Master Thesis

Empty tank container repositioning: Including a forecast

by
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Management summary

The goal of this thesis is to develop a model that supports Den Hartogh and H&S in making the decisions which tank containers to send from where to where in order to minimize the costs created by empty tank container repositioning. There are different tank container types, and an order can often be executed by multiple tank container types. Repositioning of empty tank containers is needed in order to be able to fulfill future demand. Not all orders are known for the coming weeks. To be able to fulfill unknown future demand, tank containers of certain types have to be close to the different loading locations. Besides this, there is an imbalance of supply and demand. Tank containers in a region that has a surplus of tank containers have to be transported to a region that has a shortage of tank containers.

The decisions that have to be made today for orders that have to be executed have an influence on the empty tank container repositionings in the future. Since orders can often be executed by multiple tank container types, there is a choice between several tank container types that can be used to execute an order. This research shows that by taking the future into account empty repositioning costs can be saved, because a tank container of a certain type that is used today to execute an order, can also be used close to the delivery site of the order. Taking the future into account could result in higher execution costs today in order to prevent high empty repositioning costs later.

The costs of empty tank container repositioning are not reimbursed by the customer. To minimize these costs, the constructed model takes the future into account by including a forecast. MMP, which is Den Hartogh and H&S's current planning tool, does not take the unknown future into account. Comparisons between the constructed model and a simple version of MMP show that using the constructed model results in cost savings. If both models are solved for eight weeks, the planning proposed by the constructed model results in a cost saving of about 11%. This percentage does not include the investment costs of the first week. After four weeks, the total execution costs of the constructed model are lower than the total execution costs of the simple version of MMP.

The main difference between the constructed model and MMP is that the constructed model takes the future into account. Therefore, the constructed model can send tank containers of certain types to execute orders today that can be used later close to the location where the tank container ends. MMP looks only to the orders of the coming two days. If there is a choice between several tank container types, MMP will choose the tank container that leads to the lowest costs in the optimal solution on the two-day period. However, it is possible that this tank container cannot be used close to the location where the destination site of the order is, whereas another tank container type could execute a next order close to the location where the destination site of the first order. This could save empty repositioning costs.

Using the planning proposed by the constructed model results in cost savings. Therefore, we advise Den Hartogh and H&S to take the future into account by their planning. The constructed model can be used as a basis for a new planning tool. A comparison between the constructed model and the simple version of MMP shows that using the constructed model result in cost

savings of about 11%. However, in this comparison a forecast is used that is based on actual order data. It was not the scope of this thesis to create a method of how to generate an accurate forecast. Instead, it is assumed that there is a forecast available and the forecast that is used to test the model is based on actual order data. However, this is not possible in reality. If a real forecast is used, the cost savings could be lower than 11%. Therefore, we advise Den Hartogh and H&S to investigate first how to come up with a good forecast if they want to use the constructed model.

Chapter 1

Introduction

Since the introduction of tank containers, transportation of freight by tank containers is rising (Braekersa, Janssensa, & Carisa, 2011). Tank containers are used for intermodal transportation to transport gases, liquids and powders. Intermodal transportation concerns transportation where at least two different modes are used, such as truck and train, truck and ship, but also truck, train and ship. By changing modes, the tank container is moved from one mode to the other, without any handling of the commodity in the tank container. A tank container is placed in a steel frame. Therefore, it is easy to transfer a tank container from one mode to another mode.

Tank containers cannot carry all gases, liquid chemicals and liquid foodstuff. Moreover, if a tank container is used to transport chemicals, it is not allowed anymore to transport liquid foodstuff in that tank container. There are different tank containers designed to transport different commodities. Tank containers can for instance differ in size, heating technology and the number of compartments. Therefore, there are many types of tank containers.

A company that is specialized in transporting goods or materials for a customer is called a Logistics Service Provider (LSP). Daily an LSP has to make decisions about how to transport loaded and empty tank containers, where to store tank containers, et cetera. A customer of an LSP is the one who pays for the transport of the commodity. The customer places an order which has an origin and destination site. An LSP has to deliver empty tank containers to the supplier of the commodity, which is at the origin site. An origin site is therefore a demand location for an LSP. At the destination site, the tank container is unloaded and the empty tank container has to be taken away by the LSP. Therefore, the destination site is a supply location.

A problem that arises in tank container transportation is the imbalance of supply and demand. The imbalance of supply and demand results in an imbalance of tank containers across regions. The locations where is demand for tank containers are often not the same as the locations where tank containers are delivered. If a location has demand for tank containers and also gets tank containers delivered, the commodities that are imported and exported cannot always be transported in the same type of tank container. This leads to the problem of repositioning of empty tank containers. A surplus of tank containers in a region has to be transported to a region where there is a shortage of tank containers. Another reason to reposition tank containers is that an LSP wants to be able to fulfill future demand for empty tank containers which is not known yet. To be able to fulfill this demand, a tank container of a certain type has to be close to the demand customer. Otherwise, the demand can only be fulfilled by facing high costs or the customer may go to a competitor to transport its commodity. However, an LSP also does not want tank containers to be stored empty at a location waiting for a possible future order if this tank container could also be used for another order. Therefore, a proper repositioning of empty tank containers helps to anticipate future orders. A problem is that the demand in the future is uncertain. So it is unknown where tank containers of which type are needed and how much tank containers of each type are needed. The problem is that transportation of empty tank containers is not paid by customers and hence generates only costs for an LSP. Due to the costs of empty tank container repositioning which are not reimbursed by the customer, the margins in the tank container transportation are small. A small improvement in the operations can lead to a significant decrease in the transportation costs.

1.1 Companies

In this thesis, three different companies are involved. These three companies are CQM, Den Hartogh and H&S. In the following subsections, an introduction of each company is given.

1.1.1 CQM

Consultants in Quantitative Methods (CQM) is a consultancy firm that advises and helps its clients with quantitative methods in order to improve their business activities. Examples of clients of CQM are ASML, Philips, ProRail and NS. CQM also helps Den Hartogh and H&S planning their transport.

CQM was founded in 1979. CQM started as an internal research group of Philips mainly to improve the operational processes of Philips. However, in 1993 CQM became a stand-alone consultancy firm. Nowadays, CQM has about 35 employees and mainly works in three areas: planning, product and process innovation, and chain management. CQM creates quantitative models and designs software in order to analyze and optimize processes. In this way, organizations gain insight into what decisions are the best for their organization.

1.1.2 Den Hartogh Logistics

Den Hartogh Logistics is specialized in transporting gases and liquid chemicals in bulk. The company is one of the worlds leading logistics service providers for the chemical industry. Den Hartogh has 30 offices around the world and the headquarter is located in Rotterdam.

Den Hartogh was founded by Jacobus den Hartogh in 1920 and was one of the first in intermodal transport of chemicals in Europe. In 2011 they expanded their business outside Europe and became a global logistics service provider for the chemical industry. Nowadays, Den Hartogh makes use of road transport as well as intermodal transport and operates in Europe, North and South America, Middle East, and Asia. The total fleet of Den Hartogh consists of over 6,000 tank containers. In this thesis, only intermodal transport of liquid chemicals within Europe is considered for Den Hartogh.

1.1.3 H&S Group

H&S Group is a company specialized in transporting liquid foodstuff in bulk. H&S exists for more than 65 years and is nowadays one of the largest logistics service providers for the food industry in Europe. The headquarter of H&S is located in Barneveld. H&S consists of several departments. H&S Transport is concerned with road transport and H&S Foodtrans is concerned with intermodal transport. H&S has a fleet of approximately 1,200 tank containers to transport liquid foodstuff and operates throughout Europe.

In 2001 the company Eurovos went bankrupt. Eurovos was a company that was specialized in intermodal transport of both chemicals and liquid foodstuff in Europe. Den Hartogh and H&S Transport took over the company. Den Hartogh continued with the chemical transport of Eurovos and H&S Transport continued with the liquid foodstuff transport of Eurovos. Both

Den Hartogh and H&S Transport went through a growth in intermodal transport in Europe. Eurovos was headquartered in Oss, where H&S Foodtrans is still located.

1.2 Problem definition

As already mentioned, a proper empty tank container repositioning is important to save costs. However, today Den Hartogh and H&S do not know all orders for the upcoming days, but they want tank containers close to the origin sites. The problem becomes even more complex when there are different types of tank containers and different commodities cannot be transported by the same tank container. To illustrate the problem, consider the following simple example. Assume there are two regions, region A and B, and two tank container types, T_1 and T_2. Den Hartogh has received an order to transport commodity X from region A to region B. This transportation can be done by both tank container types T_1 and T_2. However, it is until now uncertain if Den Hartogh receives an order from region B to region A. Den Hartogh forecasts that it receives an order which has to be executed in four days from region B to region A which can only be fulfilled by tank container type T_2. Therefore, if this forecast is accurate, it saves costs to send tank container type T_2 now to transport commodity X from region A to region B. This example is very simple. In reality, Den Hartogh has more tank container types and many orders every week, whereas less than 80% of the orders is known for the coming week.

Summarized, one important reason why the problem of empty repositioning is complex is that an order can be executed by several different tank container types. In order to prevent many empty repositionings for orders in the next week, it matters which tank container type Den Hartogh and H&S use today to execute an order. On top of that, not all orders for the coming weeks are known today.

Den Hartogh and H&S want to minimize the costs created by empty repositioning, since these costs are not paid by their customers. They want to know what the tank containers should do now and which tank container type to use for an order in order to minimize the costs created by empty repositioning. Therefore, the goal of this thesis is to develop a model that supports their decision in deciding what a tank container should do now and by which tank container type an order should be executed at minimal costs related to repositioning of empty tank containers. To achieve this goal, we develop a new model that determines which tank container types to send from where to where. This is done in two stages. In the first stage, we assume that all demand is given. In the second stage, this assumption is relaxed and we take into account that only a part of the orders is known.

1.3 Thesis outline

This thesis started with an introduction of the problem and an introduction of the involved companies in Chapter 1. In Chapter 2, a literature overview of previous work in the area of empty tank container transportation is given. Chapter 3 gives a more detailed background of the problem and an extensive problem description. Then in Chapters 4 until 8, the research problem is solved. Finally, the conclusion together with a discussion and some recommendations for future research are given in Chapter 9 and 10.

Chapter 2

Literature review

Since customers do not pay for empty tank container transport, whereas it is necessary to ensure the continuity of an LSP, repositioning of tank containers has become a more and more important issue. However, before 1990 not much research has been done. Since the beginning of the 1990s, empty container allocation became a more popular topic in the literature (Braekersa et al., 2011). However, most of the existing papers focused not on tank containers, but on "dry" containers (Karimi, Sharafali, & Mahalingam, 2005). In the dry container industry, there are fewer container types, and considering different container types is for that reason less an issue compared to the tank container industry where many different tank container types exist (Erera, Morales, & Savelsbergh, 2005). This chapter gives an overview of literature which is relevant to the study of this thesis.

Choong, Cole, and Kutanoglu (2002) developed an integer program to solve the problem of empty container repositioning. In their model, Choong et al. (2002) assume that there is only one container type and that the demand for containers for a certain period is given. The objective of their model is to minimize the costs which are related to moving empty containers. With their model, Choong et al. (2002) investigated the effect of the length of the planning horizon. With intermodal container transport in the Mississippi river as a case study, they investigated the difference of a 15-days planning horizon and a 30-days planning horizon. They concluded that with a larger planning horizon, the empty container repositioning costs for the first periods are lower, since slower and cheaper transportation modes are used.

Wang and Wang (2007) created a dynamic deterministic model to solve the problem of repositioning of empty containers. This model is based on integer programming. Similar as Choong et al. (2002), Wang and Wang (2007) consider only one container type and assume that the supply and demand is given. Their objective is to minimize the traveling costs of empty containers. This minimization is done under the constraints that the supply and demand for empty containers must be satisfied. Besides the constraints that the supply and demand must be met, Wang and Wang (2007) included lower and upper storage limits for empty containers at depots and ports and lower and upper limits to the number of empty containers that can be transported by a transportation mode. Wang and Wang (2007) considered three different transportation modes: road, rail, and barge. They also provide a numerical experiment in which they show that the model raised the efficiency of repositioning of empty containers.

Both Choong et al. (2002) and Wang and Wang (2007) considered one single container type. There are many other papers which consider only the single commodity case. In case of single commodity, there is only one container type and every commodity can be transported with that container type (Cheang & Lim, 2005). However, Den Hartogh and H&S have different tank container types. Since not every order can be done by every tank container, considering different tank container types is important. In case of multicommodity, there are more container types. One step further is the paper of Erera, Morales, and Savelsbergh (2005). They considered several types of supply and demand, and for each type of supply and demand there is one tank container type. Erera et al. (2005) proposed a network flow model that includes the routing of loaded tank containers and the repositioning of empty tank containers. Similar as Wang and Wang (2007), Erera et al. (2005) assume that the supply and demand is given, and they also consider different transportation modes. With a computational study, Erera et al. (2005) show that repositioning decisions should be made daily instead of weekly.

Another paper that considers multicommodity is the paper of Epstein et al. (2012). Epstein et al. (2012) also take the uncertainty of demand for containers into account. To deal with demand uncertainty they developed an inventory model to determine safety stocks. Given these safety stocks, they proposed a network flow model where one of the main decisions is how and when to reposition empty containers. Although Epstein et al. (2012) as well as Erera et al. (2005) consider multiple container types, they both assume that the demand for containers is specified by one container type. There is no choice in which container type to use to fulfill the demand. Instead, the demand is one specific container type.

Chang, Jula, Chassiakos, and Ioannou (2008) considered multicommodity and substitution. Substitution means that the demand for a certain container type can also be fulfilled by another container type according to some predefined rules. Chang et al. (2008) used two different rules. Consider two different container types T_1 and T_2. The first substitution rule states whether or not demand for container type T_1 can be fulfilled by container type T_2. The second substitution rule states how many containers of type T_2 are needed to fulfill the demand for one container of type T_1. Chang et al. (2008) used a branch-and-bound algorithm to solve the model. With a computational experiment they show that the empty traveling costs can be reduced by allowing substitution of container types.

Chang et al. (2008) assume that all supply and demand is given and there is no uncertainty. Crainic, Gendreau, and Dejax (1993) consider also multicommodity and substitution. They developed three different models. The first two models are dynamic network models where the supply and demand for containers is assumed to be given. The first of these two models is for the single commodity case, the second is for the multicommodity case. In the multicommodity case, the model is similar as of Chang et al. (2008). Crainic et al. (1993) propose a parameter that states whether it is possible to substitute two container types and how many containers of one type are needed to fulfill the demand for another container type. However, this implies that if container type T_1 can be fulfilled by container type T_2, all demand for container type T_1 can be fulfilled by container type T_2. Modeling it in this way means that a customer cannot specify which container types are allowed and which are not. It is assumed that the substitution rules hold for all customers. The third model of Crainic et al. (1993) takes into account the uncertainty of supply and demand. However, this third model only considers single commodity, which means that there is only one container type. This model was formulated as a two-stage model. The first-stage determines the first-period decisions which includes depot-depot movements and container movements which are needed to cover the demand for the first period, but also for the later periods. Given these movements, the second-stage model is a container inventory model which tracks down how the stocks of containers at depots fluctuate as a consequence of random supply and demand.

Di Francesco, Manca, Olivo, and Zuddas (2006) continued with the work of Crainic et al. (1993). They considered the multicommodity case where substitution of containers is allowed. To deal with the uncertainty in supply and demand, Di Francesco et al. (2006) use a rolling planning horizon approach. In this way, the evolution of information over time is taken into account, since the decisions are reoptimized. First, the model is solved given the current situation and information. Then, the decisions for the first period are implemented and when new information becomes available, the model is solved again. Whereas Crainic et al. (1993) does not provide a numerical example, Di Francesco et al. (2006) do. They solved the problem with and without allowing substitution. Although the computation time increases by allowing substitution, the obtained results are better in case of allowing substitution.

Most papers about empty container repositioning consider only empty container transport (Shintani, Imai, Nishimura, & Papadimitriou, 2007). A paper that considers both loaded and empty container transport is the paper of Coslovich, Pesenti, and Ukovich (2006). They developed an integer program which minimizes three different components of the operating costs: routing costs, resource assignment costs, and container repositioning costs. To solve the problem, Coslovich et al. (2006) divide the problem into three subproblems. The first subproblem is associated with the routing costs, the second with the resource assignment costs, and the last with the container repositioning costs. To test their approach, they use randomly generated instances as well as a real-world data set of an Italian container transportation company. Coslovich et al. (2006) concluded that the solutions of their numerical experiments are good compared to the optimal solution.

Chapter 3

Extensive problem description

In this chapter, a more detailed description of the research problem is given. In Section 3.1, a more detailed background of tank container transportation is given. Section 3.2 describes the current planning system of Den Hartogh and H&S. The last section of this chapter, Section 3.3, gives an extensive problem description.

3.1 Background of tank container transportation

The total logistics costs are influenced by several activities, such as transport of loaded tank containers, and cleaning, repositioning and storing of empty tank containers (Karimi et al., 2005). An important difference between empty and loaded tank container transport is that loaded transport takes place at customer request. Therefore, loaded tank container transport is paid by the customer, whereas empty tank container transport is not, it only generates costs. However, as mentioned earlier, empty tank container transport is needed to ensure the continuity of an LSP, since there is an imbalance of tank containers. Another difference between empty and loaded tank container transport is that loaded tank containers have a predetermined origin and destination site, whereas empty tank containers do not have a fixed origin and destination site. Besides this, loaded tank container transportation has a specific time schedule, whereas empty tank container transportation does not have a specific time schedule. Sometimes, if empty tank containers are not close to an origin site, an LSP can lease tank containers. However, leasing tank containers is not considered in this research.

An order consists, among other things, of a loading and a delivery time, an origin and a destination site, and specific tank container requirements. To execute the order, several decisions should be made, such as from where and which empty tank container should come and when the empty tank container should arrive at the origin site. An order that is executed by intermodal transport has the following execution steps: first an empty tank container is sent to the origin site by truck. At the origin site, the tank container is loaded. Then this tank container is transported by truck to a terminal. At this terminal the tank container is moved from the truck to another mode (rail or ferry). Thereafter, this tank container is transported by train or ship to the next terminal. Again it is possible to change the mode of transportation at the terminal, so it is possible that both modes (rail and ferry) are used or a mode is used multiple times during the execution of the order. From the last terminal a truck picks up the tank container and transports it to the destination site. At the destination site two actions are possible: the tank container stays at the delivery site and serves as storage of the commodity, or the tank container is unloaded. When the tank container is unloaded, the order is finished. This means that the tank container becomes available again. Then a tank container can perform different actions. The tank container can be transported to a new loading location for a new order. The tank container can also be stored at a depot. A depot is a location where tank containers can be stored. This location can be close by, but that does not have to be the case. There are depots which are owned by Den Hartogh or H&S, where they can store their tank containers for free. Den Hartogh has for example depots in the Netherlands, Belgium, and Germany. However, in Eastern Europe, there are no depots which are owned by Den Hartogh and if they want to store a tank container there, they need to pay for every day they store a tank container at that depot. A final option is that a tank container is transported to a cleaning location. A tank container often needs to be cleaned before reuse. The most common reason not to clean a tank container is that the order product of the previous loading and the new loading is the same. After cleaning the tank container, the tank container can be stored at a depot or used to execute a new order. Cleaning locations can be located elsewhere than at a depot. However, since most cleaning stations are located at depots (or close to a depot) and the focus is on repositioning of tank containers, cleaning is not considered in this research. Instead it is assumed that every tank container should go to a depot before executing a new order.

Den Hartogh and H&S can divide Europe into regions according to the supply and demand for tank containers. Although there can be more depots in a region, only one depot per region is considered in this research. For each region, the largest depot in that region is selected, since most tank containers that are stored in that region, are stored at that depot. The costs of storing a tank container at a depot can differ not only per depot, but also per day. At some depots a tank container can be stored for free during the first few days. After that, the costs of storing the tank container for one more day increase per day. However, the empty travel costs are relatively high compared to the storage costs. Therefore, it is assumed in this thesis that the storage costs of each depot and each day are the same.

Besides specific tank container requirements and the availability of a tank container, there is another restriction whether or not a tank container can be used for an order. Den Hartogh and H&S have what they call a green-/blacklist. This green-/blacklist states which products are allowed to be the last product that was transported by the tank container or which products are not allowed. This green-/blacklist also holds when the tank container is cleaned between the two orders. A customer has either a greenlist or a blacklist. The greenlist states which products are allowed to be the last product that was transported by the tank container. Only these products are allowed, all the other products not. The blacklist is the other way around. The blacklist states which products are not allowed to be the last product that was transported by the tank container. This green-/blacklist is very customer specific. Therefore, there is no structure in the green-/blacklist.

3.2 Planning system of Den Hartogh and H&S

In order to plan their orders, Den Hartogh and H&S work with a planning tool called Multiple-days Material Planning (MMP), which is developed by CQM. To plan the orders, information about the tank containers is needed. Information that is needed is: whether a tank container is available and, if not, when the tank container becomes available; where the tank container is / becomes available; what the last product was in the tank container; and whether or not a tank container is allowed to execute an order due to the characteristics of the tank container. Den Hartogh and H&S work with what they call the "yellow line". This yellow line displays when a tank container becomes available.

