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Specialization: Transport Engineering and Logistics

Report number: 2013.TEL.7801

Title: **Determining ITT configurations on the Maasvlakte by integer programming.**

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Title (in Dutch) Bepalen van ITT configuraties door middel van integer programming.

Assignment: Masters thesis

Confidential: no

Initiator (university): Dr. R.R. Negenborn (Delft University of Technology)

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Date: October 16, 2013

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Student:	F.E. Nieuwkoop	Assignment type:	Master thesis
Supervisor (TUD):	F. Corman	Creditpoints (EC):	35
		Specialization:	TEL
		Report number:	2013.TEL.7801
		Confidential:	no

Subject: **Modelling Inter Terminal Transport operations at the Maasvlakte I&II, Rotterdam**

The large container ports around the world use inter terminal transportation (ITT), to transport containers between different container terminals, distribution parks and empty container depots in the port area. The investment costs are high and sufficient space has to be allocated for the ITT and therefore proper planning and design is vital for an efficient and congestion free transportation system.
In the case of the Maasvlakte 2, a port expansion project in the Port of Rotterdam, an ITT system still has to be developed. A way in optimizing the configuration of such a system is by creating a tool, which analyzes ITT operations by computing vehicle and container movements in order to optimize a certain objective. In prior research ITT has been modeled by both integer programming models and simulation models, but an optimal ITT system configuration has not been investigated.

The goal of this research is to create a reliable tool with realistic outcomes, able to determine an optimal vehicle configuration (mix of AGVs, trucks, barges etc.) by evaluating different system configurations and analyzing ITT operations by computing optimal vehicle and container movements at the Maasvlakte area.

To achieve this goal your assignment is to:

1. Determine the situation in which the tool has to function, by setting system boundaries, system interfaces and indicating external influences/disturbances on the system.
2. Determine the requirements of the tool.
3. Determine the best working principle for this tool (integer programming, simulation) able to fit the requirements.
4. Use this principle to create a reliable tool with realistic outcomes, able to evaluate different system configurations and analyze ITT operations in order to provide an optimal vehicle configuration.
5. Propose a method to validate the performance of the tool.

Based on your assignment, it is expected that you conclude with a recommendation for future research opportunities and potential for more ideas and/or applications. The report must be written in English and must comply with the guidelines of the section. Details can be found on the website.

For more information, contact Dr.ir F. Corman (B-1-320; F.Corman@tudelft.nl)

The professor,

Prof.dr.ir. G. Lodewijks

This research is carried out within the framework of the TUDelft, Erasmus University and the Port of Rotterdam Authority joint project "'Inter-terminal transport on Maasvlakte 1 and 2 in 2030 - Towards a multidisciplinary and innovative approach on future inter-terminal transport options."

Summary

The large growth in containerized trade in the last decades set pressure on the current operating terminals in most ports around the world. In the Port of Rotterdam, the largest port of Europe, expansion became inevitable. With the expansion project "Maasvlakte 2" 1000 hectares of new land is created out of the sea, which made room for 5 new container terminals increasing the estimated annual container throughput in 2030 to 30 million TEU. This large flow of containers all have to leave the port to be transported all around Europe. To deal with this large flow and prevent congestion in and around the port, hinterland transport by barge and rail is promoted. To attract more containers via these modalities container flows are bundled to reduce the cost per container and make the hinterland transport more efficient. This bundling however will lead to extra movements around the port and for an efficient and congestion free connection an Inter Terminal Transport (ITT) system has been proposed. In this system vehicles transport containers between the various terminals and service providers around the port and can move over a dedicated road closed from all other traffic.

To investigate the requirements of such a system the Port of Rotterdam Authority together with the Delft University of Technology and the Erasmus University of Rotterdam set up a research group investigating several aspects of the ITT system. The research presented in this report investigates a new and fast way of determining the optimal fleet size of system using a model based on linear programming. The benefit of this modelling technique versus the conventional simulation techniques is that it can be built relatively fast resulting in tool which costs less money and presents results earlier than conventional methods. This enables companies and agencies to use this model as a tool for decision making processes which provides insight in the costs and benefits of the considered system. The main question however is: Could a reliable tool be constructed, able to determine an optimal vehicle configuration to provide a yet to be determined performance level for an ITT system?

To answer this question a deterministic minimum cost flow model with time expanded graphs is build able to calculate the optimal vehicle configuration. The model uses a network of arcs and nodes which represent the road and terminal network at the Maasvlakte area based on the principles presented in Tierney et al. [2013]. This network is copied for every time step over the total time horizon and is connected through time by arcs. For this network a demand generator presented in Jansen [2013] was used to create a demand vector forcing a flow of containers through the network. The demands range from 1.42 million TEU up to 3.26 million TEU per year depending on the scenario. Multi-commodity theory is used to enable parallel container demands sharing the same vehicle pool. The container and vehicle flow through the network is optimized by a cost function minimizing the total cost of both the number of vehicles and the delay in container delivery. The flows are constraint such that the capacity and the reliability of the model is guaranteed.

After the model was created a verification took place for small scale problems which could be analysed by hand and showed perfect behaviour. Before the full scale ITT system at the Maasvlakte could be analysed some important parameters had to be determined. The ideal time step was found to be 3 minutes for both fluctuating and constant demands. The ideal time step is depending heavily on the road lengths and can change with every adaption. It was also found that continues variables reached the same results as integer variables resulting in a strong reduction of calculation time. The ideal time horizon is 18 hours and the container generation should take place over 2/3 of the time horizon, in order to have enough time for the model to anticipate on fluctuation in the demand and to have a decent average time to transport the

containers.

The vehicle parameters used in the model are shown in Table 1 and this resulted in the results shown in Figure 1. To get these results a network is used where terminals are clustered into groups of terminals located near each other or have a internal connection to each other. It is shown that this is valid to do because the effect on the required number of vehicles is small and in some cases it even performs better than transporting containers between individual terminals. The benefit of clustering is the reduction in model size and thus calculation time and memory requirements.

Table 1: Default parameter values.

	speed (km/h)	intersection cap. (veh/timestep)	carrying cap. (TEU)	handling time (sec.)	cost function (per 24 hours)
ALV	40	8	2	30	239
AGV	40	8	2	180	162
MTS	30	3	10	180	100/28 (truck/trailers)
Barge	12	∞	50	180	1200

	Scenario 1	Scenario 2	Scenario 3
	nr vehicles	nr vehicles	nr vehicles
ALV	51	33	24
AGV	65	42	32
MTS	16 Truck +76 Trailers	12 Trucks + 59 Trailers	9 Trucks + 42 Trailers
barge	41 Truck + 2 Barges	22 Trucks + 3 barges	17 Trucks + 2 barges

Figure 1: Required vehicles for the various scenarios.

With these results some additional experiments have been done. First of all the effects of congestion are investigated. It turned out that a limit on throughput is found at which adding more vehicles will not add extra transport capacity to the model. However this limit is reached suddenly raising questions on the reliability of the model in congested situations. The demand scenarios for the ITT system in the Port of Rotterdam are still far from the capacity giving no concern about congestion issues.

During a second experiment the vehicle speed for automated vehicles has been lowered to 18km/h which is a common speed for AGVs in use nowadays. Reducing the speed significantly increased the vehicle requirements for the various scenarios up to 93 ALVs or 118 AGVs for scenario 1. The final experiment showed that varying the cost function does not have a significant influence on the required number of vehicles. It does however has an effect on the punctuality of the system because the cost for delays optimize vehicle routing.

When the reliability of the model is considered it can be concluded that all possible interactions between vehicles and processes such as the handling of containers have been modelled. The model has been verified by solving a small problem such that the model behaviour could be analysed by the researcher. This verification showed that the model was acting as expected and did not show strange behaviours. Also the outcomes for a full scale analysis show reasonable results when compared with the results of the model presented in Jansen [2013] and therefore it is expected that the model is considered reliable for uncongested systems and single load vehicles. It is also expected that the results are reliable for MTSs and barges under the assumption that enough containers are available at a single terminal to load a MTS or barge without waiting for containers. However the fact that the results for AGVs are close to the results of Jansen [2013] does confirm that the model on itself can provide reliable results. Because there is no existing ITT system anywhere in the world the model cannot be validated using data from such systems. For future research it is recommended to compare this research with the research of Schröer [2013] within the ITT project group to further evaluate the performance of all three models. Also systems related to ITT could be used to validate the results of this model such as internal transport systems in terminals or factories.

For the results presented in Figure 1 a multi criteria analysis showed that the AGV is the best vehicle type for the ITT system. Although scoring the same amount of points as the ALV the fact that the AGV system is a proven system gave it the advantage over the ALV. Also the fact that driving will consume most of the time makes that the lift ability of the ALV is less interesting and will therefore only increase the uncertainty of the system.

Samenvatting

De grote groei in het vrachtvervoer per container heeft geleid tot capaciteitstekorten in de meeste havens in de wereld. Zo ook in de haven van Rotterdam, waardoor uitbereiding van de haven niet uit kon blijven. In het nieuw aangelegde Maasvlakte 2 gebied is er ruimte voor 5 nieuwe container terminals die de totale container overslag capaciteit opvoeren tot 30 miljoen TEU per jaar. Om deze grote stroom van containers efficint en zonder opstoppingen te kunnen verwerken zijn er plannen om een Inter Terminal Transport (ITT) systeem aan te leggen. Dit systeem moet er voor zorgen dat containers binnen het haven gebied over een eigen weg te transporteren met als voornaamste doel het goedkoop kunnen bundelen van 'dunne' achterland stromen, waardoor de binnenvaart en het spoor aantrekkelijker worden.

Er is echter nog weinig bekend over het functioneren van een dergelijk systeem en daarom heeft het Havenbedrijf Rotterdam in samenwerking met de TU Delft en de Erasmus Universiteit Rotterdam een samenwerkingsproject opgezet om verschillende aspecten van een ITT systeem te onderzoeken. Het onderzoek in dit rapport heeft als voornaamste doel om een nieuwe en snelle manier voor het bepalen van de hoeveelheid benodigde voertuigen te onderzoeken. Het model wat hiervoor gebruikt wordt maakt het mogelijk om snel en goedkoop het systeem te analyseren, waardoor het een ideaal instrument is om te gebruiken voor investeringsbeslissing waarvoor vaak geen tijd en geld is om een uitgebreide simulatie te laten bouwen. De belangrijkste vraag is echter wel of het mogelijk is om een betrouwbaar model te maken die de optimale voertuig configuratie kan bepalen.

Om deze vraag te beantwoorden is er een deterministisch minimum cost flow model met tijdsexpansie gemaakt die deze ideale voertuig configuratie kan berekenen. Deze methode is gebaseerd op het model dat gepresenteerd is in de paper van Tierney et al. [2013]. Het model is opgebouwd uit knopen, die de terminals en kruispunten voorstellen, en wegen die de verschillende knopen met elkaar verbinden. Door dit netwerk rijden de voertuigen over de wegen om de containers te vervoeren die zijn gegenereerd door een generator die is gebouwd en gepresenteerd in Jansen [2013]. Het totale jaarlijkse volume die door het systeem vervoerd moet worden varieert afhankelijk van het scenario tussen de 1.42 en 3.26 miljoen TEU. De voertuig en container stromen moeten voldoen aan een aantal voorwaarden, die de capaciteit en de betrouwbaarheid van het systeem waarborgen. Daarnaast zorgt een optimalisatie functie ervoor dat de kosten voor de aanschaf van de voertuigen en de kosten voor vertragingen geminimaliseerd wordt. Een verificatie van kleine modellen heeft aangetoond dat het model werkt zoals verwacht.

Voordat het model op het ITT systeem betrouwbaar kan analyseren zijn er eerst een aantal parameters vastgesteld. De ideale stapgrootte van het model is 3 minuten voor zowel constante als fluctuerende scenario's en is erg afhankelijk van de lengte van de wegen en de tijdsduur van de verschillende processen. Ook is aangetoond dat de resultaten die berekent zijn met continue variabelen het zelfde zijn als die voor integere variabelen, wat ervoor zorgt dat de rekentijd zeer verkort wordt. De ideale tijdshorizon is 18 uur en de containers kunnen het beste gedurende 2/3 van deze horizon gegenereerd worden, zodat ze nog voldoende tijd hebben om bezorgd te worden en het model kan anticiperen op fluctuaties in de vraag naar transport. In het model zijn 4 voertuig types geintegreed: AGV's, ALV's, MTS'en en binnenvaartschepen. Deze types hebben elk hun eigen parameters die te zien zijn in Tabel 2. Het gebruikte netwerk van terminals op de Maasvlakte is geclusterd, waarbij terminals die naast elkaar liggen of een interne connectie hebben worden gezien als 1 terminal. Dit zorgt ervoor dat de rekentijd en het benodigde werkgeheugen beperkt blijft. Deze aanname is betrouwbaar omdat het verschil in totale reistijd voor het vervoeren van alle containers tussen alleen maar individuele terminals en

het clusteren van terminals verwaarloosbaar is.

De resultaten die het model heeft bepaald door het analyseren van het terminal netwerk zijn weergegeven in Figuur 2. Om de betrouwbaarheid te bepalen van deze resultaten zou het model idealiter gevalideerd moeten worden aan de hand van data uit een reeds gemplementeerd systeem, maar helaas is dit niet mogelijk omdat er nog geen ITT systemen bestaan. Om toch iets te kunnen zeggen over de betrouwbaarheid heb ik de resultaten van de AGV vergeleken met de resultaten van een ander model dat gemaakt is binnen het ITT project door Jansen [2013]. Het bleek dat de resultaten goed overeen kwamen voor scenario 2 en 3, maar voor scenario 1 zag je er een verschil ontstaan van 13 voertuigen. Dit kan worden verklaard doordat wanneer het drukker word in het systeem de planning van voertuigen belangrijker wordt en dit optimaal is in dit model en zeker niet in het model van Jansen [2013]. Hierdoor is aangenomen dat de resultaten betrouwbaar kunnen worden geacht, maar dat het wel een ondergrens aangeeft voor het benodigde aantal voertuigen. Daarnaast is aangetoond dat het veranderen van verschillende parameters, zoals bijvoorbeeld de snelheid, grote invloed heeft op het benodigde aantal voertuigen.

Table 2: Default parameter values.

	speed (km/h)	intersection cap. (veh/timestep)	carrying cap. (TEU)	handling time (sec.)	cost function (per 24 hours)
ALV	40	8	2	30	239
AGV	40	8	2	180	162
MTS	30	3	10	180	100/28 (truck/trailers)
Barge	12	∞	50	180	1200

	Scenario 1	**Scenario 2**	**Scenario 3**
	nr vehicles	nr vehicles	nr vehicles
ALV	51	33	24
AGV	65	42	32
MTS	16 Truck +76 Trailers	12 Trucks + 59 Trailers	9 Trucks + 42 Trailers
barge	41 Truck + 2 Barges	22 Trucks + 3 barges	17 Trucks + 2 barges

Figure 2: Required vehicles for the various scenarios.

List of Symbols

a_θ	Amount of TEU in demand θ.
Aeq^τ	Matrix representing the time space network of arcs and nodes.
$A^F_{i'j't}$	Set of fan arcs.
A^LT	Set of LT arcs.
A^T	Set of time space arcs.
A^S	Set of stationary arcs.
b	Demand vector.
c_d	Cost of delays.
c_h	Carrying capacity in TEU per vehicle for vehicle type h.
$c_{v,h}$	Vehicle cost for vehicle type h.
d_θ	Destination node $\in V^T$ of demand θ.
H	Set containing all vehicle types.
h	Vehicle type.
$In(i)$	A set of nodes with arcs entering node $i \in V^T$ including stationary arcs.
m_{ih}	Handling capacity at terminal $i \in V^T$ for vehicle type h.
$m_{ih}max$	Handling capacity per vehicle at terminal $i \in V^T$ for vehicle type h.
o_θ	Origin node $\in V^T$ of demand θ.
$Out(i)$	A set of nodes with arcs leaving node $i \in V^T$ including stationary arcs.
r_θ	Release time period of demand θ.
s_{ih}	Amount of vehicles of type h present at node $i \in V$ at time step $t = min(r_\theta)$.
$step$	Total number of timesteps.
t	Set containing the transverse times of all arcs.
t_{ijh}	Transverse time of arc (i, j) for vehicle type h.
u_θ	Delivery time period of demand θ.
v_h	Driving speed of vehicle type h.
V^T	Set of time space nodes.
V^T_{ih}	A set of non-stationary arcs connected to node $i \in V^T$ of vehicle type h.
V^{int}	Set of intersection nodes.
V^{tster}	Set of terminal nodes $i \in V$.
V^T_{ih}	A set of terminal nodes $i \in V^T$ connected by non-stationary arcs of vehicle type h.
x_{ijh}	The amount of vehicles on arc(i, j) of vehicle type h.
$y_{ij\theta}$	The amount of containers on arc(i, j) for demand θ.
$\delta_{ij\theta}$	Indicate wheter arc (i, j) is a stationary arc.
η_{ij}	Vehicle type allowed on arc(i, j).
ϕ_{ij}	Capacity of intersection node i_{int}.
Θ	Number of demands.

List of Abbreviations

AGV	Automated guided vehicle
ALV	Automated lift vehicle
APMT	APM Terminals
ASC	Automated stacking crane
BSC	Barge service centre
CRT	Common Rail Terminal
DCS	Delta Container Services
ECT	European Container Terminals
ED	Empty depot
FEU	Forty foot equivalent unit
FSC	Feeder service centre
FSMVRP	Fleet size and mix vehicle routing problem
FSMVRPTW	Fleet size and mix vehicle routing problem with time windows
ITT	Inter terminal transport
ISO	International Organization for Standardization
LP	Linear programming
LT	Long term
LZV	Langere en zwaardere vrachtautocombinatie (Dutch for longer and heavier truck combination) or 3-TEU truck
MTS	Multi trailer system
MV	Maasvlakte
OR	Operational Research
PoRA	Port of Rotterdam Authority
RSC	Rail service centre
RTW	Rail terminal west
RWG	Rotterdam World Gateway Terminals
STS cranes	Ship to shore gantry cranes
T3	Container terminal 3
T4	Container terminal 4
t1 to t7	Terminal cluster 1,2,3,4,5,6,7
TEU	Twenty foot equivalent unit
TT	Terminal tracktor

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Chapter 1

Introduction

Since the introduction of containerized trade in 1956, containerization has spread across the globe. The main functions of containers are protection against damages and theft, but the most important reason for its popularity is that the standardization of containers made this form of transport very cost effective and made economies of scale possible. The standard size of a container was set in 1961 by the International Organization for Standardization (ISO) and is 20ft long, 8ft wide and 8ft 6in high. This container is commonly referred to as a twenty foot equivalent unit or TEU. Another regularly used container type is 40ft long and therefore called a forty feet equivalent unit or FEU and counts as 2 TEU. Next to the TEU and FEU, a whole range of oversized containers are in use nowadays, which have exceptions in all three directions.

The widespread use of containers in worldwide trade resulted in hundreds of ports with specialized terminals to load and unload containers from ships. The largest port in Europe, Rotterdam (The Netherlands), has several of these terminals handling containers. To be able to cope with the expected growth in worldwide and containerized trade the port of Rotterdam will be expanded by the Maasvlakte 2, which will add i.a. 5 new container terminals to the port. These five new container terminals will increase the annual container throughput capacity for the port up to 34.6 million TEU in 2040 [Visser et al., 2012]. The Maasvlakte 2 will be constructed next to the already existing Maasvlakte 1 and covers an area of 1000 hectares which is reclaimed land from the sea. Besides container terminals the Maasvlakte 2 will also incorporate chemical clusters and a distribution park. In Figure 1.1 an artist impression is shown of the Maasvlakte 1&2 in 2030, when all infrastructure and terminals will have been build.

Figure 1.1: Maasvlakte 1&2 (source: Maasvlakte2.com)

In container terminals, containers are handled from ships using ship to shore gantry cranes (STS cranes) as shown in Figure 1.2a. These large cranes are able to pick up a container from above using a spreader which is able to grab the container in the four corner points as shown in Figure 1.2b It then moves to the quay side where it is placed on the ground or on top of a piece of equipment so that it can be moved to the storage area. There are several vehicles which are regularly used for the transport of containers at the terminal: yard tractors which pull one chassis with a container on top, Multi Trailer Systems (MTSs) which pull up to five chassis, Automated Guided Vehicles (AGVs), straddle carriers and reach stackers. The newest vehicle introduced in port operations is the Automated Lifting Vehicle (ALV), which is able to lift a container on a platform decoupling the loading/unloading operation between the crane and the vehicle. These vehicles will transport the containers to a storage area, where the containers are stored until they are needed for further transportation to the client. This process is e.g. explained in Pap et al. [2011].

(a) A STS gantry crane in the port of Salalah, Oman

(b) A spreader holding a container

Figure 1.2: Ship to shore handling of containers.

Once the container arrives at a container terminal it requires additional transportation to the client. In general a container can transported into the hinterland by three different modes of transport: truck, barge and train. The cost of inland transport is estimated by Notteboom and Rodrigue [2005] to be between 40-80 % of the total transportation cost of containers. As a result port choice is increasingly determined by hinterland connections and logistical services resulting in the lowest overall supply chain cost. Therefore efficient and fast connections are important ways for ports to distinguish themselves from other competing ports. In the case of the port of Rotterdam, infrastructure inside the port as well as throughout the entire nation and European Union must have sufficient capacity to handle large container flows. For the Maasvlakte 2 expansion the capacity of the hinterland transport has been enlarged by i.e. widening parts of the highway A15, the construction of the dedicated freight railway line 'the Betuweroute' and the construction of an inland container transferium just outside Rotterdam, where containers will be fed by barge [Port of Rotterdam Authority, 2010].

1.1 Inter Terminal Transport setup

The previous examples served the goal of providing fast connections to the hinterland of the port. However the transport of containers inside the port, between terminals and other service providers, should be fast, cheap and efficient as well to provide the containers to the various service providers of the hinterland transport in the port. All container flows converge at the container terminal, where the containers are loaded or unloaded from large deep sea vessels. Most of these containers are transshipped on hinterland modalities at the terminal itself, however in the port area containers are also transported to other deep sea terminals or to service centres and supporting services, which increase the efficiency of hinterland transportation. The service providers that are distinguished in this research are:

- Barge service centre (BSC): A common barge terminal, where container flows to the hinterland are bundled to provide better utilization rates on low demand connections. Better utilization rates contribute to a modal shift to intermodal transport, which reduces road congestion and lowers emissions.

- Rail service centre (RSC): A common rail terminal, which has the same function as the BSC.
- Feeder service centre (FSC): Most feeders are handled
- Empty container depots: Locations separate from a deep sea container terminal, where empty containers are stored.
- Distribution areas: Areas where value is added to goods by repacking or creating new products. From here products are further transported into the hinterland.
- Customs: At the distribution area on the Maasvlakte 1, customs has an area where X-ray scanning, nuclear detection and physical inspections of containers take place.

It is proposed to transport containers between the service providers and the deep sea terminal and between deep sea terminals by Inter Terminal Transport (ITT). This ITT could either be done by regular trucks on public roads or on a closed transport route, which is closed for public traffic and therefore vehicles on this road do not have to apply to national laws for vehicles on public roads. This makes it possible to choose for other transport options than trucks such as Automated Guided Vehicles (AGVs), Automated Lift Vehicles (ALVs) or Multi Trailer Systems (MTS). Figure 1.3 provides a representation of the container flows, which will be transported by ITT in the Maasvlakte area.

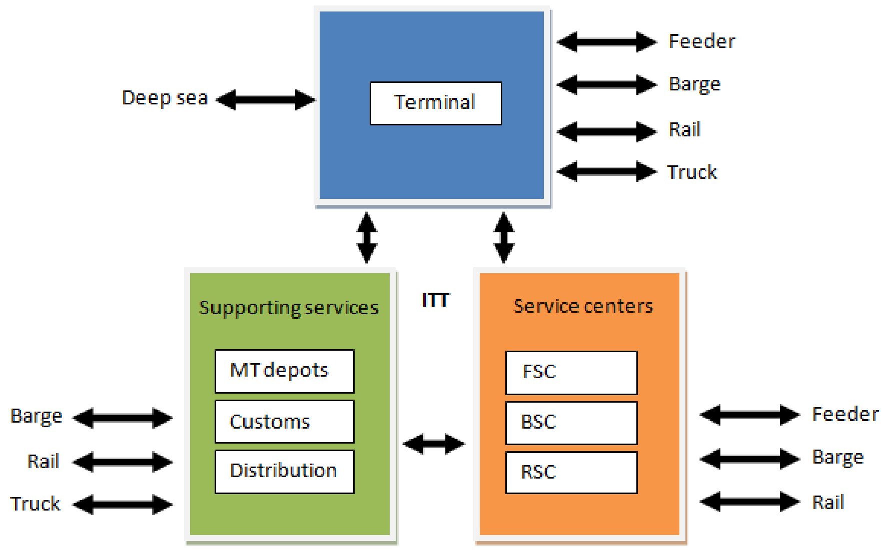


Figure 1.3: Overview on ITT flows between different port areas

In Diekman and Koeman [2010] the ITT on Maasvlakte 1 & 2 has been investigated whether the current infrastructure would have sufficient capacity or that a new closed transport route should be constructed. This research provided three scenarios about the expected demand of ITT transport by containers which have to be transported between terminals based on different assumptions. In Jansen [2013] various scenarios have also been created for the ITT demand at the Maasvlakte area in 2035. When considering the scenario creating the lowest demand, a minimum amount of 1.42 million TEU per year will be transported internally across the Maasvlakte in 2035. Although these numbers are large, it is expected that until 2020 current infrastructure is capable of handling these ITT flows. However after 2020 it is advised to build a closed transport route with 1 lane in both directions to efficiently handle all container flows across the port. The various demand scenarios are more extensively described in Section 2.3.

The location of the closed transport route has already been planned and is shown in Figure 1.4. This figure also shows the ITT demand for scenario 2 in rush hour. Although the infrastructure of the closed transport route has been determined, the type of transportation vehicles still needs to be investigated. Diekman and Koeman [2010] showed that automated vehicles have the lowest operational costs, but in this research factors like i.e. investment cost of transport equipment, reliability and maintenance costs have not been included. Also a tool that analyses the improvements in port efficiency versus the costs of the installed infrastructure and equipment would be welcome to support the decision making process for the PoRA. To investigate all the questions the port authorities still have, a project group has been formed to investigate various aspects of the ITT system.

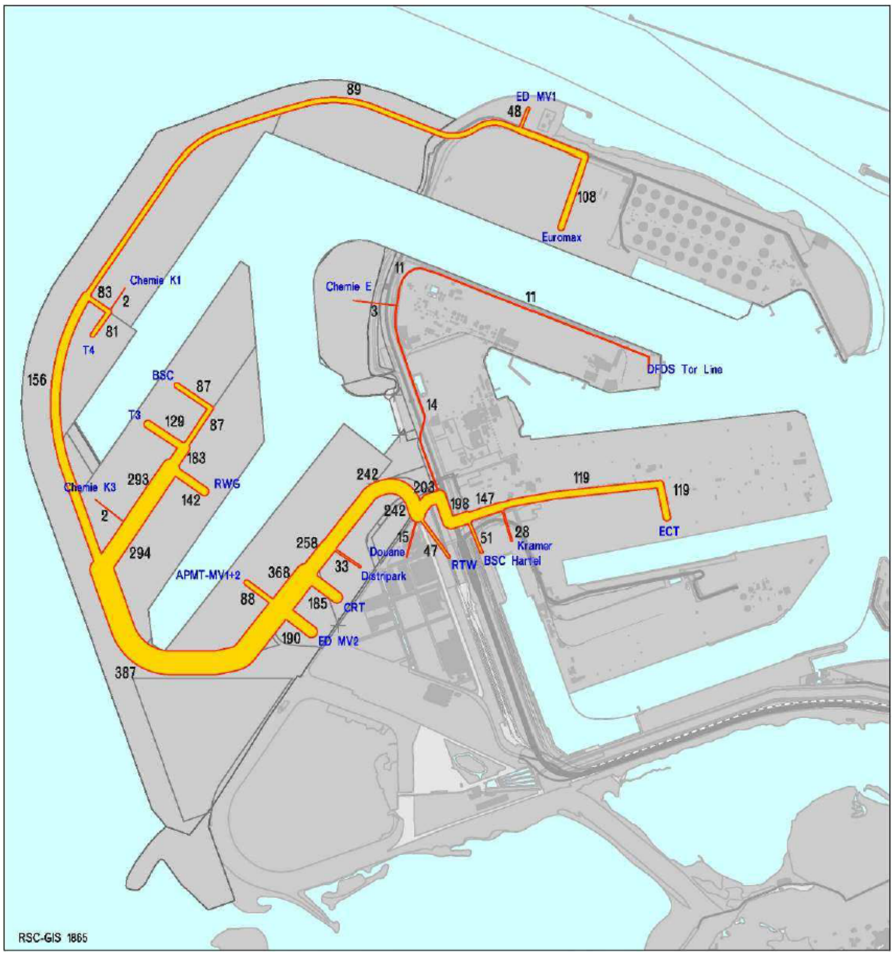


Figure 1.4: ITT route with terminals and demand flow per hour in both directions for scenario 2.

1.2 Inter Terminal Transport project group

This project is a cooperation between the Delft University of Technology, Erasmus University Rotterdam and the Port of Rotterdam Authorities which will investigate various technical and economical questions as well as the added value of information exchange between various players within the ITT system. The goal of the project is to develop innovative, non-conventional concepts for ITT for the port of Rotterdam. Within the project six subprojects are created, which are linked to each other to come up with the larger questions defined by the port authorities. The subjects that will be investigated are:

- ITT demand forecast
- ITT vehicle configurations Truck/AGV
- Asset light configuration
- Cost/Benefit evaluation of ITT configurations

- Operation evaluation of ITT configurations
- Information exchange

This research will consider ITT vehicle configurations for Truck and AGVs. In this research a model is presented which is able to analyse various vehicle configurations and determines their performance. The input required to determine the vehicle configuration is provided by Jansen [2013], who determined the ITT demand forecast and created various scenarios. The results of this research will be used as an input for Schröer [2013] who will evaluate the ITT configurations presented in this report with the use of a simulation model. It will also be the input for the cost/benefit evaluation presented in Jansen [2013], who will look at the cost/benefits for various coalitions of stakeholders within the ITT system. An asset light solution is also investigated. This research is looking if it would be interesting to hire external trucks to lower peak demands in the ITT system which should result in the requirement of less vehicles. The asset light research presented by Liu [2013] requires the tool that is developed in this research to investigate the influence of external trucks on the vehicle configuration. He also investigates an auction system which sells ITT jobs to the lowest bidder. The last project by El Koubai [2013] investigates how the information available within the system can be used to create on optimal added value.

