Break-even calculations on containerized barge hinterland shipping

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Award date:
2014
Break-even calculations on containerized barge hinterland shipping

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BSc Industrial Engineering — TU/e 2012
Student identity number 0635378

in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

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Series Master Theses Operations Management and Logistics

Subject headings: inland navigation, container, network, multimodal transportation, process industry
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Abstract

This thesis describes a new modeling approach to identify a possible modal shift to barge. Based on an analysis of the cost structure of intermodal barge transportation, two different scenarios are examined, a dedicated barge connection and a shuttle to high volume hub connection. For both scenarios a mathematical model is developed, which can be used on a set of shipments to obtain the optimal transportation plan. The models show that a modal shift can be attractive on short distances, as long as the required volume is available. A case study was conducted for a chemical company to assess the cost-effectiveness of a modal shift to barge. Results of the case study demonstrate that with current volumes a modal shift to barge is attractive for the shuttle to high volume hub scenario. For a dedicated barge scenario it is shown that additional volume has to be obtained from the industry along the waterway, or from shippers in the vicinity of the shipper. For both a mathematical expression is formulated to obtain required volumes.
Management summary
In this report the results of the master thesis on the third 4C4Chem BUNDLE subproject are presented. The 4C4Chem subprojects are aimed at investigating the possibilities of cross-chain collaboration in the chemical industry, initiated by the Dutch Institute of Advance Logistics (Dinalog). Cross-chain collaboration is active cooperation between parties which are on the same level of the supply chain (possible competitors) as well as firms operating up or downstream (for example a transporter). This master thesis project was carried out at Dow Chemical in Terneuzen.

Problem statement
The chemical industry currently ships most of its European destined cargo by truck. Due to an expected truck driver shortage, increased congestion and stricter legislation regarding truck transport, it is expected that trucking will become more expensive in the future. Changing the mode of transportation is generally seen as the best way of coping with these issues, especially as the chemical clusters are located near the main waterways connecting Western Europe. Intermodal barge transportation was typically seen as cost-effective for containerized shipments on distances over 500km, but recent examples have shown that if a sufficiently high shipment volume can be guaranteed, barge transportation can be attractive on much shorter distances. It is however unknown which factors influence the attractiveness and what the required volume is.

Transportation model
To investigate a possible modal shift, first both direct trucking and intermodal barge transport are described. Two different intermodal barge transportation scenarios are identified. First, a dedicated barge from origin to one or multiple inland terminals, secondly the shuttle to high volume scenario, where a dedicated barge travels to a single hub, from where containers are transshipped to high volume barge connections to the hinterland. Several main cost components are distinguished:

- Inventory holding and container cost, which are time-dependent
- Drayage (post-haulage) cost, are, which are distance-dependent
- Handling costs, which are fixed per shipment
- Dedicated barge costs, which depend on distance and the total amount of shipments
- The high volume barge connection cost, which only depends on distance

From these cost structures, a mathematical model is derived which calculates the optimal savings a modal shift to one of the intermodal scenarios can bring. The model shifts shipments to an intermodal connection, via one or multiple inland terminals. The result of the model is an optimal set of shipments which should be transported by barge, if the total savings are positive. In case of negative savings, the volume is insufficient and the outcome can be used to calculate the required volume for certain destinations.

Numerical Analysis
The numerical analysis serves two purposes, first a sensitivity analysis is done to investigate the relative importance of cost components and secondly to identify which scenario performs better in which case. For the numerical analysis a break-even formulation is used, derived from the model. This formulation can be used to see relations between cost components and volumes without routing effects of the model. The sensitivity analysis shows that apart from the crucial volume, handling costs are responsible for a large portion of costs. A reduction of the handling costs rapidly reduces the required volume for a positive business case. Furthermore, the distance from origin to customer and inland terminal to customer have a strong effect. The further away a customer is located from the origin, the lower the volume required for a modal shift, as long as the drayage distance stays within 100 kilometers. Time-dependent costs play only a minor role. It can be concluded that a shuttle to high volume hub scenario requires lower volumes than a dedicated barge scenario.
Case study

Historical data of Dow Chemical has been used for a case study, to assess the viability of a modal shift to barge and to identify the required volume for a modal shift. First, a set of shipments qualifying for a modal shift was determined, which resulted in the exclusion by the following criteria; geographical area (only a specific region is used), business group (some do not ship by truck), packed products shipments (due to uncertainty of customer acceptance) and lead-time (rush orders have a lead-time which is too short for barge transport). From the remaining shipments, a minimum shipment level was determined per week. This volume was then used as demand in the model.

The dedicated barge scenario yielded a negative saving, indicating that current and near-future volume is insufficient, thus confirming expectations. In order for the dedicated scenario to become attractive, a shipment increase of approximately 4-10 each week is required, depending on the destination and product. The shuttle to high volume hub had a positive resulting saving of approximately 18% per shipment. The dispersion of customers has little effect on the shuttle to high volume hub, as the high volume connections are already in place to every terminal. With a guaranteed shuttle connection, it is possible to shift more volume to an intermodal scenario. With average volume, the average saving per shipment can go up to 20%, with total savings more than doubling.

The service performance of intermodal transport has also been investigated. The effect of low and high water is not expected to cause any major problems, as utilizations will not be very high, hence height and draft restrictions are not applicable. The effect of delays is fairly small, as barge schedules include (unanticipated) waiting times. Furthermore it is recommended that a dual mode transport method is adopted, where both truck (to cope with variability) and barge transport are used.

Recommendations for Dow Chemical

1. **Do not open a dedicated barge connection, but do identify additional volume for intermodal barge transportation.**
   
   For a dedicated barge connection, the volume available is insufficient. Dow should assess whether it can find partners willing to collaborate on a dedicated barge connection to the hinterland. The volume missing is, depending on the destination, about 10 to 15 shipments per week.

2. **Identify possibility of combining the current barge connection to the ports of Rotterdam and Antwerp with the shuttle to high volume scenario.**
   
   The shuttle to high volume hub scenario is attractive for the current minimum volumes. It is recommended that the possibilities of combining marine packed cargo towards the deep-sea ports can be combined with intermodal volume towards the hinterland. A combination of volume will reduce the cost of the shuttle per container, resulting in both lower costs for the marine packed cargo, as well as for the volume destined for the hinterland.

3. **Perform an operational analysis on barge intermodal transportation for a single business**
   
   Current transportation practice does not include barge transportation. Even if barge transportation is not implemented in the near future, it might very well be implemented in a later stage, due to the expected increase of trucking cost caused by a shortage of truck drivers. Therefore it is recommended to assess operational requirements for barge transportation.

4. **Explore trimodal options.**
   
   From meetings with the barge operators, it became clear that intermodal transport should embrace both rail and barge, hence enabling trimodal options. In trimodal transport, after a first non-road movement, another non-road movement may follow. This may lead to a sharp increase
in volume qualifying for a modal shift and poses a new way of serving the Eastern European market.

Preface
This report marks the end of my Master thesis project and concludes my Master Operations Management & Logistics at the Eindhoven University of Technology. This thesis was conducted at Dow Chemical in Terneuzen.

I would like to thank my four supervisors for their help during my project. My first supervisor from university, Jan Fransoo, has been an inspiring guide throughout the project and was able to give me the little push whenever I needed it. I am very glad Jan had this project for me. Although we did have less contact than I originally expected we would have, I could always get an answer from Jan when needed. Secondly, many thanks to Tom van Woensel, who was able to show me another approach to the problem, which proved to be the solution for my project. I would like to express my gratitude also to Al Ribes, my first supervisor from Dow Chemical, who tested me on my reasoning, which seemed to be so straightforward to me, but required some more explanation. Finally, I would like to thank Peter van Egerschot, who has proved to be an amazing source of information, but was also able to bridge the academic and business side of the project.

I am grateful that so many other people, both from Dow or from other companies, contributed to this thesis, either with interesting meetings, datasets or other information. Especially within Dow, I have felt welcome since the day I came in and I hope I may let other interns feel similar in the next years.

Although I have not been in Eindhoven many times, the support from friends has always been very valuable to me. Whenever I arrived at the university on a Friday, I was amazed by the interest of so many students in my project. It is a pity that my time in Eindhoven is now over, but a new, promising, life in business waits.

Last, but not least, I would like to thank my family for their continuing support throughout my life as a student. Without my parents and my sisters, I certainly would not have become what I am now.

Tom Henkens
1. Introduction

In this report the results of the master thesis regarding the Bundle subproject of 4C4Chem is presented. The 4C4Chem project is aimed at cross-chain collaboration in the chemical industry, initiated by the Dutch Institute for Advanced Logistics (Dinalog). The Bundle subproject aims to investigate the possibilities of a modal shift towards barge transportation for the chemical industry.

1.1 Problem statement

The chemical industry ships the majority of its European destined shipments by truck and a small fraction, around 15% of tonnes-lifted, intermodal (European Commission & others, 2009). Cargo transported by barge goes typically to the ports of Antwerp and Rotterdam, from where it is shipped to its destination by short-sea or deep-sea. In the future, it is expected that trucking will become more costly, as a skilled driver shortage will occur, carbon emissions legislation will become stricter, bulk trucks are becoming scarcer and congestion will increase (McKinnon, 2007).

These problems can be alleviated by a variety of measures, but truly coping, especially as a shipper, with these issues will be difficult. For example, the driver shortage may become less, if the EU allows increased maximum vehicle gross weights, or if the trucking sector increases the shortage awareness. The carbon emissions of new trucks will decrease due to EU legislation and technological progress of truck manufacturers, but the older more pollutant trucks will remain on the road. These older trucks may however see restrictions from the European Union, such as restricted areas, reducing their usefulness.

A shift towards other modalities, such as barge transportation, is therefore desired (McKinnon, 2007). Trucks can then be used for destinations, which cannot be reached by other modes, when a certain speed is necessary and/or to cope with variability in demand or transportation time. In some other sectors, there are examples where shippers actively collaborate to make barge connections cost effective (EPCA, 2007). Although some in-house studies have been done to investigate a modal shift towards barges, all known studies have stranded due to higher costs and reliability considerations. These studies were however carried out with two limitations, first, only a single shipper was considered, and second, current practice would remain similar, hence no intermediate storage of products was included and no guarantees concerning volumes of shipments.

Intermodal transport is typically regarded as an attractive alternative on long distances compared to trucking. The cost per kilometer of a barge is lower than for a truck, but intermodal transportation requires multiple vertical movements, making it more expensive on short distances. (Kim & Van Wee, 2011)

Recent research has shown that barge hinterland shipping can be made cost-effective on short distances if the freight flows are large enough (Van Rooy, 2010), (Groothedde, Ruijgrok & Tavassy, 2005). Unfortunately, just shipping larger quantities is typically impossible, as most customers can only accept a limited amount of products due to inventory constraints. A possible solution to the inventory constraints, is storing additional products in a hub or port. These so-called intermediate storage locations or floating stocks can make larger (but less frequent) flows possible. Intermediate storages will also help to alleviate any transport disruptions, improving reliability of transport.

Another way of increasing flows is by collaboration between multiple shippers. The chemical industry is organized around a set of clusters, mostly sited along inland waterways for easy delivery of feedstock material (Ketels, 2007). Due to this clustering, large flows of freight exist between only a small set of locations, making bundling of volumes attractive. Calling at multiple shippers and inland terminals does however lengthen the transit time of the cargo, increasing the costs of inventory in transit.

Collaboration between shippers can be made much easier, if the chemical industry adopts industry commodity standards, making products interchangeable between companies. The research of Klawer
(2013) shows that in a commodity setting, collaboration between shippers has a beneficial effect on the total supply chain costs. Commoditization makes smarter transportation possible, as orders can be fulfilled by a competitor, due to its more favorable location closer to the customer. This virtual pooling of products is however impossible for differentiated products. Fortunately, the research shows that physical bundling of transportation is another main driver of the expected cost reduction. This holds a promise for the bundling on hinterland barge transportation of containerized products.

Furthermore, to reduce costs of barge transportation, shippers can offer a load on the return journey. This will reduce the time a barge is moving without a load, hence improving utilization for the barge operator and will likely reduce the cost per shipment for the shipper.

These three concepts may provide the solution to the lacking cost effectiveness of barge hinterland transportation for the chemical supply chain. In order to show what the effects of these concepts are, insights have to be obtained of the cost structure of intermodal transportation. This leads to the following research question.

Which factors determine the attractiveness of intermodal barge transportation of containerized products for the chemical industry, is a modal shift to barge transportation currently attractive for the chemical industry and what can shippers do in the future to improve this attractiveness?

The remainder of this chapter consists of a short introduction given on the used methodology and a general description of the chemical industry and the transportation of its products. This section is concluded with an outline of the reminder of the thesis.

1.2 Methodology
The model of Mitroff et al (1974) (cf. Fransoo & Bertrand, 2002) is used to structure the research, by dividing the research into different phases. The model shows the relationships between the different phases.

![Figure 1: Research Model from Mitroff et al. (1974)](image)

In the conceptualization phase a conceptual model of the problem is drawn. This requires decisions on the relevance of certain aspects, furthermore decisions regarding the selection of variables added to the model have to be made. The conceptual model represents an abstraction of reality and is capable of generating one or more scientific models.
The modeling phase consists of the composition of a quantitative model, in which causal relationships between variables are defined. This quantitative model is a formal representation of both reality and the conceptual model, in the shape of a scientific model.

In the model solving phase the scientific model is used for a case study at a chemical company. The output of this phase is the solution, which is the starting point for conclusions and recommendations.

The implementation phase consists of the conclusions and recommendations, linking the solution back to the reality.

Two other relations can be seen in the model. First, after the scientific model is made, a validation takes place to assess the correspondence of the model with reality. Secondly, feedback in the narrow sense can be obtained from comparing the conceptual model with the solution.

1.3 Transportation in the chemical industry
The chemical industry produces many different products, which are mostly used as intermediates for the manufacturing industry. Products have to be transported from chemical plants to manufacturing plants. Transportation of chemicals is mainly determined by the nature of the product in three ways; whether it is bulk or packaged, its physical form and if the product is hazardous. In addition to the nature of the product, transportation is also affected by the amount of product ordered and its destination.

First, products can be categorized as bulk or packaged material. Bulk material is all that is not transported in a package, such as a cylinder, bag, box or drum. This implies that bulk can be transported in a container, but also in bulk trucks, rail tank cars and (parcel) tanker vessels, depending on its destination. Packaged material is placed in a container or regular truck for transportation, also depending on its destination. Throughout this thesis, with a container, the actual ISO-standard container is meant, and not containers as something that can contain a product, such as a bag or box. An ISO container is available in multiple sizes, but throughout this thesis the 20ft size is used.

Secondly, the products can be distinguished among their physical form, which can be gas, liquid or solid. The physical form strongly determines by what sort of mode it can be transported. Solid materials are also referred to as dry material and are typically in pellets or granules. Dry bulk is rarely transported in quantities greater than the amount that fits in a dry box container. Liquids and gasses are on the other hand frequently transported in quantities larger than a single container load, as both liquid and gas-phase products are often used as feedstock.

Third, some products are regarded as hazardous material (hazmat). Hazmat is classified in 9 different classes, indicating which required precautionary measures should be taken. The classes are; explosives, gasses, flammable liquids, oxidizing agents and organic peroxides, toxic and infectious substances, radioactive substances, corrosive substances and miscellaneous. Due to the nature of some hazmat products, they are not allowed to be transported at all, or not allowed to be transported by some modes.

In addition to the nature of the product, the volume in which it is ordered determines the type of transport mode. Feedstock products are required in large quantities, hence are typically transported by large volume modes, such as pipeline, rail tank cars and tanker vessels. Orders of packaged material are typically ordered in one full truck load (FTL), or even less than truckload (LTL). Commodities are typically ordered in bulk and large quantities, whereas specialized products are ordered in smaller quantities and more likely to be packaged.

