Eindhoven University of Technology

MASTER

Feasibility study of the intermodal transport network in the Chemical Cluster Rotterdam

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Award date:
2017

Eindhoven, January 2017

Feasibility Study of the Intermodal Transport Network in the Chemical Cluster Rotterdam*

*Public version: monetary value is scaled.

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in partial fulfillment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

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TUE. School of Industrial Engineering.
Series Master Thesis Operations Management and Logistics.

Subject headings: transport, modal shift, multimodal, intermodal, chemical industry, simulation, chemical cluster Rotterdam, barge, rail, decoupled transport.

Abstract

This master thesis presents the feasibility study for the inclusion of rail and barge into the business of Den Hartogh Logistics as a Logistics Service Provide (LSP) in the chemical cluster Rotterdam. Intermodal transport is considered viable only over long distance, thus in this thesis, the viability of intermodal transport over shorter distance is observed. Through a simulation model, the performance of several transport network options are assessed based on the average cost per container. These options include: truck-only, modal shift (direct rail and direct barge), and decoupled intermodal transport network. Both present and future scenarios are simulated to provide insights into the influence of different parameters on the overall performance of the transport network. Along with the cost performance, the simulation also provides information on how these transport network options affects the environment sustainability based on two parameters, i.e. CO_2e and particulate matter (PM) emissions. Based on the simulation result, the decoupled intermodal transport network is not a viable business case for Den Hartogh Logistics because it is more expensive than the current truck-only system. Nevertheless, the modal shift option, where direct rail and direct barge take place, has lower average cost per container than truck-only option. This implies that the modal shift option is feasible for Den Hartogh Logistics from cost perspective. In terms of environmental sustainability, both modal shift and decoupled transport network generate lower CO_2e emissions. However, they produce higher PM emissions due to the use of diesel-powered rail and barge that generally comprises of old vessels and locomotives without advanced technology in diesel particulate filter (DPF) installed .

Acknowledgment

Rotterdam, January 2017

This master thesis concludes my two-year-long journey in TU Eindhoven. The past two years have been a very remarkable experience, and I am glad I made this decision back then.

I would like to first express my token of appreciation to my first supervisor, Jan. My final year in TU Eindhoven would not be the same without direction from him. In fact, he has been more than a supervisor; he is a mentor for his students. Jan has given me feedbacks and inputs that apparently have shaped me more than I thought it would be. Along with that, I would like to thank Maxi, my second supervisor. I thank you for your availability throughout this project. Your time, guidance and feedbacks are indispensable. All in all, it has been a great experience for me to work with Jan and Maxi. I hope we can cross path again sometime in the future.

This thesis is not going to be possible without Den Hartogh Logistics allowing me to become a part of them for the past 6 months. My gratitude goes to Luke, my first supervisor, for his availability throughout this project. Thank you for introducing me to people in Den Hartogh Logistics and bringing up the right questions during our discussions. My gratitude also goes to Joep, the one who accepted at the first time in Den Hartogh Logistics. Thank you for your enthusiasm and for always challenging me in this project. Last but not least, this thesis is impossible without the help of many people, but especially, I would like to thank Nils van der Poel, Paul Eijsvogels, and Roger Holthuis for helping me in finishing this thesis.

Further, I would like to acknowledge Lida Maclean from the Port of Rotterdam authority for her support since the start. Also, to people from Bureau Voorlichting Binnenvaart (BVB), Expertise- en InnovatieCentrum Binnenvaart (EICB), PortShuttle, and Pernis Combi Terminal B.V.; thank you for all the all-important information you have provided me with.

Lastly, but definitely not the least, I would like to thank The Almighty for accompanying me along this journey and to the Indonesia Endowment Fund for Education (LPDP) for their trust on me and making my master program possible. My gratitude also goes to my parents and siblings for their never-ending support; to my friends, for always being there; and to Yudha Prasetya, for always supporting me and restoring my faith during my hardest time.

Cheers.

Management Summary

Den Hartogh Logistics is a globally operating Logistics Service Provider (LSP) for the chemical industry. The service provided by Den Hartogh Logistics include global logistics, liquid chemical logistics, dry bulk logistics, and gas logistics[1]. Especially in Europe, the biggest business of Den Hartogh Logistics is the liquid chemical logistics, which also includes the one in the chemical cluster Rotterdam area. As per now, the transports of liquid chemical goods is done via road using tank containers or road barrels. As the business grows, Den Hartogh Logistics face capacity issues in operational planning level that is indicated by the limited flexibility of truck and driver planning. This issue also goes up to the tactical planning level, which affects how the decisions regarding capacity expansion are made.

As the attention on environmental sustainability rises, both Dutch government and the European Union aims at decarbonizing logistics through modal shift. Now, due to the generated carbon emission, the use of road transport for freights are discouraged. At the same time, the use of modes with less carbon emission, such as rail and barge, is fostered. Hence, this also becomes a concern of Den Hartogh Logistics, noticing that their biggest business in Europe is on road. At the same time, the Port of Rotterdam area is well connected by rail and barge. Therefore, together with the aforementioned motivations, this project is set out.

To determine the attractiveness of shifting transports from truck to rail or barge, cost is used as the decision parameter. However, as the ambition of Port of Rotterdam in becoming a sustainable port has put pressure on companies, thereby this project also provides insights into the environmental impact parameters along with the cost parameter. The environmental impact parameters included in this research are the greenhouse gas (GHG) and particulate matter (PM) emissions.

From a cost perspective, the internal costs are identified for both truck-only and intermodal transport networks. The internal costs include the long haul costs, handling costs, cost due to driving solo kilometer (i.e., a truck driving without a tank container), and if applicable, truck waiting costs and truck drayage costs. Different transport network settings are then simulated using a simulation model that is developed in Microsoft Excel with the support of Visual Basic for Applications (VBA). From the simulation, the corresponding costs are compared.

The simulation shows the difference between the truck-only, direct rail or direct barge, and decoupled intermodal transport networks. Based on the simulation result, the decoupled intermodal transport network is the most expensive transport option, with average cost per container of €178.4, whereas the truck-only option is only €151.4 per container on average. Based on the analysis, the high transport cost during decoupled intermodal transport is due to the extra handling processes that take place along the transport journey.

Moreover, in addition to the truck-only and decoupled intermodal transport networks, another option is assessed, i.e. the modal shift option. Modal shift is considered as one of the ways to solve capacity issue faced by Den Hartogh Logistics through shifting a portion of road transport to rail or barge, without increasing the number of handling processes. One of the disadvantage of modal shift is that not all nodes are covered such that only rail- or barge-connected nodes are advantaged from the network. Since it is clear that the biggest cost component of decoupled intermodal transport network is the handling costs, then as predicted, modal shift turned out to be the cheapest transport solution, with only €137.5 per container. The cost performance of these three transport network options are visualized in Figure 1.

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[1] http://www.denhartogh.com/company/what_we_do/

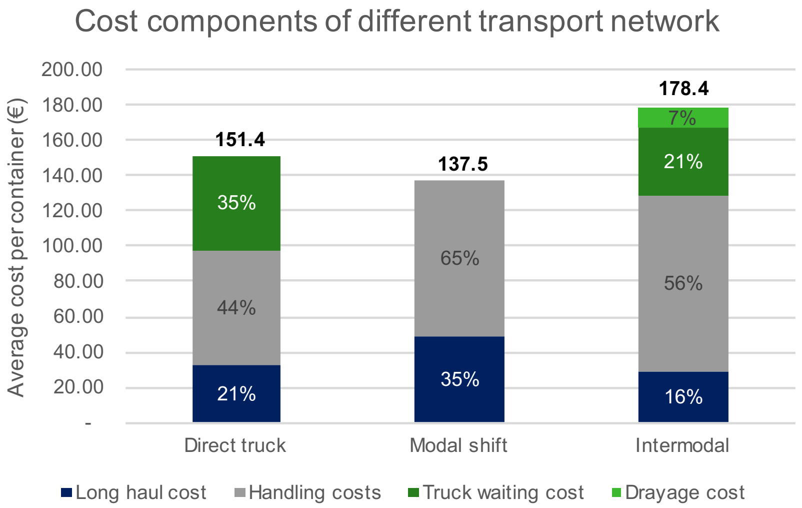

Figure 1 Result: Average cost per container

As mentioned earlier, to complete the feasibility study conducted in this thesis, an insight into the environmental sustainability of the transport network is also provided. In this thesis, greenhouse gas (GHG) emissions is calculated using CO_2e emissions, which includes CO_2, CH_4, and N_2O emissions, whereas the air quality is evaluated based on PM_{10} and $PM_{2.5}$ emissions. As predicted, the shift from trucks to rail or barge indeed results in lower CO_2e emissions as it is shown in Figure 2.

Although modal shift and intermodal transport networks generate lower CO_2e emission than the ones generated by truck-only transport, the average PM emissions show a contradictory result. The most probable reason of why this happens is because trucks with the most recent technology (including EURO 5 and EURO 6 trucks) are already equipped with Diesel Particulate Filter (DPF) that reduces the amount of PM emitted to the air. On the other hand, the average age of barge vessels is between 25-35 years. This implies that the vessels that are operating at the moment are still using a less advanced technology.

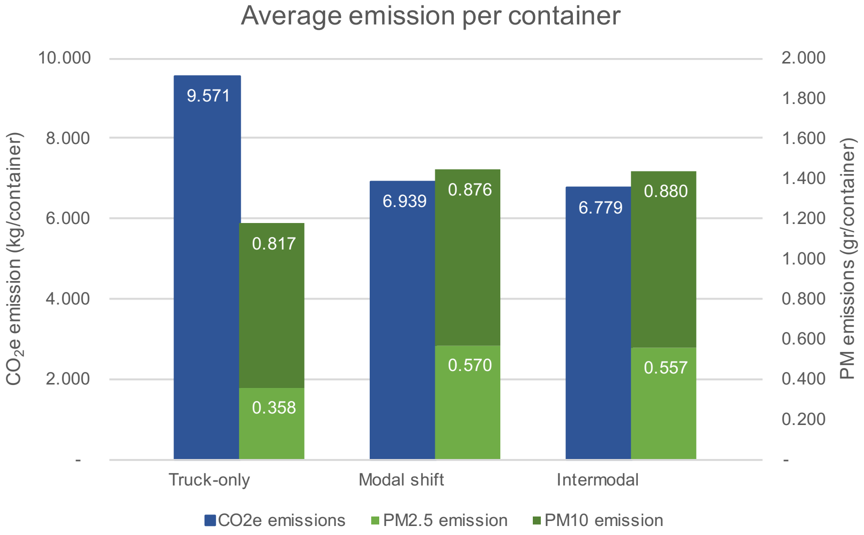

Figure 2 Result: Average CO_2e, PM_{10}, and $PM_{2.5}$ emissions per container

To conclude the results above, the modal shift option is indeed the viable business case for Den Hartogh Logistics in the chemical cluster Rotterdam. With only shifting 13 truck connections into direct rail or direct barge, 33% of the total volume in the cluster is already shifted from truck to rail and barge. To better convince the reader, a robustness analysis is also provided in this thesis, as it is shown in Figure 3 below. The robustness analysis aims at showing how changes in different parameter affect the feasibility of the business case. The graph shows that the increase of the transport and handling costs of rail and barge do not change the feasibility of the modal shift business case from cost perspective. The average cost per container remains lower than truck-only transport option.

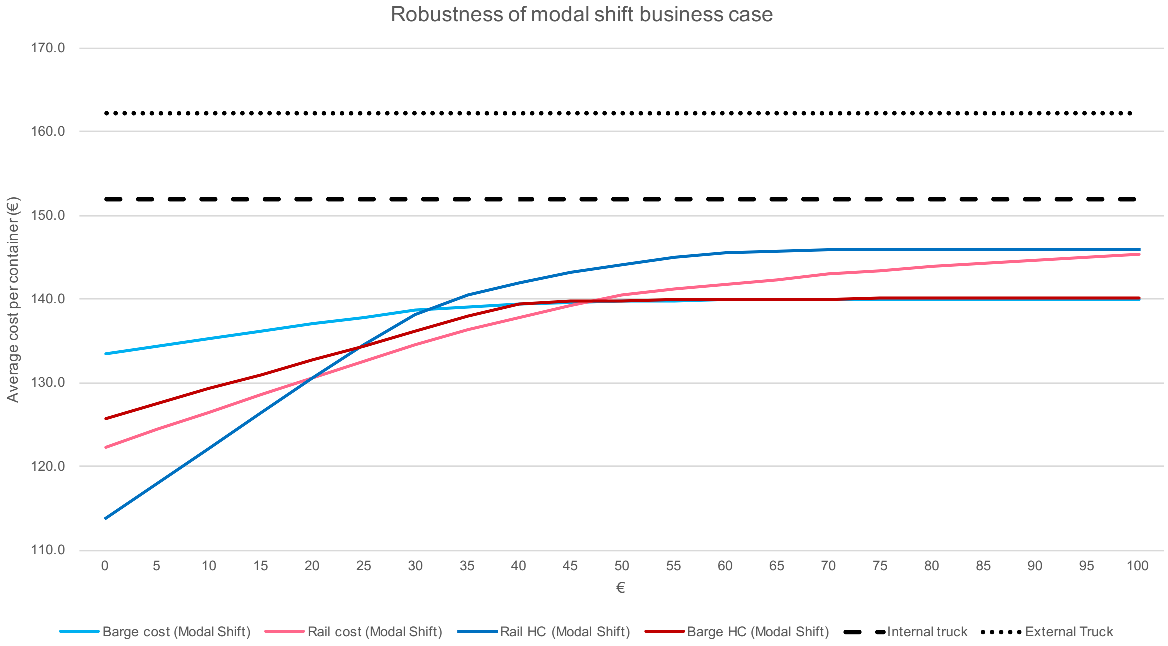

Figure 3 Robustness of modal shift business case

The implication of this thesis is twofold. From managerial perspective, this thesis provides a thorough comparison of cost structures of different transport network options. Based on the cost structure, a recommendation on the viable business case for Den Hartogh Logistics is provided. Basically, the recommendation gives light to Den Hartogh Logistics regarding the possible and innovative way to increase their capacity without jeopardizing the cost performance. Not only the truck planning issues can be solved, the viable business case also prepare Den Hartogh Logistics in overcoming future issues on truck driver shortage and road congestion in the Port of Rotterdam area, as it is discussed by Rabobank (2017). Moreover, the cost structure analysis also provides the management an insight into the behavior of different cost parameters. This implies that the cost drivers are identified, and the management can be advantaged from this information.

On the other hand, this thesis also brings about several implications to the academia. This thesis partially supports the notion that intermodal is not viable for short distance. This is supported by the result showing intermodal transport network as the most expensive option compared to truck-only and modal shift transport options. However, this result is contextual since in the context of rail and barge services in the chemical cluster Rotterdam, the transport costs are not dependent on distance.

Nevertheless, the cost model approach used in this thesis is generalizable and can be applied in different industry interested in studying the feasibility of modal shift. Lastly, this thesis also provides a hypothetical analysis on the economies of scale property for rail transport and as a result, support the economies of scale of rail transport. Unfortunately, due to limited time and information, hypothetical analysis is followed to analyze this matter instead of using real case data.

Table of contents

1. Introduction

In this chapter, the introduction of this thesis is described. The introduction is initialized by the description of problem statement that includes the description on the motivations behind this project together with the aims of this research. It is then followed by the description of the case that is the interest of this project. The literature study on intermodal transport and environmental sustainability in transports are then discussed, which leads to the identification of research gaps and the associated research questions. Following that, this chapter is then concluded by the description on the methodology used in this research.

1.1. Problem statement

Den Hartogh Logistics is a globally operating Logistics Service Provider (LSP) for chemical industry. Den Hartogh Logistics has been operating since 1920 and as per now they provide a number of services ranging from liquid, gas, dry bulk and global logistics. In this document, the result of master thesis conducted in the field of liquid, global, and gas logistics within the Rotterdam area is presented.

Basically, the business of Den Hartogh Logistics in Europe is heavily concentrated in the liquid chemical logistics business. This also applies to the business in Rotterdam area that is denser in the chemical cluster area in the Port of Rotterdam area. In addition to the liquid chemical logistics, the volume in the chemical cluster Rotterdam also comprises of a small portion of global and gas logistics. In Appendix A, the visualization of Den Hartogh Logistics' business in the chemical cluster is shown. In this thesis, the scope covers the overall volume of these three business units altogether.

Most of the transports of liquid chemical logistics in the chemical cluster Rotterdam are done via road transports (i.e. by trucks) by using either road barrels or tank containers. Since the majority of the transports are done using tank containers, this thesis focuses on the transports of liquid chemicals using tank containers. The growth in the chemical logistics business is partly an advantage gained due to the growth in the global chemical industry for the past years after the recession in 2009. Although the chemical production tends to shift to the east in the upcoming years, a moderate growth is still expected in the chemical industry in Europe. That way, the same trend is also expected in the chemical logistics industry.

As the result of the business growth, one of the notable issues faced by Den Hartogh Logistics at the moment is the truck capacity issue, especially in the chemical cluster Rotterdam area. Due to the volume growth, the flexibility in truck and driver planning decreases. This is also exacerbated by the fact that in the near future, experienced driver shortage is expected in the Netherlands (Rabobank, 2017). These issues affect Den Hartogh Logistics not only in the operational planning level, but also in the decision making in the tactical level.

One of the solutions to overcome the truck capacity issue is by subcontracting transport jobs to haulier partners. However, one issue is that there is a limited number of haulier partners that can meet Den Hartogh Logistics' requirements. Another issue is that more often than not, rates charged by haulier partners are higher than ones by internal trucking, which implies that the cost performance of road transport can be negatively affected.

From the regulatory side, as the attention on environmental sustainability rises, both Dutch government and the European Union aims at decarbonizing logistics through modal shift (European Commission, 2011). As a consequence, the use of road transport for freights are discouraged, and at the same time the use of greener modes, such as rail and barge, is supported. This clearly becomes a concern of Den Hartogh Logistics, noticing that their biggest business in Europe is on road. Nevertheless, it is fortunate that the Port of Rotterdam area is well connected by rail and barge. Therefore, taking everything into consideration, this project is set out to explore whether there is a feasible business case for Den Hartogh Logistics to shift a portion of their operation in the chemical cluster Rotterdam to rail or barge.

By definition, intermodal transport is “the multimodal transport of goods, in one and the same intermodal transport unit by successive modes of transport without handling of the goods themselves when changing modes” (UNECE, 2009, p.157). This implies the use of two or more transport modes in transporting goods from one point to another, without changing the handling units of the goods. In the chemical cluster Rotterdam, intermodal transport is made possible due to the geographical features and infrastructure developments within the cluster. Located along the *Nieuwe Waterweg*, most parts of the chemical cluster are well connected by inland waterways. Moreover, a number of intermodal terminals are available to support the freight loading and unloading processes. Additionally, most parts of the chemical cluster Rotterdam are also well connected by railway. It is then possible to transport freights from one point to another in the chemical cluster Rotterdam by using both inland waterways and railways. However, as per now, the utilization of these connections are mostly used for transporting freights arriving in the Port of Rotterdam to the hinterland terminals further in Europe, not for shuttling within the chemical cluster itself. In the same way, the transports done by Den Hartogh Logistics in the chemical cluster Rotterdam are mostly done by trucks. The information regarding the current proportion of transport mode used by each Den Hartogh Logistics’ business unit is described in Appendix A.