1.3 Research structure

The development of a tool which could be used for strategic decision making by the Port of Rotterdam Authorities have been started by Tierney et al. [2013], which uses a mathematical model based on integer programming to model the inter terminal container and vehicles flows and minimizes the delay in the arrival of containers at their destination. The model includes traffic congestion, multiple vehicle types, loading and unloading times and port layout configuration. The results presented in Tierney et al. [2013] only present the average total delay of containers for a certain vehicle configuration and do not optimize for an ideal vehicle configuration. Next to this Nieuwkoop [2013] investigated the working principles and structure of the integer programming model from Tierney et al. [2013] and he concluded with some proposed improvements for the model. The goal of this research is to create a reliable tool with realistic outcomes, able to determine an optimal vehicle configuration (mix of AGVs, trucks, barges etc.) by evaluating different system configurations and analysing ITT operations by computing optimal vehicle and container movements at the Maasvlakte area used in strategic decision making processes. A secondary goal is to investigate whether congestion will have a significant influence on the performance of the ITT system.

These goals will be reached by giving an answer to the main research question: Could a reliable tool be constructed, able to determine an optimal vehicle configuration to provide a yet to be determined performance level for an ITT system? To be able to answer this question several sub-questions are defined:

- What are the functions of ITT system?
- Describe the situation in which the ITT system will be implemented. What should be taken as the boundary of the ITT system to get a realistic model?
- Which external influences have an effect on the outcome of the model?
- What determines the performance of the ITT system?
- Which modelling technique will in theory be the best technique able to realize the research goal?
- How do you create a model which is able to realize the research goal?
- Will congestion have a significant influence on the performance of the ITT system?
- What is the optimal timehorizon which will provide reliable results, while maintaining acceptable calculation times and what will be a useful time step?
- How can the model be validated?

In the following chapters an answer will be given to these questions. The report is structured as follows: The first chapter describes the functions of the ITT system followed by a description of the current plans of the Maasvlakte 1&2 and the boundaries of the ITT system. The second chapter provides a literature overview on various modelling techniques and chooses the best approach to reach the goal of the model. The third and fourth chapter present the mathematical principles and structure of the model which is verified in the fifth chapter. Finally the whole model is submitted to a case for an ITT system at the Maasvlakte area in the seventh chapter concluded with a conclusion and future work.

1.4 Contribution of the research

This research will contribute to the understanding of the best way in applying a tool that is able to analyse the processes of an ITT system and finding an optimal vehicle configuration that can be used in decision making processes for companies or agencies such as port authorities. Several parameters will be varied to get an understanding of these parameters on the performance of the ITT system and the reliability of the tool. Secondly this research will create the understanding by applying the tool to a not yet existing case of an ITT system at the Maasvlakte area in the Port of Rotterdam.

Chapter 2

ITT system

This chapter describes the functions of the ITT system followed by a situation sketch about the current plans of the Port of Rotterdam Authority for the implementation of an ITT system. The demand scenarios for the ITT system are presented and also various vehicle options are presented which have to be considered by the tool developed in this research.

2.1 ITT system functions and requirements

As already mentioned in the Introduction, the main function of the Inter Terminal Transport system is to ensure a reliable transportation service for containers between the various container terminals and service providers in the port area. This function is stated in various literature sources describing or mentioning ITT systems such as Diekman and Koeman [2010], Tierney et al. [2013], Ottjes et al. [1996] and Vis and de Koster [2003]. To provide a reliable transportation service the delay in container delivery should be minimized. Next to this the customer will probably demand a certain punctuality level of the ITT system in order to allow their own processes to be reliable. This means that the tool developed in this research will have to take these factors into account.

As described in Evers [2006], the ITT system will operate as a separate system from the internal transport system to guarantee the autonomy of the terminal operator. Therefore the integration of the the two systems is not acceptable, while in theory the benefits of an integrated system are clear, because less vehicles are required due to mutual peak shaving and because due to optimized coordination empty driving can be reduced.

The ITT system will be managed by a fleet manager who will deploy the vehicles hired by the terminal operators to perform the ITT job. The fleet managers interest is in optimizing the efficiency of the system, while maintaining the performance requirements in order to minimize both its operational costs and fleet size, by reducing empty driving, high vehicle utilization rates, anticipating on job executions and peak shaving. This management role, requiring the ability to control the individual vehicles, will add a new function to the system which ensures that the system has to make decisions about the routing and deployment of vehicles by assigning them with a specific job. The tool will have to make these decisions as well in order to optimize the vehicle configuration and apply to the performance level demanded by the customer.

2.2 Situation description

The system considered in the case of this research is an Inter Terminal Transport system at the Maasvlakte (MV) area in the Port of Rotterdam, the Netherlands. This ITT system will connect different deep sea container terminals and other service providers located at the Maasvlakte 1&2. In the current situation space for the closed transport route is reserved along the outer rim of the Maasvlakte 2. The already existing closed transport route for the connection between ECT Delta and the Distribution area at the Maasvlakte 1 will be integrated in the new closed transport route. The layout of the route is shown in Figure 2.1.

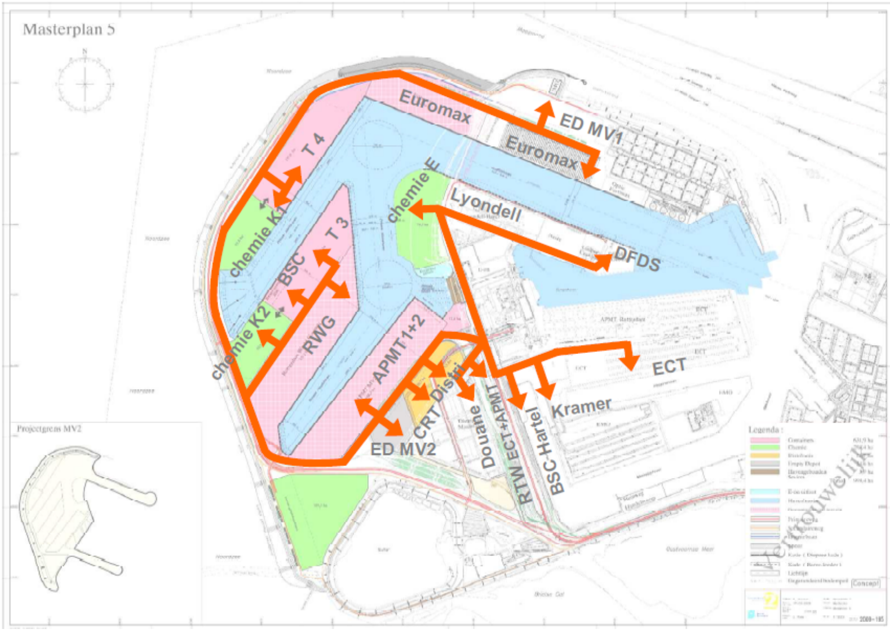


Figure 2.1: Reserved space for the closed transport route at the Maasvlakte.

However it is still undecided whether the complete route as shown in Figure 2.1 will be constructed. If one considers the cost for extending the route to certain terminals versus the volume of ITT transport they will generate some parts will probably not be realized. Although it is not officially determined by the Port of Rotterdam Authority the volume versus the added length of the route to DFDS Tor Line is considered as too low and therefore it will not be taken into account. Also the chemical clusters will not be integrated into the scope of this research because their volume of generated ITT demand is too small, less than 1% of the total ITT demand. The Barge and Rail Service Centres, including Kramer, together with the empty depots are included, because most ITT demands are heading to or coming from one of these locations. This ensures a realistic flow through the network which is required to construct a reliable model.

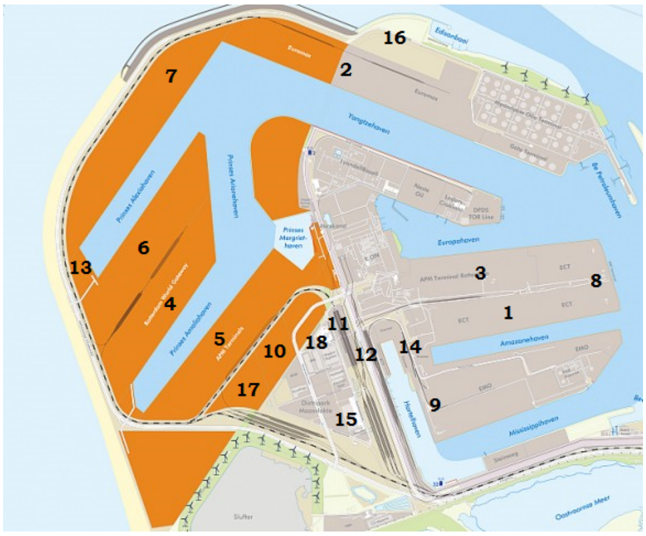
Considering the above assumptions this will create a list of 18 terminals, which are included in this research and is shown in Figure 2.2 together with their annual contribution to the ITT demand in TEU. These terminals all have a certain function in the port area such as handling containers from deep sea vessels, handling containers from trains or barges in a common area, storing empty containers or a dedicated customs area. These functions are all required for an optimal transportation of goods through the port and are used as a base for several assumptions of the demand scenarios as will be discussed in Section 2.3. All terminals of Figure 2.2a are situated along the layout of the closed transport route as shown in Figure 2.1

Terminal operations are not included in the scope of this research except for the handling of containers on the ITT vehicles. Terminal operations is left outside the scope of the research, because the ITT system operator has no influence on the operations at a terminal. However the vehicle is requiring a service from the terminal to handle its assigned container, which requires the terminal to use one of their stacking cranes. Therefore the handling procedure cannot be neglected from the model and is included by adding a waiting to the vehicles representing the handling time of the container. The terminal operator determines when he will handle the container from the ITT vehicle, which may result that the vehicle will have to wait until the stacking crane is ready. Also the location where the container is handled will be different depending on the stacking location of the container. As a result these two influences create a distribution over the average handling time.

The closed transport route will have several crossings with regular roads and rail tracks. These crossings will limit the capacity of the closed transport route to allow other vehicles to pass it.

number	Terminals and service providers
1	ECT Delta Terminal
2	ECT Euromax
3	APMT Maasvlakte 1
4	Rotterdam World Gateway (RWG)
5	APMT Maasvlakte 2
6	Terminal 3
7	Terminal 4
8	ECT Delta Barge Feeder Terminal
9	Delta Container Services
10	Common Rail Terminal
11	Rail Terminal West
12	Barge Service Centre Hartelhaven
13	Common Barge Service Centre
14	Kramer Delta depot
15	Van Doorn Container Depot
16	Empty depot Maasvlakte 1
17	Empty depot Maasvlakte 2
18	Customs

(a) List of included terminals with annual contribution to the ITT demand.



(b) Location of terminal on MV 1&2 based on number.

Figure 2.2: Included terminals with annual contribution to the ITT demand together with their geographical location at the Maasvlakte.

This influence can be neglected by creating an overpass to eliminate the interaction between ITT vehicles and other vehicles.

2.3 ITT demand and scenarios

The demand for the transportation of containers by the ITT system is generated by the deep see terminals, barge and rail service centres and empty depots along the closed transport route. The ITT demands for the various terminals at the Maasvlakte area have been investigated in the master thesis of Jansen [2013]. The container throughput through the Port of Rotterdam for the coming decades is captured by the port authorities and is presented in the Port Vision 2030 [Port of Rotterdam Authority, 2011]. Because the economy is hard to predict the port authorities have set four different scenarios based on four different economic factors. In Table 2.1 the expected annual throughput for these four scenarios through the port of Rotterdam is shown.

Table 2.1: Estimated annual throughput Port of Rotterdam per economic scenario (million TEU)

	2008	Low Growth	European Trend	Global Economy	High oil price
Total throughput	10.7	19.0	26.7	31.0	21.8
Deep sea	6.4	11.6	16.4	18.5	12.8
Transshipment	2.7	2.6	8.0	9.4	6.7
Short Sea	1.6	1.8	2.3	3.1	2.3

In this research the annual demand is not interesting on itself, because the demand is not constant throughout the year. If the demand per day is considered large deviations can be noticed from day to day and even from hour to hour. Therefore Jansen [2013] also considered the variation in demand by investigating the arrival pattern of containers by truck, barge, train and deep sea vessel as is shown in Figure 2.3. As can be seen the arrival varies per day and a clear distinction can be made between weekends and weekdays. However even if one considers an average weekday or weekend day a clear pattern can be seen. This is shown in Figure 2.4.

When all the various patterns are combined, the resulting peak factors are shown in Table 2.2. This table shows the demand which is grouped in various timeslots to assign a peak factor for that timeslot.

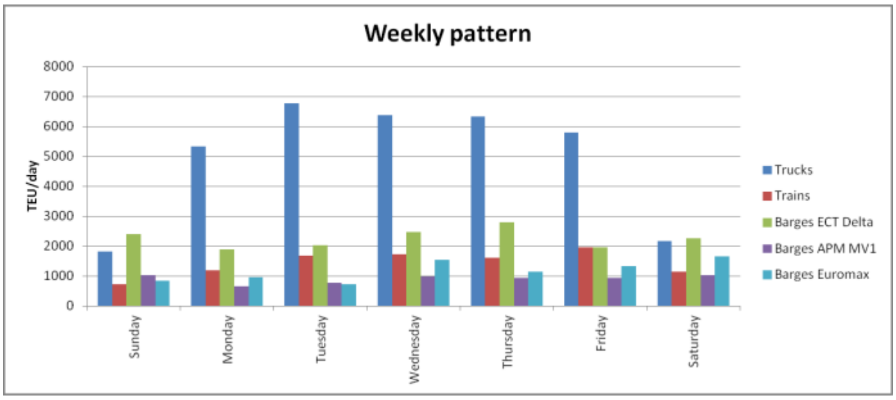


Figure 2.3: Weekly arrival pattern of containers on various terminals at the Maasvlakte 1.

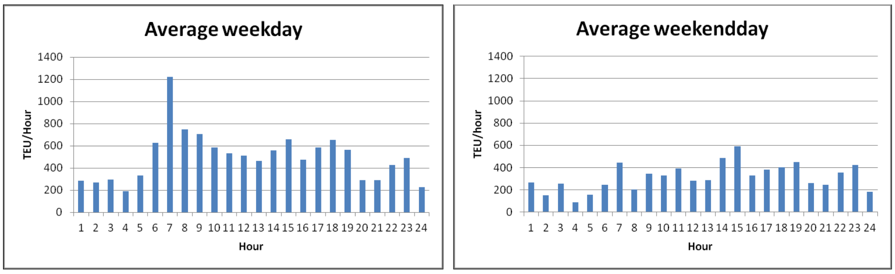


Figure 2.4: Average daily arrival pattern of containers at the Maasvlakte 1 on weekdays and weekenddays.

Table 2.2: Peak factors for the ITT demand over the day.

Timeslot	Weekday sc1	Weekendday sc1	Weekday sc2	Weekendday sc2	Weekday & Weekendday sc3
0-3h	0.57	0.71	0.8	0.9	1
3-6h	0.77	0.52	1.25	0.9	1
6-9h	1.79	1.05	1.25	1	1
9-12h	1.09	1.06	1	1.1	1
12-15h	1.12	1.45	1	1.1	1
15-18h	1.14	1.18	1	1.1	1
18-21h	0.76	1.01	0.9	1	1
21-24h	0.76	1.02	0.8	0.9	1

The economic cases combined with the capacities of the various terminals and service providers in the port, peak factors in the demand and some other assumptions, which will be declared in more detail further in this section, three different scenarios have been created for the ITT demands by Jansen [2013]. This resulted in the annual ITT demand as shown in Table 2.3.

2.3.1 Scenario 1

Scenario 1 is assuming the largest growth scenario combined with the highest change in ITT demand during the day. The various assumptions have been summarized below.

- The ITT demand between deep sea terminals is taken as 1% of the total transshipment volume of the Global Economy scenario of Table 2.1.
- All deep sea terminals have customs facilities on terminal. Only containers for second-line scanning (0.5% of total throughput) will be transported to the central customs facility.
- The ITT demand generated by empty depots and the common barge and rail terminals is 100% of their annual capacity.

Table 2.3: Annual ITT demand per scenario

	Annual ITT demand (TEU)
Scenario 1	3.340.000
Scenario 2	2.150.000
Scenario 3	1.420.000

- The common barge and rail terminal are used at full capacity and every container will be transported through the ITT system.
- The ratio of import/export of loaded(empty) containers is 60/40 (35/65), where 55% of the empty containers are transported by barge and 45% by rail.
- The new ITT system will replace the closed transport route currently available at the Maasvlakte 1.

These assumptions will result in an annual ITT demand per terminal which is presented in Appendix B. In Table 2.4 an overview can be seen on the ITT demands per terminal type.

Table 2.4: Annual ITT demand per category for scenario 1

	Deep Sea terminals	Barge terminals	Rail terminals	Customs	Empty depots
Deep Sea terminals	94.000	425.865	628.960	150.000	266.175
Barge terminals	283.910	0	0	0	146.396
Rail terminals	943.035	0	0	0	119.779
Customs	150.000	0	0	0	0
Empty depots	494.325	78.829	64.496	0	0

2.3.2 Scenario 2

The assumptions of scenario 2 are similar to those of scenario 1, but differ on the following points.

- The mutual ITT demand for deep sea terminals is based on the transshipment volume of the European growth scenario.
- The demand for second line-scanning is reduced to 0.25% of the total container throughput.
- The ITT demand generated by empty depots is reduced from 100% of their capacity to 70% of their capacity.
- The ITT demand generated by the common barge and rail terminal is reduced from 100% of their capacity to 70% of their capacity.
- The import/export ratio of loaded (empty) containers changes to 55/45 (40/60).

This will result in an annual ITT demand per terminal shown in Appendix C. Table 2.5 shows an overview of the ITT demands per terminal type.

Table 2.5: Annual ITT demand per category for scenario 2

	Deep Sea terminals	Barge terminals	Rail terminals	Customs	Empty depots
Deep Sea terminal	80.000	260.876	486.801	75.000	196.560
Barge terminal	213.444	0	0	0	108.108
Rail terminal	594.979	0	0	0	88.452
Customs	75.000	0	0	0	0
Empty depots	294.840	72.072	58.968	0	0

2.3.3 Scenario 3

The main difference in scenario 3 compared to scenario 2 is that the common barge and rail terminal will not be constructed on the Maasvlakte, which will lower the demand from and towards barge and rail terminals significantly. Some of the demand of the common barge and rail terminal is taken by the already existing terminals at the Maasvlakte 1. An overview of the ITT demands per terminal type is shown in Table 2.6 and an extensive overview on the annual ITT demands per terminal is presented in Appendix D.

Table 2.6: Annual ITT demand per category for scenario 3

	Deep Sea terminals	Barge terminals	Rail terminals	Customs	Empty depots
Deep Sea terminal	80.000	97.251	219.051	75.000	196.560
Barge terminal	79.569	0	0	0	108.108
Rail terminal	267.729	0	0	0	88.452
Customs	75.000	0	0	0	0
Empty depots	294.840	72.072	58.968	0	0

2.3.4 Discussion

It can be questioned whether or not the assumptions made in the demand generator are realistic. It however remains very unclear how an ITT system will behave and how the demand is spread out through the time. This will mostly depend on how advanced the scheduling and vehicle routing can be implemented. It will also depend on the cooperation of the various players in the port area and how they will serve the ITT vehicles. The ITT demand is assumed to vary through the day by looking at the arrival pattern of the various commodities. This might not be realistic but unfortunately no such a system does exist anywhere in the world, which can serve as an example.

2.4 Vehicle options

ITT can be performed by several different vehicle options using road, rail or water to travel on. The vehicles that can be analysed by the model and which are described in this section are:

- Automated Guided Vehicle (AGV)
- Automated Lifting Vehicle (ALV)
- Tractor Trailer (TT)
- Multi Trailer System (MTS)
- Barge

Next to these vehicle types also regular road trucks and LZV trucks (trucks with a loading capacity of 3 TEU instead of 2 TEU) could be used for ITT. However Diekman and Koeman [2010] showed that these vehicle types are significantly more expensive and are therefore not considered in the analysis. However if one would like to have an indication of the vehicle requirements of these types it can be expected that the results for regular trucks are comparable to the results for AGVs and the results of the LZV truck are between the results of ALVs and AGVs because of the higher load capacity.

AGV

An AGV is an automated vehicle able to transport containers between the stackyard and the quay crane. The benefit of automation is the reduction of operational costs for the terminal operator, despite the high investment costs this form of container transport is common in various ports in Europe. AGVs can transport one 40 ft container or two 20 ft containers with speeds up to

20 km/h at current terminals. However because the distances travelled by the AGVs in ITT transport are much longer the average speed is assumed to increase up to 40 km/h. Figure 2.5 shows AGVs operating at Container Terminal Altenwerder in the port of Hamburg.

Figure 2.5: AGVs operating in the Port of Hamburg (Gottwald.com).

ALV

The newly developed ALV is basically the same as an AGV, but the difference lies in the lifting platform of the ALV which is able to lift a container on and off a rack located in the reach of the stacking cranes handling the containers transported by the ALV. The major benefit of these racks is the decoupling of the container transport from the storage processes. This will result in a reduction of the required fleet size as a result of the increased working frequency [Gottwald Port Technology GmbH, 2008]. The average speed of an ALV is assumed to be 40 km/h and the handling time is assumed to be 30 seconds. Figure 2.6 shows the ALV including the rack used to decouple the container handling at stack.

Figure 2.6: ALV with rack (Dredgingtoday.com).

TT

A Terminal Tractor is a small truck operated by a driver. This TT pulls a chassis on which a maximum of 2 TEU will be placed to be transported to the desired location. The TT is specially designed for terminal operations which makes it more suitable than a regular truck. However the TT does not satisfy the strict regulations for vehicles to allow it on the public road, but this makes it cheaper to buy than a regular truck. The average speed for a terminal tractor is assumed to be 40 km/h and handling a container takes 180 seconds. Because TTs show large similarities with the AGV the modelling results of AGVs can be considered to be the same as for AGVs. Figure 2.7 shows a Terminal Tractor.

Figure 2.7: TT with chassis and container (Terbergbenschop.nl).

MTS

A Multi Trailer System is a manned truck capable of pulling 5 trailers behind it, which results in a capacity of 10 TEU. The trailer can be connected or disconnected on the terminal and the tractor can also drive with less than 5 chassis. The combination can reach an average speed of 30 km/h and takes 180 seconds to connect or disconnect its trailers. Because the trailers can be loaded independently from the truck the combination does not have to wait for an ASC to load or unload the containers at the stack.

Figure 2.8: MTS with chassis and container (Terbergbenschop.nl).

Barge

The last vehicle type that will be modelled is the barge. The benefit of a barge is that it can transport large amounts of containers at once so that a relative low number of barges should be enough to handle the ITT demand. The barges that will be used for ITT transport have a carrying capacity of 50 TEU and can reach speeds up to 12 km/h. The handling of containers will take 180 seconds and the mooring procedure takes up 30 minutes. Because the size of a barge compared to a handling crane only one crane can service a barge at the time. It is estimated that there are two barge cranes available for handling.

Overview on vehicle properties per vehicle type

In Table 2.7 an overview is given on all vehicle properties used in the model. The purchase costs are based on the costs presented in Port of Rotterdam Authority et al. [2002]. Although these costs might be outdated they can still be used, because for this research the relative difference between the costs of various vehicle types is important instead of the absolute costs. The speeds given to the vehicle types are the average speeds, however because the distances in the network are quite large this speed can be assumed to be near the maximum speed.

	AGV	**ALV**	**TT**	**MTS**	**Barge**
Carrying capacity (TEU)	2	2	2	10	50
Speed (km/h)	40	40	40	30	12
Length (m)	15	13.7	17	82.5	n.a.
Handling time (s/FEU/cr)	180	30	180	180	180 + 30 min. mooring
Handling capacity (TEU/cr/h)	35	35	35	35	30
Number of cranes per terminal					2
Average TEU per day sc1,2,3					10.001, 6549, 4468
Purchase costs (Euro's)[1]	340.000	500.000	97.000	250.000/Truck, 40.000/trailer	2.500.000

Table 2.7: Overview of several vehicle properties.

Chapter 3

Modelling technique

In this chapter an investigation is done to determine which modelling technique will be used by the tool to compute the optimal vehicle configuration and to reach the research goal set in Section 1.3. The available literature on ITT systems is very limited with only a few papers describing its properties. However fleet sizing in general comprise comprehensive studies for all kinds of systems, with AGV systems at a terminal providing the quay to stack transport as closest related to ITT. Extensive literature reviews on container terminal operations can be found in Vis [2006], Stahlbock and Voss [2008] and Steenken et al. [2004].

The determination of an optimal fleet is a case of the vehicle routing problem where not only variable routing costs, but also fixed vehicle costs have to be considered [Golden et al., 1984]. In the case of this research different combinations of vehicles are possible requiring the implementation of different costs and capacities for the various vehicles. This results in a special case named Fleet Size and Mix Vehicle Routing Problem (FSMVRP). When a time window is added to the problem in order to force delivery in this window the problem is extended to be a Fleet Size Mix Vehicle Routing Problem with Time Windows (FSMVRPTW) [Liu and Shen, 1999]. Due to its complexity most research has been done into heuristics which are techniques to speed up problem solving by approximating the solution [Renaud and Boctor, 2002]. These techniques have been extensively studied and a comprehensive bibliography is given in Laporte and Osman [1995]. However in this research the practical application of the problem in ITT systems results in a focus on implementing a practical situation in a mathematical model or simulation as reliable as possible. A focus on implementing real world systems in a FSMVRP environment have been investigated by e.g. Golden et al. [1984] and Etezadi and Beasley [1983].

For the determination of fleet sizes, literature distinguishes four different categories of modelling techniques [Choobineh et al., 2012]:

1. Simulation approaches,
2. Calculus approaches,
3. Deterministic operation research approaches,
4. Stochastic operation research approaches.

Next to system costs several other factors are also required by the modelling technique in order to determine the optimal fleet size such as noted in Vis [2006]:

- number of units to be transported,
- a point in time when a unit can be picked up or has to be delivered,
- pick up and delivery location,
- capacity and speed of a vehicle,
- layout of the system and the directions of paths,
- traffic congestion,
- vehicle dispatching strategies.

All four categories have their advantages and disadvantages in the implementation of the above points in their determination strategies. In this chapter a literature overview on these four categories is presented concluding with a decision about which approach can be best used to construct the tool for this research.

3.1 Simulation approaches

According to Choobineh et al. [2012] simulation models are mainly used to validate the results of analytic results. Simulation can realistically incorporate every operation and detail required by the researcher, which is often not possible with the other techniques and can therefore be used to see how the implementation will react on variations of parameters in the system. Although widely used in industry, the implementation of a reliable simulation is, due to its possibilities in optimizing the parameters, costly and time consuming [Barton and Meckesheimer, 2006].

The most extended simulation study in ITT operations is performed by Ottjes et al. [1996] and Duinkerken et al. [2007] who developed a simulation model analysing the non performance (delay) in container delivery at the Maasvlakte area in the port of Rotterdam. By setting a lower bound on the non performance by vehicles a minimum amount of required vehicles for the system was determined.

Other simulation approaches can be found in related working environments such as AGV systems in manufacturing areas and water to landside transport of containers in container terminals. Kasilingam and Gobal [1996] presented a simulation study to estimate the required number of AGVs for a manufacturing system based on the sum of the idle time costs of vehicles and machines and the waiting time of parts. Lee et al. [1990] presented a simulation study to show demonstrate the steps involved in simulating and evaluating AGV systems. It was shown that arrival rate distributions have a great influence on job throughput times. These first simulation models were small scale factory networks with a small number of AGVs resulting in a low complexity, however AGV simulations developed in time to complex systems with many vehicles able to prevent deadlocks and collisions by efficient routing and scheduling algorithms. Qiu et al. [2002] gives a literature review on problems of routing and scheduling AGVs and categorized the algorithms in three categories. Singh et al. [2011] avoids complexity by using a special case for its application for a material distribution network which is much simpler making it easy to analyse. Hsueh [2010] developed an EX-AGV system to eliminate deadlocks and conflicts and ensures that the AGV always moves along the shortest path by transferring loads from one AGV to another. Also some vehicle dispatching rules are tested and analysed. In Martinez-Barbera and Herrero-Perez [2010] AGVs were even able to navigate through changing floor plan layout by incorporating a higher degree of autonomy for the individual vehicles. Bilge and Tanchoco [1997] showed with a simulation study that AGVs in a manufacturing environment who are able to carry multiple loads perform much better than single load AGVs. This observation is interesting in the case of ITT as well because of the distinction between 40 and 20 foot container, where AGVs and other vehicles are able to transport two 20 foot containers or one 40 foot container.

Other articles are in the field of container terminal simulation such as e.g. Petering [2011] who presented a study on how different strategic and tactical decisions will influence the gross crane rate for a pure transshipment container terminal. The reason that a simulation approach was used over deterministic or stochastic operation research approaches is that simulation can incorporate stochastic properties of large and complex facilities and handling equipment, while it is still able to measure the required performance. Henesey et al. [2009] used a multi-agent based modelling simulation to compare the performance of 2 AGV systems in an automated container terminal. This approach was chosen because container terminals have a high degree of localization and distribution and is dominated by discrete decisions. Liu et al. [2002] used a simulation model to determine the design characteristics of four different automated container terminals in order to meet the projected demand. It was concluded that the performance of the four terminals were almost identical except for the costs per handled container. It was further concluded that automation could increase throughput and reduce cost compared with the non automated case.

Ozden [1988] observed that throughput within a fixed time interval behaves in a concave fashion as a function of the design factors for determining the AGV fleet size. This results in the possibility to determine the optimal configuration of parameters by a simple search algorithm. It can be assumed that this concave fashion will also be valid for ITT transport. For example a small number of vehicles will give delays in ITT transport due to a lack of available vehicles, while too many vehicles could create significant congestion, either at intersection or at handling locations, resulting in an optimum somewhere in between. This makes it interesting to investigate some of these algorithms when a simulation approach is chosen.