The final factor that determines transportation is the geographical location of origin and destination. Destinations for feedstock, which are not near sea or inland waterway, can only be supplied by rail.
tank car or pipeline. If origin and destination are relatively close to each other, then transport is typically done by truck. The geographical factor strongly determines the cost of transportation.

1.4 Thesis outline
The thesis is divided into the following sections. First, in section 2 current transportation practice is discussed and two possible intermodal scenarios are explained, following by the translation of the conceptual transport model into a mathematical model. In section 3 the data collection and analysis is given, which is used to do a numerical analysis of the models in section 4. Section 5 gives possibilities to improve the attractiveness of the modal shift towards barge. Section 6 contains an application of the model on a case study conducted at a chemical company. Finally section 7 contains the conclusions and recommendations.
2. Transportation model

This chapter contains the model with which feasibility of barge transportation of containers from a shipper to the hinterland can be determined. The first section elaborates on the current practice of road transportation in the chemical industry. In section 2.2 the conceptual model is discussed, which explains how shipments are transported inside an intermodal network. The different cost components of the transportation of shipments are discussed in section 2.3. The cost structure is translated in two mathematical models for a dedicated barge scenario and a shuttle to high volume hub scenario in section 2.4 and 0 respectively.

2.1 Truck transport

Most (non-commodity) shipments by the chemical industry to customers within approximately 500 kilometers are transported by truck. As many chemical companies do not own a fleet of trucks, the delivery of their products is outsourced to transport companies, also referred to as transporters or carriers. Although the chemical industry is fairly clustered, customers of the chemical industry are more dispersed. Manufacturing companies typically do not have the same economies of scale as the chemical industry and benefit thus less from integrated plants, where multiple stages of production are located on a single site.

Chemical companies distribute their products typically to a large set of customers. This gives great complexity to the cost calculation of transport, as there are many possible combinations of origins and destinations, therefore tariffs for transport are asked for sets of customers, located in a similar region. This procedure is called tendering and happens approximately once every 1 to 3 years. The benefit of the region-based approach is twofold, first it reduces complexity and second it increases the volume for tendering, strengthening the position of the shipper.

Transportation of products depends on the factors discussed in section 1.3. The focus of this thesis is, as discussed in chapter 1, on barge transportation, thus only products that can be shifted towards intermodal barge transport will be discussed. Intermodal barge transportation requires products to be placed in a container. Packaged products, both liquid and solid, are transported on pallets, which can be placed in a regular truck or in a container. Liquid bulk is either transported by a tank truck or by a truck loaded with an ISO-tank, which is a 20ft container frame with a tank inside. Solid bulk is mostly transported in silo trucks, but can also be transported over road by using a regular dry box container with a liner placed inside the container. Both packed and bulk products can thus be transported by barge, as long as the size of the shipment is small enough to fit inside a container.

Transportation of packed goods starts with the bagging or drumming of products. Filled bags or drums are placed onto pallets, which are placed inside the truck/container immediately or first stored in a warehouse for some time and then placed inside a truck/container. The filling of bags and drums is typically an automated process, whereas the loading of the pallets on to trucks is not. Storage and packaging of products is sometimes on site of the shipper, but can also be at a third-party storage facility. After the securement of the loaded products, the driver can drive towards the customer, where pallets are unloaded. Truck unloading can be done from the side or if a dock is available from the rear.

The transport of bulk starts with the arrival of the truck at site, where sometimes the truck its (ISO or fixed) tank or silo has to be cleaned. With a clean tank or silo, drivers place their truck underneath a loading station, from where the product is loaded into the truck. After the product is loaded, the truck drives to the customer, where the product is unloaded. Unloading of bulk products sometimes requires additional handlings, such as blowing or tilting. Loading of a container with dry bulk first requires the placement of a liner within the container.

In essence, for both packed and bulk transportation the structure is similar. In both cases some handling is required before the truck movement. At the end of the truck movement again some
handling is required when unloading the product. Transportation directly by truck, which is displayed in Figure 2, is referred to as the base case scenario, and will be used to compare intermodal transport to.

![Figure 2: Structure of direct truck transport](image)

2.2 Intermodal transport

Intermodal transportation is characterized by one or multiple non-truck movements between origin and destination. Because shipments need to be transferred between modes, a single unit of transportation is used, the container. The point where the container is transshipped from the barge or train to the truck is the inland terminal. As discussed in the introduction, the focus lies on the modal shift towards barge, therefore rail is not taken into account. Two different scenarios of intermodal barge transport are evaluated, first the dedicated barge to the hinterland, and secondly a dedicated barge (the shuttle) to a nearby barge terminal from where a high volume barge departs for the hinterland.

The first scenario, in which a dedicated barge travels from the site to one or multiple inland terminals, is defined as the dedicated barge scenario. This scenario has a longer lead-time and includes more handlings than direct truck transport. The advantage of the dedicated barge scenario comes mostly from the barge movement, which is generally more cost-efficient per shipment, per kilometer, than a truck, especially if the barge has a high utilization. A disadvantage of this scenario is that there is no existing barge connection, causing the required volume for the barge to be obtained purely from volumes which were previously trucked.

![Figure 3: Graphical representation of dedicated barge scenario (left) and shuttle to high volume scenario (right)](image)

The second scenario is the shuttle to high volume scenario, in which to a nearby inland terminal is shuttled, where the high volume barges stop on their way to the hinterland. These barges originate from the deep-sea terminals and have very large capacities. These large barges have some advantages, such as the high frequency of barge departures and the existing network reaching even the farthest inland terminals and their low cost per container due to higher volumes. The disadvantage is that additional handling is required, as the container has to be unloaded from shuttle to a barge terminal and afterwards loaded onto the high volume barge. In addition, there might be some unexpected waiting time involved, especially because these higher volume barges are coming from deep-sea terminals, which tend to be a source of variability in barge transportation. This variability comes from the fact that deep-sea vessels and barges are served by the same cranes, which tend to give precedence to the larger vessel, which usually is the deep-sea vessel.

There are two options of travelling to the high volume hub, either by barge or by truck. From recent examples, it follows that on short distances barge transportation can be more efficient than trucking, if volumes are high enough. As the geographic dispersion of freight destinations is not an issue in the
shuttle to high volume hub scenario, it is expected that these high volumes can be obtained. Therefore, in this thesis the shuttle to the high volume hub is also a barge.

2.2.1 Structure of transport chain
The transport of a single shipment consists of a set of components, displayed in Figure 4 and Figure 5. The figures are made from a time-perspective, where arrows represent duration of a component of the transport. Solid arrows also imply a movement, where dashed arrows are not related to a movement, but with storage. The vertical lines and boxes represent a handling. The length of any arrow is not representative for the duration of movement of storage.

Figure 4: Structure of dedicated barge transport

The first intermodal scenario described in the previous section, concerns a dedicated barge connection from the terminal near the site to one or multiple terminals in the hinterland, from where multiple customers are served by truck. For simplicity reasons Figure 4 only contains a single loading and unloading terminal as well as a single origin and customer.

The sequence of intermodal transport is as follows; first the shipment is loaded in a container on site, from where the loaded container is driven to the barge terminal. At the barge terminal, the container is unloaded from the truck and placed in the container yard, where the container is stored until it is placed on the barge. After all containers are loaded onto the barge, the barge travels to the hinterland inland terminal, where the containers are unloaded and placed into the yard again. Containers may have to wait a few days for the agreed delivery date, the time the container spends in the container yard is referred to as detention. The final delivery to the customer by truck is called drayage.

Figure 5: Structure of shuttle to high volume inland terminal transport

The second intermodal chain is the shuttle to a high volume hub scenario, displayed in Figure 5. This transport chain is characterized by an additional transshipment terminal between loading and unloading terminals. After the container is loaded on the first barge, the barge travels to the high volume hub, where the container is unloaded, stored for some time and then placed on the high volume barge. This barge travels to the hinterland inland terminal, from where everything is similar to the dedicated barge intermodal scenario.

2.2.2 Assumptions
Some assumptions are made to describe the process of truck and intermodal transportation.

1. Direct truck transport means a movement by truck from origin to destination without any additional handlings in between. This also implies that a direct truck movement does not include other modes of transport. In reality the carrier may occasionally place the container on a train or barge, without the shipper knowing. However, intermodal is typically seen as unattractive on short distances, thus it rarely occurs that other modes are used than truck. In case this assumption does not hold, especially on short distances the cost estimates will be off, rendering the model less useable.

2. The delivery and pickup of the container at the site or customer are outside the scope. A container is required for intermodal transportation, it is however impossible to obtain information on the delivery of the container to the site, or from its destination onwards. The cost of container delivery is
likely to be related to the customer density of the container operator. It is expected that only very small variations are present, hence a violation of this assumption has little effect. A large difference in container delivery costs, would affect the model strongly, as certain areas become more costly than others. In this case the delivery should be explicitly modeled in the handling of a shipment.

3. Inventory and production of products are not in scope and never constrain transportation. This ensures that shipments can be transported earlier in intermodal transport compared to truck. In practice production and inventory may pose constraints on transport, but if shipments have to be transported earlier, planning will take this into account. If products cannot be completed in time for an intermodal transport, this would render intermodal transport impossible.

4. Only products that can be/are containerized are in scope. This implies that products that are transported only by bulk rail and bulk vessels are excluded. In practice, transportation of these products is rarely combined with transport of containerized products. There are some examples of barge transporting dry non-chemical bulk, such as sand, and containers simultaneously. Inclusion of these combinations could reduce barge costs, but requires are shipper of the specific types of dry bulk.

2.3 Cost structure

In order to determine whether an intermodal scenario is a feasible option, a comparison has to be made between the base case scenario, where every shipment is transported by direct truck, and both the intermodal scenarios. Comparing these scenarios is however not that straightforward, as many players are involved. Just asking for prices at the different involved companies will not result in a good study, as costs are interrelated and also affected by shipment volumes and commitments. For a feasibility study ideally all margins of the involved parties should be removed, so that the total chain cost is determined. The total cost of the chain can then be compared to what the current cost is, showing a possible potential saving. The eventual benefits can then be shared among parties.

Figure 6: Dedicated barge transport

2.3.1 Direct truck transport

Bulk transport by truck is mostly done in tank or silo trucks. For these trucks a cost structure is known from the NEA reports (NEA, 2004), (NEA, 2012), but the costs in those reports do not exactly fit the prices the chemical industry sees. The explanation for this can be found in the purpose of the NEA reports. These reports are made as benchmark for transporters, for which the entire route is known. The shippers see only the part from the origin of the shipment to its destination. Before the truck arrives at the pick-up location, an unknown distance is driven. This distance is charged to the previous and next customer. The cost of direct trucking is composed of a time-dependent part and a distance-dependent part. The time-dependent part covers for example the cleaning and loading and unloading time of the truck. For liquid bulk the time dependent costs are higher, as tank cleaning is more costly for liquids transportation than for dry bulk transport.

2.3.2 Barge transport

The defining aspect of an intermodal transport is the part where the cargo is transported by another mode than truck. Barges come in many varieties, but in this thesis the focus is on only two types. The

---

1 Original picture is from Waardevol Transport by Bureau Binnenvaart Voorlichting, adapted by the author of this thesis. Report can be found on: [http://www.bureauvoorlichtingbinnenvaart.nl/pageflip/2013/NL/pageflip/](http://www.bureauvoorlichtingbinnenvaart.nl/pageflip/2013/NL/pageflip/).
medium sized Rijn-Herne class, which has a capacity of 96TEU and the large Groot Rijnschip class, which can hold up to 196 TEU. A third type, the small Kempenaar class barge, capable of holding 24TEU, is also widely used; however this barge type is not suitable for covering large distances over the main waterways. In practice these barges are used to travel through narrower canals. For the shuttle to high volume scenario, the Kempenaar class can be attractive, as the distance from origin terminal to hub is very small.

Chartering a barge has a variable fuel cost, determined per kilometer and a daily cost. Daily cost of a barge consists of many factors, such as cost of the crew, depreciation, repair and maintenance. The smaller barges are typically operated by a family and can only be operated for 16 hours a day. The larger barges have a crew on board for a limited amount of time, hence can be operated round the clock. The fuel cost of a barge is approximately 40% of the cost, depending on the route and schedule of the barge. For example, barges travelling upstream demand much more fuel than downstream. The load and velocity of the barge also have a high impact on fuel consumption. Fuel consumption ranges from approximately 70 to 150 liters per hour.

2.3.3 Container handling
Another defining cost component for intermodal transport is the vertical movement, or handlings, at both the start and end of the barge leg. The beginning of the barge leg would be at the container terminal near the site of the chemical company, whereas the end is the inland terminal where the container is unloaded from the barge.

Site
The handling of a shipment at the start of the transportation, depicted in Figure 7, can be separated in three components. The handling at the site, where product is placed in the container, the movement from the site towards the container terminal and finally the handling at the container terminal, where the container is possible stored and loaded onto the barge.

The first component on the site requires first the placement of a container from the yard onto a chassis. Then the chassis with container is driven to the loading site, from where desired cargo is transferred from a warehouse, tank or silo to the container. Then the chassis is driven to the yard again and could be unloaded from the chassis, or the container can be driven to the container terminal immediately.

If the loaded container is placed in the container yard, the second component includes the loading of the container again on a chassis and the actual movement from the site to the container terminal. There the container is unloaded to the container yard. The third component is the loading of the container from the container yard by crane onto the barge.

Inland terminal
The handling of a container at the inland only includes the unloading of the container from the barge into the container yard, and the loading of a container onto a truck. Storing a container in the inland terminal is called detention and is further discussed in section 2.3.4. The cost of the inland container
terminal is likely to be comparable to those of the container terminal located near the chemical company, although prices are likely to be lower for larger, more efficient container terminals in the hinterland. The cost components of the inland terminal are the unloading of the barge and placing in a stack and in a later stage the removal of the container from the stack onto a chassis. The activities after the barge transport are depicted in Figure 8.

![Figure 8: Inland terminal handling, detention and drayage](image)

2.3.4 Detention in the inland terminal
Containers have to be stored a few days in the inland terminal before the shipment can be delivered to the customer, because a daily barge connection requires very high volumes and some safety lead-time has to be built in. This waiting time in the inland terminal is called detention and is the result of the discrepancy between the arrival day in the inland terminal and the delivery date agreed upon by the supplier and customer. The more frequent barges arrive at the inland terminal, the shorter the detention in the inland terminal. The shipment will typically be sent on the latest possible barge to minimize the detention.

2.3.5 Drayage
The movement of a shipment from an inland terminal to the customer by truck is called drayage. Inland terminals either have a small fleet of trucks that handle the truck movement to the customers, and return empty containers to the inland terminal, or have a transporter handle this for the inland terminal. The distance from the inland terminal to the customers is typically very short, hence multiple deliveries and/or pick-ups can be made during the day. Additional chassis are very inexpensive and can improve trucking performance, as the truck can deliver one shipment, while the other is loaded at the same time on another chassis. The operating time of a truck has maximum of 10 hours per day, due to driver restrictions. Due to the limited amount of driving hours and the cost structure, in practice drayage is limited to customers located up to 200 km from the inland terminal.

2.3.6 Inventory holding
Having inventory is necessary for most producing companies, however holding too much inventory is costly. Inventory is tied up capital, which has to be financed in some way. Most companies work therefore with a specific percentage, the weighted average cost of capital (WACC), to calculate the cost of holding inventory. This percentage is based on both the yearly rate of return shareholders expect and the interest rate on the various outstanding loans. Together with the cost of the product, the WACC can be used to calculate a cost of holding inventory per day.

2.3.7 Container cost
Containers exist in many different forms and sizes and are typically owned by transport companies. Dry bulk and packed cargo is placed in normal box containers, whereas liquid bulk is placed in ISO containers, which is a tank inside a frame. Containers are typically 20 or 40ft long. The 40ft containers are less used for continental transport, as 20ft can already contain the road legal maximum for most European countries. Obtaining a container can be done in many ways, but most shippers do not own containers for transportation. If shippers need to ship something in a container,
the container is supplied by the transporter. Another way of obtaining a container, is leasing one for a limited amount of time from container leasing companies.