Apart from the capacity expansion perspective, intermodal transport is coherent with the vision of Port of Rotterdam in 2030[2]. Port of Rotterdam perceives sustainability not only from the observation on its impact on climate, but also from what most customers want when choosing products for them now. Port of Rotterdam realizes that the development and encouragement on intermodal transport is can be offered as a solution in overcoming climate change and sustainability issues in the port area.

Alas, the focus of most environmental sustainability watchers is on the climate change; therefore, the greenhouse gas (GHG) emissions. In fact, apart from GHG emissions, air quality is also an important parameter of environmental sustainability. In contrast to the global and long-term effect of GHG emissions, the impact of air quality (indicated by particulate matter, for instance) is more localized and can be recognized in a shorter time span. Based on this motivation, this thesis aims at investigating how modal shift, which is perceived as a way to achieve greener transports, can affect the environment differently from another perspective. Thus, by considering both the advantages and disadvantages of intermodal transports, this thesis project aims at getting insights regarding:

- The opportunity for Den Hartogh Logistics to implement intermodal transports within the chemical cluster Rotterdam
- The sensitivity of different parameters on the cost performance of intermodal transports and the robustness of intermodal transports based on different types of changes in the future
- How different transport network options affect the environmental sustainability.

1.2. Case description

The chemical cluster Rotterdam is visualized in Figure 4. It is shown that the chemical cluster Rotterdam stretches from the newly built westernmost point, Maasvlakte 2, to the easternmost point that is directly connected to the city of Rotterdam area, which are about 46 kilometers away from one and another. The chemical cluster comprises six oil refineries, five vegetable oil refineries, more than 45 chemical companies, 15 storage terminals for bulk liquid

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[2] https://www.portofrotterdam.com/sites/default/files/upload/Port-Vision/Port-Vision-2030/index.html#18-19/z

chemicals, and 25 active container depots and terminals ("Refining & Chemicals", 2015). With a substantial number of members, the chemical cluster Rotterdam occupies about 34,598,000 m^2 or 60% of the total land of Port of Rotterdam.

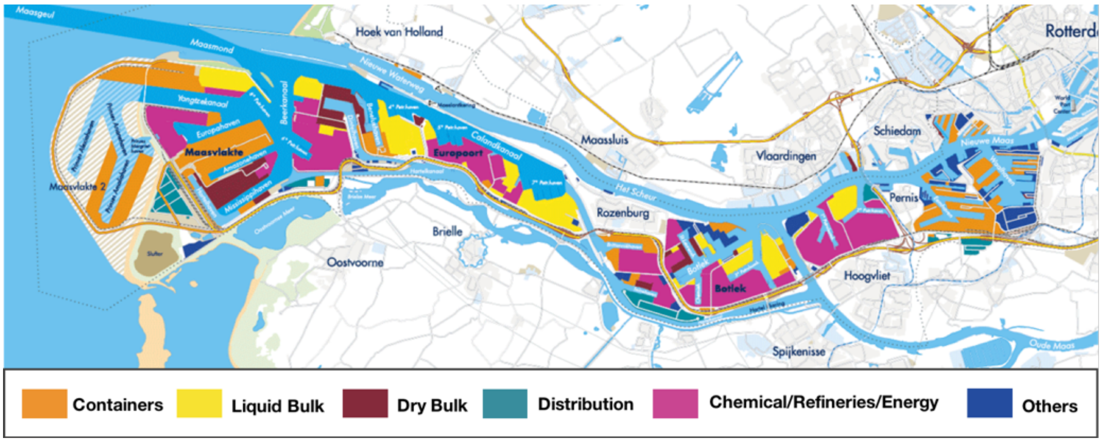

Figure 4 Map of the Port of Rotterdam (Source: from www.portofrotterdam.com, 2015)

In the chemical industry, most transport activities are outsourced to LSPs. Companies who send the products are called the 'shipper', whereas companies who are responsible in transporting these products are called the 'carrier'. Den Hartogh Logistics is one of the latter examples. In the context of chemical industry, a typical transport flow of a carrier starts with the pickup of a tank container at a terminal. In this case, a terminal is a facility where transshipments of loads between one and another mode take place. At the terminal, the tank container is placed on the truck chassis and delivered to the chemical plant where the (un)loading process takes place. After the (un)loading process finishes, the tank container can be dropped at a terminal to be delivered to the next node (e.g., tank container depot) or at another types of cluster nodes, such as tank depot or cleaning stations. Figure 5 shows an instance of which a typical job is started and ended at a terminal.

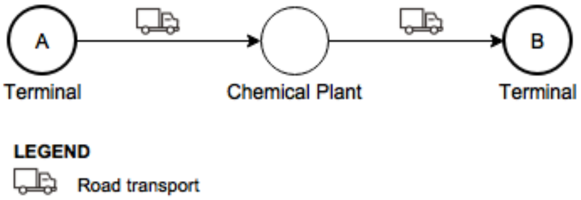

Figure 5 Typical job in the chemical cluster Rotterdam

As the intention of this thesis is to see how much portion of the total truck movements can be shifted to rail and barge, the above typical job is then disaggregated into two parts, resulting in the flow visualized in Figure 6. In this figure, a transport flow is characterized by two nodes, i.e. an origin node and a destination node. On both nodes, two different activities take place. The node can be a terminal, a depot, a cleaning station, or a chemical plant; whereas an activity can either be picking up a tank, dropping a tank, cleaning a tank, taking a tank to a depot, and also (un)loading process of a tank.

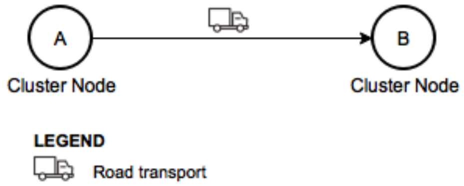

Figure 6 Disaggregated flow in the chemical cluster Rotterdam

1.3. Literature review

This section is divided into two parts. In the first part, the literatures on intermodal transports are discussed. This includes different views in the academia regarding the viability of intermodal transport network for short distance. Following that, a literature study on environmental sustainability in transports take place. This includes the explanation on the greenhouse gas (GHG) and particulate matter (PM) emissions.

1.3.1. Intermodal transport

Different transport modes are available in freight transports, i.e. road, rail, maritime, and pipeline. Transport alternatives can be created by employing different types of modes and combine them into a multimodal freight transport chain. UNECE (2009) defines multimodal freight transport as “the transport of goods by at least two different modes of transport” (p.157). A specialization of multimodal transport, i.e. intermodal transport, is used in this research. Intermodal transport is defined as “multimodal transport of goods, in one and the same intermodal transport unit by successive modes of transport without handling of the goods themselves when changing modes” (UNECE, 2009, p.157). Some examples of intermodal transport units are containers, rail vehicles, and vessels. The interested transport unit in this thesis is the containers.

Currently, as a result of the advancement of sustainable logistics, there is an increasing interest on intermodal transports. Since it is widely accepted that road transport generates higher level of greenhouse gases (GHGs) than rail or inland waterways transports, shifting a portion of road transports to greener modes, such as rail or inland waterways transports, is considered favorable. Unfortunately, the attention to intermodal transport has been given more on the long distance transports. For instance, the European Commission (2011) suggests that in the future, the use of intermodal logistics chain should be optimized especially for long distance freight, where options for road de-carbonization are more limited. It is also stated that by 2030, 30% of road freight over 300 km should shift to other modes, such as rail and waterborne transport. Moreover, it is also recommended to keep the freight shipments over short and medium distances on trucks (European Commission, 2011, p.7).

The notion to focus the implementation of intermodal transport for the longer distance is supported by Bärthel and Woxenius (2004). In the context of the use of rail over road transport, they report that intermodal transport should be used in medium and long distance transports only, so that the extra cost and time incurred during pre- and post-haulage can be offset during the long haul through the lower cost and higher speed of rail.

Janic (2007) also supports the notion by showing that intermodal transport network exhibits economies of scale and distance by modelling the full costs (i.e., internal and external costs) of an intermodal and equivalent road transport networks. The result shows that the operational cost of road transport is generally lower than the operational cost of the intermodal transport over short, medium, and long-distance. Yet, the full costs of both networks decrease more than proportionally as door-to-door distance increases, suggesting economies of distance for both type of networks. Meanwhile, especially for the intermodal transport network, the average full costs decrease at a decreasing rate as the quantity of loads increases, which exhibits the property of economies of scale.

The above findings are complemented by the research by Bouchery and Fransoo (2014) who argue that under certain conditions, intermodal transport can be viable over short and medium distances. This is true when (1) The volume is large, and (2) The distance of pre- and post-drayage are short. They also argue that it is not recommended to restrict the scope of intermodal transport only to long distance transport, because in return, it may exacerbate road congestions. Therefore, the study on intermodal transports over short distance should be carried on, with the emphasize on the analysis on volume and pre-/post-drayage distances. Nonetheless, Kim and van Wee (2011) investigate the relative importance of different factors on the break-even distance to increase intermodal share. The research suggests that there is no definitive break-even distance that is generally applicable in different market situations. It is also found that an increase in road transport costs or a decrease in rail costs are the most important factors in determining the attractiveness of intermodal transport network. On the contrary, terminal distance, terminal handling costs, and drayage costs only play a minor role. This research concludes that intermodal transport is only viable when the costs of road transport are significantly higher than the costs of the other modes, or when the costs of rail transport are significantly lower than the costs of other modes.

Albeit it receives less attention in the research, intermodal transport over short distance is an interesting topic to investigate (Bouchery & Fransoo, 2014; Kim & van Wee, 2011). All the research described above mention the effects of distance on the cost performance of intermodal transport network, but none of those research actually took place in the context of short distance, i.e. less than 300 kilometers. It should be noted that over short distance, the variable cost (i.e., fuel-dependent cost) incurred is much lower than it is in longer distance. Hence, different cost characteristics might be disclosed. All things considered, this research aims at addressing the research gap defined above. By identifying the cost components, as well as looking at and exploiting different system parameters, such as volume and cost components (e.g., long haul and transshipment costs), the feasibility of applying the intermodal transport network in a short distance environment is explored.

1.3.2. Environmental sustainability in transport

Considered as the main cause of climate change, the greenhouse gases (GHGs) have been received much criticism by the global society. GHGs are generally classified into two categories, i.e. the non-fluorinated and the fluorinated gases. The non-fluorinated gases include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O); whereas the fluorinated gases include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The mentioned non-fluorinated gases are those with the relevance to freight transports.

Among all the non-fluorinated GHGs, CO_2 is the major anthropogenic one, accounting for 76% of total anthropogenic GHG emissions in 2010, whereas CH_4 contributes 16% and N_2O contributes 6.2% to the total (IPCC, 2014). In spite of their small proportions, CH_4 and N_2O are more potent than CO_2 at trapping heat within the atmosphere; thus, more impactful in climate change. Therefore, it is important to mitigate CO_2, CH_4, and N_2O emissions altogether in order to decarbonize the transport sector. For a more in-depth explanation of each non-fluorinated GHG, the reader is recommended to explore the literature study by Mansur (2016a).

It is widely known that among all transport modes, road transport emits the most CO_2 emissions. The road-dominated transport system of the Netherlands contributes about 20% to the total CO_2 emissions, two thirds to the total NO_x emissions, and one third to the particulate matter (PM) emissions (Statistics Netherlands, 2015). As comparison, truck generates tank-to-wheel emissions of 118 gCO_2/ton.km, whereas inland waterway vessels emit between 17-61 gCO_2/ton.km depending on the capacity of the vessels (Boer et al., 2011). With such level of emissions, it explains why modal shift is considered as an initiative to reduce the negative impact of transport sector on the environment.

In addition to the climate change, another important parameter of environmental sustainability is the air quality. Compared to the climate change, the impact of air quality is easier to detect because the impact is more straightforward on human beings than the impact of climate change that usually takes a long time to be detected. One of the common parameters of air quality is the PM emissions.

By definition, PM is "a collective name for fine solid or liquid particles added to the atmosphere by processes at the earth's surface"[3]. There are two classes of PM emissions, i.e. PM_{10} and $PM_{2.5}$. PM_{10} is the mass of inhalable airborne particulate with diameter less than 10 micrometers per unit volume, whereas $PM_{2.5}$ is a fine inhalable airborne particulate with diameter less than 2.5 micrometers (Jones, 2006). Since there is always a proportion of $PM_{2.5}$ within a total mass of PM_{10}, an emission profile can be used to estimate the amount of $PM_{2.5}$.

Both PM_{10} and $PM_{2.5}$ emissions possess great health threats to human beings since they are inhalable, making it possible to get into the lung and bloodstream, and thereby deteriorating human's health. World Health Organization (2013) found that short-term exposure to PM_{10} has effects on respiratory health, but $PM_{2.5}$ is a stronger risk factor for mortality, especially in a case of long-term exposure. The recommended PM emission threshold recommended by World Health Organization is described in Table 1.

Table 1 Air Quality Guidelines for PM emission[4]

	Annual mean	24-hour mean
PM10	20 μg/m^3	50 μg/m^3
PM2.5	10 μg/m^3	25 μg/m^3

In total, more than one third of PM emissions in the Netherlands are generated by the transport sector, with sea shipping contributes 40%, road freight 21%, and inland freight transport 7% to the total PM emissions (Statistics Netherlands, 2015). In 2013, EU transport sector contributed 13% of the total PM_{10} and 15% of the total $PM_{2.5}$ emissions (European Environment Agency, 2016). Eurostat (2015) found that one of the key anthropogenic sources of PM emissions is the combustions originated from diesel engines. From road transports, PM_{10} emissions include the one from exhaust emissions (i.e., fuel combustion) as well as the ones from non-exhaust emissions (i.e., the wear of tyre, brake lining, and road surface).

Kittelson et al. (2004) outline two important characteristics of PM emissions. First, diesel engines are found to emit more PM emissions than petrol engines do per vehicle. Second, PM emissions increases during high speed due to higher engine load, exhaust temperature, and exhaust flow. However, it is important to note that as per now, trucks used by Den Hartogh Logistics are classified into either EURO 5 or EURO 6 category. This implies that these trucks are already equipped with particulate filters in order to meet the emission limits. On the other hand, the average age of barge vessel varies between 25-30 years, implying that most barges on board at the moment should be using the old filter technology. These facts make it interesting to see how the intermodal transport solution that is perceived as a solution to decarbonize the logistics sector might instead exacerbate the air quality at the same time.

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[3] http://www.eea.europa.eu/themes/air/air-quality/resources/glossary/particulate-matter

[4] http://www.who.int/mediacentre/factsheets/fs313/en/

1.4. Research questions

As described in the first chapter, the aims of this thesis project revolve around getting the insights on the opportunity for Den Hartogh Logistics to implement the intermodal transport network in the chemical cluster Rotterdam. Furthermore, based on the literature study in the previous section, there are at least two research gaps to be addressed, i.e.:

1. Investigate the feasibility of intermodal transport network in short distance and explore the characteristics of the relevant input parameters.
2. Investigate the impact of intermodal transport as an initiative to minimize the carbon emission on the other environmental sustainability parameter, i.e. air quality.

To achieve the research objective and to address the research gaps above, the following research questions are formulated:

1. How can the inclusion of intermodal in Den Hartogh Logistics' service in the chemical cluster Rotterdam lead to lower cost and environmental impact?
    1.1 What is the current performance of Den Hartogh Logistics' service in the chemical cluster Rotterdam, in terms of cost and environmental impact?
    1.2 What quantitative model should be developed to determine the inclusion of intermodal transport on Den Hartogh Logistics' service in the chemical cluster Rotterdam?
    1.3 What is the impact of the inclusion of short-rail and barge on the performance of Den Hartogh Logistics' service in the chemical cluster Rotterdam, in terms of cost and environmental impact?
2. How can different parameters of intermodal transport be fine-tuned to increase Den Hartogh Logistics' potential flexibility in the chemical cluster Rotterdam?

These research questions play role as the guide through the process of understanding the current system and the intermodal transport practices in the chemical cluster Rotterdam. This understanding becomes the foundation in getting the insights on employing intermodal transport based on a quantitative model. By answering these research questions, the research gaps are addressed and the following scientific contributions are made. First, the viability of intermodal transport for short distance (less than 300 km) is tested by comparing the total of internal costs incurred. Second, the important factors that determine the viability of intermodal transport for short distance are identified. Furthermore, the relationship between these factors are also described. Third, this research also includes another parameter of environmental impact (i.e., air quality) into consideration. By doing this, the trade-off between air quality and GHGs can be demonstrated.

1.5. Methodology

This research is structured using the reflective and regulative cycle by van Aken (2004) as visualized in Figure 7. The case class where this research is positioned in the literature is the intermodal transport network over short distance (i.e., less than 300 km). The specific case under investigation is then the intermodal transport network for short distance in the chemical industry. Following the regulative cycle, the problem solving cycle takes place and the results of this problem solving process is used for developing a generic design knowledge that can be used to address the similar cases in the same case class, i.e. the intermodal transport network for short distance.

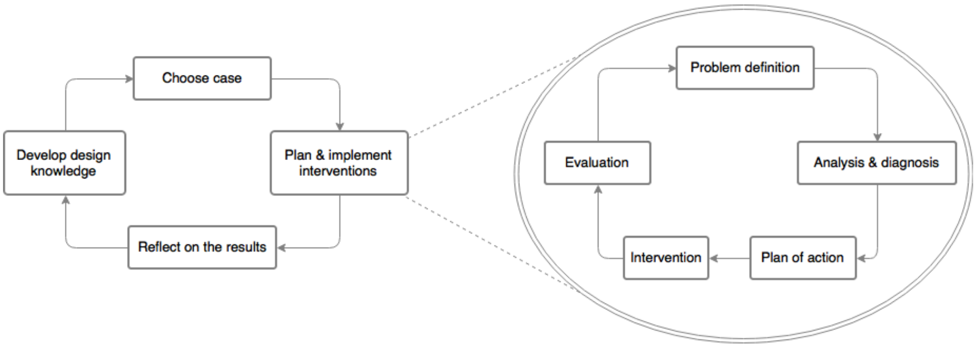

Figure 7 Reflective cycle (left) and regulative cycle (right) (van Aken, 2004)

In addition to the reflective and regulative cycle above, the model by Mitroff et al. (1974) is used for the type of quantitative empirical research as shown in the Figure 8. Based on the four types of model-based operations management research by Bertrand and Fransoo (2002), this research is classified as an empirical normative (EN) research, where a fit between observation and reality is in the interest of the project. Furthermore, this project is not interested in understanding the underlying processes, but instead it focuses in developing recommendations to improve the current situation. Therefore, this research follows a complete cycle of "conceptualization – modeling – model solving – implementation" stages.