3.2 Calculus approaches

In most cases one tries to get an initial estimation for the total fleet size by making some hand calculations. These calculations are not very accurate, but the estimation will give some decision making directives and are therefore often used at the start of a investment procedure. Maxwell and Muckstadt [1982] presented a paper calculating both the empty vehicle transport time and loaded vehicle transport time for AGVs in manufacturing facilities. By adding both times together one can determine the minimum required fleet size. The calculation of empty and full transportation times is incorporated in a lot of papers presenting analytical models for the determination of fleet size. Egbelu [1987] presented 4 different analytical methods to calculate the fleet size of AGVs in a manufacturing area. By comparing the methods with a simulation model it was shown that the analytical methods underestimated the required number of AGVs. This was mainly due to the fact that analytical models do not include vehicle dispatching strategies, which were identified as greatly affecting the vehicle requirements by congestion and blocking effects. Other similar analytical models are presented by e.g. Sinriech and Tanchoco [1992], Mahadevan and Narendran [1993], Ilic [1994], Arifin and Egbelu [2000] and Diana et al. [2006].

Underestimation occurs in most analytical methods, however Malmborg [1990] presented a method giving an upper bound for the vehicle fleet size by incorporating a dispatch strategy forcing vehicles to return empty to the workstation farthest from the unloading workstation.

3.3 Deterministic OR approaches

Deterministic approaches usually incorporate linear programming techniques to optimize a certain objective value, which is generally chosen to be costs. The optimization of the objective value results in a lower bound on the required fleet size, because a smart algorithm is able to find an optimal feasible solution satisfying all constraints given to the system and considering every possible solution. The major issue of linear programming is that stochastic processes, which occur in several ITT processes, can not be modelled and have to be modified to a deterministic process. This modification could reduce the validity of the model output. Also the time disceti-zation could result in a lower accuracy of the model, because processes and travelling times will be rounded of to the nearest time step.

As already mentioned in the introduction Tierney et al. [2013] presented an integer programming model for analysing ITT systems in the port of Rotterdam and Hamburg. In this model a minimum cost flow network is introduced, where the costs of the delay in the arrival of containers is minimized. The model considers flows of both containers and vehicles flowing through a network of arcs and nodes, representing the roads and terminals or intersections respectively. The model uses a time-expanded graph to incorporate e.g. the handling of containers at the terminal and travelling time realistically. Congestion is also incorporated in the model by allowing a maximum capacity of vehicles over an intersection. Evers [2006] also developed an integer programming model based on a minimum cost flow network concerning the deployment of container transporting vehicles in a network of roads and logistic sites. There is a decoupling between the site operator, responsible for the logistic operations at the terminal, and the fleet manager, responsible for deploying the fleet of transport vehicles, taking the objectives of both actors into account resulting in a win-win situation for both. Although it is not specifically mentioned, this research is directly applicable in ITT systems, because of the actor decoupling and overall nature of the model.

Literature related to intra terminal transport implementing deterministic approaches for both fleet size approximation and vehicle routing are abundantly available. Koo et al. [2005] presented a two phase fleet management procedure able to find both the minimum fleet size and the travelling route for each vehicle in a container transportation system. The first phase determines the lower bound on the vehicle fleet size by constructing an optimization model based on the model presented in Maxwell and Muckstadt [1982]. Phase two an Tabu Search (TS) algorithm is implemented to solve a transportation problem, where the solution of phase one serves as an input. The goal of the TS algorithm is to minimize the makespan of the available vehicles meaning that all jobs have to be completed within a pre set time and if this is not possible the fleet size will be increased by one vehicle. However this approach requires that all jobs are available at the beginning of the simulation making it less applicable in an ITT environment, because jobs can be issued at any time.

Vis et al. [2001] developed a minimum flow algorithm to determine the AGV fleet size in a semi automated container terminal. The minimum flow algorithm allows large data sets being handled, making it an interesting technique to be used in the tactical decision making process. Two graphs will be constructed, where the result of the maximum flow through the second graph will be used to reduce the first graph to a minimum flow. Although this methods looks promising for solving large problems, the application in ITT systems might my difficult because only one origin and destination are modelled and the waiting times for jobs is assumed to be zero. In the case of ITT we do however allow waiting times for jobs for both the pick up terminal as for the delivery terminal.

Beaujon and Turnquist [1991] constructed a general model which can be seen as a stochastic programming model, but because this form was found unattractive in term of computation time it was reformulated into a deterministic minimum cost flow model with a non linear objective function. The expected profit is maximized by implementing both the revenue gained from completing transportation jobs and the costs for vehicle ownership, vehicle movement and unmet demand. The stochastic behaviour of demand and travel time is implemented by introducing a net vehicle pool which is able to model a distribution on the vehicle availability at each location and time. The problem is neither convex or concave because of the variance in the stochastic elements of the model, but a solution is obtained by fixing the variance and solving the problem using the Frank-Wolfe algorithm. An iterative procedure will than search for a solution where a set of given variances used as input will produce the same variances in the results of the network flow problem.

Kim and Bae [2004] presented a mixed integer programming model that uses pre arrival information of containers heading to the terminal to assign the delivery tasks to AGVs. To reduce the computational time a heuristic is proposed which, according to a numerical experiment, solved the problem 100 times faster than the mathematical formulation while the increase of the objective function was less than 10%. Confessore et al. [2011] presented a minimum cost flow model with nodes representing the task which have to be completed connected by arcs with route specific characteristics.

Klosterhalfen et al. [2013] developed a two stage model able to determine the fleet size and structure of a rail car fleet. First a mixed integer linear programming technique optimizes the number of rail car types by minimizing the direct rail car costs. During the second stage the fleet size is determined using the result of the first stage as an input for a model based on an inventory model calculating the required stock levels for the various rail car types. The inventory model is able to include stochastic properties into the final fleet composition, providing a more realistic result than when only the purely deterministic first linear programming technique would have been used.

Although various approaches exist mainly all deterministic modelling techniques found in literature are based on linear programming sometimes combined with some smart heuristics able to speed up the computational times.

3.4 Stochastic OR approaches

Stochastic approaches have the advantage that stochastic processes can be implemented realistically with correct distributions in a model. Most stochastic processes make use of queueing networks to determine the required number of vehicles. For example Mantel and Landeweerd [1995] presented a hierarchical queueing network approach to analyse vehicle requirements and transportation control in a job-shop and a flow-shop. Choobineh et al. [2012] determined the number of AGVs in a manufacturing or distribution environment, by implementing a closed queueing network under steady state conditions. Processors representing the necessary tasks of AGVs such as loading, unloading, empty driving and loaded driving are modelled to have single server Markovian properties with infinite queues. The utilization of the individual processors to achieve the required system throughput is minimized by a linear program, which will result in a lower bound on the minimum number of AGVs.

Instead of queueing networks Kahraman et al. [2008] used Markov chains to analyse AGV performance of a single AGV in a closed loop path operating in a manufacturing environment. The AGV can pick up loads at multiple machines which are each modelled by an independent Markov chain. The results of these chains will be used to determine important parameters such as: the average inventory requirements per machine, the capacity of an AGV, the average Long-Run cost and the probability that not all waiting jobs can be fulfilled.

The stochastic properties of the various models unfortunately result in extensive calculation times making stochastic approach not very interesting for large applications such as an ITT system.

3.5 Summary and choosing a modelling approach

After an extensive literature research four different modelling approaches are identified: simulation, calculus, deterministic and stochastic. Each approach has its own advantages and disadvantages, as presented in Table 3.1, making a clear decision on the best approach difficult.

Approach	**Advantages**	**Disadvantages**
Simulation	- Most realistic approach - Validation	- Takes a lot of time to build - No optimizing character
Calculus	- Fast hand calculation - Can present a lower and upper bound	- Unreliable results
Deterministic modelling	- Optimizing character - Reasonably fast calculation times and programming - Can incorporate details deterministically - Easily adaptable	- No stochastic processes - Time discretization - Reduced reliability
Stochastic modelling	- Stochastic processes can be incorporated	- large models require excessive calculation times - No optimizing character

Table 3.1: The advantages and disadvantages of several modelling approaches.

To make a fair trade off between the advantages and disadvantages of the four techniques a multi criteria analysis is made. The criteria receive a score between 1 and 5 points and the concept with the highest overall score is the most recommended technique for implementation. The criteria assessed in this analysis are:

- Adaptability
- Calculation time
- Reliability of the results
- Construction time

- Possibilities for analysis

Adaptability of the deterministic and stochastic modelling technique are considered as equal because they can both implement changes relatively easy and are therefore rated with 4 points. When a new process has to be included in a simulation program a lot of new code has to be written requiring a lot of time and therefore the simulation technique scores 1 point on adaptability. The calculus technique is assumed to have the most flexibility, because the high level of abstraction resulted in only a few input possibilities and when a new assumption is investigated most of the extra required time will have to be paid to creating the new input values instead of adapting the formulas. Therefore the calculus method scored the full 5 points.

The calculation time of the calculus technique is the shortest of all techniques because this approach determines its results with a simple calculation and therefore it receives the maximum score of 5 points. The calculation time for determistic approaches is a lot slower, however because of its optimization techique it only requires one single run to determine the best fleet size. This reduces the total time required to determine all vehicle combinations to a minimum and results in a score of 4 points. Both stochastic and simulation models require large amounts of time for their calculations, because they lack the optimization techniques several runs are required to determine the optimal vehicle configuration. Therefore these techniques score only 1 point.

Reliability of the results is very important to be able to use the results in the decision making processes of the port authority. In theory the most reliable model can be build with a simulation technique, because this technique can incorporate all processes and details realistically without major short cuts or assumptions. Therefore the simulation technique scores 5 points. Both deterministic and stochastic approaches can incorporate various details realistically, however both techniques have shortcomings to create a fully realistic model. This results in a score of 3 points. The calculus method is a very basic approach only able to incorporate basic parameters and cannot include exceptions. This results into rough values which have a high level of uncertainty. Therefore the calculus method scores 1 point on reliability.

The calculus method is a fixed formula which does not require time to construct, however the values required as input for this formula have to be determined taking some time. This technique will still require less time then the other techniques therefore receiving 5 points. The deterministic approach scores 4 points because constraints can be constructed quite fast compared to the other techniques. The stochastic modelling technique can be constructed also relatively fast however when combined with the linear programming technique as presented in Choobineh et al. [2012] additional time is required resulting in a score of 3 points. The worst performing technique on construction time is the simulation, because to make a simulation approaching the realism of an implemented ITT system a lot of programming time has to be invested. Therefore the simulation technique scores 1 point.

The last criteria are the possibilities to analyse the results. The best approach for this is the simulation technique, because all processes are simulated and stored. This results in a score of 5 points for the simulation technique. When the right deterministic technique is chosen a lot of analysing possibilities are available resulting in a score of 4 points. The calculus technique has no analysing possibilities and therefore receives 1 point. The stochastic approach is a bit more advanced with several analysing options, but its possibilities are more limited than for simulations or deterministic techniques resulting in a score of 2 points.

Before the overall score can be determined some weights will be added to the various criteria. These weights show the criteria found most important to realize the function and goal of the model as was determined in the introduction. The goal of this research is to create a reliable tool with realistic outcomes, able to determine an optimal vehicle configuration (mix of AGVs, trucks, barges etc.) by evaluating different system configurations and analysing ITT operations by computing optimal vehicle and container movements at the Maasvlakte area used in strategic decision making processes. This results in a weight of 3 for the reliability of the model because this is explicitly mentioned in the formulation. Also the construction time is considered important because for strategic decision making time is often a limiting factor, resulting in a weight of 2.

The overall scores for the modelling techniques are shown in Table 3.2

As can be seen in Table 3.2 the deterministic approach is recommended to be used. When the

Table 3.2: Multi criteria analysis for the various modelling techniques.

Criteria	Deterministic	Stochastic	Simulation	Calculus	Weight
Adaptability	4	4	1	5	1
Caculation time	4	1	1	5	1
Reliability	3	3	5	1	3
Constuction time	4	3	1	5	2
Analysing possibilities	4	2	5	1	1
Overall score	**29**	**22**	**24**	**24**	

literature overview of deterministic approaches is considered in Section 3.3, it shows a that in Tierney et al. [2013] also ITT configurations have been analysed. The deterministic minimum cost network flow model with a time-space expanded graph enables the solution to be optimized giving an approximation on the number of required vehicles for an ITT system. Although this approach is deterministic, the time expansion allows the modelling of full trips, empty trips, idling times, handling times and congestion. This congestion includes congestion on roads as well as waiting times for loading and unloading at the terminal. The only stochastic process which can not be modelled realistically is the handling process of containers at the terminal. However the variance in handling time is very small in comparison to the total transport time of a container this effect will only have a limited effect on the required number of AGVs. Compared to other deterministic techniques the time-space expanded graph will provide the possibility for extensive analysing options, which can not be realized when choosing for an other strategy.

Chapter 4

Mathematical principles and algorithm

This chapter presents the mathematical principles used to create a minimum cost network flow model with time-space expanded graphs and how the algorithm is able to find an optimal solution of the cost function. The described techniques are commonly used in Operational Research and provide a solid basis for a reliable tool to determine the optimal vehicle configuration.

4.1 Base structure

The model is based on the graph theory which uses nodes and arcs. The nodes represent vertices and the arcs, representing the edges, are used to connect the nodes into a network. The arcs can have a capacity and can be directed or undirected. This representation can than be used to model a flow through the network. Flows have an incoming and an outgoing node who are called the sink and source respectively. All nodes in the network have the restriction that the flow entering a node equals the flow exiting the node, making it impossible to 'stick' in a certain node. These network flow models are widely used to model various types of relations and processes in subjects ranging from logistical, chemical, biological, social, information and communication systems. In the case of this research network flows are used to model the ITT through the Maasvlakte 1&2, where transport vehicles and containers will flow through a network of roads (the arcs) connecting each terminal (the nodes). With the connection of terminals the roads often cross each other creating an intersection. These intersections are also modelled as nodes to be able to model congestion as will be explained in Section 5.2.3. To get a better visual understanding of how a network is mathematically modelled a representation is given in Figure 4.1.

To be able to solve problems using networks Ford and Fulkerson [1956] were the first to construct an algorithm which was able to find the maximum flow through a network. This algorithm makes use of a given graph $G(V, A)$ where V is a set containing all nodes and A is a set containing all arcs(i, j) where $i, j \in V$. Each arc$(i, j) \in A$ has a positive capacity $c(i, j)$. Two nodes are distinguished of V, one as the source s and one as the sink t. The algorithm now determines the maximum flow $f(s, t)$ from node s to node t in graph G as $\sum_{(i,j)\in A} f(i, j)$ where value $f(s, t)$ is the max flow from node s to node t and under the constraints of:

$$f(i, j) \leq c(i, j) \quad \forall(i, j) \in A \quad \text{(capacity constraint)} \tag{4.1}$$

$$f(i, j) = -f(i, j) \quad \forall(i, j) \in A \quad \text{(anti symmetry constraint)} \tag{4.2}$$

$$\sum_{j\in V} f(i, j) = 0 \quad \forall i \in V - \{s, t\} \quad \text{(flow conservation constraint)} \tag{4.3}$$

In the scope of this research we are not interested in finding the maximum flow on itself, but in finding the optimal vehicle configuration to transport the total container demand through the

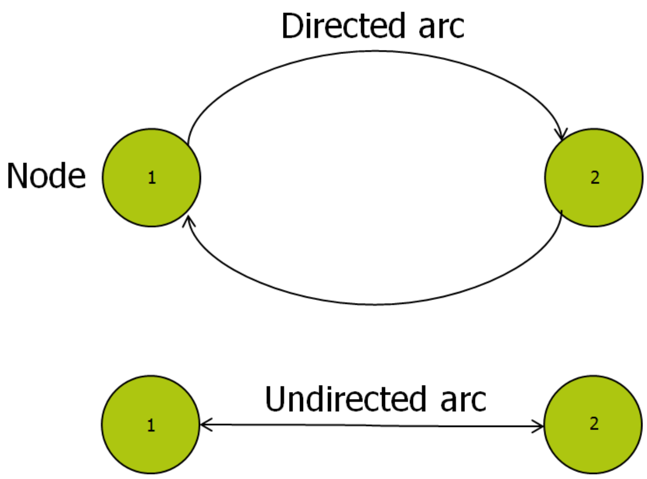


Figure 4.1: Basic network containing 2 nodes connected by arcs

network. This will basically mean that we are interested in finding the minimum amount of required vehicles under certain performance constraints. To be able to provide such a solution the previous described network has to be expanded to a minimum cost flow problem as described in Edmonds and Karp [1972]. A cost function is added assigning a non negative cost $p(i, j)$ to every arc$(i, j) \in A$, which makes the cost of flow $f(s, t)$: $\sum_{(i,j)\in A} p(i, j)f(i, j)$ and take the value of $f(s, t)$ as the total cost of the maximum possible flow.

In most instances however one is interested in a finite amount of flow from source to sink instead of the maximum possible flow. In this case some additional constraints are required. A flow is introduced of θ from node s to node t. To ensure that this flow is created and drained from the system a constraint is added:

$$\sum_{j\in V} f(s, j) = \theta \quad \text{and} \quad \sum_{j\in V} f(j, t) = -\theta \tag{4.4}$$

4.2 Time expansion

A time space network is used to model nodes in time in order to be able to incorporate factors like driving times, waiting times and loading times experienced by vehicles and containers in the inter terminal transport. Time is introduced in the model by copying the base network on top of each other. Let τ be the number of time periods, than graph $G^T = (V^T, A^T)$. Let n be the number of terminal nodes and m be the number of intersections in the base graph. Because the nodes will be copied through time this will mean that the length of vector $V^T = \tau(n+m)$. This is represented in Figure 4.2, where the two terminals represented by node 1 and 2 from Figure 4.1 are copied. In this case time is represented on the vertical axis and the location on the horizontal axis. Arcs are connecting the nodes through time, where the arcs between node 1 and 2 could represent driving and loading time while the arcs between the same node in time could represent waiting or idling time. This means that arcs not only have capacity and cost properties, but also time properties [Yan and Shih, 2007]. The arcs between the same node trough time are called stationary arcs and are created for every node.

In this way time is modelled discreet and therefore the time step size and the actions taking place in these steps should be proportional in order to have a reasonable amount of slack time within a period. The reliability of a model increases when the amount of slack time per time period is lower, because this would certain tasks take more or less time than in reality and over larger time horizons these errors could add up to large deviations from reality. On the other hand having a small time step over a large time horizon would increase calculation times significantly. Therefore a good balance between time step size and time horizon has to be found in order for the model to be meaningful while at the same time preventing over excessive calculation times

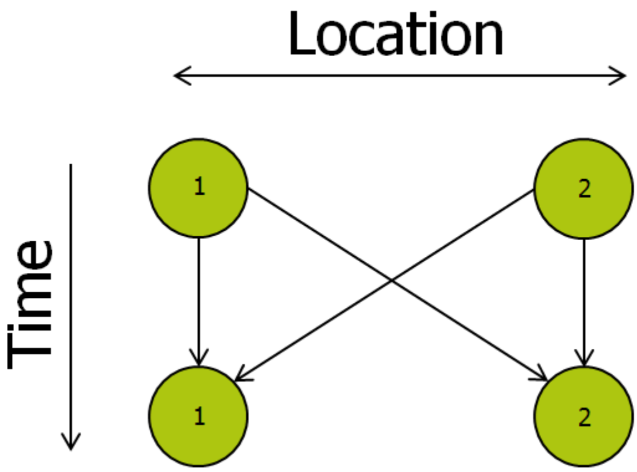


Figure 4.2: Representation of a time space network

[Haghani and Oh, 1996]. The ideal step size depends on several aspects and might therefore be different for every change in the network.

4.3 Total layout in matrix representation

Before any mathematical algorithm is able to perform calculations on network flows it needs an input which represent the constraints of network in matrix notation. The constraints are build from linear equations containing the arcs, nodes and flows to be constraint as will be explained in 4.5. The base network can be represented in matrix notation by making a vector α_v representing each $arc(i,j) \in A$. In this case the created vectors are combined in matrix Aeq as columns representing the basic network, where all arcs are represented by a vector column and the nodes are represented as an element in the column. Therefore let the length of α_v be the number of nodes in the network, where

$$\alpha_v(i) = \begin{cases} 1 & \text{if } \alpha(i) \text{ is the origin node,} \\ -1 & \text{if } \alpha(i) \text{ is the destination node,} \\ 0 & \text{otherwise.} \end{cases}$$

In the case of the base network as represented in Figure 4.1 the two arcs will create vector $\alpha_v(1) = [1 \quad -1]$ and $\alpha_v(2) = [-1 \quad 1]$ into matrix Aeq.

$$Aeq = \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}.$$

When the time expansion is applied, extra columns will be introduced because extra arcs are added, but also additional rows will be added because more nodes are present. The matrix representing the time extended network in Figure 4.2 would be:

$$Aeq^{\tau} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & -1 & -1 & 0 \\ -1 & 0 & 0 & -1 \end{bmatrix}$$

4.4 Flow and multi-commodity flows

To model a flow through the network demand θ, introduced in constraint 4.4, is incorporated in the set of flow conservation constraints presented in constraint 4.3. This creates the following set of constraints incorporated the network of matrix Aeq^{τ}, where a flow of value a_{θ} is introduced from node 1 in timestep 1 to node 2 in timestep 2:

$$
\begin{aligned}
f_{1,2} + f_{1,1} &= a_\theta \\
f_{2,1} + f_{2,2} &= 0 \\
- f_{2,1} - f_{1,1} &= 0 \\
- f_{1,2} + f_{2,2} &= -a_\theta
\end{aligned}
$$

for simplicity demand vector b is introduced, which incorporates the values after the equality sign of constraints 4.3. In the case of previously introduced flow this will shape vector b in

$$
b = \begin{bmatrix} a_\theta \\ 0 \\ 0 \\ -a_\theta \end{bmatrix}.
$$

Multi-commodity flows

In the scope of this research it is required to model more than one flow in a network, to represent flows of containers between different terminals. It is possible to create multiple demands by introducing the multi-commodity flow principle, where a commodity represents a single demand for the network. This was presented for the first time by Tomlin [1966].

A multi-commodity flow can be created by introducing Θ number of commodities. The generated flow vectors $b_{(\theta)}$, where θ is a single demand generation, will be combined in one large demand b vector, where $b = [b_1 \quad b_2 \quad ... \quad b_\Theta]^T$. To create matrix Aeq^τ, let I be the unit matrix of size Θ, then matrix Aeq^τ becomes $IAeq^\tau$ or

$$
Aeq^\tau = \begin{bmatrix} Aeq^{\tau_1} & 0 & 0 & 0 \\ 0 & Aeq^{\tau_2} & 0 & 0 \\ & & \ddots & \\ 0 & 0 & & Aeq^{\tau_\Theta} \end{bmatrix}.
$$

4.5 Constraints

As already mentioned the algorithm requires a cost function in combination with a set of linear equations creating the constraints of the network to optimize the objective. The first set of linear equations is formed by combining matrix Aeq^τ and vector b representing the flow conservation constraints for the network as presented in Equation 4.3. This set is created by $Aeq^\tau \cdot f = b$:

$$
\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & -1 & -1 & 0 \\ -1 & 0 & 0 & -1 \end{bmatrix} \cdot f = \begin{bmatrix} a_\theta \\ 0 \\ 0 \\ -a_\theta \end{bmatrix}
$$

In this set of linear constraints every row, representing a certain node at a certain time, constraints which arc or sum of arcs has to be equal to the value after the equality sign. So i.e. the first row, representing the connecting arcs of terminal 1 in time step 1, constraints the sum of flows over arc 1 and arc 3 to be equal to a_θ. Next to equality constraints it is also possible to create inequality constraints, which can be used to set i.e. a maximum capacity or lower bound for certain arcs. By setting these constraints the algorithm is forced to provide a solution which satisfies each individual constraint.

Chapter 5

Model structure

This chapter explains the model structure based on the mathematical principles presented in Chapter 4. The model will use a minimum cost flow network with time expanded graph and should be able to determine the optimal vehicle configuration for the ITT system at the Maasvlakte in the Port of Rotterdam. This will mean that the model has to be able to simulate various vehicle types and containers as well as the flow of these elements through time. Both the vehicles and containers will experience delaying factors such as handling times, driving times, congestion and waiting times. The vehicle types which are included in the model are AGVs, ALVs, MTSs and barges. The model should give a reliable indication about the required number of vehicles for the various configurations which will be useful in decision making processes.

5.1 Key assumptions

Before the model structure is presented in this chapter, it is important that its structure is based on several general assumptions which are summarized below:

- Arcs in the model have only one vehicle type travelling on them. This results in that vehicle interaction is only possible during container handling at terminals;
- All vehicles of one type have the same characteristics, such as speed and accelerations, therefore no distinction is made between i.e. empty and full vehicles;
- Short vehicle activities such as connecting a tractor to a trailer are neglected;
- No distinction in handling is made between different types of containers, such as dangerous goods, refrigerated or out-of-gauge containers;
- Due to the discrete time of the model all processes are rounded off to the nearest time step with a minimum of 1 time step.
- Strict separation of the ITT system and the Intra terminal distribution system, So no ITT vehicle will ever be used to transport containers from ship to stack or vice versa.
- Dedicated handling equipment for ITT vehicles. So ITT vehicles only have to wait for vehicles within the ITT system, vehicles outside the system will be served by separate handling equipment.

5.2 Nodes and arc types

In the model nodes and arcs are creating the network. The nodes represent a terminal, intersection or LT node and together with the arcs they all have their own function. This section will present the various functions of arcs and nodes in the model. First several parameters are introduced, containing certain arcs, to be able to assign constraints in Section 5.6.

Let $In(i) = [j|(j,i) \in A^T]$ be a set of nodes with arcs entering node $i \in V^T$ and $Out(i) = [j|(j,i) \in A^T]$ be a set of nodes with arcs leaving node $i \in V^T$.

5.2.1 Terminals and roads

Each terminal in the model is represented by a node and are collected in set V^{tster}. Every terminal will be modelled by one node for every time step as was explained in Section 4.2 and is connected by a road to the other terminals on the maasvlakte. These bidirectional roads are modelled by 2 unidirectional arcs between the terminal and the nearest intersection. All arcs will have a transverse time t consisting of the travelling time and the average handling time of a container and the arcs connected to a terminal are assigned with a handling capacity m_{ih}, representing the loading capacity of the cranes and will force the vehicle to wait if the capacity is exceeded. For vehicles having the possibility of loading multiple containers and additional variable is introduced, $m_{ih}max$, which indicates the maximum handling capacity per vehicle per time step. This is an important addition in cases where the full loading capacity of the terminal cannot be applied to only one vehicle, resulting in a more realistic handling process.

The model requires a basic network of arcs and nodes representing matrix Aeq and transverse time t corresponding to the arc variable as input and will extend this into a fully expanded network over the total number of timesteps represented by parameter *step*. In order to keep the model size as small as possible to ensure reasonable calculation times it is important to reduce the number of terminals, intersections and roads as much as possible, while still ensuring a reliable network. This can be realized by combining terminals which are located in close proximity of each other or have no mutual demand.

5.2.2 Stationary arcs

In order to model the possibility for vehicles to stay at the same place in time stationary arcs are introduced as already has been mentioned in Section 4.2. Let these stationary arcs be collected in set $A^S = \bigcup_{1\le t\le \tau} \bigcup_{1\le i\le n+m} [(i_t, i_{t+1})]$, let the incoming stationary arcs of terminal node $i \in V^{tster}$ be collected in set $In^S(i)$ and the outgoing stationary arcs of terminal node $i \in V^{tster}$ be collected in set $Out^S(i)$. Stationary arcs are not constraint in the number of vehicles or containers flowing over them. They also allow containers flowing over them without the presence of vehicles and all vehicle types are allowed on the stationary arcs. However to prevent containers being stored at an intersection the flow over containers over the stationary of all intersections is constraint to be at most the flow of vehicles over these arcs. Let $\delta_{ij\theta}$ indicate whether arc $(i,j) \in A^T$ is a stationary arc for demand θ, where

$$\delta_{ij\theta} = \begin{cases} 0 & \text{if } \delta_{ij\theta} \text{ is a stationary arc,} \\ 1 & \text{otherwise.} \end{cases}$$

5.2.3 Intersections and congestion

When more than 2 terminals exist, which are connected to each other by road, an intersection is included to connect the roads. In the model the intersection is not only used as a crossroad, but also as the location where congestion will occur.

Two different intersection variants have been considered. The first technique makes use of two nodes representing the intersection, connected by two or more so called fan arcs [Kohler et al., 2002]. These arcs have all have their own maximum capacity and an increasing transverse time when having a higher maximum capacity. When a flow of vehicles enters the intersection it is forced to take one of the fan arcs depending on the volume of the flow and the maximum capacity of the fan arc. It is obvious that there will be a flow over the fan arc having the lowest transverse time while applying to the capacity constraint. If i.e. a flow is forced into a fan arc with a transverse time of multiple time steps, the flow entering the intersection before the previous flow exited the intersection is forced to flow over a later fan arc with the same delay as the previous flow. This prevents vehicles from overtaking each other at an intersection. An intersection modelled by fan arcs is shown in Figure 5.1.

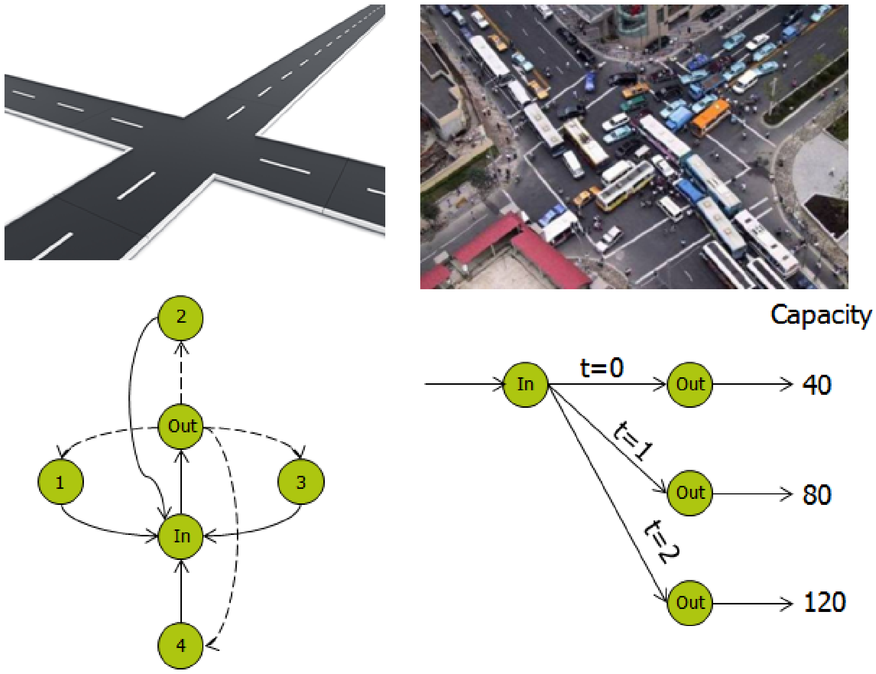


Figure 5.1: Representation of an intersection by fan arcs.

