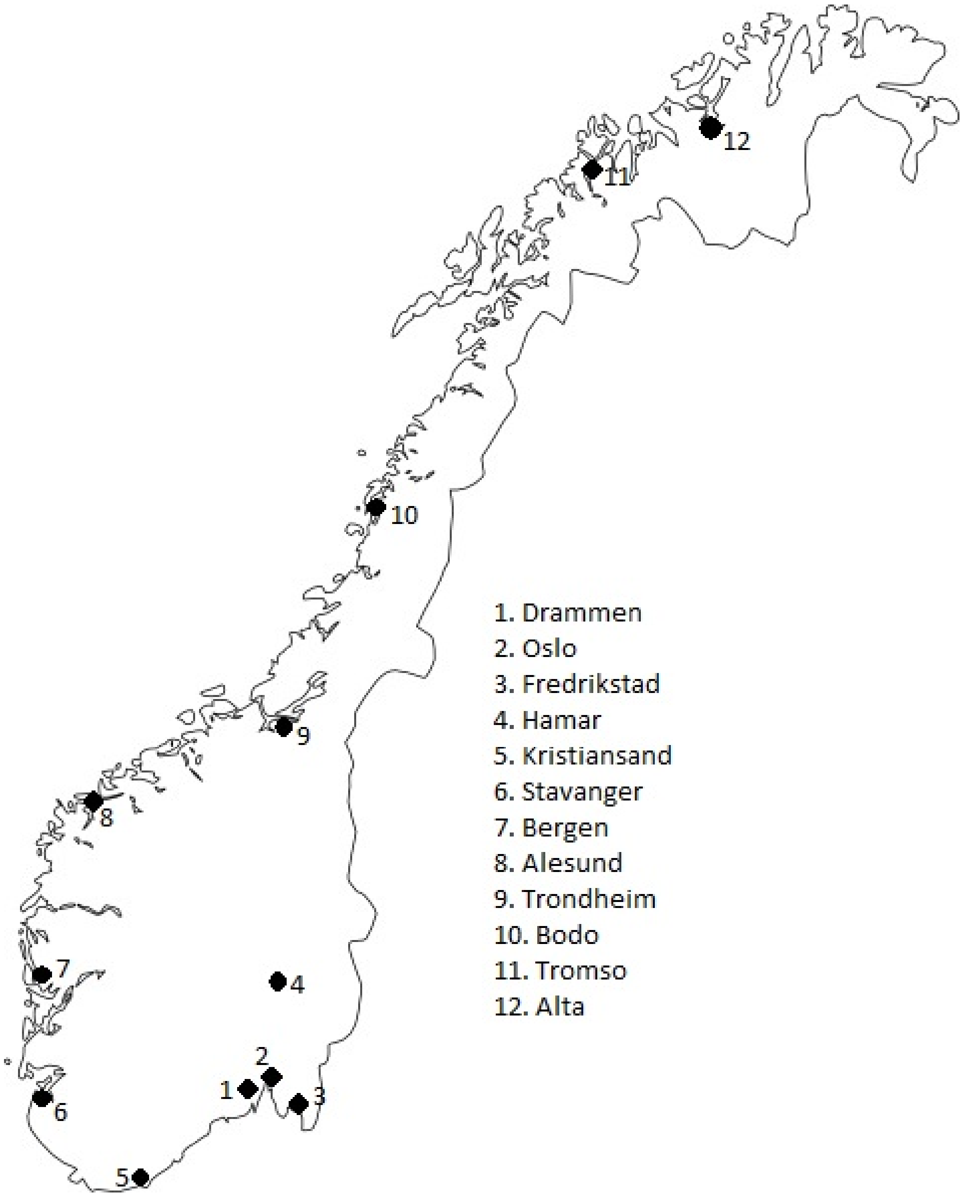
5.2 Indexes

Once pertinent demand data were gathered, the network flow could be created and the indexes could be defined. Next, the indexes are listed. The nodes of the network are big Norwegian cities to be found on figure 5.3.

Table 5.1: Data for the different indexes

Index	Size	Names
N	12	Alesund, Alta, Bergen, Bodo, Drammen, Fredrikstad, Hamar, Kristiansand, Oslo, Stavanger, Tromso, Trondheim
M	3	Truck, Boat, Train
P	9	Manufacture of food, Wood products, Non-mineral products, Machinery equipment, Waste collection, Wholesale of food, Wholesale of household goods, Wholesale of machinery equipment, Other wholesale

Figure 5.3: Map of Norway with the cities of the network

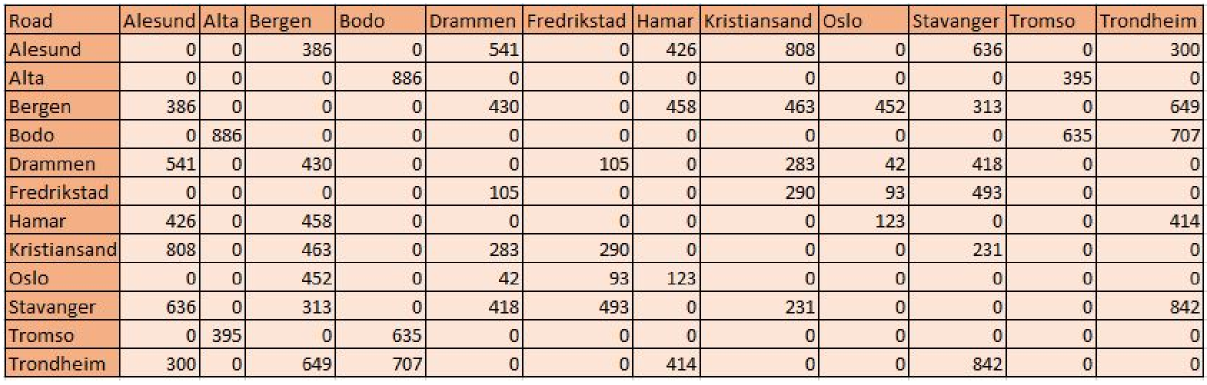


5.3 Links of the network

In this model, the links of the network are represented by a distance parameter $L_{i,j,m}$ and by a parameter $A_{i,j,m}$ defining whether or not the link exists.

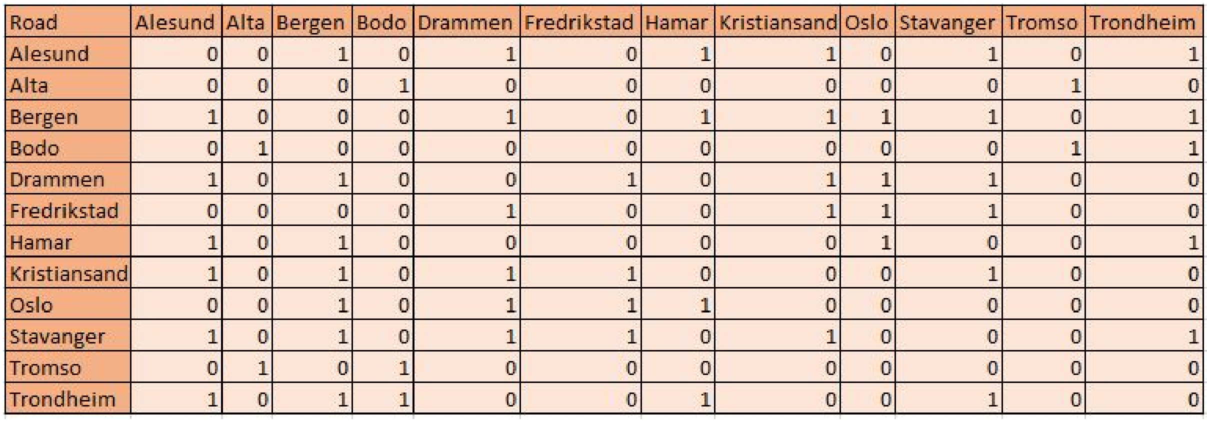
For the road transport, a special distance calculator was used (Transportica, 2019). It allowed to calculate the road distance between two different cities for freight transport. In order to have a precise view on the number of vehicles on each link, only the direct links were defined. For example, Trondheim and Oslo are connected by road, but the shortest road passes by Hamar. Therefore, Trondheim and Oslo are not directly linked, but can be reached trough their common link with Hamar.

Figure 5.4: Road distance in km between cities



Road	Alesund	Alta	Bergen	Bodo	Drammen	Fredrikstad	Hamar	Kristiansand	Oslo	Stavanger	Tromso	Trondheim
Alesund	0	0	386	0	541	0	426	808	0	636	0	300
Alta	0	0	0	886	0	0	0	0	0	0	395	0
Bergen	386	0	0	0	430	0	458	463	452	313	0	649
Bodo	0	886	0	0	0	0	0	0	0	0	635	707
Drammen	541	0	430	0	0	105	0	283	42	418	0	0
Fredrikstad	0	0	0	0	105	0	0	290	93	493	0	0
Hamar	426	0	458	0	0	0	0	0	123	0	0	414
Kristiansand	808	0	463	0	283	290	0	0	0	231	0	0
Oslo	0	0	452	0	42	93	123	0	0	0	0	0
Stavanger	636	0	313	0	418	493	0	231	0	0	0	842
Tromso	0	395	0	635	0	0	0	0	0	0	0	0
Trondheim	300	0	649	707	0	0	414	0	0	842	0	0