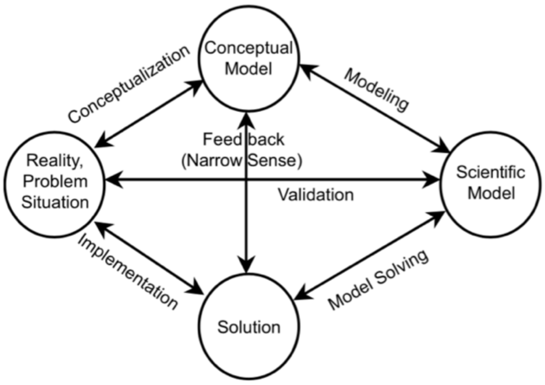

Figure 8 Research model by Mitroff et al. (1974) (Source: Bertrand & Fransoo, 2000)

In Chapter 2, the conceptual model for defining the transport network is presented. Following that, Chapter 3 provides the method to identify the full cost for a transport network. In Chapter 4, the simulation model is discussed. The results of the simulation are discussed in Chapter 5, whereas Chapter 6 discusses the implications, limitations, and future research based on this thesis project. For detailed detailed description of this thesis' methodology, the readers are advised to access Mansur (2016b).

2. Modeling

In this chapter, the foundation of this thesis is developed such that the research questions discussed in the previous chapter are well addressed. Moreover, the models defined in this chapter are useful for the simulation model later. First, the understanding of the current operation in the chemical cluster is developed. Based on this understanding, a conceptual model is designed, followed with the cost and environmental impact models of the transport networks in interest.

2.1. Introduction

In order to explore the opportunity of employing rail or barge in the chemical cluster, it is important to start with the understanding about the current volume in the cluster itself. In exploring the opportunity of intermodal transport network, Janic (2007) starts with the understanding of the current network size (i.e., spatial coverage and number of nodes) and the operation intensity (i.e., the volume of demand being served). Therefore, a pre-study initializes this thesis project such that different insights on the chemical cluster Rotterdam can be obtained. These insights include the identification of important nodes and connections where significant volume is situated, and also the established and not yet established connections, which are important for the base of this research.

As shown earlier in Figure 4, the spatial coverage in this research stretches from the newly developed Maasvlakte 2 in the westernmost point to the easternmost point that is directly connected to the city of Rotterdam area. Although in this area there are at least 150 nodes served by Den Hartogh Logistics per year, 43.9% of the total demand volume is concentrated in only 12 nodes as illustrated in Figure 9. This total demand volume extends across 22 different directed connections. From the same figure, it is also shown that the operation of Den Hartogh Logistics in the chemical cluster is denser in a number of areas only. These areas include, from the westernmost to the east: Rozenburg, Botlek, Pernis, and Waalhaven.

As mentioned above, this pre-study also provides the information regarding the established rail and barge connections between these nodes. Appendix A provides the detailed information regarding the described nodes above. All in all, although Figure 9 shows only a handful number of nodes and connections. Later in this thesis, more nodes and connections are taken into consideration such that a comprehensive analysis is done.

Figure 9 Nodes and connections with the most volume in the chemical cluster Rotterdam

In addition to the explanation regarding the network size, the discussion on the operation intensity is also important. To describe the operation intensity, a heat map is developed to study the magnitude of the served volume as well as the dispersion across the chemical cluster. Figure 10 shows the heat map of the operation of Den Hartogh Logistics in the chemical cluster Rotterdam. The size of the circle shows the scale of operation intensity in each area, which represents the total number of jobs served between August 2015 and July 2016. These jobs include all jobs that either start or end at the nodes located in the given areas. Coherent with what is explained earlier in Figure 9, most demand volume is concentrated in (in volume-decreasing manner): Botlek and Rozenburg area (red), followed by Pernis area (yellow), Waalhaven area (orange), Europoort area (green), and Maasvlakte area (blue).

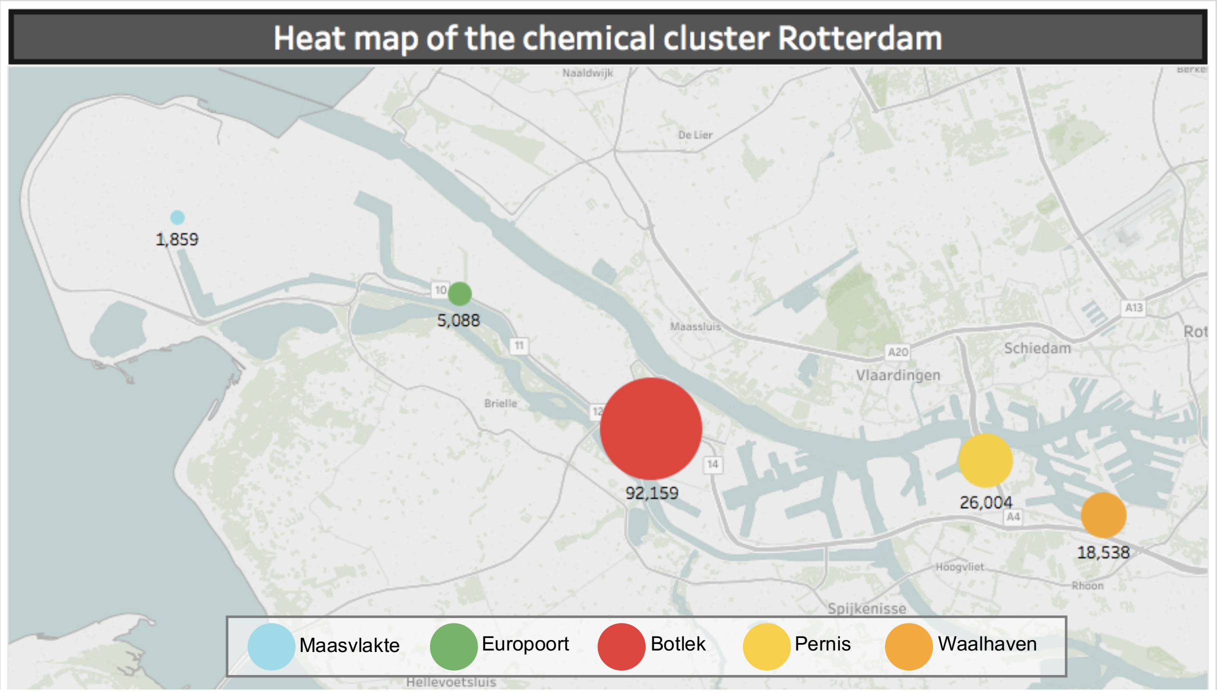

Figure 10 Heatmap of chemical cluster Rotterdam

To better understand the operation intensity, Figure 11 shows how the traffic characteristic in the chemical cluster Rotterdam differs between one area and another. Note that this figure shows the proportions, not the absolute values. It is apparent that especially for Botlek area, most of the transport flows stay in Botlek area, which means that the destination nodes are also in the Botlek area. This is in contrast with the rest of the areas, especially the Maasvlakte area, where most of the volume goes to the other areas.

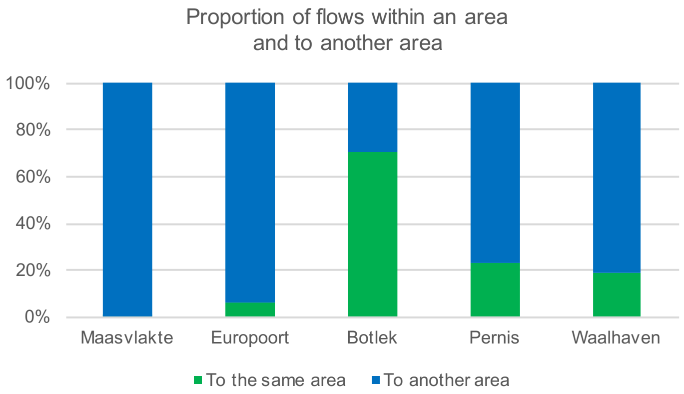

Figure 11 Proportion of area as destination

The information provided in Figure 11 is useful later during the development of the conceptual model. All things considered, the pre-study explored in this section should suffice to become the foundation in building the conceptual model of intermodal transport network in the chemical cluster Rotterdam.

2.2. Conceptual model

As an abstraction of how the real system works, a conceptual model is useful to describe which factors are influential to the system. Therefore, a relevant conceptual model for intermodal transport network is developed. Referring to the above discussed network size and operation intensity in the chemical cluster Rotterdam, Figure 12 summarizes the three factors to consider when designing an intermodal transport network, i.e. (1) The areas in which the nodes are located, (2) The geographical features of the nodes, and (3) The available decoupling terminals. Further discussions on these factors are as follows.

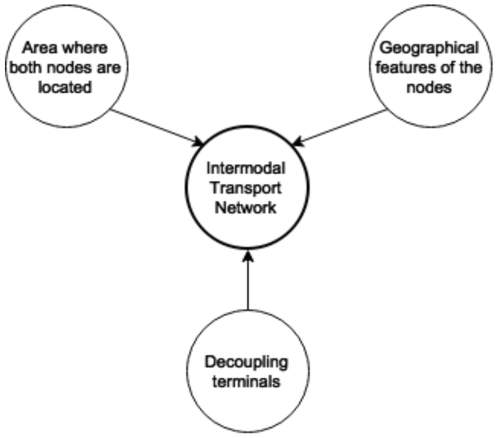

Figure 12 Important factors in designing an intermodal transport network

Area where the nodes are located

In the context of this thesis, this factor is considered important because generally the average distance traversed within an area is relatively short, or about 15 kilometers away. One exception is the average distance between nodes within the Maasvlakte area where it can be as far as 22 kilometers. Thus, this research limits the scope of intermodal transport only to the transports between different areas. As a consequence, the only viable transport option for transports between nodes in the same area is road transport.

Geographical features of the nodes

Furthermore, the decision on whether an intermodal transport network is viable or not is also subject to the geographical features of the nodes being studied. Although the chemical cluster Rotterdam is generally well connected by road, rail, inland waterways, and even pipeline, it does not mean that every node in the chemical cluster is advantaged from this connectivity. This implies that not all directed connections can be shifted to intermodal. For a connection to be qualified for intermodal, either one of the nodes should be rail- or barge-connected. Furthermore, to be qualified for modal shift (direct rail or direct barge connection), both nodes should be either rail- or barge-connected. Otherwise, a connection should remain on road. By considering the geographical features of the nodes in the chemical cluster, intermodal potentials from both established and the not yet established connections can then be explored.

The availability of decoupling terminal

The availability of a decoupling terminal is one of the important components in designing an intermodal transport network. In fact, there are 34 nodes that are classified as terminals, among 150 nodes studied in this thesis. However, as described earlier in Figure 10, the volume within the chemical cluster is concentrated in several areas, then it is reasonable to dedicate one decoupling terminal in one area, such that the network can advantage from the economies of scale properties in the future. Essentially, two requirements are specified in selecting a decoupling terminal, i.e. (1) It should be tri-modal connected, and (2) It should be able to handle hazardous substances.

A decoupling terminal should be tri-modal connected such that these terminals can be connected to both rail and barge. Among all the available terminals, there are a total of 10 tri-modal terminals as listed in Table 2.

Table 2 List of possible tri-modal terminals in the chemical cluster Rotterdam

Nr.	Terminal	Area
1	APM Terminals Maasvlakte II	Maasvlakte
2	APM Terminals Rotterdam	Maasvlakte
3	Euromax Terminal Rotterdam	Maasvlakte
4	Rotterdam World Gateway	Maasvlakte
5	ECT Delta Terminal	Maasvlakte
6	Rotterdam Container Terminal	Maasvlakte
7	Stena Line Europoort	Europoort
8	C. RO Ports Nederland BV	Botlek
9	Pernis Combi Terminal Twente BV	Pernis
10	Rotterdam Short Sea Terminals	Waalhaven

Nevertheless, Figure 13 shows that on average, 30% of the goods transported by Den Hartogh Logistics is classified as ADR[5] goods (i.e, hazardous substances). Since there are special regulations in transporting ADR goods, including the ones during the handlings at a terminal, then it is important to put the capability of handling ADR goods into the requirements on assigning a decoupling terminal. Since all of the tri-modal terminals listed in Table 2 are capable of handling ADR goods, then especially for Maasvlakte area, there are sufficient number of terminals options to be chosen from. Any terminals in Maasvlakte can be selected as the designated decoupling terminal in the Maasvlakte area. With no special preferences, Euromax Terminal Rotterdam is selected in this case. A straightforward decision is then made for Europoort (Stena Line Europoort), Botlek (C. Ro Ports Nederland BV), Pernis (Pernis Combi Terminal Twente BV), and Waalhaven (Rotterdam Shortsea Terminals) areas.

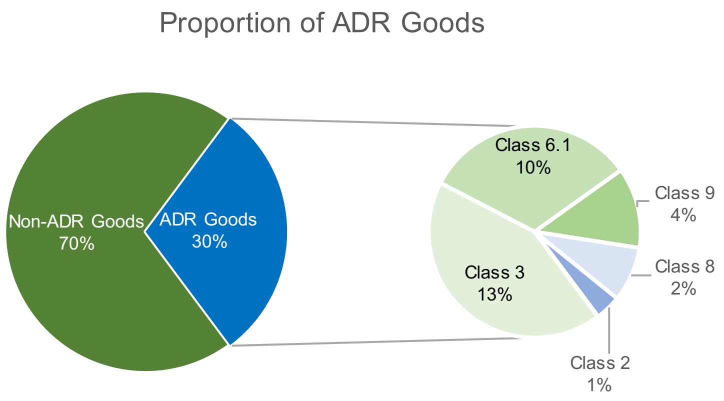

Figure 13 Proportion of ADR goods handled by Den Hartogh Logistics

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[5] ADR stands for “Accord européen relatief au transport international de marchandises Dangereuses par Route” and relates to the international transportation of dangerous goods.

By definition, intermodal transport is "the multimodal transport of goods, in one and the same intermodal transport unit by successive modes of transport without handling of the goods themselves when changing modes" (UNECE, 2009, p.157). However, in this conceptual model, the opportunity to employ rail and barge is not limited only to intermodal transport, but also to modal shift in general. Therefore, in the conceptual model shown in Figure 14, there are both modal shift (direct connections by rail or barge) as well as intermodal network as the transport options in this thesis project.

For instance, in Figure 14, when both node i and node j are located in Area 1, then there is no viable option of intermodal transport network; the flow should remain on road transport, or modal shift (direct rail or direct barge) if applicable. When two nodes are not located in the same areas, then geographical features of the nodes first need to be considered to determine the potential intermodal transport network. For direct connections, a rail or barge connection is only viable when both node i and node j are connected to rail or barge. On the other hand, for decoupled intermodal transport, a rail/barge connection is only required on one end of the journey, due to the presence of decoupling terminal in between.

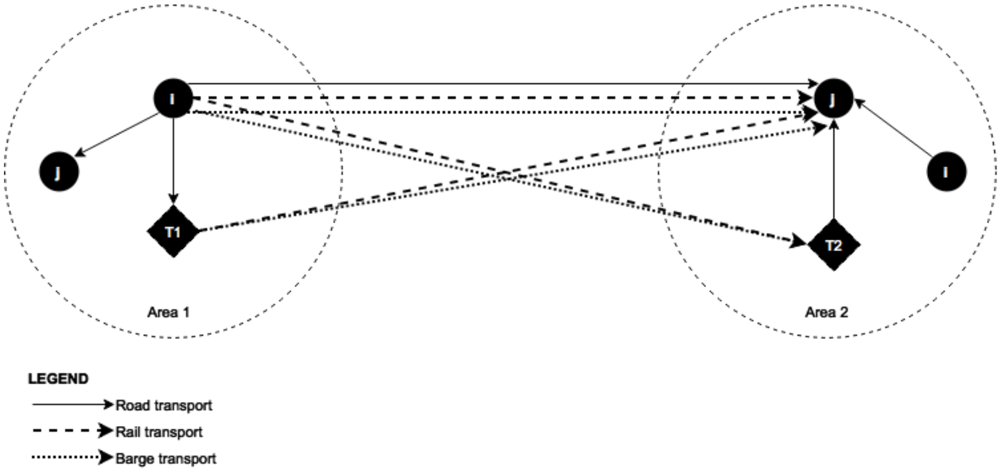

Figure 14 Conceptual model of intermodal transport

All in all, the above discussions regarding a node's area, geographical features and the assignment of a decoupling terminal conclude the conceptual model of intermodal network design as it is visualized in Figure 12 and Figure 14.

2.3. Cost model

In this section, two cost models for (1) Direct transport flow and (2) Intermodal transport network are developed. Along with the environmental impact model (discussed later in the next section), this cost model partially answers the research question 1.2.

Janic (2007) investigate the effect of European Union policy aiming at internalizing the external costs of transports by comparing the full costs of both truck-only and the equivalent intermodal transport of a given network. The full costs defined by Janic (2007) consist of both internal and external costs. The internal costs represent the transport cost, time cost, and handling costs incurred, whereas the external costs represent the cost of damages by burdens (e.g., air pollution, congestion, noise, and traffic accidents. In this thesis project, only the internal cost is considered. Moreover, the environmental impact is not internalized as a decision variable of the transport network, instead it will be discussed separately as additional insights for Den Hartogh Logistics. In the following, first the sets and indices used in the model are described. It is followed by the description of the cost model for direct and decoupled transport flows.

Sets

N	Set of nodes, where $i, j, k \in N$
M	Set of transport modes, where $m \in M$= {Truck, Rail, Barge, Rail-Truck, Barge-Truck, Truck-Rail, Truck-Barge}

2.3.1. Cost model of direct transport flow

Referring to Figure 6, the typical flow discussed in this thesis comprises two nodes (i.e., origin and destination nodes), where two different activities (i.e., pickup, drop, cleaning, delivery, depot) take place. In between these two nodes, a transport leg takes place, which is mostly done by trucks as per now. In this section, the cost model of direct transport flow is discussed. This type of transport flow includes direct flows using truck, rail, and barge.

Below, Figure 15 and Figure 16 visualize the cost components of direct truck, direct rail, and direct barge. It can be seen that the cost of direct rail and direct barge consist of fewer components, i.e. (1) Rail/barge transport cost and (2) Handling costs at both ends. Yet, more cost components are imposed if direct truck is used, i.e. the truck waiting cost, in addition to the truck transport cost and the handling costs at both ends.