The second technique models an intersection by one node, which will be collected in set $V^{i}nt$. The terminals and other intersections connected to the intersection node will get two directed arcs to the intersection, one incoming and one outgoing arc. The congestion will be incorporated by capacitating the total flow over the outgoing arcs with a maximum of ϕ vehicles per time step. A representation of the intersection modelling approach is given in Figure 5.2.

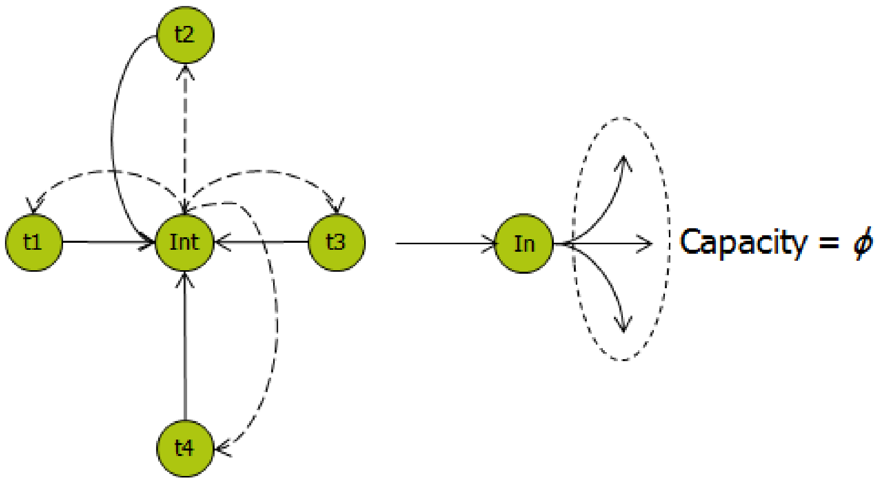


Figure 5.2: Representation of an one node intersection

Both methods have their advantages and disadvantages. The first approach has a first in first out character, because the flow entering the intersection is forced to pick a fan arc with at least the same delay as the flow currently crossing the intersection. The second methods lack this property, because excess flow will be forced over the stationary arc to the next time period where it can mix with the flow entering the intersection that time period. However the first in first out property also has it limitations. The capacity constraint does not consider the direction of the vehicles coming in, resulting in i.e. if more vehicles than capacity ϕ enter the intersection they all will experience a delay. However if they just have to cross the intersection without turning left or right they in reality would not been slowed down. In this case the total delay experienced by vehicles would have been lower when the intersection was modelled by the one node approach. In most cases traffic at an intersection have a main road, generating the highest volumes of traffic and a secondary road, generating a relatively low percentage of traffic volume of the intersection. This will result in that the situation as described above will occur more often than situations, where vehicles will turn at an intersection. A second reason to chose for modelling an intersection by just one node is that it will result in a lower calculation time, because the amount of nodes, variables and constraints will be significantly lower.

Capacity ϕ of the intersection is determined in by calculating the worst case capacity of the intersection. For the worst case the following assumptions are used:

- Only one vehicle at the time is allowed on the intersection.
- All vehicles have to stop before entering the intersection and thus have a speed of $v = 0m/s$ when entering the intersection.
- Always one vehicle will be crossing the intersection, so the capacity is independent from breaking.
- Vehicles will have an acceleration of 1 m/s^2 and a cornering speed $v_{cor} = 0.5 \cdot v_{avg}$ as presented in Table 2.7.
- The radius of a corner is 8.5m for an ITT system with AGVs and ALVs and 18.5m for an ITT system with MTSs [Port of Rotterdam Authority et al., 2002].
- The length of the vehicle as presented in Table 2.7 and a vehicle cleared the intersection when the back of the vehicle crossed the intersection.

With these assumptions the capacity of the intersection can be determined, which will make use of the standard formulas for speed and distance as shown in Formula 5.1, 5.2 and 5.3. The calculation is shown only for AGVs

$$v = a \cdot t \tag{5.1}$$

$$s = 0.5 \cdot a \cdot t^2 \tag{5.2}$$

$$s = v \cdot t \quad \text{(when a = 0)} \tag{5.3}$$

The length of the intersection is:

$0.5 \cdot r \cdot \pi + l_{veh} = 28.35m$

time to accelerate up to v_{cor} is:

$t = v_{cor} \backslash a = 5.556s$
$s = 0.5 \cdot 1 \cdot 5.556^2 = 15.43m$

The time required to cross the remaining distance is:

$s = 28.35 - 15.43 = 12.9$
$t = 12.2 \backslash 5.556 \approx 2.3s$

So the total time required for one vehicle to cross the intersection is:

$t = 5.556 + 2.3 \approx 7.9s$

Resulting in a intersection capacity ϕ for AGVs of about 8 vehicles per minute. Doing the same calculation for the other vehicle types as well will result in the intersection capacities shown in Table 5.1.

	AGVs	**ALVs**	**MTSs**
intersection capacity (vehicles/min)	8	8	3

Table 5.1: Intersection capacities for various vehicle types.

The intersection capacity calculated in this section is a worst case scenario and is in reality depending on how smart the vehicle system really is. If one considers the automated systems, in theory a constant flow of vehicles over the intersection is possible, because the computer system can adapt the speeds of the vehicles nearing the intersection such that they will precisely fill up a gap between two vehicles at the intersection. Therefore the intersection capacity will be varied to see what this will do with the performance of the ITT system.

5.2.4 Long Term (LT) loading/unloading

In order to incorporate barges and trains more realistically a LT node is introduced for each terminal, enabling the ability to create a parallel network with the correct properties for the transportation of containers by these LT vehicles. This is necessary, because unrealistic handling and transportation times would be used for LT vehicles otherwise. The arcs(i^{LT}, j^{LT}) who connect the terminal node with the LT node are called LT arcs and are represented in set $A^{LT} = \bigcup_{1 \leq t \leq \tau} \bigcup_{1 \leq i \leq n} (i^{LT}, j^{LT})$. All arcs will have a vehicle property assigned, which makes flows over the LT arcs only possible for barges or trains and not for road vehicles. The fact that it runs parallel to the road network enables the possibility to remove the network for non barge or train instances, which reduces calculation time significantly. As can be seen in Figure 5.3 vehicles can move from node 1 to node 2 by either road or LT connection. The loading and unloading of LT vehicles is done independently from road vehicles by separate equipment. The equipment available at a terminal for LT vehicle handling operations is shared by all docked LT vehicles and for that reason an undirected arc is modelled for the loading and unloading operations of LT vehicles.

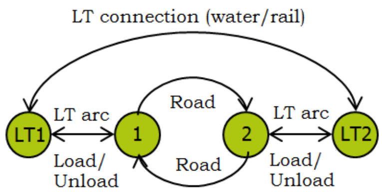


Figure 5.3: LT node representation and connection to the terminal network. The LT network works parallel to the road network and can be removed for non barge or train instances.

5.2.5 Total layout

The total port layout is build from the previous discussed arcs and nodes. Each arc is assigned with properties for allowing certain vehicle types, transverse time, capacity and cost. For the Maasvlakte area, i.e. Voss et al. [2012] used the layout as presented in Figure 5.4. The notes on the arcs give an indication of the representation of the arc.

5.2.6 Demand generator

The demand generated for the model are combined in the demand vector b. This vector which has been introduced in Section 4.4 contains all the information required for the model to realize a realistic flow. To construct vector b the generator need to generate the following properties for every container:

1. Origin terminal (o_θ)
2. Destination terminal (d_θ)
3. Release time (r_θ)

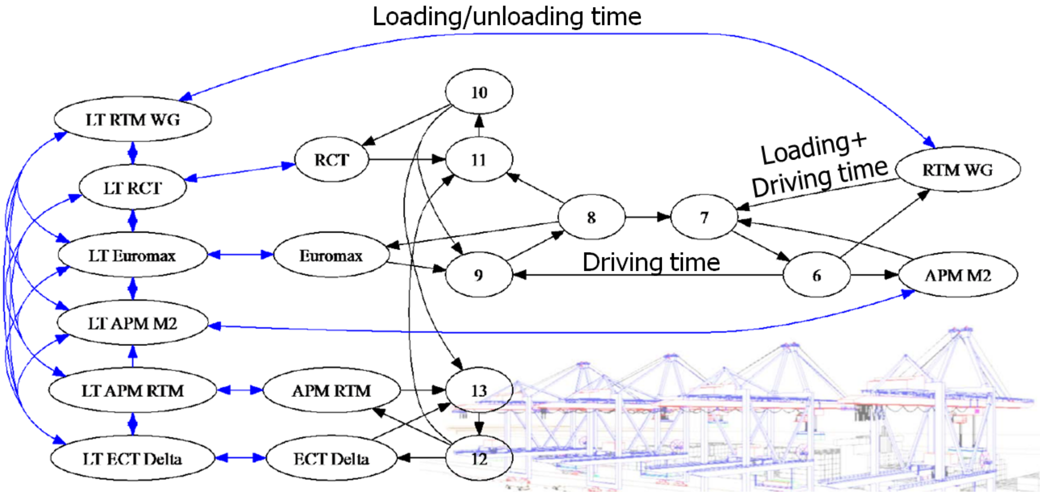


Figure 5.4: Representation of the layout used to model the Maasvlakte area (Voss et al. [2012]).

4. Delivery time (u_θ)
5. Size of the container in TEU (TEU)

The model uses this information to create various demand vectors by collecting the individual containers based on the delivery time within a certain hour and the destination terminal of the generated container into one commodity. The amount of TEU of the containers that are collected create parameter a_θ for demand θ. The containers are collected by destination terminal and delivery time to be able to assign the correct penalty cost for delays in the objective function, which will be further explained in Section 5.5. It is possible to create a demand vector which contains containers with various origin terminals and release times. When it happens that the delivery time is later than the time horizon of the model the delivery time of that container will be reduced to the last time period of the model.

The model is able to let vehicles carry two 20' containers instead of one 40' container, by having a carrying capacity expressed in TEU instead of containers. Therefore two 20' containers will have the same volume as one 40' container. This should theoretically result in a lower number of required vehicles, which makes it important that the demand generator explicitly states whether the generated container has a size of 20' or 40'.

The total demand over the time horizon of the model is kept constant for the number of containers generated by the generator for the whole system, so fluctuations due to the stochastic behaviour of the generator are eliminated. This means that the total volume of containers is constant over the time horizon.

5.2.7 Multi-commodity flow

Multi-commodity flow is introduced to be able to implement all the demand vectors for the various destination terminals and delivery times into one model. The total number of demand vectors (commodities) are represented by parameter Θ. The generated flow vectors $b_{(\theta)}$, where θ is a single demand generation, are combined into one large demand b vector as already mentioned in Section 4.4.

For every commodity θ next to an extra demand vector, also a complete network Aeq^τ is created. This means that the amount of decision variables will increase rapidly when adding extra commodities, which will increase the calculation time. Therefore it is important to reduce the amount of commodities as much as possible by combining i.e. multiple containers into one commodity, combining terminals which have no mutual demand, combining terminals who have almost the same geographical location or by increasing the length of time in which the release time of containers will be combined. Unfortunately combining containers into one commodity might have a negative effect on the reliability of the model, but is inevitable when creating large networks with small time steps.

5.3 Vehicles, vehicle types and containers

The model can use different types of vehicles $h \in H$, where H is a set consisting of all vehicle types. Each vehicle type has its own cargo carrying capacity h_{ij} per vehicle on arc$(i,j) \in A^{\tau}$, and is set to 2 TEU for AGVs and ALVs, up to 10 TEU for MTSs and up to 50 TEU for barges. The amount of vehicles of vehicle type h that are present in a node is s_{ih}, with $i \in V^T \quad \text{and} \quad h \in H$. Each arc$(i,j) \in A^T$ is also given a property of which vehicle type it carries by parameter η_{ij}. It is assumed that all terminal nodes start with a certain amount of vehicles s_{ih} at the earliest release time $min(r_\theta)$ of the demands. For all intersection and LT nodes s_{ih} at the earliest release time is set to zero.

To implement vehicles in the model, so that the algorithm can make a distinction between different vehicle types and containers, is to create a new set of variables for each vehicle type $h \in H$, where $x_{ijh} \in [0, ..., s_{ih}]$ represents the amount of vehicles of vehicle type h on arc$(i,j) \in A^{\tau}$. Also a set of containers corresponding to vehicle type h is required, represented by variable $y_{ij\theta h}$, where $y_{ij\theta h} \in [0, ..., a]$ is the amount of containers on arc$(i,j) \in A^T$ for demand θ and of vehicle type h.

At terminals containers are loaded and unloaded on vehicles by Automated Stacking Cranes for AGVs and by Reach Stackers or Straddle Carriers for MTSs. Because of the automated lifting system of a ALV, ALVs do not have to wait under a crane until it is handled, therefore the handling time of a ALV is reduced as can be seen in Table 2.7. They are however still restricted by a handling rate, because the loading locations are limited and the cranes are still restricted by their own movement to replenish the loading platforms. For every vehicle type the handling rate m_{ih} at terminal node $i \in V^T$ is based on the available handling equipment and the handling process. The handling rate of AGVs is set by default to 30 moves per hour per crane and the handling rate for MTSs is set to 35 moves per hour per crane. The rate for MTS is higher, because efficiency gain is reached by handling multiple containers in a set of trailers. Next to road vehicles barges whom are being unloaded by special barge cranes having a rate of 30 moves per hour per crane. Loading and unloading moves only apply for non-stationary arcs entering and leaving time space terminal node i of vehicle type h and therefore set $V^T_{ih} = [\text{arc}(i,j) \in A^T \backslash A^S \wedge \eta_{ij} = h]$ is a set of terminal nodes connected by non-stationary arcs of vehicle type h.

All vehicles types have been assigned with a driving speed v_h in order to calculate the transverse period $t_{ijh} \in t$ for each arc depending on the different properties for each vehicle type, where t is a set containing the transverse periods for all arcs. The speeds set for an AGV, ALV, MTS are presented in Table 2.7.

5.4 Parameters

For a clear overview on all used parameters in the objective function and constraints, the parameters are summarized in this section and are shown in Table 5.2.

5.5 Objective function

To determine the objective function of the model it is important to consider the main performance indicators of an ITT system. The customers of the ITT system demand reliability in the delivery of their containers at the correct destination, while the ITT system operator wants to have low operational and investment costs. After consultation with various container terminal logistics experts three main objectives have been identified:

1. lead time reliability

Table 5.2: List of parameters.

a_θ	Amount of TEU in demand θ.
Aeq^τ	Matrix representing the time space network of arcs and nodes.
A^T	Set of time space arcs.
A^S	Set of stationary arcs.
b	Demand vector.
c_d	Cost of delays.
c_h	Carrying capacity in TEU per vehicle for vehicle type h.
$c_{v,h}$	Vehicle cost for vehicle type h.
d_θ	Destination node $\in V^T$ of demand θ.
H	Set containing all vehicle types.
h	Vehicle type.
$In(i)$	A set of nodes with arcs entering node $i \in V^T$ including stationary arcs.
m_{ih}	Handling capacity at terminal $i \in V^T$ for vehicle type h.
$m_{ih}max$	Handling capacity per vehicle at terminal $i \in V^T$ for vehicle type h.
o_θ	Origin node $\in V^T$ of demand θ.
$Out(i)$	A set of nodes with arcs leaving node $i \in V^T$ including stationary arcs.
r_θ	Release time period of demand θ.
s_{ih}	Amount of vehicles of type h present at node $i \in V$ at time step $t = min(r_\theta)$.
u_θ	Delivery time period of demand θ.
V^T	Set of time space nodes.
V^T_{ih}	A set of non-stationary arcs connected to node $i \in V^T$ of vehicle type h.
V^{int}	Set of intersection nodes.
V^{tster}	Set of terminal nodes $i \in V$.
V^T_{ih}	A set of terminal nodes $i \in V^T$ connected by non-stationary arcs of vehicle type h.
x_{ijh}	The amount of vehicles on arc(i, j) of vehicle type h.
$y_{ij\theta}$	The amount of containers on arc(i, j) for demand θ.
$\delta_{ij\theta}$	Indicate wheter arc (i, j) is a stationary arc.
η	Punctuality of the system.
ϕ_{ij}	Capacity of intersection node i_{int}.
Θ	Number of demands.

2. number of required vehicles
3. costs for infrastructure

In this investigation only the first two factors will be considered, because infrastructure costs are fixed costs which cannot be influenced by the objective function of the network. To be able to implement both objectives into 1 objective function each objective will be realized in a separate objective function, after which both functions will be added to create one overall objective function.

The lead time reliability is measured by taking the total delay of containers in arrival at the destination. The goal of the objective function is obviously to minimize the total amount of delay hours. To be able to have a delay in the ITT system negative flows have to be allowed, because the flow would otherwise have been drained at the delivery time of the container. When the delivery time of the container could not be met the problem would have been infeasible. To prevent timetravelling negative flow is only allowed on the stationary arcs of the destination node after the delivery time of the commodity. In this way the container first has to flow to the destination and can then flow backwards to the supposed delivery node before it gets drained from the system. The delay can now be measured by evaluating the amount of negative flow over these stationary arcs.

The cost value c_d of delays is hard to determine. It is depending on several factors such as container type, the value of the transported goods, value depreciation of goods, scheduled hinterland transportation etcetera. Because this value is hard to determine, three different values will be used. In the first case their will be no costs for delay, the second case the cost of delay will be 6 Euro's per hour based on 0,5% depreciation per day over a total container value of 30.000 euro/TEU Martonosi et al. [2005] and in the third case the delay will have an infinite cost for delay. By setting a cost of zero and infinite for the delay an examination can be made about the extreme cases, only time insensitive goods and only highly time sensitive goods, and how this will influence the required number of vehicles.

The delay objective is:

$$min \quad \sum_{1\leq\theta\leq\Theta} \sum_{u_\theta\leq t\leq\tau} \sum_{i\in In^S(i)} c_d \cdot y_{ij} \tag{5.4}$$

For the required number of vehicles the objective function will assign a penalty cost $c_{v,h}$for every added vehicle of vehicle type h based on the cost of one vehicle operating during the runtime of the model. This will mean that the total cost per added vehicle is the purchase cost presented in Table 2.7 multiplied with an interest rate of 5% per year over a depreciation time equalling the lifetime of the vehicle added with an estimated maintenance cost of 10% of the purchase cost. In the model however the total cost is transformed into the cost per added vehicle over the runtime of the model. This requires to divide the total vehicle cost over the number of hours per year multiplied by the runtime in hours. To implement the purchase cost in the objective function additional decision variables are created for every terminal, where in the first time period s_{ih} vehicles are created. The purchase objective is:

$$min \quad \sum_{i\in V_{ih}^T} \sum_{1\leq h\leq H} c_{v,h} \cdot s_{iht=min(r_\theta)} \tag{5.5}$$

Combining Function 5.4 and 5.5 the overall objective will be:

$$min \left(\quad \sum_{i\in V_{ih}^T} \sum_{1\leq h\leq H} c_{v,h} \cdot s_{iht=min(r_\theta)} \quad + \quad \sum_{1\leq\theta\leq\Theta} \sum_{u_\theta\leq t\leq\tau} \sum_{i\in In^S(i)} c_d \cdot y_{ij} \right) \tag{5.6}$$

5.6 Constraints

This section presents the constraints incorporated in the model. Based on these constraints and the objective function presented in Section 5.5 the model can make a prediction of the optimal vehicle configuration required to satisfy the given demand. The constraints that are used describe the following properties:

- network with demand flow,
- vehicle balance,
- container carrying,
- handling capacity,
- intersection capacity,
- punctuality of container delivery,
- restriction of container flow over stationary arcs of intersections,
- lower bounds on variables,
- upper bounds on variables.

Network with demand flow

The first set of constraints ensures that the demand θ will flow through the network via the arcs and nodes implemented in matrix Aeq^{τ}. Vector $\bar{b}$ constraints the origin and demand node in having an outflow respectively inflow of the number of containers as indicated by a_{θ}. This constraint includes all arcs in A^T over all commodities θ.

$$Aeq^{\tau} y_{ij\theta} = \bar{b} \quad \forall (i,j) \in A^T, \quad 1 \leq \theta \leq \Theta \tag{5.7}$$

Vehicle balance

This set of constraints restricts the flow of vehicles by forcing the flow of vehicles coming in a node having to be equal to the flow of vehicles leaving the same node. This will ensure that no extra vehicles can be created or that existing vehicles are removed from the model. The set of constraints consist of two different constraints, because the first will set a start amount of vehicles in every node at $t = min(r_{\theta})$. This means that Formula 5.8 will force the sum of flows of the outgoing arcs of the nodes in timestep 0 must have a flow of $s_i h$. Which means that the sum of the outgoing flows of intersection nodes in timestep 0 is set to zero, because no vehicles will start from an intersection and the sum of outgoing flows of the terminal nodes is set to s_{ih}. Parameter s_{ih} is a decision variable of which its value is determined by the objective function. Constraint 5.9 will balance the incoming and outgoing flows of all other nodes in the model to realize realistic vehicle flows.

$$\sum_{j \in Out(i,h)} x_{ijh} = s_{ih} \quad \forall \quad i \in V, h \in H \tag{5.8}$$

$$\sum_{j \in Out(i,h)} x_{ijh} = \sum_{k \in In(i,h)} x_{ijh} \quad \forall \quad i \in V^T \backslash V, h \in H \tag{5.9}$$

Containers carried by vehicles

The set of constraint of 5.10 connect a vehicle to the container when it is transported through the network and thus prevent the containers from flowing freely through the network. Containers are only allowed to flow freely over the stationary arcs therefore parameter $\delta_{ij\theta}$ is introduced which will indicate whether or not arc (i,j) is a stationary arc.

$$\sum_{1\leq\theta\leq\Theta} \delta_{ij\theta}(y_{ij\theta} \leq c_h x_{ijh}) \quad \forall(i,j) \in A^T \tag{5.10}$$

Handling capacity

The set of Constraints 5.11 offers the possibility to restrict the number of handling moves per time step to be at most m_{ih} at a terminal node. It adds both the loading and unloading moves from the handling equipment over all commodities of the same vehicle type for the non-stationary arcs of terminal node $i \in V_{ih}^T \cap V^{tster}$.

$$\sum_{1\leq\theta\leq\Theta} y_{ij\theta} \leq m_{ih} \quad \forall i \in V_{ih}^T, h \in H \quad \forall \quad i \in V_{ih}^T \cap V^{tster}, h \in H \tag{5.11}$$

Because of the carrying capacity of multiple containers for MTSs and LT vehicles an additional constraint is introduced when these types are available. Constraint 5.12 restricts the number of TEU being handled at a single vehicle per time step, by allowing a maximum flow of containers to be equal or less than the flow of vehicles multiplied by $m_{ih}max$.

$$\sum_{1\leq\theta\leq\Theta} y_{ij\theta} \leq m_{ih}^{max} x_{ijh} \quad \forall i \in\in V_{ih}^T \cap V^{tster}, h \in H \tag{5.12}$$

Intersection capacity

The flow over the intersections is constraint by the set of constraints 5.13, where the sum of the flows over the outgoing arcs of intersection node $i \in V^{int}$ are restricted to be at most ϕ.

$$\sum_{j\in V_{ih}^T} x_{ij} \leq \phi \quad \forall \quad i \in V^{int}, h \in H \tag{5.13}$$

Restrict container flow over stationary arcs of intersections

As already mentioned in Section 5.2.2 to prevent containers being stored at an intersection the flow over containers over the stationary of all intersections is constraint to be at most the flow of vehicles over these arcs. Therefore the Constraint 5.14 is applied.

$$\sum_{1\leq\theta\leq\Theta} Out(i) y_{ij\theta} \leq \sum_{h\in H} Out(i) x_{ijh} \forall i \in V^{int}, (i,j) \in A^S \tag{5.14}$$

Punctuality of container delivery

Although the delay of containers is already minimized by the objective function this only considers the total amount of delay summed over all containers. This could result in a high percentage of containers being delayed for only a few timesteps having a lower total delay than when a few containers are delayed for many time steps. However for the customers of the ITT system it is important to have a reliable delivery and therefore they might demand certain punctuality values for container delivery. This set of constraints ensures that at least a factor η of the containers is delivered on time. This is realized with Constraint 5.15.

$$\sum_{1\leq\theta\Theta} y_{ijt} \leq 1 - \eta \quad (i,j) \in A^S, t = u_\theta + 1 \tag{5.15}$$

Lower bounds on variables

In order to get reasonable results out of the model lower bounds on variables are introduced. The variables represent the arcs of the model and there are also variables created for the start amount of vehicles at every terminal node $\in V^{tster}$. All variables (arcs) have a lower bound of 0 except for the stationary arcs leaving terminal node $i \in V^{tster}$ after the delivery time of demand θ. The value for these arcs can be infinite negative, because they can allow the delayed containers to be transported to the sink in order to create a feasible flow. This means that:

$$y_{ij\theta} = \begin{cases} -\infty & \forall \quad (i,j) \in A^S \cap Out(i)_{t \geq u_\theta}, 1 \leq \theta \leq \Theta \\ 0 & \text{otherwise.} \end{cases} \tag{5.16}$$

and

$$x_{ij} = \begin{cases} -\infty & \forall \quad (i,j) \in Out(i) \cap A^S | t \geq u_\theta \\ 0 & \text{otherwise.} \end{cases} \tag{5.17}$$

Upper bounds on variables

The upper bounds on all variables is set to ∞ by default, but to decrease the calculation time for the model some variables are set to 0. The first group of variables which is set to 0 are the non-stationary arcs leaving the destination node of demand θ. This is allowed, because once a container reached the destination it does not have to travel to any other node. The second group of variables which is set to 0 are all arcs before the release time of demand θ. This is allowed, because it is not possible to have a flow of containers before the release time of the demand. The vehicle variables however will be set to 0 until the earliest release time of all the demands. Because the vehicles can be created at any terminal so there is no need for repositioning before the earliest release time of the demands. If the punctuality is set to 1 all variables representing container arcs after the delivery time of a commodity are set to 0, because delays are not allowed and therefore arcs after the delivery time are not used. These three sets of variables will lead to upper bounds on shown in 5.18 and 5.19 [Tierney et al., 2013].

$$y_{ij\theta} = \begin{cases} 0 & \forall \quad (i,j) \in V_{(ih)} | i = d_\theta \\ 0 & \forall \quad (i,j) \in A^T | \tau < r_\theta \\ 0 & \forall \quad (i,j) \in A^T | \tau > u_\theta \\ \infty & \text{otherwise.} \end{cases} \tag{5.18}$$

and

$$x_{ij} = \begin{cases} 0 & \forall \quad (i,j) \in A^T | t < min(r_\theta) \\ \infty & \text{otherwise.} \end{cases} \tag{5.19}$$

5.7 Total model

When the objective and the constraints are combined the total model is obtained.

$$min \left(\sum_{i \in V_{ih}^T} \sum_{1 \leq h \leq H} c_{v,h} \cdot s_{iht=min(r_\theta)} \quad + \quad \sum_{1 \leq \theta \leq \Theta} \sum_{u_\theta \leq t \leq \tau} \sum_{i \in In^S(i)} c_d \cdot y_{ij} \right) \tag{5.20}$$

subject to

$$Aeq^{\tau} y_{ij\theta} = \bar{b} \quad \forall (i,j) \in A^T, \quad 1 \leq \theta \leq \Theta \tag{5.21}$$

$$\sum_{i \in Out(i)} x_{ijh} = s_{ih} \quad \forall i \in V, h \in H \tag{5.22}$$

$$\sum_{i \in Out(i)} x_{ijh} = \sum_{i \in In(i)} x_{ijh} \quad \forall i \in V^T \backslash V, h \in H \tag{5.23}$$

$$\sum_{1 \leq \theta \leq \Theta} \delta_{ij\theta}(y_{ij\theta} \leq c_h x_{ijh}) \quad \forall (i,j) \in A^T \tag{5.24}$$

$$\sum_{1 \leq \theta \leq \Theta} y_{ij\theta} \leq m_{ih} \quad \forall i \in V_{ih}^T \cap V^{tster}, h \in H \tag{5.25}$$

$$\sum_{1 \leq \theta \leq \Theta} y_{ij\theta} \leq m_{ih}^{max} x_{ijh} \quad \forall i \in V_{ih}^T \cap V^{tster}, h \in H \tag{5.26}$$

$$\sum_{j \in V_{ih}^T} x_{ijh} \leq \phi \quad \forall i \in V^{int}, h \in H \tag{5.27}$$

$$\sum_{1 \leq \theta \leq \Theta} Out(i) y_{ij\theta} \leq \sum_{h \in H} Out(i) x_{ijh} \forall i \in V^{int}, (i,j) \in A^S \tag{5.28}$$

$$\sum_{1 \leq \theta \leq \Theta} y_{ijt} \leq 1 - \eta \quad \forall (i,j) \in A^S, t = u_\theta + 1 \tag{5.29}$$

The objective function and constraints are programmed in Matlab and will be solved by the CPLEX solver integrated in Matlab, which uses the CPLEX algorithm to solve the integer problem but can use Matlab double matrices as an input for the algorithm. The large amount of constraints and variables tend to create memory issues. Fortunately the relative low amount of non-zero elements make it possible to use sparse matrices to prevent any memory issues. For large problem sizes the model therefore uses sparse matrices.

5.8 Differences with Tierney et al. [2013]

As already mentioned this model is based on the principles used in Tierney et al. [2013] it is however different on the following points:

- The most important difference is the fact that this model is able to determine an optimal number of vehicles by minimizing both the cost for delays and the cost when adding an addition vehicle. In Tierney et al. [2013] only the delay is minimized given a fixed number of vehicles.
- In addition to optimizing the number of vehicles a new constraint is introduced ensuring a certain punctuality of container delivery. Because the cost for adding additional vehicles is a lot higher than the cost for having a small delay the punctuality constraints insist in a certain performance level, which might be obliged by the customers of the ITT system.
- When MTSs are used not only the number of trucks is optimized, but the number of trailers as well. This makes it possible that the ideal train for an MTS is not 5 trailers but less.
- The handling constraints for MTSs and LT vehicles have been extended so that not only the total amount of containers being handled per time step is considered, but also the amount of containers per vehicle per time step is considered. This results in situations that for example at most one crane per vehicle can be used while the terminal has two cranes.
- The intersection capacity has been calculated and published to be able to apply congestion realistically.
- To prevent container storage at intersections, the flow of containers over the stationary arcs is restricted to the number of vehicles flowing over that arc while respecting the loading capacity of the vehicle.