2.4 Dedicated barge model

2.4.1 Introduction

Quantitative modeling is used to assess the attractiveness of a modal shift as well as its robustness and sensitivity to various parameters. Furthermore, the model is generic and easily scalable, making it suitable for calculating and comparing different scenarios. The model is formulated as an optimization model. Solving an optimization model will result in an optimal solution. In this case this will result in the least-cost, highest saving solution, which is desired for a business case. The model is an integer programming model, and is referred to in the remainder of the thesis as the optimization model. Solving the model can be done in various programs, but for this thesis AIMMS was used. AIMMS is a software package capable of solving various programming models.

In this section, the model is discussed in terms of the sets, parameters, decision variables, assumptions model formulation and its explanation respectively. A simple formula for break-even calculation of barge connections is given finally, which can be used to obtain fast results and perform simple sensitivity analyses. The model for the shuttle to high volume hub is discussed separately in the next section.

2.4.2 Sets

- **T**: Set of inland terminals in the hinterland
- **N**: Set of regions
- **P**: Set of product types (can be as detailed as necessary, from all products as a single product type, up to a different product type for each stock keeping unit level)

2.4.3 Parameters

- **C_{j,p}^{dt}**: Cost of transporting a shipment of product type \( p \in P \) by direct truck from origin to destination \( j \in N \).
- **C_{i,j,p}^{imD}**: Cost of transporting an intermodal shipment of product type \( p \in P \) from origin via inland terminal \( i \in T \) to destination \( j \in N \), excluding any allocated barge cost.
- **C_{x}^{b}**: Cost of barge transport roundtrip from terminal \( x-1 \), with \( x=0 \) being the origin terminal.
- **D_{j,p}**: Weekly demand of shipments of product type \( p \in P \) with destination \( j \in N \)
- **K^{b}**: Capacity of barge in shipments
- **M**: Very large number
- **s**: Departures of barge connection per week
- **r**: Barge cost coverage by return load

The three cost parameters, \( C_{j,p}^{dt}, C_{i,j,p}^{imD} \) and \( C_{x}^{b} \), are calculated using three formulas. For simplicity reasons, the detailed cost formulas are left out of the objective function. Furthermore, if better estimates (or estimation techniques) of any of these costs are available, only the underlying cost calculation has to be adapted, while the model itself will not change.

\[
\begin{align*}
C_{j,p}^{dt} & = c_{p}^{dt} t_{j,p}^{dt} + c_{p}^{dt,d} d_{j}^{dt}
\end{align*}
\]
\[ c^{y,t}_{x,j,p} \] Waiting cost per hour for drayage transport
\[ t^y \] Time spent by drayage truck waiting
\[ c^y,d \] Cost per kilometer of drayage truck
\[ d^y_{x,j} \] Drayage distance in kilometer from inland terminal \( x \in T \) to
\[ w^s \] Average detention in inland terminal when using schedule \( s = \{1,2,\ldots\} \)
\[ t^b_{0,x} \] Barge transit time in hours from origin to inland terminal \( x \in T \)
\[ c^c_p \] Hourly cost of a container capable of holding of product type \( p \in P \)
\[ h_p \] Hourly inventory holding cost of product type \( p \in P \)
\[ c^H_{p,o} \] Cost of handling a product of product type \( p \in P \) at the origin
\[ c^H_x \] Cost of handling a product of product type \( p \in P \) at inland terminal \( x \in T \)

\[ c^{imp}_{x,j,p} = c^{y,t} t^y + c^y,d d^y_j + \left(w^s + t^y + t^b_{0,x}\right) (c^c_p + h_p) + c^H_{p,o} + c^H_x \] (1.2)

\[ c^{b,t} \] Hourly cost of barge
\[ t^b_{x,x-1} \] Transit time between terminal \( x \in X \) and preceding terminal \( x - 1 \in X, x = 0 \) is the origin terminal.
\[ c^{b,d} \] Cost per kilometer of barge
\[ d^b_{x,x-1} \] Barge distance between terminal \( x \in X \) and preceding terminal \( x - 1 \in X, x = 0 \) is the origin terminal.

\[ c^b_x = c^{b,t}\left(t^b_{x,x-1} + t^b_{x-1,x}\right) + c^{b,d}\left(d^b_{x,x-1} + d^b_{x-1,x}\right) \] (1.3)

2.4.4 Decision variables
\[ H_x \] Binary variable for inclusion of inland terminal \( x \in T \) in set of passed terminals
\[ S_{x,j,p} \] Integer variable for the shipment volume of product type \( p \in P \) to region \( j \in N \), via terminal \( x \in T \), shifted to intermodal transport

2.4.5 Assumptions
1. The cost of transporting is independent of the load of a container or truck. Although in reality less than truckload shipments see lower tariffs than full truckloads, the cost only decreases slightly for smaller loads, as only the amount of fuel is dependent on the load. In addition, the chemical industry rarely ships less than truckload shipments, hence the implications of this assumption are limited. If the transporters introduce a tariff strongly dependent on the load, an additional load parameter should be used in the model, adjusting the cost of a shipment. Otherwise, the cost of less than truckload shipments will be overestimated, resulting possible in a false-positive outcome.

2. The inventory cost per day is equal per product type and is stable throughout the chosen time period. The cost of inventory depends on the weighted average cost of capital (WACC) and the cost of the product. The WACC is a very stable figure, as the financial structure of large companies can only change slowly over time. The cost of products fluctuates during a year, fluctuations on a weekly level are however small. Therefore the assumption of a stable inventory cost throughout the week has minor implications. If fluctuations are heavy, the
costs will still be representative, however on a longer term the results are not as valid, as the values may change.

3. Terminals work 24 hours per day, 365 days per year. This assumption holds for the larger terminals. The smallest terminals are only operating on workdays from early morning till the evening. Most terminals are 6 days a week operational and have wide opening hours per day. This assumption places the timing of arrivals is out of scope. If terminal service windows are smaller, additional planning has to be used to ensure arrival at the terminal when it is open, introducing some waiting time. This can however be offset by slower barge travelling, reducing financial impact.

4. Barges can operate 365 days a year, the amount of operating hours per day depends on the size of the barge. This assumption makes sure that during transport, days off can be ignored, hence a movement is uninterrupted. Barge may not operate 365 days per year, but if a barge is not available, another barge can takeover. If this assumption is violated, barge costs are not representative anymore, and should be corrected accordingly.

5. Inland terminals have ample capacity for handling barges, hence barges never have to wait for unloading upon arrival. This assumption implies that barge waiting time can be excluded from the analysis. If utilization of inland terminals starts to reach more critical levels, the schedule has to be adapted, in order to correct for waiting time. If this is not done, the cost of the barge will become lower than in reality, resulting possibly in the rejection of positive outcome.

6. The container is paid for until the delivery at the customer. This is similar to the current practice for ISO tank deliveries, where the container operator is responsible for the container after delivery at the customer.

7. The inland waterway has no terminals on branches of the waterway. This ensures that cost calculation of routing is possible, by using distances between each subsequent terminal. If a terminal is located on an inland waterway, this would render the use of adding the subsequent distances impossible. In Figure 9 this effect can be seen clearly. The upper diagram shows three terminals, represented by the circles, on a waterway. The distance between the first and second terminal is represented by A, the distance between the second and third by B. Because all terminals are along the same waterway, the distance between the first and third terminal C is equal to the sum of A and B. When the second terminal is situated on a branch, one can immediately see that C is not the sum of A and B, but less.

In reality, not all inland terminals are situated on the banks of the main waterway. Some are located a short distance away, however these small errors in distances will not severely
impact the outcome. Large branches, especially with multiple inland terminals should be modeled as separate waterways.

8. Demand is corrected for rush orders, hence the volume can be satisfied within the longer time window of the intermodal transportation. If this is not done, volumes available for intermodal transport are higher, possibly resulting falsely in a negative outcome.

2.4.6 Model formulation (dedicated barge)

Maximize:

$$\sum_{x \in T} \sum_{j \in N} \sum_{p \in P} (C_{j,p}^{dt} - C_{x,j,p}^{imD}) S_{x,j,p} - r \cdot s \sum_{x \in T} C_x^b \cdot H_x$$

Subject to:

$$\sum_{x \in T} S_{x,j,p} \leq D_{j,p} \quad \forall j \in N, \forall p \in P$$

(1.5)

$$S_{x,j,p} \leq M H_x \quad \forall x \in T, \forall j \in N, \forall p \in P$$

(1.6)

$$\sum_{x \in T} H_x \geq 1 \quad \forall x \in T$$

(1.7)

$$\sum_{x \in T} \sum_{j \in N} \sum_{p \in P} S_{x,j,p} \leq s K^b$$

(1.8)

$$H_x \geq H_{x+1} \quad \forall x \in T$$

(1.9)

$$S_{x,j,p} \in \{0,1,2, \ldots\} \quad \forall x \in T, \forall j \in N, \forall p \in P$$

(1.10)

$$H_x \in \{0,1\} \quad \forall x \in T$$

(1.11)

2.4.7 Explanation of model formulation

(1.4) The objective function maximizes the savings of intermodal transportation minus the costs of the barge connection, corrected for the return loads.

(1.5) This constraint forces the total flow of a product to a certain destination to be as large as the total demand for this specific combination.

(1.6) Implies that a flow via a hub is only possible if that hub is used.

(1.7) Forces at least one hub to be used, ensuring that even if intermodal transport is not cost efficient, a solution can be obtained. The savings, although negative, can be used to determine the necessary volume from other sources.

(1.8) Forces the total volume to be transported to be smaller than the capacity of the barge connection.

(1.9) Ensures that all hubs are used up until the last used one. This implies that the distances between hubs can be used for the total distance.

(1.10) Integer constraints on the flow of products from origin via hub to destination

(1.11) Binary constraint on the hub usage.

2.4.8 Break-even formulation

The integer programming problem calculates the least-cost solution for a given set of volumes. It cannot be used to obtain information on the required volumes for barge transportation to become
cost effective. A simple formula is therefore derived to identify which regions are more promising than others. The formula can give the break-even quantity for any combination of inland terminal, destination and product. The sensitivity of the model to parameters can also be tested using this formula. It follows from the objective function 1.4. The cost of the barge to a certain inland terminal, is in the numerator of expression 1.12. The barge cost has to be covered by the savings obtained from shifting from direct truck to intermodal transport. This saving is calculated in the denominator of formula 1.12. The result is a break-even volume (in shipments) is denoted as $B_{E_{x,j,p}}$, where $x \in T, j \in N, p \in P$.

$$B_{E_{x,j,p}} = \frac{r \sum_{a=1}^{x} C_{a}^{b}}{C_{x,j,p}^{dt} - C_{x,j,p}^{imp}}$$

(1.12)

The break-even volume does however not automatically satisfy all constraints of the mathematical model. First, the break-even volume has to be a non-negative integer value (follows from constraint 1.10), and secondly it has to satisfy the barge capacity constraint (1.8). The break-even volume has therefore to be rounded up to the nearest integer. In addition, the following constraint has to be satisfied, otherwise there is no feasible solution of the IP possible.

$$0 < B_{E_{x,j,p}} \leq K_{a}^{b}$$

(1.13)

In the numerical analysis in section 4.1, the result of the break-even formulation is validated with the model, showing that if the result of the break-even formulation (1.12), is used as $S_{x,j,p}$ in the IP, the result of the model is a resulting saving of zero or slightly higher (due to rounding).

2.5 Shuttle to high volume hub

2.5.1 Introduction

For the shuttle to high volume hub, the model of the dedicated barge is adapted. The structure of the model is kept intact, keeping the outcomes comparable. As the shuttle can only go to a single hub, the routing variable $H_{u}$ can be removed from the model. Although a single routing variable could be included for the shuttle, the model has to be forced to open at least one barge connection, so that even a negative optimal saving can be obtained. There would however be only one routing variable, hence it is easier to remove both the forcing constraint and the routing variable for the hub. The cost parameter for the barge is then a constant in the objective function and can be removed, as it has no effect on the decision variables. It is chosen to keep the constant cost however in the model, as it will result in a negative saving if volumes are insufficient, which can be used for volume requirement calculations afterwards.

Some other constraints are removed due to the absence of the routing variables. The cost of intermodal shipment is also changed, including both the cost of barge transport from the hub toward the inland terminal, as well as the additional handling.

The remainder of this section is similar to the previous chapter, discussing respectively the included sets, parameters, decision variables, assumptions, model formulation and its explanation. Again a break-even formula is given for simple insights.

2.5.2 Sets

- $T$ Set of inland terminals in the hinterland
- $N$ Set of regions
- $P$ Set of product types

2.5.3 Parameters

- $C_{i,p}^{dt}$ Cost of transporting a shipment of product type $p \in P$ by direct truck from origin to
destination $j \in N$.

$C_{x,j,p}^{imSH}$ Cost of transporting an intermodal shipment of product type $p \in P$ from origin via inland terminal $x \in T$ to destination $j \in N$, excluding any allocated barge cost.

$C_N^b$ Cost of barge transport round-trip from origin terminal to the hub.

$D_{j,p}$ Weekly demand of shipments of product type $p \in P$ with destination $j \in N$

$K^b$ Capacity of barge in shipments

$s$ Departures of barge connection per week

The three cost parameters in the model are calculated using the following formulas. First, the parameters where the cost functions are based on are given.

\[
C_{j,p}^{dt} = c_p^{dt} t_j^{dt} + c_p^{dt} d_j^{dt}
\] (2.1)

$c_p^{yt}$ Waiting cost per hour for direct truck transport of product type $p \in P$

t$_j^{yt}$ Time spent by direct truck waiting destination $j \in N$

$c_p^{yd}$ Cost per kilometer of direct truck transport of product type $p \in P$

d$_j^{yt}$ Direct truck distance from origin to destination $j \in N$

\[
c_{x,j}^{yt} = c_p^{yt} t_{x,j}^{yt} + c_p^{yd} d_{x,j}^{yt}
\] (2.2)

$c_p^{yt}$ Waiting cost per hour for drayage transport

t$_x^{yt}$ Time spent by drayage truck waiting

$c_p^{yd}$ Cost per kilometer of drayage truck

d$_{x,j}^{yt}$ Drayage distance in kilometer from inland terminal $x \in T$ to destination $j \in N$.

$M_{x,j}$ Barge transit time in hours from origin to inland terminal $x \in T$

$h_p^c$ Hourly cost of a container capable of holding of product type $p \in P$

$h_p$ Hourly inventory holding cost of product type $p \in P$

$c_p^{Ho}$ Cost of handling a product of product type $p \in P$ at the origin

$c_p^{Hi}$ Cost of handling a product of product type $p \in P$ at inland terminal $x \in T$

$w^s$ Average detention in inland terminal when using schedule $s = 1$

\[
c_{x,j,p}^{imSH} = c_{x,j}^{yt} t_{x,j}^{yt} + c_{x,j}^{yd} d_{x,j}^{yt}
\] (2.2)

$c_p^{yt}$ Hourly cost of barge

t$_{0,M}$ Transit time between origin terminal and hub

c$_p^{bd}$ Cost per kilometer of barge

d$_{0,M}$ Barge distance between origin terminal and hub

\[
c_M^b = c_p^{yt} (2t_{0,M}^b) + c_p^{yd} (2d_{0,M}^b)
\] (2.3)

2.5.4 Decision variables

$S_{x,j,p}$ Integer variable for the shipment volume of product type $p \in P$ to region $j \in N$, via terminal $x \in T$, shifted to intermodal transport
2.5.5 Assumptions

All assumptions discussed in section 2.4.5 are also applicable to the shuttle to high volume hub scenario. In addition, the following assumptions are used solely for the shuttle to high volume hub model:

1. The cost of transporting the shipment from the hub to the inland terminal in hinterland is independent of the volume provided. Due to the large volumes on the high volume barges, the added volume does not imply a large volume increase, hence the fixed cost and volume risk allocation is limited. If the cost does depend on the volumes provided, the model its usefulness will be limited, as an underestimation of costs will be used. The model will not allow for a volume dependent barge cost parameter, hence an adapted model of the dedicated barge model should be used, with a fixed share of total barge cost already allocated to other shippers.