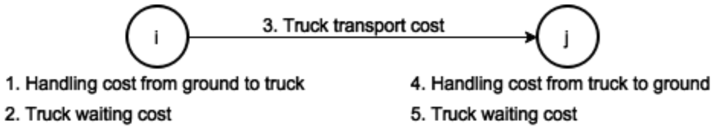

Figure 15 Cost model of direct truck flow

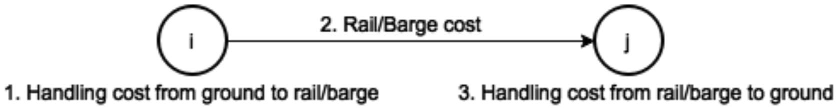

Figure 16 Cost model of direct rail/barge flow

The generic cost model for direct transport flow is formulated as follows.

$$C_m^{i,j} = x_m^{i,j}\left(c_m^{i,j} + s_m + \sum_{m\in M}\sum_{i,j\in N}\left(h_m^i + w_m^i\right)\right) \qquad \text{for } m\text{=\{truck, rail, barge\}} \qquad (1)$$

where:

$C_m^{i,j}$ = Total transport cost using transport mode m from node i to node j (€)
$x_m^{i,j}$ = Binary input parameter indicating whether node i and node j is connected by mode m
$c_m^{i,j}$ = Cost of transport from node i to node j using mode m (€)
s_m = Estimated cost of solo kilometer driven by trucks due to the use of mode m, allocated to each job performed (€)
h_m^i = Handling cost per lift to or from mode m incurred at node i (€)
w_m^i = Truck waiting cost incurred at node i due to the use of mode m (€)

Furthermore, to calculate $c_m^{i,j}$ the following Equation (2) is used.

$$c_m^{i,j} = \left(a + \frac{b}{v}\right) * d_{i,j} \tag{2}$$

where:

a = Truck cost per kilometer (€/km)
b = Truck cost per hour (€/hour)
v = Average speed of truck (km/hour)
$d_{i,j}$ = Distance between node i and node j (km)

2.3.2. Cost model of decoupled transport flow

In this section, the generic cost model for decoupled transport flows is described. As listed in the Table 3, there are four different types of decoupled intermodal transport flows considered in this thesis project. The decoupled intermodal flows are limited to the flow types with only one truck drayage on either the beginning or the end of the journey. It is presumed in this master thesis project that a journey with two drayage on both ends are not going to be feasible in terms of cost.

Table 3 Set of intermodal flow connections

Nr.	Flow Type
1	Decoupled Barge – Truck
2	Decoupled Rail – Truck
3	Decoupled Truck – Barge
4	Decoupled Truck – Rail

In contrast to the cost components of the direct transport flows, the decoupled transport flows have more cost components along the journey from node i to node j via the decoupling terminal k, as visualized in Figure 17 and Figure 18. Figure 17 visualized the flows (1) Decoupled barge-truck and (2) Decoupled rail-truck. These types of intermodal connections are appropriate for connections where the origin nodes are rail- or barge-connected, and not the other way around.

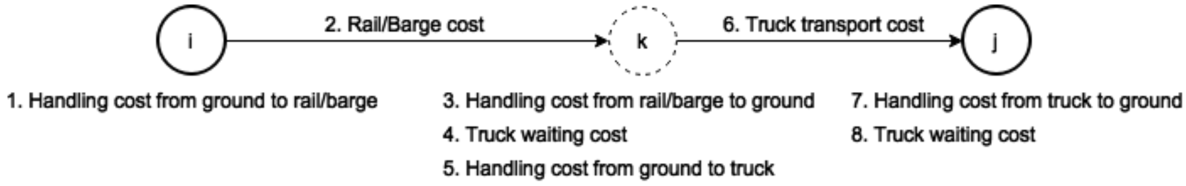

Figure 17 Cost model of decoupled rail-truck or barge-truck flow

Furthermore, Figure 18 visualizes flows (3) Decoupled truck-barge and (4) Decoupled truck-rail. This flow is suitable for connections by which the destination node is rail- or barge-connected, and not origin node.

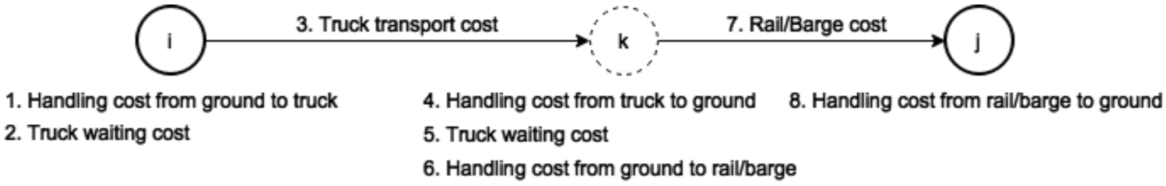

Figure 18 Cost model of decoupled truck-rail or truck-barge flow

The generic cost model for the flows above is described in Equation (3) below.

$$C_m^{i,k,j} = x_m^{i,j}\left(c_m^{i,k} + c_m^{k,j} + s_m + \sum_{m\in M}\sum_{i,k,j\in N}\left(h_m^i + w_m^i\right)\right) \qquad (3)$$

where the similar descriptions of parameters and variables used in Chapter 2.2.1 are applied.

2.4. Environmental impact model

As mentioned in Chapter 1, the environmental impacts discussed in this master thesis project include (1) The greenhouse gas (GHG) emission that is represented by CO_2e emissions and (2) Air quality that is represented by the particulate matter emissions (i.e., PM_{10} and $PM_{2.5}$). In modeling the GHG emissions, GLEC Framework for Logistics Emissions Methodologies (Smart Freight Centre, 2016) is used, whereas the PM emissions are modeled following the Methods for calculating the emissions of transport in the Netherlands by the Task Force on Transportation of the Dutch Pollutant Release and Transfer Register (Klein et al., 2015). In this chapter, the model for both CO_2e and PM emissions for truck, rail, and barge transports are discussed. To make a sound comparison, the CO_2e emission unit used in this master thesis project is kg/container.km, whereas the PM emission unit is gr/container.km.

2.4.1. CO_2e emission model

The reference used in calculating the CO_2e emission in this master thesis project is the GLEC Framework for Logistics Emissions Methodologies (Smart Freight Centre, 2016), along with the STREAM Freight Transport (2016) that provides a number of default logistics parameter values. The central of GLEC framework's emission accounting is on the amount of fuel used by a transport mode on a given journey. Hence, for every transport mode used in each type of transport flow, the following parameters are necessary for modeling the CO_2e emissions: (1) Fuel type, (2) Fuel consumption factor, (3) Emission factor, and (4) Distance traversed. Especially for rail and barge, additional information on the average payload is also necessary. The parameters used in calculating the environmental impact are described in Chapter 3.

The following Equation (4) and (5) express the generic model to calculate the CO_2e emission. The calculation of CO_2e emission starts with the consumption factor of a mode, which basically represents the total amount of fuel used by a mode to travel a given kilometer. In most cases of carrier, the consumption factor data is available through historical data. Otherwise, the default values provided by a standard such as GLEC Framework (Smart Freight Centre, 2016) can be used.

$$Consumption\ Factor[kg\ fuel/container.km] = \frac{fuel\ used[kg]}{container.km} \qquad (4)$$

By using the obtained consumption factor for each type of transport mode, the total amount of fuel consumed during a transport leg can be calculated. To calculate the total CO_2e emission generated during a transport leg, this total amount of fuel used is multiplied by an emission factor. An emission factor represents the amount of CO_2e emission generated per amount of fuel. This implies that the emission factor is unique per type of fuel used.

$$CO_2e\ emission[kgCO_2e] = fuel\ used[kg\ fuel] * emission\ factor[\frac{kgCO_2e}{kgfuel}] \qquad (5)$$

2.4.2. Particulate Matter (PM) emissions model

Methods for calculating the emissions of transport in the Netherlands (Klein et al., 2015) is used as the central reference for calculating the PM emissions. As discussed earlier in the literature study in Chapter 1.3, there are two types of PM emissions, i.e. PM_{10} and $PM_{2.5}$ emissions. Furthermore, the PM emission can be classified into two sources, i.e. exhaust and non-exhaust emissions. The exhaust emission is generated by the combustion of fuels, whereas the non-exhaust emission is only applicable for road transport, which includes the PM emissions due to the wear of tyre, brake linings, and asphalt road surface.

Exhaust PM emissions

The following Equation (6) and (7) describe the calculation model for the exhaust PM_{10} that is applicable for different transport mode. Since there is always a part of $PM_{2.5}$ emissions within a mass of PM_{10} emission, then to estimate the level of of $PM_{2.5}$ emissions, an emission factor profile can be used. In this thesis, the emission factor profile by Klein et al. (2015) is used.

For each transport mode, a unique emission factor is used to calculate the PM_{10} emission. This emission factor is multiplied by the total distance traveled by that given particular mode. This calculation is shown in Equation (6).

$$PM_{10}^{m}(exhaust)[gram] = EF_{PM_{10}}^{m}[gram/km] * d_{ij}^{m}[km] \tag{6}$$

As shown in Equation (7) below, to estimate the level of $PM_{2.5}$ emissions, an emission profile is used. This emission profile is unique for each transport mode.

$$PM_{2.5}^{m}(exhaust)[gram] = EP_{PM_{2.5}}^{m} * PM_{10}^{m}[gram] \tag{7}$$

Non-exhaust PM emissions

Apart from the exhaust PM emission described above, there is also a non-exhaust PM emission that is relevant only for road transport. This type of emission is generated due to the wear of tyre, brake linings, and asphalt road surface. In contrast to the exhaust PM emissions, it is important to note that the size of non-exhaust PM emission are mostly larger than 10 micrometers. Hence, a share of PM_{10} (in this case, is denoted by $y_{PM_{10}}$) should also be taken into account when calculating the non-exhaust emissions. The calculations are shown in Equation (8) and (9). Moreover, the same approach is also applied to the calculation of the non-exhaust $PM_{2.5}$ emissions.

Basically, Equation (8) and (9) work similarly with the way Equation (6) and (7) work. However, $y_{PM_{10}}$ that represents the proportion of PM_{10} within the overall non-exhaust PM emission is also taken into account.

$$PM_{10}(non - exhaust)\ [gram] = EF_{PM_{10}}[gram/km] * d_{ij}[km] * y_{PM_{10}} \tag{8}$$

$$PM_{2.5}(non - exhaust) = EP_{PM_{2.5}} * PM_{10}(non - exhaust) \tag{9}$$

All in all, the total PM emissions for road transport are described in the Equation (10) and (11) below.

$$PM_{10}^{Road} = PM_{10}^{Road}(exhaust) + PM_{10}^{Road}(non - exhaust) \tag{10}$$

$$PM_{2.5}^{Road} = PM_{2.5}^{Road}(exhaust) + PM_{2.5}^{Road}(non - exhaust) \tag{11}$$

3. Data description

In the previous chapter, cost and environmental impact models for different transport flows are already discussed. To complement those models, the relevant input parameters for the calculation are described in the following. This chapter comprises of two parts. First, the data relevant for cost calculations are described. Following that, the data relevant for the calculation of the environmental impact are described.

3.1. Data for the calculation of cost

In this section, first the relevant parameters for the calculation of transport cost for trucks are introduced. As described in Chapter 2.3, the truck transport cost is an important component in the direct truck and decoupled intermodal transport networks. The input parameters relevant for truck transport costs are summarized in Table 4.

Table 4 Logistics parameter for truck cost calculation

Constant	Value
a	0.83 €/km
b	57.95 €/hour
v	40 km/hour

Basically, the truck transport cost comprises of the truck long-haul itself and also the handling and truck waiting costs at the origin and destination nodes. Three constants are introduced in Table 4, namely a, b, and v.

Constant a represents the cost per kilometer traversed by a truck. This constant is derived from the sum of truck variable costs per year divided by the total kilometers traversed per year. The variable costs include the costs of fuel, as well as the costs of maintenance and repair (truck, chassis, and tyre). In this thesis, the total kilometer traversed per year is assumed 25,000 kilometers.

On the other hand, constant b is in cost per hour, which represents the amount of fixed cost per time unit (hour). The fixed cost comprises of the costs of depreciation, taxes, insurance, and satellite phone. The value of constant b is derived from the sum of driver wages and truck fixed costs per year, divided by the total productive hours of a driver per year.

Apart from the constants a, b, and v above, other parameters are also relevant for the calculation of truck transport cost. These parameters are the solo kilometer cost (s_m), handling costs of mode m at node i (h_m^i), and truck waiting cost at node i at node m (w_m^i). The solo kilometer cost (s_m) are calculated using the matching probabilities described in van de Bunt (2015) for 100% flexible demands. In the following, the calculation of solo kilometer cost is described following van de Bunt (2015).

To define a matching probability, first the number of solo trips from and to each area has to be determined. To do this, the total number of *drop* actions that take place in an area of origin and the total number of *pickup* actions that take place in an area of destination per day are obtained from historical data. Based on these number of drops and pickups per day in an area, a matching probability is obtained. Using this matching probability for each area, the number of solo trip and the average distance traversed without a tank container (i.e., solo kilometer) and can be estimated. The cost due to solo kilometer and the other input parameters are described in Appendix B.

Additionally, the parameters relevant for the calculation for rail and barge calculations are described in Table 5. The handling cost for rail and barge are described in Appendix B.

Table 5 Logistics parameter for rail and barge transport cost

Parameter	Rate per container
Rail cost	€48
Barge cost	€30

3.2. Data for the calculation of environmental impact

In this section, the necessary data for calculating the CO_2e and PM emissions are described. Since the central of CO_2e emission accounting is on the amount of fuel used, then for calculating the CO_2e emissions, the following parameters are necessary, i.e. (1) Fuel type, (2) Fuel consumption factor, (3) Emission factor, and (4) Distance traversed. In the followings, the values for these logistics parameters are described.

3.2.1. Relevant data for CO_2e emission calculation

In this research, all trucks, rail, and barge are diesel-powered. Therefore, one emission factor value is used, which is obtained from the emission factor recommended by GLEC Framework (Smart Freight Centre, 2016). The distance used to calculate the CO_2e emission for truck and rail is the actual distance traversed from the origin node to the destination node are shown in Appendix C. Additionally, the distance traversed by barge are obtained in terms of nautical mile, which is then translated in to kilometer.

For rail transport, an additional reference by STREAM Freight Transport (2016) is used. In this standard, the emission factors are distinguished for bulk and containerized transports; by which the interest of this thesis is the latter. Moreover, in this standard there are three weight categories for each type of transports, i.e. light, medium, and heavy. The heavy containers are containers that weigh more than 14 ton/TEU. Generally, Den Hartogh Logistics transport chemicals with volume of 21,000-26,000 liters on a 20- or 23-feet container. In general, the density of the chemical products transported by Den Hartogh Logistics range from 0.9 to 1.2 kilogram/liter. Therefore, the containers transported by Den Hartogh Logistics are classified as heavy weight goods.

Earlier in Chapter 2.4.1, it is mentioned that the consumption factor can be obtained from a carrier’s recorded historical data. Table 6 shows the average consumption factor for trucks, that is obtained from historical data. On the other hand, the consumption factor of rail is derived from the default value provided by GLEC Framework (Smart Freight Centre, 2016).

Table 6 Logistics parameter for CO_2e emission calculation (WTW)

	Truck	Rail	Barge
Fuel type	Diesel-fuel		
Consumption factor (kg fuel/container.km)	0.33	0.13	0.045
Emission factor (kg CO_2e/kg diesel-fuel)	3.9		

On average, rail consumes 0.009 kg diesel-fuel/tkm. STREAM Freight Transport (2016) suggests that for heavy containerized transports, the average share of loaded and empty containers is 72%:28%, where the average payload is 80%. Thus, the rail consumption factor (kg/container.km) is derived by using the formula in Equation (12) below.

$$Consumption\ Factor\ (Rail) = 0.009\frac{kg}{tkm} * \left(\frac{72}{100} * 24000 + \frac{28}{100} * 2250\right) * 0.8 = 0.13\frac{kg}{cont.km} \qquad (12)$$

On the other hand, to derive the consumption factor for barge transport, information from the Experties- en InnovatieCentrum Binnenvaart (EICB) is used, as it is summarized in Table 7. In this thesis, the Rhine-Herne Canal Vessel that is classified into CEMT Va waterway class is used as the inland waterway vessel. On full power, generally the Rhine-Herne Canal Vessel is supplied with 1,500 horsepower (HP). With consumption factor of 17 liter/100 horsepower, it requires 255 liters/hour on full power. However, while shuttling in the port area, less power is required (around 20% of the full power). Correspondingly, this type of barge vessel requires 51 liters of diesel-fuel/hour during shuttling in port area. On average, a barge vessel moves with the speed of 10 km/hour, which makes consumption factor of 4.3 kg diesel-fuel/km, or equal to 0.045 kg diesel-fuel/container.km.

Table 7 Inland waterway vessel specification

Waterway class	CEMT Va (2000-4000 tonnes)
Vessel category	Rhine-Herne Canal Vessel
Capacity	96 TEU
Consumption factor	17 liter diesel-fuel/100 horsepower

3.2.2. Relevant data for PM emission calculation

In this section, the relevant parameter values for calculating exhaust PM emission is described in Table 8, whereas the ones for calculating the non-exhaust PM emission (only for road transport) is described in Table 9. The truck category considered in this thesis is the EURO6 category to well represent the trucks owned by Den Hartogh Logistics.

Table 8 Logistics parameter for exhaust PM emission calculation (Klein et al., 2015)

Transport mode	PM_{10} Emission Factor (gram/container.km)	$PM_{2.5}$ Emission Profile
Truck	0.030	100%
Rail	0.126	95%
Barge	0.056	95%

Table 9 Logistics parameter for non-exhaust PM emission calculation (Klein et al., 2015)

Non-exhaust PM emission category	PM_{10} Emission Factor (gram/container.km)	Share of PM_{10}	$PM_{2.5}$ Emission Profile
Wear of tyre	0.658	5%	20%
Wear of brake linings	0.063	49%	15%
Wear of asphalt road surface	0.922	5%	15%

4. Simulation model

In the previous chapter, both conceptual and detailed cost model for truck and intermodal transport network have been described. In this chapter, the design of simulation model to determine the cost and environmental sustainability of both truck and intermodal transport network is discussed. Following that, the verification and validation performed in the simulation are discussed.

4.1. Simulation model design

In this section, the key components of the simulation model are outlined. The objective of the simulation model is clear and has been mentioned several times earlier in the previous chapter. Thus, based on Robinson (2014), now the following components are discussed: the inputs, outputs, content, assumptions, and simplifications taken in the simulation model.

The inputs or the experimental factors are the demand for each connection in the chemical cluster. These demands are regarded as a random variable in this simulation. Moreover, other parameters are also classified as inputs, including the handling costs, truck waiting costs, distance between nodes, as well as emission factor and consumption factors of different transport modes.

There are three outputs (results from the simulation runs) from this simulation. These are the average cost per container, average CO_2e emission per container, and average PM_{10} emission per container.