Den Hartogh and H&S do not know all orders for the coming days. Figure 3.1 illustrates the percentage of the orders that are known a certain number of workdays before the orders have to be executed. As Figure 3.1 shows, less than a half percent of the orders is not known one workday before the execution. However, only 45% of the orders are known five workdays

Figure 3.1 – Percentage of orders of Den Hartogh not known before execution

before the execution.

As already mentioned, Den Hartogh and H&S work with MMP to plan their orders and tank containers. MMP determines which tank container should execute which order. The MMP tool that Den Hartogh and H&S currently work with, is the second version of the algorithm of MMP. The first version of the algorithm of MMP plans two types of orders: orders that are already in the system and dummy orders. Dummy orders are orders that are not in the system yet, but are expected to come. The benefit of dummy orders is that they contain the same information as real orders, such as loading and delivery locations. Therefore, they can be treated in the same way as real orders. However, CQM examined if these flows are predictable and it appeared that this was not the case. On the other hand, if only those orders are used which are in the system, unnecessary repositioning is sometimes required. An example is the following. Consider the situation in Figure 3.2. There are two tank containers available in a region, one at place T_1 and one at place T_2. There are two orders which have a loading location at O_1 and at O_2. Order O_1 has to be executed today, whereas order O_2 has to be executed in three days. Since the closer the tank container the cheaper the travel costs, MMP will determine that tank container T_1 should execute order O_1 and tank container T_2 should execute order O_2. However, it could be the case that it is expected that a tank container ends somewhere in the blue area, which is close to the loading location of order O_2. In this case, it is better to use tank container T_2 for order O_1 and the tank container that comes available for order O_2. Since these expected orders are not taken into consideration, MMP will not see this as a possibility.

Since order flows are hard to predict and future supply and demand for tank containers can influence the decisions which have to be taken today, a new version of the algorithm of MMP was created. This new version considers first only the known orders for the coming two days.

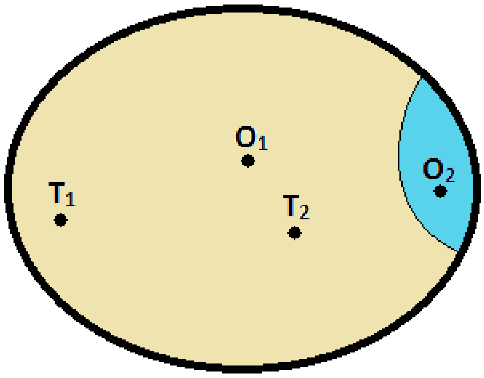


Figure 3.2 – Example

It combines each order with a tank container that is available such that the costs to execute the orders are minimized. All tank containers that are not used, are connected with a depot. Each depot has a minimum and maximum number of tank containers that can be stored at a depot. Through limitations at a depot, repositioning costs due to imbalance of supply and demand are included into the model. However, these limitations do not take tank container types into account. The model searches for the cheapest way to send tank containers and it does not matter which tank container types are stored at a depot and which tank container types are transported to another depot. After solving the model with the known orders for the coming two days, the tank containers that are used for the first day are fixed and these tank container - order combinations cannot change anymore. Then again the orders which are known and needed to be executed in two or three days are planned. The tank containers which were used for the orders for the first day are not available anymore. However, new tank containers will become available and these can also be used. Then the tank containers used for orders for the second day are fixed, and the orders for the third and fourth day are planned, et cetera. With this procedure hard orders are found. Hard orders are orders which can only be executed by a few tank containers and hence, are difficult to plan. These hard orders are treated differently as the other orders. However, these hard orders are only a small fraction of the orders. One advantage of this version is that the tank containers that are used for the orders that need to be executed the first day have minimal execution costs. However, a disadvantage is that MMP does not take the future into account. Take for example the situation in Figure 3.2 again. When order O_1 has to be executed the next day and order O_2 in three days, order O_2 is not considered in the first optimization. So tank container T_2 is assigned to order O_1. In the next optimization run, order O_2 is considered, but tank container T_2 is not available anymore. Therefore, tank container T_1 will be used for order O_2.

The solution created by MMP can be manually adapted by the planners of Den Hartogh and H&S. There are several planners working at Den Hartogh. Each planner has his own region and sends tank containers to loading locations within his region and determines what should happen with tank containers that become available in his region. Therefore, if an order can be done by multiple tank containers and the delivery location of the order is in another region, a planner does not have clear insight into the orders of another region and may send a tank container which cannot be used in that region. Besides that, there is a maximum number of containers at each depot. So if a tank container becomes available in a region and it is not needed for an order, a planner can send the tank container to a depot. However, if the depot close to the tank container is already full, the planner often sends the tank container to a depot which is owned by the company. The reason for this is that these depots are in Western Europe and often in these regions the demand for tank containers is higher than the supply and it is cheaper to store tank containers at these depots. However, sending the tank container to another depot or sending the tank container to another region is not considered, whereas this may be a better option.

Since MMP does not take the future into account, many unnecessary repositionings can occur and costs could be saved when this is taken into account. Besides this, MMP does not take into account tank container types. It treats every tank container as a separate tank container and it says only something about the number of tank containers stored at a depot instead of tank container types. In addition, it only looks at whether a tank container is able to execute an order and not whether that tank container could be used later in the region where the delivery location of the order is.

As already mentioned, Den Hartogh and H&S do not known all orders for the coming days. Besides this, dummy orders are also not possible, since the forecast of dummy orders will be unreliable. Even when the forecasted orders do not contain loading and delivery locations, but instead consist of loading and delivery regions, the forecast will be unreliable. The problem is that order flows between regions are hard to predict. However, the supply and demand for tank container types is predictable. In this forecast, the combination (the flow) between a loading region and delivery region is removed. One reason why this forecast is possible is that there is for example a factory that requires every week certain commodities which are needed to make the end product. It does not matter where these commodities come from, but the factory needs these commodities. On the other hand, the factory makes certain products which need to be transported to the users of those products every week. Similarly, the regions where these users are can differ, but that the factory wants to use tank containers to transport the end products is predictable. So, the flow may not be predictable, but the supply and demand are. However, this is not the only reason, since Den Hartogh and H&S are not the only ones who can transport the commodity for the customer. There are also competitors who can do the transport of that factory. The number of tank containers and tank container types is more predictable when the forecast is made per region. Hence, an aggregation to regions, time periods and tank container types, leads to a more predictable forecast of supply and demand for tank container types.

It is not the scope of this thesis to create a method of how to come up with an accurate forecast. Instead, it is assumed that there is a reliable forecast. It is assumed that it is possible to come up with a reliable forecast which has per region, per time period, a supply and demand for a certain number of tank container types. The reason that the forecast consists of several tank container types is that an order can be executed by more than one tank container type, as will be shown in Chapter 4. An example of such a forecast is the following: region A needs in one week five tank containers of tank container types T_1 or T_2 and, in that week, three tank containers of tank container types T_1 and T_3 will become available.

3.3 Problem description

As mentioned in Section 1.2, the goal of this thesis is to develop a model that supports the decisions of Den Hartogh and H&S which tank containers to send from where to where in order to minimize the costs created by empty tank container repositioning. To achieve this goal, the first problem is to determine tank container types. Since a tank container has many specific characteristics, many tank containers can be seen as unique tank containers. Modeling every tank container as a separate tank container results in a large model. To create tank container types only a couple of the characteristics of tank containers are considered. This is done in Chapter 4.

Given these tank container types, a model is created. The problem is to answer the question what should Den Hartogh and H&S do with their tank containers today. This includes the decision which tank container type to use for which order. Den Hartogh and H&S want to minimize the costs created by empty repositioning. The decision which tank container type they send today to execute an order has an influence on the empty repositioning movements in the future. As explained in the previous section, Den Hartogh and H&S currently work with MMP. However, one important disadvantage is that MMP does not take future orders into account, even when they know some of the future orders today. Therefore, the decision which tank container to send from where to where they make now is not made in order to minimize the empty repositioning costs. Instead the costs to execute the orders for the coming two days are minimized. However, this decision can lead to high empty repositioning costs in the future. In order to save costs in the future, the future should be taken into account. Therefore, our goal is to create a model that includes empty repositioning costs, even when they are made in the future.

To include empty repositioning costs in the problem, known orders and expected future supply and demand for tank containers should be taken into account. Costs related to empty repositioning are empty traveling costs and the costs to store a tank container at a depot. When a tank container is not used for a while or is not needed, a tank container can be stored at a depot. Den Hartogh and H&S have to pay for not using this tank container and store it at a depot. It can be a reason to reposition a tank container to another region, since it is cheaper to store it at another depot. Furthermore, if it is expected that there is no demand in that region and this tank container is stored for a long time at a depot in that region and is therefore not used, it can save costs to reposition the tank container to another region in order to be able to use the tank container in the future in that region. The model that is constructed which includes empty repositioning costs is described in Chapter 5 and 6.

Chapter 4

Defining tank container types

A tank container has many specific characteristics. A tank container can for example have an electric or hydraulic pump, or have no pump at all. Other characteristics are the position where a tank container can be loaded and unloaded, the maximum temperature to which the material can be heated, and the size of the tank container. These four characteristics are only a couple of examples of the characteristics tank containers have and these characteristics can differ per tank container. Every order has specific requirements for a tank container. Therefore, not all tank containers are suitable for every order. If every tank container is separately considered in the model, the model will be very detailed and large. Therefore, it is desirable to aggregate tank containers into tank container types. The fewer tank container types, the easier to handle. On the other hand, the more tank container types, the more accurate the model is. Tank containers can be divided into different tank container types according to important characteristics of tank containers. These important characteristics often play a key role in whether or not a tank container can execute an order. In this chapter, data of Den Hartogh and H&S are analyzed. In Section 4.1, the procedure how to decide whether a categorization of tank containers is appropriate is described. This procedure is partly based on earlier work of Post (2010). In Section 4.2, testing whether the categorization of tank containers is appropriate is done for Den Hartogh, and in Section 4.3, this is done for H&S.

4.1 Criteria for an appropriate categorization

First of all, we define a threshold. A threshold is set to decide whether or not an order can be executed by a specific tank container type. To explain this in more detail, consider a threshold of 30%. An order can be executed by tank container type A when at least 30% of the tank containers of tank container type A are allowed to execute the order. With this definition it can be tested whether the categorization of tank containers is appropriate. We define a categorization as appropriate when the categorization satisfies three desirable properties. The first desirable property is that (almost) no orders should be excluded. Orders can be excluded when only a few tank containers of a tank container type can execute an order, but this percentage tank containers of a tank container type is less than the threshold. Therefore, no tank container type can execute the order due to the definition of the threshold, whereas there are tank containers that are able to execute the order. The second desirable property is that the categorization of tank containers is robust. A categorization is said to be robust when most of the tank containers of a tank container type are actually able to execute that order, when it is stated that a tank container type can execute an order. In an ideal situation, all or none of the tank containers of a certain tank container type can execute an order. However, in reality this is not the case, because there are many characteristics which differ per tank container and orders require certain characteristics. The last desirable property is that the categorization of tank containers is distinctive. A categorization is said to be distinctive when there is significant difference in the orders tank container types can execute.

To test whether a categorization is robust it is first tested whether every tank container type is robust. Per tank container type only the orders are considered which can be executed by that tank container type. For every order that can be executed by that tank container type, the percentage of tank containers of that type that can actually execute that order is calculated. The average of all these percentages is taken and this number is called the robustness of that tank container type. In formula:

$$R_t = \frac{1}{|O_t|} \sum_{i \in O_t} \frac{C_{it}}{N_t} \cdot 100\% \tag{4.1}$$

where R_t is the robustness of type t, O_t is the set of orders that can be executed by tank container type t according to the categorization, C_{it} is the number of tank containers that belongs to tank container type t that can actually execute order i, and N_t is the number of tank containers that belongs to tank container type t. Since the robustness depends on historical data, the robustness can change over time.

The robustness is calculated for every tank container type. The total robustness is defined as the weighted average over the robustness of all tank container types. In formula:

$$Total\ robustness = \sum_t P_t \cdot R_t \tag{4.2}$$

where P_t is the fraction of tank containers of type t of the whole fleet.

To test whether a categorization is distinctive the average number of tank container types that can execute an order is considered. This is calculated with the following formula:

$$Distinctiveness = \frac{1}{|O|} \sum_{i \in O} A_i \tag{4.3}$$

where O is the set of orders and A_i is the number of tank container types that can execute order i. The closer this number to the number of tank container types, the less distinctive the categorization is. On the other hand, a number close to zero means that a lot of orders cannot be executed at all.

Before the total robustness and distinctiveness can be calculated, the value of the threshold should be determined. The value of the threshold has influence on the percentage of the orders that are excluded, the robustness and the distinctiveness. The higher the value of the threshold, the more orders are excluded, the more robust and the more distinctive the categorization will be. The reason is that orders which are just above the lower threshold value cannot be done by that tank container type if the threshold value increases. This increases the robustness and lowers the average number of tank container types that can execute an order. In addition, more orders cannot be done anymore by a tank container type, which increases the percentage of the orders that cannot be executed anymore.

It should be mentioned that a threshold of 30% could be seen as a low percentage. However, if an appropriate categorization is made, most orders can be executed by almost all tank containers of a tank container type or by only a few or none of the tank containers of a tank container type. There are relatively few orders which can be executed by about the half of the tank containers of a tank container type. As is shown in the next sections, the robustness with a threshold of 30% appears to be above 90%, which is much more than the threshold of 30%.

4.2 Tank container categorization for Den Hartogh

In Subsection 4.2.1, the tank container categorization of Den Hartogh is described. Then, in Subsection 4.2.2 this categorization is analyzed using the criteria introduced in Section 4.1.

4.2.1 Categorization of tank containers for Den Hartogh

For the categorization of tank containers for Den Hartogh there are six important characteristics of tank containers. First, these characteristics will be listed. Subsequently, these characteristics will be explained. In case of Den Hartogh, the important characteristics of tank containers are:

- Number of compartments
- Heating system
- ISO standard
- Size
- Baffles
- High isolation

A tank container can consist of only one compartment or multiple compartments. If an order consists of multiple products, the order can only be executed by tank containers with multiple compartments. An order that consists of only one product can also be executed by a tank container with multiple compartments. However, not all customers allow this. The number of compartments of a tank container is at least one and at most four.

A tank container of Den Hartogh always has a heating system. A tank container can be heated by either electric, glycol or steaming technology. Orders that can be executed by a tank container with an electric heating system can almost always also be executed by a tank container with a glycol heating system, and vice versa. In order not to introduce many tank container types, tank containers with an electric heating system are in the same type as tank containers with a glycol heating system.

A tank container meets the ISO standards if the length, width and height of the tank container lies within certain ranges according the ISO standards. Therefore, a tank container either meets or does not meet the ISO standards. Some customers require a tank container that meets the ISO standards.

The size of a tank container can be divided into three different measures: small, medium or large. The size of a tank container plays an important role in the volume that can be transported by the tank container. An order has a minimum and a maximum fill rate of a tank container. Besides this, it also determines whether or not a tank container can be transported via a certain route by train or ferry and the price of this transport. A large tank container requires more space than a small tank container. Therefore, the price to transport a large tank container by ferry can be more expensive than to transport a small tank container by that ferry. A tank container that meets the ISO standards is always a small tank container. Tank containers that do not meet the ISO standards differ in size. Therefore, these tank containers are further subdivided with respect to their size.

The last two important characteristics of tank containers of Den Hartogh are whether a tank container has baffles or not and whether a tank container is high isolated or not. Den Hartogh has no tank containers that have baffles and at the same time are high isolated. A baffle tank container is a tank container that has baffles in the tank container, which decrease sloshing of

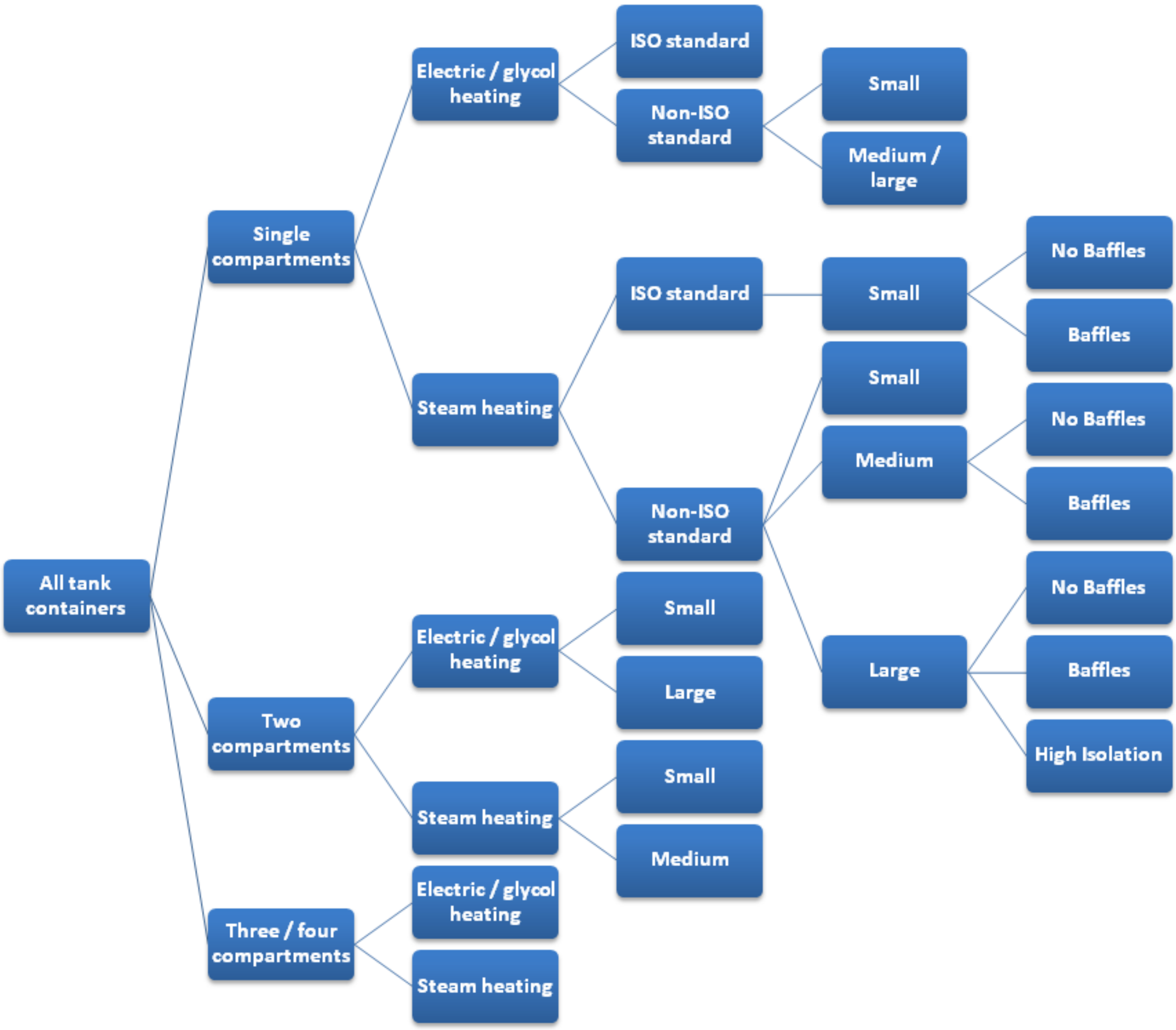


Figure 4.1 – Tank container categorization of Den Hartogh

the material in the tank container. Therefore, the size of the tank container is less important if a tank container has baffles. A high isolated tank container ensures that the temperature of the material in the tank container decreases less fast during the transportation. This can be important if the material is not allowed to come below a certain temperature. Due to the high isolation, the volume that can be transported by a high isolated tank container is lower than the volume that can be transported by a tank container of the same size, but without high isolation.

In Figure 4.1, the categorization of tank containers is presented. For some tank container types not all properties are (completely) distinguished. There are several reasons that not all tank container types are further distinguished. The most important reason is that the impact on the three criteria that an appropriate categorization should satisfy, is small. Therefore, if distinguishing the tank container types further results in a very small tank container type and the impact is small, the tank container types are not further distinguished. For example, only 9 out of 2,515 tank containers have three or four compartments, have a steam heating system and have size medium. Likewise, it could be that there are no tank containers of that type. For example, Den Hartogh has no tank containers with two compartments, a steam heating system and size medium. The last reason is that it is not useful to distinguish the tank container type further. As already mentioned, tank containers with an electric heating system are in the same tank container type as tank containers with a glycol heating system, because these tank containers can almost always execute the same orders. Table A.1 in Appendix A shows the composition of the fleet of Den Hartogh. Den Hartogh has in total 2,515 tank containers which they use for their intermodal transport in Europe.

4.2.2 Categorization analysis for Den Hartogh

In this subsection, the categorization of Den Hartogh is analyzed. First of all, the effect of the value of the threshold is investigated. The threshold is raised from 1% to 50% with steps of 5%. The results are presented in Table A.2 in Appendix A. As Table A.2 shows, the robustness increases if the threshold increases. Besides this, the average number of suitable container types decreases if the threshold increases. However, the percentage of orders that cannot be executed increases, if the threshold increases. This is in line with the expectation explained in Section 4.1. For this study, the threshold is set at 30%. The reason not to choose a higher threshold is that the robustness does not increase much, whereas more orders are excluded. The reason not to choose a lower threshold is that the robustness decreases, whereas at a threshold of 30% only one order is excluded, which is less than 0.1% of the orders.