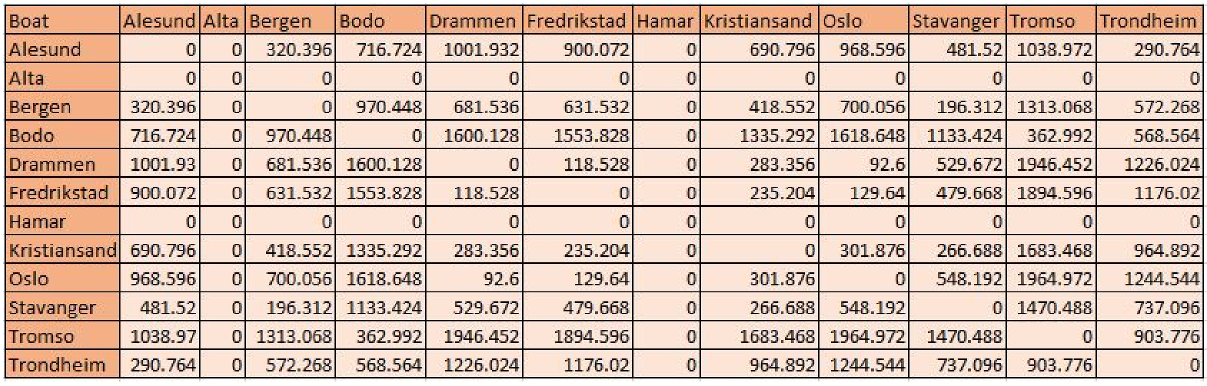
Figure 5.5: Existence of a direct link by road between cities



Road	Alesund	Alta	Bergen	Bodo	Drammen	Fredrikstad	Hamar	Kristiansand	Oslo	Stavanger	Tromso	Trondheim
Alesund	0	0	1	0	1	0	1	1	0	1	0	1
Alta	0	0	0	1	0	0	0	0	0	0	1	0
Bergen	1	0	0	0	1	0	1	1	1	1	0	1
Bodo	0	1	0	0	0	0	0	0	0	0	1	1
Drammen	1	0	1	0	0	1	0	1	1	1	0	0
Fredrikstad	0	0	0	0	1	0	0	1	1	1	0	0
Hamar	1	0	1	0	0	0	0	0	1	0	0	1
Kristiansand	1	0	1	0	1	1	0	0	0	1	0	0
Oslo	0	0	1	0	1	1	1	0	0	0	0	0
Stavanger	1	0	1	0	1	1	0	1	0	0	0	1
Tromso	0	1	0	1	0	0	0	0	0	0	0	0
Trondheim	1	0	1	1	0	0	1	0	0	1	0	0

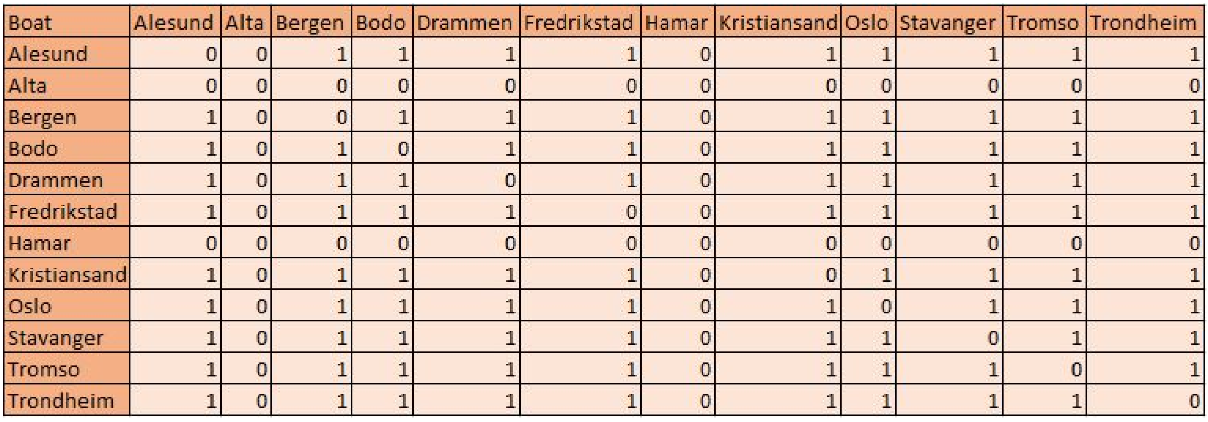
The distance by boat was calculated by another online software used to calculate short-sea distances (Sea-distances.org, 2019). Here, all the cities that have a harbour are connected. Since the distance to stop by a port on a journey is significant, it is more accurate to add links between two harbours even if a third harbour is crossed during the trip, in contrary to road transport.

Figure 5.6: Boat distance in km between cities



Boat	Alesund	Alta	Bergen	Bodo	Drammen	Fredrikstad	Hamar	Kristiansand	Oslo	Stavanger	Tromso	Trondheim
Alesund	0	0	320.396	716.724	1001.932	900.072	0	690.796	968.596	481.52	1038.972	290.764
Alta	0	0	0	0	0	0	0	0	0	0	0	0
Bergen	320.396	0	0	970.448	681.536	631.532	0	418.552	700.056	196.312	1313.068	572.268
Bodo	716.724	0	970.448	0	1600.128	1553.828	0	1335.292	1618.648	1133.424	362.992	568.564
Drammen	1001.93	0	681.536	1600.128	0	118.528	0	283.356	92.6	529.672	1946.452	1226.024
Fredrikstad	900.072	0	631.532	1553.828	118.528	0	0	235.204	129.64	479.668	1894.596	1176.02
Hamar	0	0	0	0	0	0	0	0	0	0	0	0
Kristiansand	690.796	0	418.552	1335.292	283.356	235.204	0	0	301.876	266.688	1683.468	964.892
Oslo	968.596	0	700.056	1618.648	92.6	129.64	0	301.876	0	548.192	1964.972	1244.544
Stavanger	481.52	0	196.312	1133.424	529.672	479.668	0	266.688	548.192	0	1470.488	737.096
Tromso	1038.97	0	1313.068	362.992	1946.452	1894.596	0	1683.468	1964.972	1470.488	0	903.776
Trondheim	290.764	0	572.268	568.564	1226.024	1176.02	0	964.892	1244.544	737.096	903.776	0

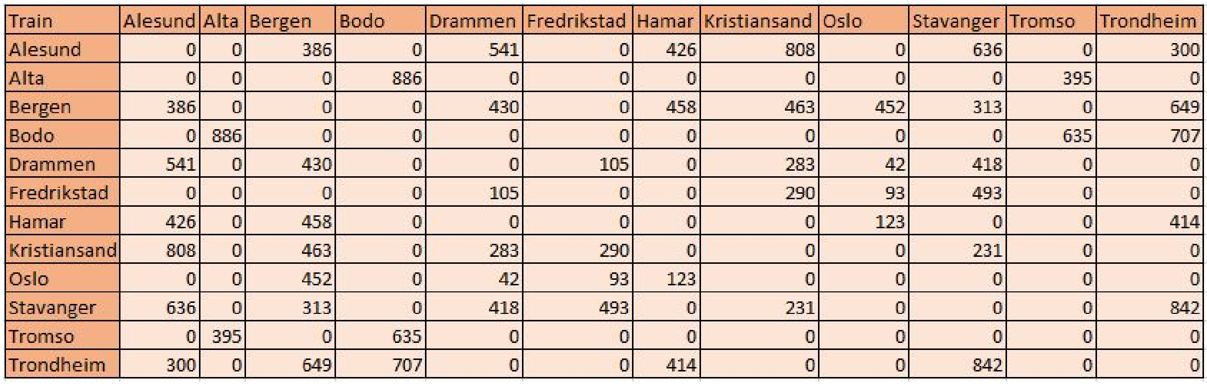
Figure 5.7: Existence of a direct link by boat between cities



Boat	Alesund	Alta	Bergen	Bodo	Drammen	Fredrikstad	Hamar	Kristiansand	Oslo	Stavanger	Tromso	Trondheim
Alesund	0	0	1	1	1	1	0	1	1	1	1	1
Alta	0	0	0	0	0	0	0	0	0	0	0	0
Bergen	1	0	0	1	1	1	0	1	1	1	1	1
Bodo	1	0	1	0	1	1	0	1	1	1	1	1
Drammen	1	0	1	1	0	1	0	1	1	1	1	1
Fredrikstad	1	0	1	1	1	0	0	1	1	1	1	1
Hamar	0	0	0	0	0	0	0	0	0	0	0	0
Kristiansand	1	0	1	1	1	1	0	0	1	1	1	1
Oslo	1	0	1	1	1	1	0	1	0	1	1	1
Stavanger	1	0	1	1	1	1	0	1	1	0	1	1
Tromso	1	0	1	1	1	1	0	1	1	1	0	1
Trondheim	1	0	1	1	1	1	0	1	1	1	1	0

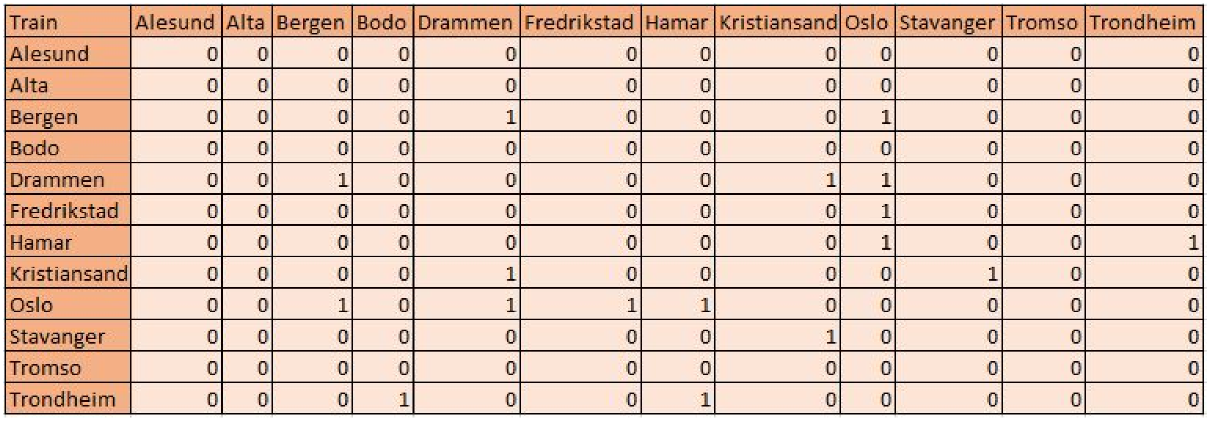
As exact data about train distances were not available, the distance used for the railway are the same as for road transport. The advantage of this is the possibility to add potential new railway links in order to assess the efficiency of a new railway. As well as road links, only the direct links are included in the data. The links between cities are based on the data obtained from the National rail company of Norway (NSB, 2019).