- The upper bound for arcs leaving the destination node is set to 0.
- LT intersections have been included in order to reduce the size of the LT network. These intersection do not capacitate the the flow of LT vehicles crossing them as is the case for the regular road intersections.
- A distinction is made between 40' and 20' containers.
- The demand generator is based on the expected ITT flows through the Maasvlakte area instead of a random demand generator.
- Input parameters such as speeds, distances, capacities etcetera will mostly differ from the parameters used in Tierney et al. [2013].

5.9 Summary

In this chapter the model structure has been presented. To determine the optimal vehicle configuration of an ITT system for the Port of Rotterdam a network of nodes and arcs is created representing the terminals, intersections and roads. The minimum cost flow theory is used to minimize both the delay and the required number of vehicles under a set of constraints realizing a certain demand of containers as well as ensuring a reliable flow of both containers and vehicles through the network. To reduce the calculation time several improvements are proposed. By setting the upper bounds for various variables to 0 and by combining multiple containers into one commodity the overall size has been reduced. All together this formed a minimum cost network model based on the model presented by Tierney et al. [2013] however the previous section clearly indicated the differences with this model.

Chapter 6

Verification

In this chapter the model presented in Chapter 5 is verified by applying the model to a few simple cases where the optimal number of required vehicles can be calculated by hand and the where the movements of the vehicles and containers through the network can also be analysed by a quick scan of the results. For every vehicle type an verification is made to analyse the reliability of the model by discussing the calculated results.

To be able to verify the working principles of the Matlab model, a simple network containing 2 or 3 terminals and 1 intersection is used depending on the chosen scenario. The model is run for all road vehicle types and in the case of ALVs, the model is run either with and without barges. ALVs are chosen to be modelled in combination with barges, because the loading constraints for ALVs are unnecessary and therefore the runtime of the model can be limited by using less time periods. This will contribute in minimizing the amount of time needed for verification.

The model will be run for various ITT vehicle configurations which create 4 different scenarios as follows:

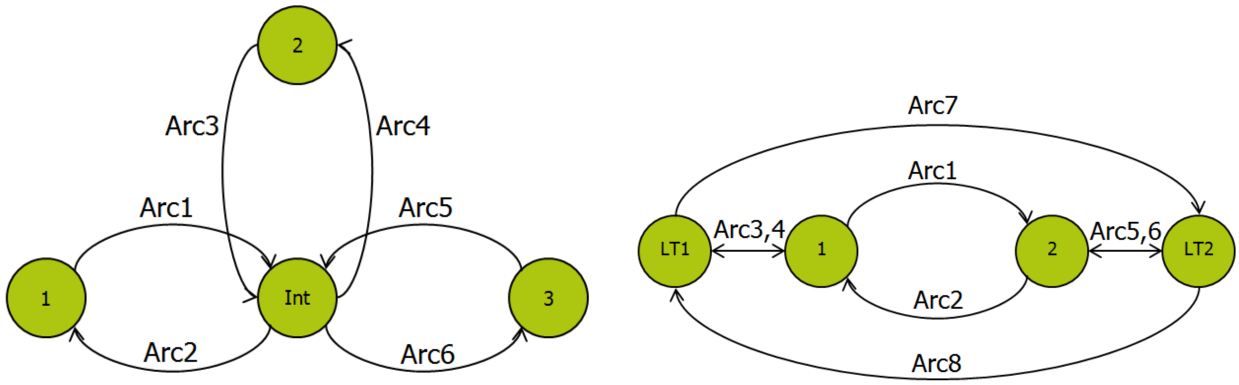
1. AGVs,
2. MTSs,
3. ALVs,
4. ALVs and barges.

The first three scenarios have the same network matrix Aeq and Aeq^{τ} with 3 terminals and 1 intersection and for scenario four the network is reduced to 2 terminals without an intersection and is extended with variables and arcs for barges. The number of terminals for scenario 4 is reduced in order to reduce the overall size of the model, which makes it easier to evaluate. The main goal for this scenario is to investigate the processes related to barges and therefore the road network can be reduced to be as small as possible. The road network consisting of 3 terminals and one intersection is scematically represented in Figure 6.1a and the network with LT nodes is given in Figure 6.1b. The transverse time t for all arcs is set to 1 except when it is clearly indicated to be otherwise.

To investigate the results of the various scenario outputs four points are checked:

- Is the demand satisfied with the correct origin and destination?
- Is every transported container properly connected to a vehicle?
- When containers are transported from an origin, are there enough vehicles available to be able to start the transportation?
- Is the objective value (found number of required vehicles plus the total delay) corresponding to the expectations?

The results of the various scenarios are presented in Section 6.1 to 6.4, which will also discuss the found results. The figures representing the results not only show the values for every variable,



(a) Graphical road network layout.

(b) Graphical network layout with barges.

Figure 6.1: Graphical network layout.

but also matrix A is shown, which show the arc representing the output variable. This will provide a clear view on the validity of the result. A note should be made that in most cases more than one possible optimum can be found, but the algorithm finds only one. Therefore only the found optimum is discussed whether it is a possible optimum according to the four points which are checked.

6.1 Scenario 1: AGVs

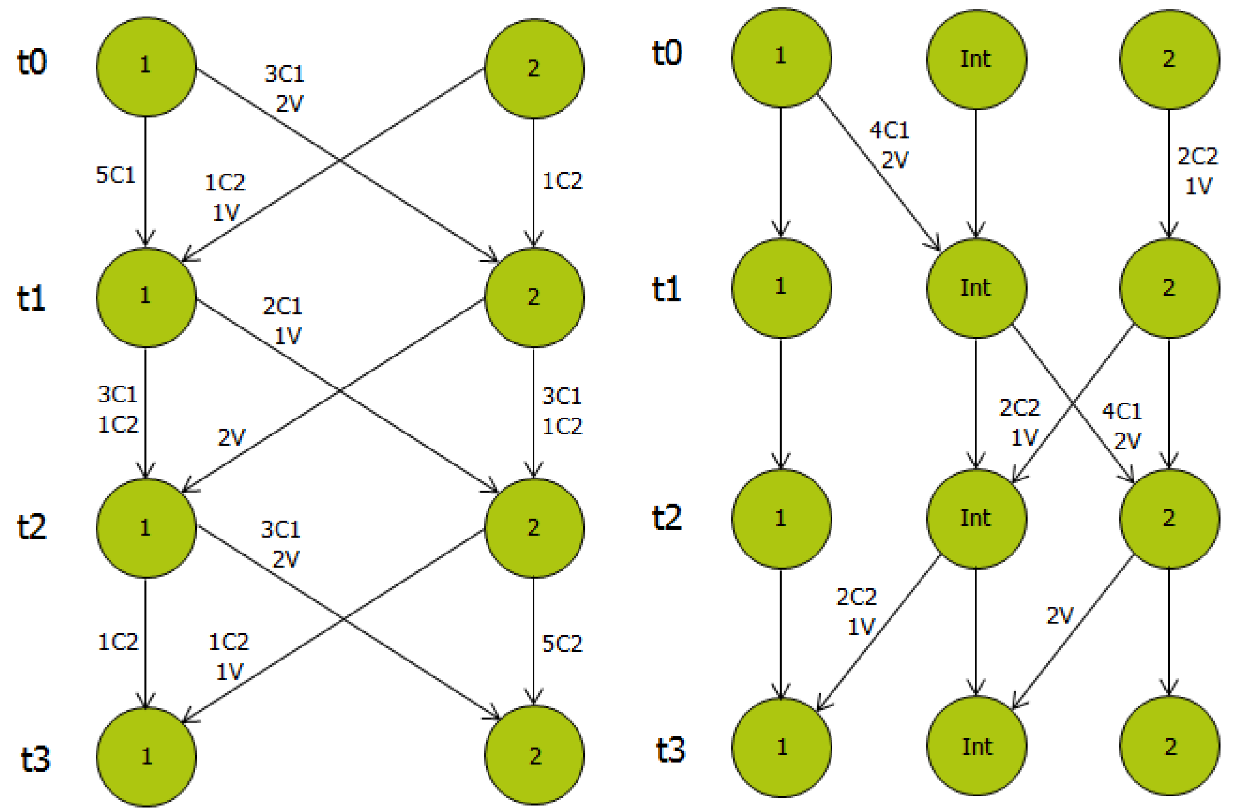
In the AGV scenario two terminals are modelled without an intersection. A flow of 8 TEU is created to flow from terminal one to terminal two. A reverse flow of 2 TEU is created to flow backwards from terminal 2 to terminal 1. The time horizon is set to 3 time periods and a loading rate is allowed of 3 TEU per time step. This ensures that the demand of 8 TEU of terminal one cannot be loaded in one time step and that instead of two vehicles, three vehicles are required to transport the demand in time. The result of this verification is shown in Figure 6.2a, where variable C1 represents the flow of containers of commodity 1, C2 represent the flow of containers of commodity 2 and V represent the flow of AGVs. The complete result with the outcome of every variable and an overview of the arcs in the network is given in Appendix E.

The results of Figure 6.2a match with the set expectations beforehand. The optimal number of vehicles according to the model is three and the handling constraint is applied correctly. All containers are connected properly to a vehicle and containers do not start moving before a vehicle becomes available.

6.2 Scenario 2: ALVs

The ALV scenario is modelled by two terminals and one intersection. The goal of this verification is to check if the congestion on the intersection is interpreted correctly and if the model is able to make a proper decision between the priority of two flows when one flow is prone to experience a delay while the other is not. This is all incorporated by creating a demand of 4 TEU from terminal one to terminal two, with delivery period 2 and a reverse flow of 2 TEU with delivery period 3. The time horizon is set to 3 time periods and the intersection capacity is set to 2 vehicles per time period. These constraints should give the flow of 4 TEU from terminal one to terminal two priority over the reverse flow and require 3 vehicles to deliver all the demand within the time horizon. The results are shown in Figure 6.2b and in Appendix F the full result including the complete network is shown.

As Figure 6.2b shows do all the flows correspond to the expectation prior to the verification run. The intersection capacity prevented that all containers started flowing at time step zero and the penalty assigned to arc 20 of commodity 1 forced the model to give the flow of commodity 1 priority over the flow of commodity 2 and by doing that it prevented a higher objective value.



(a) Flow of AGVs and containers through the AGV scenario network.

(b) Flow of ALVs and containers through the ALV scenario network.

Figure 6.2: Results of scenario 1 & 2.

6.3 Scenario 3: MTSs

For the MTS scenario a demand is created to force the model to pick up containers at two different terminals and bring them both to the third terminal. Therefore a demand of 2 TEU is created in time step 0 at both terminal one and terminal two and a demand of -4 is created at terminal three at time step 5. Also the transverse time t between the intersection and terminal three is set to 2. In order to satisfy the demand one truck is forced to drive with one container to the other terminal and bring 4 TEU to the destination terminal. The time horizon of the model is set to 5 time steps which is the smallest time horizon to create a feasible flow. The result of the MTS scenario is shown in Figure 6.3, where variable C represents the flow of containers, variable Tr represents the flow of trucks and variable Ta represents the flow of trailers through the network. Appendix G contains the precise output of the model with a full matrix containing all arcs of the model.

As can be seen in Figure 6.3 the results match with the expectations how the vehicles and containers should move through the network. It satisfies the demand and vehicles nor containers make unexpected movements. Also the found objective function is correct requiring 1 truck and 2 trailers to transport all the containers in time.

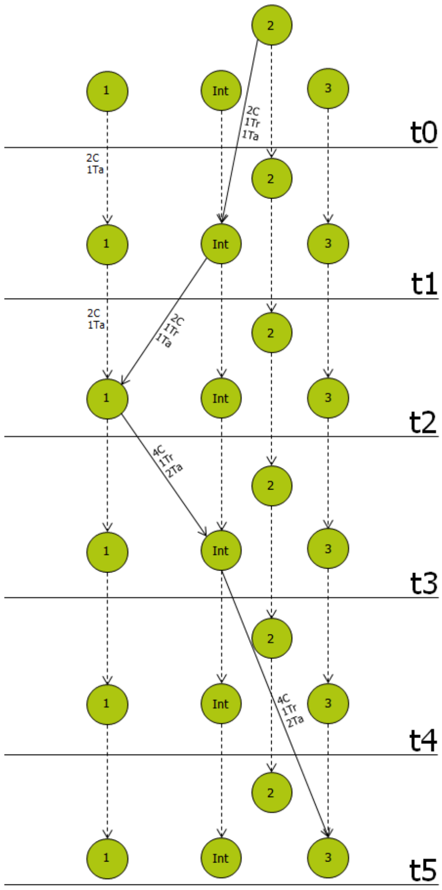


Figure 6.3: Flow of trucks, trailers and containers through the MTS scenario network.

6.4 Scenario 4: ALV and barge

To verify the LT network a barge scenario is created. In this scenario two terminals are created together with two LT nodes, where all transverse times of the arcs are one time step. The LT nodes are connected through a LT intersection and in contrast with the road intersections, LT intersections are only used to bundle flows and are not constraint by a throughput capacity. A demand is created of 42 TEU between terminal 1 and 2, with a time horizon of four periods. The handling rate is set to 40 TEU per time step for barges in order to be able to give the barge the opportunity to benefit from its capacity over the ALV within this short time horizon. By setting the handling rate to 40 TEU per time step the model is forced to use at least one ALV as well, because one barge cannot transport the total demand within the time horizon. The results are shown in Figure 6.4 and in Appendix H the full result including the complete network is shown.

The flow through the network is as was expected. The model used one barge and one ALV to transport the demand resulting in the expected objective value, because using 11 vehicles would give a higher objective value (note that using two barges would result in an infeasible solution). If the barge handling process is considered it can be seen that the barge moves over the stationary arc while the containers are loaded, which is the correct representation for barge handling.

6.5 Concluding remarks

By testing various scenarios the model is verified for small scale problems, able to solve by hand as well. The results of these problems are analysed and it can be concluded that they provided the expected results and that the model is now ready to be used for large problems representing the ITT situation at the Maasvlakte area in the port of Rotterdam.

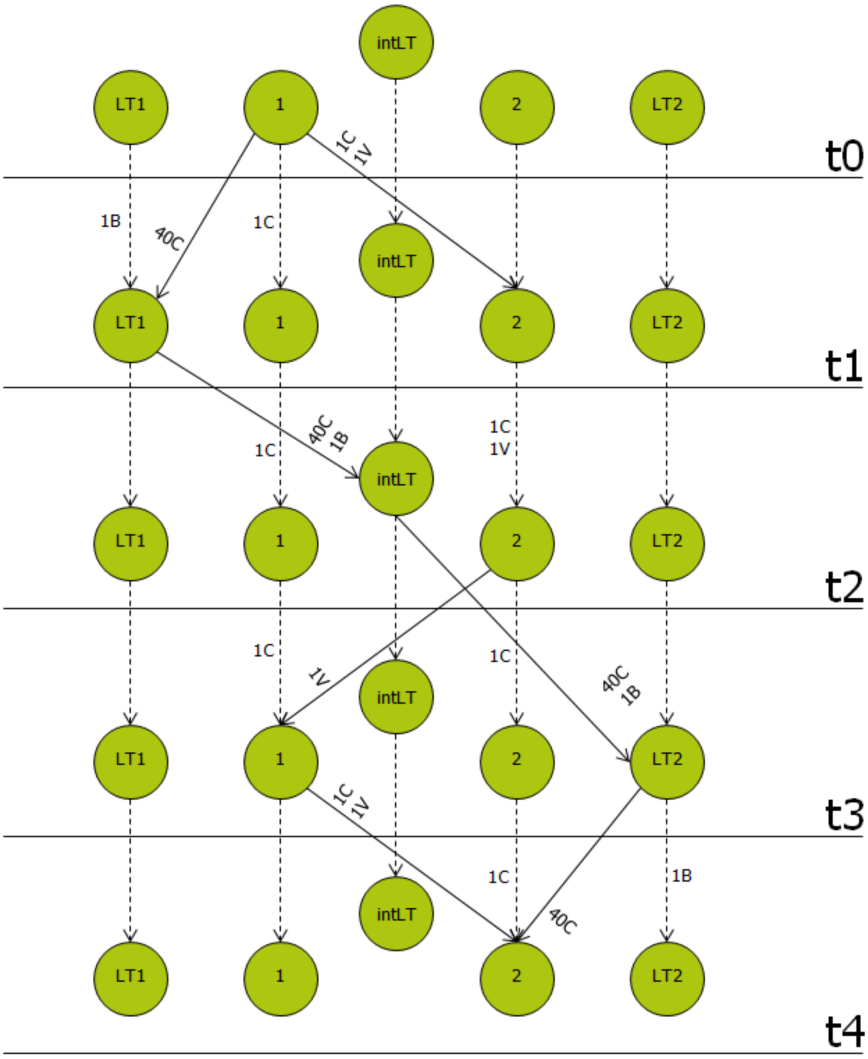


Figure 6.4: Flow of ALVs, barges and containers through the ALV and barge scenario network.

Chapter 7

Case: ITT at Maasvlakte 1&2

In this chapter the minimum cost flow model as presented in Chapter 5 is used in the case, where an ITT system has to be designed for the Maasvlakte area in the Port of Rotterdam. The high uncertainty in the forecast of many parameters up to 2030 resulted that many variations in the parameters are necessary to get an understanding in the effects of every parameter to the performance of the system.

The results computed in this section are received using a quad core Intel Core I7 - 2670QM processor with eight 2.2 GHz threads and at least 3 GB of usable RAM memory.

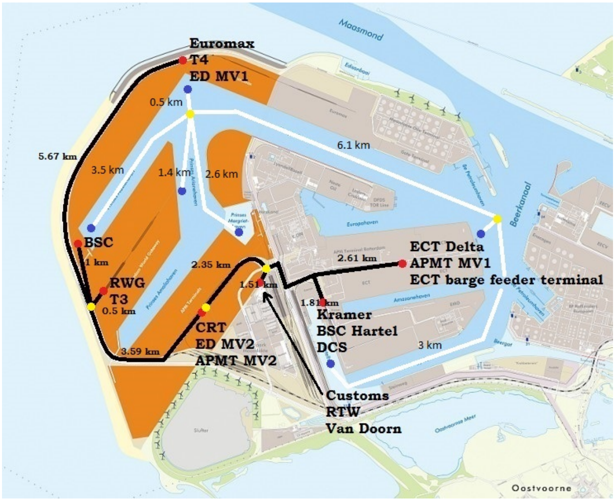
7.1 Layout of the ITT system

The model requires a basic layout of the system to be able to build its network and constraints. This layout is based on the 3 different scenarios and the Maasvlakte layout as shown in Figure 2.1. The size of the overall model and thus the calculation time and memory requirements will increase for every extra included terminal. Therefore to reduce the calculation time an memory requirements as much as possible, while still ensuring a reliable model, some terminals are combined. This is a valid assumption, because there is no ITT demand between the combined terminals or the terminals are located close to each other and therefore their mutual demand will have a very limited influence on the optimal vehicle configuration.

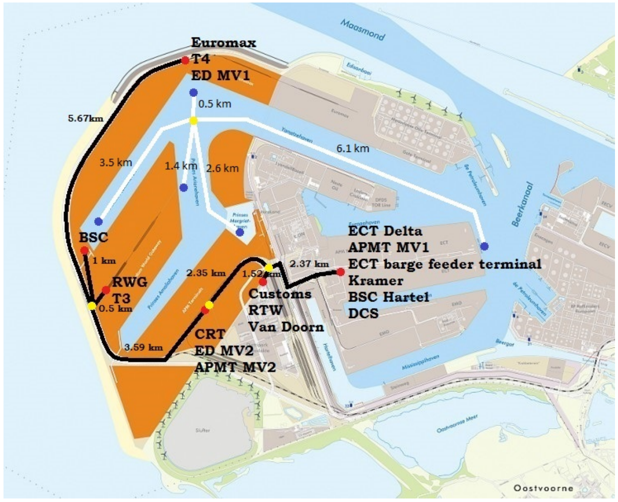
Due to the various assumptions in the scenarios three different networks have been created, one for every scenario. The network for scenario 2 has combined the terminal node for the ECT Delta peninsula and the barge service centres of Kramer and BSC Hartelhaven, because the ITT demand is settled internally. The network for scenario 3 is reduced in comparison with that of scenario 2, due to the absence of the common barge and rail terminal. The terminals in the model are clustered in order to reduce the model size and by that reducing the overall calculation time.

In Figure 7.1 all three networks are presented for both road vehicles and barges also the distances of the various arcs are shown. The location of every terminal node with respect to the nearest intersection is determined by the weighted average of the location of every individual terminal and their expected ITT volume. The distance divided by the average vehicle speed will result in the transverse time of that specific arc. Next to the distance the transverse time is also depending on the handling time of vehicles when the arc is connected to the terminal node, which will increase the transverse time by the amount as was shown in Table 2.7 under handling time.

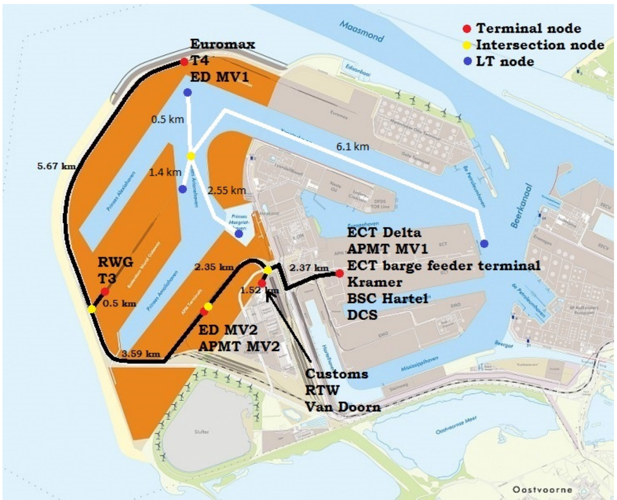
To validate the use of clustering terminals in the network, the total transportation time of all generated containers in the system is compared between a clustered network and a network containing all individual terminals connected by the same intersections as the clustered network. The results are than compared with the real transportation plus handling time based on the real distances between terminals and handling times without rounding to integer values and are



(a) Network scenario 1.



(b) Network scenario 2.



(c) Network scenario 3.

Figure 7.1: Overview of the terminal, intersection and LT nodes on the Maasvlakte.

shown in Table 7.2. Various time steps have been investigated to see if smaller time steps would improve the reliability as can be expected. For the clustered network the road distances shown in Figure 7.4a are used. The real distances are shown in Appendix I and are the same as the distances used by Jansen [2013].

Figure 7.2: Reliability of cluster and individual terminals network versus pure transportation times.

step = 3					
ALV	real time	cluster	%	individual	%
sc3	5647.8	6707	119	7329	130
sc2	8271.45	9998.6	121	11091	134
sc1	11816	14670	124	15847	134
AGV	real time	cluster	%	individual	%
sc3	8130	8820.3	108	8988.3	111
sc2	11910	12598	106	13191	111
sc1	17372	18573	107	19233	111

step = 2					
ALV	real time	cluster	%	individual	%
sc3	8106.9	10387	128	10062	124
sc2	11120	13844	124	12926	116
sc1	16981	19373	114	20203	119
AGV	real time	cluster	%	individual	%
sc3	11830	13105	111	13157	111
sc2	16577	18969	114	18430	111
sc1	25315	28414	112	28145	111

step = 1					
ALV	real time	cluster	%	individual	%
sc3	16281	17270	106	17619	108
sc2	22240	24543	110	24307	109
sc1	33963	35923	106	37119	109
AGV	real time	cluster	%	individual	%
sc3	23727	24540	103	25213	106
sc2	33155	36882	111	36038	109
sc1	50631	53551	106	55033	109

step = 0.5					
ALV	real time	cluster	%	individual	%
sc3	30346	35095	116	34035	112
sc2	44480	51869	117	49887	112
sc1	67925	75561	111	76183	112
AGV	real time	cluster	%	individual	%
sc3	45239	49988	110	49040	108
sc2	66310	73699	111	71881	108
sc1	101260	108900	108	109770	108

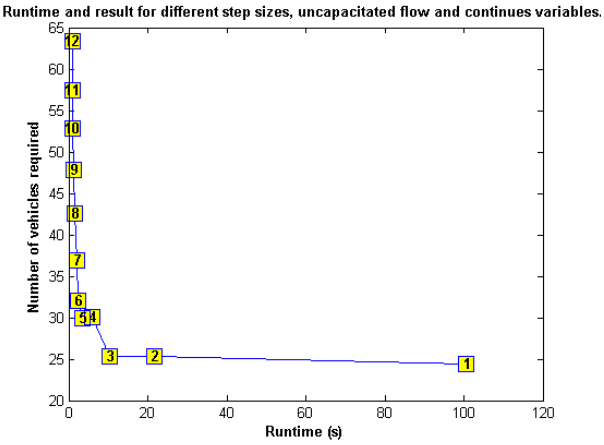
When the differences between the clustered and the individual network is considered it can be seen that depending on the scenario and time step, the relative difference of the total transportation time compared with the real transportation time of one of the two is slightly better than the other one. Because this difference is small and the calculation time of the clustered network is considerably lower clustering the network is preferred and does not result in a significant reduction of the reliability compared to a network containing only individual terminals.

It should be noted that clustering terminals might not provide reliable results for vehicle types with a carrying capacity of more than one container. For example in the case of the MTS when terminals are clustered, the chance that a train of 10 TEU is available when a MTS arrives at the terminal is higher for a clustered terminal because the containers of all clustered terminal become available at one location instead of several locations. However for high demand scenarios the arrival rate of containers is higher so that the chance that enough containers are available is higher. Also in the real implementation not single containers arrive at the terminal but a block of containers coming from a ship, barge or train such that in most cases complete MTS can be loaded. Therefore it is assumed in this research that the clustering terminals does not influence the vehicle requirements for MTSs because there are always enough containers available to load the MTS. The same applies to barges whom although they have an even higher loading capacity the low loading rate will require several hours of mooring time to fully unload and load a barge resulting in enough time to gather containers to fill up a barge. Also the optimization algorithm is able to plan the ITT moves in such a way that it minimizes the slack time so that it is able wait for additional containers as long as possible.

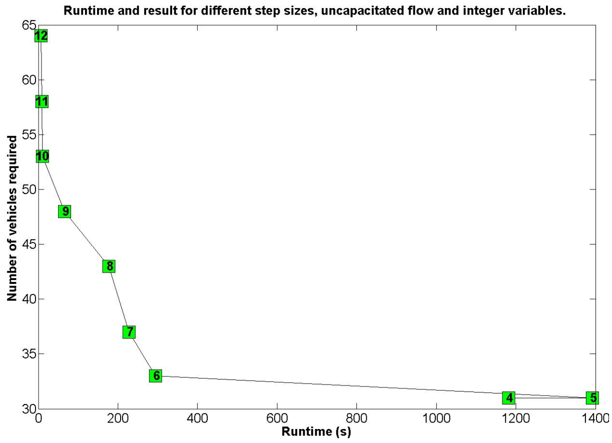
7.2 Time step and integer or continues modelling

To get realistic results within a reasonable calculation time it is important to implement a time step which is small enough to be able to incorporate all processes with a realistic time, but large enough to not increase the calculation time beyond proportion. Therefore various time steps are investigated with a step between 1-12 minutes which is applied to scenario 3. In Figure 7.3 the results can be seen for a run of 8 simulated hours with a demand of 1368 TEU and a capacitated flow. The number inside the square box represent the time step.

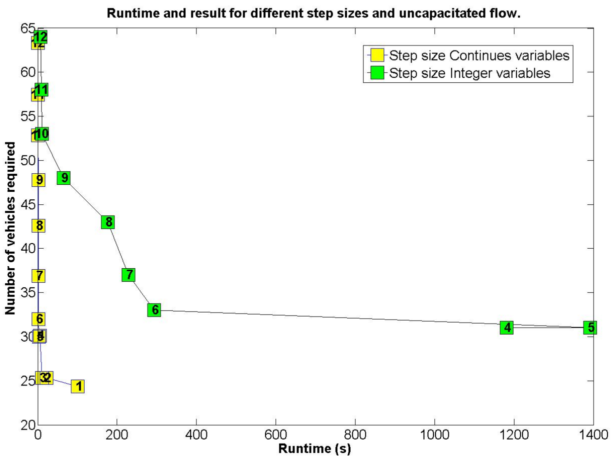
Also a comparison is made between the results with only integer variables and with continues variables. In practice only integer solutions will exist, because i.e. 0.5 vehicle carrying 0.8 container cannot happen and the value will always be at least 1. However modelling wise it is very interesting to also allow continues solutions, because this will significantly reduce the calculation time of the model and by that it allows other time consuming procedures to become possible such as i.e. time horizon extension, LT networks and fan arc intersection modelling. This is obviously only allowed when the objective value of the continues solution is within acceptable margins from the integer solution. Therefore in Figure 7.3 the difference between the integer solution and the continues solution is shown, where the blue line with yellow blocks represent the continues solution and the black line with green blocks represent the integer solution. To get results from the integer calculation a gap tolerance is allowed of 3%. The gap tolerance is the ratio between the objective value of the LP relaxation of the non set variables over the objective value of the solution where all non set variables are rounded to an integer value.



(a) Continues solution result for various time steps.



(b) Integer solution result for various time steps.