With a threshold of 30% the categorization of Den Hartogh is analyzed in more detail. The robustness per tank container type is illustrated in Figure 4.2. The robustness is calculated with Formula 4.1. The robustness of the first tank container type, 1Comp|Elec/Glyc|Iso|Small, is 96.3%. This means that on average 96.3% of the tank containers of 1Comp|Elec/Glyc|Iso|Small are actually able to execute the order, if the type 1Comp|Elec/Glyc|Iso|Small is defined as able

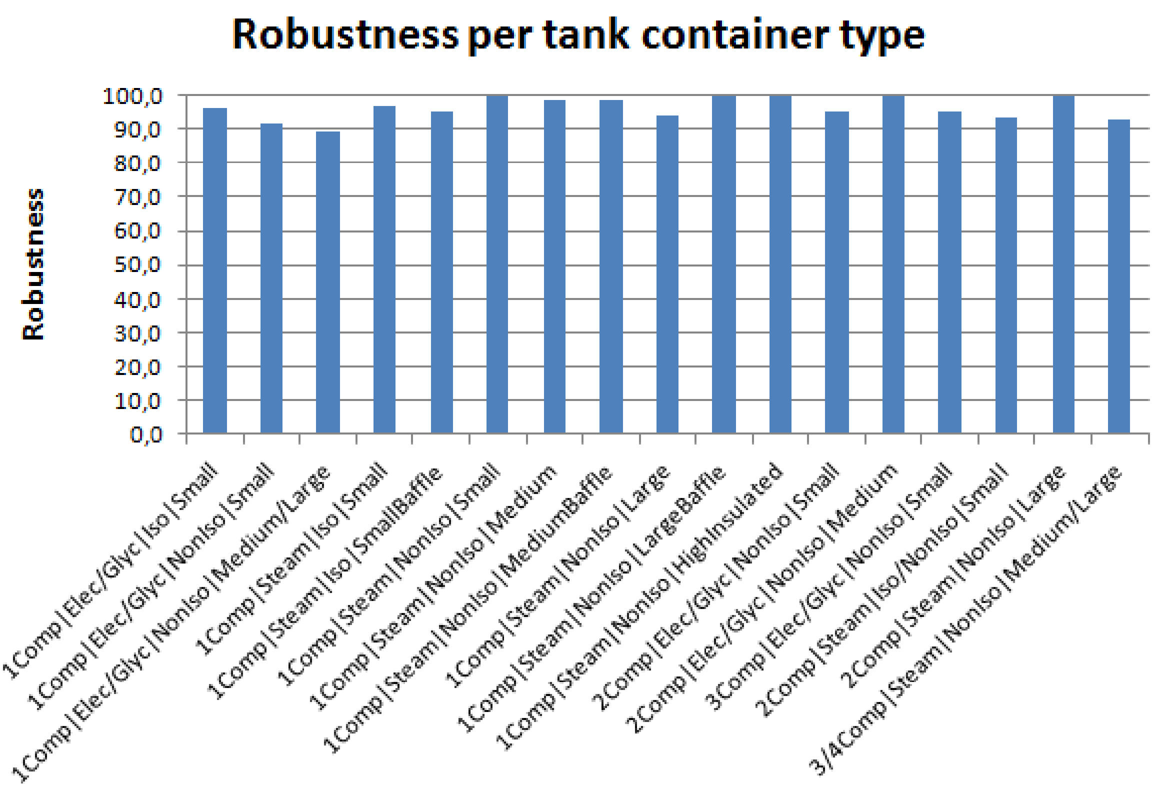


Figure 4.2 – Robustness of every tank container type of Den Hartogh

to execute the order. The tank container type 1Comp|Elec/Glyc|NonIso|Medium/Large has a robustness of 89.5% and has the lowest robustness of all tank container types. The total robustness is calculated with Formula 4.2. The total robustness of this categorization of Den Hartogh is 96.9%.

In Figure 4.3, the distinctiveness of the categorization of Den Hartogh is illustrated. This figure shows the percentage of orders that can be executed by a certain number of tank container types. For example, 5.2% of the orders can be executed by only one tank container type. There is one notable spike in the figure. There are relatively many orders that can be executed by six tank container types. The reason for this spike is that there are six tank container types that have an electric or glycol heating system and there are six tank container types with one compartment that have size medium or large. There are many orders that require a single compartment tank container, and for these orders sometimes a small tank container is not possible. Another spike is at eleven tank container types. This is because there are eleven tank container types with a single compartment and, as just mentioned, some orders are only allowed to be executed by a single compartment tank container. There is only one order that cannot be executed by any tank container type and 4.7% of the orders can be executed by all tank container types. The average number of tank container types that can execute an order is 7.09. What should be mentioned is that there is a certain structure in the orders and by which tank container types these orders can be executed. For example, orders require a single compartment tank container, or a steam tank container, or a single compartment steam tank container. Not all combinations of tank container types occur. Besides that, there are combinations that occur a lot.

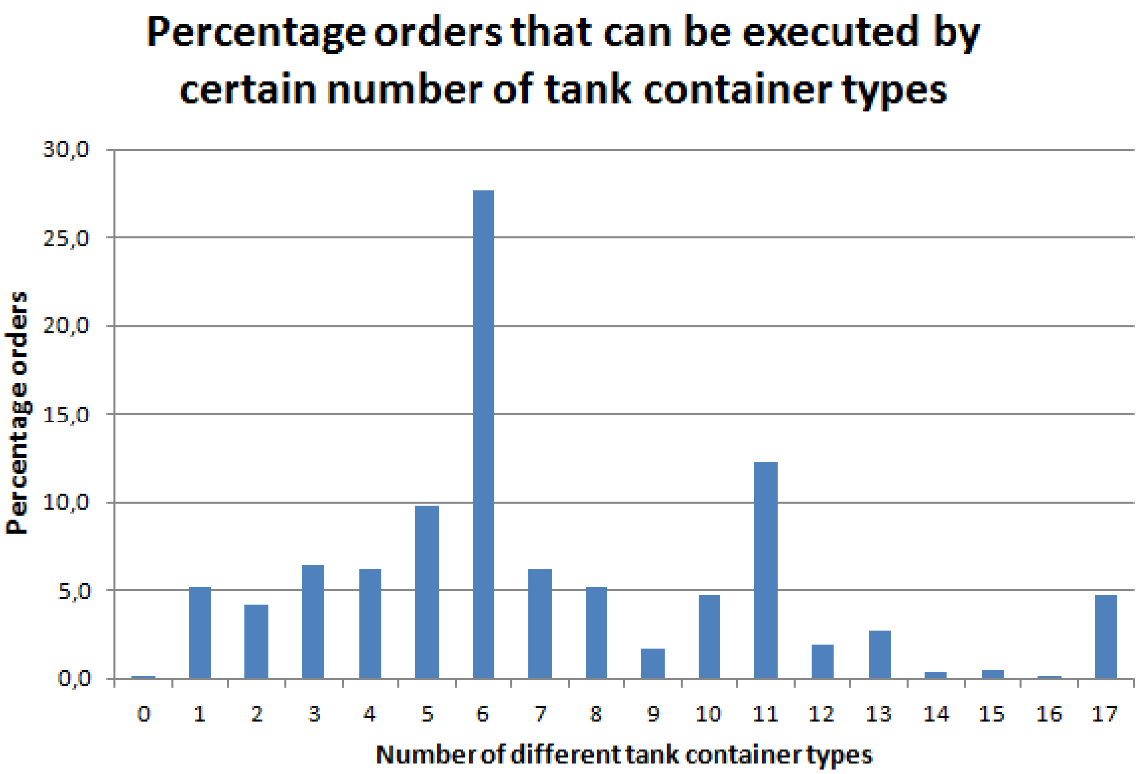


Figure 4.3 – Distinctiveness of tank container types of Den Hartogh

4.3 Tank container categorization for H&S

In Subsection 4.3.1, the tank container categorization of H&S is described. Then, in Subsection 4.3.2 this categorization is analyzed using the criteria introduced in Section 4.1.

4.3.1 Categorization of tank containers for H&S

Den Hartogh transports liquid chemicals and gases, whereas H&S transports liquid foodstuff. Therefore, the important characteristics of tank containers are different for H&S. The important tank container characteristics of H&S are:

- Food type
- Number of compartments
- Heating system
- Size
- High isolation
- Sterile filter
- Fully ground operated

H&S has two types of tank containers: tank containers that are only allowed to transport human food and tank containers that are only allowed to transport other products than human food, which are also related to food, such as fatty alcohol and stearic acids. Food is the name H&S gives for products which are for humans, and non-food for all the other products.

The following four important characteristics of H&S are the same as the important characteristics of Den Hartogh. However, there are some differences which should be mentioned. In case of H&S, the number of compartments can only be one or three. H&S has also three different heating systems, which are the same as Den Hartogh. However, in case of Den Hartogh tank containers with electric or glycol heating systems can often execute the same orders. By H&S this distinction in heating system should be made. Just like Den Hartogh, the size of a tank container can be divided into three different measures: small, medium and large. The last important characteristic of H&S that is the same as Den Hartogh is whether a tank container is high isolated or not. H&S has more different tank containers than Den Hartogh that have high isolation.

An important characteristic which is different from Den Hartogh is whether a tank container has a sterile filter or not. Since most of the commodities H&S transports is human food, it is important to have a sterile filter for safe consumption.

The last important characteristic of H&S is whether a tank container is fully ground operated or not. A tank container is fully ground operated if loading and unloading can be performed completely from the ground. On top of every tank container is an air valve. If a tank container is not fully ground operated, this air valve is only reachable when you climb on the tank container. However, if a tank container is fully ground operated, the tank container has a lever. With this lever the air valve can be opened and closed from the ground. For safety reasons some customers of H&S require a fully ground operated tank container.

In Figure 4.4, the categorization of tank containers of H&S is presented. Similarly as Den Hartogh, for some tank container types of H&S not all properties are (completely) distinguished. The reasons are similar to the reasons for the Den Hartogh case. For example, all food tank containers with electric heating system and size small have no high isolation. Table B.1 in

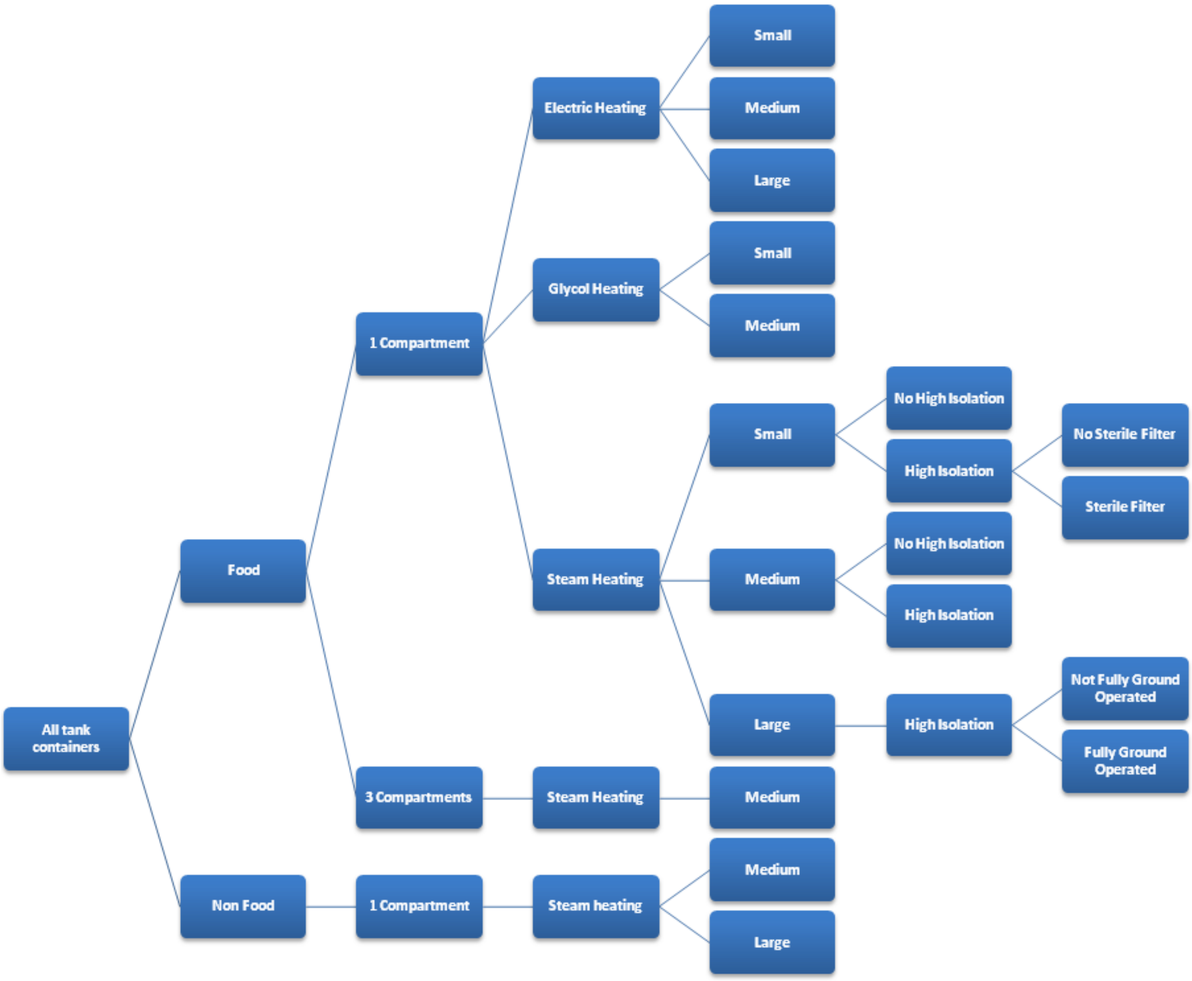


Figure 4.4 – Tank container categorization of H&S

Appendix B shows the composition of the fleet of H&S. H&S has in total 736 tank containers which they use for their intermodal transport.

4.3.2 Categorization analysis for H&S

In this subsection, the categorization of H&S is analyzed. Just like for Den Hartogh, the effect of the value of the threshold for H&S is investigated. The threshold is raised from 1% to 70% with steps of 5%. The results are presented in Table B.2 in Appendix B. As Table B.2 shows, also for H&S holds that if the threshold increases, the robustness increases. Besides this, the average number of suitable tank container types decreases and the percentage orders that cannot be executed increases if the threshold increases. For H&S the threshold is set at 65%. The reason not to choose a higher threshold is that the percentage orders that are excluded rises much. The reason not to choose a lower threshold is that the robustness decreases, whereas the percentage orders that is excluded does not decrease until the threshold of 20%. The difference in robustness between a threshold of 20% and a threshold of 65% is almost 3.5%, whereas only a few more orders are excluded with a threshold of 65%. Besides this, the robustness of tank container type Food|1Comp|Steam|Small|HighIsolation|NoSterile is 10.1% higher with a threshold of 65% compared to the threshold of 20%.

With a threshold of 65% the categorization of H&S is analyzed in more detail. The ro-

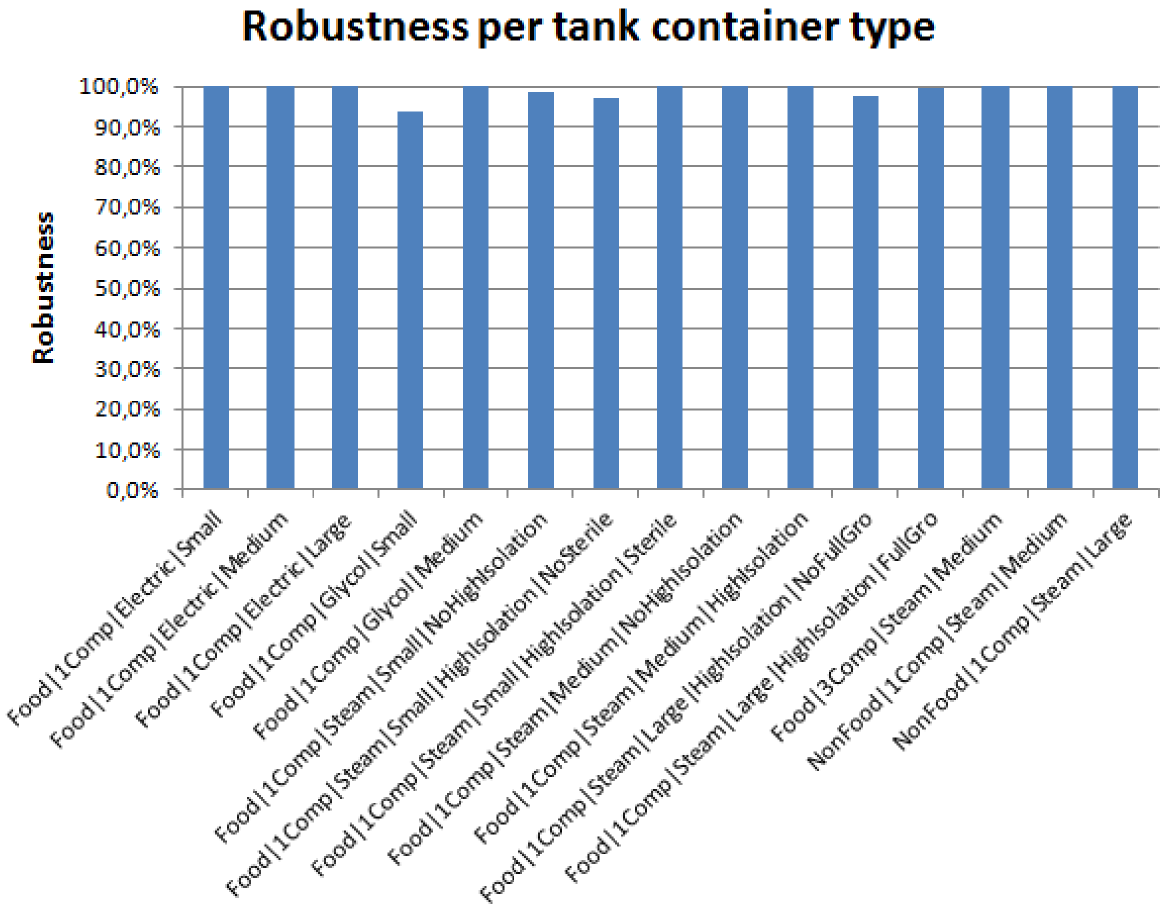


Figure 4.5 – Robustness of every tank container type of H&S

bustness per tank container type is illustrated in Figure 4.5. The robustness is calculated with Formula 4.1. The tank container type Food|1Comp|Glycol|Small has a robustness of 93.6% and has the lowest robustness of all tank container types. There are ten tank container types which have a robustness of 100.0%. Each of these tank container types consists of relatively few tank containers and are for that reason very specific, which results in a robustness of 100.0%. The total robustness is calculated with Formula 4.2. The total robustness of this categorization of H&S is 98.0%.

In Figure 4.6, the distinctiveness of the categorization of H&S is illustrated. This figure shows the percentage of orders that can be executed by a certain number of tank container types. For example, 4.7% of the orders can be executed by only one tank container type. There is one notable spike in the figure. There are relatively many orders that can be executed by twelve tank container types. The reason for this spike is that there are twelve food tank container types with one compartment. There are many orders that require a single compartment food tank container. No order can be executed by all tank container types. The reason for this is that H&S makes distinction between food and non-food tank containers and a tank container can only transport either food or non-food products. The percentage of the orders that cannot be executed by any tank container type is 0.4%. The average number of tank container types that can execute an order is 7.04. Similar as Den Hartogh, there is a certain structure in the orders and by which tank container types these orders can be executed.