Figure 5.8: Train distance in km between cities



Train	Alesund	Alta	Bergen	Bodo	Drammen	Fredrikstad	Hamar	Kristiansand	Oslo	Stavanger	Tromso	Trondheim
Alesund	0	0	386	0	541	0	426	808	0	636	0	300
Alta	0	0	0	886	0	0	0	0	0	0	395	0
Bergen	386	0	0	0	430	0	458	463	452	313	0	649
Bodo	0	886	0	0	0	0	0	0	0	0	635	707
Drammen	541	0	430	0	0	105	0	283	42	418	0	0
Fredrikstad	0	0	0	0	105	0	0	290	93	493	0	0
Hamar	426	0	458	0	0	0	0	0	123	0	0	414
Kristiansand	808	0	463	0	283	290	0	0	0	231	0	0
Oslo	0	0	452	0	42	93	123	0	0	0	0	0
Stavanger	636	0	313	0	418	493	0	231	0	0	0	842
Tromso	0	395	0	635	0	0	0	0	0	0	0	0
Trondheim	300	0	649	707	0	0	414	0	0	842	0	0

Figure 5.9: Existence of a direct link by train between cities



Train	Alesund	Alta	Bergen	Bodo	Drammen	Fredrikstad	Hamar	Kristiansand	Oslo	Stavanger	Tromso	Trondheim
Alesund	0	0	0	0	0	0	0	0	0	0	0	0
Alta	0	0	0	0	0	0	0	0	0	0	0	0
Bergen	0	0	0	0	1	0	0	0	1	0	0	0
Bodo	0	0	0	0	0	0	0	0	0	0	0	0
Drammen	0	0	1	0	0	0	0	1	1	0	0	0
Fredrikstad	0	0	0	0	0	0	0	0	1	0	0	0
Hamar	0	0	0	0	0	0	0	0	1	0	0	1
Kristiansand	0	0	0	0	1	0	0	0	0	1	0	0
Oslo	0	0	1	0	1	1	1	0	0	0	0	0
Stavanger	0	0	0	0	0	0	0	1	0	0	0	0
Tromso	0	0	0	0	0	0	0	0	0	0	0	0
Trondheim	0	0	0	1	0	0	1	0	0	0	0	0

5.4 Cost & capacity parameters

The cost parameters are very important in the model. They influence directly the importance of each term of the objective function. Small inaccuracies can lead to strong biases in the final set of solution. That is why the sources must be thoroughly searched through to define these parameters as close as possible to reality. Luckily, the financial cost parameters for a lot of transport modes have already been calculated through a research led by the Institute of Transport Economics of Norway (2011a). These cost models were made as an input to the Norwegian Transport Plan. As the data is gathered as a purpose to show the usefulness of such a model, more than for the exact results that it will give, the aim is to keep the model simple. Therefore, only one type of vehicle is selected for each mode. The type of vehicle selected for each transport mode has been analysed precisely. The choice is made on a good compromise between the different options and suited for general cargo and manufactured goods which are the categories of goods assumed for all the goods in this experiment.

The corresponding capacity of each vehicle is given by de Jong et al. (2013a). These were calculated for the use of the cost data in Norway. The capacity is different for different types of freight goods. An average of the two (out of three) main profiles was chosen to suit the type of commodity of this research that include a mix of both profiles.

Concerning the transfer costs for each mode, no similar data is available to public access. Therefore, the use of the results of another research from the Norwegian Institute of Transport was made. This research concerns intermodal competition and has calculated the minimum amount of kilometers needed for each transport mode to be competitive with direct road transport. For general cargo, a rail transport chain and a maritime transport chain are competitive with direct road transport from respective distances of 500 and 550 km (Institute of Transport Economics of Norway, 2011b). Calculations were made in order that the cost functions based on the two cost parameters are reflecting this competitiveness of modes.

For emission costs, the experiment bases its data on conversion factors recommended by McKinnon and Piecyk (2011). It contains data for each transport mode, but also for the transfer to each mode. The same factors were also used in one of the models this experiment is based on (Qu et al., 2014). To convert emissions into monetary units, the price V of 500 Norwegian Kroners (NOK) per ton of CO^2 is used (Energy Facts Norway, 2019b). The price of 500 NOK/ton or 0.0005 NOK/g is used to use the same units. This price is the trade price that companies have to pay per tonne of CO^2 emitted.

Here below, the table summarizes all the cost & capacity parameters used to compute the experiment.

Table 5.2: Data for the cost and capacity parameters

Parameter	Notation	unit	Road	Boat	Rail
Capacity	K_m	tonnes	30	2250	45
Transport Cost	C_m	NOK/vehicle	15.28	154.4	2.71
Handling Cost	H_m	NOK/tonne	20	242.36	267.01
Emissions	E_m	g/tonne.km	67	22	16
Emissions of transfer	G_m	g/tonne	47	42	52

The difference in handling costs might seem surprisingly high. To understand the sources of such a difference, it is important to have a look at the whole transfer process. In these costs, the transfer towards the selected mode m, but also the transfer from the mode m is counted. For road transport, it usually means to handle the freight once as the trucks meant for the long-distance transport are easily able to reach the terminals were the freight are stored or delivered by another vehicle. For rail and maritime transport, terminals are seldom at the same places and usually some short-distance transport is needed to reach the wagon or ship that will handle the long-distance transport. This means that goods are handled more than once for each transfer and that the time needed to transfer is also much higher. Knowing that handling costs, short-distance transport, inventory costs, terminal infrastructures, cost of deterioration of the goods during handling, cost of scheduling the departures for train/boat ... are all accounted for in the average transfer costs, the difference is coherent.

6 Results

This section contains all the results obtained with the previously described model and data. The results of the experiment are first broadly presented. In the meantime, the performance of this computational experiment is being assessed by a comparison to the actual distribution over the modes in Norway. A thorough analysis of these results has been performed and is also presented in the following of this section. Afterwards, different improvements and policies and the impact of them are assessed. The different measures tested are the decrease of the fixed costs of handling, an increase of the price of emitting CO_2, a road tax, a subsidy for rail and maritime transport and a fuel tax. They are also tested in combination with each other. This analysis is focused on ways to reach win-win solutions in environmental and financial terms. Finally, a small section concerns the potential of increasing coordination in the transport sector.

6.1 Results of the computational experiment

6.1.1 Bi-objective function

For the reason that it is difficult to find precise estimates for both types of costs on a same cost unit, the objective function used here is the bi-objective function defined by Bektas et al. (2018). Their article states this objective function:

Minimize

$$\omega(f(x) + c(x)) + \zeta m(x) \tag{6.1}$$

where ω and ζ are parameters defined by the user and depending on the importance that the user wants to give to each part of the costs. The first term represents the financial costs and the second term represents the emission costs of transport.

While defining the objective function, it seems important to define two special cases that this objective function can handle.

1. When $\omega = 0$, $\zeta >0$, in which the problem is to minimize emissions.
2. When $\omega >0$, $\zeta = 0$, in which the objective is to minimize the financial costs.

The optimal solution of a problem can be called a win-win solution when it is also the optimal solution of both above mentioned problems. In this case, a firm only focusing on its own costs would also automatically minimize its emissions and vice versa. The externalities are correctly internalized. This means that the decision-maker pays a sufficiently high environmental cost and he therefore wants to reduce its emissions in order to minimize the costs.

For the results calculated in Section 6.1, this type of bi-objective function has been used and the three different cases are calculated. The objective function in this section is therefore :

Minimize

$$\begin{aligned} TC = \omega * \Bigg(\sum_{i \in N} \sum_{j \in N} \sum_{m \in M} y_{i,j,m} * L_{i,j,m} * C_m + 1/2 * \sum_{n \in N} \sum_{p \in P} \sum_{m \in M} \mid \sum_{i \in N} x_{i,n,m,p} - \sum_{j \in N} x_{n,j,m,p} \mid * H_m \Bigg) \\ + \zeta * V * \Bigg(\sum_{i,j,m,p} x_{i,j,m,p} * L_{i,j,m} * E_m + 1/2 * \sum_{n \in N} \sum_{p \in P} \sum_{m \in M} \mid \sum_{i \in N} x_{i,n,m,p} - \sum_{j \in N} x_{n,j,m,p} \mid * G_m \Bigg) \end{aligned} \tag{6.2}$$

6.1.2 Optimizing both costs simultaneously

Here, the parameters ω and ζ of the objective function are both equal to 1. This allows to obtain an objective function that represents the best possible the costs faced by the freight transport market. The results should therefore resemble the actual distribution of the goods transport in Norway. In order to reach a feasible solution in a decent time. The flow constraint 4.5 had to be very slightly relaxed. In fact, the minimum fulfilment of demand has been set to 99,9% of the demand. The right part of the equation was therefore multiplied by the factor 0,999. With the total initial stocks being perfectly equal to the total demand for each node, relaxing this constraint very slightly is needed in order to allow the Optimizer to have a minimal margin to play with. The model and dataset from sections 4 and 5 are computed in AMPLIDE, a software using AMPL language. The solver used is the CPLEX Optimizer 12.8.0.0 on a HP laptop with Intel Core i5 CPU and 8Gb RAM. The initial program was solved in 24 seconds and after 759 MIP simplex iterations. The solver stops running when the solution reaches a gap smaller than 0.0001% of the solution.