2. The cost of the transport from the hub to the inland terminal does not include additional handling compared to the dedicated barge scenario. As the major drawback of the shuttle scenario is the additional handling, this is modeled explicitly. Handling at the inland terminal is similar to the dedicated barge scenario, hence independent of barge size. Handling cost at the hub includes detention.

3. Barges depart from the hub at least once a day to every destination. This might not exactly true for the farthest and smaller destinations, but it ensures that additional waiting time can be disregarded in the model. The waiting time would only be 1 or 2 days, which is only a small increase for the shipments with the longest transit times, hence the effect is limited on the costs. For most destinations this assumption holds. If this assumption is violated, additional waiting time has to be included, similar to average detention for the dedicated barge scenario.

4. Ample capacity is available on the barge connection from hub to inland terminal, hence capacity on this connection is never a constraint. In reality the maximum capacity could be a constraint, if the current connection is already highly utilized. In that case, it is likely that the barge operator will increase the number of barge connections or use larger barges to cope with the increase in volume.

5. Only a single hub is considered from which the large barges depart. In reality multiple terminals would geographically qualify as the inland hub, however only the largest hubs will be visited by the feeder barges. Modeling-wise it is however less complicated to perform separate analyses for different hubs, than to include multiple hubs in the model.

6. There is no additional load available for the shuttle from the hub towards the origin terminal. In reality this partly true, as the chemical plants are part of integrated sites, which require mostly feedstock material delivered by high volume bulk transport, i.e. pipeline or tanker vessels. If this assumption is violated, the cost of the barge will decrease, resulting in a more positive outcome.

2.5.6 Model formulation (shuttle to high volume hub)

Maximize:

\[
\sum_{x \in T} \sum_{j \in N} \sum_{p \in P} (C_{j,p}^{dt} - C_{x,j,p}^{lmSH})S_{x,j,p} - sC_H
\]  

(2.4)
Subject to:

\[
\sum_{x \in T} \sum_{j \in N} \sum_{p \in P} S_{x,j,p} \leq sK^b
\]  
(2.5)

\[
S_{x,j,p} \in \{0,1,2,\ldots\} \quad \forall x \in T, \forall j \in N, \forall p \in P
\]  
(2.6)

2.5.7 Explanation of model formulation

(2.4) The objective function maximizes the savings of intermodal transportation minus the costs of the shuttle barge connection

(2.5) Forces the total volume to be transported to be smaller than the capacity of the shuttle barge connection.

(2.6) Integer constraints on the flow of products from origin via hub to destination

2.5.8 Break-even formulation

Similar to the dedicated barge scenario, a break-even function is formulated. Where the integer programming model described is used to find the optimal routing of volume, the break-even formulation can be used to obtain insights in the required volumes for break-even. The expression in 2.7 is similar to the formulation for dedicated barge, with the exception of a single barge cost parameter from the shuttle and a higher intermodal cost, due to higher handling cost and high volume barge costs.

\[
BE_{x,j,p} = \frac{C^b_H}{C^{'dd}_{x,j,p} - C^{'msH}_{x,j,p}}
\]  
(2.7)

Similar to the break-even formulation for dedicated barge, the result should be rounded to the nearest non-negative integer and is constrained by the barge capacity. If the constraint in 2.8 is not satisfied, the outcome of the optimization model is infeasible.

\[
0 < BE_{x,j,p} \leq K^b
\]  
(2.8)
3. Data collection & analysis

This chapter contains the sources of data and the results of the data analysis are presented. Section 3.1 contains the methods for data collection and the difficulties during the collection phase. A first analysis of the obtained data is given in section 3.2. This data is later used as input for the mathematical model and case study.

3.1 Data collection

3.1.1 Data sources

The data required for input in both the mathematical model and case study, could not be obtained at one place. Although the chemical company where this research was carried out had a substantial amount of data on their own operations, other figures had to be retrieved elsewhere. As a starting point for the construction of the mathematical model, a literature review was carried out in advance. This literature review (Henkens, 2013) consists of two sections; a section written using literature from various industry associations and a more in-depth analysis on academic literature. The information used for the first section was publicly available. Literature used for the in-depth section was mostly found via Google Scholar and search engines provided by the Eindhoven University of Technology. Most articles found are not publicly available and can only be accessed after a payment or via a license of an academic institution. The findings of this literature review were used to develop an understanding of the necessity of improving supply chain performance in the chemical industry and about the characteristics of barge hinterland supply chains. Furthermore, a starting point with regards to modeling of hinterland supply chains is described. As a second source, various interviews within the company were held to collect both field data and get a good understanding of processes inside the company. Interviews with people outside the company were also carried out, notably with barge and inland terminal operator. A very useful source of information was the consultant of the Inland Navigation Promotion Bureau. He has advised many companies on a possible modal shift towards barge transportation, hence had many insights into cost structures of intermodal transportation.

Most data was gathered from the chemical company, as other players in industry were less willing to discuss confidential or sensitive information. As the sponsor of this project only uses barges to the ports of Antwerp and Rotterdam, information on barges and inland terminals was largely absent. Only details on the nearby container terminal, which is adjacent to the site of the chemical company, could be used for information. Data obtained from these operations, combined with data found in barge cost estimates literature (NEA, 2008), were used to make estimates on barge hinterland transportation along the Rhine. The barge cost estimates are however figures from 2008, which is pre-economic downturn. It is likely therefore likely that the estimates deviate somewhat from current figures. Additional information was obtained from the Inland Navigation Promotion Bureau. Both sources were then checked with a barge and inland terminal operator, whether it roughly corresponded with his own cost figures.

The handling costs at a terminal were difficult to obtain, as in literature no specific attention is paid to inland terminals. In addition, the inland terminals have various cost structures and have different sizes and capabilities, therefore a general cost function could not be determined easily. The costs on inland terminals were based on the tariffs of transporting via different terminals, which were obtained from the barge and terminal operator. For the nearby container terminal, tariffs were available, as well as a discount structure if the throughput of the container terminal would increase. A final source of handling data was the Inland Navigation Promotion Bureau, where a rough empirical number could be obtained from.

Trucking tariffs could be obtained from the chemical company. A single rate for trucking per kilometer was not readily available, as volume commitments and transporter presence in the vicinity of the lane influence transport pricing. In addition to this source, a cost analysis on truck transport
(NEA, 2012) was obtained. The cost differences between the chemical company its data and the cost calculation are likely due to the margin of the transporters and round-trip versus single trip differences. An estimate has been made in the end what a workable number is for the cost of direct trucking.

### 3.1.2 Tariffs versus costs

A major challenge in this thesis is the choice between tariffs and costs. For a feasibility analysis, either tariffs or cost figures should be used. A combination could result in an over or underestimation of savings. The use of tariffs would show a clearer image of what the solution would cost for the shippers, however tariffs are based on many assumptions, which are hard to exclude by shippers. For example, a barge operator will make an assumption on the utilization of his barge, and will use that number in the tariff calculation for a single container of a shipper. If the utilization turns out to be higher, the barge operator receives more revenue, and might make a loss if the utilization turns out to be lower. The fixed costs of operations are allocated using the utilization of the barge, making tariffs hard to use for different volumes than calculated for. The same holds for terminal operators, where the high fixed costs from depreciation have to be attributed to shipments. For trucking, tariffs include the network of the transporter. The truck operator is able to use a lower tariff if there is a high chance, that a subsequent load is available near the unloading site.

Due to these difficulties, using the actual cost of the activity, gives a better overview on whether there is a business case. Major drawback is the retrieval of these cost figures, as it is typical confidential information. Another drawback is that the final figures are not representative what the cost will be to the shipper, but only shows the cost of the total supply chain. If all parties in the supply chain would collaborate the cost would be representative, but still a sharing mechanism has to be in place.

### 3.2 Data analysis

#### 3.2.1 Return loads

Containers that are brought to the hinterland may be returned empty to its origin, or can be re-used in the hinterland. The latter is much more efficient, but does require a customer and coordination from the container operator. The import freight flows, ie. the flows from outside Europe to the hinterland, is since many years larger than the export flow (hinterland towards ports and onwards). This has to do with the fact that the manufacturing center of the world shifted towards Asia, hence much freight destined for Germany and central Europe comes in via the ports of Rotterdam and Antwerp. Flows originating from chemical sites in the Netherlands compete with import flows concerning the re-use of containers. The flow imbalance of containers is roughly estimated to be 2 container imports for every container export (De Brito & Konings, 2011). Assuming that this ratio also holds for inland waterway transportation, it is expected that approximately half of the one-way volume can be used and paid for on the return journey. This effectively reduces the amount of barge costs that has to be covered by the original volume. If the barge is used for 50% on the import leg, the export leg will be used, according the ratio 2 to 1, for 25%. The allocation of barge costs is then 50/75 for the import route and 25/75 for the export route. The import leg indirectly thus covers a part of the barge costs for the export volume. The barge costs are thus corrected with factor 2/3, indicating that 2/3 of the barge cost has to be covered by the import volume.

#### 3.2.2 Average detention

Containers that are discharged from the barge are placed subsequently in the container yard of the inland terminal. Here, containers will have to wait for the day of delivery in the inland terminal. If every week a single barge arrives, the longest a container is detained in the container yard is then 6 days. Table 1 shows the time between arrival in inland terminal and delivery at the customer. Assuming that delivery can never take place on the same day and the drayage takes one day, an average of 3 days of detention can be found.
For two barge arrivals the average detention drops to 1.5 days and when a schedule of 3 weekly barge arrivals is used on average only 1 day has to be waited. These schedules assume that arrival is not on subsequent days, as this would minimize the effect of the additional barge(s).

Although a barge connection is regarded by the barge operator industry as a reliable mode of transport, there is still some uncertainty involved when it comes to barge arrivals. The detention of the shipment in the inland terminal is a natural buffer to cope with lead-time disruptions. In order to cope with shocks for the demand that has only limited detention in the inland terminal, products that have only a single day of detention, should be lengthened. This additional day changes the detention to an average value of 4 days of detention. For a more frequent schedule the effect is stronger, increasing the detention to 2 days for two barge arrivals and 1.8 for 3 arrivals.

### 3.2.3 Tariffs versus costs

#### Direct truck transportation

The transportation tariff is composed of three parameters for a shipper. First aspect is the origin of the shipment, determined on a region level. The second component is the destination, also on a region level. Finally, the type of product has an effect on the tariff of transportation. The shipper knows these aspects, but does not know the hauler specific aspects, such as its network. Using a regression model, a cost per kilometer and fixed cost can be calculated from the tariffs, which can be compared to other cost parameters. The fixed costs will include, amongst others, the loading and unloading time. The linear regression, displayed in Figure 10, shows a significant model that explains 76% of variation, more details on the regression can be found in Appendix B, Error! Reference source not found.. An explanation for the remaining 24% might be found in the size of the region, the customer density of that region and the presence of the carrier in the region. Whether the region is located within the Ruhr area is found not to contribute significantly to the model. Details on this regression can also be found in the appendix.

The loading and unloading times are for liquids approximately 1 to 2 hours, but vary depending on the nature of the product, such as the viscosity or desired temperature. If for both unloading and loading combined a total time of 4 hours would be assumed, this would result in a cost per hour and a cost per kilometer.
Figure 10: Analysis of direct trucking cost lanes; costs are converted to relative figures due to confidentiality reasons

Comparing these estimates to the costs from the NEA research (NEA, 2012), a significant discrepancy can be noticed. For tank transport, i.e. liquids transport, with a distance of 500km to Germany, a cost per km of € 1.61 or a cost of € 77.24 per hour is given. These cost estimates assume that a truck drives 125,000 km or 2,600 hours per year. The NEA costs per kilometer are however not comparable to the regression analysis, as the regression uses geodesic distance and the NEA figures use the actual distance. The difference in kilometers has to be corrected for the road network.

For dry bulk transport, the regression on tariffs yields a fixed cost per shipment and a cost per kilometer, which are different from the transport costs for dry bulk according to NEA (2012) as they estimate € 1.59 per km or € 76.53 per hour, for the same amount of kilometers and hours yearly as for liquid bulk. The difference is again significant, but can be explained also (partly) to the gap between actual distance and geodesic distance.

For further calculation, the costs obtained from the regression are used, as these reflect the costs of the direct truck transport from a shipper perspective the best, and eliminate the need for actual distances.

Handling at terminal
Tariffs for handling at the container terminal near the site are known for the current flows to Antwerp or Rotterdam. In addition, a credit structure is known how tariffs are affected if volumes increase, but the reduction in tariff per handling is very small for large increases in shipments (multiple thousands required per year), hence are left out. The tariffs are split for different handlings. The component affected most by a fixed cost allocation, is the movement onto the barge, as here the cost of the crane and yard is taken into account. Transshipment costs reported by SEALS Consortium (2008, p. 171) are lower than the tariffs obtained from the container terminal near the site. The respondents of the survey carried out by the SEALS Consortium report a transshipment cost per move of approximately € 18 to € 25 per move. The latter cost corresponds roughly with the figures from the barge and terminal operator, hence these costs are used for hinterland terminals.

Barge transportation
Concerning barge transportation, four sources have been identified. First are cost figures from NEA (2008), these give a cost per kilometer and a cost per hour for waiting. In addition, estimates from a consultant are known, which are tariffs based on an entire barge, hence without utilization effects, a source from literature is a report by Bruinsma et al. (2012), which gives both tariffs and costs. Actual tariffs were obtained from the barge and terminal operator. For a 196 TEU barge, the costs of fuel from the consultant and from the NEA figures are consistent, from both an average value of € 8 per
kilometer was found. The remaining cost per day would be around € 2,400 according to the NEA figures, which is in line with the estimates (€ 2,100 - € 2,500) of the consultant.

In a report for the European Commission (Bruinsma, et al., 2012) around the impact of climate change on barge transportation, estimates of the costs and prices of general barge transportation per ton for transport from Rotterdam to Basel and to Duisburg. The research uses an average load of 12 tonnes per TEU, which would lead to a cost for transport of around € 43 for a shipment from Rotterdam to Duisburg, or € 135 for a shipment from Rotterdam to Basel. These figures are lower than the costs obtained from NEA or the consultant. Where these differences originate from is not clear, apart from the fact that the report of Bruinsma et al. (2012) uses a low average weight of a container. Using a higher average weight would increase the cost of the container, however a maximally loaded container would largely overestimate the costs of NEA and the consultant.

The tariffs of the barge operator are more difficult to interpret and are strongly affected by utilization effects. Nonetheless an idea of the effects of drayage and differences between costs to various terminals can be obtained. The barge transportation cost is higher for inland terminals further away and obviously higher for customers located further away from the inland terminal. The difference between most terminals are very small and less than € 100 per shipment. This would confirm other estimates, if utilizations are high. In the remainder of the thesis, the actual costs can not be used and thus the NEA and consultant estimates are used for the cost calculations.

![Figure 11: One-way barge tariffs for 20ft container, including drayage and handling at destination terminal](image)

Drayage

The cost of drayage has been obtained from the consultant and from the tariffs of the barge operator. The drayage was expected to be a fixed amount per day plus a small surcharge per kilometer. The surcharge per kilometer can be derived from the tariffs of the barge operator, which are somewhere around € 1 to € 1.5 per kilometer. The fixed charge cannot be obtained from the tariffs analysis and therefore the estimates of the consultant were used.
4. Numerical analysis
This chapter contains the application of the model on a fictitious case, for both scenarios. Some parameters were varied to analyze when intermodal is more attractive than direct truck transport. The numerical analysis is carried out using the break-even formulations described in section 2.

4.1 Break-even calculation for dedicated barge scenario
This section is built up in the following way, first the design of experiments is discussed where all the parameters of interest are explained. Both the reason why these parameters are of interest is given, as well as the bounds between the parameters are varied. The subsequent section contains the results for each parameter. The actual values of the parameters are listed in Appendix C.