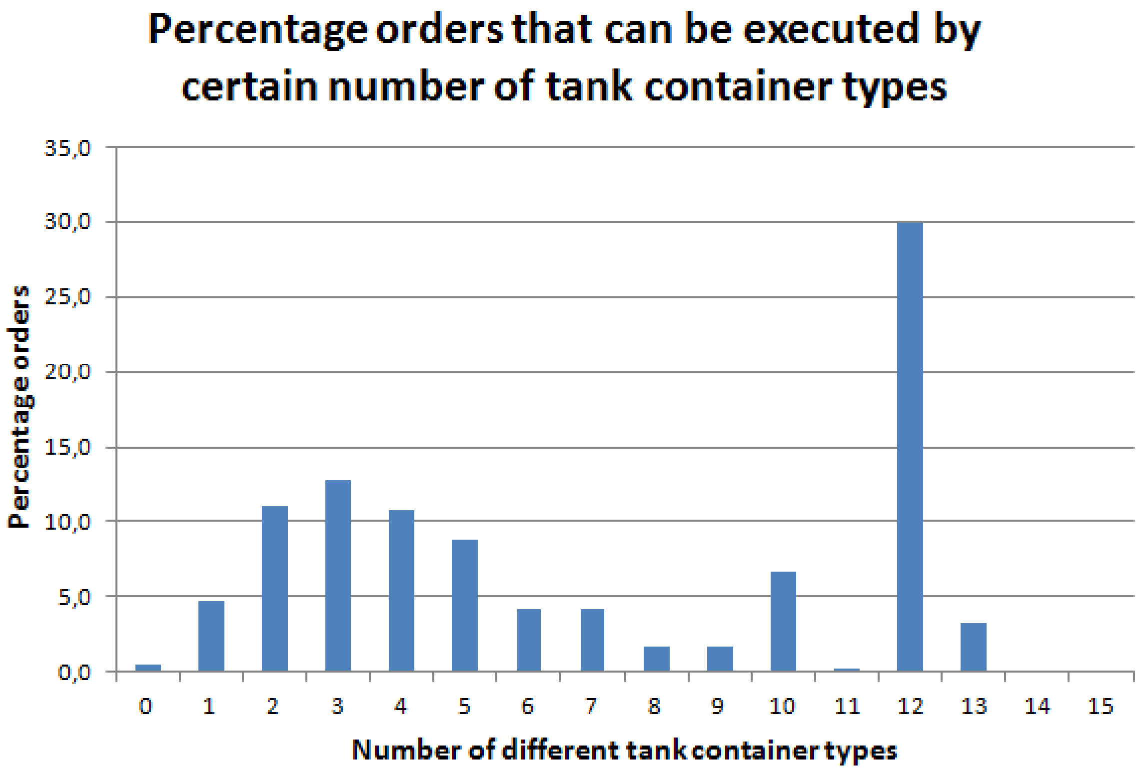


Figure 4.6 – Distinctiveness of tank container types of H&S

Chapter 5

Empty tank container repositioning model with all orders known

In Chapter 4, the categorization of tank containers of Den Hartogh and H&S is introduced. Given this categorization, we will construct a model for empty tank container repositioning. In this chapter, we assume that all orders for the coming weeks are known. In Section 5.1, more context of the research problem is given. In Section 5.2, the model is described, and in Section 5.3, the mathematical formulation is presented. In Section 5.4, the problem size is reduced for the Den Hartogh case. In the last section of this chapter, the solvability of the model with AIMMS is considered.

5.1 Context and objectives

The goal of this thesis is to construct a model that minimizes the empty repositioning costs and helps Den Hartogh and H&S in their decisions which tank containers to send from where to where. What is important is that everything that has an influence on the decisions which should be made today is taken into account. Decisions which should be made today are what every available tank container should do. A tank container can be used to execute an order, can stay at a depot, or can be transported to a depot. A tank container is available if it is at a depot or immediately after it has finished an order and the decision to where to send the tank container has not yet been made. Examples of features that have an influence on the decision from where to where to send a tank container are:

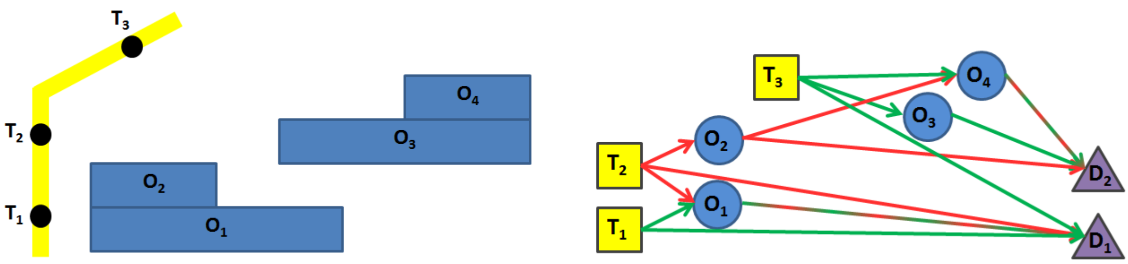
- Current positions of tank containers
- Availability of tank containers
- Origin and destination sites of the orders
- Loading and delivery times of the orders
- By which tank container types the orders can be executed
- Green-/blacklist
- Empty travel times and costs

The position and the availability of tank containers can be found in the yellow line. As described in Section 3.2, the yellow line contains the current status of all tank containers, including the moment when and the location where the tank container becomes available, and if the tank container is already available, where the tank container is. The following three listed examples are about the orders. As explained in Section 3.1, all known orders consist of an origin and destination site, a loading and delivery time, and the required characteristics of tank containers. The loading time states when a tank container should be at the origin site, and the delivery time states when the tank container becomes available at the destination site. With the constructed tank container categorization introduced in Chapter 4, it can be defined for each order by which tank container types the order can be executed. The next listed example is the green-/blacklist, which was explained in Section 3.1. Den Hartogh and H&S know what the last product in the tank container was and this results in a matrix that states whether a tank container is allowed to execute an order according to the green-/blacklist or not. Besides this, it is known whether two orders can be executed subsequently by the same tank container according to the green-/blacklist. The last listed example are the empty travel times and costs. The empty travel time and cost depend on the size of the tank. It is assumed that there is only one route to transport the tank container. In reality, it is often possible to transport a tank container in several ways from one location to another. As mentioned in Section 3.1, it is assumed that every tank container should go to a depot before executing a new order. The chosen route is the cheapest route to transport the tank container via a depot.

5.2 Description of the model

This section describes the model that is constructed to minimize the empty repositioning costs. The constructed model is a flow model with a rolling horizon. An advantage of a rolling horizon is that only the decisions for the first day are implemented and the next day, the model is solved again. In this way, new information can be taken into account. Although in this chapter we assume that all orders are known, we relax this assumption in the next chapter. The model is described with the aid of an example and Figure 5.1.

In the example, the planning horizon is seven days, starting at the beginning of day 1 and ending at the end of day 7. There are three tank containers, four orders and two depots. Figure 5.1a visualizes the tank containers and orders. In Figure 5.1a, a time axis could be included. The yellow line represents when the tank containers become available and the rectangles represent the orders. A rectangle starts at the loading time of an order and ends at the delivery time of an order. In Figure 5.1b, the flow network of the situation in Figure 5.1a is displayed. The yellow line is replaced by tank container nodes, the squares, and the orders are replaced by order nodes, the circles. This figure also includes time. The more to the right a tank container node is, the later it becomes available. The same holds for the order nodes: the more to the



(a) Planning situation

(b) Flow network

Figure 5.1 – Example of a planning situation with the graphical representation

right an order node is, the later the loading time of the order. However, the location of an order node does not say anything about the delivery time. The triangles represent the depots. All flows should start at a tank container node and end at a depot node. Flows cannot start or end in an order node. Instead, a flow of value one should enter and leave an order node, since every order has to be executed.

The set of depot nodes where flows can end does not consist of all depots. Instead, a subset of the depots is used. The reason not to include all depots is that if a tank container is not needed anymore nearby the place where the tank container ends, storing the tank container at a depot nearby and not using it only generates costs. In this way, tank containers are only repositioned if necessary. An example for Den Hartogh is Turkey. In Turkey, only orders end and (almost) no orders start. If a tank container can be stored at the depot in Turkey, it will not be used anymore, since it is more expensive to transport the tank container to a region where there is demand for tank containers, than to store the tank container at the depot, because the storage costs are relative low compared to the empty traveling costs. In this way, the tank containers accumulate at the depot in Turkey and repositioning of tank containers occur only when the tank containers are highly necessary. However, these tank containers should be used someday, since storing a tank container for a very long time at a depot only generates costs. Since tank containers should return someday, the costs of not using the tank container should therefore include the repositioning costs. By repositioning a tank container earlier, the storage costs can decrease and this tank container can be used for other orders, since the tank container is then stored in a region where there is demand. What is important is that the model uses a rolling horizon. This means that a tank container is only repositioned if it is expected that the tank container is not used during the whole planning horizon. If a tank container is not used during the whole planning period, the tank container can be repositioned to a region where there is demand for tank containers and this tank container can be used there. In the example, this means that there can be, for example, five depots, but only two depots are used as depot nodes. The depots that are included in the depot nodes are in the Den Hartogh case the depots that are in regions where many orders start, have a large capacity and are owned by Den Hartogh. Therefore, the set of depots for the Den Hartogh case consists of three depots, one in Belgium, one in Germany and one in the Netherlands.

In Tables 5.1 and 5.2, information about the tank containers and the orders of the example

Tank container	**Tank container type**	**Day available**
T_1	Type B	Day 1
T_2	Type A	Day 1
T_3	Type B	Day 2

Table 5.1 – Information about the tank containers

Order	**Can be executed by tank container type**	**Loading day**	**Delivery day**	**Tank containers not allowed according to green-/blacklist**	**Orders not allowed as last order according to green-/blacklist**
O_1	Type A and B	Day 1	Day 5	-	-
O_2	Type A	Day 1	Day 3	-	O_3
O_3	Type B	Day 4	Day 8	T_1	-
O_4	Type A and B	Day 6	Day 8	T_1, T_2	O_1

Table 5.2 – Information about the orders

are presented. Tank containers T_1 and T_2 are available at the start. Orders O_3 and O_4 end after the end of the planning horizon.

In the flow model, there are four different types of arcs:

1. Tank container and order
2. Tank container and depot
3. Order and order
4. Order and depot

Tank container - order arc

The first type of arc is the connection between a tank container node and an order node. A tank container node and an order node can be connected if the following three conditions are satisfied:

1. The tank container can be on time at the origin site of the order.
2. The order can be executed by the tank container type.
3. The tank container is allowed to execute the order according to the green-/blacklist.

In the example, this means that due to the first condition, an arc, for example, from T_3 to O_1 is not included in the network. An arc from T_1 to O_2 is not included in the network due to the second condition. Due to the last condition, an arc from T_1 to the orders O_3 and O_4 is not included in the network. Tank container type A is represented by a red arc and tank container type B is represented by a green arc. Since tank container T_2 belongs to tank container type A, only red arcs leave the tank container node T_2. Similarly, since tank containers T_1 and T_3 belong to tank container type B, only green arcs leave tank container nodes T_1 and T_3. The costs of this type of arc consist of two cost factors: empty travel costs and storage costs. The empty travel costs are calculated by the costs to travel from the location where the tank container is / becomes available to a depot plus the costs to travel from the depot to the origin site of the order. It is possible that a tank container is already at a depot. Consequently, the empty travel cost consists only of the costs to travel from the depot to the origin site of the order. The storage costs are the costs of storing a tank container at a depot. These costs are calculated by the product of the number of days a tank container is stored at a depot and the costs per day of storing a tank container at a depot. In the example, tank containers T_1 and T_2 are available at the beginning of the planning horizon. Tank container T_3 is executing an order which is finished at day 2. Therefore, tank container T_3 ends at a destination site and should first be transported to a depot before executing an order. If the total travel time to the origin site of order O_4 is one day, the tank container is stored for three days at a depot. If the travel costs to the depot are 50 euros and from the depot to the origin site are 80 euros and the storage costs are 5 euros per day, the costs of an arc between tank container node T_3 and order node O_4 are: $50 + 80 + 3 \cdot 5 = 145$ euros.

Tank container - depot arc

The next type of arc is the connection between a tank container node and a depot node. If a tank container is at a depot, the costs of the arc between the tank container and that depot only consist of the storage costs. If a tank container is not at a depot yet, or a tank container is repositioned to another depot, the costs of this type of arc consist of the empty travel costs to the depot plus the storage costs. The number of days a tank container is stored at a depot can be calculated by considering the number of days between the day the tank container arrives at the depot and the end of the planning horizon. What should be mentioned is that it can be determined beforehand which tank container-depot arcs will not be used, since with multiple depot nodes, only the cheapest tank container-depot arc is likely to be chosen. This is the case, since there is no constraint at the depot nodes and all flow end at the depot nodes. Therefore, only the cheapest tank container-depot arc has to be added to the flow network. In Figure 5.1b, only one arc leaves a tank container node and enters a depot node. If tank container T_1 is already at depot D_1 the costs of an arc between T_1 and D_1 consists of the storage costs of the whole planning horizon. These costs are: $7 \cdot 5 = 35$ euros. If the travel time to depot D_2 is two days and the costs are 100 euros, the costs of the arc between T_1 and D_2 is: $100 + 5 \cdot 5 = 125$ euros. Since the costs of an arc between T_1 and D_1 is lower than the costs of an arc between T_1 and D_2, only the arc between T_1 and D_1 is included in the flow network.

Order - order arc

The third type of arc is the connection between two orders. There can be more than one arc between the same two orders. The reason for this is that for every tank container type, a different arc is used. In the example, order O_1 can be executed by two tank container types. This means that there is a choice between two tank container types to fulfill this order and hence, two different arcs, one for each tank container type, are needed. Therefore, an order-order arc also depends on the tank container type. For the previous two types of arcs there is only one tank container type possible, since a tank container belongs to only one tank container type. An order-order arc of tank container type t is included in the flow network if the following four conditions are satisfied:

1. The first order can be executed by tank container type t.
2. The second order can be executed by tank container type t.
3. The time between the loading moment of the second order and the delivery moment of the first order is larger than the travel time of tank container type t between the destination site of the first order and the origin site of the second order.
4. It is allowed according to the green-/blacklist.

In the example, this means that according to the first two conditions no arc of tank container type B is included in the flow network from order O_2 to order O_4 and no arcs are included in the flow network from order O_2 to order O_3. Due to the third condition no arcs are included in the flow network from order node O_1 to order node O_3. Due to the last condition, no arcs are included in the flow network from O_1 to O_4. This green-/blacklist is independent of the tank container type. Again, the costs of this type of arc consist of the empty travel costs and the storage costs. The empty travel costs are calculated by the costs to travel from the destination site of the first order to the depot plus the costs to travel from the depot to the origin site of the second order. The storage costs are calculated in the same way as the storage costs of a tank container-order arc.

As mentioned in Section 5.1, the depot that is chosen between the tank container-order arcs and order-order arcs, is the depot which has the lowest cost. A tank container can sometimes be transported via different routes, and hence, also via different depots. Therefore, by creating the network, the decision is made via which depot the tank container could go. The depot which leads to the lowest empty traveling costs and storage costs is chosen. In the example, there is an arc between order node O_2 and order node O_4. To travel from the destination site of order O_2 to the origin site of order O_4 the tank container can go via depot D_1 and via depot D_2. If the total travel time via depot D_1 is two days and the empty travel cost is 120 euros, the total costs via depot D_1 would be: $120 + 1 \cdot 5 = 125$ euros. If the total travel time via depot D_2 is one day and the empty travel cost is 70 euros, the total costs via depot D_1 would be: $70 + 2 \cdot 5 = 80$ euros. As a result, the cheapest way to transport the tank container from the destination site of order O_2 to the origin site of order O_4 is via depot D_2. In this way, the costs of the arc between order node O_2 and order node O_4 is 80 euros.

Order - depot arc

The last type of arc is the order-depot arc. Similar as for the order-order arcs, this type of arc depends on the tank container type, since an order can be executed by multiple tank container types. As can be seen in Figure 5.1b, the arc between order node O_1 and depot node D_1 is a red-green striped arc. This means that there are two arcs between order node O_1 and depot node D_1, one for tank container type A and one for tank container type B. Order O_1 can be executed by both tank container types, whereas order O_2 can only be executed by tank container type A. Therefore, only red arcs leave order node O_2. The costs of this type of arc consist again of the empty travel costs and the storage costs. However, it is possible that the delivery time of an order lies after the end of the planning horizon. If this is the case, the order-depot arc does not really exists. To solve this problem, the costs of these arcs are zero and are connected with one depot. It does not matter which depot is chosen, since there is no constraint at the depot nodes and this transportation lies after the planning horizon and does not need to be executed today. The costs are zero, because repositioning this tank container is only possible after the end of the planning horizon. These repositioning costs will be included if the tank container becomes available within the planning horizon and then the decision to where to send the tank container can be made. In the example this holds for order O_3 and order O_4. These order nodes are both connected with depot node D_2. Another possibility is that the order is finished within the planning horizon, but the time the tank container will arrive at the depot is later than the end of the planning horizon. In this case, there are no storage costs. However, the empty travel costs are included, since the tank container will be sent within the planning horizon and is therefore not available anymore until the tank container arrives at the depot. Similar as for the tank container-depot arcs, it can be determined beforehand which order-depot arcs will not be used, since with multiple depot nodes, only the cheapest order-depot arc is likely to be chosen, since there is no constraint at the depot nodes. Therefore, for every order node, there is only one order-depot arc included in the flow network.

5.3 Mathematical model

In the previous section, the description of the flow network is given. This section presents the mathematical formulation of the model. Subsection 5.3.1 describes the constructed flow network. In Subsection 5.3.2, the integer programming formulation is stated.

5.3.1 The flow network

The constructed model is a minimum-cost multicommodity flow model. In a minimum-cost multicommodity flow problem there are multiple commodities and the goal is to minimize the costs of sending flow over arcs under the constraint that the total demand for the commodities should be fulfilled. In this thesis, all orders should be executed and the goal is to minimize the empty repositioning costs. Therefore, the model is formulated as a minimum-cost flow model. Besides this, Den Hartogh and H&S have multiple tank container types. Consequently, the minimum-cost flow problem becomes a minimum-cost multicommodity flow problem.

Before the integer programming formulation can be given, the flow network of all nodes and arcs should be defined. First of all, the definitions of the sets are given.

Sets:

T is the set of tank container types

V is the set of nodes

$C \subset V$ is the set of tank containers which is a subset of the set nodes

$O \subset V$ is the set of orders which is a subset of the set nodes

$D \subset V$ is the set of depots which is a subset of the set nodes

A is the set of arcs

As explained in Section 5.2, there are three different types of nodes: tank container nodes, order nodes and depot nodes. These sets form together the set nodes: $C \cup O \cup D = V$. Before the definition of the set of arcs can be given, some parameters should be defined.

Parameters:

$$e_{vt} = \begin{cases} 1 & \text{if } v \in C \text{ and tank container } v \text{ belongs to tank container type } t \\ 1 & \text{if } v \in O \text{ and order } v \text{ can be executed by tank container type } t \\ 1 & \text{if } v \in D \\ 0 & \text{otherwise} \end{cases}$$

l_v is the loading time of order v if $v \in O$

$$a_v = \begin{cases} \text{time tank container } v \text{ becomes available} & \text{if } v \in C \\ \text{delivery time of order } v & \text{if } v \in O \end{cases}$$

r_{uvt} is the transportation time from node u to node v with tank container type t

gb_{uv} states whether node u and node v are allowed to follow one another according to the green-/blacklist

h_{vd} states whether depot d is the depot to which the empty repositioning costs from the location where the tank container becomes available are the lowest

P is the time of the end of the planning horizon

So, the parameter e_{vt} states, if v is an order node, whether node v can be executed by tank container type t or not. If v is a tank container node, e_{vt} is 1 if tank container node v belongs to tank container type t. If v is a depot node, e_{vt} is 1, independent of the tank container type t. Note that the parameters l_v and a_v are not defined for all nodes. The parameter l_v states the time when flow should arrive at node v. Since flow can only leave tank container nodes, l_v is not defined if $v \in C$. If $v \in D$, l_v should define the time when flow should arrive at depot v. However, a tank container can arrive at a depot every day, which means that there is no time restriction at depot nodes. Therefore, l_v is not defined if $v \in D$. The parameter a_v states the time when flow can leave node v. Since flow cannot leave a depot node, a_v is not defined if $v \in D$.

With these parameters, the definition of the set of arcs can be given. The set of arcs can be divided into two sets. The first set is the set for all tank containers that become available before the end of the planning horizon and for all orders that are finished before the end of the planning horizon. The second set of arcs is the set for all tank containers that become available after the end of the planning horizon and for all orders that are finished after the end of the planning horizon. For the first set of arcs this means that from all tank container nodes that become available before the end of the planning horizon and all order nodes that are finished before the end of the planning horizon an arc can be included in the flow network to cheapest depot node. This first set is defined as:

$$A_1 = \{(u, v, t) : u \in C \cup O, v \in O \cup D, e_{ut} = 1, e_{vt} = 1, gb_{uv} = 1,$$
$$a_u - l_v \geq r_{uvt} \text{ if } v \in O, h_{uv} = 1 \text{ if } v \in D, a_u < P\}$$

This means that an arc of tank container type t between two nodes is not included in the flow network if tank container type t cannot leave or arrive node u or node v, the tank container cannot be on time at the origin site of order v ($\in O$), or the green-/blacklist does not allow the nodes to follow each other directly.

The second set of arcs is defined for all tank containers that are not available before the end of the planning horizon and for all orders that are finished after the end of the planning horizon. In this case, there is only an arc from the tank container node or order node to the depot node that represents the depot to which the empty repositioning costs are the lowest. This type of arc only concerns the arcs that ends in a depot node, since it is not possible to be on time at an origin site of an order due to the fact that only orders which loading time is before the end of the planning horizon are taken into account. Since an arc of this type ends in a depot node, the green-/blacklist is also not a restriction anymore. A depot has no restriction on the last order product in the tank container. The second set of arcs is defined as:

$$A_2 = \{(u, v, t) : u \in C \cup O, v \in D, e_{ut} = 1, h_{uv} = 1, a_u \geq P\}$$

The total set of arcs is the union of the two sets: $A = A_1 \cup A_2$. With the definition of the set of arcs, the other parameters can be given:

tc_{uvt} is the empty travel costs from node u to node v with tank container type t

n_{uvt} is the number of days a tank container is at a depot if a tank container of tank container type t is transported from node u to node v

sc is the storage cost per day of a tank container

c_{uvt} is the costs of using arc (u, v, t) and is defined as $c_{uvt} = tc_{uvt} + n_{uvt} \cdot sc$

The parameter tc_{uvt} is defined as the empty travel costs from node u to node v with tank container type t. This means that tc_{uvt} is equal to zero if arc $(u, v, t) \in A_2$. In that case, the tank container cannot be transported within the planning horizon to a depot node, since the tank container is available after the end of the planning horizon. The parameter n_{uvt} is defined as the number of days a tank container is at a depot if a tank container of type t is transported from node u to node v. This means that n_{uvt} is equal to zero if a tank container cannot arrive at depot node v before the end of the planning horizon. What should be mentioned is that the storage cost per day is independent at which depot the tank container is stored. However, this could easily be added to the cost function c_{uvt}, since it is known via which depot the tank container is transported from node u to node v.