The content of the model that is described in terms of two dimension, namely the scope of the model and the level of detail. The model boundary is as follows:

- The considered flows are the transport legs (see the disaggregated flow described in Chapter 1.2) that both start and ends in the chemical cluster Rotterdam. Although these transport legs can be a part of a longer transport flow that probably does not start or end in the chemical cluster Rotterdam, the other transport legs are out of scope.
- Although there are about 1,500 directed connections served by Den Hartogh Logistics in the chemical cluster Rotterdam, this simulation focuses on the heaviest directed connections (i.e., connections with minimum demand per week of 1 container).

Moreover, the details and simplifications taken for each component in the model's scope are described in the following. This also explains what are the simplifications taken in this simulation.

- The generated demand for the simulation inputs are only characterized based on the origin node, destination node, and the number of containers per day between these nodes. The action that takes place on each node is not taken into account.
- Since the aim of this thesis is to explore the opportunity of modal shift or intermodal transport network, the detail is limited to the availability of rail and barge services. The number of rail or barge services per day or the timetable are not in the scope of this simulation.
- Capacity of rail and barge is simplified such that there is ample capacity available on every scheduled service.
- On every handling moment, only one-time lift is required to relocate a tank container from one transport mode to another.

In the followings, the assumptions considered in this simulation are described. These assumptions are ways of incorporating uncertainties and beliefs about the real system (Robinson, 2014).

- The demands within the chemical cluster Rotterdam are characterized with stochastic behavior. Furthermore, empirical distribution is used to generate demands per connection such that the characteristics of each connection is preserved.

In this master thesis project, different scenarios are simulated, which includes the present (as-is) and the future (to-be) scenarios. The logic flow diagram for the simulation procedure is visualized in Figure 19. For each scenario (1) Truck-only, (2) Modal shift, and (3) Decoupled intermodal transport, this logic flow diagram is followed.

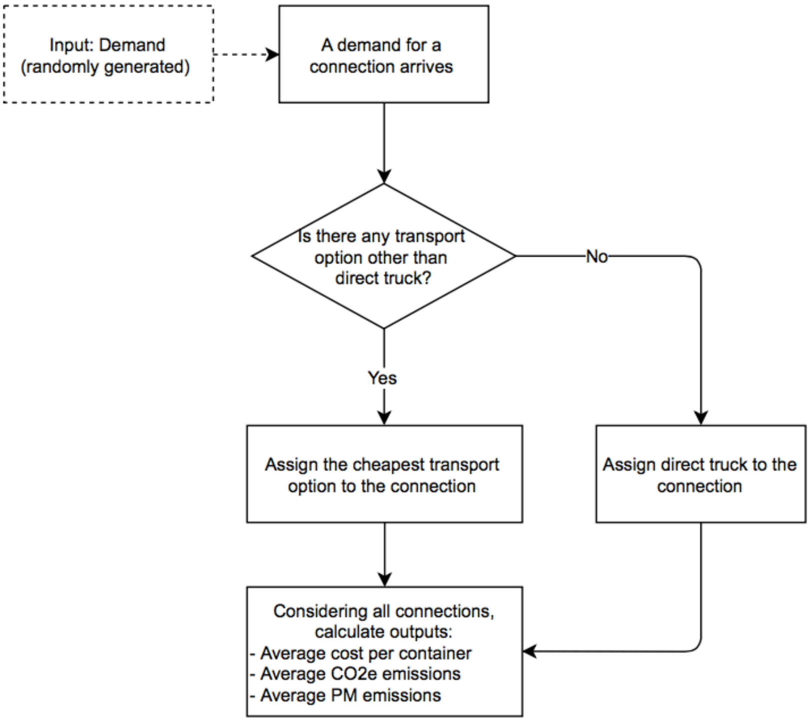

Figure 19 Logic flow diagram of the general simulation procedure

Similarly to what is shown in Figure 19, the objective function of this simulation model is to minimize the transport cost. The following objective function is as follows:

Scenario: Modal shift

$$\min\left(C^{i,j}_{DirectRoad}, C^{i,j}_{DirectRail}, C^{i,j}_{DirectBarge}\right)$$

Scenario: Decoupled intermodal transport

$$\min\left(C^{ikj}_{DecRailRoad}, C^{ikj}_{DecBargeRoad}, C^{ikj}_{DecRoadRail}, C^{ikj}_{DecRailRoad}\right)$$

where each of this cost is calculated using formulas in Equation (1) to Equation (3).

A terminating simulation is selected in this thesis project instead of steady-state simulation. The motivation behind this decision is is due to the interest of this research that aiming at the tactical decision making level concerning the involvement of rail and barge, instead of looking at how the day to day operation of rail and barge will look like in the future. The general procedure in Figure 19 is run for 365 days (one year) and replicated for 10 times. Ten independent replications are considered sufficient based on the obtained confidence interval for confidence level of 95%. The confidence interval obtained is considered sufficiently small, which is probably due to the fact that only one random variable involved in this simulation. The simulations results are shown in Appendix D.

4.2. Verification and validation

Verification is related with the process of ensuring whether the simulation model design has been correctly translated into a computer model (Robinson, 2014). On the other hand, validation is related with the process of ensuring that the simulation model is an accurate representation of the reality.

4.2.1. Verification

Verification is done by debugging the simulation model. The simulation model is built in different separate parts, making it possible to do verification separately as well. Especially for the cost calculation, all types of connections are calculated in separate part, making it easier to trace. The verification process includes reading through the code and confirms the correctness of the code with a modeling expert.

4.2.2. Validation

Validation is done several times together with the responsible parties who have the sufficient knowledge on the validity of different parameters. The validations include: (1) Input parameters (e.g., transport and handling costs) and (2) Outcome values. Furthermore, the validation process performed in this simulation entails the white-box validation (Robinson, 2014). This type of validation involves a detailed micro check on the model to make sure that each part of the model represents the real world. For instance, this includes checking a few real life examples and see if it matches with the output results of the simulation.

The black-box validation to compare the simulation result with the real system is not possible in this thesis because the system is not implemented yet. Therefore, the validation process is limited to the validity check of input and output of the simulations.

5. Model application

In the previous chapter, the simulation model is developed. The outcome of this simulation is presented in this chapter. As mentioned earlier, the simulation includes as-is and to-be simulations. These simulations are described in the followings.

5.1. As-is simulation

There are three scenarios studied in the as-is simulation, i.e. (1) Truck-only, (2) Modal shift, and (3) Intermodal transport network. The truck-only scenario represents the current practice of Den Hartogh Logistics' operation, where only truck is used for transports in the chemical cluster Rotterdam. In modal shift scenario, the possible transport options include direct truck, direct rail, and direct barge. Whether a connection can be traversed by direct rail or direct barge depends on the availability of connections on both origin and destination nodes.

Next, in the intermodal transport network, the decoupled transport options are available. This includes decoupled barge-truck and rail-truck, where the drayage is located at the end of the transport leg, and also the decoupled truck-barge and truck-rail, where the drayage is located at the beginning of the transport leg. In addition to these 4 decoupled transport options, there is also the direct truck connection as the baseline to indicate whether any of the decoupled transport option is cost feasible or not.

The result of this simulation is useful for answering the research questions 1.1 and 1.3. Figure 20 shows the results of these three scenarios complete with the proportions of the cost components. The long haul cost represents the cost of truck, rail, or barge when it is used for the longer distance leg of the whole transport journey. The handling costs cover the all handling costs across all types of transport modes involved. The drayage cost represents the cost of truck transport from a decoupling terminal to the destination node during decoupled intermodal transport. Lastly, the truck waiting cost represents the cost due to non-productive time spent by trucks waiting.

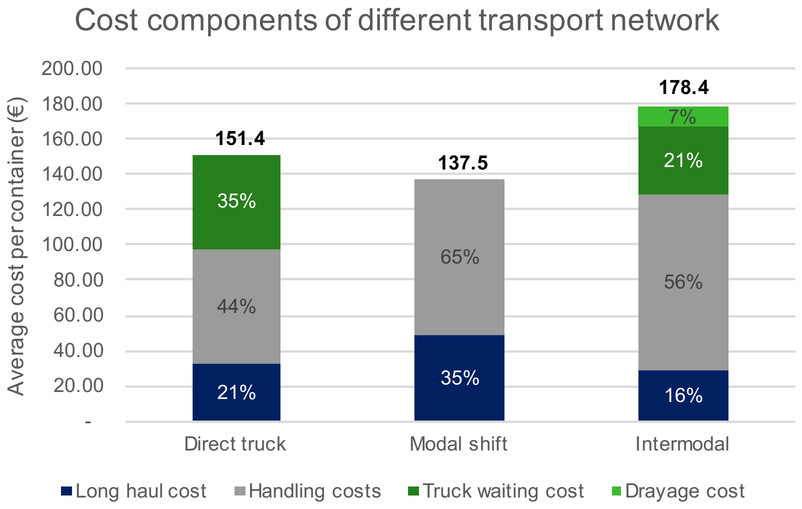

Figure 20 Result: Average cost per container

It is apparent that the modal shift outperforms the truck-only scenario by 9.3% (€137.5 to €151.4 per container). In the modal shift scenario, a total of 110 connections are shifted to rail and barge, out of the total 296 truck connections in study. This shift represents 34.8% of Den Hartogh Logistics' volume in the chemical cluster Rotterdam (based on the number of containers) as visualized in Figure 21. Also in Figure 20, it can be seen that handling cost comprises about half of the overall cost per container. It is followed by the truck waiting cost (that is negligible in the modal shift scenario) and the long haul cost. Truck waiting cost is less interesting to explore than the handling and long haul costs. Therefore, further analysis on the influence of the level of handling costs and long haul costs are discussed in the next section.

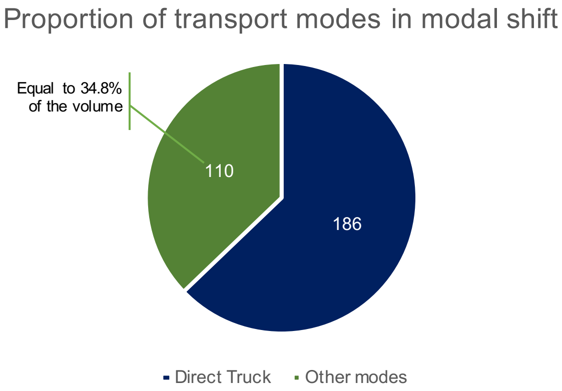

Figure 21 Result: Optimum proportion of truck, rail, and barge during modal shift

Figure 22 visualizes the level of environmental impact for all three transport scenarios. First, the average CO_2e emission per container (kilogram) is shown. Similar to what is exhibited in terms of cost, the average CO_2e emission per container decreases as the modal shift is introduced. The reason behind this is straightforward; rail and barge replaces the use of trucks. It is well known that rail and barge emits less CO_2e emission than trucks. Nevertheless, the average CO_2e emission generated in intermodal transport scenario does not significantly differ from the modal shift scenario (i.e., 6.779 to 6.939 kg CO_2e emission/container). It is interesting to point that there are 132 connections available to be shifted to decoupled intermodal transport, out of the total 296 connections. However, since trucks are still utilized in the decoupled intermodal transport, the decrease of CO_2e emission are not significantly shown.

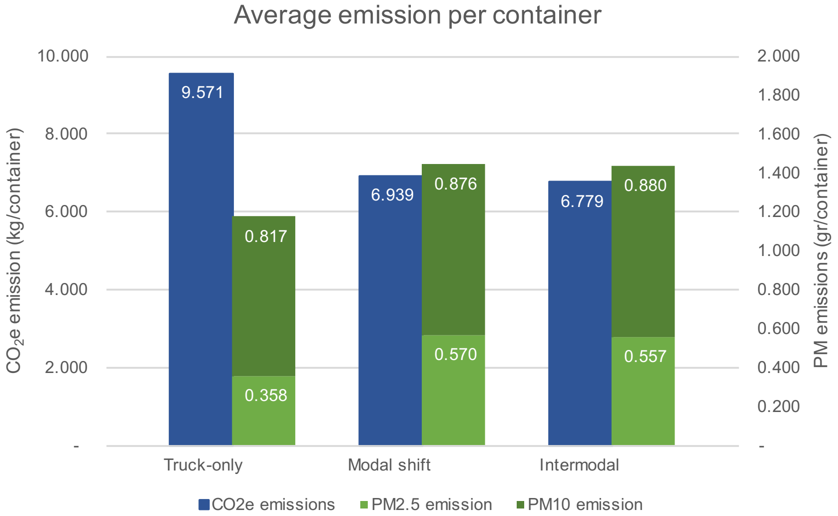

Figure 22 Result: Average emissions per container

Conversely, the average gram of PM_{10} and $PM_{2.5}$ emissions per container increases in modal shift and decoupled intermodal transport scenarios. The modal shift generates a significantly higher PM emission of 0.876 gram per container, where 0.570 gram of it classified as $PM_{2.5}$. This is 7.2% higher than PM emission generated by truck-only scenario. Moreover, the $PM_{2.5}$ emission generated by modal shift scenario is 59.2% higher than truck-only transport network (from 0.570 gram to 0.358 gram). This result is confounding because although the increase in

PM emissions in general is expected, the increase of $PM_{2.5}$ as much as 59.2% is not. The attention particularly on this result is essential because $PM_{2.5}$ actually possesses greater threat to human beings than PM_{10}.

Another interesting remark in Figure 22 is that the amount of PM emissions generated by decoupled intermodal transport scenario is more or less the same with the one generated during modal shift scenario. It is probably expected that the level of PM emission should be between the one generated during truck-only and modal shift scenarios. Nonetheless, the use of truck drayage in decoupled intermodal transport network also increases the rate of PM emission, because although relatively small, truck also generates the non-exhaust PM emissions. Therefore, due to this PM component, it is possible to have a relatively higher level of PM emissions even though the utilization of rail or barge is compensated with the use of trucks.

As per now, based on the as-is simulation results shown in Figure 20 and Figure 22, it seems that modal shift scenario is the feasible business case for Den Hartogh Logistics. Both from cost and environmental impact perspective, modal shift outperforms the other two scenarios. Nonetheless, this proposition should be supported by the result of the to-be simulations in the following section.

5.2. To-be simulation

The continuation of the simulation model is shown in this section, where two parts of future scenario simulations are performed. In the following, first a sensitivity analysis is conducted. This is done to gain insights into the characteristics of different input parameters. Based on the result of the sensitivity analysis, different future scenarios are performed.

5.2.1. Sensitivity analysis

As mentioned above, in the sensitivity analysis, the influence of different input parameters on the system performance (i.e. average cost per container and average emission per container) is studied. The sensitivity analysis focuses on two main parameters, i.e. the rail/barge cost and the rail/barge handling cost.

Rail and barge cost

In this section, the sensitivity of rail and barge cost to the average cost per container is analyzed. Figure 23 shows the change in average cost per container when rail or barge cost is changed. The changes are shown for both modal shift (red and blue dashed lines) and decoupled intermodal transport scenarios (red and blue solid lines).

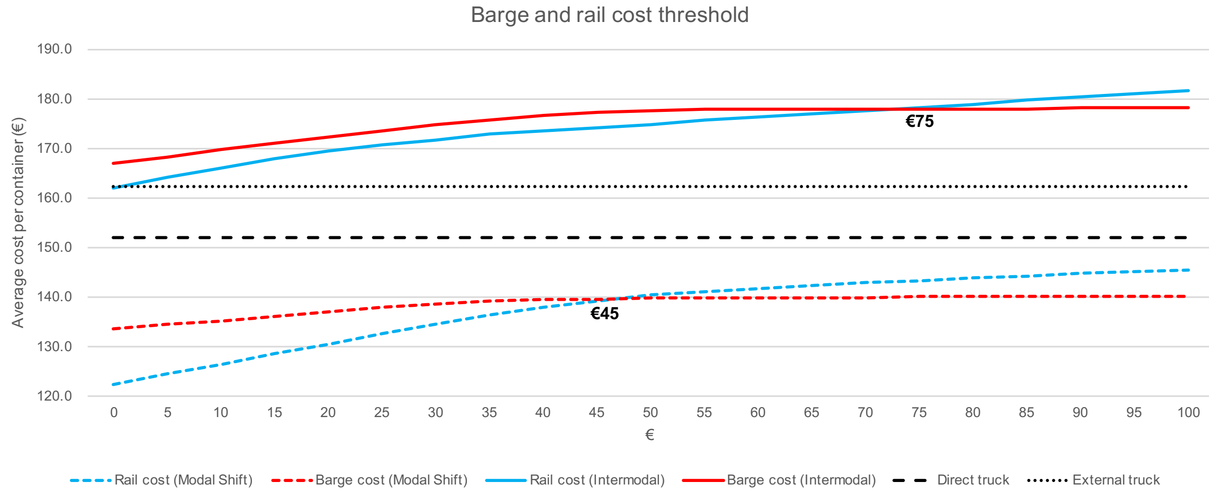

Figure 23 Result: influence of rail and barge cost on the average cost per container

Also in the graph is the average cost per container for the truck only scenario (black dashed line) and the average cost per container for the external truck (black dotted line). These two lines are included in the graph at the first time to see whether in any conditions these lines can cross each other. However, it is obvious that none of the blue and red lines cross the black lines, implying that there is no break-even point between the truck-only and modal shift scenario.

At the moment, the rate offered by a rail operator within the chemical cluster Rotterdam is €48 per container. This rate goes from one end to the other end of the chemical cluster Rotterdam, which is about 40 kilometers. On the other hand, barge service within the chemical cluster Rotterdam is now offered at the rate of €30 per container.

It can be seen in Figure 23 that with the current cost structure and parameters, the modal shift is a viable business case for Den Hartogh Logistics. This is due to its lower average cost per container compared with road transports (for both cases of internal and external trucking). Also, for both modal shift and intermodal transport network, at the current offered rate, rail is indeed the cheapest solution.

Barge outperforms rail in terms of the average cost per container when the offered rate is €45 per container. This figure also shows that the rail cost is more sensitive than barge cost, shown by the steeper slope of rail cost when the cost is between 0 and €45. Looking at the current rate offered for rail cost, this figure implies that the rail cost of €48 per container is already attractive enough for Den Hartogh Logistics. However, this characteristic of rail cost will be further explored in the next section.

On the other hand, the impact of rail and barge cost on the environmental sustainability is also studied. The results are shown in Figure 24 and Figure 25. These graphs show a similar trend for the emissions. This is due to the fact that the difference on rail and barge cost affects the system in terms of number of connections that are shifted from truck to rail or barge. Hence, the composition of rail and barge should not be much different, and thereby the emissions figures are also alike. In both figures, as rail and barge cost increases, the CO_2e emission also increases because there are less number of connections are shifted to rail and barge. As expected, in return the PM_{10} and $PM_{2.5}$ emissions decrease due to the fewer number of rail and barge involved in the network.