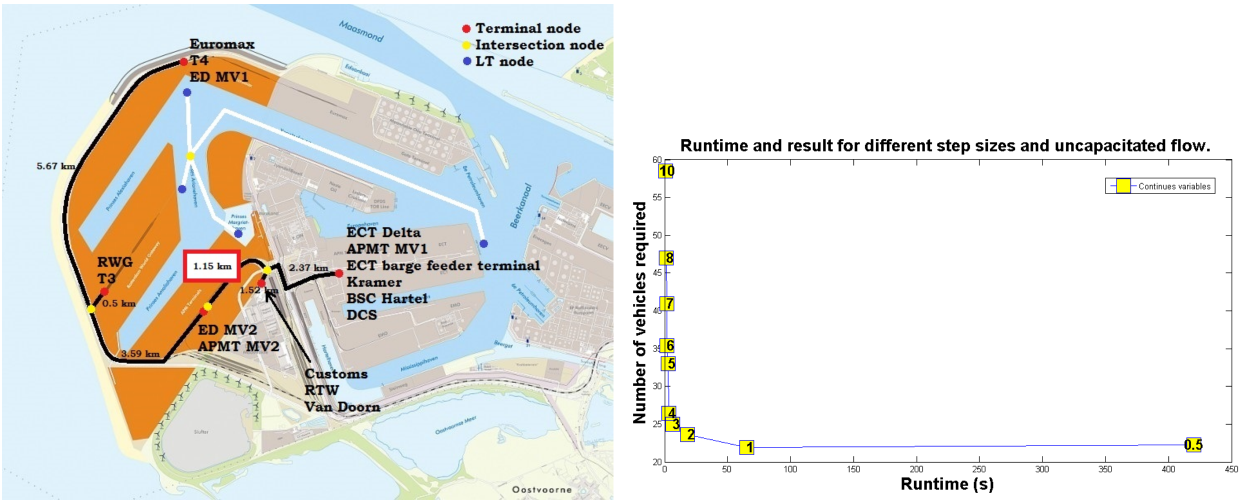
(c) Integer and continues solution result combined.

Figure 7.3: Required number of vehicles versus runtime for various timesteps.

A few interesting behaviours can be noticed in Figure 7.3. First of all it can be seen that for both integer and continues variables the number of required vehicles converge to around 25 when decreasing the step size. It also shows that the calculation time increases with a decreasing step size, which is obvious because the model size will increase. To chose the best step size both the result and the calculation time have to be considered, where the result has to be considered as most important. By doing this the optimal step size of 3 min is chosen, because the result is only 4% larger than for a step size of 1 while the calculation time is almost 10 times shorter. When a larger step size is chosen the result becomes too far off the real value.

When the difference between the integer solution results and the continues solution results is considered it can be noticed that they are exactly the same. However the calculation time for the integer solution is multiple times larger and therefore the results are determined allowing continues variables and thus solutions. It can also be noticed that the calculation time for the integer solution does not always have the same behaviour as that of the continues solution, because it shows some random peaks in the calculation time for specific instances. Although this is not shown in Figure 7.3 it does occur and there are two possible explanations for this behaviour. The first explanation is that the solution needed more iterations to reach the acceptable gap of 3%. The second explanation is that the algorithm first started exploring the wrong branch in its optimization process and later has to go backwards when noticing it is exploring the wrong branch.

Although the ideal time step has been determined for the network shown in Figure 7.1 it can be expected that the the ideal time step is depending on the real transverse time of the arcs and that changing one or multiple important arcs can change this ideal time step instantly. To show this the length between the intersection at the distripark and the intersection at the Common Rail Terminal is reduced to 1.15 km as shown in Figure 7.4a. This resulted in the the ideal time step when only considering the result of 1 minute as shown in Figure 7.4b. However when a time step of 1 minute is used in full scale analysis the calculation time soon becomes to large and therefore from a practical point of view still a 3 minute time step should be used and accepting a reduction in the reliability of the result.



(a) Maasvlakte network where the length of an important arc is changed.

(b) Continues solution result for various time steps.

Figure 7.4: Effect of changing important arc length on the ideal time step.

With this illustration we can conclude that the ideal time step is depending strongly on the arc transverse time determined by the road lengths in the network, the speed of the vehicle travelling over it and the duration of a process such as loading or unloading. This also means that the ideal time step is different for every individual case and will require some time to investigate. However when the ideal time step becomes to low resulting in a rapid expansion of the model size will increase the ideal time step due to practical considerations caused by excessive calculation times.

7.3 Time horizon

To determine the optimal time horizon for the optimization of the ITT system various time horizons have been tested to investigate the performance of the three scenarios. Time horizons between 8 - 24 hours have been tested and the results are shown in Figure 7.5. To give the system enough time to be able to transport all containers, the demand generator generated containers up to 2/3 of the time horizon. By doing this the total demand through the system is only two thirds of demand the system should be able to handle, therefore the containers that are generated are multiplied by a factor ensuring that the total demand per day is a constant value. This also ensures a valid comparison between the various time horizons, because this factor creates a constant demand over when the time horizon is expanded up to 24 hours. It can also be expected that the ideal runtime might differ between a constant demand such that of scenario 3 and a high fluctuating demand such as scenario 1. Therefore for scenario 1 to different starting times are used: one starting at t=0 and one starting at t=6. In this way the peaks are accounted in different ways for these two cases.

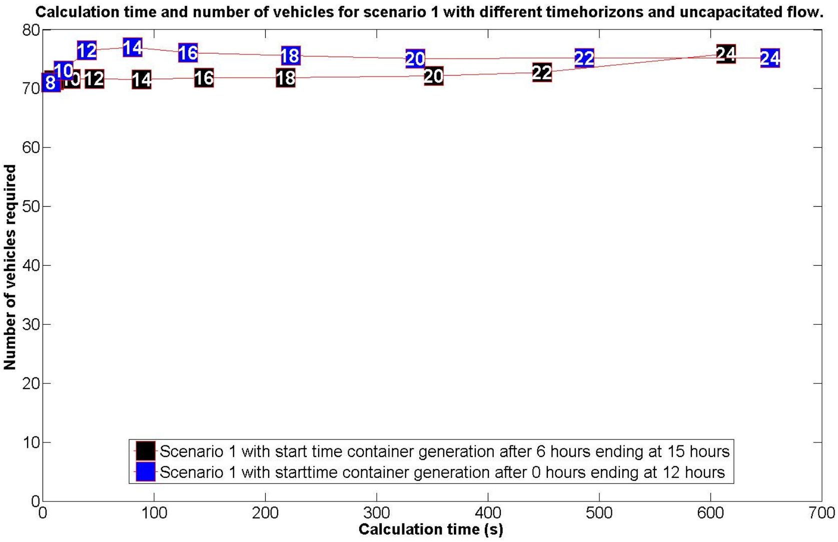
It can be noticed from Figure 7.5a that the starting time of the model does have an influence on the ideal runtime when peaks are occurring. The peaks require a certain settling time before the model becomes stable and therefore it is best to use a time horizon of at least 18 hours. For scenarios such as scenario 3, with a flat demand, Figure 7.5b shows that the required number of vehicles is also depending on the time horizon of the model, where for small time horizons the required number of vehicles is slightly higher than for larger time horizons. This can be explained because average time between the arrival of the container in the system and the delivery time of the container is larger in systems with a longer time horizon than in systems with a short time horizon. Therefore also for constant demand scenarios a time horizon of at least 18 hours is favourable. A note should be made that the differences in the result are of such magnitude that in cases where the size of the model increases such that the calculation times rise to unreasonable lengths, shorter time horizons still provide a good indication of the expected number of vehicles required for a proper functioning system. This might be the case for systems with integer variables, systems with LT networks or MTSs.

Because the time horizon is less than a day the peak factors might not have been properly accounted in the results. The peak factors have an influence in the results, and therefore the previous experiment can show an incomplete picture because the required number of vehicles is not only depending on the time horizon but on other factors as well. In order to test this two additional experiments are done. The first experiment it is tried to show both the effect on the required number of vehicles when varying the time horizon for generating containers and when the starting times are varied and thus considering the peak factors at different moments in the model.

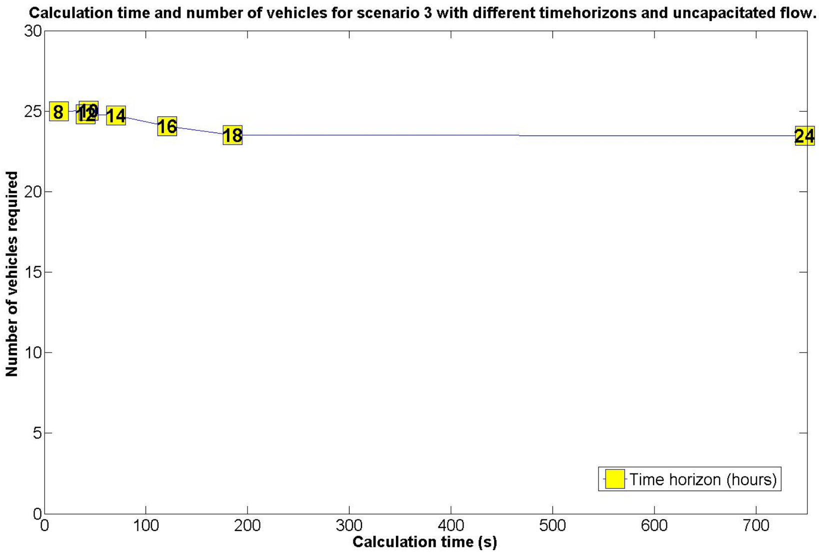
Because containers need time to travel from one terminal to the other it is not possible to generate containers over the full time horizon of the model. Therefore three different generation lengths are tested for a model with a total time horizon of 18 hours. Container generation time horizon of 9 hours, 12 hours and 17.5 hours are investigated. To investigate the effect of different starting times, the start time of the model is varied by starting every run three hours later than the previous run beginning at 12 a.m. for scenario 1. Scenario 3 has a constant demand over time and therefore this affect should not have any influence. The results are shown in Figure 7.6. This experiment investigates if the peak in the arrival times of containers will have an influence on the performance.

As can be seen in Figure 7.6 the fluctuation in required vehicles is the largest when generating containers almost for the complete time horizon of the model. This could be expected because the containers generated in the last part of the time horizon only have a small possible transportation time before they have to be delivered. The high peaks in the result are created when the peak factors in scenario 1 create a lot of containers in the last part of the time horizon, which gives the model no time to anticipate on the high demand on the system and therefore has to hire more vehicles. This effect is shown in Figure 7.7, where in Figure 7.7a the total handling demand is shown for all terminals per hour. This clearly shows a high demand at the second half of the time horizon compared with the first half of the time horizon. Figure 7.7b shows the reason for this high demand, because the cumulative function is shown of the generation of containers over the time horizon showing that almost 45% of all containers are generated in the last 6 hours of the time horizon. It also shows the cumulative delivery time of the containers showing that more than 55% of the containers have to be delivered in the last hour of the time horizon.

However it can also be seen in Figure 7.6 that for the other container generation time horizons the fluctuations are a lot smaller. This can be explained by the fact that the final containers have more time to be delivered before the end of the model time horizon and therefore the model has more time to anticipate for future demands. Figure 7.8 shows the best case for scenario 1,



(a) Required number of vehicles for various time horizons for scenario 1.



(b) Required number of vehicles for various time horizons for scenario 3.

Figure 7.5: Required number of vehicles versus calculation time for various time horizons.

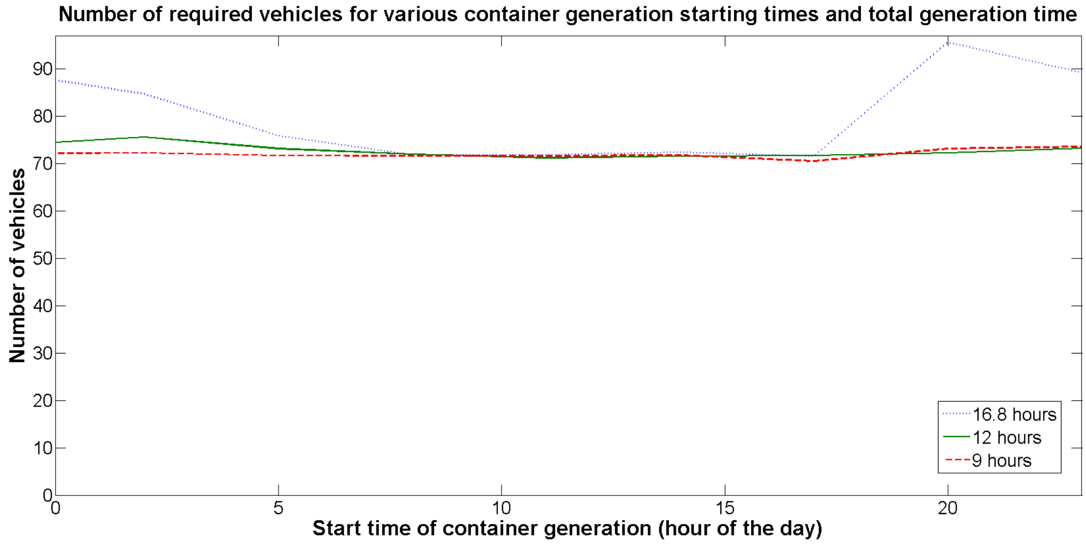
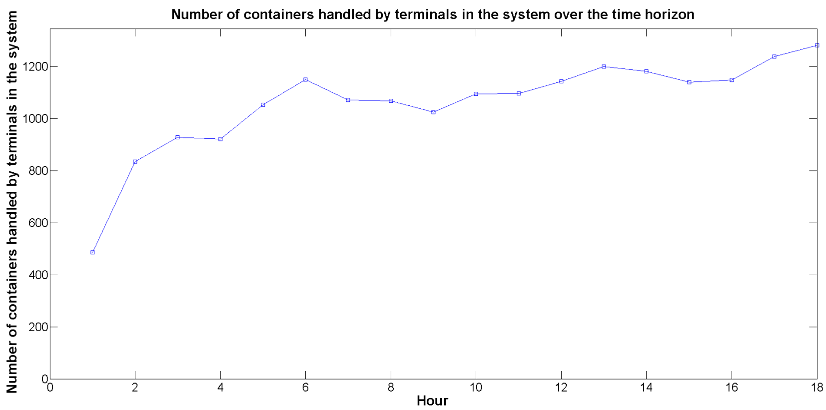


Figure 7.6: Required number of vehicles for various starting times and container generation lengths for scenario 1.

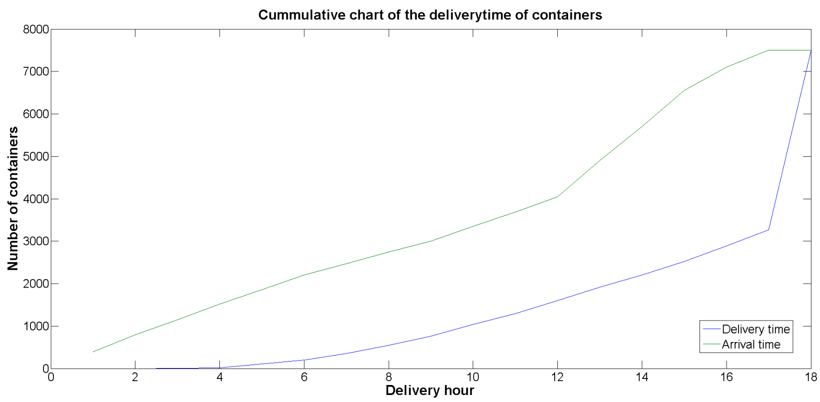
where containers are generated for 12 hours of the total time horizon, showing in Figure 7.8a an almost constant demand on the handling equipment over the whole time horizon. This means that the model is able to anticipate well and has the time to transport high priority containers first before regular containers in order to reduce the required vehicles because there is no chance for delays. Figure 7.8b shows that this is possible, because the model has enough container to transport from the beginning so that the ITT system is able to work at full capacity after a few hours already in comparison to the case shown in Figure 7.7a

The previous experiment was done for a scenario with high peak factors. To investigate the effect of the container generation time horizon on constant demands the experiment is now carried out on scenario 3, where containers are generated for 6 up to 17.5 hours over a total time horizon of 18 hours. The results are shown in Figure 7.9.

Figure 7.9 shows that the optimal required number of vehicles decrease when the containers are generated closer to the time horizon. However up from 12 hours of container generation the optimum seems to stabilize and remains constant up to near the time horizon. An explanation for the fact that the optimum rises when the time in which the containers are generated can be given due to a constant total demand through the network. This results that all the containers generated by the generator are multiplied by a factor such that the sum is always equal to a set daily demand. However when containers are generated only in the first few hours of the time horizon this factor forces the model to deliver a lot of containers in the first part of the time horizon resulting in a higher vehicle demand in the first half of the time horizon. When the containers are generated over a larger period the peak demand is flattened out because the factor creating an constant total demand is lower resulting in a more evenly derived arrival pattern of containers. However generating containers up to 17,5 hours with a time horizon of 18 hours make that the only a very short time is left to transport those final containers, but because it is able to anticipate better on these final containers the model is able to have a lower vehicle demand then for the first container generation scenario. The differences in peak delivery demand are shown in Figure 7.10, where Figure 7.10a shows the handling demand when containers are generated up to 6 hours and Figure 7.10b shows the handling demand per hour when containers are generated up to 17.5 hours. It can be seen that the demand when generating 17.5 hours of containers show a more constant handling demand than when containers are generated for only 6 hours. From this it is possible to conclude that the objective value is determined by the peak demand for vehicles required to satisfy the constraints. The better this demand can be spread out evenly over the time horizon the lower the objective value and thus the required number of vehicles will be even when the last generated containers only have a very short time to be delivered. It can also be concluded that the ideal container generation time horizon is 2/3 of the model time horizon.

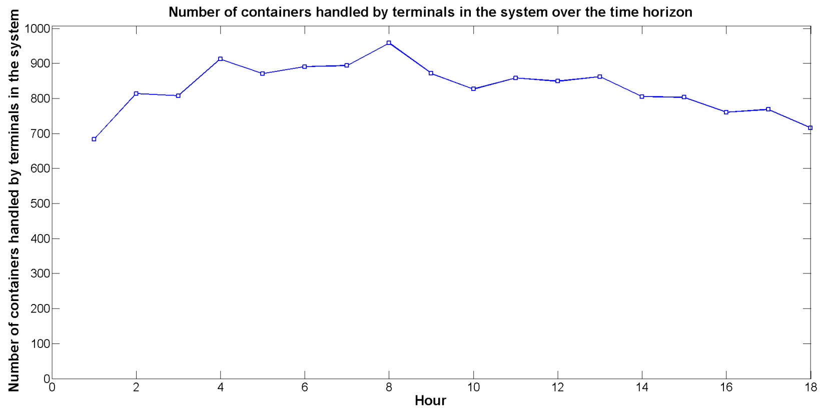


(a) Handling demand in TEU per hour when generating containers in the first 16.8 hours for scenario 1.

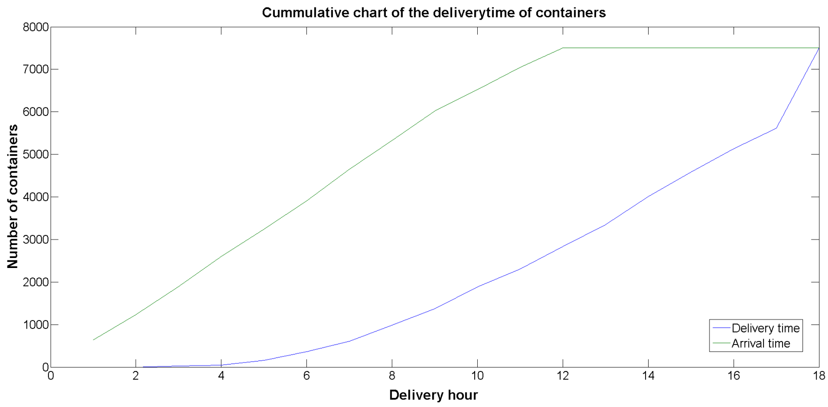


(b) Cumulative function of the generation time and delivery time of containers in the model.

Figure 7.7: Handling demand in TEU per hour and cumulative function of generation and delivery time of containers for scenario 1 when generation containers up to 16.8 hours starting from 20:00 p.m.



(a) Handling demand in TEU per hour when generating containers in the first 12 hours for scenario 1.



(b) Cumulative function of the generation time and delivery time of containers in the model.

Figure 7.8: Handling demand in TEU per hour and cumulative function of generation and delivery time of containers for scenario 1 when generation containers up to 12 hours starting from 11:00 a.m.

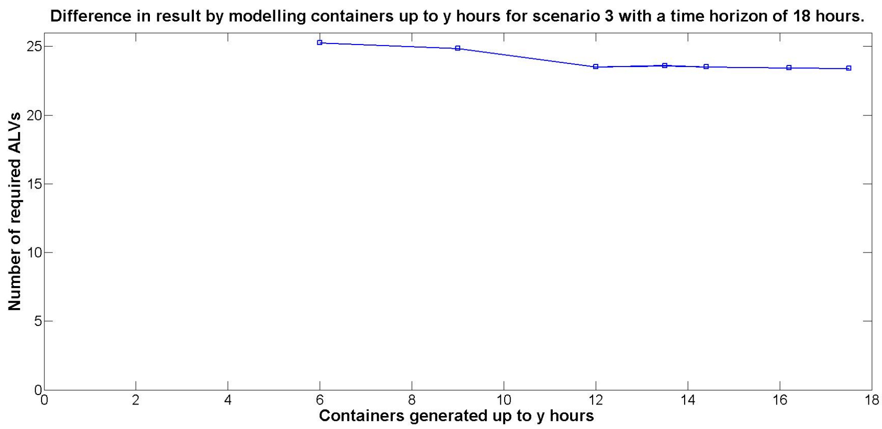
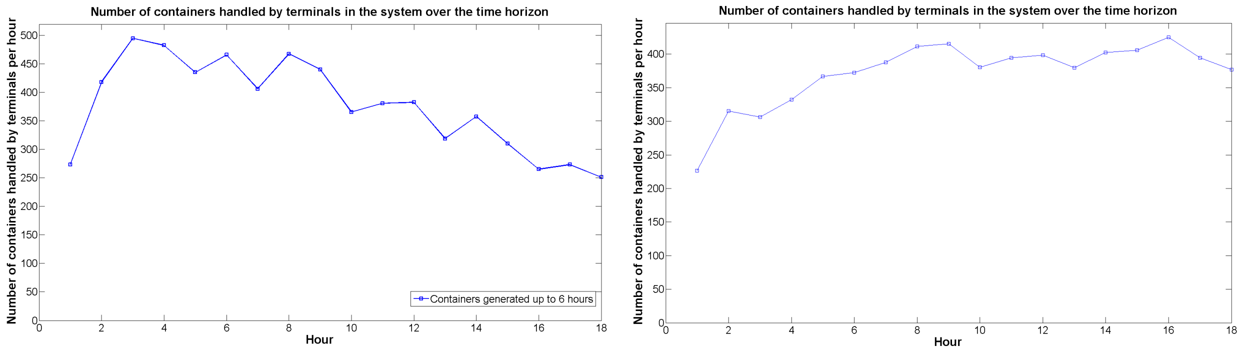


Figure 7.9: Effect of differences in the maximum time of container generation up to time horizon.



(a) Handling demand in TEU per hour when generating containers in the first 6 hours for scenario 3.

(b) Handling demand in TEU per hour when generating containers in the first 17.5 hours for scenario 3.

Figure 7.10: Handling demand in TEU per hour for 2 different container generation lengths.

The last experiment is done to investigate if a peak in the delivery times of containers will influence the performance. In this experiment all containers which are expected to arrive within a two hour time period are multiplied by 2 for scenario 2. The results are shown in Figure 7.11. The container generation start time is chosen in such a way that the demand is

Figure 7.11: Required number of vehicles with a 2 hour delivery peak at various moments.

After investigating all the results it can be concluded that:

- For uncapacitated flow the performance of the system is dependent from the time horizon for constant demands. This is a result of the fact that for shorter time horizons on average containers have less time to be delivered than for larger time horizons.
- For uncapacitated flow the performance of the system is dependent from the time horizon for fluctuating demands, when the system has no time to anticipate on the changes in the demand. This means that when the system has enough time from the moment the peak ends to the time horizon of the model the system is able to balance out all the flows evenly over the time horizon.
- The ideal model time horizon for fluctuating demand scenarios is 18 hours and for constant demand scenarios 18 hours.
- The ideal container generation time horizon is 2/3 of the model time horizon.
- The total throughput is the major variable influencing the performance of the ITT system as long as the constraints and network remain the same.

7.4 Congestion

Congestion may have a significant influence on the performance of the ITT system, because vehicles are slowed down when too many of them are willing to cross an intersection at a single time step. As already explained in Section 5.2.3 the capacity of an intersection is around 8 vehicles per minute. The experiments done in this section are performed on the network of scenario 3, with a time step of 3 minutes and a time horizon of 8 hours. This means that the intersection capacity is set to 24 vehicles per time step and the handling capacity is removed to only measure the effects of the intersection congestion. The results of the experiment are shown in Figure 7.12, where the average delivery time of a container is shown versus the number of vehicles in the system. The numbers inside the point boxes represent the total demand in TEU x 1000 which flowed through the network.

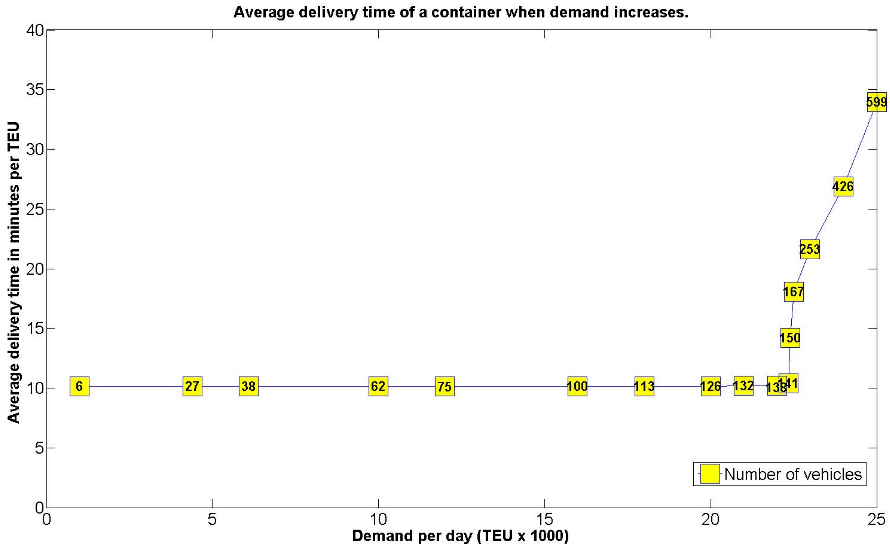


Figure 7.12: Average delivery time in minutes per TEU versus the number of vehicles.

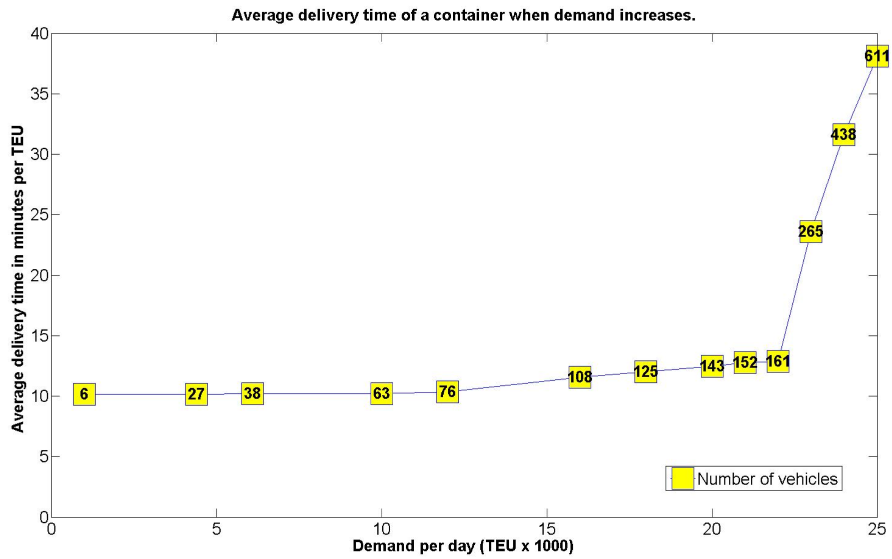


Figure 7.13: Average delivery time in minutes per TEU versus the number of vehicles for intersections with fan arcs.

The average delivery time of containers is constant with an increase in the demand of TEU per day for the ITT system. It requires a daily demand of 23.000 TEU until a rapid increase is seen. When following normal queuing theory this increase can be expected to occur a bit smoother, however the maximum capacity of the ITT system can be seen as 23000 TEU per day. An explanation for the sudden increase can be found in the fact that the intersection capacity is set as a boundary for the amount of vehicles able to cross the intersection at a certain time period. However it does not matter whether this vehicle crosses the intersection as the first vehicle or as the last, because they all are passing the intersection as if it was the first vehicle. To increase the realism of crossing an intersection fan arcs are introduced, giving a time penalty for vehicles entering an intersection after half of a time period has expired. All intersections are modelled as two nodes, connected to each other by two arcs. One arc has a transverse time of zero time steps, while the other arc has a transverse time of 1 time step and both arcs have a capacity of half of the normal intersection capacity per time step. This is shown in Figure 7.14. Modelling fan arcs at an intersection create time differences between the first half of the vehicles crossing the intersection in a time step and the vehicles crossing the intersection at the second half of the time step, while keeping the same intersection capacity per time step. When the model is run with these intersections the results presented in Figure 7.13 are acquired.

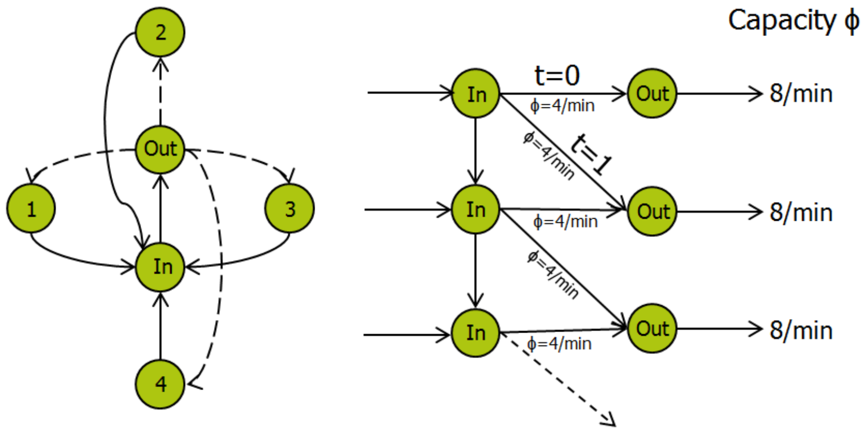
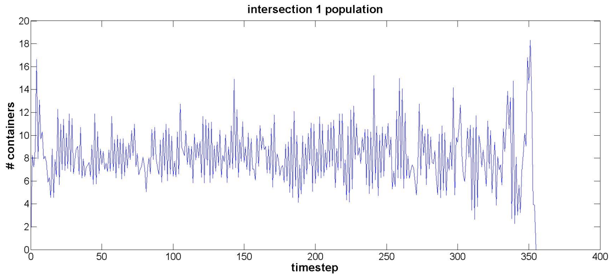


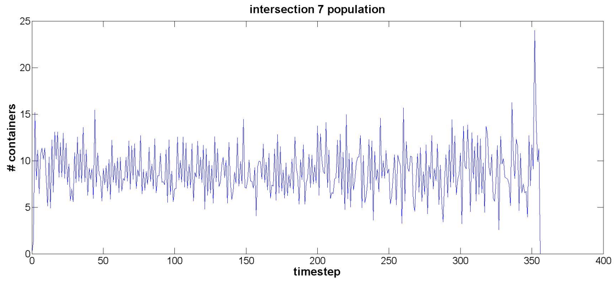
Figure 7.14: Intersection modelled by fan arcs.