4.1.1 Design of experiments
Distance origin to inland terminal
A large set of inland terminals is available in the hinterland, of which some are relatively near each other. Four hubs are considered for the break-even calculation, each 150 km farther along the Rhine. Logically, customers are farther away from the origin for hubs located farther away from the origin. Therefore, the distances between customer and origin and the distance between inland terminal and origin are interrelated. Because the Rhine is not a canal without bends, the distances between origin and hub and between origin and customer can only be determined if the geography of the waterway is taken into account. The distances between origin and hub are actual barge distances, whereas distances between origin and customer are geodesic distances. The use of geodesic distances makes calculation easier, as a simple coordinates-based (Haversine) formula can be used to determine (many) distances. In comparison, actual barge distances can be used as only a very small amount of barge distances are required. Table 2 shows these distances.

Table 2: Distances between origin, terminals and customers

<table>
<thead>
<tr>
<th>Barge distance origin – terminal</th>
<th>Truck distance origin – customers within 50 km of terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>150 – 250 km</td>
</tr>
<tr>
<td>450</td>
<td>230 – 330 km</td>
</tr>
<tr>
<td>600</td>
<td>310 – 410 km</td>
</tr>
<tr>
<td>750</td>
<td>360 – 460 km</td>
</tr>
</tbody>
</table>

The nearest of the four defined terminals is chosen as standard value, as this hub would be situated in the middle of the Ruhr area, which typically has the largest volume and highest density.

Drayage distance
Current practice shows that customers located more than 100 km from an inland terminal are rarely served by intermodal transport via that inland terminal. For break-even purposes it is interesting to investigate what the effect is of the drayage distance on the required volume in shipments. Therefore, the drayage distance is varied between 0 and 100 km. The effect of the drayage distance on the break-even volume is highly correlated with the distance between origin and customer. It should be noted that some combinations of (geodesic) distances are impossible, due to the limitation on the drayage distance of 100 km. For example, if the customer is located 350 km away from the origin and the origin and terminal are 200 km from each other, then the drayage distance has to be at least 350-200=150 km. Similarly, if a customer is situated 150 km away from the origin and the origin and terminal are again 200 km apart, the drayage distance again is minimally 50 km, hence a drayage distance of 0 to 50 km is impossible.

Time-dependent costs
Two separate costs are dependent of time, inventory holding and container leasing or rental costs. The holding cost of a product depends on two factors, the cost of the product and the financing
structure of the company. The cost of raw materials of the product is especially volatile, as most see for example the price of ethylene, which is displayed in Figure 12. Although the price of the feedstock may vary heavily over time, the cost of products is more stable. The financing structure of the company, denoted in the weighted average cost of capital is even less flexible. Although companies are able to refinance their debt structure, significant changes cannot be made easily, nor does the company have much direct effect on the expected return on investment of the shareholders.

![Figure 12: Ethylene price for 2012-2013](image)

The inventory holding cost is correlated with the lead-time of shipments, hence the effect of a holding cost increase will be stronger for hubs located further away. For each hub a customer is chosen to investigate the combined effect of distance and inventory holding cost.

The cost of leasing a container is a matter of supply and demand, with respect to import and export flows. Certain areas in the world see high volumes of empty containers, whereas some areas are in need of empty containers. Repositioning these containers is costly and should be minimized. It is not exactly clear how costly repositioning to the origin is, therefore a wide range is used. Both the inventory holding costs and container costs are evaluated over a -50 to +50% range, to identify the effect of false assumptions and for variations in supply and demand.

**Handling cost**

The handling or vertical movement has been regarded in literature as the most important, limiting, factor for attractiveness of intermodal transport. To see what the effect of this vertical movement is on the cost of intermodal transport, thus the break-even volume, the handling cost is varied between -75% and +25%. This large variation is due to the uncertainty of the discrepancy between tariffs and actual costs of handling at inland terminals (especially the terminal near the origin). It is unlikely that handling will become (much) more expensive in the future, as volumes are expected to increase, improving terminal efficiency.

**Variable cost of trucking**

One of the reasons for this research is the forecasted shortage of truck drivers, as well as the forecasted increase in congestion. Both reasons will likely lead to an increase in trucking costs. A reduction of trucking cost is not anticipated, thus a sensitivity analysis will be conducted for only for an increase in costs. As both direct and drayage trucking will be influenced, both are increased with the same percentage to see how sensitive the required volume is to increases in trucking costs. The
costs are increased by 0 to 100%, effectively ranging up to double the current cost. The effects of increases in variable cost of trucking are obviously correlated with the distance of the customer from the origin, hence for every inland terminal the effect of the variable cost of trucking is studied.

Type of barge
The type of barge used influences many components of the intermodal transport chain. Most obvious is the difference in capacity, although for a break-even volume calculation this is least important, as it only shows feasibility if the required volume does not exceed the capacity of the barge. More important components are the daily cost and cost per kilometer associated with the barge. In addition, the small 24TEU capacity barge is only operated 16 hours a day, making it slower effectively, as all inland terminals are more than 16 hours away from the origin.

Return loads
The return load parameter is based on an import-export imbalance of 2 to 1. It is expected that the imported volume will grow faster than the exported volume. This would increase the ratio, increasing the amount of volume that the import volume on the barge has to compete with. Therefore, an increase in the ratio is expected to increase the break-even volume. The range is set to assess also an overestimation of the possibility of retrieving a return load. The ratio is evaluated on the range of 1.5:1 up to 4:1. The ratio is transformed in a return load parameter, which indicates the fraction of total round-trip costs allocated to the import volume.

4.1.2 Results
This section contains results on the break-even calculations for different experiments. Break-even calculations were carried out using expression 1.12. In each experiment, one component was evaluated. The parameters that were used in the experiments are listed in Appendix C. The input parameters that were varied during the break-even analysis are listed in Table 3, due to confidentiality reasons, figures have been transformed to relative figures. For each analysis, one parameter is varied on the given range, whilst all other values are kept at the fixed level. The volumes are given per week in shipments measured in TEU (twenty foot equivalent unit).

Table 3: Input parameter for break-even calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range</th>
<th>Value if fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d^b_{o,i}$</td>
<td>Barge distance from origin</td>
<td>300 - 750</td>
<td>300</td>
</tr>
<tr>
<td>$d^p_{j,x}$</td>
<td>Drayage distance</td>
<td>0 - 100</td>
<td>50</td>
</tr>
<tr>
<td>$d^d_{t,i}$</td>
<td>Direct truck distance</td>
<td>Depends on $d^p_{o,i}$</td>
<td>Midpoint of range</td>
</tr>
<tr>
<td>$h^p_i$</td>
<td>Holding cost per day</td>
<td>50% - 150%</td>
<td>100%</td>
</tr>
<tr>
<td>$c^c_p$</td>
<td>Container cost per day</td>
<td>50% - 150%</td>
<td>100%</td>
</tr>
<tr>
<td>$c^h_i$</td>
<td>Handling cost at origin $i \in O$</td>
<td>25% - 125%</td>
<td>100%</td>
</tr>
<tr>
<td>$c^l_i$</td>
<td>Handling cost at terminal $i \in T$</td>
<td>25% - 125%</td>
<td>100%</td>
</tr>
<tr>
<td>$c^d_y$</td>
<td>Variable drayage truck cost</td>
<td>100% - 200%</td>
<td>100%</td>
</tr>
<tr>
<td>$c^{d,t}_b$</td>
<td>Variable direct truck cost</td>
<td>100% - 200%</td>
<td>100%</td>
</tr>
<tr>
<td>$b$</td>
<td>Barge type</td>
<td>24, 96, 196 TEU</td>
<td>96 TEU</td>
</tr>
<tr>
<td>$K^b$</td>
<td>Capacity of barge</td>
<td>Depends on $b$</td>
<td>Depends on $b$</td>
</tr>
<tr>
<td>$c^{d,b}_b$</td>
<td>Variable barge cost per km</td>
<td>Depends on $b$</td>
<td>Depends on $b$</td>
</tr>
<tr>
<td>$c^{t,b}_b$</td>
<td>Variable barge cost per day</td>
<td>Depends on $b$</td>
<td>Depends on $b$</td>
</tr>
<tr>
<td>$r$</td>
<td>Return load total cost percentage</td>
<td>50% - 80%</td>
<td>66% (2:1)</td>
</tr>
</tbody>
</table>

First, a breakdown on the cost of the individual shipment is given, on basis of the fixed values. This will result in an insight on the components that make up a large portion of the total cost, thus showing a first look on which parameters will have a large effect. Figure 13 shows two major factors and two minor, the handling and drayage costs are much larger than the time dependent costs of
inventory and containers. It is thus likely that changes in handling or drayage (cost) parameters have a far greater effect on the break-even volume than parameters for inventory and container leasing.

![Figure 13: Breakdown of the cost of intermodal shipment (for dedicated barge scenario), excluding the barge cost](image)

**Validation of break-even formulation**

As discussed in the introduction of the break-even formulation, the result of the break-even formulation should result in a total saving of zero, or slightly higher positive saving. A break-even volume requirement of 56 shipments is obtained, using the base case estimates. The optimization model is implemented in AIMMS, a software program which can be used to design and solve various types of large-scale optimization problems. Inserting 56 shipments and all other base case estimates in the AIMMS program results in the output displayed in Table 4. The result is a small positive resulting saving. If the required volume is reduced by one, a negative saving of -1.3% is found. It can thus be concluded that the break-even formulation gives the desired result.

**Table 4: Validation of break-even formulation**

<table>
<thead>
<tr>
<th>Dedicated barge scenario</th>
<th>Resulting savings</th>
<th>Cost of barge</th>
<th>Initial savings</th>
<th>Destination</th>
<th>Product</th>
<th>Volume</th>
<th>Initial saving per shipment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€ 38.6</td>
<td>€ 8,137</td>
<td>€ 8,176</td>
<td>Hub</td>
<td>Product</td>
<td>Volume</td>
<td>€ 146 (19.4%)</td>
</tr>
</tbody>
</table>

**Drayage distance & direct truck distance**

It is clear that the further the customer is situated from the origin, the lower the break-even volume. Similarly, the nearer the customer is to the inland terminal, the lower the break-even volume. The lowest break-even volumes are thus obtained by the customers located furthest away, but the closest to the inland terminal. In Figure 14 this is graphically displayed. For a given distance from the hub, indicated by the blue arc, there is only one nearest to the inland terminal, indicated by the red circle. The point where the arc and circle touch, is the customer (the triangle) satisfying both requirements.

![Figure 14: Furthest customer (triangle) from hub (circle), but nearest to inland terminal (square)](image)
These customers are thus positioned in line with the hub and the inland terminal. For every drayage distance one lowest break-even volume can be determined, shown in Figure 15 with the red dotted line, corresponding to a direct truck distance.

### Figure 15: The effect of drayage and direct truck distance on the break-even volume for the dedicated barge scenario

**Time dependent costs**

As is found in previous sections on other parameters, the required volume is lower for more distant customers. The effects of time-dependent costs are small for the nearby customers, and become even smaller for customers situated further. Shown in the breakdown of the intermodal cost, the time-dependent costs are limited compared to handling and drayage, hence the effect of an increase in inventory holding costs or container costs are also limited.
Handling cost

As can be seen in Figure 13, the handling cost is a significant part of the total cost of intermodal transport. This is clearly reflected in Figure 17. A decrease in handling costs would make especially barge transport on short distances attractive, as the handling component is independent of distance. In the current analysis the handling costs are very high, due to uncertainties around the difference between tariffs and costs. A better and foremost lower estimate on the cost handling will result in a great improvement in feasibility of intermodal transportation. This result also confirms ideas from practice, stating that the vertical movements are crucial to the feasibility of intermodal transport over short distances.

Variable cost of trucking

The increase of variable trucking costs has an impact on both direct trucking and drayage. For simplicity reasons both are assumed to be equally affected. As the direct trucking distance is in all cases (much) larger than the drayage distance, a higher trucking cost makes intermodal transport more attractive. Although the effect of an increase in trucking rate is stronger for longer distances, this is not shown in Figure 18. This can be explained by evaluating the cost of barge compared to the direct truck cost, the latter is relatively less important for longer distances. The attractiveness of short distance connections is greatly enhanced by the increase in variable trucking costs, an increase of 50% in variable trucking costs leads to a decrease of the break-even volume of 50%.
Figure 18: The effects of an increase in variable trucking costs, for different locations in the hinterland

**Type of barge**

For each of the three barges a calculation is made regarding the break-even volume. In Figure 6 the blue area depicts the required volume for break-even, the remaining capacity of the barge is the red column on top or below the blue bar. If the red column is on top of the blue column, the barge is not fully loaded. This is the case for both the 96 and 196 TEU barges. The difference in break-even volume is very small for the two large barges, hence from a very early point it becomes attractive to start using the largest barge.

The small Kempenaar barge capable of holding of 24 TEU has the red column underneath the blue column, indicating that the Kempenaar has to be loaded more than its capacity to reach break-even. This implies that a Kempenaar is not attractive on this scenario, where only to the nearest terminal is travelled. As discussed in section 2.3.2, Kempenaar class barges rarely travel on large waterways and further than 300 km, hence it is not surprising that the outcome is negative for the Kempenaar.

![Figure 19](image1.png)

Figure 19: Excess capacities and break-even volumes for different barge types

**Return loads**

The sensitivity of the break-even volume is relatively small to the return load offering. The effect of a return load is significant, as an import to export ratio of 2:1 decreases barge costs for import volume
by 33%. Increases or decreases are always mitigated by the total volume, which moves in the same directions as the in or decrease. This gives a dampening effect on the break-even volume.

**Figure 20: Effect of return load changes, on break-even volumes**

4.2 Break-even calculation for shuttle to hub scenario

This sections is built up in the following way, first the design of experiment is discussed where all the parameters of interest are explained. The subsequent section contains the results for each parameter.

4.2.1 Design of experiments

For the design of experiments for the shuttle scenario most values for parameters are kept equal to the calculation for the dedicated barge scenario, except for the distances and handling costs. The locations of the inland terminals are kept similar to those of the dedicated barge scenario, however now a high volume connection from a hub is used to travel to these hubs. The cost of the high volume connection is a fixed amount per shipment. The original barge connection is reduced to only a small leg from origin to the hub. This results in far lower barge costs, which however have to be covered by a smaller saving.

Cost of high volume connection

The cost of transporting a container by the high volume connection between hub and hinterland is likely to be a major cost factor. The cost of the shipment depends on the distance, which is known, but also on the loading grade, which is unknown. The utilization factor of the barge is assumed to be relatively high, ensuring competitive prices (compared to road and rail transport). Nonetheless, due to uncertainty on the utilization factor, the analysis on cost of the high volume connection is carried out on a wide range of -50% to +50%. As the cost of the barge connection is dependent on the distance, for each inland terminal the experiment is repeated.

Handling costs

The handling costs make up for an even larger fraction of the intermodal cost of a shipment in the shuttle scenario, hence the break-even volume is expected to be even more sensitive to this cost component. A similar range is used as for the dedicated barge scenario.
Variable cost of trucking

Similar to the dedicated barge scenario, the variable cost of trucking will have a strong impact on the break-even volume of the shuttle barge. Both the drayage cost and direct truck costs are evaluated. The costs are increased by 0 to 100%, effectively ranging up to double the current cost. The effects of increases in variable cost of trucking are obviously correlated with the distance of the customer from the origin, hence for every inland terminal the effect of the variable cost of trucking is studied.