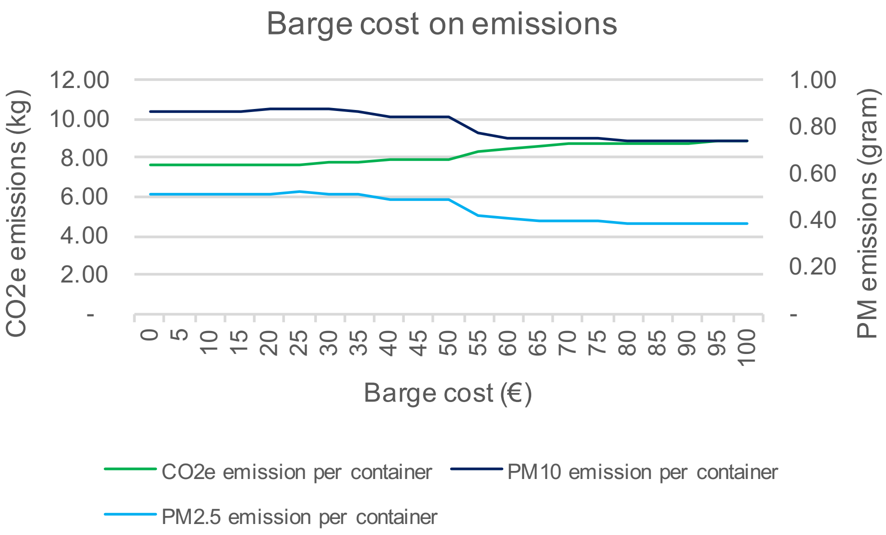

Figure 24 Barge cost on emissions

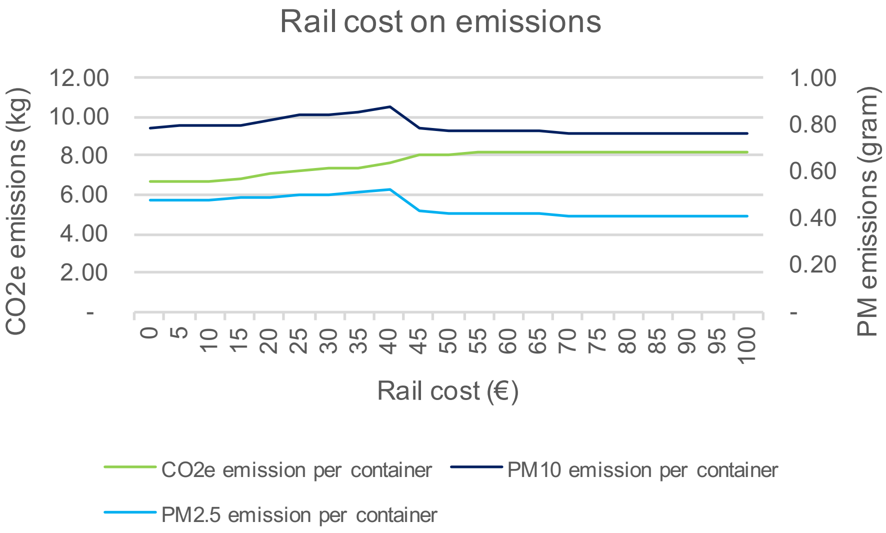

Figure 25 Rail cost on emission

Rail and barge handling cost
At the moment, different rail/barge handling costs are offered depending on which terminals where the handling process takes place. The average handling cost is offered in the rate of €40 per lift (details on Appendix B). Similar with Figure 23, Figure 26 also shows how rail and barge handling cost influence the average cost per container for two different transport network scenarios, i.e. (1) Modal shift and (2) Intermodal transport network.

Likewise, the influence of handling cost is very much alike to the influence of rail and barge cost on the average cost per container. To some extent, maintaining the rail handling cost yields lower average cost per container. However, when the average rail handling cost goes higher than €25 per lift, barge outperforms rail. Based on this, maintaining the rail handling cost lower than €25 per lift makes the modal shift more attractive. Since the rate of €25 per lift in Figure 26 represents the average rail handling cost, further analysis is done in the next section to see which terminals play the biggest role in driving the average rail cost.

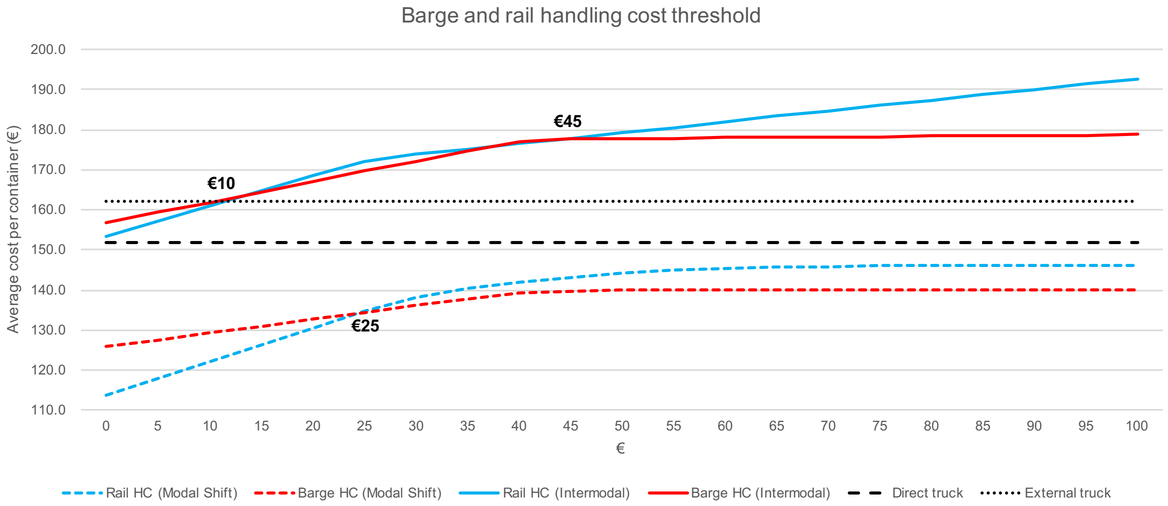

Figure 26 Result: influence of rail/barge handling cost on the average cost per container

In Figure 27, rail and barge handling costs are treated altogether as an entity. Hence, a more significant change in the CO_2e and PM emissions are apparent. If it is possible to treat all the handling costs similarly, then based on Figure 27, the point where trade-off between CO_2e and PM emissions takes place can be obtained. As shown, the intersection of CO_2e and PM emissions are when on average, the barge and rail handling costs are €45 per lift. This way, the level of CO_2e emissions are kept as low as possible without jeopardizing the PM emission level.

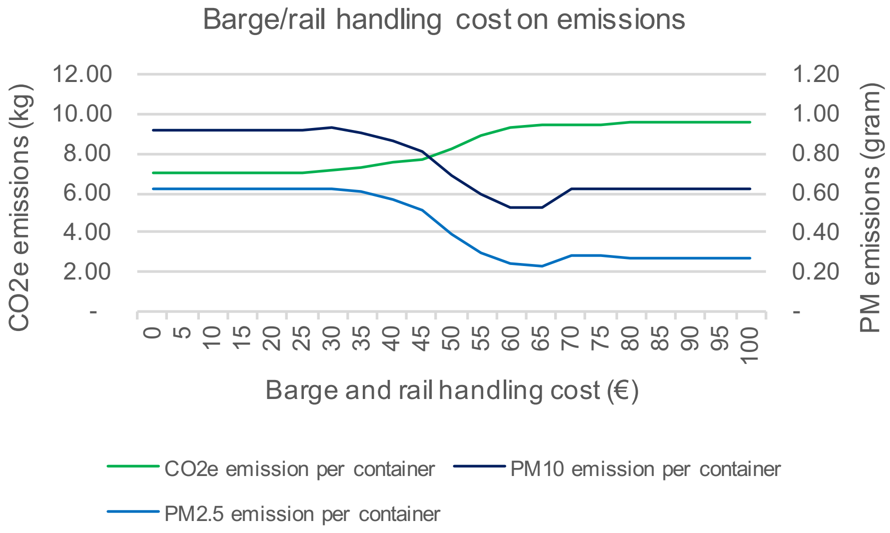

Figure 27 Barge/rail handling costs on emissions

5.2.2. Future scenarios

In this section, different future scenarios are simulated to see how fine-tuning different parameters can improve the business case for Den Hartogh Logistics. The scenarios discussed in this section include: (1) How committed volume can lead to cost decrease of direct rail, (2) The effect of an area's rail and barge handling cost on the average cost per container, and (3) The effect of using external truck partners for late deliveries in the modal shift scenario.

Volume

As previously mentioned in the sensitivity analysis of rail and barge cost, maintaining the rail cost up to €45 per container will give the most optimum average cost per container for modal shift scenario. In practice, one of the ways to negotiate with rail partners is by committing a number of volume for a period of time. This section will explore the volume that Den Hartogh Logistics have and translate it into the opportunity for negotiation with the rail operator.

Based on statistics[6], cost of rail freight transport is 30% contributed by energy, 24% by locomotives, 11% by staff wages, and 10% by the wagons itself. This cost structure implies that the proportion of fixed and variable costs of rail operation lies in the ratio 70%:30%. This structure is used in the analysis made in this section to see the how fixed cost decreases as the number of container increases.

One of the findings by European Commission (2015) is in the Netherlands, the operating cost of rail freight is about €40 per train.kilometer. Combining this information with the maximum distance in the chemical cluster Rotterdam, which is about 40 kilometers, the total train operating cost from Waalhaven area (i.e., Rail Service Center) to the other end in Maasvlakte area is then €1,600 per one-way trip.

The variable cost per container is determined based on the minimum payload per trip to reach break-even point between the total operating cost and the income from the customers. In this case, a payload of 44% (i.e., 40 TEU per trip) is used as a reference point, which gives variable cost of about €12 per container.

On the other hand, in practice it is assumed that on each trip, the average payload is 60%, which is used as the reference point in estimating the fixed cost per container. In Chapter 2.4 it is mentioned that the average payload is 80%, however it is the case of international train trips. In the case of train shuttle in the chemical cluster Rotterdam, where the practice is not common yet, the assumed average payload of 60% is considered as sensible. With every one additional containers, the payload increases and this leads to a decrease of the fixed cost per container. This relationship is visualized in Figure 28.

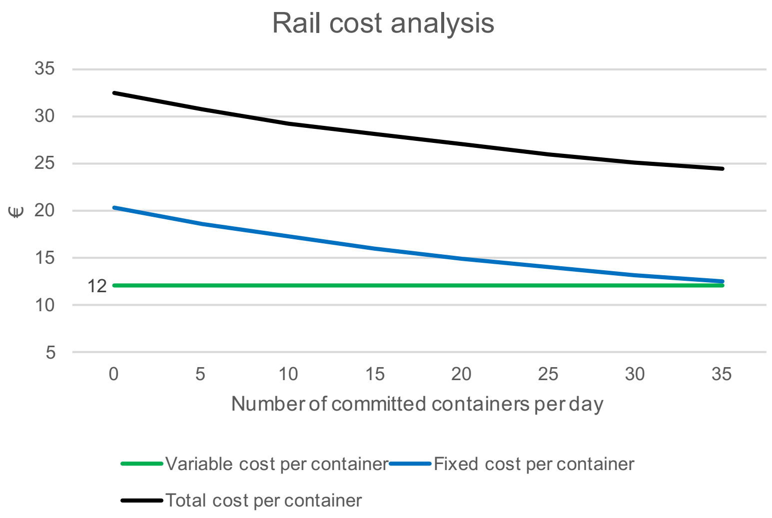

Figure 28 Rail cost analysis

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[6] http://www.railcargo.nl/bibliotheek/studentenrubriek/tarieven

Although Figure 28 shows the decrease of total cost per container, which obviously also leads to the decrease of the average cost per container, there is no increase in the number of connections that are shifted into direct rail due to this decrease. This is due to the fact that rail itself is already the cheapest transport option among trucks and barge.

Rail and barge handling cost

The sensitivity analysis in the previous chapter shows that rail handling cost of €25 per lift is the threshold when the barge outperforms rail in the average cost per container. In this section, further analysis on which rail and barge handling costs are the most influential on the average cost per container.

First, the influence of different rail handling costs on the average cost per container is studied. In this analysis, rail handling costs are classified per area within the chemical cluster. In addition to that, there is another handling cost category of "Others" in this analysis. In this handling cost category is the nodes where there are no available information regarding the handling costs yet. The motivations behind the creation of this category is the fact that later in a newly developed connections, the cost of handling should be different because private sidings are going to take place instead of regular handling process. Although investment on private sidings are not taken into account in this analysis, the handling cost should be not equal to the regular types of handling process.

Figure 29 shows the sensitivity of different class of handling costs on the average cost per container. Opposed to the handling costs of in Waalhaven, Botlek, Pernis, and even Maasvlakte areas, the handling costs classified as "Others" is very sensitive. Since this category consists of nodes with connections that are not established yet, then it is an important factor to be monitored by Den Hartogh Logistics in the future when the modal shift actually takes place.

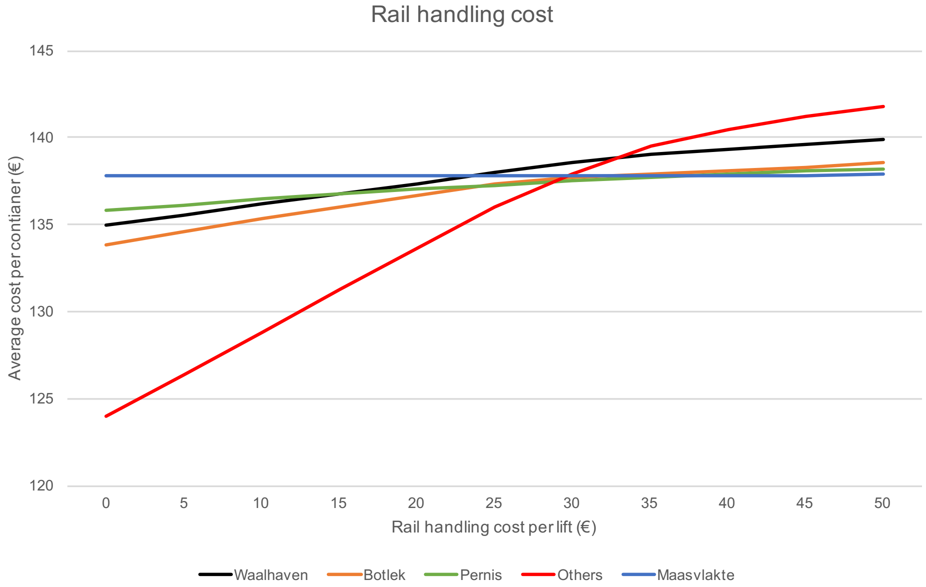

Figure 29 Rail handling cost on average cost per container

In addition to the handling cost of rail, the handling cost of barge is also studied in this section. The influence of different barge handling costs on the average cost per container is illustrated in Figure 30. The categorization of handling costs is alike with the categorizations used in the analysis of the rail handling cost. Apparently, the similar influence is also exhibited in the relationship between barge handling cost (especially Waalhaven and Others categories) on the average cost per container.

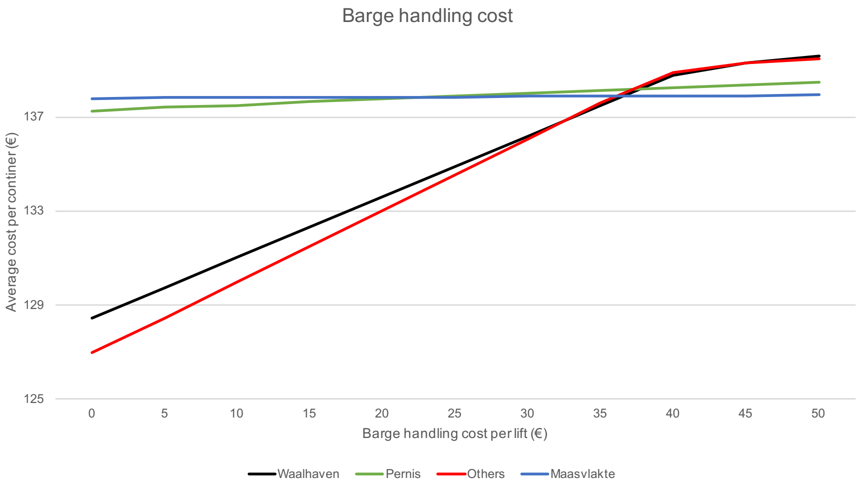

Figure 30 Barge handling cost on average cost per container

Using external trucks for late containers

One of the downsides of using public services like rail and barge is that time flexibility ought to be sacrificed. Although this master thesis is not interested at looking the day to day operational challenges, but it is worth noting that in the future, this can be a potential problem and threaten the feasibility of modal shift. Therefore, one of the future scenario to be analyzed is on how the modal shift business case reacts to the case where any containers arriving later than the scheduled service are then transported using external trucks. This scenario is considered sensible because in the truck planning level, flexibility is scarce at the moment.

In this analysis, the following scenario is used. Den Hartogh Logistics replaces the truck-only transport system with the modal shift network. On special cases where containers are about to be delivered using rail or barge service but arriving later than the scheduled service, then these late containers are delivered using trucks from the external partners.

Figure 31 shows how the average cost increases as the proportion of containers coming late to the terminals also increase. When 80% of the total jobs are delivered using the external trucks, then modal shift starts to lose its cost competitiveness.

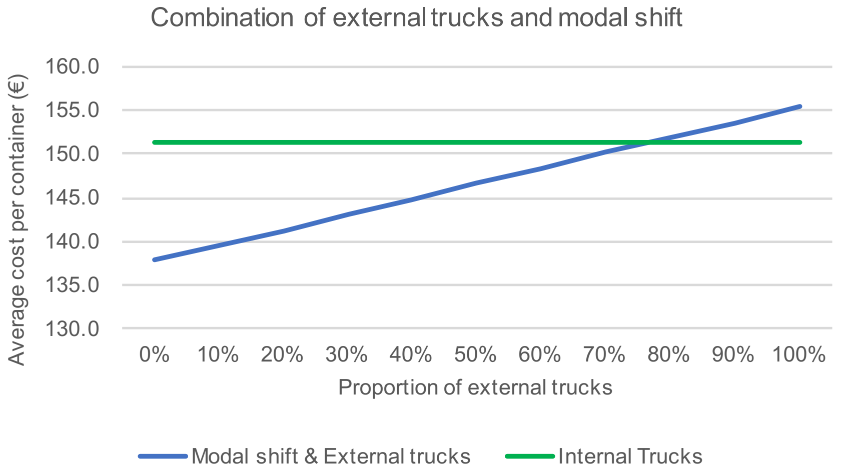

Figure 31 Cost for using external trucks for late deliveries

6. Conclusions and recommendations

This chapter concludes the report of this thesis project. In this chapter, the overall conclusions are discussed first. It is followed by the discussions on the managerial implications, scientific implications, and the limitation and future research.