The result of the optimal objective is 7 118 279 000 NOK. It is the lowest cost possible to transport all the goods as asked in the data. As the real interest of this research relies on the distribution over modes and the importance of environmental costs, further results are expressed in percentages of the total costs. This allows a better understanding of the results and an easier comparison between the different elements of the solution. Furthermore, the actual results are based on a flow survey concerning only a part of the total goods transported in Norway. The assumption is made that this quite large sample is a good representation of the distribution of the types of goods in Norway. Therefore, relative weights are of a very significant value while purely numerical results are way less interesting to interpret.

As stated before, the situation represented with this parameters is near to reality. Concerning the costs, the relative importance of each element of the cost function can be retrieved. Direct financial costs of transporting and handling costs have a relative importance of respectively 53.6% and 42.3% of the total costs. The financial costs of emissions produced during transport and during transfers account respectively for 4.1% and 0.01%. This means, at first sight, that the costs of emissions are playing a quite minor role when it comes to decide how commodities are transported. A more in-depth analysis of the influence of the pricing of emissions is carried further in this paper.

Concerning the distribution of goods on the different links and different modes, the three tables below contain a recap of the number of vehicles sent on each link for each mode. The results might seem huge, especially when looking at the number of wagons and trucks used. But, when we put these figures into their context, their high numbers seem much more understandable. In fact, the amount of goods that needs to be transported concerns a lot of types of goods and is the amount of goods transported over one year. These numbers need to be divided by 365 to obtain a daily average flow of vehicles. Another surprising aspect of the results below is the "all or nothing"-looking distribution of the goods over the different links. This reminds that it is here tactical planning and therefore only general and important cost elements and constraints are taken into account. Operational planning on a micro-level would more than probably diversify the distribution due to more detailed elements depending on the value or perishability of the goods, for example. However, it is permitted to consider that the general trend would be in line with the following results.

Table 6.1: Number of boats from node i to j

	Ale	Alt	Be	Bo	D	F	H	K	O	S	Trm	Trd
Alesund	0	0	1	37	0	12	0	31	85	65	46	0
Alta	0	0	0	0	0	0	0	0	0	0	0	0
Bergen	0	0	0	157	0	50	0	0	0	0	194	288
Bodo	9	0	34	0	6	5	0	6	34	13	138	17
Drammen	0	0	0	0	0	1	0	0	0	1	107	0
Fredrikstad	79	0	330	0	0	0	0	2	0	288	89	0
Hamar	0	0	0	0	0	0	0	0	0	0	0	0
Kristiansand	21	0	0	11	0	0	0	0	0	2	13	26
Oslo	135	0	0	1	1	1	0	0	0	0	207	0
Stavanger	46	0	1	25	0	75	0	0	0	0	31	57
Tromso	10	0	42	141	7	6	0	6	37	15	0	22
Trondheim	1	0	111	111	0	0	0	13	1	30	139	0

Table 6.2: Number of train wagons from node i to j

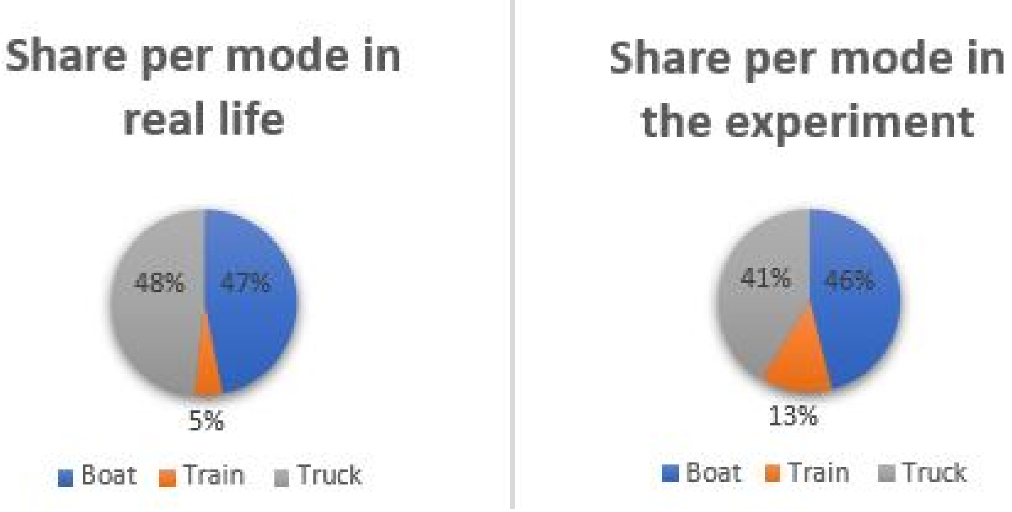
	Ale	Alt	Be	Bo	D	F	H	K	O	S	Trm	Trd
Alesund	0	0	0	0	0	0	0	0	0	0	0	0
Alta	0	0	0	0	0	0	0	0	0	0	0	0
Bergen	0	0	0	0	0	0	0	0	1	0	0	0
Bodo	0	0	0	0	0	0	0	0	0	0	0	0
Drammen	0	0	0	0	0	0	0	3870	12192	0	0	0
Fredrikstad	0	0	0	0	0	0	0	0	8868	0	0	0
Hamar	0	0	0	0	0	0	0	0	10404	0	0	43810
Kristiansand	0	0	0	0	1450	0	0	0	0	3870	0	0
Oslo	0	0	0	0	4926	872	44519	0	0	0	0	0
Stavanger	0	0	0	0	0	0	0	1450	0	0	0	0
Tromso	0	0	0	0	0	0	0	0	0	0	0	0
Trondheim	0	0	0	16236	0	0	6534	0	0	0	0	0

Table 6.3: Number of trucks from node i to j

	Ale	Alt	Be	Bo	D	F	H	K	O	S	Trm	Trd
Ales	0	0	27962	0	1088	0	740	0	0	0	0	5135
Alta	0	0	0	3220	0	0	0	0	0	0	5709	0
Bergen	27962	0	0	0	4566	0	3103	9304	26724	20522	0	0
Bodo	0	3220	0	0	0	0	0	0	0	0	10	0
Dram	7128	0	29911	0	0	36422	0	28674	72567	57488	0	0
Fredr	0	0	0	0	36422	0	0	9796	46608	0	0	0
Hamar	3190	0	13388	0	0	0	0	0	33890	0	0	8266
Krist	0	0	6577	0	8799	2544	0	0	0	20566	0	0
Oslo	0	0	42602	0	92143	36380	67408	0	0	0	0	0
Stav	0	0	14508	0	17233	0	0	20566	0	0	0	0
Tromso	0	17847	0	0	0	0	0	0	0	0	0	0
Trond	1997	0	0	0	0	0	4920	0	0	0	0	0

Then, the share of transport processed by each transport mode is calculated. To do so, the total tonne.km are calculated for each mode. Tonne.km is the unit used to express the total goods transported and is related to the total weight and km transported for each transport mode. For example, a truck with a load of 20 tons that transport over 300 km will account for a total of 6000 (20*300) tonne.km. In this computation, the total amount of goods transported is of 15 419 690 000 tonne.km. The weight in comparison to this total is expressed for each mode in the next diagram. The diagram is also compared to the share for each mode how it actually is happening in Norway. These data were gathered from Statsbanken (2018) and concern the year 2017.

Figure 6.1: Share per mode in real life and as a result of the experiment



The share obtained with the model of this thesis seems quite consistent when comparing it with the distribution over modes that is taking place in Norway. While the share of boat transport seems to be the same in both, train transport seems to be overestimated in the model. The main reason of this overestimation might be the capacity of railway that is not modeled here. There are often only one or two railroad tracks that connect different cities. This track has also to be shared with passenger transport and precise scheduling is needed in order to send commodity trains between cities. As the same distances are used for train and truck links between cities, rail transport is taking over some transport that would be carried by trucks in real life. This is due to the difficulty to take the difficulties of railroad planning into account in such global models. Except for this small difference, the results compare quite well to the real-life distribution over the modes. It confirms the fact that the model is a good estimate of the parameters that decision-makers have to take into account on a tactical level.

6.1.3 Minimizing only emissions

In this case, the ω parameter associated with the first part of the costs is put to zero while $\zeta = 1$. By doing so, the model is finding the best solution set that realizes the transport asked by the parameters at the lowest cost of emissions. It is interesting to compare this to the previously calculated solution in order to see if the actual CO_2 prices are influencing the transport choices effectively. Even though these costs are not optimized at all in this configuration, it is also interesting to see what the financial costs woulds look like in a solution that is completely environment-oriented. For this optimization, the solver needed barely a second and 36 iterations to reach a solution with a gap of less than 0.0001 % of the new solution.

The optimization of the emission costs allows to reach total emissions of 296 000 tons of CO^2. In terms of emissions, it represents a reduction of 49,2 % compared to the initial solution. It means that emissions could theoretically almost be cut by half only by changing the distribution of transport over modes and links. To reach such a solution, there is no need for a reduction in the goods transported, nor for changes in infrastructure or even new less-emitting technologies.

Naturally, such an optimization implies a total change in the distribution over modes. There is effectively an almost total transfer of resources transported by truck to rail transport. The train clearly becomes the number one mean of transport in this configuration. And it is not very surprising since it is the mode that emits the lowest amount of emissions across all modes. When minimizing the emissions, the truck is only used in extreme cases where a city is not reachable by train or by boat like in Alta.