4.2.2 Results

This section contains results on the break-even calculations for different experiments. In each experiment, one component was evaluated. The parameters that were not varied during the experiments are listed in appendix 0. The input parameters that were varied during the break-even analysis are listed in Table 3. For each analysis, one parameter is varied on the given range, whilst all other values are kept at the fixed level. The volumes are given in shipments, measured TEU (twenty foot equivalent unit).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range</th>
<th>Value if fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{jX}^y$</td>
<td>Drayage distance</td>
<td>0 - 100</td>
<td>50</td>
</tr>
<tr>
<td>$d_{j}^{dt}$</td>
<td>Direct truck distance</td>
<td>Depends on $d_{i,j}^p$</td>
<td>Midpoint of range</td>
</tr>
<tr>
<td>$c_P^H$</td>
<td>Handling cost at origin</td>
<td>25% - 125%</td>
<td>100%</td>
</tr>
<tr>
<td>$c_X^H$</td>
<td>Handling cost at terminal $x \in T$</td>
<td>25% - 125%</td>
<td>100%</td>
</tr>
<tr>
<td>$c_{HM}^H$</td>
<td>Handling cost at hub</td>
<td>25% - 125%</td>
<td>100%</td>
</tr>
<tr>
<td>$c_{jRSH}^H$</td>
<td>Cost of high volume barge</td>
<td>50% - 150%</td>
<td>100%</td>
</tr>
<tr>
<td>$c_y^d$</td>
<td>Variable drayage truck cost</td>
<td>100% - 200%</td>
<td>100%</td>
</tr>
<tr>
<td>$c_{dt}^d$</td>
<td>Variable direct truck cost</td>
<td>100% - 200%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Again, first a breakdown is made regarding the relative importance of the cost components. The picture is fairly similar to the dedicated barge scenario, with the exception of the addition of the high volume barge cost. The handling component has become even more important due to the transshipment at the hub. For the nearest customers, the different handling costs add up to almost 50%. It is therefore likely that a change in handling costs has a strong effect on the break-even volume. For more distant customer, the relative importance of the handling is reduced, and the cost of the high volume barge becomes more important.

![Figure 21: Intermodal cost breakdown for the high volume scenario](image)

The differences between direct truck and intermodal costs are also evaluated, to see the potential saving per location. The locations are based on 4 different inland terminals in the hinterland. The relative costs are displayed in Figure 22, where the cost of intermodal transport to the nearest
location is chosen as 100%. Clearly, for the situation where the inland terminal is located 200km from the hub, the potential savings are too small (even negative) to cover the shuttle barge. The distance is the determining factor for direct truck transport, whereas it only influences the intermodal transport to a limited extent.

Validation of break-even formulation

Again, the break-even formulation is checked with the optimization model. The optimization model is again implemented in AIMMS. As found, the result of the customer located 200km from the origin result in a negative break-even volume, hence does not satisfy constraint 2.8. To validate the result of the break-even formulation is used as volume in the optimization model. The result of the break-even model is 35 shipments, which results in a saving of 0.38% in the optimization model. Reducing the volume by one reduces the saving to -0.41%, hence the break-even formulation and optimization model results are as expected.

Table 5: Validation of break-even formulation of the shuttle to high volume scenario

<table>
<thead>
<tr>
<th>Shuttle to high volume scenario</th>
<th>Resulting savings</th>
<th>€ 20</th>
<th>0.38%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of barge</td>
<td>€ 5,300</td>
<td></td>
<td>15.9%</td>
</tr>
<tr>
<td>Initial savings</td>
<td>€ 5,320</td>
<td></td>
<td>16%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Destination</th>
<th>Hub</th>
<th>Product</th>
<th>Volume</th>
<th>Initial saving per shipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>Base case</td>
<td>Base case</td>
<td>35</td>
<td>€ 152 (16%)</td>
</tr>
</tbody>
</table>

Cost of high volume connection

Unfortunately, a modal shift in fixed case scenario is not attractive, even a decrease in high volume connection cost of 50% does not change this. The break-even amount of shipments exceeds barge capacity, and is therefore not shown in Figure 23. The other lines are relatively flat, due to the low amount of shipments required for break-even.
Handling costs

As discussed in the cost breakdown, the handling costs play the most important role in the attractiveness of intermodal transport. This can be easily seen in Figure 24, where the break-even volume for especially the shorter distances is strongly dependent on the handling costs. It becomes very clear that terminal costs are key in a shuttle to high volume hub scenario.

Variable cost of trucking

An increase in variable cost of trucking widens the gap between intermodal and direct truck cost displayed in Figure 22. Because a small increase in savings can already make a large difference in break-even volume, especially the shorter distances benefit from an increase in variable trucking costs.
4.3 Comparison between scenarios

From the numerical analysis it can be concluded that the volume required to reach break-even is much smaller for the shuttle to high volume scenario, than for the dedicated barge scenario. Although break-even is reached with lower volumes for the high volume scenario, the question remains when the dedicated barge scenario outperforms the shuttle to high volume scenario. The barge cost that has to be covered is larger for the dedicated barge costs, but it the dedicated barge scenario benefits from fewer handlings per shipment. For each scenario and each customer location, defined by the direct truck distance from the origin a profitability graph is drawn, displayed in Figure 25. The dashed lines show the dedicated barge scenarios and the solid lines the shuttle to high volume hub scenarios.

From previous chapters, one can already conclude that:

1. The volume requirements for the shuttle scenario are lower than for the dedicated barge scenario, for any distance.
2. For customers farther away, volume requirements are lower for both scenarios.

From Figure 26 it follows clearly that although volume requirements are lower for the high volume scenarios, once the volumes are large enough, the dedicated barge scenario outperforms the high volume scenario. This is fairly straightforward, as once the break-even volume is achieved for the dedicated barge scenario, the added saving per shipment is larger for dedicated barge scenario. This corresponds with the steeper lines for dedicated barge scenarios. Combining the data for each scenario, direct trucking, shuttle to high volume and dedicated barge, Figure 26 is derived. With this figure, it is possible to get an insight in the optimal mode for transportation, for any given volume and any direct trucking distance. Roughly speaking, a barge has to be utilized for two-thirds for the dedicated barge scenario to outperform the shuttle to high volume hub. The border between the shuttle to high volume and dedicated barge areas is not as nicely distributed as the border between direct truck and shuttle. An explanation for this is found in the geography of the used areas. The ratio between barge and direct truck distances is not identical for each used location. Would this have been used, the border would have been more evenly distributed.

![Graph](image.png)

**Figure 26: Optimal decision for any distance to and volume of customer**

The effect of a volume larger than a single barge, has been extended for volumes up to 196 TEU. This raises the issue of choosing two 96 TEU barges, or choosing for a single 196 TEU barge, in addition to scenario choice of dedicated barge, shuttle to high volume or direct truck. The results of this analysis are displayed in Figure 27. For a dedicated barge scenario, the slope of the graph is identical for different barge sizes. The break-even volume differs however, where the larger barge requires more volume for break-even. Once volumes reach maximum capacity of the 96TEU barge, every additional container requires a second barge, which brings a high fixed cost. This high fixed cost first has to be covered by a sufficient volume, until the resulting savings will rise again after the break-even volume of the second barge. If volume is insufficient for the second barge, the volume over 96TEU will be transported by direct truck, causing the graph to move horizontally until break-even of the second barge. Obviously, the 196TEU barge is not hindered by its capacity, causing the high volume barge to be more profitable.
Figure 27: Effect of multiple barges versus a single large barge
5. Improving the attractiveness of modal shift to barge

The modal shift to barge is only attractive after the required volume to reach the break-even is obtained, hence efforts have to be made to gather volume. Three possible solutions to increasing transport volume have already been identified, hub and line bundling and return loads. Although return loads are not increasing volume on the transport to the hinterland, it does reduce barge costs for container transport and is therefore included in this chapter.

The following section assumes a finished application of the model, from where a shortcoming, or negative saving is obtained, which is denoted as $SC$.

5.1 Hub bundling

Increasing volume by bundling at the terminal near the origin is the most classical example of bundling. In many cases this already exists, however shippers are not actively collaborating with each other, as bundling of their products occurs via the barge operator. Additional volume provides benefits in the form of sharing the barge costs. Freight of other parties is not affected by the additional volume provided, hence no costs increases are applicable to the original volume. It is likely that the additional volume has to be trucked (farther) to the origin terminal, hence some additional costs may be incurred compared to cost per shipment of the original volume. These costs can be included as handling costs, as the additional volume should be defined as a different product type.

Every additional shipment for which a saving can be identified on the shipment specific costs, hence all costs except the barge cost, will attribute to a saving on the total cost. The total savings have to be allocated to each party participating in the barge connection. The sharing of benefits is however not discussed in this thesis.

A calculation can be made what the required volume for another party would be to reach the break-even point of the barge connection. For a given situation, a shortcoming volume can be calculated. This is larger than zero if the barge connection does not reach a break-even volume. The shortcoming volume has to be covered with the new volume from the additional source by hub bundling (or line bundling, which is discussed in the next section).

\[
BE_{x,j,p} = \frac{SC}{C_{j,p}^{dt} - C_{x,j,p}^{im}}
\]  

(3.1)

5.2 Line bundling

In order to increase volume, a line bundling concept may be applied. In a line bundling scenario, the barge stops at several inland terminals to load additional volume, which have the same inland terminal destination as the freight from the origin. The additional volume can bring savings, which can offset the total cost of the barge. There are however some downsides to additional stops:

1. Total lead-time becomes longer, hence time-dependent costs will increase, such as inventory holding and container leasing costs.
2. The barge lead-time increases, hence the cost of the barge will increase.
3. The barge might have to deviate from its original route, increasing the travel distance.

Following from our experiments in the numerical analysis, the time-dependent costs are only a minor fraction of the total cost of intermodal transport and the increase in time will be limited as the additional stopping time is small compared to the barge transit and average detention time. If the effect of the increase in time dependent costs is neglected, the calculation of a break-even volume for an origin-hub-destination combination becomes straightforward, as it does not changes costs of shipments which are already on the barge.

To investigate what are the conditions for an additional stop to be attractive, the break-even volume is calculated. Two cases are identified; the first is a connection which operates already with a volume higher than its break-even volume. For this case, the shortcoming savings are zero, hence only the
additional barge costs should be covered by the additional savings. The second case is where the break-even volume cannot be obtained from the previous inland terminal, and additional volume is necessary to cover both the costs of the additional stop, as well as the shortcoming savings \( SC \) of the previous hub.

The cost of the additional stop in the barge move from origin to terminal \( t \in T \) at terminal \( k \) is denoted by \( c_{k}^{\text{stop}} \). Products originating from this new origin are modeled as different product types, eliminating the need for an additional origin set.

\[
BE_{x,t,j}^{p} = \frac{c_{k}^{\text{stop}} + SC}{C_{j,p}^{\text{rt}} - c_{x,j,p}^{\text{im}}} 
\]  

(3.2)

5.3 Return loads
A final possibility to increase attractiveness of barge transportation is the reduction of total round-trip costs by offering a return load. The barge cost is then shared among more containers, thus reducing cost per container. There are however some difficulties with return load (export volume) offering. First, the destination of the exported volume has to be similar to the origin of the import volume. In the chemical industry this is typically not the case, therefore the return trip should go via one or multiple terminals near the destinations of the export volume. Additionally, the destination of export volume is typically away from the continent, hence has to go to one of the main deep-sea ports. These ports are a source of variability in the system that is hard to incorporate into the model. The last drawback is the cost associated with transport to the deep-sea ports. This transport is less prone to short lead-times, as lead-times to Asia or the Americas are already much longer. Therefore the exported volume may already use the more efficient barge connections from the inland terminals directly to the port. Due to these difficulties it is impossible to obtain a formula to calculate the return load offering. A possible way is to vary the return load ratio inside the model, however this a very crude way of evaluating effects.
6. Case study
This section applies the model described in the previous sections to a case of Dow Chemical. First an introduction is given about the company and about its current (transport) operations. In the second section, the application of the model is described and the results of the model are discussed. The possibilities of improving the results as well as the service performance of barge transportation are discussed in the final section.

6.1 The Dow Chemical Company
The Dow Chemical Company, in short Dow, is an international provider of plastics and chemicals. It has over 180 production locations in 35 countries and employs 50,000 employees worldwide. It is active in the development and production of more than 5,000 types of plastics and chemicals. Dow has its second largest plant and Benelux office in Terneuzen. In the Netherlands and Belgium, Dow has 23 factories, which combined produce over 6 million tons of plastics and chemicals yearly.

The first activity in the Netherlands was the opening of a trade office in Rotterdam, but soon the construction of a site in Terneuzen was started. In 1964 the first polystyrene factory was started up, which was followed by many other plants, including three naphtha crackers. Many supporting departments are also present in Terneuzen, such as Supply Chain Operations, Site Logistics and various R&D groups.

The Supply Chain Operations group provides a range of transportation, warehouse and terminal management services, to help meet the needs of the Dow businesses. The group is involved in the moving, handling and storing of chemicals in a safe and secure manner that complies with regulatory requirements, at the lowest cost. The operations include, among others, road, rail, marine, marine packed cargo, outplants and air. Some of these operations are also carried out for Styron, which operations used to be a part of Dow, in recent years Styron has however become a separate company. Combination of volumes between Styron and Dow may result in more cost efficient tenders for transport lanes.

Next to the production site in Terneuzen, the Valuepark is located. This industrial park is a joint venture between Zeeland Seaports and Dow Benelux and is home to a deep-sea and barge terminal, a Bertschi rail terminal and many other logistics companies. The Valuepark ships 30 million tonnes of sea borne cargo and an additional 25.5 million tonnes cargo by barges annually.

6.1.1 Export flows to hinterland
Dow has many customers situated in western Germany. Many are located in or near the major industrial clusters along the Rhine. Two major areas can be distinguished, the Lower Rhine and Upper Rhine areas. The Lower Rhine region is from the Dutch border till Bonn and encompasses the Ruhr area, which is very densely populated and has a high concentration of customers. One Dow plant is located in the Lower Rhine area, in Ahlen. The Upper Rhine region is much larger as it ranges from Bingen till Basel (Switzerland). The Rhine also flows partly through France, in addition to Switzerland and Germany. The customer density is much lower in this area, but more Dow plants are situated in the Upper Rhine region. These sites are located in Erstein, Drusenheim, Lauterbourg (all in France) and also one in Rheinmünster (Germany). For simplicity the Rhine Areas are defined by a specific set of postal codes, see Table 6.

<table>
<thead>
<tr>
<th>Table 6: Definition of Rhine Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Postal Codes included</strong></td>
</tr>
<tr>
<td>Lower Rhine Area</td>
</tr>
<tr>
<td>Germany 4XXXX, 50XXX, 51XXX, 52XXX, 53XXX, 57XXX, 58XXX, 59XXX</td>
</tr>
<tr>
<td>Upper Rhine Area</td>
</tr>
<tr>
<td>Germany 55XXX, 56XXX, 6XXXX, 7XXXX</td>
</tr>
</tbody>
</table>
Dow has one major production location in the Benelux, Terneuzen, where it produces and ships products to the hinterland. The Dow site in Terneuzen is the largest plant in Europe. Another important location in the Benelux is Antwerp, where many products from overseas enter Europe and are stored. The flows originating from Terneuzen destined for the Rhine areas is however triple the size of the flow originating from Antwerp. Therefore the focus lies on export flows from Terneuzen to the Lower and Upper Rhine Area.

The nearest customer within the Rhine area is approximately 200km trucking distance from Terneuzen. The farthest customer in the designated area is located around 750 km from Terneuzen. On average the trucking distance to a customer is 392km. The Rhine Area customer base (excluding Hydrocarbon and EO/EG groups, see next section) consists of 199 customers, which are situated in 144 different cities.

In Table 7 the total volumes shipped and modal split of the different business groups is shown, where one can clearly see that only the Hydrocarbons and EO/EG Groups are shipping their products with another mode than truck or intermodal rail. These groups are excluded from further analysis, as their products are not transported by truck. The mode Truck/IM includes also freight transported by intermodal rail, however less than 2% of shipments to the Rhine area are transported using an intermodal rail connection.