5.3.2 Integer programming formulation

With the flow network which is constructed in the previous subsection, the integer programming formulation can be given. First of all, the variables should be defined.

Variables:

$$Y_{ot} = \begin{cases} 1 & \text{if order } o \text{ is executed by tank container type } t \\ 0 & \text{otherwise} \end{cases}$$

$$X_{uvt} = \begin{cases} 1 & \text{if arc } (u, v, t) \text{ is used} \\ 0 & \text{otherwise} \end{cases}$$

The variable Y_{ot} states by which tank container type an order is executed and the variable X_{uvt} states whether flow is sent over arc (u, v, t). All sets, parameters and variables are defined, which are needed in the model. The mathematical formulation of the model is:

$$\text{minimize} \quad \sum_{u,v,t:(u,v,t)\in A} c_{uvt} \cdot X_{uvt} \tag{5.1}$$

$$\text{such that} \quad \sum_{o} Y_{ot} = 1 \quad \forall o \in O \tag{5.2}$$

$$\sum_{u:(u,o,t)\in A} X_{uot} - Y_{ot} = 0 \quad \forall o \in O, \forall t \in T \tag{5.3}$$

$$\sum_{v:(o,v,t)\in A} X_{ovt} - Y_{ot} = 0 \quad \forall o \in O, \forall t \in T \tag{5.4}$$

$$\sum_{v,t:(c,v,t)\in A} X_{cvt} = 1 \quad \forall c \in C \tag{5.5}$$

$$X_{uvt} \geq 0 \quad \forall u, v \in V, \forall t \in T \tag{5.6}$$

$$Y_{ot} \in \{0, 1\} \quad \forall o \in O, \forall t \in T \tag{5.7}$$

The objective function asks to minimize the total empty travel and storage costs, as stated in objective function 5.1. These costs are defined as the sum of the costs of all arcs that are used. Constraint 5.2 ensures that all orders are executed by exactly one tank container type. This also means that each order should be executed and each order can be executed only once. Constraints 5.3 and 5.4 state that for all orders, the flow of a tank container type which enters the order node should also leave the order node. These constraints guarantee the preservation of the tank container type. Constraint 5.5 states that a flow of value one should leave every tank container node. This means that either the tank container is used and the costs of using the tank container are included, or the tank container is not used and it is sent to and stored at a depot and the costs of not using the tank container are included in the cost minimization. Constraint 5.6 states that the flow that is sent over an arc cannot be negative. Constraint 5.7 ensures that Y is a binary variable. So each order is executed completely by tank container type t or not by tank container type t.

5.4 Reducing the problem size for the Den Hartogh case

The definition of the arcs given in Section 5.3 can result in a large network. For Den Hartogh, there are 17 tank container types and an order can be executed on average by 7.09 different tank container types. This results in several arcs between two nodes. If the planning horizon is four weeks, the number of variables is well above twelve million. One way to decrease the computation time is to decrease the number of arcs. Some arcs can be removed beforehand, since these arcs will never be used in the optimal solution. To remove arcs between order nodes, the region of the destination site of the first order and the region of the origin site of the second order are considered. Some regions are far away from each other, such as Spain and Russia, and orders of which the destination site of the first order is in Spain and the origin site of the second order is in Russia, are therefore unlikely to follow each other using the same tank container. Some routes between two regions are cheap and some routes between two regions are expensive. Routes which are expensive are less likely to be used than routes which are cheap. The last reason to exclude some arcs is that in a region there is much demand every week. Therefore, it is likely that a tank container which ends in that region, will be used soon after the order is finished. Order combinations for which the loading time of the second order is, for example, one week after the delivery time of the first order, are unlikely to be used, since the tank container which executed the first order is already used for another order for which the loading time was earlier.

Table A.3 in Appendix A states, for every region where the destination site of the first order is and for every region where the origin site of the second order is, the number of days which are allowed to be between the delivery day of the first order and the loading day of the second order. Order combinations which are excluded from the flow network since the regions are too far away from each other have a minus sign in the table. Order combinations which make use of a cheap route are not excluded from the flow network unless the orders are too far apart in time. The last reason to exclude order combinations is that the tank container for the first order is likely to be used before the loading time of the second order is. This reason is represented by setting a maximum number of days which are allowed between two orders.

5.5 Solving the model with AIMMS

To solve the model that is introduced in Subsection 5.3.2, the model is implemented in AIMMS. CPLEX 12.4 is used as solver. After reducing the problem size and with a planning horizon of four weeks, the flow network for the Den Hartogh case consists of about 6,200 nodes and over the 7 million arcs. In the integer programming formulation, this results in more than 7 million variables and about 130,000 constraints. The execution time to solve this instance in AIMMS with CPLEX 12.4 was about two hours. Knowing that in this model it is assumed that all orders for the coming four weeks are known, the model is solvable within a reasonable amount of time.

Chapter 6

Empty tank container repositioning model with a forecast

In Chapter 5, we assumed that all orders for the coming weeks are known. In this chapter, we relax this assumption. As mentioned in Chapter 3, Den Hartogh and H&S do not know all orders for the coming weeks. Therefore, in addition to the list stated in Section 5.1, unknown future supply and demand for tank containers also have influence on the decisions which tank containers to send today. Some orders, which were assumed to be known in the previous chapter, are now included in the forecast of supply and demand for tank container types. In this thesis, it is assumed that unknown future supply and demand for tank container types can be forecasted. Recall that flows of tank container types between regions are not predictable, as explained in Section 3.2. Instead, the forecast consists only of supply and demand for tank container types for every region and time period. It is assumed that there is a forecast available. In Section 6.1, the model which includes a forecast of supply and demand for tank container types is introduced. In Section 6.2, the mathematical formulation is presented. In the last section, the solvability of the model with AIMMS is considered.

6.1 Description of the model including forecast

To include a forecast of supply and demand for tank container types, the model described in Chapter 5 is expanded. This means that this model is still a minimum-cost multicommodity flow model with a rolling horizon. Since in this chapter we assume that not all orders are known anymore, a rolling horizon limits the impact of a wrong forecast. Every day new information becomes available and orders which were first in the forecast are now known and the forecast for the coming days can be more accurate. Therefore, a rolling horizon can overcome the uncertainty of supply and demand for tank container types. The expanded flow model is described with the aid of an example.

An example of the flow network which includes a forecast is displayed in Figure 6.1. This example is an expansion of the example of Chapter 5. In this example, the planning horizon is again seven days, starting at the beginning of day 1 and ending at the end of day 7. There are five tank containers, three known orders, two nodes of forecasted demand for tank container types, two nodes of forecasted supply of tank container types, and two depots. Figure 6.1 includes a forecasted demand for tank container types, forecast nodes M_1 and M_2, and a forecasted supply of tank container types, forecast nodes P_1 and P_2. Since a forecasted demand for tank container types only requires tank containers, and no tank containers become available, no arcs leave these nodes. Likewise, a forecasted supply of tank container types results in the availability of tank

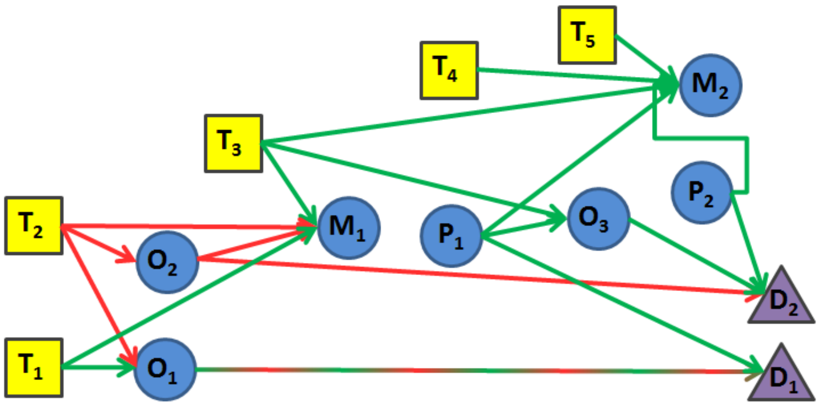


Figure 6.1 – Example of a flow network including forecast

containers and no tank containers are needed. Hence, no arcs enter these nodes. This means that all flows should start at a node representing a forecasted supply of tank container types or at a tank container node and end at a node representing a forecasted demand for tank container types or at a depot node. In Table 6.1, information about the tank containers of the example is presented, in Table 6.2, information about the known orders of the example is given, and in Table 6.3, information about the forecast of the example is given. From now on, we will refer to a forecasted demand for tank container types as a min forecast, and a forecasted supply of tank container types as a plus forecast.

In addition to the four types of arcs presented in Chapter 5, there are five more different types of arcs in this model. These five new types of arcs are:

1. Tank container and min forecast
2. Order and min forecast
3. Plus forecast and min forecast
4. Plus forecast and order
5. Plus forecast and depot

Tank container - min forecast arc

The first new type of arc is the connection between a tank container node and a min forecast node. A min forecast is a forecasted demand for tank container types for a region for a time period. In the example, M_1 has a forecasted demand for two tank containers of tank container type A or B. This means that a flow of value two should enter node M_1. This can be a flow of tank container type A, B, or both. These tank containers should be present on day 4 in the region. The depot of the region is used as the origin site of the forecast. Hence, there should be two tank containers of tank container type A or B at the depot of the region on day 4. A tank container node and a min forecast node can be connected if the following two conditions are satisfied:

1. The tank container can be on time at the depot of the region of the forecasted demand.
2. The forecasted demand allows the use of the tank container type as where the tank container belongs to.

Tank container	Tank container type	Day available
T_1	Type B	Day 0
T_2	Type A	Day 0
T_3	Type B	Day 2
T_4	Type B	Day 5
T_4	Type B	Day 6

Table 6.1 – Information about the tank containers

Order	Can be executed by tank container type	Loading day	Delivery day	Tank containers not allowed according to green-/blacklist	Orders not allowed as last order according to green-/blacklist
O_1	Type A and B	Day 1	Day 5	-	-
O_2	Type A	Day 1	Day 3	-	O_3
O_3	Type B	Day 6	Day 9	T_1, T_4	O_1

Table 6.2 – Information about the orders

Forecast	Type forecast	Tank container type	Size of the forecast	Day
M_1	Demand	Type A and B	2	Day 4
M_2	Demand	Type B	2	Day 7
P_1	Supply	Type B	2	Day 5
P_2	Supply	Type B	1	Day 7

Table 6.3 – Information about the forecast

In the example, this results in including an arc from tank container nodes T_1, T_2 and T_3 to min forecast node M_1 and an arc from tank container nodes T_1, T_3 and T_4 to min forecast node M_2. In Figure 6.1, there is no arc displayed between tank container node T_1 and min forecast node M_2 in order to keep the picture of the flow network clear, without too many crossing arcs. For the same reason, the tank container-depot arcs are not displayed. The costs of this type of arc consist of the empty travel costs and the storage costs, and are calculated in the same way as the previous types of arcs, introduced in Chapter 5.

Order - min forecast arc

The second new type of arc is the connection between an order node and a min forecast node. This type of arc depends on the tank container type, since an order can be executed by multiple tank container types and the forecasted demand consists of a choice of several tank container types. An order-min forecast arc of tank container type t is included in the flow network if the following three conditions are satisfied:

1. The order can be executed by tank container type t.
2. Tank container type t belongs to the possible tank container types for the demand of the min forecast.
3. The time between the arrival time of the min forecast node and the delivery moment of the order is larger than the travel time for tank container type t between the destination site of the order and the depot of the region of the min forecast.

In the example, this results in including an arc from order nodes O_1 and O_2 to min forecast node M_1 and an arc from order nodes O_1 and O_3 to min forecast node M_2. In Figure 6.1, there is no arc displayed between order node O_1 and min forecast node M_2 in order to keep the picture of the flow network clear, without too many crossing arcs. The costs of this type of arc consist of the empty travel costs and the storage costs, and are calculated in the same way as the previous types of arcs, introduced in Chapter 5.

Plus forecast node

The third additional type of arc is the connection between a plus forecast node and a min forecast node. Before introducing this type of arc, the definition of a plus forecast is explained in more detail. A forecasted supply of tank container types consists of the tank container types which could become available and the number of tank containers which are expected to become available. For example, it could be expected that at day 5 two tank containers become available of tank container type A or B. If it was an order, the tank container which enters the order node determines which tank container type leaves the order node. However, in case of a forecast, the supply and demand for tank container types are disconnected. If the model has freedom in determining which tank container types leave the plus forecast node, the tank container types that result in the lowest total costs will be chosen. This can result in expensive repositioning due to the fact that other tank container types become available and decisions which are made now depends on the forecast. Consider for example a company which has 99 tank containers of tank container type A and one tank container of tank container type B. In five days, there is an order which requires tank container type B. It is forecasted that in four days a tank container will become available nearby the origin site of the order. This tank container can be of tank container type A or B. The model is solved and in the optimal solution it is determined that a tank container of type B leaves the plus forecast node. However, the probability that a tank container of type B becomes available is very small, since there is only one tank container of tank container type B and 99 tank containers of tank container type A. If it appears that, in four days, a tank container of type A becomes available, an expensive repositioning of tank container type B is required to execute the order. Therefore, the tank container types which become available are predetermined and there is no choice in the model. This actually also holds for orders. There is a choice in determining which tank container type should execute an order. However, the tank container type that enters the order node, should also leave the order node.

To explain the determination of tank container types that will leave a plus forecast node, the example stated in the beginning of this section is used. Suppose that the tank container types which can leave plus forecast node P_1 are tank container types A and B. The fleet consists of one tank container of tank container type A and of four tank containers of tank container type B, as the first column of Table 6.4 shows. This means that the fraction of tank containers of tank container type A is 0.2 and for tank container type B this is 0.8, as shown in the second column of Table 6.4. The tank container types that will leave the plus forecast node are the ones with the largest fractions. Since the forecast is that two tank containers will become available, the fraction of tank containers is multiplied by 2. This means that the fraction of tank container type B which can leave plus forecast node P_1 is 1.6 and for tank container type A this is 0.4, as can be seen in the third column of Table 6.4. Subsequently, the fractions are rounded down to the nearest integer and the remainder is calculated. The remainder is defined as the difference between the fraction and the rounded fraction. The tank container types that leave a plus forecast node are the number of tank container types according to the rounded fractions. In the example, this means that there is one tank container of tank container type B. If these number

Tank container type	Number of tank containers in fleet	Fraction of tank containers in fleet	Fraction tank containers leave plus forecast node P_1	Rounded fraction	Remainder
Type A	1	0.2	0.4	0	0.4
Type B	4	0.8	1.6	1	0.6

Table 6.4 – Determining which tank container types leave P_1

of tank containers does not sum up to the size of the forecast, the remainder is used to chose the remaining tank container types. In the example, the remainder of tank container type B is 0.6 and the remainder of tank container type A is 0.4, as shown in the last column of Table 6.4. Since one more tank container is needed and 0.6 is larger than 0.4, the second tank container type that leaves P_1 is also tank container type B. Therefore, in Table 6.3 it can be found that only two tank containers of tank container type B should leave plus forecast node P_1.

Plus forecast - min forecast arc

Now the third new type of arc can be introduced. Similar as the second new type of arc, this type of arc depends on the tank container type, since the forecasted supply and the forecasted demand can both consist of multiple tank container types. A plus forecast-min forecast arc of tank container type t is included in the flow network if the following three conditions are satisfied:

1. Tank container type t can leave the plus forecast node.
2. Tank container type t belongs to the demand of the min forecast.
3. The time between the arrival time of the min forecast and the departure time of the plus forecast is larger than the travel time of tank container type t between the depot of the region of the plus forecast and the depot of the region of the min forecast.

Tank container type t can leave the plus forecast node if it is determined that tank container type t is one of the tank container types that should leave the plus forecast node, as described in the previous paragraph. What should be mentioned is that if the departure day of a plus forecast and the arrival day of a min forecast are the same, the tank containers which leave that plus forecast node can fulfill the demand of the min forecast if the regions are the same. In this way, only the net inflow of tank container types, or the net outflow of tank container types remains. Therefore, it is possible in the example to fulfill the demand of min forecast node M_2 with the supply of plus forecast node P_2. The net flow is -1, since M_2 requires two tank containers of tank container type B, whereas P_2 can only fulfill the demand for one tank container. This means that only one other tank container of tank container type B should enter min forecast node M_2. The other plus forecast-min forecast arc in the example, is the arc of tank container type B from plus forecast node P_1 to min forecast node M_2. Again, the costs of this type of arc consist of the empty travel costs and the storage costs, and are calculated in the same way as the previous types of arcs.

Plus forecast - order arc

The fourth new type of arc is the connection between a plus forecast node and an order node. Similar as the previous new type of arc, this type of arc depends on the tank container type, since the forecasted supply and an order can both consists of multiple tank container types. A plus forecast-order arc of tank container type t is included in the flow network if the following three conditions are satisfied:

1. Tank container type t can leave the plus forecast node.
2. Tank container type t is allowed to execute the order.
3. The time between the loading moment of the order and the departure time of the plus forecast is larger than the travel time of tank container type t between the depot of the region of the plus forecast and the origin site of the order.

Tank container type t can leave the plus forecast node if it is determined that tank container type t is one of the tank container types that should leave the plus forecast node, as described before. In the example, this results in including an arc of tank container type B from plus forecast node P_1 to order node O_3. Again, the costs of this type of arc consist of the empty travel costs and the storage costs, and are calculated in the same way as the previous type of arc.

Plus forecast - depot arc

The last new type of arc is the connection between a plus forecast node and a depot node. Similar as the previous new type of arc, this type of arc depends on the tank container type, since the forecasted supply can consists of multiple tank container types. Again, the costs of this type of arc consist of the empty travel costs and the storage costs, and are calculated in the same way as the previous type of arc. Similar as the order-depot arcs, which are introduced in Section 5.2, it is possible that a tank container which leaves a plus forecast node, arrives after the end of the planning horizon. If this is the case, the storage costs are zero. Similar as for the tank container-depot arcs and the order-depot arcs, it can be determined beforehand which plus forecast-depot arcs will not be used, since with multiple depot nodes, only the cheapest plus forecast-depot arc is likely to be chosen, since there is no constraint at the depot nodes. In the example, this means that plus forecast node P_2 is only connected with depot node D_2.

6.2 Mathematical model including forecast

The previous section provided a description of the model which includes a forecast of supply and demand for tank containers. This section presents the mathematical formulation of this model. Subsection 6.2.1 describes the constructed flow network that includes a forecast of supply and demand for tank container types. In Subsection 6.2.2, the integer programming formulation for the model that includes a forecast is stated.

6.2.1 The flow network including forecast

The model that is constructed in this chapter continues with the model which is introduced in Chapter 5. The definition of sets and parameters is only stated if it is new or different compared to the mathematical model in Section 5.3. The new sets are:

$M \subset V$ is the set of forecasted demand for tank container types which is a subset of the set nodes

$P \subset V$ is the set of forecasted supply of tank container types which is a subset of the set nodes

The two new sets are the sets for the min forecast nodes and for the plus forecast nodes. Compared with the model in Section 5.3, the set nodes consists now of more different types of nodes. The set nodes is now defined as: $C \cup O \cup M \cup P \cup D = V$. Besides the change in the definition of the set of the nodes, the definition of the set of the arcs is changed. Before providing this new definition, changes in the definitions of the parameters should be given.

$$e_{vt} = \begin{cases} 1 & \text{if } v \in C \text{ and tank container belongs to tank container type } t \\ 1 & \text{if } v \in O \text{ and the order can be executed by tank container type } t \\ 1 & \text{if } v \in M \text{ and the demand is for tank container type } t \\ 1 & \text{if } v \in P \text{ and tank container type } t \text{ becomes available} \\ 1 & \text{if } v \in D \\ 0 & \text{otherwise} \end{cases}$$

$$l_v = \begin{cases} \text{loading time of order } v & \text{if } v \in O \\ \text{arrival time of min forecast } v & \text{if } v \in M \end{cases}$$

$$a_v = \begin{cases} \text{time tank container } v \text{ becomes available} & \text{if } v \in C \\ \text{delivery time of order } v & \text{if } v \in O \\ \text{departure time of plus forecast } v & \text{if } v \in P \end{cases}$$

Added to all these definitions are the values of the parameters for the min forecast nodes ($v \in M$) and plus forecast nodes ($v \in P$). With these parameters, the definition of the set of arcs can be given. The definition of the sets A_1 and A_2 still hold. What should be added to the set of arcs are the arcs to the min forecast nodes and the arcs from the plus forecast nodes. The first new set of arcs are the arcs to the min forecast nodes:

$$A_3 = \{(u, v, t) : u \in C \cup O \cup P, v \in M, e_{ut} = 1, e_{vt} = 1, a_u - l_v \geq r_{uvt}\}$$

Set A_3 contains the first three new types of arcs. This set includes all arcs of tank container type t from a tank container node, an order node or a plus forecast node to a min forecast node, if tank container type t can leave the tank container, order or plus forecast node and can arrive in the min forecast node, and if the tank container can be on time at the depot of the min forecast node.