6.1. Conclusions

To begin with, earlier in Chapter 1, the following research gaps were identified based on the analysis on the literature study:

1. Investigate the feasibility of intermodal transport network in short distance and explore the characteristics of the relevant input parameters.
2. Investigate the impact of intermodal transport as an initiative to minimize the carbon emission on the other environmental sustainability parameter, i.e. air quality.

The first research gap is then translated to the objective of this research, which is to explore the opportunity to employ intermodal transport network in the chemical cluster Rotterdam, by which the nodes are short distance apart from one and another. In Chapter 3, the cost structure for both types of flow have been defined. It is already apparent that decoupled intermodal transport have more cost components than the direct truck has. Based on this cost structure, Figure 20 shows that modal shift is a more attractive business case than intermodal transport network. In fact, the modal shift business case outperforms the intermodal transport network by 9.3%.

To implement the proposed modal shift, there are a total of 110 conenctions to be shifted from road to rail and barge. The details of these shift are available in Appendix D. However, further analysis found that it is more efficient to work with only a number of connections with the most impact, rather than working on many nodes with smaller impacts. Therefore, in Table 10 the lists of the heaviest connections to be shifted to rail connections are described.

The list on Table 10 is derived based on Figure 28 and the analysis of the optimum modal shift for Den Hartogh Logistics' business case. Based on that, the maximum number of committed containers per day should be around 59 containers per trip (i.e., a total of 118 containers per day). Since these connections have a balanced ingoing and outgoing volume, thereby the total number of container to shift to rail can be obtained by multiplying the stated number of container per day by 2.

Table 10 Connections to be shifted to direct rail transport

Nr.	Connection	#Container per day
1	Huntsman Holland B.V. – C. Steinweg Botlek Terminal	19
2	RSC – Rotterdam Shortsea Terminal	9
3	Huntsman Holland B.V. – RSC	9
4	Pernis Combi Terminal B.V. – RSC	6
5	Huntsman Holland B.V. – Vopak Terminal Chemiehaven	4
6	Huntsman Holland B.V. – C. Ro Ports Nederland B.V.	3
7	RSC – C. Ro Ports Nederland B.V.	3
8	P&O Euro – C. Ro Ports Nederland B.V.	2
9	Pernis Combi Terminal B.V. – Huntsman Holland B.V.	2
10	LBC Rotterdam B.V. – C. Ro Ports Nederland B.V.	2
Total number of containers per day		**59**

From the results in Table 10, it is apparent that most of the nodes are similar with the nodes described earlier in Figure 9. The total number of containers stated in Table 10 constitutes about 12.42% of the total volume. Therefore, if all of these connections (both ways) are shifted into rail transport, it is possible to shift as much as 24% of the total volume in the chemical cluster to direct rail connection.

On the other hand, the volume to be shifted to barge is concentrated in a fewer number of connections, as shown in Table 11. The total of 31 containers per day constitute 6.3% of the total volume in the chemical cluster Rotterdam. Therefore, if both directed ways are shifted into direct barge, then around 12.5% of the total volume of Den Hartogh Logistics can be shifted to other transport modes.

Table 11 Connections to be shifted to direct barge transport

Nr.	Connection	#Container per day
1	Kemira Rotterdam B.V. – C. Ro Ports Nederland B.V.	20
2	Vopak Terminal Chemiehaven – C. Steinweg Botlek Terminal	8
3	Pernis Combi Terminal Twente B.V. – C. Ro Ports Nederland B.V.	3
Total number of containers per day		**31**

In total, the connections described in Table 10 and Table 11 altogether already contribute to a total of 36.5% of the volume in the chemical cluster Rotterdam, with only shifting a total of 26 directed connections out of the possible 110 connections. If all 110 connections are shifted into rail or barge, the total volume shifted is 37.2%. However, the effort and volume does not justify the shifts.

To support the business case, the robustness of the proposed business case of modal shift is shown in Figure 32 below. This figure shows the performance of the modal shift if different parameters are modified. It is apparent that no matter how high the parameters are; the modal shift business case is always going to be more attractive than the direct truck scenario.

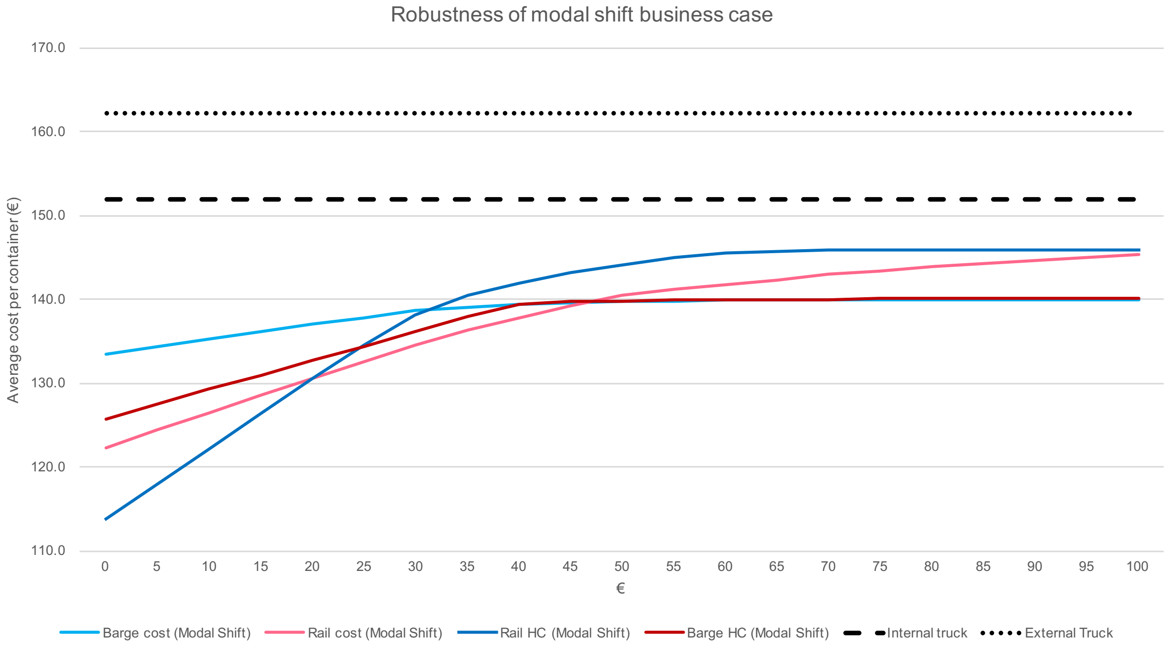

Figure 32 Robustness of modal shift business case

On the other hand, the feasibility of intermodal business case is also exhibited through the graph showing the robustness of intermodal business case in Figure 33 below. Based on the figure, it is clear that intermodal business case is not going to be viable for the case of Den Hartogh Logistics in the chemical cluster. One exception is if the trucking cost increases, for instance, to the same level of the current external trucking. Holding other parameters constant, the intermodal transport network can then be viable when rail and barge handling costs are offered €10 per lift.

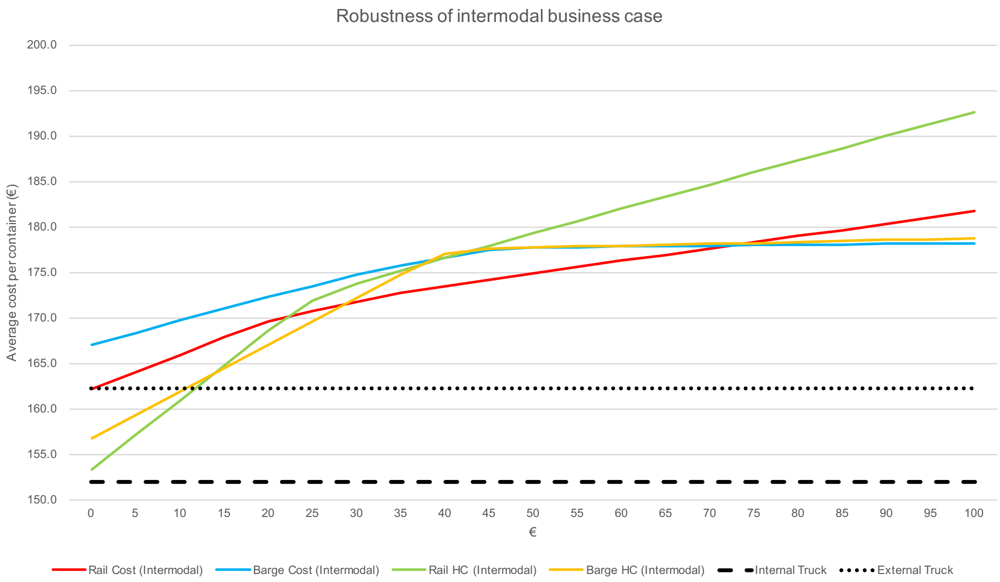

Figure 33 Robustness of intermodal business case

With respect to the predefined research gaps, the second research gap revolve around the investigation of the impact of intermodal as one initiative to reduce GHG emissions, on the other environmental impact, i.e. air quality. Based on the results, indeed the modal shift scenario is effective in reducing the GHG emissions without jeopardizing the air quality.

This is mostly due to the fact that the types of trucks that are allowed in the Port of Rotterdam area are either EURO5 or EURO6 classes. These types of trucks are advanced in terms of environmental impact, which includes the low level of PM emissions emitted due to the advanced technology in diesel particulate filter (DPF) installed on the vehicle. On the other hand, the age of a barge vessel for instance, can be up to 40 years of age. Then the type of technology used on a vessel operating these days is probably a very old one. The same thing also applies to rail wagon.

It is important to find a way such that the reduction on PM emissions can be done to complement the more common reduction of GHG emissions. To obtain the advantages of GHG emission reduction without jeopardizing the air quality, one of the possible ways is through Port of Rotterdam authority to regulate the use of Diesel Particulate Filter (DPF) for diesel vessels operating in the premise of Port of Rotterdam. Especially for older larger diesel vehicles, including barge vessels and rail locomotives, one of the forms of DPF is the retrofit exhaust abatement (Client Earth, 2013). There are three types of retrofit exhaust abatement technologies, i.e. the wall-flow filter, partial flow filter, and diesel oxidation catalyst. The decision on which technology to use depends on required scale of emission reduction and the available budget. Since modal shift is at the moment really encouraged, yet less attention is given on PM emission than on the GHG emission, then it is sensible for Port of Rotterdam authority to regulate the use of DPF more strictly.

All in all, the answers to the predetermined research questions are:

RQ1: How can the inclusion of intermodal in Den Hartogh Logistics' service in the chemical cluster Rotterdam lead to lower cost and environmental impact?

RQ1.1: What is the current performance of Den Hartogh Logistics' service in the chemical cluster Rotterdam, in terms of cost and environmental impact?

With truck-only transports in the chemical cluster Rotterdam, the average cost is €151.4/container. The corresponding environmental impact is on average of 9.6 kg CO_2e/container and 0.82 gram PM_{10}/container.

RQ1.2: What quantitative model should be developed to determine the inclusion of intermodal transport on Den Hartogh Logistics' service in the chemical cluster Rotterdam?

To determine the inclusion of rail and barge into Den Hartogh Logistics' service in the chemical cluster, the internal cost model is used. This internal cost consists of different cost components that incurred during a transport journey, such as the long haul cost (e.g., truck, rail, and barge cost), handling cost, truck waiting cost (only when trucks are involved in long haul or drayage transports), and the truck drayage cost (only for the case of intermodal transport network). Additionally, cost due to solo kilometer is also taken into account. However, the proportion of this solo kilometer cost is very small such that it can be neglected. The detailed description on this cost model is described in Chapter 2 and Chapter 3.

Based on the simulation result, the modal shift scenario is the most cost feasible scenario for Den Hartogh Logistics. In modal shift scenario, some of the direct truck connections are replaced with the direct rail or direct barge connections. In fact, by only shifting 13 connections (26 directed connections), about 36.5% of the volume in the chemical cluster Rotterdam is already shifted from road to rail and barge.

RQ1.3: What is the impact of the inclusion of short-rail and barge on the performance of Den Hartogh Logistics' service in the chemical cluster Rotterdam, in terms of cost and environmental impact?

By using the model described and used to answer research question 1.2, the intermodal transport network is not viable for Den Hartogh Logistics' service in the chemical cluster. Instead, modal shift is a viable option. By employing the modal shift transport network, the average cost per container goes down to €137.5 per container. There are a total of 68 connections shifted to direct rail, 42 connections shifted to direct barge, and the rest 186 connections remain transported by direct trucks. This composition shifts 37.2% of the total volume in the chemical cluster. By using this modal shift network, the average CO_2e emissions decreases to 6.94 kg CO_2e/container and the PM_{10} emission increases to 0.876 gram PM_{10}/container.

RQ2: How can different parameters of intermodal transport be fine-tuned to increase Den Hartogh Logistics' potential flexibility in the chemical cluster Rotterdam?

In this master thesis, rail and barge's transport and handling costs are fine-tuned to explore the possibility to increase Den Hartogh Logistics' flexibility. Additionally, for rail, the possibility to gain savings based on the number of committed containers are explored. Also, the use of external trucks in the future to deliver tank containers that arrive later than the scheduled services of rail and barge is analyzed.

Based on the analysis on the committed volume, there is indeed a possibility to decrease the rail cost based on the exploitation on the fixed cost of rail transport. This analysis was made only to rail, but not to barge. This is due to limitation on time and the difficulty to approach barge operators. Therefore, the analysis on the committed volume on barge is not performed.

Additionally, rail and barge handling costs are also studied. The influence of rail and barge handling costs on the average cost per container are analyzed. It is apparent that there is one handling cost category that is very sensitive on the average cost per container compared to the other handling costs. This handling cost category is the one for the not yet established connections.

Additionally, the scenario to involve the external trucking to deliver tank containers arriving at terminals later than the scheduled service is explored. The number of tank containers arriving later than the scheduled service is denoted by a percentage. It is apparent that as long as the percentage of tank containers delivered by external trucks does not exceed 80% of the total volume, then the use of modal shift is still viable for Den Hartogh Logistics, compared to the use of direct truck scenario.

6.2. Discussions

6.2.1. Managerial implications

The managerial implications discussed in this section comprise the implications for both Den Hartogh Logistics and the regulators, such as the Port of Rotterdam authority. For Den Hartogh Logistics, this thesis has a number of straightforward implications. First is the heat map developed in the beginning of this thesis have revealed the operation intensity in the chemical cluster Rotterdam, such that the areas and connections with the heaviest volume in the chemical cluster Rotterdam are disclosed. Furthermore, this thesis has shown that the modal shift scenario is a viable business case for Den Hartogh Logistics in the chemical cluster Rotterdam. This is supported by the fact that modal shift has the lowest average cost per container compared to the other scenarios.

On the other hand, the result of this thesis also shows that the modal shift scenario generates lower CO_2e emissions than it is generated by the truck-only scenario. This is an insightful finding for the Port of Rotterdam authority and other regulators in general. Modal shift or intermodal transport is indeed considered effective in reducing the greenhouse gas (GHG) emissions, and thereby considered effective in achieving the global goal to mitigate the climate change. However, the focus on particulate matter emissions is somewhat still neglected. Contrary to the result of GHG emissions, during modal shift and intermodal transport, the level of PM emission is higher than it is during truck-only scenario. Thus, this shed a light in the importance of using a diesel particulate filter (DPF) and retrofitting initiatives for diesel-powered barge vessels and rail locomotives.

Moreover, the cost model developed in this thesis has revealed the what are the cost components altogether with the proportions to the total cost. The result shows that about half of the transport cost, in general, is the handling costs. This is applied in all cases, i.e. truck-only, modal shift, and intermodal transport network. In the to-be simulation, the effects of changes in the rail and barge handling costs has shown that in modal shift. When the rail handling cost does not exceed €25 per lift, rail is still the cheapest option. Otherwise, barge outperforms rail in terms of average cost per container. This finding reveals how the handling cost influences the cost performance of a transport mode. Furthermore, the average handling cost charged now for both rail and barge is around €33 per lift, with exception in Maasvlakte area, €50 per lift. It is worth noting that the trend for the global chemical industry is that the value chain is increasingly move eastward due to the economic growth and vast market opportunities in Asia (Deloitte, 2011; AT Kearney, 2012). Therefore, a volume increase in the terminals in the Maasvlakte area is expected in the future. If it is the case, a higher average cost per container should be expected due to the high volume in Maasvlakte area. Therefore, a further analysis in the future should be gone through to see if this handling cost €50 can be lowered to make any business case of Den Hartogh Logistics remains viable.

Although the interest of Den Hartogh Logistics at the moment is mainly to explore whether there is a viable business case from cost point of view, there are various worth-considering benefits of shifting truck operations to rail or barge. First, road congestion is an issue in the chemical cluster Rotterdam. With a moderate increase expected in the Europe in the upcoming years, road congestion is not expected to lessen in the upcoming years. Not only that, Rabobank (2017) also suggests that there will be shortage on experienced drivers in the near future. This implies that it is going to be difficult to strive in the road operations. Hence, it is beneficial for Den Hartogh Logistics to consider starting modal shift from now.

Additionally, based on the discussion with the Port of Rotterdam authority, it is concluded that there are indeed incentives for the companies participating in modal shift. Yet, a strict regulation to force other companies to get involved in modal shift and environmental sustainability initiatives are not enforced. However, it is believed that in the future environmental related regulations are going to be stricter in the Port of Rotterdam premise. Therefore, this thesis project should be remarked as the starting point for Den Hartogh Logistics in shifting their operations to rail and barge in the chemical cluster Rotterdam.

6.2.2. Scientific implications

Referring to the research gaps defined in Chapter 1.4, from science perspective, this thesis revolves around two main subjects; the viability of intermodal transport over short distance and how different parameters influence it, as well as the impact of modal shift or intermodal transport on environmental impact.

First, the result shows that the modal shift is a viable business case for Den Hartogh Logistics and intermodal transport is not. Thus, a partial support on the notion that intermodal transport is only viable over long distance is expressed. Partial because the intermodal transport is indeed not cost competitive for Den Hartogh Logistics' case, yet in the sense of shifting a portion of truck operations into greener transport modes as shown in modal shift scenario, then it is viable.

The result of this thesis is obtained based on the developed cost model. Based on this cost model, it is apparent that in containerized freight transports, the handling costs are more influential than the other costs on the average cost per container. It is also worth noting that from cost perspective, rail is more interesting than barge and trucks. Nonetheless, if the rail cost and rail handling cost is increased, at some point barge outperforms rail.