Table 7: Distribution of volumes of business groups from Terneuzen to Rhine areas

<table>
<thead>
<tr>
<th>Business group name</th>
<th>Size of flow in %kg</th>
<th>Modal split</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocarbons Group</td>
<td>54.5%</td>
<td>Barge/Vessel (98%), Rail (2%)</td>
</tr>
<tr>
<td>Packaging &amp; Specialty Plastics</td>
<td>18.1%</td>
<td>Truck/IM (100%)</td>
</tr>
<tr>
<td>Polyurethanes</td>
<td>16.7%</td>
<td>Truck/IM (100%)</td>
</tr>
<tr>
<td>EO/EG Group</td>
<td>6.45%</td>
<td>Rail (100%)</td>
</tr>
<tr>
<td>Polyglycols, Surfactants &amp; Fluids</td>
<td>3.80%</td>
<td>Truck/IM (100%)</td>
</tr>
<tr>
<td>Automotive Systems</td>
<td>0.20%</td>
<td>Truck/IM (100%)</td>
</tr>
<tr>
<td>Formulated Systems</td>
<td>0.19%</td>
<td>Truck/IM (100%)</td>
</tr>
<tr>
<td>Functional Materials</td>
<td>0.05%</td>
<td>Truck/IM (100%)</td>
</tr>
<tr>
<td>Amines</td>
<td>0.04%</td>
<td>Truck/IM (100%)</td>
</tr>
<tr>
<td>Epoxy</td>
<td>0.01%</td>
<td>Truck/IM (100%)</td>
</tr>
</tbody>
</table>

The business group Dow Packaging & Specialty Plastics produces only solid products, mainly in granules. The Automotive Systems group produces both liquid and solids, all other groups only produce liquid products.

Orders have various sizes, but are mostly determined by maximum shipment sizes. The maximum shipment size may be determined by road weight legislation, volume restrictions and/or specific container restrictions. Most orders (95%) can be transported as a single shipment. Order lead times are ranging from a few days up to 75 days, where on average orders are demanded with a lead time of 3 weeks, with lead time defined as time between order entry date and desired delivery date. The time between goods issue (loading on site) and delivery was on average only two days for customers in the Rhine Areas.

Solid products are transported to the Rhine Area for 78% in bulk trucks and for 20% packaged in regular full truckload trucks. Both containers with an inner liner and silo trailers are considered bulk trucks.
The majority of shipments (92%) of liquids are shipped in bulk tank trucks, 3% is packaged and transported by regular truckload trucks and 3% is shipped in ISO containers. For both groups a very small portion is shipped by intermodal rail, in less than truckload filled trucks or by parcel service. The products shipped in trucks from Terneuzen are generally not considered as hazardous, except for the products from the Amines group.

Customers receiving packaged products are typically small customers and may not have the same unloading capabilities, such as docks, as larger customers. Smaller customers are sometimes not able to unload from the rear of a truck, hence unload trucks from the side. Containers will thus never be used for these customers, as containers are only (un)loadable from the rear. In addition, the prices of transporting packed products are much lower, as the transport of packed plastics and chemicals is not very different from transporting any other packed product, therefore this part of the transport market is much larger than the market dedicated to transporting bulk goods.

**6.1.2 Barge transportation network**

The network of inland terminals has grown in the last decades extensively, due to high volume of containers between the German hinterland and the port of Rotterdam. Road congestion has become an increasing problem, causing a gradual transition from road to inland waterway transportation. Appendix A contains a list of cities that have one or multiple inland terminals, which are capable of handling containers. Most container terminals are capable of dealing with hazardous materials, but only a few can store these containers on their premises. Of the inland terminals in the designated hinterland, only the inland terminals in Frankfurt am Main and Dortmund are not situated on the Rhine, but on the Main and Rhine-Herne canal respectively.

The Rhine is a river that flows from the Swiss Alps to the North Sea, and is highly influenced by the melting of snow in the Alps. This gives relatively high fluctuations in water levels, resulting in very high and very low water levels, making barge transportation sometimes more difficult or even impossible. When the water levels are very low, barges with a higher draft will hit the bottom of the river. Due to the bridges over the Rhine, high water levels sometimes impose constraints on the number of containers that can be stacked on a barge. The flow of water also results in a higher fuel consumption and/or lower speed of the barge when travelling upstream compared to going downstream. Barges have additional traveling time between Basel and Iffezheim due to the set of locks that have to be passed. Due to this additional travelling time, time tables for barge travelling should be used, and not solely the distance and an average barge velocity.

**6.2 Modeling the data**

**6.2.1 Input**

1. The obtained data has to be prepared for the case study. First, demand data has to be filtered, where only products transported by truck in bulk, both solid and liquid, remain. In addition, only orders with a lead-time of less than 7 days are left out, as these orders can never be transported intermodal.
The shipments are summed per lane (origin-destination and product type combination). If for both product types the volumes are summed per week, the variability is relatively small. It can be seen in Figure 29 that every week at least 28 and 14 shipments, of liquids and solids respectively, go towards the designated area. The yearly distribution of volume is then used to obtain the composition of the weekly volume. This approach however does neglect the small flows, of on average less than a container per week, as shipments have to be integer values. The composition is therefore not an exact representation, but does take the largest, most important, flows into account.

The terminals included are listed in Error! Reference source not found. of Appendix C. All are situated along the Rhine, with the exception of Frankfurt am Main. This terminal is located on the Main, 20 km from the point where the Main meets the Rhine. This implies that the model assumption stating waterways could not be branched is violated, however the branch is very short, thus gives only a small error on barge cost if Frankfurt is not used as unloading point, while farther upstream terminals are used. The distances are obtained from barge route planner (Periskal), and the barge travel times were obtained from inland promotion bureau (Bureau Voorlichting Binnenvaart).

The cost parameters are kept mostly equal to those listed in the numerical analysis. Liquid and solid transportation costs are mostly equal, with handling of solids slightly higher but container lease somewhat lower. The exact values are shown in the Appendix C.
6.2.2 Results

The optimization model is implemented in AIMMS, which is able to solve many large-scale optimization models. The parameters introduced in the previous section have been inserted into multiple data tables in AIMMS. Within less than a second, the models were solved to optimality. Exact details on the performance when using larger data sets were not available.

The results of the dedicated barge and shuttle to high volume hub models are displayed in tables Table 8 and Table 9 respectively. The dedicated barge model is not to be found more cost-attractive compared to direct trucking, as it shows a negative resulting saving of -7% on the direct trucking cost for the minimum volume. This is conform expectations, due to the very small volume available, which is geographically scattered as well.

Table 8: Results of dedicated barge modeling of case study

<table>
<thead>
<tr>
<th>Dedicated barge scenario</th>
<th>Resulting savings</th>
<th>Cost of barge</th>
<th>Initial savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-7%</td>
<td>-40%</td>
<td>37%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Destination</th>
<th>Hub</th>
<th>Product</th>
<th>Volume</th>
<th>Initial saving per shipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEU40</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>2</td>
<td>32%</td>
</tr>
<tr>
<td>DEU45</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>1</td>
<td>45%</td>
</tr>
<tr>
<td>DEU46</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>1</td>
<td>44%</td>
</tr>
<tr>
<td>DEU47</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>1</td>
<td>43%</td>
</tr>
<tr>
<td>DEU59</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>13</td>
<td>39%</td>
</tr>
<tr>
<td>DEU63</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>1</td>
<td>5%</td>
</tr>
</tbody>
</table>

The shuttle to high volume scenario has positive resulting savings, which can be explained by the larger applicable volume. In order to travel towards the farthest hubs, a certain required volume is necessary to cover the barge costs. This volume cannot be achieved by Dow on itself. This utilization factor is taken out of the equation when using the high volume barge, which does not take volumes into account. Only a small fixed cost has to be covered, shared by volume destined for any customer. The total volume that can be used is therefore much larger. Although the savings per shipment are smaller, the fixed cost of the barge is also much smaller.

In practice, if the volume that can be guaranteed yields a positive business case, the remaining shipments per week can also be shifted to the barge if the individual shipment promises a saving. From Figure 29 it follows that the average volumes are around 40 for liquids and 28 for solids, which can be used in the model again. The results of the model are listed in Appendix D, where using the average volume the savings increase to an average 20% per shipment.

A more detailed analysis shows that approximately 77% of the liquids volume is generated by a single business of Dow. Appendix E contains the results of the modeling of the volume solely from this business.

Table 9: Results of shuttle to high volume hub modeling of case study

<table>
<thead>
<tr>
<th>Shuttle to high volume hub scenario</th>
<th>Resulting savings</th>
<th>Cost of barge</th>
<th>Initial savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18%</td>
<td>-10%</td>
<td>28%</td>
</tr>
</tbody>
</table>
### 6.2.3 Bundling opportunities

**Hub bundling**

As found in the previous section, the dedicated barge scenario is not cost-attractive, due to the low volume to cover the barge cost. The gap in savings can possibly be bridged by obtaining additional volume though hub bundling or line bundling.

Hub bundling, discussed in section 5.1 is the most straightforward method, as it does not change the cost of the barge, if the same inland terminals are used in the hinterland. It is possible that the optimal barge route changes if volume increases, but with current hubs a simple calculation can show what is necessary to reach a break-even scenario for the dedicated barge.

Although it is impossible to calculate the exact costs of current and intermodal transport for possible regional partners, it is possible to use Dow data to get an initial insight. For example, it can be calculated using the formula in section 5.1 to assess the increase in volume required from any destination, hub and product combination.

**Table 10: Effects of hub bundling**

<table>
<thead>
<tr>
<th>Destination</th>
<th>Hub</th>
<th>Product type</th>
<th>Initial saving per shipment</th>
<th>Required individual volume</th>
<th>Model resulting savings after volume increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEU40</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>32%</td>
<td>5</td>
<td>€ 106</td>
</tr>
<tr>
<td>DEU45</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>45%</td>
<td>4</td>
<td>€ 311</td>
</tr>
<tr>
<td>DEU46</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>44%</td>
<td>4</td>
<td>€ 243</td>
</tr>
<tr>
<td>DEU47</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>43%</td>
<td>4</td>
<td>€ 191</td>
</tr>
<tr>
<td>DEU59</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>39%</td>
<td>4</td>
<td>€ 319</td>
</tr>
<tr>
<td>DEU63</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>5%</td>
<td>22</td>
<td>€ 9,884</td>
</tr>
</tbody>
</table>

In Table 10 it can be seen that higher savings per lane imply a lower required volume. For lanes with low savings, the required volume would exceed the barge capacity, hence unless routing would change, this could not result in a positive business case. A routing change is exactly what occurs when increasing the demand for lane DEU63-Liquid by 22 shipments. The route changes from solely traveling to Emmelsum, to travelling to Strasbourg. DEU63-Liquid has a higher saving from Frankfurt. The cost difference for travelling additionally to Strasbourg is outweighed by the savings that can be
obtained from that hub. The remaining barge capacity can easily be filled with volume from any inland terminal between origin and Strasbourg.

Although an initial insight can be obtained by using the break-even model, it does work in a worst-case way. The possibility of a better result may exist, whereas a worse result is not possible when using the break-even calculation of section 3.5.

Bundling for the shuttle to high volume hub is also possible, but as the result of the modeling phase was already positive, every addition to the current volume results in an improvement, as long as the individual saving on the shipment is positive.

**Line bundling**

Where hub bundling does not increase barge costs, line bundling does change the total barge cost. As possible loading terminals along the inland waterway are usually nearer to the hinterland, the savings associated with these terminals are lower. The cost of making an additional stop along the waterway is however not very costly, as it is assumed there is no waiting time and the terminal is aware of the shipments that have to be loaded onto the barge, hence the largest cost comes from a possible deviation.

Using the formula described in section 5.3 the required volumes for break-even are calculated. In order to model the new costs, it is assumed that the new origin is the chemical cluster in Moerdijk (the Netherlands), affecting (only) the direct truck distance. The remaining costs are kept equal to those of Dow liquids. The additional cost of the barge is neglected; as the inland terminal would normally be passed, hence no additional distance has to be travelled. The saving per shipment is smaller than the saving from Terneuzen, as the direct truck distance is smaller for most destinations. The negative saving of a liquid shipment from Moerdijk to DEU63 via Emmelsum is due to the lower direct truck cost.

<table>
<thead>
<tr>
<th>Destination</th>
<th>Hub</th>
<th>Product type</th>
<th>Saving per shipment</th>
<th>Required individual volume</th>
<th>Model resulting savings after increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEU40</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>16%</td>
<td>12</td>
<td>€ 87</td>
</tr>
<tr>
<td>DEU45</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>32%</td>
<td>6</td>
<td>€ 117</td>
</tr>
<tr>
<td>DEU46</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>30%</td>
<td>6</td>
<td>€ 9</td>
</tr>
<tr>
<td>DEU47</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>29%</td>
<td>7</td>
<td>€ 118</td>
</tr>
<tr>
<td>DEU59</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>27%</td>
<td>6</td>
<td>€ 111</td>
</tr>
<tr>
<td>DEU63</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>-5%</td>
<td>Impossible</td>
<td>-</td>
</tr>
</tbody>
</table>

Using a similar approach as in the previous section on hub bundling, each required value is put in the model to assess the real effect. The effect on the resulting saving is displayed in the last column of Table 11.

**6.2.4 Driver shortage**

As discussed in the introduction, one of the reasons for this research was the expected driver shortage in Europe. Although a driver shortage is expected, exact numbers on the effects of the shortage are not available. Some research has been done on this topic before the economic downturn of 2009, and it is expected that the downturn only caused the driver shortage to be temporarily paused, and is about to resurface once the economy picks up. A report by Ball (2011) for the European Commission, describes the European situation using data from before the economic downturn. There was expected to be a estimated driver shortage of approximately 74,480 drivers for the EU-27 in 2008 (Ball, 2011).
From the Transport Monitor (Cap Gemini Consulting & Transporeon, 2012) the relation between capacity and prices levels on a quarter to quarter basis can be evaluated. The economic downturn of 2009 can be clearly seen, where demand rapidly decreased, with as result dropping prices and a steep increase in available capacity.

![Price and capacity index (quarterly figures)](image)

Figure 30: Relation between price and capacity for European road transport (Cap Gemini Consulting & Transporeon, 2012)

It can be seen that between Q3-2008 and Q3-2012 the price of direct trucking decreased approximately 3.8%. Supposing that demand would reach pre-economic downturn levels, this would imply an approximate increase of 3.8%. This percentage is used as a starting point, rounded up to 5%. For the analysis, three scenarios are evaluated; a 5, 10 and 15% increase in total trucking costs, including both direct and drayage trucking. Results for both scenarios are displayed in Figure 31. The reason for the steeper slope of the shuttle to high volume scenario is due to the higher volume allocated, which is further away than the volume allocated to the dedicated bare scenario. Locations located further from the origin are less sensitive to trucking cost changes.

![Figure 31: Effect of driver shortage on both scenarios for case study](image)

6.3 Service performance

For a modal shift, not only the cost of the alternative is important, but also the performance with regards to service. If a product is delivered repeatedly after the agreed delivery date, it is highly likely that the customer will source the product from a competitor. Especially in the commodity market
this is an important aspect, but for many other products substitutes are also available. In order to assess the performance with regards to service, the effects of disruptions in barge transportation are evaluated against direct truck transport. Direct truck transport benefits from its unit of transportation of only one; an accident or problem with a single truck only affects a single shipment. The unit of transportation of a barge is up to 96 shipments for a 96 TEU barge, hence a disruption of the barge has a larger magnitude. Due to this aspect, the focus lies on the barge connection when determining the service performance.

6.3.1 High water levels
The effect of water levels is typically regarded as a drawback of barge transportation. High water levels can be an issue, as barges with highly stacked containers may not be possible to pass underneath certain bridges and riversides may be damaged by large barges. This issue has been researched in the broader scope of climate change, in which it is expected that water levels will fluctuate more heavily in the future. Figure 32 shows the water levels throughout the years 2003-2007, at the gauge of the Rhine at Kaub (between Koblenz and Wiesbaden). In these 5 years, only once the high water mark HSW has been crossed, which indicates that all waterborne transport will be halted. The second highest peak does already allow a stack of 5 low-cube containers, which only occurs on ships not discussed in this thesis. A stack of 4 containers can always be transport if the water level is below HSW. The risk of high water on service performance is therefore really small, as high water rarely occurs and only affects barges that are very highly utilized.