The next new set of arcs are the arcs from a plus forecast node. The set of arcs for all plus forecast nodes where the tank containers become available before the end of the planning horizon is defined as:

$$A_4 = \{(u, v, t) : u \in P, v \in O \cup D, e_{ut} = 1, e_{vt} = 1, a_u - l_v \geq r_{uvt} \text{ if } v \in O, h_{uv} = 1 \text{ if } v \in D\}$$

The set A_4 contains all arcs of tank container type t from a plus forecast node to an order node, if tank container type t can leave the plus forecast node and can arrive in the order node, and if the tank container can be on time at the origin site of the order. The set A_4 also contains all arcs from a plus forecast node to a depot node of tank container type t, if tank container type t can leave the plus forecast node and this depot is the depot to which the empty repositioning costs are the lowest.

The two new sets of arcs are given. This means that the total set of arcs consists of four subsets. The total set of arcs is defined as: $A = A_1 \cup A_2 \cup A_3 \cup A_4$.

Besides the parameters of Chapter 5 and the changes in the parameters, some new parameters are needed:

fm_m is the number of tank containers needed to fulfill the forecasted demand of min forecast node m

fp_{pt} is the number of tank containers of tank container type t of the forecasted supply of tank containers of plus forecast node p

s_{uvt} is the capacity of arc (u, v, t)

The parameters fm_m and fp_{pt} state the size of the forecast or in other words, the number of tank containers which are needed or become available. The parameter fm_m does not depend on the tank container type, since the forecast states the number of tank containers that are needed to fulfill the demand and only arcs of tank container types that can fulfill this demand are included in the flow network. The parameter fp_{pt} does depend on the tank container type, since it is predetermined which tank container types should leave the plus forecast node. The last new parameter is s_{uvt}. In the model where all orders are known, the capacity of an arc was always one. The reason for this is that an order requires only one tank container, so only a flow of value one can enter and leave the node. Besides this, only a flow of value one can leave a tank container node, since for every tank container there is a separate node. The model in this chapter includes a forecast. A forecast can consist of multiple tank containers of a certain tank container type. Therefore, it is possible to have a flow of a value more than one that leaves a plus forecast node, or arrives at a min forecast node. In the example of Section 6.1, the number of tank containers which should leave plus forecast node P_1 is two, and the number of tank containers which should arrive at min forecast node M_2 is also two. Therefore, the arc between P_1 and M_2 has a capacity of two. The capacity of each type of arc is given in Table 6.5.

6.2.2 Integer programming formulation including forecast

The flow network that includes a forecast is defined in the previous subsection. With this flow network, the integer programming formulation can be constructed. First, the variables should be redefined. The definition of the variable Y_{ot} does not change. Y_{ot} is still equal to one if order o is executed by tank container type t, and zero otherwise. The definition of the variable X_{uvt} is slightly changed. X_{uvt} defines the value of the flow over arc (u, v, t). If this value is zero, the arc (u, v, t) is not used. If this value is α, where $\alpha \in \mathbb{N}$, α tank containers are transported from the first node to the second node. Since each arc has a maximum capacity, the value of X_{uvt} cannot exceeds this capacity.

With the new definition of the sets, parameters and variables, we can give the mathematical formulation of the model in which a forecast of supply and demand for tank container types is included.

First type of node	Second type of node	Capacity of the arc
Tank container	Order	1
Tank container	Min forecast	1
Tank container	Depot	1
Order	Order	1
Order	Min forecast	1
Order	Depot	1
Plus forecast	Order	1
Plus forecast	Min forecast	$\min(fp_{pt}, fm_m)$
Plus forecast	Depot	fp_{pt}

Table 6.5 – Capacity for every type of arc

$$\text{minimize} \quad \sum_{u,v,t:(u,v,t)\in A} c_{uvt} \cdot X_{uvt} \tag{6.1}$$

$$\text{such that} \quad \sum_{o} Y_{ot} = 1 \quad \forall o \in O \tag{6.2}$$

$$\sum_{u:(u,o,t)\in A} X_{uot} - Y_{ot} = 0 \quad \forall o \in O, \forall t \in T \tag{6.3}$$

$$\sum_{v:(o,v,t)\in A} X_{ovt} - Y_{ot} = 0 \quad \forall o \in O, \forall t \in T \tag{6.4}$$

$$\sum_{v,t:(c,v,t)\in A} X_{cvt} = 1 \quad \forall c \in C \tag{6.5}$$

$$\sum_{u,t:(u,m,t)\in A} X_{umt} = fm_m \quad \forall m \in M \tag{6.6}$$

$$\sum_{v,t:(p,v)\in A} X_{pvt} = fp_{pt} \quad \forall p \in P, \forall t \in T \tag{6.7}$$

$$0 \leq X_{uvt} \leq s_{uvt} \quad \forall u, v \in V, \forall t \in T \tag{6.8}$$

$$Y_{ot} \in \{0, 1\} \quad \forall o \in O, \forall t \in T \tag{6.9}$$

The objective function asks to minimize the total empty travel and storage costs, as stated in objective function 6.1. This is the same as in the model of Chapter 5. Constraints 6.2 - 6.5 and Constraint 6.9 are also the same as in the model of Chapter 5. A new constraint is Constraint 6.6. This constraint ensures that the forecasted demand for tank containers is fulfilled exactly. The same holds for Constraint 6.7. This constraint ensures that the number of tank containers of tank container type t which becomes available at the plus forecast node, actually leave the plus forecast node. Constraint 6.8 ensures that the flow of an arc cannot be negative and not above its maximum capacity.

6.3 Solving the model with AIMMS

To solve the model that is introduced in Subsection 6.2.2, the model is implemented in AIMMS. CPLEX 12.4 is used as solver. After reducing the problem size as described in Section 5.4, and with a planning horizon of four weeks, the flow network for the Den Hartogh case consists of about 4,500 nodes and about 1.3 million arcs. In the integer programming formulation, this results in about 1.3 million variables and about 35,000 constraints. The execution time to solve this instance in AIMMS with CPLEX 12.4 is less than one minute. So, the model is solvable within a reasonable amount of time.

Chapter 7

Setup of the test

Before an analysis on the results of the model can be made, decisions about the choice of the length of the planning horizon and how to include the forecast exactly should be made. In Section 7.1, the length of the planning horizon is discussed. In Section 7.2, it is described how the forecast is included in the model.

7.1 Planning horizon

The length of the planning horizon has an influence on the decisions which should be made today. The more the future is taken into account, the lower the costs of empty repositioning can be. Therefore, the longer the planning horizon, the more information could be taken into account. This is especially the case when all orders are known. However, in the previous chapter we assumed that not all orders are known. Instead, there is a forecast of supply and demand for tank container types. This forecast could be wrong: more tank containers or fewer tank containers can be needed, or other tank container types are required. The longer the planning horizon, the fewer orders are known and the larger the forecast. The further in the future, the larger the uncertainty. Hence, there is a tradeoff between the reliability of the forecast and the information which can be taken into account.

The length of the planning horizon also has an influence on the computation time. The longer the planning horizon, the larger the flow network and the more variables in the model. This leads to an increase in the computation time. Since every day new information becomes available, the model should be solved every day. This means that the computation time may not be too long.

Other examples that have an influence on the decision of an appropriate length of the planning horizon, is the duration of an order, the empty travel time, and the utilization of tank containers. The decision which tank container type to use today for an order depends on which tank container types could be used nearby the destination site of the order. Therefore, it should be possible to execute several orders consecutively with one tank container in the planning horizon. Hence, the longer the duration of an order, the longer the planning horizon should be. The reason that the empty travel time has an influence on the decision of the length of the planning horizon is similar. The longer empty travel times are, the fewer orders can be executed consecutively with one tank container in the planning horizon. Consequently, the longer the empty travel time, the longer the planning horizon should be. The last example is the utilization of tank containers. The utilization of tank containers is the fraction of time tank containers are used to execute orders. The utilization depends on the number of orders and the number of tank containers. If an LSP has many orders and a few tank containers, the utilization will be high. On the other hand, if an LSP has many tank containers, but only a few orders, the utilization will be low. The lower the utilization, the fewer orders can be executed consecutively with one tank container in the planning horizon. Therefore, the lower the utilization, the longer the planning horizon should be.

As mentioned in Chapter 3, Den Hartogh knows only about 5% of the orders in the fourth week. The duration of an order for Den Hartogh varies from one day to several weeks. For about 85% of the orders the duration is between one day and one and a half weeks. Empty travel times in Western Europe are only a few days. In these regions, the most orders start or end. However, the farther away from Western Europe, the longer empty travel times are. All travel times are at most 12 days.

For Den Hartogh the planning horizon is chosen to be four weeks. The reason to choose this length is to take into account that several orders can be executed consecutively with one tank container. Even for the orders that have a long duration and ends in a region far from Western Europe, there is now a possibility to execute or to start with a new order. However, only 5% of the orders are known in the last week of the planning horizon. Consequently, a reliable forecast is required in order to prevent expensive repositioning.

7.2 Forecast

The forecast consists of the number of tank containers of certain types that are needed or become available in a region in a time period. The data that are used to analyze the performance of our model for the Den Hartogh case are the data of January 2014. The order data from January are also used to make a forecast. It is known when orders became known for Den Hartogh. So on January 1, only the orders that were not known yet are used in the forecast. The order data are aggregated on the basis of the regions where the orders start / end, time period, and ordertype. An ordertype is defined as a combination of tank container types which can execute the order. As mentioned in Chapter 4, there is a structure in the orders and by which tank container types these orders can be executed. Some combinations occur a lot and some combinations do not occur. The most frequent ordertypes are used for the aggregation. Each order belongs to one ordertype. This ordertype is the ordertype which resembles the best the tank container types that can execute the order.

As mentioned in Chapter 3, Den Hartogh has defined regions in Europe according to the supply and demand for tank containers. For each region, a depot is selected to be the regional depot. Therefore, the order data can be aggregated on the basis of the regions where orders start for the min forecast nodes and on the basis of the regions where orders end for the plus forecast nodes. The origin site of the min forecast nodes and the destination site of the plus forecast nodes are defined to be the regional depots.

The time period is chosen to be one week. This means that if January 1 is the first day of the planning horizon, the orders that start no earlier than January 1 and no later than January 7 are aggregated to be the min forecast nodes of the first week, the orders that start no earlier than January 8 and no later than January 14 are aggregated to be the min forecast nodes of the second week, et cetera. If the loading time of a min forecast is set to the first day of the week, all tank containers are expected to be in time to execute the orders. Similar, if the delivery time of a plus forecast is set to be the last day of the week, all tank containers are expected to be available at that time. For example, the loading times for the min forecast nodes of the second week are set at the start of January 8 and the delivery times for the plus forecast nodes are set at the end of January 15. However, some of the tank containers that become available in the second week, can fulfill some of the demand of the second week. Therefore, each one-week forecast is split into two min forecast nodes for that week, where the loading time of the first min forecast is still at the start of the first day of the week and for the second min forecast

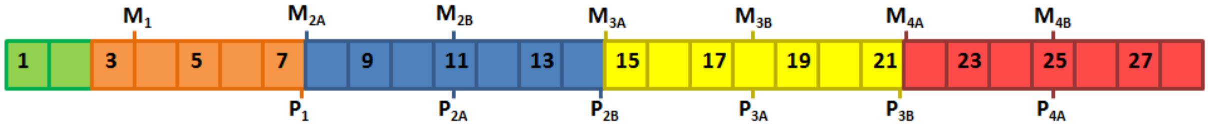


Figure 7.1 – Place min forecast nodes and plus forecast nodes at planning horizon

this is set at mid week. Similar, each one-week forecast is split into two plus forecast nodes for that week, where the loading time of the first plus forecast is at mid week and for the second plus forecast this is still the end of the week. Thus, the tank containers that leave the first plus forecast node of the week can fulfill the second min forecast of that week, and the second plus forecast can fulfill the demand of the first min forecast of the next week. In this way, only the net flow remains. So, although the forecast is made for one week, the forecast is split into two nodes in order to allow that some of the tank containers that become available that week can fulfill some of the demand of that week. The exact place of each min forecast and plus forecast node can be found in Figure 7.1.

It is assumed that the orders of the first two days are known, which are represented by the green rectangles in Figure 7.1. Sometimes, orders become known one day before the day of execution. These orders are only accepted if a tank container that can execute the order is nearby. If it is too expensive or not possible to execute the order, the order will not be accepted. Therefore, the positions of the tank containers are important in deciding whether or not these orders will be accepted. The situation in the model will be different than the actual situation. Since the percentage of the orders that are known just before they should be executed are very small, it is assumed that all orders for the first two days are known. Due to this assumption, there is only one min forecast in the first week (M_1). Besides this, the percentage of the orders that are not known for the third day are less than 10%. This percentage increases to 40% at the end of the first week. If the loading time of the forecasted demand for the first week is at the beginning of the third day, it is possible that several tank containers should be transported today to fulfill the total demand of the first week, whereas only a relatively small percentage of orders will actually occur at the third day, and a relatively large percentage of orders occurs later. In order to limit the impact of empty tank container transportations that should be made today to fulfill unknown demand for the first week, the loading time of the first min forecast is set at the beginning of the fourth day. This could have been done for the other min forecast nodes as well. However, the percentage orders that is not known increases less rapidly. In Figure 7.1, the place of M_1 is therefore placed at the start of day 4. This M_1 consists of the orders that have a loading time in one of the orange rectangles.

There is no plus forecast node at the fourth day, as shown in Figure 7.1. The first plus forecast node is at the end of the first week and consists of the orders that have a delivery time in one of the orange rectangles. This is because there should occur forecasted demand for tank containers before forecasted supply of tank containers can occur. It is assumed that if a tank container is executing an order, it is known when and where the tank container becomes available (the yellow line).

The forecast of the last week of the planning horizon consists of one plus forecast node, since the second plus forecast node of the last week cannot fulfill the demand of that week. This plus forecast node could only be connected to the depot nodes. However, only one arc would leave each of these plus forecast nodes, since it can be determined beforehand which plus forecast-depot arc is the cheapest. Since there are no constraints at the depot nodes, these last plus forecast nodes are not included in the flow network.

The next day, this procedure of creating a forecast is repeated. The orders that were not known at January 2 are used in the forecast and the loading and delivery times are all shifted to the next day.

Chapter 8

Analysis of the results for the Den Hartogh case

In this chapter, our model is applied to the Den Hartogh case and the results are analyzed. Data about the actual execution of the orders of Den Hartogh are available. It appeared that the actual execution was not comparable to our model, which will be explained in Section 8.1. Therefore, an alternative must be found in order to compare our model to the current performance of Den Hartogh. This is done in Section 8.2. In Section 8.3, the current performance is compared to the results obtained by using our model. Section 8.4 analyzes the differences in the decisions of our model and MMP that have to be executed the first day.

8.1 Comparison issues

The data that are obtained from Den Hartogh contain information about the actual execution of the orders. It is known for every order by which tank container it is executed. Besides this, it is known when orders became known for Den Hartogh and where all tank containers were on January 1 and when they became available. However, some of the actual executions appeared to be impossible in our model, which makes a comparison with the results obtained by using our model very difficult.

There are several reasons why some of the actual executions are not possible in our model. One reason is that there are about 370 tank containers used in the actual execution in January that are not present in the data. An explanation is that the obtained tank container data contain the tank containers that could be used at one specific moment, whereas new tank containers that are purchased in January or were being repaired at that moment, could also be used to execute orders. More than 15% of the orders are executed by these unknown tank containers. Another important reason is that about 15% of the executions of the orders are not possible in our model due to the fact that a tank container cannot be on time at the origin site. In reality, the loading and delivery times can sometimes be different than in the data. Planners can manually adapt the solution proposed by MMP. In this way, a planner can, for example, call to the origin site of an order and ask whether it is possible to load later than the specified loading time. These changed loading and unloading times are not present in the initial order data.

Due to the previously mentioned reasons, the actual execution is not comparable to the planning made by our model. In addition, we cannot see from the execution data how the tank containers are transported to execute the orders and whether the tank containers are repositioned to other locations between executing two orders. It is only known which tank containers have executed which orders, and not how the tank containers are transported. MMP has a capacity restriction on the number of tank containers that can be stored at a depot. This means that tank containers cannot always be stored at the depot that is the closest to the location of the tank container. Tank containers can also be stored at other depots close to the location of the tank container or at a depot in the core region if the number of tank containers at the depots close to the location of the tank container are at their maximum. So these repositionings occur in reality, but are not included in the obtained data of the actual execution. By contrast, the planning made by our model includes these repositionings, which means that the costs of these repositionings are also included in the total costs. Our model sends a tank container to the core region if it is expected that the tank container is not needed anymore for the coming four weeks. Besides this, it is possible that a tank container is transported to a region since it is expected to be used in that region, whereas, after the tank container is repositioned, it is not used in that region. This means that our model could reposition tank containers that are not used there and these costs to reposition the tank containers are included in the total costs, whereas these costs are not known for the actual execution.

Due to the fact that not all information is present, a comparison between the actual execution and the results obtained by using our model is not possible. Therefore, a simple version of the algorithm of MMP is constructed, which will be introduced in the next section. However, this means that all manual adjustments of the planners are not in the comparison. It is possible that planners know more than is present in the system and that is used by MMP. Planners can change the tank container that is used to execute an order. MMP proposes for example to execute order O_1 with a tank container that belongs to tank container type A. However, the planner knows from experience that tank containers of type B are often needed close to the destination site of order O_1. So, if a planner has more information, he could adjust the planning solution proposed by MMP. The planner sends tank container type B to execute order O_1. As a consequence, empty repositioning costs could be saved due to the adjustment of the planner. The number of adjustments and the impact of these adjustments are not known. However, in the experience of CQM, planners do not look at the whole picture and could not make quantitative cost considerations.

8.2 Simple version of MMP

In the previous section, it was described why the results obtained by using our model were not comparable to the actual execution. In order to make a comparison to the current performance of Den Hartogh, an alternative must be found. Therefore, a simple version of the algorithm of MMP is constructed. The current version of the algorithm of MMP was described in Chapter 3. This algorithm first considers only the known orders for the coming two days and minimizes the costs to execute these orders. All tank containers that are used for the first day are fixed. Next, the orders for the second and third day are considered and the tank containers that are used for the orders for the second day are fixed. This procedure repeats and in this way hard orders are found. However, these hard orders are only a small fraction of the orders, and are not considered in the simple version of MMP. Since these hard orders are not considered and only the tank containers that should be transported today are needed, only the orders that have to be executed the first two days are considered each day.

For the simple version of MMP, the tank containers are connected with the orders for the coming two days, just like in the current version of the algorithm of MMP. A tank container-order arc is only included in the flow network if it satisfies the three conditions of a tank container-order arc that are introduced in Chapter 5. Although MMP does not consider tank container types, it is still used that an order can be executed by a tank container if the tank container belongs to the tank container type that can execute the order. The costs of a tank container-order arc are calculated in the same way as in our model, which is introduced in Chapter 5. Also for the simple version of MMP, it is assumed that the tank container should be transported via a depot.

The tank container-depot arcs are also similar to the tank container-depot arcs that are introduced in Chapter 5. However, in the simple version of MMP all depots are used as depot nodes instead of a subset of the depots. A tank container is not connected with all depot nodes, but only with a selection of the depots. Just like in the current version of the algorithm of MMP, a tank container is connected with a depot node if the depot is close to the current location of the tank container, and with the depot nodes that represent the depots that are in the core region for Den Hartogh. These depots are owned by Den Hartogh, have a large capacity, and are located in the regions where many orders start. So, these depots are the same as the ones that are included in the depot nodes of our model. The costs of a tank container-depot arc are again calculated in the same way as introduced in Chapter 5. Since a tank container does not have to be available within the planning horizon of two days, there is also a dummy depot node. Tank containers that become available after the planning horizon are connected with this dummy depot only. This dummy depot does not have restrictions on the maximum number of tank containers that can arrive at the dummy depot node.

The last type of arc is the order-depot arc. These order-depot arcs are similar as the tank container-depot arcs. Orders that have a delivery time later than the end of the planning horizon are connected with the dummy depot only. Orders that have a delivery time before the end of the planning horizon are connected with the depots that are close to the destination site of the order and the depots in the core region. The costs of an order-depot arc are calculated in the same way as introduced in Chapter 5.