Regarding the total costs that such a solution would involve, these are considerable with the actual cost structure. The initial total costs increase by 50% when optimizing exclusively environmental costs. However costs of transport and both transport and handling costs of emissions decrease a lot with this solution set. The increase in total costs is only caused by the handling costs that experience an increase of more than 200%. This increase is totally due to the change of dominant mode from road to train transport which has high transfer costs.

Even though minimizing only emissions without any regard to the costs generated in such a solution set is a very idealistic attempt, some interesting lessons can be learned from it. First of all, and not surprisingly at all, truck transport is more or less left aside in favor of less consuming transport means like train and boat. Ignoring the financial costs of transport means also ignoring a lot of parameters that make transport decisions so sophisticated. Creating a transport network without the use of road transport over long distance is barely impossible. Rail transport has limited capacity and maritime transport is facing a lot of other obstacles. On the other hand, it is interesting to note that the only increasing costs are the transfer costs. It confirms the fact that a reduction in transfer costs of rail and maritime transport would really have a positive effect for the environment on the decisions made by the freight transport decision-makers.

6.1.4 Minimizing only costs without CO_2 pricing

For this purpose, ω is set to 1 and $\zeta = 0$. This configuration is maybe less useful than the previous one, but can be used to assess the actual method of emission pricing. This configuration models a situation where there would not be any cost of emitting greenhouse gases. A feasible solution set with a sufficient small gap is found in 78 seconds and 41818 MIP iterations this time.

The financial costs -the left part of the objective function- have decreased by only 0,2% which can be considered as negligible. Concerning emissions, they are 8 % higher than in the first solution set. The new share of transport performed per mode is slightly different. As predicted, road transport is taking over some of the market shares held previously by maritime and rail transport. The new market shares for maritime, rail and road transport are respectively 42,5%, 8,2% and 49,4%.

To summarize, the actual CO_2-pricing methods are still very soft. They help to create a slight modal shift in favor of less polluting means of transport. In fact, the actual pricing method allows train and boat transport to be lightly more competitive with trucks. The small part of goods that were initially on the edge of the competition between road and other transports is now transported by train or boat instead of by truck.

6.1.5 Summary of the different configurations

Here below, a summary of important results for each scenario. Scenario 1 includes both costs while scenario 2 and 3 are minimizing respectively emissions and costs without any environmental concern.

Table 6.4: Recap of the results

	Scenario 1	Scenario 2	Scenario 3
ω	1	0	1
ζ	1	1	0
Total Costs (NOK)	7 118 279 886	10 698 399 729	6 815 740 000
Total Emissions (tonnes CO_2)	583 440	296 000	630 822
Share of road transport	41.2%	2.4%	49.4%

Scenario 1 is modeling the parameters and cost function such as in the actual state of things in Norway. It is therefore the perfect basis to compare with when some other policies or cost parameters are used like in the following sections. Scenario 2 shows that there is already a significant potential for a decrease in emissions without the addition of new technologies. But reaching this potential is quite hypothetical. It is known that truck transport cannot easily be replaced as alternative transport means do not offer the same flexibility or total capacity. Finally, scenario 3 shows how things would go if there was not any pricing emissions occurring. The difference is not that big, but the scenario demonstrates that the actual method allows to shift a small part of the transport from road to maritime and rail transport.

6.2 Effects of transfer costs reduction

As seen in the literature and in previously calculated results, transfer costs are a very important aspect influencing the mode choice decision. The main reason why trains and boats have so much difficulties to compete with trucks is to find in these transfer costs. While direct costs of transport per km are much lower for other transports, truck transport still has, by far, the lowest handling and transfer costs. In his National Transport Plan (Norwegian Ministry of Transport and Communications, 2017), the Norwegian government aims to increase the competition between modes by decreasing transfer costs. In next sections, the potential reductions in transfer costs will be tested in the model in order to assess the efficiency in terms of costs, but more especially in terms of CO_2 emissions.

6.2.1 Ways to reduce transfer costs

Some possible improvements are listed in a small summary of the National Transport Plan (Institute of Transport Economics of Norway, 2015). First of all, the proximity between freight terminals and industry is very important. In general, big volumes of goods are transported by truck from the plant or storage to the port or train terminal. This means a lot of handling and already road transport before the products are put on a ship or train. It obviously costs a lot and the new strategy is now to make space for industry in port areas. A transport chain with two short truck trips and two ship terminal handlings is competitive with direct road transport for distances over 500 km. In comparison, a direct maritime transport without the short truck trips and the supplementary handlings would be competitive from 200 km distance.

A decentralized terminal structure can also help increase competitiveness of sea and rail transport by decreasing the need for road transport to reach these terminals. In Norway, more rail terminals are specially needed. By combining this with the first solution, these terminals can be local and regional drivers of development and competition of sea and rail transport.

A third improvement needed is the improvement of the quality of services provided by sea and rail transport. Therefore, the frequency of the transports should be increased as well as the delivery time needs to be reduced. Road transport is still performing much better on these two aspects. These factors are still the source of huge costs for the transport of high-value and fragile or perishable goods. Due to the high costs they create for companies, road transport is keeping a large competitive advantage when it comes to transport this type of goods.

These improvements on their own are very important to mitigate the biggest drawback of maritime and rail transport when it comes to transport goods over quite short distances (less than 500-600 km). But, improving the competitiveness of these transport modes is only a first step towards modal shift. This increase in competitiveness needs to be supported by investments in new capacity to handle these new volumes. It is especially true for rail transport where the potential increase of capacity is very limited without additional railways. All these investments have huge costs and are not always feasible. These costs and limitations are however not considered in the model and would therefore need further analysis to assess the feasibility of the next solutions.

6.2.2 Results with transfer costs reduction

According to the National Transport Plan summary by Institute of Transport Economics of Norway (2015), a reduction by 20% of the minimal distance needed to have a competition between road and other modes can be reached thanks to the ambitions of the national plan. The corresponding costs can easily be calculated and implemented in the model. In order to look at marginal effects of reducing transfer costs, the results have been calculated for reductions of 10%, 20% and 30%.

Table 6.5: Results with reduction of minimal distance required for competition with road transport

Reduction of distance	0%	10%	20%	30%
Transfer cost H_m Boat	242.36	220.12	197.88	175.65
Transfer cost H_m Train	267.01	242.31	217.61	192.91
Direct Transport costs	3 816 420 000	3 371 600 000	2 157 970 000	2 083 950 000
Transfer costs	3 010 140 000	3 213 430 000	4 139 230 000	3 774 110 000
Emission costs	291 719 886	273 071 027	214 165 613	210 353 642
Total Costs (NOK)	7 118 279 886	6 858 101 027	6 511 365 613	6 068 413 642
Total Emissions (tonnes CO_2)	583 440	546 142	428 331	420 707
Share of road transport	41.2%	34.2%	16.7%	15.7%
Share of sea transport	46.1%	53.2%	59.9 %	59.8%
Share of rail transport	12.7%	12.6%	23.4 %	24.5%

Surprisingly, total transfer costs first increase when reducing the transfer costs per ton. This means that the amount of goods transferred has increased a lot. It leads to the point that the reduction of the costs is allowing a lot more combined transport chains. Since the cost of transferring goods from road to another mode has decreased, using rail or boat has become interesting for shorter distances and thus for more potential trips.

Less surprisingly and as intended, a modal shift is happening from road to sea, first, and to rail, when costs decrease more importantly. As explained before, this modal shift is certainly overestimated. The data do not include a sufficient level of details for that. The type of goods is not sufficiently precise to prohibit transports for some of them. The availability or not of sufficient capacity has not been precised either. This modal shift is not to neglect and a reduction of 20% already allows a huge modal shift. This modal shift contains almost all of the potentially interchangeable volumes of goods.

Concerning emissions, the 20% reduction is also having the biggest impact on it. It is also quite predictable that modal shift goes with reduction of emissions. Again, the 20% reduction aimed by the Norwegian government seems to be the most cost-efficient one. Even if the modal shift is overestimated here, it is clear that the majority of goods that can be transported with alternative transport means has been transferred.

6.3 Effects of tax changes

An important measure used to regulate the distribution over modes is taxation. Indeed, a lot of different types of taxes can be implemented to promote the use of a certain mode or cut down other modes. It is important -and not always easy to implement- that taxes are cost-efficient and reaching the desired objective. A cost-efficient tax is a tax that will always favor marginal improvement at the lowest cost possible. I.e. a transporter that can cut its emissions at the lowest price on the market should be the first one to be influenced by this tax.

The already existing carbon tax will first be commented and a potential increase of this tax will be computed. After this, a tax targeting specifically road transport is experimented. Quite similarly, an environmental subsidy for rail and/or maritime transport is assessed in the third part of this section. Finally, some more complex tax types like fuel taxes are reviewed. Even if their complexity and their level of detail are too high to be implemented with the data of this experiment, a way of including them in the model is presented.

It is important to specify that the demand here is exogenous. This means that the flow from and to each city is given and is the same in every situation. It is a strong assumption since it seems quite evident that the demand would change slightly with a different cost structure. In order to avoid this small bias, a demand forecasting model should be implemented. With such a model, demand can be forecasted in function of the cost parameters and feasibility constraints.

6.3.1 Carbon pricing

According to the Worldbank, "Carbon pricing is an instrument that captures the external costs of greenhouse gas (GHG) emissions (...) and ties them to their sources through a price, usually in the form of a price on the carbon dioxide (CO2) emitted." Carbon pricing can take the form of different types of tax. Two important ones are a pure carbon tax and an emission trading system (ETS).