6.3.2 Low water levels
Low water situations occur more frequently. The amount of containers loaded onto the barge affects the draft of the vessel, hence when water levels drop, the utilization of the barge has to become lower. Barge operators use a low water tax when water levels are below certain levels, which increase when water levels drop. This mechanism makes barge transportation less attractive when water levels become lower. For a dedicated barge scenario this mechanism is however not in place.

The maximum barge capacity drops when water levels drop, until barge operators do not have the obligation to transport anymore, defined as the GIW level. It can be seen that the GIW level is crossed in three years, sometimes for multiple days. The light grey area is entered in every year,
indicating that low water can be witnessed every year. It should be noted however that the lower Rhine is rarely affected, whereas at Kaub, see Figure 32 is affected often. The effect is basically that the capacity is strongly reduced, according to the percentages of the tax. This can be used as input for the model described in section 2.4.

Like with high water levels, the impact is expected to be relatively small, as low water levels are more easily forecasted, and impact first the highly utilized vessels. The impact of low water levels on the dedicated barge scenario can be assessed using the model, by adapting the capacity of barges according to the taxes, used by barge operators, corresponding to water levels.

The effect of the low water on the shuttle to high volume hub scenario can be evaluated by increasing the cost component of high volume barge transport. The model is assessed using three scenarios; 25%, 50% and 75% tax. The shuttle is assumed not to be affected by the low water levels, as the water levels in the Netherlands are much higher normally. The results are shown in Table 12:

<table>
<thead>
<tr>
<th>Shuttle to high volume hub scenario</th>
<th>Low water tax</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resulting savings</td>
<td>100%</td>
<td>88%</td>
<td>76%</td>
<td>64%</td>
<td></td>
</tr>
</tbody>
</table>

The effects are found to be very limited, as the high volume barge component is only a minor component of the total cost, which is dominated by cost of handling and drayage. It is therefore no surprise that the savings decrease, but the resulting savings are still positive.

6.3.3 Delays

Various sources of delays can be considered for barge transportation, sources may be unexpected waiting time at a terminal, unexpected waiting time at a lock, delayed arrival of the barge at the origin, accidents, failures of equipment and more. If barge schedules are planned very tightly, the probability of a delay is higher, as there is no built-in slack. Intermodal transport, especially in the case of the dedicated barge scenario has its built in slack. The detention at the hinterland terminal is necessary to cope with a single arrival of a barge per week. The container has to wait for some days before it can be delivered on the agreed delivery date. Only for containers that have to be delivered the next day, a possible delay will be problematic. Adding a day of slack for these containers, effectively adding them to a barge earlier, removes the effects of all barge delays shorter than 1 day. For delays longer than 2 days, a possible emergency shipment can be sent, as there are enough days to send a truck directly to the customer. In any case, two modes for transportations will be present, giving flexibility to the shipper, capable of optimizing the total cost of transportation, including cost of inventory in transit. For additional material on this topic, which is referred to as dual transport mode, see the article by Kiesmüller, De Kok, & Fransoo (2005).
7. Conclusions and recommendations

7.1 Conclusion

For this master thesis a model was designed to assess the possibilities of a modal shift towards barge for the chemical industry. Although the thesis was conducted from the standpoint of the chemical industry, the models can be applied to many other businesses and findings are applicable to many other industries. It should be noted however that the model only works with goods that can be containerized. Two different scenarios were obtained for a modal shift to barge, which complement each other.

The first scenario employs a dedicated barge connection from origin to one or multiple destinations. The cost of the dedicated barge has to be shared among the containers on the barge, hence a high volume is required for low barge costs. The second scenario employs two barge connections, a dedicated shuttle, transporting only to a single hub, from where another high volume barge connection is employed by a third party. The latter scenario assumes a well utilized connection from the hub, hence only for the dedicated shuttle a certain volume is required.

In order to construct a model for analyzing the costs of intermodal transport, first an analysis was conducted on the cost structure of intermodal transport. There are 4 main types of costs involved for intermodal transport. First, there is handling cost at many different stages, at the origin, inland terminal(s) and the customer, where containers are lifted, loaded and/or unloaded. Secondly, there is a time-dependent cost, comprising of an inventory holding cost and a container rental cost. The third cost component is drayage, which is the truck movement from inland terminal to customer. Drayage cost depends on the distance from customer to inland terminal. The fourth cost is the cost of the dedicated barge movement, which is dependent on the total volume on the barge. Regardless of the load of the barge, the total barge cost is equal hence the cost per shipment is highly dependent on the load of the barge, as a similar cost can be allocated to multiple shipments. A fifth cost could be a secondary barge connection, in case of the shuttle to high volume hub scenario.

A mathematical formulation was obtained from the cost structures, which is able to determine the optimal routing for shipments and generate the savings of a modal shift. Combining the outcomes of both models, results in Figure 33. It can be concluded from this figure that the dedicated barge scenario is only attractive if a relatively high number of shipments can be guaranteed by the shipper. The graph shows for each distance an attractive modal shift, if the required volume is achieved. It can thus be concluded that intermodal transportation is currently an attractive alternative to direct trucking for the chemical industry.

![Figure 33: Totals savings against volume on barge (96 TEU) for both scenarios](image)
In addition to volume, the numerical analysis showed that the cost of handling and the distance between inland terminal and customer are also strongly influencing the cost of intermodal transport. If the cost of handling would decrease, intermodal transportation becomes more cost-effective rapidly. Customers located more than 100 km away from an inland terminal are very unlikely to qualify for a modal shift via that inland terminal.

Improving the attractiveness of the modal shift is aimed solely at obtaining additional volume. Two main approaches are identified. First, hub bundling contains the sourcing of additional shipments from other parties around the origin. Secondly, using line bundling, barges may make additional stops on their way to the hinterland adding shipments from (other) parties. The addition of return load could also improve the modal shift, however it proved to be impossible to produce quantiative results on this.

The case study for Dow Chemical yielded surprising results. It was anticipated that current shipment volumes would be insufficient for a modal shift towards barge. This was confirmed for a dedicated barge connection. For a shuttle scenario, the contrary was shown, with a positive business case for the current shipment levels. The volume that can be guaranteed is very dispersed in the hinterland, due to a few large customers, and therefore for the dedicated barge connection the volume is too small. The shuttle to high volume hub is not hindered by this, hence the useable volume for the shuttle is much higher. A cost saving of up to 18% can be obtained on shipments for the designated region, using minimum volumes. This saving can increase, if more shipments are shifted to barge. For example, if an average volume is shifted, a cost reduction of 20% on the volume applicable for a modal shift can be realized.

Although the unit of transportation is larger for a barge than for a truck, the service performance of a barge is expected to be very high. Three main sources of disruptions are identified and discussed; high water, low water levels and delays. The occurrence of severe high water levels is very improbable and affects only very highly utilized barges. Low water levels are more frequent, and are coped with using a low water tax. It has been shown that the effects on a shuttle scenario are very limited, reducing savings by a fraction of the tax percentage. The dedicated scenario is not affected unless utilization is very high. The risk of delays is mitigated due to natural buffers in intermodal transportation, either due to required detention in inland terminal, or barge schedules.
7.2 Recommendations for Dow Chemical

1. Do not open a dedicated barge connection, but do identify additional volume for intermodal barge transportation.
   The case study shows that a dedicated barge connection is not attractive with the current volumes. Although intermodal transport presents savings to many shipments, the flow to the hinterland is not large and not stable enough to start a barge connection to the hinterland. It is recommended that the Logistics Accelerator Zeeland association, a regional logistics development organization is asked whether companies in the vicinity of the chemical company can provide the additional volume. A second possibility for additional volume is the packed material. This type of freight was excluded from the analysis due to operational constraints of some customers. With a detailed customer analysis, a fraction of the volume may qualify for a modal shift. A third possibility is volume from parties along the waterway, participating in the 4C4Chem project. Even if the additional volume does not add up to a positive dedicated barge scenario, it is also beneficial to a shuttle to high volume scenario.

2. Identify the possibility of combining the current barge connection to the ports of Rotterdam and Antwerp with the shuttle to high volume scenario.
   As Dow already employs a barge connection to the ports of Rotterdam and Antwerp, it may be possible to use this barge connection to provide volume to Moerdijk. Combining the existing marine packed cargo barge with the intermodal volume has two advantages. First, if more volume is put on the shuttle, the cost per shipment will decrease for both marine packed cargo and for the hinterland cargo. Secondly, it raises the possibility of starting with a very small pilot for hinterland transportation. A more detailed analysis on the outcome of the model shows that the Polyurethanes business is responsible for approximately 70% of the volume that is shifted to the shuttle to high volume hub scenario.
   If all volume is shifted, intermodal transport using a high volume connection is an attractive alternative for direct trucking even without bundling with marine packed cargo. The modal shift would be capable of delivering an average saving per week of 18% on the direct trucking cost of the shifted volume. This could however be much higher, as this estimate is based on a minimum volume per week. Calculations with the average volume per week lead to a saving of 20% per shipment. In absolute terms, the reduction in shipping costs could be up to half a million euro yearly.

3. Perform an operational analysis on barge intermodal transportation.
   Even if neither of the scenarios appears to be cost attractive, the analysis of driver shortage is showing that barge transportation may very well become a feasible alternative to direct trucking in the future. It is therefore recommended to perform a study to analyze the operational requirements for barge intermodal transportation. Barge transportation to the hinterland is not present in the company currently, thus implementing intermodal barge transportation probably poses some operational difficulties. Therefore it is wise to start assessing what would (operationally) be required for implementing barge transportation as a new mode of transport.

4. Explore trimodal options.
   From meetings with the barge operators, it became clear that intermodal transport should embrace both rail and barge, hence enabling trimodal options. If a rail connection from inland terminals in Germany to Eastern Europe is included, the amount of possibilities increases rapidly. It may however be cost-attractive alternative to current transport to Eastern Europe and it lowers barge costs per shipment for the original volume.
7.3 Recommendations for future research

1. **Improve the model so it is able to handle trimodal connections.**
   In the current models only two ways of improving attractiveness are listed. It is possible however to find other ways of additional volumes. An option could be the use of trimodal connections, where another mode is used to reach the barge inland terminal, or from the barge inland terminal onwards. For example, volume transported to Eastern Europe can be reached very well by train from Duisburg, which in turn can be reached by barge from the inland terminal near the site of the chemical company. This increases the amount of volume qualifying for intermodal transport greatly, but also increases complexity. A new model, which combines dedicated barge with (multiple) high volume shuttles, should be derived. This model should then eliminate the need of the two separate models shown in this thesis.

2. **Improve the estimates on service performance of barge transportation.**
   One of the main concerns shippers have is the reliability of barge transportation. A detailed risk analysis should be made, where the effect of water levels, accidents and other delays is investigated, in combination with the possibility of sending emergency shipments. It is expected that the service reliability of barge transportation is much higher than for truck transportation, but this has not shown in literature so far.

3. **Review articles focusing on break-even distance.**
   In most research around barge transportation, the focus was strongly on calculating the distance from which intermodal transport would become a cost-attractive alternative. It is shown in this thesis that the amount of volume available for a modal shift strongly affects the feasibility of a modal shift. In some applications the feasibility of barge transportation on very short distances is already shown, hence articles aimed at calculating break-even distances might not be representative any more.

   The article by Kim & Van Wee (2011) gives an overview on break-even distance improvements discussed by several other articles. Although the article briefly mentions that a higher volume may decrease the non-road cost per shipment, the effects are not analyzed. The sensitivity of the break-even distance to non-road cost of movement is the highest, and recommendations are aimed at reducing this cost, but interestingly increasing the volume is not considered, which is shown to be the most effective in this thesis.

   The studies reporting a barge connection show either a break-even distance of over 200 km, but without any drayage, or over 400 km including drayage. In this thesis it has been shown that this can be much shorter, even in a scenario where both the origin and destination is not a deep-sea terminal. The research of Kim & Van Wee (2011) focuses on the geographical implications, and concludes which pairs of origin and destination may be interesting for intermodal transport. A similar study could be conducted, but with the inclusion of volume implications. This could be helpful to identify which customers, terminals and origins are most promising for a modal shift.
8. Bibliography


Appendix A. List of German Rhine cities with inland terminal

- Emmerich
- Emmelsum
- Duisburg
- Dortmund
- Krefeld
- Düsseldorf
- Neuss
- Dormagen
- Leverkusen
- Köln
- Bonn
- Andernach
- Koblenz
- Mainz
- Frankfurt am Main
- Worms
- Mannheim
- Ludwigshafen
- Germersheim
- Wörth
- Karlsruhe
- Strasbourg
- Ottmarsheim
- Weil am Rhein
Appendix B. Linear regression on tariffs

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Appendix C. Parameters for numerical analysis & case study

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Appendix D. Case study for shuttle scenario – average volume

From the analysis in section 6.2.2 it follows that using minimum volume a positive saving can be obtained. If the connection is in place, adding additional shipments yields a higher positive saving. In this appendix section, it is researched what the effect on savings is when the average volume is shifted. From the shipments over time analysis, a liquids volume of 28 shipments per week and 14 for solid products are obtained. Using the same distribution as in the minimum volume scenario, a sample set of demand is generated. The outcome of the model is straightforward, as more volume can be shifted to the barge. The relative resulting savings are 2% higher than for the minimum volume, as the fixed barge costs can be shared among more shipments. Comparing the minimum volume outcome and the average volume outcome, the resulting savings increase by 70%.

<table>
<thead>
<tr>
<th>Destination</th>
<th>Hub</th>
<th>Product type</th>
<th>Volume</th>
<th>Initial saving per shipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEU40</td>
<td>Dusseldorf</td>
<td>Liquid</td>
<td>3</td>
<td>23%</td>
</tr>
<tr>
<td>DEU45</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>2</td>
<td>27%</td>
</tr>
<tr>
<td>DEU46</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>2</td>
<td>26%</td>
</tr>
<tr>
<td>DEU47</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>1</td>
<td>25%</td>
</tr>
<tr>
<td>DEU57</td>
<td>Koblenz</td>
<td>Dry</td>
<td>1</td>
<td>11%</td>
</tr>
<tr>
<td>DEU59</td>
<td>Emmelsum</td>
<td>Liquid</td>
<td>18</td>
<td>23%</td>
</tr>
<tr>
<td>DEU63</td>
<td>Frankfurt</td>
<td>Liquid</td>
<td>1</td>
<td>42%</td>
</tr>
<tr>
<td>DEU67</td>
<td>Mainz</td>
<td>Liquid</td>
<td>1</td>
<td>38%</td>
</tr>
<tr>
<td>DEU71</td>
<td>Heilbronn</td>
<td>Liquid</td>
<td>4</td>
<td>38%</td>
</tr>
<tr>
<td>DEU72</td>
<td>Heilbronn</td>
<td>Dry</td>
<td>1</td>
<td>22%</td>
</tr>
<tr>
<td>DEU72</td>
<td>Heilbronn</td>
<td>Liquid</td>
<td>2</td>
<td>33%</td>
</tr>
<tr>
<td>DEU73</td>
<td>Heilbronn</td>
<td>Dry</td>
<td>1</td>
<td>20%</td>
</tr>
<tr>
<td>DEU73</td>
<td>Heilbronn</td>
<td>Liquid</td>
<td>1</td>
<td>33%</td>
</tr>
<tr>
<td>DEU74</td>
<td>Heilbronn</td>
<td>Dry</td>
<td>1</td>
<td>16%</td>
</tr>
<tr>
<td>DEU79</td>
<td>Freiburg im Breisgau</td>
<td>Dry</td>
<td>1</td>
<td>15%</td>
</tr>
<tr>
<td>FRA67</td>
<td>Freiburg im Breisgau</td>
<td>Liquid</td>
<td>5</td>
<td>36%</td>
</tr>
</tbody>
</table>
Appendix E. Case study for Polyurethanes business

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Appendix F. Tariffs of barge operator

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