The mathematical model of the simple version of MMP is defined as follows:

Sets:

V is the set of nodes

$C \subset V$ is the set of tank containers which is a subset of the set nodes

$O \subset V$ is the set of orders which is a subset of the set nodes

$D \subset V$ is the set of depots which is a subset of the set nodes

A is the set of arcs

Parameters:

c_{uv} is the costs of using arc (u, v)

max_d is the maximum number of tank containers that is allowed to be stored at depot d

Variables:

$$X_{uv} = \begin{cases} 1 & \text{if arc } (u, v) \text{ is used} \\ 0 & \text{otherwise} \end{cases}$$

$$
\begin{aligned}
\text{minimize} \quad & \sum_{u,v:(u,v)\in A} c_{uv} \cdot X_{uv} && (8.1)\\
\text{such that} \quad & \sum_{u:(u,o)\in A} X_{uo} = 1 \quad \forall o \in O && (8.2)\\
& \sum_{v:(o,v)\in A} X_{ov} = 1 \quad \forall o \in O && (8.3)\\
& \sum_{v:(c,v)\in A} X_{cv} = 1 \quad \forall c \in C && (8.4)\\
& \sum_{u:(u,d)\in A} X_{ud} \le max_d \quad \forall d \in D && (8.5)\\
& X_{uv} \ge 0 \quad \forall u,v \in V && (8.6)
\end{aligned}
$$

This simple version of MMP minimizes the costs of all arcs that are used, as stated in objective function 8.1. Constraints 8.2 and 8.3 ensure that every order is executed. Constraint 8.4 ensures that every tank container is used for an order, or is sent to and stored at a depot. Besides these constraints, there is a maximum number of tank containers that can be stored at a depot. Therefore, the total flow that enters a depot node may not above this maximum, as stated in Constraint 8.5. The last constraint, Constraint 8.6, states that the flow that is sent over an arc cannot be negative.

8.3 Comparison of the results obtained by using our model and MMP

In this section, the results obtained by using our model are compared to the results obtained by using MMP. If we refer to MMP in this section, we refer to the simple version of MMP that is described in Section 8.2. In this section, there are two comparisons performed. In the first comparison, the planning made by our model and the planning made by MMP are compared in case the start and end location of the tank containers are the same. This will be done in Subsection 8.3.1. In the second comparison, our model and MMP are both solved for eight weeks. This will be done in Subsection 8.3.2.

These two comparisons that are performed in this section are two different ones. The first comparison is a kind of combinatorial comparison, since the start and end situation are the same and the costs of the execution of the orders are minimized. On the other hand, the second comparison does not require the same end situation. In the second comparison, our model and MMP are both solved for eight weeks and the costs that have to be paid to execute the proposed planning are compared.

8.3.1 Comparison 1: ending up in the same end situation

For the first comparison our model and MMP are solved for the first four weeks of January. After solving the last day, all tank containers are sent back to the depot in Rotterdam (in the core region). In this way, you pay a kind of penalty for tank containers that are far away from the core region. In this first comparison, only the orders of the first four weeks have to be executed. Therefore, tank containers are sent back to Rotterdam as soon as they have finished their last order, even if they are repositioned to another depot after finishing this last order to execute another order that starts after the first four weeks of January. Our model reacts earlier on future orders than MMP, because our model takes the future into account. This means that our model also repositions some tank containers in order to fulfill the demand that occurs after the first four weeks of January, whereas MMP does not look that far into the future. Since only the orders that start within the planning horizon have to be executed, the repositionings for (unknown) orders after the planning horizon are removed. Instead, the tank container is sent to Rotterdam after it has finished its last order. In this way, the penalty costs are not only made at the last day of the planning horizon, but spread over the four weeks. Since the tank containers are sent to Rotterdam after finishing their last order, this comparison investigates whether our model or MMP performs better in January by using those tank containers that save the most empty repositioning costs. Costs can be saved if those tank containers are used that can be used for a next order close to the destination site of the previous order.

The results of this comparison are presented in Figure 8.1. This figure shows the difference between the results obtained by using our model and the results obtained by using MMP. The difference is defined as the costs of the execution proposed by our model minus the costs of the execution proposed by MMP. The execution costs of a day are the empty travel costs of all tank containers that are transported that day to a depot or to an origin site of an order plus the storage costs of all tank containers that are stored at a depot that day. If a tank container is planned to be repositioned the second day, these costs are not considered, since this decision has to be executed the next day and can be revised the following day. Figure 8.1 shows that the costs of the execution proposed by MMP are lower for the first five days. At January 1, MMP minimizes the costs for the first two days, whereas our model looks to the costs of the whole planning horizon. Therefore, the costs of our model are higher than MMP. Our model does not always use the cheapest tank containers for the coming orders. Besides this, our model also sends tank containers earlier than MMP to other regions in order to be able to fulfill the expected demand in those regions. After the first week, the costs of MMP increase and our model saves more costs compared to MMP. Our model benefits from the fact that it looks further in the future and sends those tank containers that can be used nearby the locations where the tank containers end. As Figure 8.1 shows, MMP is sometimes cheaper than our model in the next weeks. This is possible if the costs of repositioning tank containers for future orders, which is done by our model, are higher than the minimization of the costs to execute the orders of the coming two days, which is done by MMP. Although MMP is cheaper than our model for a couple of days in the next weeks, our model performs overall better in the second, third and fourth week.

The difference between the costs of the execution proposed by our model and the costs of the execution proposed by MMP is almost 67,000 euros after four weeks. The costs of the execution proposed by MMP are almost 1,340,000 euros after four weeks and for our model this is less than 1,273,000 euros. So 67,000 euros could be saved if our model is used and tank containers have to pay a penalty to be far away from Rotterdam. These 67,000 euros result in a cost saving of 5.0%.

8.3.2 Comparison 2: solving for eight weeks

In the first comparison, the tank containers start and end in a situation that is the same for our model as for MMP. In this second comparison, the start situation is only the same. Both models are solved for eight weeks. This means that there is no penalty for tank containers that are far away from the core region and our model repositions tank containers already for orders that start after the eight weeks. Therefore, this comparison looks at the difference in the performance of both models by comparing the repositioning and storage costs that have to be paid.

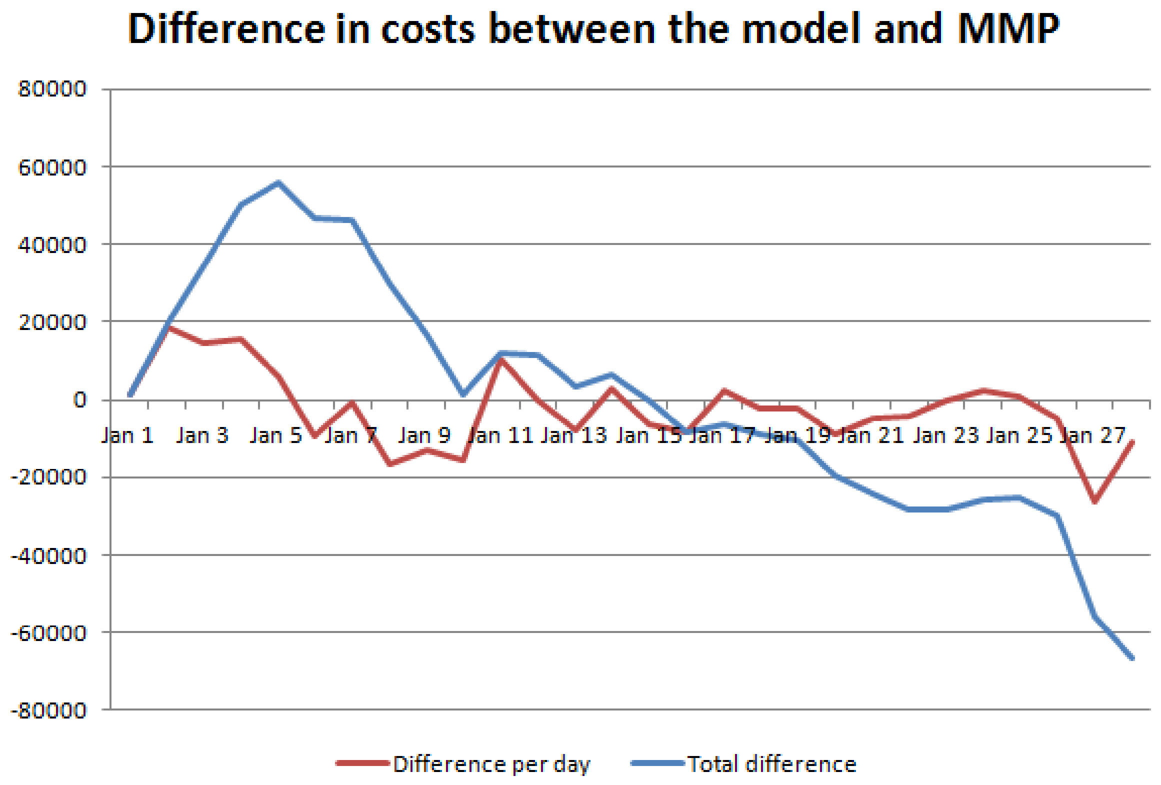


Figure 8.1 – Difference in costs between the model and MMP: costs model - costs MMP

The results of this comparison are shown in Figure 8.2. Again, the costs of execution proposed by our model are higher in the first week than the costs of the execution proposed by MMP. Our model repositions tank containers earlier than MMP in order to be able to execute future orders. In case of our model, the tank containers are not at the right locations on January 1, and therefore, much costs are made in the beginning to reposition these tank containers. On the other hand, MMP minimizes the costs of the first couple of days and as a consequence, these costs are lower. However, the investment of our model to reposition these tank containers in the beginning are earned back in the next weeks. At January 6, our model is for the first time cheaper that day than MMP. After the first week, the costs of execution proposed by our model are more often lower than the costs of execution proposed by MMP. After more than four weeks, the total execution costs of our model are for the first time lower than the total execution costs of MMP.

The costs of each week to execute the planning proposed by our model and MMP are presented in Table 8.1, together with the difference per week and the total difference. The costs of execution proposed by MMP are in the first week more than 100,000 euros lower than all other weeks. The tank containers are at the right locations at the start of the planning horizon, which results in fewer repositionings and hence, lower costs. Besides this, on January 1, some depots have fewer tank containers stored than the maximum number that is allowed to store at these depot. If tank containers are close to a depot that have not reached its maximum, tank containers are often transported to this depot since this is cheaper than repositioning the tank container to one of the depots in the core region. Therefore, the further in time, the more depots reach their maximum. This results in more repositionings of tank containers to the core region later in time compared to the number of repositionings to the core region in

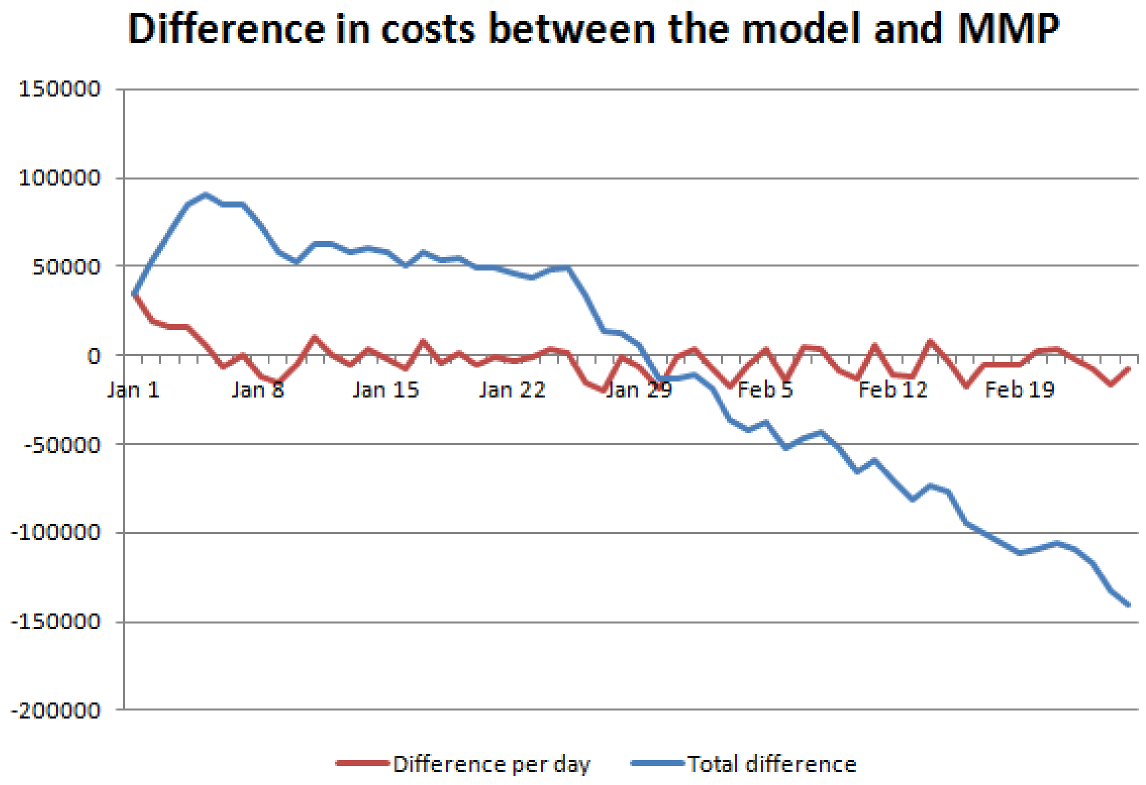


Figure 8.2 – Difference in costs between the model and MMP: costs model - costs MMP

the beginning. Besides this, more expensive repositionings occur in order to be able to execute the orders. These two increasing costs result in higher execution costs of MMP the further in time. So, after the first week, the costs of MMP are not lower anymore. Our model already repositioned some tank containers in the first week in order to be able to execute the orders in the second week. Except for the first week, our model saves costs every week compared to MMP. After eight weeks, the difference between the total costs of the execution proposed by our model and MMP are 140,000 euros. This results in cost savings of almost 6%.

The cost saving of six percent includes the first week of January where the planning of MMP results in lower costs compared to all other weeks. Most depots have reached the maximum number of tank containers that can be stored at their depot. Therefore, it is expected that if

Week	Model	MMP	Difference	Total difference
1	270,000	184,000	86,000	86,000
2	274,000	299,000	-25,000	61,000
3	286,000	298,000	-12,000	49,000
4	271,000	307,000	-36,000	13,000
5	282,000	336,000	-54,000	-41,000
6	302,000	320,000	-18,000	-59,000
7	282,000	328,000	-46,000	-105,000
8	276,000	311,000	-35,000	-140,000

Table 8.1 – Costs per week of the model and MMP and the differences

our model and MMP are solved for another eight weeks, our model continues with saving costs every week compared to MMP. If the first week is not taken into consideration in determining the cost savings after eight weeks, the difference between the execution costs of our model and MMP is 226,000 euros, which results in a cost saving of about 11%.

8.4 Comparison of the decisions in case of the same situation

The previous section compared the costs of the execution using our model and using MMP, and we showed that our model saves costs by taking the future into account. To analyze the difference between our model and MMP in more detail, this section compares the decisions that our model and MMP make in case they are in the same start situation.

For this third comparison, we analyze the decisions on January 29. The locations of the tank containers on January 29 in the simulated execution using our model and the orders that our model still has to plan are used as the start situation for both our model and MMP. We will refer to this start situation as the model start situation. Our model and MMP are solved in case of the model start situation and the decisions that have to be executed on the first day are analyzed. We also compare the proposed planning of MMP in case of the model start situation to the proposed planning of MMP in case MMP is used for four weeks. We will refer to this start situation as the MMP start situation.

We could also have used the decisions on January 1 in this comparison. However, many repositionings occur on January 1, since the tank containers were not at the right locations on January 1 for our model. On January 29, our model is already used for four weeks and some repositionings for future orders have already been made. So, the situation on January 29 gives better insight in the differences between the execution proposed by our model and the execution proposed by MMP.

The execution costs per type of arc in case of the model start situation for our model and for MMP are shown in Table 8.2. In addition, the costs per type of arc in case of the MMP start situation for MMP are shown. The costs of the execution proposed by our model are 45,000 euros, whereas the costs of the execution proposed by MMP in case of the model start situation are only 36,000 euros. MMP minimizes the costs for the coming two days, whereas our model minimizes the costs that are expected to be made in the coming four weeks. This can result in higher costs for the first day for our model compared to MMP.

One of the results is that our model already repositions more tank containers in order to be able to execute orders that have to be executed in the future and are known on January 29. One explanation for this is that our model considers all known orders for the coming four weeks

Type of arc	**Costs of the model**	**Costs of MMP in case of model start situation**	**Costs of MMP in case of MMP start situation**
Tank container-order	34,000	26,500	34,000
Tank container-min forecast	6,000	-	-
Tank container-depot	2,500	9,000	16,000
Order-order	500	-	-
Order-min order	2,000	-	-
Order-depot	0	500	1,000
Total	45,000	36,000	51,000

Table 8.2 – Costs per type of arc for the model and MMP

in the planning, whereas MMP only considers the orders that have to be executed the first two days. Our model repositions tank containers on January 29 for some of those orders, whereas MMP repositions these tank containers on January 29 only to a depot close to the current location of the tank container or to a depot in the core region, since MMP does not consider these orders. Besides that our model repositions tank containers for orders that are already known, it also repositions tank containers in order to be able to fulfill the forecasted demand. Since MMP does not consider demand that is not known on January 29, the planning of MMP does not include this kind of repositionings.

As Table 8.2 shows, the costs that are made on January 29 to send a tank container to execute an order are higher in the planning proposed by our model compared to the costs of the planning proposed by MMP in case of the model start situation. However, as already mentioned, our model repositions more tank containers on January 29 to a depot for future orders that are known on January 29. These costs are in case of MMP included in the costs of the tank container-depot arcs. The planning proposed by our model also includes repositionings for the forecasted demand, which results in empty transportation costs for our model that are made on January 29. There are a few orders that are finished on January 29 and decisions to where to send these tank container have also be made on January 29. Therefore, these costs are also included in the execution costs on January 29.

The costs of the planning proposed by MMP in case of the MMP start situation are higher than the costs of the planning proposed by MMP in case of the model start situation. Tank containers still have to be repositioned in order to be able to execute the orders, whereas our model has done this earlier and these repositionings are already included in the start situation. This results in higher costs of the tank container-order arcs compared to MMP in case of the model start situation. Besides this, the costs to reposition tank containers to a depot are higher for MMP in case of the MMP start situation. The model start situation has fewer tank containers stored at several depots compared to the MMP start situation. In those depots, the number of tank containers is not at their maximum yet and more tank containers can be stored there, whereas if the maximum has been reached, the tank containers should be repositioned to a depot nearby, or to a depot in the core region. This results in higher costs in the planning of MMP in case of the MMP start situation compared to the planning of MMP in case of the model start situation. It also results in higher costs compared to the planning of our model.

In order to analyze the differences in the decisions of our model and MMP in case of the model start situation, the differences in which tank containers and which tank container types execute the orders are investigated. For the orders that require actions on January 29 in the planning of both our model as MMP, the differences in tank containers and tank container types that execute these orders are investigated.

For about 50% of the orders, the tank container that executes the order belongs to the same tank container type and starts at the same location. If tank containers belong to the same tank container type and are at the same location, the only difference between these tank containers for our model as well as for MMP is the last order that is executed by these tank containers, since this can be important for the green-/blacklist restrictions. If it is allowed to execute the order according to this green-/blacklist, tank containers that belong to the same tank container type and are at the same location have equal execution costs. If we only look to the orders that are executed by the same specific tank container for our model and MMP, the percentage of the orders decreases to 25%.

For about 25% of the orders that require actions on January 29 in the planning of our model and MMP, the execution costs and the location of the tank container are the same, but the tank container type that is used to execute the order is different. There are many tank containers that are stored at the depots in the core region. If the origin site of an order is in the core region, there is often a choice between several tank container types which have the same execution costs. Since our model looks further in the future, the tank container that is used on January 29 to execute the order is often planned to be used later. For 50% of orders that are executed by another tank container type, the tank container is expected to be used to fulfill the forecasted demand after executing the order. For 20% of orders that are executed by another tank container type, the tank container is expected to be used to fulfill an order that is already known. In both cases, the tank container type is important, since another tank container type may not be able to execute the next order. In the other cases, the tank container is planned to be transported to a depot in the core region. So for about 18% of the orders that require actions on January 29, the tank container type that is used to execute the order is different and the tank container is planned to be used to execute another order or to fulfill unknown future demand in the planning proposed by our model. For the tank containers that are planned to execute a next order, we compare whether the tank container type that is used by MMP to execute the first order could also execute that next order. In 70% of the cases, this appeared to be possible. However, in the other 30% this is not possible.

For about 15% of the orders that require actions on January 29 in the planning of our model and MMP, the costs of execution proposed by our model are higher than the costs of execution proposed by MMP. In 60% of these cases, another tank container type is used to execute the order. There are also a few orders that have higher execution costs in the planning of MMP. This is possible, since the tank container that is used in the planning of our model is in the planning of MMP used for another order, or is sent to a depot, which results in lower total costs for MMP.

Chapter 9

Extensions of the model

This chapter proposes some extensions of our model. In Section 9.1, the extension allowing to use uncleaned tank containers is proposed. Section 9.2 considers the extension to introduce different storage costs per depot per day. In Section 9.3, another idea to include a forecast in the model is proposed. Section 9.4 describes how a specific short-term forecast can be included in the model.

9.1 Allowing to use unclean tank containers

Cleaning of tank containers is not considered in this thesis. Instead, the assumption is made that a tank container should go via a depot before it can execute another order, because most of the cleaning stations are located at depots or close to a depot. As mentioned in Chapter 3, the most common reason not to clean a tank container is that the order product of the previous loading and the new loading is the same. If an order can be executed by an unclean tank container, this saves cleaning costs. Therefore, one reason to reposition a tank container that is not considered in this thesis is to make use of the possibility not to clean a tank container between two subsequent orders. It is possible that this leads to an increase in the empty tank container transportation costs in order to save cleaning costs. This is only beneficial if the cleaning costs are higher than the empty travel costs. In this way, the empty travel costs can increase compared to case without cleaning costs, whereas the total costs, that includes cleaning costs, are lower. In order to include this, cleaning costs should be added to the model. If two subsequent orders have the same type of product, no cleaning costs have to be paid. If two subsequent orders have different types of product, cleaning costs should be added to the empty travel costs and storage costs.