A carbon tax is quite easy to implement and to understand. It basically just consists of a fixed tax per amount of CO_2 output. The result of the reduction of CO_2 is not pre-defined (Worldbank). An emission trading system is a little more complex tax system. Here, the importance of the environmental impact is defined. To reach the emission targets, entities can either chose to cut down their own emissions or buy emission permits from other entities on the market. Therefore, an entity will chose to reduce its own emissions if it is less costly than it costs to the other market players to reduce its emissions. Thanks to this automatic regulation of the emission market, ETS are a cost-efficient method to reduce emissions.

In the initial experiment, a total cost of about 500 NOK/ton of CO_2 is used for the output of transport. This total cost includes all the possible carbon taxes. As explained in section 6.1, this tax allows to shift the few transport works that are on the edge of competition from road to one of the less-polluting modes. Here below, an increase in the carbon tax is tested. Whether it is a classic carbon tax, ETS or any other type of tax is not part of this research. The aim here is to measure the impact that the tax decisions have on the allocation of the transport to different modes and on the total emissions.

Table 6.6: Results with increase of carbon price

Carbon tax (NOK/ton CO_2)	0	500	750	1000
Emission costs	0	291 719 886	427 290 590	566 738 320
Total Costs (NOK)	6 815 740 000	7 118 279 886	7 263 460 590	7 405 238 320
Total Emissions (tonnes CO_2)	630 822	583 440	569 720	566 738
Share of road transport	49.4%	41.2%	39.3%	38.2%
Share of sea transport	42.5%	46.1%	48.0%	49.2%
Share of rail transport	8.2%	12.7%	12.7%	12.7%

The difference between no emission taxes and the actual 500 NOK price has already been discussed in section 6.1. The results of an increase of the tax are not very surprising and go in the same direction. Even by doubling the total carbon price, the CO_2 emissions only decrease by less than 3 % if we suppose that the goods are perfectly transferable from any mode to another. Therefore, it seems quite easy to conclude that an increase in carbon taxes would not be effective. In the actual state of things and thanks to the ETS, the market already regulates itself and reduces emissions cost-efficiently. Therefore, a carbon tax and especially ETS is a good tool to decrease the emissions that are the 'easiest' to get rid off. For a more drastic decrease of emissions caused by the transport industry, supplementary solutions are required.

6.3.2 Tax on road users

It is well known that road transport is the biggest producer of GHG emissions of the sector. In Europe, road transport is producing 72.1% of the total greenhouse gases from the transport industry (Eurostat, 2017). Therefore, a modal shift from road to sea or rail is needed to reduce the impact of the transport industry on the climate change. In order to do so, one of the simplest way is to increase the costs for the use of road transport. That is why a tax on road transport is tried in this model. Such a tax is quite easy to add. A parameter T_m is added. This parameter has a value of zero for sea and rail transport. For road transport, the parameter is equal to the tax in NOK/km. It is then simply added in the first term of the objective function that now becomes $\sum_{i \in N} \sum_{j \in N} \sum_{m \in M} y_{i,j,m} * L_{i,j,m} * (C_m + T_m)$. The tax does apply for each vehicle and is not depending on the goods transported in the vehicle.

In order to find a good range of 'test' taxes, the summary of the National Transport Plan (Institute of Transport Economics of Norway, 2015) was used. In this paper, charges from 2 NOK/km for light trucks to 4 NOK/km for heavy trucks are advised. Therefore, both will be tried and the results are in the table below. The governmental benefits are equal to the total taxes paid by transporting companies to the government. The model still optimizes in function of the costs faced by the decision makers of the transport sector. Thus, the governmental part is calculated after the optimal solution has been found. Again, it is interesting to look at the results and counterparts generated in both cases.

Table 6.7: Results with road tax

Road tax (NOK/km)	0	2	4
Emission costs	291 719 886	273 029 018	223 053 061
Total Costs (NOK)	7 118 279 886	7 496 679 018	7 718 653 061
Governmental benefits	0	355 522 000	326 727 000
Total Emissions	583 440	546 058	446 106
Share of road transport	41.2%	34.2%	14.9%
Share of sea transport	46.1%	53.2%	70.1%
Share of rail transport	12.7%	12.6%	14.9%

A road tax of 2 NOK/km already allows an important switch of road transport to sea. The total costs are almost the same and make this measure very effective. Increasing the road tax up to 4 NOK/km allows even more switch from road to sea transport. This outcome was quite predictable as the trucks (capacity of 30 tons) considered here are heavy trucks. It is however another indicator of the correct modeling of the real situation. Even though the total costs to transport all the goods are increasing, it is worth it when looking at the big decrease of emissions. With the tax revenues taken into account, the increase of the total costs can be diminished. These revenues decrease with a tax of 4 NOK/km because of the modal shift which is more important than the tax increase. But, once again, while the general findings are valuable, the exact outcomes and especially the modal shift might be overestimated. This type of tax is also quite easy to calculate, however it is not always as easy to implement this in reality. In a big country whit long roads, it is always difficult to be able to track the distances covered by each truck.

Despite all these positive points, a more complex road tax structure would result in better environmental results. Indeed, by increasing the price of any road trip, the average transfer price to train and port terminals is also increasing. Remember that transfer cost need to decrease in order to increase competitivity of combined transport chains and i.e. of rail and sea transport. A method that discourages long distances without any disadvantage for the shorter distances would therefore be preferable. Such a method could be the high mileage road tax, suggested again by Institute of Transport Economics of Norway (2015). Such a tax is increasing or is only valid if a truck covers a lot of kilometers through the year. Implementing such a tax structure in a model would need the precision of much narrower operational planning models for each truck company. It would in fact need information about the total distance covered by each specific truck over a whole year. This distance should also include the kilometers covered with an empty load. The management of empty trucks, better known under the word backhauling, is not included in this thesis.

The above-mentioned tax is based on the total kilometers covered over a year. For reminder, the objective of this tax is to discourage the transport by truck over long distance without harming the competitiveness of combined transport chains. Even though the link between long-distance trips and trucks covering a lot of kilometers over a year seems quite evident, a tax rate calculated for each trip would be more accurate to reach the objective. Therefore, a tax rate variable over the distance covered might be a very effective policy to favor modal shift. The problem of such a policy resides in the implementation. To be able to calculate the amount of tax having to be paid, the government would need a record of all the trips of a company. So much information could only be provided by a GPS tracker or any similar tool. Even with a record of all the movements of a truck, how much time between two trips is needed to separate them, what about trips with different pick-up and delivery location...

6.3.3 Subsidies for maritime and rail transport

As well as road transport can be taxed, alternative means of transport can also be subsidised. As one of the most important factors of competitiveness of these transport means is the transfer cost or handling cost, the subsidy should have an effect on it. And in fact, a subsidy for each ton handled can help decrease the costs of handling for the deciding transport firms.

Again, it is quite simple to add to the model. The subsidy just need to be substracted from the handling costs in the objective function. Therefore, the new handling costs become now $1/2 * \sum_{n \in N} \sum_{p \in P} \sum_{m \in M} z_{n,p,m} * (H_m - S_m)$. With S_m the subsidy received for the handling of one ton of goods from any mode to mode m.

Based on actual transfer prices, some subsidies from a range between 25 and 50 NOK/tonne handled were used. The price suggested by Institute of Transport Economics of Norway (2015) in their summary a few years ago is also implemented. The price suggested is 500 NOK/container. Knowing that the maximal payload of a container is around 25 ton, an average load of 20 tons is used. Therefore, the price used to test the suggestion in this model is of 25 NOK/tonne. This price is suggested to be used in combination with other policies and bigger amounts of subsidies are therefore also tested here. The governmental costs are calculated in the same way as the benefits in last section.

Table 6.8: Results with subsidies for rail and maritime transport

Subsidies (NOK/km)	0	25	50
Emission costs	291 719 886	273 101 032	226 813 104
Total Costs (NOK)	7 118 279 886	6 829 831 032	6 430 133 104
Governmental costs	0	310 981 000	941 236 000
Total Emissions	583 440	546 202	453 626
Share of road transport	41.2%	34.2%	15.9%
Share of sea transport	46.1%	53.2%	70.1%
Share of rail transport	12.7%	12.6%	14.0%

When the 25 NOK/tonne subsidy is used as only new action against greenhouse gases, a small share of road transport is shifted to maritime transport. When doubling this subsidy, which is a quite huge subsidy, the shift is becoming much more significant and the road transport share drops to numbers around 16 %. As it is the minimal share of road transport that always remains even when policies are used in extreme measures, it can be considered that all the potential transferable goods from road to other means has been transfered. Even though the amount transfered is surely too high compared to the potential transferable goods in real life, policies that allow a transfer of a huge amount of goods in the model will also allow a shift of a big part of the goods that can be shifted in real life. A disadvantage of these subsidies is the high cost that it implies for the government. In this model, it costs almost a billion NOK to the government for a subsidy of 50 NOK/tonne.

6.3.4 Fuel tax

A last type of tax that is important to mention in this thesis is the fuel tax. This tax just adds an additional cost to the price of fuel. A lot of fuel taxes already raise the price of fuel. A fuel tax has a lot of consequences in common with the carbon tax. It makes it costlier to use vehicles that consume a lot of fuel. As greenhouse gases emissions are directly depending on fuel consumption, both taxes target the same aspect of transport. The advantage of a fuel tax is that it is very easy to implement and fuel cost are an important factor when strategic decisions are made in the transport sector. This fuel tax, as all the other environmental policies, increases the relative costs of the most polluting transport modes. It also triggers the development of new technologies and less consuming vehicles.

It is here quite easy to model. There is a need for additional data which is the average consumption per vehicle type that can be called U_m for all m being the different modes or different types of vehicles for more detailed datasets. In the model and data, fuel costs are already included in the cost parameter C_m Therefore, the fuel tax Q is the tax on one liter of fuel. The total cost of the tax for the transporting firms is $\sum_{i \in N} \sum_{j \in N} \sum_{m \in M} y_{i,j,m} * L_{i,j,m} * U_m * Q$. And the first element of the objective function becomes an addition of all the previously calculated costs and the new additional tax, $\sum_{i \in N} \sum_{j \in N} \sum_{m \in M} y_{i,j,m} * L_{i,j,m} * (C_m + U_m * Q)$.