It can be seen in Figure 7.13 that the results show a small increase in the average delivery time up from a daily demand of 12.000 TEU. Up from a demand of 23.000 TEU the same sharp increase can be seen as was shown in Figure 7.12. The increase in delivery time between 12.000 and 23.000 TEU shows that the new approach of intersection modelling by fan arcs gives a more realistic result regarding congestion as what can be expected according to queuing theory. However because the demand region concerned for this research for all scenarios is below 12.000 TEU intersections are still modelled without fan arcs, which will reduce the calculation time. It can also be concluded that congestion does not have a significant influence on the performance of the ITT system in the Port of Rotterdam for the presented scenarios in Section 2.3. The intersection capacity also ensures that a maximum demand is found that can flow through the model. In queuing theory general rules of thumps are available, which can show the expected waiting time for various occupancy rates. If the value is used that still allows a free flow through the model this technique will give a reliable result on the performance of the system.

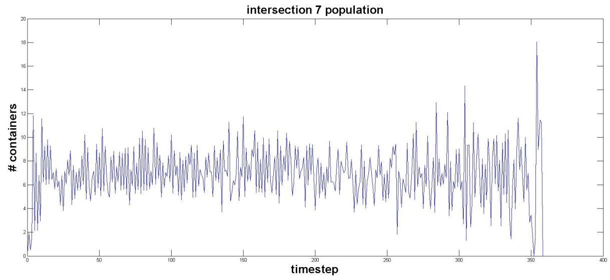
When the three intersections are evaluated individually, the average intersection occupation for the daily volume of 4353 TEU of scenario 3 is 4.5 for intersection 1, 4.1 for intersection 2 and 2.9 for intersection 3. This shows that for scenario 3 intersection 1 has the highest density and if volumes will increase the first congestion problems will arise at intersection 1. The intersection occupancies for scenario 2 with a daily volume of 6143 TEU are 4.74 TEU per time step for intersection 1, 5.52 TEU per time step for intersection 2 and 4.51 TEU per time step for intersection 3. For scenario 2 the busiest intersection is intersection 2, which can be explained, because the common rail and barge terminals are included in this scenario creating significant additional traffic over intersection 2 and 3. Scenario 1 has an intersection occupancy of 8.1, 8.94 and 6.95 TEU per time step for intersection 1,2,3 respectively. Figure 7.15 gives a representation of the intersection occupancy per time step of all three intersections for scenario 1.



(a) Number of vehicles crossing intersection 1 at time step x for scenario 1.



(b) Number of vehicles crossing intersection 2 at time step x for scenario 1.



(c) Number of vehicles crossing intersection 3 at time step x for scenario 1.

Figure 7.15: Number of vehicles crossing an intersection through time for scenario 1.

7.5 Results

In this section various scenarios will be modelled in order to determine the required number of vehicles for several vehicle configurations. As already mentioned the model will simulate the use of ALVs, AGVs, MTSs and barges for all three determined demand scenarios. Next to these results also several input parameters are varied in order to get an understanding about the effects these changes have on the optimal vehicle configuration. The following experiments are executed:

- Normal run (with default values for the various parameters) for all vehicle types and scenarios
- Varying the cost function: no penalty for delay is incorporated versus delays are unacceptable
- Effect of speed: the default vehicle speed is reduced to speeds commonly seen at terminals today.

7.5.1 Results normal run

The results shown in Table 7.16 up to 7.18 are obtained by simulating the three scenarios with the parameter values shown in Table 7.1 for all vehicle types. The handling rates at terminals are set to infinity, because it is assumed that the capacity is designed in such a way that it should not form a bottleneck. To provide designers an idea about the handling demand per terminal the average number of containers handled per terminal per hour is given. The handling of barges is however restricted to 1 crane per barge with a maximum of 2 cranes per terminal.

A note should be placed to the average handling rates for the barge case, which only included the handling rates for the road vehicles. If this is considered it is interesting to see that when comparing with the ALV case the average handling rate of terminal cluster 6 is very low. From this it can be concluded that terminal cluster 6 is found very interesting to be served by barge, which looks obvious because of the large distance from other terminals require a relative high amount of transportation time by road compared to the barge.

Table 7.1: Default parameter values.

	speed (km/h)	intersection cap. (veh/timestep)	carrying cap. (TEU)	handling time (sec.)	cost function (per 24 hours)
ALV	40	8	2	30	239
AGV	40	8	2	180	162
MTS	30	3	10	180	100/28 (truck/trailers)
Barge	12	∞	50	180	1200

						Average handling demand (TEU/hour)						
Scenario 1	TEU/day	nr vehicles	timehorizon	stepsize	punctuality	t1	t2	t3	t4	t5	t6	t7
ALV	10001	51	18	3	0.9941	117	80	144	196	98	46	154
AGV	10001	65	18	3	0.9974	118	80	144	196	98	46	154
MTS	10001	16 Truck +76 Trailers	18	3	1	120	85	141	204	102	54	153
barge	10001	41 Truck + 2 Barges	8	3	0.9876	111	83	143	153	98	50	90

Figure 7.16: Results of scenario 1 for various vehicle types with default parameter values.

						Average handling demand (TEU/hour)					
Scenario 2	TEU/day	nr vehicles	timehorizon	stepsize	punctuality	t1	t2	t3	t4	t5	t6
ALV	6549	33	18	3	0.9924	121	92	132	61	33	106
AGV	6549	42	18	3	0.9929	121	92	132	61	33	106
MTS	6549	12 Trucks + 59 Trailers	18	3	1	133	100	146	70	33	118
barge	6549	22 Trucks + 3 barges	8	3	1	103	89	96	51	28	49

Figure 7.17: Results of scenario 2 for various vehicle types with default parameter values.

						Average handling demand (TEU/hour)				
Scenario 3	TEU/day	nr vehicles	timehorizon	stepsize	punctuality	t1	t2	t3	t4	t5
ALV	4468	24	18	3	0.99	92	104	70	40	68
AGV	4468	32	18	3	0.99	92	104	70	40	68
MTS	4468	9 Trucks + 42 Trailers	8	3	1.00	93	103	70	37	70
barge	4468	17 Trucks + 2 barges	8	3	0.99	73	103	59	40	32

Figure 7.18: Results of scenario 3 for various vehicle types with default parameter values.

The results cannot be validated because no ITT system exist in the world from which data could be used to validate the model. To determine the reliability of the results the minimum total number of time steps required for transportation of the containers is determined for the various vehicle types and this is compared with the total number of time steps at which the vehicles are available for transportation. This resulted in percentages between 85 and 90 percent meaning that vehicles theoretically have enough time to transport all containers and obtain a high occupation rate. Also the verification shown in Chapter 6 showed that the model works as expected.

The second way to determine the reliability of the model is by comparing the results with the results determined with the model presented in Jansen [2013]. In his research an average handling time of 120 seconds is used instead of the 180 seconds used in this research. Therefore Table 7.2 shows the results of both models for the three scenarios with an average handling time of 120 seconds. Jansen investigated vehicle requirements for AGVs and MTSs however the modelling of MTSs is found not reliable, because of the dispatching rules for these vehicles. As a consequence only the results for AGVs are compared.

Table 7.2: Comparison of the AGV requirements between the results of Jansen and this research. Determined with a handling time of 120 seconds.

	nr. AGVs Nieuwkoop	nr. AGVs Jansen
Scenario 1	57	70
Scenario 2	40	41
Scenario 3	29	27

The results in Table 7.2 show that the model presented in this research determined lower vehicle requirements than the model presented in Jansen [2013] for scenario 1. This can be explained because the model by Jansen [2013] does not have an optimization algorithm which will increase the vehicle requirements. His model also did not investigate the best method for modelling ITT because the focus of his research was on investigating various coalitions. Therefore his dispatching strategy will probably perform worse than the best dispatching strategies used in the industry nowadays especially for higher demand scenarios. In case of scenario 3 the vehicle requirements determined by the model presented in this report are higher. This can be explained because the for low demand scenarios the rounding errors of the transverse times of arcs will have a bigger effect on the results than a sub optimal dispatching rule.

Although the numbers for the road vehicles look realistic it can be questioned whether reliability of the barge network can be assumed. The main reasons for this are that the time horizon is only 8 hours, while fully loading and unloading a barge takes 5 hours assuming a handling rate of 20 moves per hour. When also sailing to the destination is taken into account the barge can hardly make one journey in this 8 hours. Also the continues modelling reduces the reliability, because after the first TEU is loaded this TEU can start sailing to another terminal, while it normally has to wait until the barge is fully loaded. This would ask for a model with both a longer time horizon and the usage of integer variables. Unfortunately the computer used for this research does not have the capability of producing the results.

7.5.2 Varying cost function

The goal of varying the cost function is to investigate what the extra costs will be to have a punctuality of 1, or in other words what will be the extra costs for having no delays. On the other hand it is interesting to investigate what the costs would be when delays are not important and what the reduction would be in the number of required vehicles. To investigate these effects the model was run with cost functions containing either the vehicle cost or delay cost component in the cost function. Table 7.19 shows the results of the experiment.

The results in Table 7.19 show hardly any effects when changing the cost function. Only the punctuality drops when the delay costs are not considered is dropped to around 77%, but this can be explained because the vehicles do not bother to bring any container in time as long as the

Scenario 3				
cost function	nr. ALV	punctuality	nr. AGV	punctuality
vehicles & delay	24	0.99	32	0.99
vehicles	24	0.78	32	0.79
delay	24	1	32	1

Scenario 2				
cost function	nr. ALV	punctuality	nr. AGV	punctuality
vehicles & delay	33	0.99	42	0.99
vehicles	33	0.77	42	0.76
delay	34	1	42	1

Figure 7.19: Results for various cost functions

total demand is fulfilled. The number of vehicles is constant for all cost functions and this could be the case because the number of vehicles is reduced to the absolute minimum required by the model to fulfil the demand while having the lowest overall cost when delays are also considered. This means that the demand is evenly spread out over the time horizon resulting in a optimal punctuality versus number of vehicles. When the number of vehicles is reduced the punctuality will drop rapidly, because the model is unable to deliver all containers in time. Because the optimal number of vehicles is so close to the minimum required number of vehicles needed to transport all the demands in time, that there is no possibility to lower the number of vehicles when the costs for delay are excluded. With this result it can be concluded that the values of the cost function do not influence the result of the model when considering both delay and a single vehicle type.

7.5.3 Effect of speed

The used speeds in the model for AGVs and ALVs are higher than current day practise. This is done on purpose because it can be expected that in 20 years from now the automated technology incorporated in these systems advance and therefore higher speeds can be realized. The vehicles are applied in environments where large stretches of roads have to be crossed instead of the relative small distances on terminal sites, which also enables the possibility for higher speeds. However if these assumptions turn out to be false this could have drastic consequences on the system performance and result in a much higher vehicle requirement. In order to get a feeling on the effects of speed in the results of the model all three scenarios are evaluated, where the speed of the AGVs and ALVs is reduced to 18 km/h which is the maximum speed of these vehicles in terminals today. In Table 7.20 the results of this evaluation is shown.

Scenario 3		
v (km/h)	nr. ALV	nr. AGV
40	24	32
18	51	62

Scenario 2		
v (km/h)	nr. ALV	nr. AGV
40	33	42
18	61	76

Scenario 1		
v (km/h)	nr. ALV	nr. AGV
40	51	65
18	93	118

Figure 7.20: The effect of reducing the speed to that of current operating automated vehicles on the required number of vehicles in an ITT system.

From the results it can be said that the vehicle speed has a significant impact in the required number of vehicles for all scenarios. The results almost dubble which will mean that the investment costs will be a lot higher when conventional speeds are applied to the vehicles. Although the development of automated vehicles which can safely and effectively operate in the ITT system will also cost a lot of money, the results of Table 7.20 clearly show that this development should be seriously considered.

7.6 Best vehicle option for ITT at the Maasvlakte

After investigating various vehicle configurations in this section the best vehicle option is determined based on various criteria by a multi criteria analysis. The criteria receive a score between 1 and 5 points and the concept with the highest overall score is the most recommended concept for implementation. The criteria assessed in this analysis are:

- Total costs

- Punctuality
- Feasibility
- Sustainability
- Flexibility

The total costs are divided into four categories: vehicle costs, handling cost, infrastructure cost and personnel cost. These categories are based on the costs presented in Diekman and Koeman [2010] and Port of Rotterdam Authority et al. [2002] for the road vehicles and Hekkenberg [2005] for the barge costs. The total cost calculation is shown in Table 7.3 for all three scenarios. The calculation of the four subcategories is shown in Appendix J. The infrastructure costs for the automated vehicles are assumed to be 1.5 times higher than the cost for the non automated vehicles, which includes the additional costs for the technology applied in or along the road to direct the automated vehicles. The handling cost for barges is assumed to 15 Euros per TEU based on an average price between the ALV and barge handling costs where the barge handling costs are assumed to be more expansive than the MTS handling costs because the handling equipment is more capital intensive.

Table 7.3: Costs per TEU for all three scenarios.

	AGV	ALV	MTS truck	MTS trailer	Barge
Scenario 1					
Annual volume (TEU)	3340	3340	3340	3340	3340
Required # vehicles	65	51	16	76	2
Cost/vehicle	49.1	72.0	43.7	16.6	1708
Vehicle costs/TEU	0.96	1.10	0.21	0.38	1.91
Infrastructure costs/TEU	1.12	1.12	0.75	0.00	1.12
Handling costs/TEU	10	10	15	0	15
Personnel costs/TEU	0	0	1.05	0	0
Total costs/TEU	**12.07**	**12.22**	**17.00**	**0.38**	**18.02**
Costs/TEU/MTS combi			**17.38**		

	AGV	ALV	MTS truck	MTS trailer	Barge
Scenario 2					
Annual volume (TEU)	2150	2150	2150	2150	2150
Required # vehicles	42	33	12	59	3
Cost/vehicle	49.1	72.0	43.7	16.6	1708
Vehicle costs/TEU	0.96	1.10	0.24	0.46	3.12
Infrastructure costs/TEU	1.74	1.74	1.16	0.00	1.74
Handling costs/TEU	10	10	15	0	15
Personnel costs/TEU	0	0	1.22	0	0
Total costs/TEU	**12.70**	**12.84**	**17.62**	**0.46**	**19.86**
Costs/TEU/MTS combi			**18.08**		

	AGV	ALV	MTS truck	MTS trailer	Barge
Scenario 3					
Annual volume (TEU)	1420	1420	1420	1420	1420
Required # vehicles	32	24	9	42	2
Cost/vehicle	49.1	72.0	43.7	16.6	1708
Vehicle costs/TEU	1.11	1.22	0.28	0.49	3.27
Infrastructure costs/TEU	2.63	2.63	1.75	0.00	2.63
Handling costs/TEU	10	10	15	0	15
Personnel costs/TEU	0	0	1.39	0	0
Total costs/TEU	**13.74**	**13.85**	**18.42**	**0.49**	**20.90**
Costs/TEU/MTS combi			**18.91**		

After the cost calculation it can be concluded that the AVGs and ALVs are cheaper than the other vehicle configurations mainly because of the low handling costs. Based on cost there is no clear advantage for either AGVs or ALVs therefore they both score 5 points. The MTSs score 2 points and the barges score 1 points based on the large additional costs for these systems. A note should be placed that fuel costs are not included into the cost analysis. Also the additional cost for the infrastructure of the automated systems are an assumption.

The punctuality for all vehicle configurations is almost 100% therefore all configurations score the maximum of 10 points.

With feasibility the practical implementation of the configurations is considered. As mentioned already in previous sections barges are considered to be not practical because they require extra quay and crane capacity which is already heavily congested at current operating terminals. A second drawback is that not all terminals have a barge connection and therefore a road ITT system is still required. Also additional handling is required because the barges cannot reach the stack directly, which will increase the ITT costs by barge. These arguments result that barges score only 1 point on feasibility. The feasibility for both AGVs and MTSs are considered are very good, because both systems are mature and a lot of experience with these systems is already available in the port. Therefore the maximum score of 5 points is assigned to both AGVs and MTSs. The ALV on the other hand is a new system and therefore it still has to prove its feasibility. However theoretically the system looks very attractive because it decouples the handling process from the transportation process. Also the implementation of these ALVs in the new terminals show that terminal operators trust the new technology. ALVs score 4 points loosing one from the maximum because of the existing uncertainties.

On sustainability both AGVs and ALVs score equal because they both have a the same load capacity and can be equipped with electric engines. The lower vehicle requirement for ALVs is compensated by a higher energy consumption because of the higher weight and the energy consumption by the lifting platform. Therefore ALVs and AGVs are given 3 points. The MTS system has a load capacity 5 times larger than for AGVs and ALVs resulting in a low number of vehicles. When MTSs are equipped with electric engines the sustainability is much better and therefore MTSs score 5 points on sustainability. The barge has the highest carrying capacity, however a barge ITT system still needs a lot of other vehicles working parallel to the barges. For long inland distances the barge emits less emissions per TEU than trucks, but for ITT barges are expected to be waiting most of the time while being loaded or unloaded having their engines still on to provide power to the ship. This results in a lot of unnecessary emissions which give the barge concept a score of 2 points for sustainability.

The flexibility is assessed by how well a vehicle is able to cope with fluctuations in demand and if the vehicles full capacity can be utilized optimally. In the case of barges it is clear that they are the least flexible, because they have a large load capacity taking a lot of time to load. Also the number of terminals they can reach is limited to the ones connected to the water. Therefore barges score only 1 point on flexibility. The MTS system is also not very flexible. Although they can serve every terminal this system is not able to be handled by the automated stacking cranes of the terminal and requires its own handling equipment. Also the carrying capacity of 10 TEU will probably mean that it has to wait longer before enough containers are available to transported to another terminal this higher capacity also means that the speed of the MTS is lower than for the automated vehicle types resulting in longer drive times. This will mean that the MTS scores 2 points on flexibility. The AGV and the ALV are both very flexible, because of their high speed and small loading capacity makes that they can be quickly send to a terminal to pick up a single container with a high priority without wasting much of the total capacity of the system. The ALV has however one advantage over the AGV and that is that this vehicle does not have to wait to be handled because it can pick up a container from a rack. Therefore the flexibility score for ALVs is 5 points and for AGVs 4 points.

All these scores together result in the total score per concept as shown in Table 7.4. The score for costs is assigned with a weight of 2 because this will eventually be the most important criteria. An economical non feasible system will never be implemented and therefore the costs will be the go/no go criteria.

Table 7.4: Multi criteria analysis for the various ITT concepts.

Criteria	ALV	AGV	MTS	Barge
Costs (x2)	10	10	4	2
Feasibility	4	5	4	1
Punctuality	5	5	5	5
Flexibility	5	4	2	1
Sustainability	3	3	5	2
Total points	**27**	**27**	**20**	**11**

With these scores it can be concluded that an automated system of AGVs or ALVs is recommended. At this point AGVs have a slight advantage over ALVs due to the uncertainties of the ALVs. This can change once ALVs are fully operational in the new terminals at the Maasvlakte and work according to the expectations so that the flexibility will be the advantage. However most of the time the vehicle is driving and not loading or unloading, which is the opposite to terminal operations. The decoupling also does not increase the capacity of the loading and unloading because the limiting factor will probably be the ASCs. Therefore the flexibility advantage is less important than the currently existing uncertainties. It can also be expected that the ALV is more likely to experience from breakdowns because it has more moving parts due to the lifting platform and when this platform does not work properly the vehicle is useless until it is repaired. MTSs perform especially worse on costs resulting in a lower overall score. When the handling costs for MTSs can be reduced to values near that of the automated systems the MTS system can become a serious option otherwise it will remain economically infeasible. According to the analysis barges cannot be considered as a serious option being outperformed on almost all criteria.

7.7 Concluding remarks and limitations of the model

In this section all major parameters for modelling an ITT system have been determined. For each scenario a network is created, which is used for the various experiments presented in this chapter. The network contained all arc distances and connections to intersections. Also the barge network is included. This network provided the base for all the experiments done in this research. The following conclusion are drawn from the experiments.

- The the transverse times of the arcs in the network is the major factor in the ideal time step, where for the network used in this research the ideal time step is 3 minutes;
- For the model size used in this research the practical limit is experienced with a time step of 3 minutes. Meaning excessive calculation times for time steps smaller than 3 minutes;
- Continues variables provided the same results as integer variables;
- The ideal time horizon is found to be 18 hours for both constant and fluctuating demands. Choosing a smaller time horizon will increase the required number of vehicles;
- It is best to have a container generation time up to 2/3 of the model time horizon in order to have enough time to deliver the final containers without a large increase in required number of vehicles.
- Congestion will not be an issue with current demand scenarios. However modelling congestion in this way only gives an upper bound on the throughput the model is able to realize. It can therefore be expected that the results for scenarios with a high chance on congestion will be too low.
- The model found reasonable vehicle requirements for all three scenarios and all vehicle types.
- The speed of vehicles have a large impact on the results. When developing an automated ITT system it is worth it to seriously investigate to options for AGVs or ALVs with higher speeds than currently available.
- Varying the cost function has little effect on the required number of vehicles.
- Clustering terminals into one node does not result in a large deviation of the results compared with a system of individual terminals. This allows a significant saving in model size and thus calculation time.

After analysing the results it can be concluded that the reliability of the model is shown for road vehicles. However the results should be interpreted as a lower bound for high demand scenarios, because of the optimization performed on the vehicle routing. For lower demand scenarios the rounding error will become more important resulting in a small overestimation of the vehicle requirements. Also neglecting certain interactions such as downtime for maintenance or wait times for crossings with railways and public roads will result in a higher vehicle requirement than calculated by the model. The real system probably requires an amount of vehicles between the results of the model presented in this report and the model presented in Jansen [2013], however a proper simulation model should be used to verify this assumption. Within the ITT project group Schröer [2013] is working on building a simulation model and once his results are published the reliability of this model can be determined with more certainty. Also for cases when congestion becomes a problem the reliability of the model can be questioned, because although a limit in throughput is found the limit appears suddenly, where normally a more gentle transition is expected. Before more conclusions can be drawn about the effect of congestion more research is required. However the fact that the results for AGVs are close to the results of Jansen [2013] does confirm that the model on itself can provide reliable results for uncongested systems and single load capacity vehicles. However under the assumption that enough containers are available at a single terminal to load a MTS or barge without waiting for containers these results can also be considered reliable.

When the results are considered reliable the best option for ITT is by using AGVs who scored the most points in the multi criteria analysis. Although the model and results presented can be considered reliable the model does have some limitations which are:

- Stochastic processes cannot be modelled and have to be made deterministic;
- No crossings with public roads or railways are implemented;
- Downtime due to maintenance or refuelling is not considered into the vehicle requirements;
- Rounding of transverse times of arcs create a reduction in the reliability;
- There is no control over individual containers or vehicles only over the total flow over a certain arc at a specific time;
- Large models require a lot of processing power and memory capacity;
- Congestion at intersections is only experienced once nearing the ultimate capacity of the intersection.

Chapter 8

Conclusions and future research

After investigating various modelling techniques it was concluded that a deterministic minimum cost flow network with time expended graphs is the best way to determine the optimal vehicle configuration of an Inter terminal transport system. This model is submitted to an ITT case at the Maasvlakte for several vehicle types after which various conclusions can be drawn and an answer to the main research question: Could a reliable tool be constructed, able to determine an optimal vehicle configuration to provide a yet to be determined performance level for an ITT system? can be given.

A network of arcs and nodes is constructed where a flow of containers and vehicles is directed through this network by various constraints. For small scale problems it is verified that the network and constraints work properly and show reliable results. For the case at the Maasvlakte the network is clustered into groups of terminals to reduce both the calculation time and the memory requirements of the model. Although it may look like this reduces the reliability of the model it is shown that the results are comparable to that of a non clustered network and therefore this assumption is allowed.

The model is tested for three different scenarios, which have been determined by Jansen [2013]. The realism of the demand scenarios can be argued, however it will always be uncertain because they forecast demands for more than 20 years ahead. These demand scenarios are therefore considered as an input, which can be updated when new information is available and the change in the expected number of vehicles can be calculated. The uncertainty in demand scenarios does not influence the reliability of the model it self presented in this research. These demand scenarios are used to determine the vehicle requirements of the ITT system, where the system has to be able to minimize the costs for the delay of containers as well as minimizing the costs for vehicle investments. The model is able to balance these conflicting requirements to an overall minimum cost for the ITT system.

Before the model can present reliable results for the case at the Maasvlakte several important parameters are determined. It is shown that for this specific case the ideal time step is 3 minutes. Because the discrete model requires integer transverse times of the arcs in the model the ideal time step is depending strongly on the real transverse times of the arcs and the extent to which they are rounded for a specific time step. The same experiment also showed that the results of integer and continues variables have the same value and therefore for vehicle types with small loading capacities continues solutions are allowed. This significantly reduces the calculation time which is favourable when the reliability of the results does not decrease disproportionately.

The performance of the system is depending on the time horizon for both fluctuating and constant demands. For all three demand scenarios it is shown that the ideal time horizon is 18 hours. It is however also shown that for fluctuating demands it is important that the model has enough time to evenly distribute the peak demand over the time horizon. Therefore the time horizon in which the containers are generated by the demand generator is also important. It is shown that for the demand generator a time horizon of 2/3 rd of the model time horizon is ideal.

When the demand for ITT transport raises in the future it can be expected that congestion might occur. With deterministic modelling it is possible to incorporate congestion in the analysis by constraining the throughput through an arc with a certain capacity. It is shown that the model is able to find a limit caused by congestion, however this limit is reached very instantaneously so that for cases nearing the capacity limit the reliability of the model can be questioned. In order to improve the congestion behaviour fan arcs are incorporated in the intersections. This slightly improved the congestion behaviour, but the model is still able to plan the movements in such a way the required number of vehicles is hardly effected. This would probably mean that in cases when congestion should become a problem the model will present results that are too low. However the demand scenarios analysed in this report are in no danger of congestion which means that it will not influence the results negatively.

Since all parameters have been determined the required number of vehicles are determined resulting in the requirement shown in Figure 8.1.

	Scenario 1	Scenario 2	Scenario 3
	nr vehicles	nr vehicles	nr vehicles
ALV	51	33	24
AGV	65	42	32
MTS	16 Truck +76 Trailers	12 Trucks + 59 Trailers	9 Trucks + 42 Trailers
barge	41 Truck + 2 Barges	22 Trucks + 3 barges	17 Trucks + 2 barges

Figure 8.1: Required vehicles for the various scenarios.

With the use of a multi criteria analysis it is shown that the best vehicle configuration for an ITT system at the Maasvlakte are AGVs. At this moment AGVs have a slight advantage over ALVs due to the uncertainties of the ALVs. This can change once ALVs are fully operational in the new terminals at the Maasvlakte and work according to the expectations. The decoupling of the handling for ALVs is considered as less important for an ITT system, because most of the time the vehicles are driving. This makes the main advantage of the ALV to be insignificant. The other vehicle types are considered to be inferior to the automated vehicle types.

One of the assumption that is made in the report is that the speed of AGVs and ALVs in the future can be increased to an average of 40 km/h, due to both changes in the work environment of the vehicle as well as improvement of technology. However if one would assume that this increase could not be realised the required number of vehicles would increase significantly. It is shown that when the average speed of the vehicles remains 18 km/h as is current practise nowadays the vehicle requirements almost double for all 3 scenarios. This means that investing in the development of automated vehicles should be seriously considered if the choice is made for this type of vehicles. Faster vehicles both reduce the number of vehicles needed as well as reducing the chances on congestion within the system.

When we consider the reliability of the model it can be concluded that all possible interactions between vehicles and processes such as the handling of containers have been modelled. The model has been verified by solving a small problem such that the model behaviour could be analysed by the researcher. This verification showed that the model was acting as expected and did not show strange behaviours. Also the outcomes for a full scale analysis showed reasonable results when compared with the outcomes of Jansen [2013] for AGVs and therefore the results are considered reliable for uncongested systems and single load vehicles. It is also expected that the results are reliable for MTSs and barges under the assumption that enough containers are available at a single terminal to load a MTS or barge without waiting for containers. However the fact that the results for AGVs are close to the results of Jansen [2013] does confirm that the model on itself can provide reliable results. Unfortunately because there is no existing ITT system anywhere in the world the model cannot be validated using data from such systems. To get a better understanding about how the model is able to determine reliable results, this research should be compared with the work of Schröer [2013] who is also a member of the ITT project group set up in cooperation with the Erasmus University and the Port of Rotterdam Authorities. At this moment his results are not available yet.

There is one important thing to notice and that is that this type of modelling will always find the optimal route through the network and that all origins and destinations are known in advance. When the system in the real situation has a far from optimal routing planner the implemented system will also work far from optimal resulting in a higher vehicle requirement than calculated. Therefore it is important to keep in mind that the eventual implementation requires the same level of planning as the model to be able to use the model as a useful early design tool.