9.2 Different storage costs per day per depot

In this thesis, it is assumed that the storage costs are the same for every depot. In addition, it is assumed that the storage costs have a fixed rate per day. The reason for these assumptions is that the storage costs are relatively low compared to the empty travel costs and have therefore little influence on the decisions that are made today. However, to model this situation more accurately, this should be included in the cost function of the arcs. At some depots a tank container can be stored for free during the first few days. After that, the costs of storing the tank container for one more day increase per day. Not using this tank container for a long time becomes more expensive. In our model, there is no difference between a tank container that is stored at a depot one day ago and a tank container that is stored two weeks ago. So, in order to make a distinction between these two tank containers, different storage costs per day should be included in the cost function of the arcs. Since the number of "free days" and the storage costs differ per depot, the total storage costs differ per depot.

9.3 Supertypes

The ordertypes which are introduced in Chapter 7, can also be used as "supertypes" in the model. Instead of determining beforehand which tank container types leave the plus forecast nodes, a supertype can leave the plus forecast node. A supertype is a combination of tank container types. So if a supertype leaves a plus forecast node, one of the tank container types that belongs to that supertype is expected to leave the plus forecast node. An order can be executed by a supertype if at least $X\%$ of the tank containers belonging to that supertype can execute the order, and a connection between the plus forecast node and the order node is included in the flow network.

An advantage of this approach is that it is not needed to determine beforehand which tank container types should leave the plus forecast node. However, one of the possible drawbacks of this approach is that this introduces many additional types, which means many additional variables. Not only plus forecast-order arcs, but also plus forecast-min forecast arcs, plus forecast-depot arcs, order-order arcs, order-min forecast arcs, and order-depot arcs depend on the tank container type. Each possible type creates one additional arc and hence, one additional variable. Therefore, it is expected that the computation time of the model increases.

Another drawback is that if many tank containers leave the plus forecast node, the approach that a supertype leaves the plus forecast node can be a very safe option, which results in not including arcs in the flow network, whereas these arcs could be used. The probability that some of the tank container types that belong to the supertype leave the plus forecast node can be large in case many tank containers leave the plus forecast node. Some arcs between, for example, a plus forecast node and an order node will not be included in the flow network, since too few tank container types of the supertype can execute the order, whereas an arc would be included if one specific tank container type leaves the plus forecast node. So due to being safe, some arcs will not be included, whereas these arcs could probably be used. This does not only hold for the plus forecast-order arcs, but also for the plus forecast-min forecast arcs, the order-order arcs, and the order-min forecast arcs. If a supertype leaves the plus forecast node, this tank container belongs to the supertype until it reaches a depot node or a min forecast node in the flow network, because in those nodes the flow ends. For example, if a supertype is used to execute an order, the supertype leaves the order node, but is not able to fulfill the forecasted demand after executing the order. If a specific tank container type leaves the plus forecast node and is used to execute an order, that specific tank container type can fulfill the forecast demand.

The previously mentioned drawback is for the case that many tank containers are expected to become available. If only a few tank containers are expected to become available, the approach that a supertype leaves the plus forecast node can be better. By determining beforehand which tank container types leave the plus forecast node, there is a larger probability that another tank container type becomes available. In that case, using a supertype is a safer option and can therefore be better.

Besides the two mentioned drawbacks, which supertypes to create and what the value of X should be, need to be determined carefully. The approach of introducing supertypes in the model is not investigated in this research. Although it is expected to have some drawbacks, it is not known what the impact is and should therefore be investigated.

9.4 Short-term forecast

As mentioned in Chapter 3, the demand for orders from a fixed region to a fixed region is hard to predict. Therefore, the forecast in this model consists only of forecasted demand and forecasted supply within each region, and hence misses the link between the loading and delivery region. However, Den Hartogh and H&S have more information that can be used to create the short-term forecast. One example are the quotes. Quotes are similar to real orders since they contain information about, for example, the loading and delivery time, and loading and delivery location. Quotes can be seen as the last step before they become real orders. The customer indicates that he has a commodity that has to be transported and is negotiating with the LSP. However, quotes are not real orders and it is possible that they will not become real orders. Information on these quotes can be used for the forecast, which can result in forecasted flows. So, especially the forecast for the first days of the planning horizon can become more accurate by considering these forecasted flows. This can easily be included in the model by considering these forecasted flows similar to orders, since flow must enter and leave these nodes. However, the difference between orders and forecasted flows is that in case of orders only flow of value one could enter and leave the order node, whereas in case of forecasted flows more flow could enter and leave the node, since multiple tank containers are needed to fulfill these forecasted flows.

Chapter 10

Conclusion

This chapter starts with a discussion on the results and the research that has been performed. In Section 10.2, a conclusion on the research problem is given. In the last section of this chapter, Section 10.3, some suggestions for future research are given.

10.1 Discussion

To analyze the performance of our model, a forecast was required. Since it was not the scope of this thesis to create a good forecast, the forecast was based on the actual orders. So for the analysis of our model, the forecast is done on the basis of perfect information. However, it is not a perfect forecast. The time period of the forecast is one week, but this one-week forecast is split into two nodes in the network, where, in case of forecasted demand, the loading time is set at the beginning of the week and at mid week. It is possible that orders start at the second half of the week that are in the forecast in the beginning of the week, and the other way around. Since the loading times of the forecasted demand are set at the beginning of the week and at mid week, most of the loading times of the forecasted demand are expected to occur earlier than the real loading times of the orders. Tank containers that are used to fulfill this demand have to wait before they are used to execute an order that is included in the forecasted demand, whereas they could possibly be used for other orders, and other tank containers that become available later could be used to execute the orders of the forecasted demand. This is similar for the forecasted supply. The unloading times of the forecasted supply are set at mid week and at the end of the week, so most of the unloading times of the forecasted supply are expected to occur later than the real unloading times of the orders. Tank containers that are expected to become available have to wait before they are used to execute an order, whereas they could possibly be used earlier to execute orders. In this way, the forecast is somewhat pessimistic.

Besides this, orders are aggregated based on the ordertypes. Each order is assigned to an ordertype that resembles the best the tank container types that can execute the order. Therefore, it is possible that a tank container type belongs to the ordertype that cannot execute the order, and the other way around. Although it is not a perfect forecast, the forecast is still based on the actual orders, whereas in reality these orders are not known. A forecast is then based, for example, on historical data or on contracts with customers. The results of another forecast can differ from the results obtained in this study.

Since it was not possible to compare the planning made by our model with the actual execution, the results obtained by using our model are compared to the results obtained by using a simple version of MMP. This simple version is different from the actual version in the sense that this simple version does not search for hard orders, and as a consequence, these hard orders are not treated differently. If an order can only be fulfilled by a few tank containers and this is not taken into account in the model, this can lead to high empty repositioning costs. MMP takes these hard orders into account which can result in lower empty repositioning costs than the simple version obtains. Therefore, the difference between MMP and our model could be smaller. However, the percentage of the orders that are hard orders is very small. The prevailing thought at CQM is that the cost savings of our model are not only made due to these hard orders. An option to test the impact of hard orders is to detect those hard orders and then run our model and MMP without those orders or to treat those hard orders differently, just like in the actual version of MMP.

Besides the hard orders, the simple version of MMP does not include the manual adjustments of the planners. Planners may know more than the information that MMP uses. For that reason, they can change the actions of the tank containers. So the simple version of MMP does not take the hard orders into account and does not include the changes of the planners. Therefore, the actual execution can be better than the results obtained by the simple version of MMP, that is used in the comparisons.

The depot nodes of the flow network consist of a subset of the depots. There is no constraint at the depot nodes. As a consequence, only the cheapest arcs that are connected to a depot node are included in the flow network. However, in theory, this could lead to an undesirable distribution of tank containers across these depots. Since the depots are close to each other, it is expected that this impact is small, also because the cheapest reposition to one of the depots is already chosen. One option to include a distribution of tank containers at the depots is to add constraints to the model that impose a minimum and maximum number of tank containers at a depot. This could also be done for tank container types instead of only the number of tank containers. In case of limitations at depots, only the arcs that have to be executed today should be included in this constraint, since these arcs lead to actual repositionings of tank containers.

10.2 Conclusion

The main difference between our model and MMP is that our model takes the future into account. Therefore, our model can send tank containers of certain types to execute orders today that can be used later close to the location where the tank container ends. MMP looks only to the orders of the coming two days. If there is a choice between several tank container types, MMP will choose the tank container that leads to the lowest costs in the optimal solution on the two-day period. However, it is possible that this tank container cannot be used close to the location where the destination site of the order is, whereas another tank container type could execute a next order close to the location where the destination site of the first order. This can save empty repositioning costs.

Besides this, MMP does not take into account which tank container types to store at a depot. At the first step of the algorithm, the cheapest solution for the first two days is found and the actions that should be made today are executed. This means that the tank containers that are stored at a depot outside the core region are the tank containers that generate higher costs to send to the core region compared to the tank containers that are sent to the core region. In contrast, our model sends the tank containers to the core region that are expected not to be needed in the coming four weeks. So our model stores the tank containers that are expected to be used in the first four weeks and hence, takes into account which tank container types to store at a depot.

We advise Den Hartogh and H&S to take the future into account by their planning, because this leads to cost savings. Their current planning tool does not take the future into account. Our model can be used as a basis for a new planning tool. After solving our model and the simple version of MMP for eight weeks, the planning proposed by our model results in a cost saving of about 11% if the investment costs of the first week are not included in the calculation. In reality, this percentage could be lower, since the forecast that is used to test our model is based on actual order data. Therefore, we advise Den Hartogh and H&S to investigate first how to generate a good forecast.

10.3 Future research

The main recommendation is to investigate how to come up with a good forecast. The forecast in this thesis is based on actual order data. However, this is not possible in reality. It is interesting to know what the performance of our model is with a real forecast that is, for example, based on historical data, or on information that the planners have, but MMP does not have. Besides this, if Den Hartogh and H&S want to use the model, a real forecast is required, The forecast in this thesis is an aggregation of real orders on the basis of the regions where the orders start or end, time period, and ordertype. It could be investigated if forecasting on the basis of those regions, time periods and ordertypes is possible. For example, the time period in our forecast was one week, whereas for the forecast of the first week, this time period might be a few days. As mentioned in Section 9.4, it is expected that it is possible to come up with a good short-term forecast by using additional information.

Another recommendation for future research is to include a method that deals with the uncertainty of the forecast. The actions depend on the forecast, but what if this forecast is not accurate? To be more robust against a wrong forecast, the model could minimize the total costs of several possible forecasted scenarios with the constraint that the actions that should be executed today are the same for every forecasted scenario.

A last recommendation is to investigate the impact of the length of the planning horizon. What is the best length and what is possible with the forecast? In this thesis, the planning horizon is chosen to be four weeks. However, if the forecast for the fourth week is unreliable, it can be better not to include this fourth week in the optimization. On the other hand, if it is possible to make a good forecast for the fifth week, it can be better to have a longer planning horizon. Also the computation time should be taken into account in making this decision.

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Appendix A

Data Den Hartogh

<table>
<tr><th>Tank container type</th><th>Number of compartments</th><th>Heating system</th><th>ISO standard</th><th>Size</th><th>Baffles</th><th>High isolation</th><th>Number of tank containers</th><th>Percentage tank containers</th></tr>
<tr><td>1Comp|Elec/Glyc|ISO|Small</td><td>1</td><td>Elec/Glyc</td><td>Yes</td><td>Small</td><td>No</td><td>No</td><td>35</td><td>1.4%</td></tr>
<tr><td>1Comp|Elec/Glyc|NonIso|Small</td><td>1</td><td>Elec/Glyc</td><td>No</td><td>Small</td><td>No</td><td>No</td><td>89</td><td>3.5%</td></tr>
<tr><td>1Comp|Elec/Glyc|NonIso|Medium/Large</td><td>1</td><td>Elec/Glyc</td><td>No</td><td>Medium/Large</td><td>No</td><td>No</td><td>161</td><td>6.4%</td></tr>
<tr><td>1Comp|Steam|Iso|Small|NoBaffle</td><td>1</td><td>Steam</td><td>Yes</td><td>Small</td><td>No</td><td>No</td><td>629</td><td>25.0%</td></tr>
<tr><td>1Comp|Steam|Iso|Small|Baffle</td><td>1</td><td>Steam</td><td>Yes</td><td>Small</td><td>Yes</td><td>No</td><td>68</td><td>2.7%</td></tr>
<tr><td>1Comp|Steam|NonIso|Small</td><td>1</td><td>Steam</td><td>No</td><td>Small</td><td>No</td><td>No</td><td>181</td><td>7.2%</td></tr>
<tr><td>1Comp|Steam|NonIso|Medium|NoBaffle</td><td>1</td><td>Steam</td><td>No</td><td>Medium</td><td>No</td><td>No</td><td>742</td><td>29.5%</td></tr>
<tr><td>1Comp|Steam|NonIso|Medium|Baffle</td><td>1</td><td>Steam</td><td>No</td><td>Medium</td><td>Yes</td><td>No</td><td>242</td><td>9.6%</td></tr>
<tr><td>1Comp|Steam|NonIso|Large|NoBaffle</td><td>1</td><td>Steam</td><td>No</td><td>Large</td><td>No</td><td>No</td><td>52</td><td>2.1%</td></tr>
<tr><td>1Comp|Steam|NonIso|Large|Baffle</td><td>1</td><td>Steam</td><td>No</td><td>Large</td><td>Yes</td><td>No</td><td>17</td><td>0.7%</td></tr>
<tr><td>1Comp|Steam|NonIso|Large|HighIsolation</td><td>1</td><td>Steam</td><td>No</td><td>Large</td><td>No</td><td>Yes</td><td>111</td><td>4.4%</td></tr>
<tr><td>2Comp|Elec/Glyc|NonIso|Small</td><td>2</td><td>Elec/Glyc</td><td>No</td><td>Small</td><td>No</td><td>No</td><td>26</td><td>1.0%</td></tr>
<tr><td>2Comp|Elec/Glyc|NonIso|Medium</td><td>2</td><td>Elec/Glyc</td><td>No</td><td>Medium</td><td>No</td><td>No</td><td>21</td><td>0.8%</td></tr>
<tr><td>3Comp|Elec/Glyc|NonIso|Small</td><td>3</td><td>Elec/Glyc</td><td>No</td><td>Small</td><td>No</td><td>No</td><td>20</td><td>0.8%</td></tr>
<tr><td>2Comp|Steam|Iso/NonIso|Small</td><td>2</td><td>Steam</td><td>Yes/No</td><td>Small</td><td>No</td><td>No</td><td>39</td><td>1.6%</td></tr>
<tr><td>2Comp|Steam|NonIso|Large</td><td>2</td><td>Steam</td><td>No</td><td>Large</td><td>No</td><td>No</td><td>58</td><td>2.3%</td></tr>
<tr><td>3/4Comp|Steam|NonIso|Medium/Large</td><td>3/4</td><td>Steam</td><td>No</td><td>Medium/Large</td><td>No</td><td>No</td><td>24</td><td>1.0%</td></tr>
</table>

Table A.1 – Composition of the fleet of Den Hartogh

Value threshold	1%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
Percentage orders excluded	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.3%	0.3%	0.7%
Total robustness	92.2%	93.3%	94.2%	94.3%	94.8%	96.6%	96.9%	97.0%	97.1%	97.1%	97.3%
Distinctiveness	7.37	7.32	7.22	7.22	7.17	7.12	7.09	7.07	7.06	7.06	6.97

Table A.2 – Criteria of tank container categorization for Den Hartogh for different threshold values

	Region of origin site of second order						
Region of destination site of first order	BE, DE, NL, FR North	GB	IR	IT, PT, SP, FR South	DK, NO, PL, SE	FI, RU	South East Europe
BE, DE, NL, FR North	3	5	7	7	7	10	14
GB	5	3	5	7	7	-	-
IR	7	5	5	-	-	-	-
IT, PT, SP, FR South	7	7	-	5	-	-	-
DK, NO, PL, SE	7	7	-	-	10	10	14
FI, RU	10	-	-	-	10	10	14
South East Europe	14	-	-	-	14	14	14

Table A.3 – Maximum number of days between two subsequent orders

Appendix B

Data H&S

<table>
<tr><th>Tank container type</th><th>Food container</th><th>Number of compartments</th><th>Heating system</th><th>Size</th><th>High isolation</th><th>Sterile filter</th><th>Fully ground operated</th><th>Number of tank containers</th><th>Percentage tank containers</th></tr>
<tr><td>Food|1Comp|Electric|Small</td><td>Yes</td><td>1</td><td>Electric</td><td>Small</td><td>No</td><td>No</td><td>No</td><td>3</td><td>0.4%</td></tr>
<tr><td>Food|1Comp|Electric|Medium</td><td>Yes</td><td>1</td><td>Electric</td><td>Medium</td><td>No</td><td>No</td><td>No</td><td>22</td><td>3.0%</td></tr>
<tr><td>Food|1Comp|Electric|Large</td><td>Yes</td><td>1</td><td>Electric</td><td>Large</td><td>Yes</td><td>No</td><td>Yes</td><td>161</td><td>6.4%</td></tr>
<tr><td>Food|1Comp|Glycol|Small</td><td>Yes</td><td>1</td><td>Glycol</td><td>Small</td><td>Yes/No</td><td>No</td><td>No</td><td>35</td><td>4.8%</td></tr>
<tr><td>Food|1Comp|Glycol|Medium</td><td>Yes</td><td>1</td><td>Glycol</td><td>Medium</td><td>No</td><td>Yes</td><td>No</td><td>7</td><td>1.0%</td></tr>
<tr><td>Food|1Comp|Steam|Small|NoHighIsolation</td><td>Yes</td><td>1</td><td>Steam</td><td>Small</td><td>No</td><td>No</td><td>No</td><td>68</td><td>9.2%</td></tr>
<tr><td>Food|1Comp|Steam|Small|HighIsolation|NoSterile</td><td>Yes</td><td>1</td><td>Steam</td><td>Small</td><td>Yes</td><td>No</td><td>No</td><td>180</td><td>24.5%</td></tr>
<tr><td>Food|1Comp|Steam|Small|HighIsolation|Sterile</td><td>Yes</td><td>1</td><td>Steam</td><td>Small</td><td>Yes</td><td>Yes</td><td>No</td><td>29</td><td>3.9%</td></tr>
<tr><td>Food|1Comp|Steam|Medium|NoHighIsolation</td><td>Yes</td><td>1</td><td>Steam</td><td>Medium</td><td>No</td><td>No</td><td>No</td><td>12</td><td>1.6%</td></tr>
<tr><td>Food|1Comp|Steam|Medium|HighIsolation</td><td>Yes</td><td>1</td><td>Steam</td><td>Medium</td><td>Yes</td><td>No</td><td>No</td><td>43</td><td>5.8%</td></tr>
<tr><td>Food|1Comp|Steam|Large|HighIsolation|NoFullyGround</td><td>Yes</td><td>1</td><td>Steam</td><td>Large</td><td>Yes</td><td>No</td><td>No</td><td>250</td><td>34.0%</td></tr>
<tr><td>Food|1Comp|Steam|Large|HighIsolation|FullyGround</td><td>Yes</td><td>1</td><td>Steam</td><td>Large</td><td>Yes</td><td>No</td><td>Yes</td><td>59</td><td>8.0%</td></tr>
<tr><td>Food|3Comp|Steam|Medium</td><td>Yes</td><td>3</td><td>Steam</td><td>Medium</td><td>No</td><td>No</td><td>No</td><td>10</td><td>1.4%</td></tr>
<tr><td>NonFood|1Comp|Steam|Medium</td><td>No</td><td>1</td><td>Steam</td><td>Medium</td><td>No</td><td>No</td><td>No</td><td>4</td><td>0.5%</td></tr>
<tr><td>NonFood|1Comp|Steam|Large</td><td>No</td><td>1</td><td>Steam</td><td>Large</td><td>No</td><td>No</td><td>No</td><td>7</td><td>1.0%</td></tr>
</table>

Table B.1 – Composition of the fleet of H&S

Value threshold	1%	5%	10%	15%	20%	25%	30%	35%	40%
Percentage orders excluded	0.0%	0.3%	0.3%	0.3%	0.3%	0.4%	0.4%	0.4%	0.4%
Total robustness	92.7%	93.2%	93.9%	94.2%	94.6%	95.2%	95.2%	95.3%	95.3%
Distinctiveness	7.46	7.44	7.40	7.34	7.32	7.29	7.29	7.28	7.28
Value threshold	45%	50%	55%	60%	65%	70%	75%	80%	85%
Percentage orders excluded	0.4%	0.4%	0.4%	0.4%	0.4%	1.1%	1.1%	1.1%	1.2%
Total robustness	95.3%	95.5%	95.5%	95.6%	98.0%	98.7%	98.7%	98.7%	98.7%
Distinctiveness	7.28	7.23	7.23	7.21	7.04	6.96	6.96	6.96	6.96

Table B.2 – Criteria of tank container categorization for H&S for different threshold values