This fuel tax is very interesting on a more detailed level with different types of vehicle per mode. It emphasizes on the use of less consuming vehicles or even zero-consumption transport modes.

6.4 Combination of different policies

After having been through a lot of different measures to reduce CO_2 emissions, a quick review of combinations of different policies is made. Each measure was tested and assessed separately, but some of them can surely be complementary and synergies can appear between them. Therefore, some of the best results from section 6.2 and 6.3 are combined and tested in the model. With the synergies that are certainly gonna be found between different policies, it is highly probable that the policies themselves are gonna be made less important when implementing in combination with different policies. In other words, the amounts taxed or the reduction of cost needed for an efficient reduction of emissions are lower when different actions are taken at the same time. It is clearly preferable, for a same result, to have a combination of two or three different soft solutions supported by a lot of different actors rather than one very constraining policy whose pressure is only on a small part of the actors of the transport market.

Here below, a recap of the best combinations found. In order to reach these scenarios, the first combinations tried were containing the most efficient policies with their most efficient parameters. As these situations already resulted in quite efficient emissions reduction, a softening of some of the rules was tried in order to find good results without abusing from any of the different solutions. As explained here above, this is to thank to synergies between the policies. Scenario 1 is the actual state of things in Norway.

Table 6.9: Results of different scenarios

Scenario	1	2	3
Transfer costs reductions	0	20%	20%
Carbon pricing (NOK/tonne)	500	500	500
Tax on road users (NOK/km)	0	2	2
Subsidies (NOK/tonne)	0	0	25
Total costs	7 118 279 886	6 675 623 649	6 158 868 094
Governmental benefits	0	163 379 000	-417 928 000
Total Emissions	583 440	420 787	395 936
Share of road transport	41.2%	15.5%	24.7%
Share of sea transport	46.1%	60.2%	63.9%
Share of rail transport	12.7%	24.3%	11.4%

Table 6.10: Results of different scenarios

Scenario	4	5	6
Transfer costs reductions	20%	0	20%
Carbon pricing (NOK/tonne)	500	500	500
Tax on road users (NOK/km)	0	2	4
Subsidies (NOK/tonne)	25	25	0
Total costs	6 030 073 016	7 074 680 090	6 809 114 002
Governmental benefits	-506 724 000	-320 968 000	249 738 000
Total Emissions	404 886	446 120	394 688
Share of road transport	13.7%	14.9%	24.7%
Share of sea transport	61.6%	70.1%	63.2%
Share of rail transport	24.7%	15.0%	12.1%

For the transfer costs, the 20% reduction has been used all along the scenarios. The reason for this decision is based on literature. The 20% are an actual and reasonable objective for cost reduction in Norway (Institute of Transport Economics of Norway, 2015). The results obtained with a 20% cost reduction are also the most efficient ones in terms of emission reduction relatively to the cost reduction. The subsidies policy for train and boat transport is also reducing the costs of handling for these transport means.

While the reduction is calculated in percentages of initial costs, the subsidies are the same for both rail and sea transport. Therefore, the reduction has a bigger effect for the most expensive handling costs (rail) while subsidies have the same effect and it favors therefore the initially less expensive handling (sea). This is overall the only difference between both policies. Of course, a reduction of the costs is preferable, but not always reachable on a short term. Therefore, subsidies can be used when the handling costs cannot be decreased enough to reach the objective of CO_2-emissions.

Concerning the carbon pricing, the same price is kept in all the scenarios. The reason for this can be found in section 6.3.1. The conclusions of the analysis of this carbon pricing state that an increase would have a very small impact on the modal distribution. The initial 500 NOK/tonne of CO_2 is kept because it allows a slight modal shift than cannot be neglected. As this tax is mainly due to the Emission Trading System, the revenues of this tax are not accounted for in the governmental benefits. The ETS is a market where emission permits are exchanged at a certain market price between different actors of the markets. The government is therefore not directly earning this 'tax'.

Finally, the tax on road users allows to strengthen the competitiveness of the other transport means in almost any situation. A 2 or even a 4 NOK/km tax is helping a decrease of emissions even when other policies or actions or taken. The optimal tax price should therefore be analysed more thoroughly through more precise models.

The scenario allowing the biggest reduction of CO_2 emissions is naturally the one where the measures taken are the most important. It is most likely not the best one in terms of social welfare. Some types of goods need specific transport conditions, the transport network has its own constraints and innovation can cost a lot. It is simply not possible to optimize emissions without paying any attention to other important factors. But, it is possible to influence the optimal solutions of the decision makers of the transport sector.

6.5 Potential of coordination

A last but not the least improvement covered in this thesis is the coordination between the actors responsible of the transport. If companies cooperate and optimize their transport together, it has a big potential for reduction of emissions, but also for the costs. The social welfare can therefore only gain from coordination in the logistics. With coordination, the amounts that need to be transported are bigger and it leaves therefore more room for optimization. In an ideally coordinated system, the destination nodes are served by the closest nodes where goods are available. It can therefore help reduce drastically the average distance for the delivery of commodities. Of course, all the goods are not perfect substitutes of each other. It is very difficult to coordinate for the transport of finished products, but it is much more plausible to do so for raw materials for example.

In the actual free and competitive markets, it is quite counter-intuitive to imagine perfectly interchangeable goods. It is also very difficult to force Northern companies source only from other Northern companies. But, by increasing the importance of transport costs, for example, the market players will logically give more attention to the proximity factor when organizing transport. In a country with huge distances between the big cities, the potential of coordination can be considerable.

In this paper, coordination between different regions will be implemented in the model and the potential reduction will be calculated. The data are already aggregated per region and companies from the same region are therefore already considered as coordinating companies. Initially, the transport flows between regions are already fixed in the data and the model is forced to respect these flows for its optimization. To include some coordination in the model, the flows are gonna be relaxed for the goods that are not too differentiated between a commodity group. For these groups, the goods are not differentiated by their origin anymore. Doing like this is obviously a quite gross method regarding the poor level of detail of the commodity groups. The aim of this section is therefore to show how coordination can easily be implemented in this type of model. The results are shown for information and for a better understanding of what happens when there is coordination between companies, or regions in this case, in place. The exact numbers themselves are not of a great value. A much more detailed model including more constraints about the goods and companies that can be coordinating and to which extend is needed to calculate exact results.

In order to model the coordination, some slight modifications have been made in the data and model. First of all, two subsets P_c and $P_{nc} \in P$ were created. The first one contains all the product types where coordination is possible, the second one contains the other products that cannot be coordinated. The products in P_c chosen are all the manufacturing goods except machinery equipment, but also waste management.

Table 6.11: Subsets of products

Subset	Products
Coordinating products (P_c)	Manufacture of food, Wood products, Non-mineral products, Waste collection, Wholesale of food, Wholesale of household goods, Wholesale of machinery equipment, Other wholesale
Non-coordinating products (P_{nc})	Machinery equipment, Wholesale of food, Wholesale of household goods, Wholesale of machinery equipment, Other wholesale

Of course, these categories are still way too large to totally coordinate in real life. But, these are the commodity groups that can be divided into more or less important groups of substitutable goods. For the purpose of this thesis, the transport of goods from one of the groups of P_c can be totally coordinated.

The difference in modeling of these two different sets occurs in the flow constraint 4.5. As a reminder, an index $o \in N$ had been added in combination with the index $p \in P$ to differentiate the products from different origins. The aim here is to remove this differentiation for products for which it is possible to coordinate, i.e. where the source of the products does not bother anymore. For P_c, a sum on all the origins o is added in order that no difference is made anymore between products from different origins. The flow constraint is therefore split into two constraints:

$$\sum_{i\in N}\sum_{m\in M} x_{i,n,m,p,o} - \sum_{j\in N}\sum_{m\in M} x_{n,j,m,p,o} + I_{n,p,o} \geq F_{n,p,o} \qquad \forall n \in N, \forall p \in P_{nc}, \forall o \in N \tag{6.3}$$

$$\sum_{i\in N}\sum_{m\in M}\sum_{o\in N} x_{i,n,m,p,o} - \sum_{j\in N}\sum_{m\in M}\sum_{o\in N} x_{n,j,m,p,o} + \sum_{o\in N} I_{n,p,o} \geq \sum_{o\in N} F_{n,p,o} \qquad \forall n \in N, \forall p \in P_c \tag{6.4}$$

The results are very satisfying in terms of costs and emissions reduction. The coordination for 4 out of the 9 commodity groups allows to decrease the total costs by 34.7% compared to the initial situation. The emissions decrease by 32.8%. All the reductions of the costs are due to the reduction of distances of transport of goods. The total amount of tonne.km performed decreases by 31.5% thanks to coordination. For the 4 commodity groups of the subset P_c, the reduction of the tonne.km performed for them is of 55.5%.

As already explained before, the numbers mentioned here above are there for information and the precise value of them can not be given any value in real life. They however confirm the fact that more coordination can help a lot in the decrease of costs and greenhouse gas emissions. It might sound weird to encourage coordination between companies competing on the same market, but the actual transport sector needs to give more focus on the social welfare. The little changes in the subsets and constraints here above also show that it is quite easy to include coordination in actual transport allocation models.