Moreover, from the environmental sustainability perspective, this thesis casts a light on how freight transport affects the environmental sustainability in different ways. As expected, the use of greener mode such as rail and barge indeed generates a lower level of GHG emission. However, since the diesel-powered vessels and locomotives operating at the moment are not of the most recently developed, then the amount of particulate matter emissions generated are higher than the one generated in truck-only scenario. Therefore, this thesis argues that although modal shift or intermodal transport are considered effective solutions for mitigating the climate change, but there is a flaw that has been overlooked all this time. Indeed, the effect of GHG emission is longer and more global, but PM emission should not be neglected as it is now. The effect of PM is more local and shorter in terms of time, but it possesses great health threats to the society. Therefore, this thesis argues that the recommendation on the DPF initiatives should be fostered.

6.2.3. Limitation and future research

Despite the contributions of this master thesis to the intermodal transport literature and logistics in the chemical industry, this study is subject to some limitations. First, due to time limitation, this thesis does not provide the insights into how the demand change affects the result. Although the cost structure in the context of the chemical cluster does not show the economies of scale property, but the difference in volume proportion should affect the average cost in general. In return, the effect of the demand changes on the behavior of each cost components can also be observed.

To some extent, the simplifications taken in this thesis should also probably be removed. This includes the variation of tank container size and types of actions taking place in the nodes that should be included in the future research to enrich the analysis. Furthermore, the operational level can be the starting point for the future research. Since this thesis presents a tactical outlook regarding the opportunity of employing intermodal transport, later the challenges encountered during operational planning of modal shift or intermodal transport can be interesting. Another possibility is to increase the complexity of the model by including the schedule of the rail or barge services into account as well as the capacity of rail or barge services as a function of time spent for planning the delivery.

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Appendix A

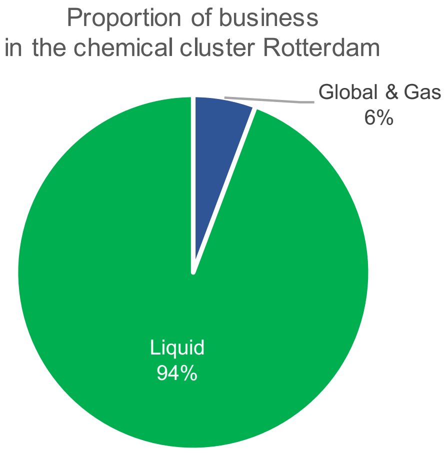

Figure 34 Den Hartogh Logistics's business in the chemical cluster Rotterdam

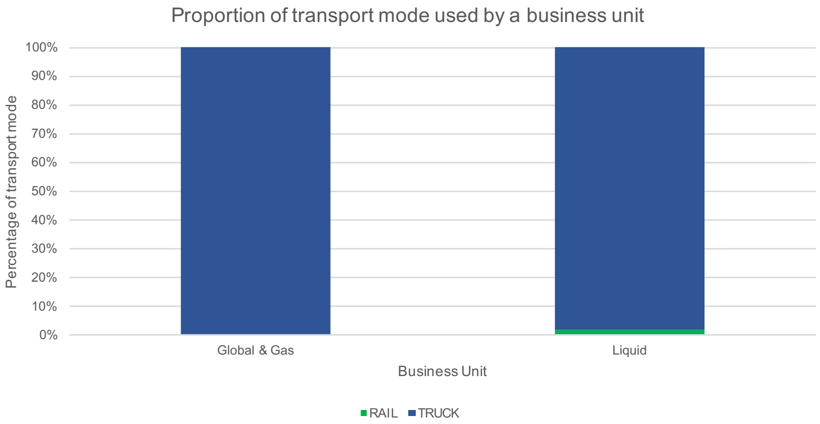

Figure 35 Proportion of transport mode

Table 12 Nodes with the heaviest volume

[redacted]

Appendix B

Table 13 Solo kilometer cost (s_m)

[redacted]

Table 14 Rail handling cost

[redacted]

Table 15 Barge handling cost

[redacted]

Table 16 Truck handling cost

[redacted]

Table 17 Truck waiting cost

[redacted]

Appendix C

Table 18 Connections distance (in kilometer)

Connection	Km	Connection	Km	Connection	Km	Connection	Km	Connection	Km	Connection	Km	Connection	Km	Connection	Km
ANAVLA-DENBOT	18.70	CROBOT-VLSPER	18.43	DENBOT-VOPVLA	14.56	DERBOT-DENCHE	3.94	KOOVON-CROBOT	17.60	PERROT-DENBOT	9.77	RSCROT-VOPBOTC	14.05	SYNHOE-HUNROZ	39.96
ANAVLA-TCEEUR	28.75	CROBOT-VOPBOTC	4.61	DENBOT-WILBOT	3.81	DERBOT-HUNROZ	5.88	KOOVON-DENCHE	12.73	PERROT-DENCHE	10.90	RSCROT-WILROT1	18.07	SYNHOE-LSC3014	32.10
APMMAA-ASPEUR	16.34	DENBOT-ANAVLA	16.68	DENBOT-WILROT1	3.67	DERBOT-VOPBOT	3.98	KOOVON-RSCROT	12.03	PERROT-HUNROZ	15.36	RSTROTN-DENBOT	12.34	SYNHOE-PERROT	32.47
APMMAA-DENBOT	25.83	DENBOT-ASPEUR	12.13	DENCHE-BONBOT	2.69	DERBOT-VOPBOTC	4.24	KUWEUR-RSCROT	24.46	PERROT-LSC3014	0.37	RSTROTN-RSCROT	1.40	SYNHOE-RSTROTN	30.84
APMMAA-TCEEUR	15.45	DENBOT-BONBOT	3.76	DENCHE-CROBOT	5.19	DIAROZ-NTCBOT	13.75	LBCBOT-CROBOT	11.89	PERROT-RSCROT	7.58	RSTROTZ-CROBOT	18.63	SYNHOE-SCAPER	29.90
ASPEUR-CROBOT	6.86	DENBOT-BREROT	1.23	DENCHE-DENBOT	1.23	EMEBOT-DENCHE	1.31	LBCBOT-DENBOT	5.89	PERROT-RSTROTZ	7.63	RSTROTZ-DENBOT	12.64	TCEEUR-ANAVLA	27.42
ASPEUR-DENBOT	13.01	DENBOT-CROBOT	7.19	DENCHE-DENROZ	5.22	EMEBOT-RSCROT	15.11	LBCBOT-DENCHE	7.02	PERROT-TSPPER	0.07	RSTROTZ-DENCHE	13.76	TCEEUR-ASPEUR	0.88
ASPEUR-HUNROZ	8.44	DENBOT-DENCHE	1.23	DENCHE-DERBOT	2.63	ESSBOT1-DENBOT	4.70	LBCBOT-LSC3014	12.79	POEURO-CROBOT	9.60	RSTROTZ-HUNROZ	18.22	TCEEUR-DENBOT	12.12
ASPEUR-LSC3014	24.28	DENBOT-DENROZ	7.22	DENCHE-EXXVON	14.04	EXXVON-CROBOT	15.65	LBCBOT-PERROT	13.16	POEURO-DENBOT	15.76	RSTROTZ-KEMBOT	15.91	TCEEUR-LSC3014	23.39
BCWROT-DENBOT	12.61	DENBOT-DERBOT	3.02	DENCHE-HEXHOO	9.48	EXXVON-DENBOT	9.66	LBCBOT-POEURO	20.38	POEURO-DENCHE	13.64	RSTROTZ-NTCBOT	12.29	TCEEUR-POEURO	5.31
BONBOT-CROBOT	3.39	DENBOT-EMEBOT	2.36	DENCHE-HUNROZ	2.73	EXXVON-POEURO	24.14	LBCBOT-RSCROT	12.99	POEURO-DIAROZ	11.91	RSTROTZ-PERROT	8.93	TICROT-EURMAA	34.34
BONBOT-DENBOT	6.43	DENBOT-EXXVON	12.89	DENCHE-KEMBOT	2.23	EXXVON-RSCROT	7.46	LBCBOT-RSTROTZ	13.04	POEURO-HUNROZ	11.18	RSTROTZ-RSCROT	1.70	TSPPER-DENCHE	10.83
BONBOT-DENCHE	4.31	DENBOT-HEXHOO	8.34	DENCHE-LBCBOT	10.62	HEXHOO-DENBOT	8.03	LSC3014-APM2MAA	34.49	POEURO-KEMBOT	12.38	RSTROTZ-RSTROTN	0.30	TSPPER-DENROZ	15.73
BONBOT-HUNROZ	5.19	DENBOT-HUNROZ	3.81	DENCHE-LSC3014	13.81	HEXHOO-DENCHE	9.15	LSC3014-CROBOT	15.88	POEURO-LBCBOT	23.84	RSTROTZ-STEEUR1	25.03	TSPPER-EXXVON	0.07
BONBOT-RSCROT	18.22	DENBOT-KEMBOT	4.47	DENCHE-NAMBTL	8.60	HUNROZ-BONBOT	0.41	LSC3014-DENBOT	9.88	POEURO-PERROT	27.40	RSTROTZ-TCEEUR	22.68	TSPPER-KOOVON	7.32
BONBOT-VOPBOTC	2.99	DENBOT-KOOPER	7.63	DENCHE-NAMPRW1	14.21	HUNROZ-CROBOT	3.80	LSC3014-DENCHE	11.01	POEURO-RSCROT	27.20	RSTROTZ-TSPPER	8.86	TSPPER-LBCBOT	10.23
BREROT-APM2MAA	23.79	DENBOT-KOOVON	10.37	DENCHE-NAMRTD1	15.63	HUNROZ-DENBOT	3.78	LSC3014-DENROZ	15.91	POEURO-RSTROTZ	27.25	RSTROTZ-VOPBOTC	14.06	TSPPER-LSC3014	0.30
BREROT-CROBOT	5.18	DENBOT-KUWEUR	12.13	DENCHE-PERROT	14.18	HUNROZ-DENCHE	2.73	LSC3014-DERBOT	11.70	POEURO-STEEUR1	2.15	RUBBOT-DENCHE	3.04	TSPPER-PERROT	0.70
BREROT-RWGMAA	24.70	DENBOT-LBCBOT	9.48	DENCHE-POEURO	13.68	HUNROZ-DENROZ	6.25	LSC3014-EURMAA	45.85	QUAROT-ASPEUR	15.40	RUBBOT-NAMBTL	8.52	TSPPER-RSCROT	7.51
COTBOT-DENBOT	1.89	DENBOT-LSC3014	12.66	DENCHE-RSCROT	13.98	HUNROZ-DERBOT	4.38	LSC3014-HUNROZ	15.47	QUAROT-DENBOT	24.89	SHEVOP-CROBOT	14.86	TSPPER-SYNHOE	30.92
CROBOT-ASPEUR	7.20	DENBOT-LYOBOT	3.04	DENCHE-RSTROTZ	14.03	HUNROZ-KEMBOT	3.31	LSC3014-LBCBOT	10.41	QUAROT-TCEEUR	14.51	SHEVOP-DENCHE	9.99	UNIPROT-DENBOT	13.64
CROBOT-BONBOT	5.15	DENBOT-NTCBOT	8.60	DENCHE-RUBBOT	3.08	HUNROZ-LSC3014	18.09	LSC3014-PERROT	0.37	RPPBOT-RSCROT	14.32	STEBOT-DENBOT	3.13	UNIWAA-DENBOT	13.60
CROBOT-DENBOT	6.43	DENBOT-PERROT	13.03	DENCHE-SHEVOP	8.77	HUNROZ-PERROT	18.46	LSC3014-RSCROT	7.69	RSCROT-ASPEUR	23.56	STEBOT-DENCHE	2.08	VLSPER-DENBOT	10.13
CROBOT-DENCHE	4.31	DENBOT-POEURO	15.68	DENCHE-STEBOT	2.08	HUNROZ-POEURO	14.71	LSC3014-RSTROTZ	7.74	RSCROT-BONBOT	18.17	STEBOT-DENROZ	5.59	VOPBOT-DERBOT	2.63
CROBOT-DENROZ	1.83	DENBOT-RPPBOT	2.34	DENCHE-STEEUR1	11.58	HUNROZ-RSCROT	18.26	LSC3014-TSPPER	0.30	RSCROT-CROBOT	18.62	STEBOT-HUNROZ	0.65	VOPBOT-HUNROZ	1.90
CROBOT-HUNROZ	5.19	DENBOT-RSCROT	12.84	DENCHE-SYNHOE	37.04	HUNROZ-RSTROTZ	18.31	NAMBTL-DENCHE	5.83	RSCROT-DENBOT	12.63	STEBOT-VOPBOT	1.24	VOPBOT-STEBOT	1.24
CROBOT-KEMBOT	3.06	DENBOT-RSTROTZ	12.89	DENCHE-TSPPER	14.11	HUNROZ-STEBOT	0.65	NAMBTL-NAMPRW1	11.00	RSCROT-DENCHE	13.75	STEBOT-VOPBOTC	2.38	VOPBOTC-BCWROT	13.75
CROBOT-KUWEUR	7.20	DENBOT-SHEVOP	7.63	DENCHE-VOPBOTC	0.30	HUNROZ-VOPBOT	1.90	NAMPRW1-DENCHE	10.93	RSCROT-HUNROZ	18.21	STEEUR1-CROBOT	7.45	VOPBOTC-DENBOT	1.53
CROBOT-LBCBOT	14.52	DENBOT-STEBOT	3.15	DENCHE-VOPNEC	4.26	HUNROZ-VOPBOTC	3.03	NAMPRW1-NAMBTL	11.97	RSCROT-LSC3014	8.54	STEEUR1-DENBOT	13.60	VOPBOTC-DENCHE	0.30
CROBOT-LSC3014	17.70	DENBOT-STEEUR1	13.58	DENROZ-CROBOT	1.82	HUNROZ-WAABOT	5.53	NAMPRW1-NAMRTD1	8.70	RSCROT-NTCBOT	12.28	STEEUR1-DENCHE	11.48	VOPBOTC-DENROZ	5.52
CROBOT-PERROT	17.70	DENBOT-SYNHOE	35.89	DENROZ-DENBOT	8.21	KEMBOT-CROBOT	3.92	NAMPRW1-TSPPER	0.10	RSCROT-PERROT	8.91	STEEUR1-HUNROZ	9.03	VOPBOTC-DERBOT	2.93
CROBOT-POEURO	10.76	DENBOT-TICROT	1.91	DENROZ-DENCHE	4.55	KEMBOT-DENCHE	2.27	NAMRTD1-NAMPRW1	10.33	RSCROT-POEURO	27.11	STEEUR1-POEURO	2.23	VOPBOTC-HUNROZ	3.03
CROBOT-RSCROT	17.88	DENBOT-TSPPER	12.96	DENROZ-HUNROZ	5.45	KEMBOT-HUNROZ	3.33	NTCBOT-LSC3014	11.91	RSCROT-RSTROTN	1.40	STEEUR1-VOPBOTC	11.78	VOPBOTC-STEBOT	2.38
CROBOT-RSTROTZ	17.93	DENBOT-UNIPROT	13.46	DENROZ-LSC3014	19.48	KEMBOT-POEURO	12.41	NTCBOT-POEURO	19.50	RSCROT-RSTROTZ	1.70	STEROT1-DENBOT	13.25	VOPBOTW-STEROT1	19.15
CROBOT-STEEUR1	8.66	DENBOT-VOPBOTC	1.53	DENROZ-TSPPER	19.79	KEMBOT-RSTROTZ	16.20	NTCBOT-RSCROT	12.11	RSCROT-STEEUR1	25.02	SYNHOE-CROBOT	40.37	WAABOT-DENBOT	4.24
CROBOT-TCEEUR	6.32	DENBOT-VOPBOTT	6.16	DENROZ-VOPBOTC	4.85	KOOPER-CROBOT	14.86	NTCBOT-VOPBOTT	9.97	RSCROT-TSPPER	8.84	SYNHOE-DENBOT	34.38	WAABOT1-DENBOT	4.47
CROBOT-TSPPER	18.00	DENBOT-VOPBOTW	6.46	DERBOT-DENBOT	4.41	KOOPER-RSCROT	9.29	PERROT-CROBOT	15.77	RSCROT-UNIPROT	2.27	SYNHOE-DENCHE	35.50	WILROT1-RSCROT	18.13

Appendix D

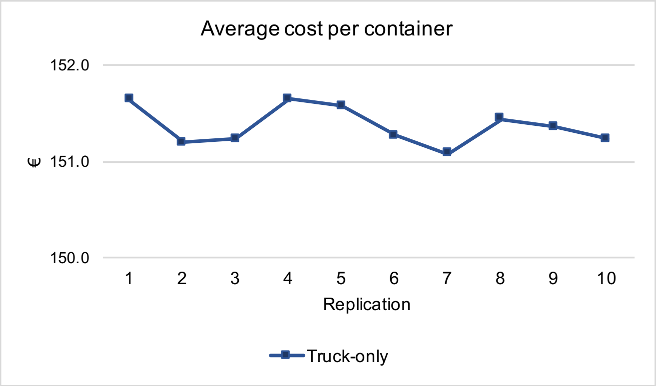

Figure 36 Simulation result: Truck-only scenario

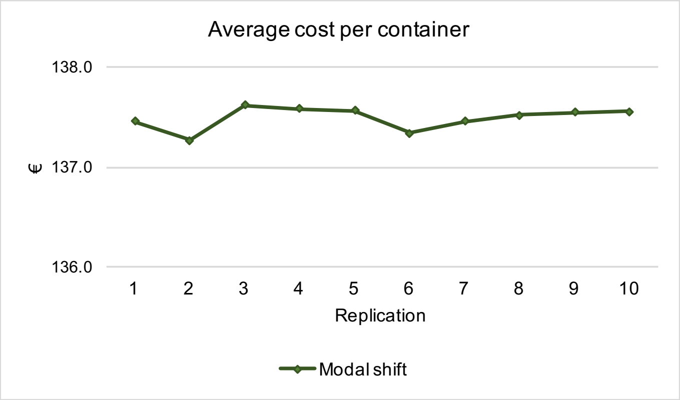

Figure 37 Simulation result: Modal shift scenario

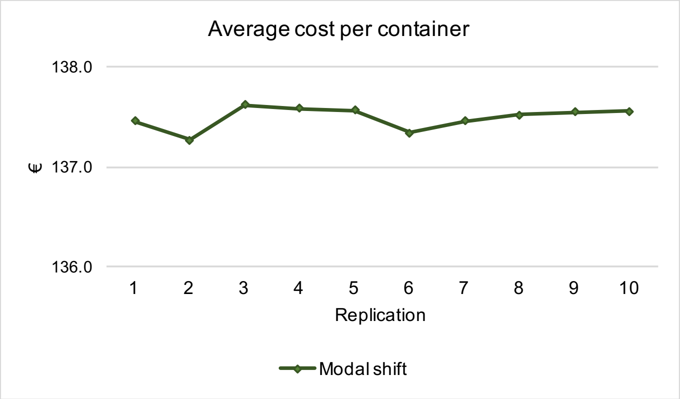

Figure 38 Simulation result: Intermodal scenario