7 Conclusion

This thesis began with some appealing figures about freight transport and its influence on climate change. Indeed, the actual standards of the transport sector are not in line with the emission targets. In order to reach these targets, the transport sector requires to allow much more credit to the environmental cause in the future. Of course, innovation will bring us new technologies with lower impacts on the environment. Of course, people are becoming more and more aware of the need for less polluting transport means. But, the environment needs more consideration at every level of decision. In fact, the weight of environmental considerations needs to be increased from the everyday decisions of individual carriers to the most strategic decisions taken at continental levels.

In this paper, Operations Research is used as a tool to assist the strategic decision-making for regional, national or even international transport areas. In order to do so, a model has been built. The aim of this model is to align the cost-minimizing objective of freight carriers with the emission-minimizing objective that humanity will seek for in the next decades.

The outcomes of this thesis are multiple. On a theoretical level, a tactical planning model has first been built. This model and the further implementation of different policies can totally be applied to many different situations around the world and can help strategic decision-makers to make the most effective decisions.

On a practical level, the application of this model on a real life situation has also brought plenty of lessons. First of all, it allowed to illustrate clearly how such planning models work in practice and how to use them efficiently. Secondly, Norway is a sparsely populated country with long transport distances between important cities. The conclusions obtained in this practical case can, to a certain extent, be generalized to other similar situations. These conclusions showed the importance of the decrease of transfer costs in order to increase the competitiveness of rail and maritime transport. Different tax implementations were also calculated and it has been showed that they can also help increase the competitiveness of these transport modes compared to road transport. Finally, the potential of coordination in freight transport has been discussed. The demonstration of it showed that researchs in this domain could have great potential for the future of the environment in the transport sector.

To conclude, the lessons and outcomes of this thesis about the use of tactical planning models as a helping tool for environmental strategic decisions in freight transport are numerous and of many different kinds. Overall, all these results need a lot more development before they can effectively influence strategic decisions. First, more detailed models and data should test the different measures on each planning level. Operations Research cannot be used as only tool for the implementation of new policies. Many other aspects of the policies need to be searched through before making their implementation effective. While this thesis has brought valuable methods for the use of OR for the environmental cause, the number of further steps needed before obtaining a cost-effective environmental measures are not to be underestimated.

References

Bektas, T., Ehmke, J. F., Psaraftis, H., and Puchinger, J. (2018). The role of operational research in green freight transportation. *European Journal of Operational Research*, 274:807–823.

Business Dictionary (2018). Business dictionary.

Böhm, T. (2012). Calculation tools for the documentation of the environmental performance of freight transport alternatives. Master's thesis, Molde University College, Molde.

Crainic, T. G. (2000). Service network design in freight transportation. *European Journal of Operations Research*, 22:272–288.

de Jong, G., Ben-Akiva, M., Baak, J., and Grønland, S. E. (2013a). Method report - logistics model in the norwegian national freight model system (version 3). https://www.ntp.dep.no/Transportanalyser/Transportanalyse+godstransport/-attachment/526626/binary/847833?\textunderscorets=14135402fc8.

de Jong, G., Gunn, H., and Walker, W. (2004). National and international freight transport models overview and ideas for future development. *Transport Reviews*, 24:103–124.

de Jong, G., Vierth, I., Tavasszy, L., and Ben-Akiva, M. (2013b). Recent developments in national and international: freight transport models within europe. *Transportation*, 40:347–371.

Energy Facts Norway (2019a). Energy use by sector. https://energifaktanorge.no/en/norsk-energibruk/energibruken-i-ulike-sektorer/.

Energy Facts Norway (2019b). Taxes and emission tradings. https://energifaktanorge.no/en/et-baerekraftig-og-sikkert-energisystem/avgifter-og-kvoteplikt/.

European Union of Road Transport (2018). Freight transport 2017. ttp://erf.be/statistics/freight-transport-2017/.

Eurostat (2017). International trade in goods by mode of transport. https://ec.europa.eu/eurostat/statistics-explained/pdfscache/1180.pdf.

Eurostat (2018). Freight transport statistics - modal split. https://ec.europa.eu/eurostat/statistics-explained/pdfscache/1142.pdf.

Fleet Speak (2019). Market report: European road freight transport 2018. https://fleetspeak.co.uk/market-report-european-road-freight-transport-2018/.

Freightquote (2018). What is freight shipping? https://www.freightquote.com/define/what-is-freight-shipping.

Guélat, J., Florian, M., and Crainic, T. G. (1990). A multimode multiproduct network assignment model for strategic planning of freight flows. *Transportation Science*, 24.

Institute of Transport Economics of Norway (2011a). Summary: Cost models for transportation and logistics. https://www.toi.no/getfile.php/1316537/Publikasjoner/T\%C3\%98I\%20rapporter/2011/1127-2011/1127-2011-sum.pdf.

Institute of Transport Economics of Norway (2011b). Summary: Intermodal competition in norwegian freight. https://www.toi.no/getfile.php/1316234/Publikasjoner/T\%C3\%98I\%20rapporter/2011/1125-2011/1125-2011-sum.pdf.

Institute of Transport Economics of Norway (2015). National transport plan(norway.

International Chamber of Shipping (2018). Shipping and world trade. http://www.ics-shipping.org/shipping-facts/shipping-and-world-trade.

McKinnon, A. and Piecyk, M. (2011). Measuring and managing co2 emissions of european chemical transport.

Norwegian Ministry of Transport and Communications (2017). National transport plan 2018–2029. https://www.regjeringen.no/contentassets/7c52fd2938ca42209e4286fe86bb28bd/en-gb/pdfs/stm201620170033000engpdfs.pdf.

NSB (2019). Here is a map of all nsb stations in norway. https://www.nsb.no/en/our-destinations/map-of-railway-lines.

OECD (1997). The environmental effects of freight. http://www.oecd.org/environment/envtrade/2386636.pdf.

OECD (2018a). Greenhouse gas emission statistics - emission inventories. https://ec.europa.eu/eurostat/statistics-explained/pdfscache/1180.pdf.

OECD (2018b). Key transport statistics. https://www.itf-oecd.org/sites/default/files/docs/key-transport-statistics-2018.pdf.

Qu, Y., Bektas, T., and Bennell, J. (2014). Sustainablity si: Multimode multicommodity network design model for intermodal freight transportation with transfer and emission costs. *Netw Spat Econ*, 16:303–329.

Rodrigue, J.-P. (2017). *The geography of transport systems*. Routledge.

Sea-distances.org (2019). Sea distance calculator. https://sea-distances.org/.

Statsbanken (2014). Commodity flow survey. https://www.ssb.no/en/transport-og-reiseliv/statistikker/vsu.

Statsbanken (2018). Domestic transport performance. https://www.ssb.no/en/transport-og-reiseliv/statistikker/transpinn.

Steadieseifi, M., Dellaert, N. P., Nuijten, W., Woensel, T. V., and Raoufi, R. (2014). Multimodal freight transportation planning: A literature review. *European Journal of Operations Research*, 233:1–15.

Thomlinson, J. (2009). History and impact of the intermodal shipping container. Technical report, Pratt Institute.

Transportica (2019). Distance and freight rate calculator.

Wikipedia (2019). Intermodal container. https://en.wikipedia.org/wiki/Intermodal_container.

Worldbank. What is carbon pricing? https://carbonpricingdashboard.worldbank.org/what-carbon-pricing.

Appendix

A1 Model

Indexes

N Set of nodes in the network

M Set of modes used in the network

P Set of products

Parameters

$L_{i,j,m}$ Length of the link of mode m between i and j

$A_{i,j,m} = 1$ if the link of mode m between i and j exists. 0 otherwise.

C_m Cost of a vehicle of mode m over one unit of distance

H_m Cost of handling one ton from any mode to mode m

E_m Emission output for transporting one ton over one unit of distance with transport mode m

G_m Emission output for handling one ton from any mode to mode mode m

K_m Capacity of one vehicle of mode m

$B_{p,m}$ =1 if product p can be transported on mode m. 0 otherwise

$F_{n,p}$ Demand in node n for product p

$I_{n,p}$ Initial stock of product p at node n

V Cost of emitting one unit of emissions

Variables

$x_{i,j,m,p}$ Quantity of product p transported by mode m from node i to node j

$y_{i,j,m}$ Quantity of vehicles of mode m used from node i to j

Objective function

Minimize

$$\begin{aligned} TC = \sum_{i\in N}\sum_{j\in N}\sum_{m\in M} y_{i,j,m} * L_{i,j,m} * C_m + 1/2 * \sum_{n\in N}\sum_{p\in P}\sum_{m\in M} z_{n,p,m} * H_m \\ +V * \left(\sum_{i\in N}\sum_{j\in N}\sum_{m\in M}\sum_{p\in P} x_{i,j,m,p} * L_{i,j,m} * E_m + 1/2 * \sum_{n\in N}\sum_{p\in P}\sum_{m\in M} z_{n,p,m} * G_m \right) \end{aligned} \tag{.1}$$

Constraints

$$\sum_{i\in N}\sum_{m\in M} x_{i,n,m,p} - \sum_{j\in N}\sum_{m\in M} x_{n,j,m,p} + I_{n,p} \geq F_{n,p} \qquad \forall n \in N, \forall p \in P \tag{.2}$$

$$x_{i,j,m,p} \leq \sum_{n\in N} I_{n,p} * B_{p,m} \qquad \forall i \in N, \forall j \in N, \forall m \in M, \forall p \in P \tag{.3}$$

$$\sum_{p\in P} x_{i,j,m,p} \leq K_m * y_{i,j,m} * A_{i,j,m} \qquad \forall i \in N, \forall j \in N, \forall m \in M \tag{.4}$$

$$x_{i,j,m,p} \geq 0 \qquad \forall i \in N, \forall j \in N, \forall m \in M, \forall p \in P \tag{.5}$$

$$y_{i,j,m} \in \{0, 1, 2, ...\} \qquad \forall i \in N, \forall j \in N, \forall m \in M \tag{.6}$$