8.1 Future research

This research provides a basis for the deterministic modelling of ITT systems such as the ITT system in the Port of Rotterdam. However future research is required to deepen out and investigate more properties and behaviours of the presented model. The following points are recommended to investigate further:

- The most important recommendation is to validate the model. Unfortunately no ITT systems are installed in the world, but validation could also be done to other systems related to the ITT system used in this research. One could think about other AGV systems in ports or factories, but maybe completely different systems are also suited for validation as long as it has the same properties as the ITT system.
- The assumption that enough containers are available for multiload vehicles so that they do not have to wait for available containers should be validated. For this research this was not possible due to the high hardware requirements and that the available time slots for computing were too short to get a result.
- For a future implementation of an ITT system it is important that the vehicle routing is optimized such that the results are comparable with the results provided by the model presented in this research. Therefore it is interesting to investigate the possibilities of integrating deterministic linear programming tools into the dispatching rules of simulation models and eventually in the planning algorithms of the ITT system. In this way the ITT resources can be optimally used.
- It is important to investigate the behaviour of the model for cases where congestion occurs. In the writers opinion the model underestimates the required number of vehicles in these cases because the average delivery times shows a flat behaviour which should increase more once approaching the total capacity of the system. Because the in the case investigated in this research did not come close to the demand capacity, congestion behaviour is not investigated thoroughly.
- It could not be pressed more to invest in increasing the speed of automated vehicles applied in ITT systems. The large effects of higher speeds have been shown in this research and therefore it is important to invest effort and money into the development of fast automated systems.
- If the port authority wants to consider barges as a serious option for ITT transport it should be investigated what the cost difference will become between barges and road transport vehicles. This difference will in the end determine whether or not it is worth it to design an ITT system in which the terminals and service providers with a water connection are served by barges. The fact that not every terminal or service provider is connected by water results that a road ITT system is still required to transport the demand from and to those terminals. Also practical issues such as sufficient queue and handling capacity for barges at the existing terminals create issues that have to be solved before ITT by barge becomes a serious option.
- In this research interactions with other neighbouring systems have been neglected. In future research interferences by i.e. railway crossings or public road crossings could be investigated. Both the way of implementation in the model as well as the effects on the required number of vehicles in the system are interesting aspects which are important for future implementations.

- Model size is an important factor in the required calculation time for the algorithm. By implementing sparse matrices and eliminating the variables not required for a certain situation the size and memory issues are reduced in this research. However in this research improvements in the algorithm, heuristic or the way how the constraints are fed into the algorithm are not considered. It is interesting to investigate the possibilities in reducing the calculation times by paying attention to this side of the model.

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Appendix A

Scientific research paper

Determining Inter Terminal Transport Configurations at the Maasvlakte by Integer Programming.

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***Abstract*—A dedicated Inter Terminal Transport (ITT) system is able to efficiently transport containers inside the port area over a separate road preventing congestion on the ports entry roads. This will increase the competitiveness of the port because container flows can be bundled before they are heading into the hinterland which reduces the total transportation cost. In this paper a deterministic minimum cost flow model with time expanded graphs is presented able to quickly calculate the optimal vehicle configuration saving time and money in the early phases of decision making processes. The model is applied on three different demand scenarios at the Maasvlakte area in the Port of Rotterdam resulting in an optimal vehicle configuration. It is shown that**

***Index Terms*—Inter Terminal Transport, ITT, Linear Programming, Maasvlakte, Minimum Cost Flow, Port of Rotterdam.**

I. Introduction

The large growth in containerized trade in the last decades set pressure on the current operating terminals in most ports around the world. In the Port of Rotterdam, the largest port of Europe, expansion became inevitable. The expansion project "Maasvlakte 2" made room for 5 new container terminals increasing the estimated annual container throughput in 2030 to 30 million TEU. This large flow of containers all have to leave the port to be transported all around Europe. To deal with this large flow and prevent congestion in and around the port, hinterland transport by barge and rail is promoted. To attract more containers via these modalities container flows are bundled to reduce the cost per container and make the hinterland transport more efficient. This bundling however will lead to extra movements around the port and for an efficient and congestion free connection an Inter Terminal Transport (ITT) system has been proposed by the Port of Rottedam Authority. In this system vehicles transport containers around the port over a dedicated road closed for all other traffic.

To investigate the requirements of such a system the Port of Rotterdam Authority together with the Delft University of Technology and the Erasmus University Rotterdam set up a research group investigating several aspects of the ITT system. The research presented in this paper investigates a new and fast way of determining the optimal fleet size using a model based on linear programming. The benefit of this modelling technique versus the conventional simulation techniques is that it can be built relatively fast resulting in tool which costs less money and is able to present results faster than conventional methods. This enables companies and agencies to use this model as a tool for decision making processes which provides insight in the costs and benefits of the considered system. The main research question however is: Could a reliable tool be constructed, able to determine an optimal vehicle configuration to provide a yet to be determined performance level for an ITT system?

To answer this question the paper is structured such that first a literature overview is presented followed by the demand scenarios and the layout of the ITT system. Then the structure of the model is presented which will determine the optimal vehicle configurations presented in the next section. Finally the conclusions about the model and results are given as well as the directions on future work.

II. Literature Review

In literature four different modelling techniques can be identified, which are able to determine the optimal vehicle configuration of a system [1]. These approaches can be categorized as:

- Simulation techniques
- Calculus techniques
- Stochastic techniques
- Deterministic techniques

Each of them have their advantages and disadvantages which are shown in Table I. This table also shows relevant literature describing the assigned approach. The approach used in this research is a deterministic minimum cost network flow model with a time-space expanded graph based on the paper presented in [14]. This technique suits the goal of this research perfectly, because a tool for decision making processes often has to be available on short notice giving a useful result on in this case the best vehicle configuration. The minimum cost flow technique enables the solution to be optimized giving an approximation on the number of required vehicles for an ITT system. Although this approach is deterministic, the time expansion allows the modelling of full trips, empty trips, idling times, handling times and congestion. This congestion includes congestion on roads as well as waiting times for loading and unloading at the terminal. The only stochastic process which can not be modelled realistically is the handling process of containers at the terminal. However the variance in handling time is very small in comparison to the total transport time of a container this effect will only have a limited effect on the required number of AGVs. Compared to other deterministic techniques the time-space expanded graph will provide the possibility for extensive analysing options, which can not be realized when choosing for an other strategy.

III. ITT SYSTEM AND DEMANDS

The Maasvlakte area in the Port of Rotterdam consist out of several deep sea, barge and rail terminals as well as service providers such as customs and empty depots which will be connected by a dedicated ITT road. The layout of this road and the terminals considered in this research are shown in Fig. 1.

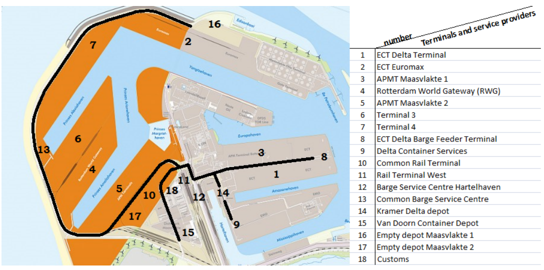


Fig. 1: ITT road layout at the Maasvlakte area with the considered terminals in the model.

A. Scenarios

Between the various terminals flows of containers are generated by a demand generator which is given in [6]. This demand generator can create demands according to three different scenarios as presented in Table II. The demand scenarios differ in total annual TEU throughput and peak factors. Also the terminals where the ITT is performed internally differ between the scenarios. In scenario 3 a major assumption is that the common barge and rail terminal (nr. 10 and 13) are not constructed.

TABLE II: Properties of the 3 different scenarios.

	Annual demand (TEU)	Peak factor	Internal connection
Scenario 1	3.34 million	High	2-7,2-17,4-6,5-10-17,6-13
Scenario 2	2.15 million	Medium	Scenario 1 + 1-3-8-9-12-14
Scenario 3	1.42 million	No	Scenario 2

The demand generator uses these properties and creates a set of single containers with a release time in the system r, a deliverytime u, an origin o, a destination d and the size of the container in TEU. The set created by the demand generator serves as an input for the model.

The model can make use of the internal connections by clustering the single terminals into one terminal when an internal connection exists. This will lower the calculation time and reduces the required memory to store the constraints of the model. The resulting network of the Maasvlakte for scenario 1 and 3 are shown in Fig. 2. The network for scenario 2 is the same as for scenario 3 except that the common barge and rail terminal are added. The validity of this clustering is shown in Section V-A.

B. Vehicle types

Several vehicles types are considered by the port authorities: Multi trailer systems (MTSs), Automated Guided Vehicles (AGVs), Automated Lift Vehicles (ALVs) and Barges. The barge is handled as a special case and is called an LT vehicle, which will be explained in Section IV. All these vehicles types have their own specifications required by the model as input and are shown in Table III.

IV. PROPOSED MODEL

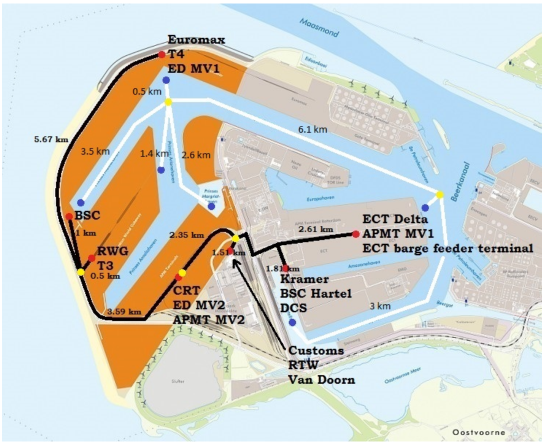
The model investigated in this research is based on the model presented in [14]. It is build from a base network of arcs and nodes, where a node i represent a location in the network and and arc (i, j) represent the connection between two nodes. The network $N = (V, A)$ is a graph used to model the layout of the Maasvlakte area and is copied τ times to create a time expansion. Every copy creates a time step and all time steps combined create the time horizon. The time expanded network $Aeq^T = (V^T, A^T)$ is a graph used by the model to create a realistic flow through port area. Between the time steps stationary arcs are constructed, which connect node i between two time steps with each other, meaning that a

Approach	Advantages	Disadvantages	Literature
Simulation	- Most realistic approach - Validation	- Takes a lot of time to build - No optimizing character	[3], [12]
Calculus	- Fast hand calculation - Can present a lower and upper bound	- Unreliable results	[4], [8], [11]
Deterministic modelling	- Optimizing character - Reasonably fast calculation times and programming - Can incorporate details deterministically - Easily adaptable	- No stochastic processes - Time discretization	[5], [14], [16]
Stochastic modelling	- Stochastic processes can be incorporated	- large models require excessive calculation times - No optimizing character	[1], [7], [9]

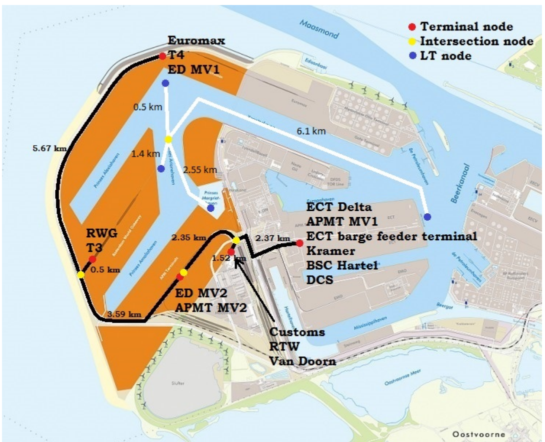
TABLE I: The advantages and disadvantages of several modelling approaches.

	AGV	ALV	MTS	Barge
Carrying capacity (TEU)	2	2	10	50
Speed (km/h)	40	40	30	12
Length (m)	15	13.7	82.5	n.a.
Handling time (s/FEU/cr)	180	30	180	180 + 30 min. mooring
Number of cranes per terminal				2
Average TEU per day sc1,2,3				10.001, 6549, 4468
Purchase costs (Euro's)[1]	340.000	500.000	250.000/Truck, 40.000/trailer	2.500.000

TABLE III: Overview of several vehicle properties.



(a) Network scenario 1.



(b) Network scenario 3.

Fig. 2: Overview of the terminal, intersection and LT nodes on the Maasvlakte for scenario 1 and 3.

flow over this arc remains in one position through time. The arc connecting two different locations with each other has a transverse time tt and is connected from node i in the time step τ to node j in time step $\tau + tt$. A representation of a two node network is presented in Fig. 3.

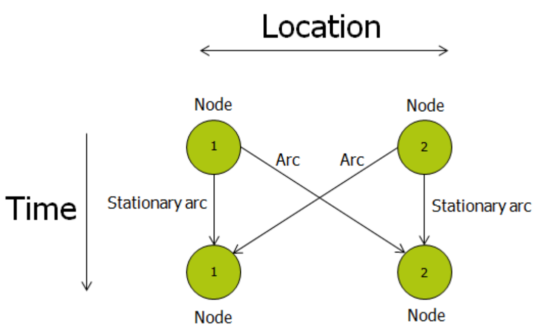


Fig. 3: Representation of a time space network containing two base nodes and one time steps.

When vehicles which require different properties, interactions or layout than regular road vehicles, such as barges or trains, are implemented the network is extended with a separate LT network containing its own LT arcs and LT nodes. Both networks are connected to each other by incorporating the same terminal nodes, making it possible for both all the vehicles to work parallel to each other.

To enable multiple flows of containers heading to and from various directions simultaneously in the network multi-commodity flows are introduced [15]. This theory copies the network Θ times for each group of containers creating a set of decision variables $y_{(i,j,\theta)}$ representing the flow of containers over arc (i,j) for each commodity of containers and one copy of the network creates a set of variables $x_{(i,j,h)}$ for each vehicle type h representing the flow of vehicles over arc (i,j). The last set of decision variables is collected in set s_{ih} which represent the number of vehicles of type h present in node i at the first time step.

A. Intersections and congestion

In the model an intersection is not only used as a crossroad, but also as the location where congestion will occur. Let all intersection nodes be collected in set V^{int}. Congestion is modelled at an intersection by allowing a maximum capacity ϕ to flow over the outgoing non-stationary arcs of the intersection node $[j|(i,j) \in A^T\ A^S, i \in V^{int}]$. The capacity is set to 8 vehicles per minute for all road vehicles exept MTSs which have a capacity of 3 vehicles because the length of this vehicle type. In the calculation of the intersection capacity it is assumed that only one vehicle can be present on an intersection at a time, an acceleration of 1 $m/s^2$and have a maximum corner speed which is $1/2 \cdot v_{avg}$.

B. Demand

The containers from the demand generator have to be preprocessed before they can be implemented in the constraints of the model. The input values coming from the demand generator are collected into commodities per destination terminal per hour according to the delivery time. The time over which containers are generated is 2/3rd of the time horizon in order to allow enough time to complete all the demands. To create a constant demand which equals the average demand over the time horizon each container is multiplied by a factor α such that the total amount of containers is constant. For each commodity also a demand vector b_θ is created, which contains the information about the amount of containers heading to the destination terminal with the corresponding origin terminal, release time and amount of TEU.

C. Objective function

The goal of the model is to determine the optimal vehicle configuration. To do this a trade of is made between the added cost of adding an additional vehicle and the cost of delays in the system. This results in the objective to minimize the cost of delay c_d plus the cost of the required number of vehicles per vehicle type c_{vh}. The delay costs are estimated at 6 Euro's per hour [10] and the costs per vehicle are presented in Table III, which will be deducted to the cost over the time horizon.

D. Parameters

The following parameters are used to construct the various constraints.

TABLE IV: List of parameters.

V^T	Set of time space nodes.
A^T	Set of time space arcs.
A^S	Set of stationary arcs.
Aeq^τ	Matrix representing the time space network of arcs and nodes.
b	Demand vector.
V^{tster}	Set of terminal nodes $i \in V^T$.
V^{int}	Set of intersection nodes $i \in V^T$
$\delta_{ij\theta}$	indicate whether arc (i,j) is a stationary arc.
ϕ_{ij}	Capacity of intersection node i_{int}.
Θ	Number of demands.
o_θ	Origin node $\in V^T$ of demand θ.
d_θ	Destination node $\in V^T$ of demand θ.
r_θ	Release time period of demand θ.
u_θ	Delivery time period of demand θ.
H	Set containing all vehicle types.
h	Vehicle type.
c_h	Carrying capacity in TEU per vehicle for vehicle type h.
s_{ih}	Amount of vehicles of type h present at node $i \in V$ in time step $t = min(r_\theta)$.
m_{ih}	Handling capacity at terminal $i \in V^T$ for vehicle type h.
$m_{ih,max}$	Handling capacity per available vehicle at terminal $i \in V^T$ for vehicle type h.
η	The punctuality demanded from the ITT system.
x_{ijh}	The flow of vehicles on arc(i,j) of vehicle type h.
$y_{ij\theta}$	The flow of containers on arc(i,j) for demand θ.
$In(i)$	A set of all arcs entering node $i \in V^T$.
$Out(i)$	A set of all arcs leaving node $i \in V^T$.
V^T_{ih}	A set of non-stationary arcs connected to node $i \in V^T$ of vehicle type h.

E. Objective and constraints

$$min \left(\sum_{i \in V^{tster}} \sum_{h \in H} c_{v,h} s_{ih} + \sum_{1 \le \theta \le \Theta} \sum_{u_\theta \le t \le \tau} \sum_{(i,j) \in A^S} c_d y_{ij\theta} \right. \tag{1}$$

subject to

$$Aeq^\tau y_{ij\theta} = \bar{b} \quad \forall (i,j) \in A^T, \quad 1 \le \theta \le \Theta \tag{2}$$

$$\sum_{i \in Out(i)} x_{ijh} = s_{ih} \quad \forall i \in V, h \in H \tag{3}$$

$$\sum_{i \in Out(i)} x_{ijh} = \sum_{i \in In(i)} x_{ijh} \quad \forall i \in V^T \backslash V, h \in H \tag{4}$$

$$\sum_{1 \le \theta \le \Theta} \delta_{ij\theta} (y_{ij\theta} \le c_h x_{ijh}) \quad \forall (i,j) \in A^T \tag{5}$$

$$\sum_{1\le\theta\le\Theta} y_{ij\theta} \le m_{ih} \quad \forall i \in V_{ih}^T \cap V^{tster}, h \in H \tag{6}$$

$$\sum_{1\le\theta\le\Theta} y_{ij\theta} \le m_{ih}^{max} x_{ijh} \qquad \forall i \in V_{ih}^T \cap V^{tster}, h \in H \tag{7}$$

$$\sum_{j\in V_{ih}^T} x_{ijh} \le \phi \quad \forall i \in V^{int}, h \in H \tag{8}$$

$$\sum_{1\le\theta\le\Theta} Out(i) y_{ij\theta} \le \sum_{h\in H} Out(i) x_{ijh} \qquad \forall i \in V^{int}, (i,j) \in A^S \tag{9}$$

$$\sum_{1\le\theta\le\Theta} y_{ijt} \le 1-\eta \quad \forall (i,j) \in A^S, t = u_\theta + 1 \tag{10}$$

Equation 2 constraints the demand collected in vector b to flow through the network. Equation 3 creates the required number of vehicles in the system in the first time step by acting as a source which can create as many vehicles as required, however every vehicle will come at a cost as will be considered by the objective function. The number of vehicles for the intersection nodes is to zero. Equation 4 ensures that the flow of vehicles entering a node equal the flow of vehicles leaving a node. Vehicles are connected to the containers by Equation 5 which only allows a container flow over a non-stationary arc when a vehicle is present. Equation 6 constraints the number of TEU handled per time step in a terminal for both road vehicle and LT vehicle types. As a second handling constraint for vehicles with a carrying capacity of more than 2 TEU, Equation 8 constrains the handling to a maximum amount of moves per vehicle present at the terminal. The intersection capacity is applied to the outgoing non-stationary arcs of the intersection in Equation 9, while Equation 10 constraints the number of containers flowing over an intersection stationary arc to be at most the number of vehicles flowing over the same stationary arc, to prevent the storage of containers at an intersection. Equation 11 ensures that a certain punctuality η is reached in container delivery.

Several improvements are made to reduce the calculation time. The non-stationary arcs leaving the destination node of demand θ are set to 0. Secondly all arcs before the release time of demand θ are set to 0 and in the case of AGVs and ALVs the arcs entering the origin nodes of the commodity are also set to 0. The final group of variables that are set to 0 can be set when a punctuality of 1 is required. All variables representing container arcs after the delivery time of a commodity are set to 0, because delays are not allowed and therefore arcs after the delivery time are not used. The relative high sparsity of the matrices used to represent the constraints is used to reduce the memory requirements by providing a sparse matrix as input to the algorithm.

V. CASE: ITT AT THE MAASVLAKTE

The model is evaluated by investigating the vehicle configurations for an ITT system at the Maasvlakte. The results computed in this section are received using a quad core Intel Core I7 - 2670QM processor with eight 2.2 GHz threads and at least 3 GB of usable RAM memory.

A. Terminal network

The network used in this case merged the various terminals at the Maasvlakte as shown in Section III. The reliability of this merge is shown in Fig. 4, where the total time required for the delivery of all containers in the clustered network is compared with the total delivery time of the network containing single terminals and with the total delivery time in the situation where the pure distance is taken. This latter is the most reliable case because the rounding error in the transverse times of the arcs is small. The results show that, the relative difference between the total transportation time compared with the real transportation time of the clustered network is slightly better than that of the individual network. Therefore the clustered network is used, because the calculation time of the clustered network is considerably lower while it does not reduce the reliability of the model. It is also assumed that clustering terminals is valid for vehicle types with a multiple load capacity, because it is assumed that in the real implementation blocks of containers will become available for ITT transport instead of single containers and for high demand scenarios enough containers will become available to fully fill up the load capacity.

step = 3						
ALV	realdtime		cluster	%	full	%
sc3	5647.8		6707	119	7329	130
sc2	8271.45		9998.6	121	11091	134
sc1	11816		14670	124	15847	134
AGV	realdtime		cluster	%	full	%
sc3	8130		8820.3	108	8988.3	111
sc2	11910		12598	106	13191	111
sc1	17372		18573	107	19233	111

Fig. 4: Reliability of cluster and individual terminals network versus pure transportation times.

B. Time step and time horizon

Before the final results can be determined the ideal time step and time horizon are investigated. The ideal time step is depending mostly on the processes and distances of the various arcs. Because of the deterministic nature all arc transverse times have to be rounded off to the nearest integer value creating large deviations with reality for larger time steps. This explains the high results shown in Fig. 5 for the larger time steps. It can be seen that for a time step of 3 minutes an optimum is reached between the calculation time and the required number of vehicles. Increasing the time step will increase the number of vehicles while the decrease in calculation time is small. However decreasing the time step will hardly reduce the required number of vehicles while significantly increasing the calculation time. Also a comparison is made between integer solutions and continues solutions of the model for the ALVs. Fig. 5 shows that the required number of vehicles are the same, but the calculation time of the integer solution is much longer. Therefore the continues solution is used to determine the results presented in this research.

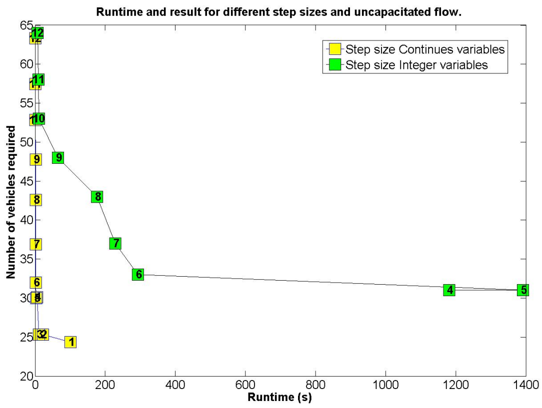


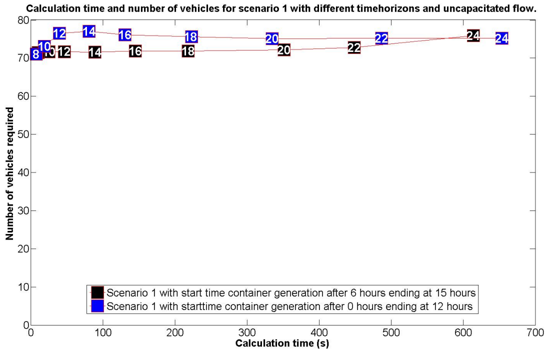
Fig. 5: Required number of vehicles versus runtime for various timesteps.

The time horizon is determined by comparing the results for various time horizons for scenario 1 and 3 as is shown in Fig. 6

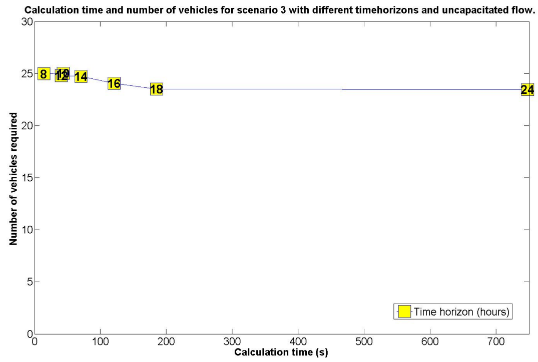
It can be seen that a time horizon of 18 hours is ideal for both fluctuating demands as well as constant demands. This can be explained by the fact that the model requires a certain time to spread out the demand over the time horizon as well as it requires sufficient time to transport all the containers through the network.

C. Congestion

The benefit of constructing a model with time expanded graphs over other deterministic techniques is the implementation of congestion. The effectiveness of modelling congestion in this way is shown in Fig. 7. The model is able to find the



(a) Required number of vehicles for various time horizons for scenario 1.



(b) Required number of vehicles for various time horizons for scenario 3.

Fig. 6: Required number of vehicles versus calculation time for various time horizons.

maximum capacity of the system, up from demands of 22.000 TEU per day, which is far more than the capacity the current system is designed for. Therefore it can be concluded that congestion will not be an issue in this case.

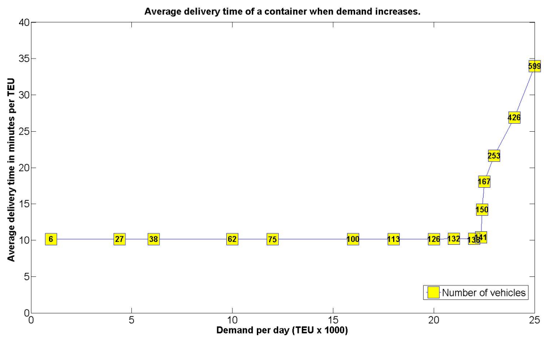


Fig. 7: Average delivery time in minutes per TEU versus the number of vehicles.

D. Results

The results for the various scenarios and vehicle types are shown in Fig. 8. The handling rates at terminals are set to infinity, because it is assumed that the capacity is designed in such a way that it should not form a bottleneck. To provide designers an idea about the handling demand per terminal the average number of containers handled per terminal per hour is given. The handling of barges is however restricted to 1 crane per barge with a maximum of 2 cranes per terminal.

						Average handling demand (TEU/hour)						
Scenario 1	TEU/day	nr vehicles	timehorizon	stepsize	punctuality	t1	t2	t3	t4	t5	t6	t7
ALV	10001	51	18	3	0.9941	117	80	144	196	98	46	154
AGV	10001	65	18	3	0.9974	118	80	144	196	98	46	154
MTS	10001	16 Truck +76 Trailers	18	3	1	120	85	141	204	102	54	153
barge	10001	41 Truck + 2 Barges	8	3	0.9876	111	83	143	153	98	50	90

						Average handling demand (TEU/hour)					
Scenario 2	TEU/day	nr vehicles	timehorizon	stepsize	punctuality	t1	t2	t3	t4	t5	t6
ALV	6549	33	18	3	0.9924	121	92	132	61	33	106
AGV	6549	42	18	3	0.9929	121	92	132	61	33	106
MTS	6549	12 Trucks + 59 Trailers	18	3	1	133	100	146	70	33	118
barge	6549	22 Trucks + 3 barges	8	3	1	103	89	96	51	28	49

						Average handling demand (TEU/hour)				
Scenario 3	TEU/day	nr vehicles	timehorizon	stepsize	punctuality	t1	t2	t3	t4	t5
ALV	4468	24	18	3	0.99	92	104	70	40	68
AGV	4468	32	18	3	0.99	92	104	70	40	68
MTS	4468	9 Trucks + 42 Trailers	8	3	1.00	93	103	70	37	70
barge	4468	17 Trucks + 2 barges	8	3	0.99	73	103	59	40	32

Fig. 8: Results of scenario 1,2 and 3 for various vehicle types with default parameter values.

The results shown in Fig. 8 are reasonable and provide a good starting point to prove the reliability of the model. Unfortunately no ITT system in the world exist and therefore a real validation cannot take place. To validate the model the results are compared with the results from other projects within the ITT research group. The only available result at this moment is presented in [6] and in Table V the results of his research are shown and compared with the results of the model presented in this paper. It should be noted that his results are determined only for AGVs with a handling time of 120 seconds.

TABLE V: Comparison of the AGV requirements between the results of Jansen and this research. Determined with a handling time of 120 seconds.

	nr. AGVs Nieuwkoop	nr. AGVs Jansen
Scenario 1	57	70
Scenario 2	40	41
Scenario 3	29	27

The results in Table V show that the model presented in this research determined lower vehicle requirements than the model presented in [6] for scenario 1. This can be explained because the model by [6] does not have an optimization algorithm which will increase the vehicle requirements. His model also did not investigate the best method for modelling ITT because the focus of his research was on investigating various coalitions. Therefore his dispatching strategy will probably perform worse than the best dispatching strategies used in the industry nowadays especially for higher demand scenarios. In case of scenario 3 the vehicle requirements determined by the model presented in this report are higher. This can be explained because the for low demand scenarios the rounding errors of the transverse times of arcs will have a bigger effect on the results than a sub optimal dispatching rule.

E. *Effect of speed*

The vehicle speeds assumed in this research are higher than the speeds of similar vehicles in use at terminals nowadays. In this research it is expected that because of the changed working environment with long straight road and the improvements in technology of the past two decades and in the near future these speeds can be achieved. However to create an understanding in the importance of speed the speed of AGVs and ALVs have been reduced to 18 km/h to investigate the effect. The results are shown in Fig. 9 and from the results it can be concluded that speed has a large effect on the vehicle requirements.

Scenario 3			Scenario 2			Scenario 1		
v (km/h)	nr. ALV	nr. AGV	v (km/h)	nr. ALV	nr. AGV	v (km/h)	nr. ALV	nr. AGV
40	24	32	40	33	42	40	51	65
18	51	62	18	61	76	18	93	118

Fig. 9: The effect of reducing the speed to that of current operating automated vehicles on the required number of vehicles in an ITT system.

VI. CONCLUSION AND FUTURE WORK

With the expansion of the Maasvlakte area ITT transport is required to guarantee efficient port logistics. This paper proposed a deterministic minimum cost flow with time expanded graphs to determine the vehicle requirements for an ITT system. This model is easily build within a short amount of time making it ideal for the port authority to use it in their decision making process about the future of the port.

Various model parameters have been determined in order to realize a realistic result such as time step and time horizon. It is also shown that congestion is not creating any problems for the current scenarios. However when vehicles with conventional speeds are used the required number of vehicles is significantly increased up to a point that congestion might become an issue. Therefore it is advised to implement vehicles with higher maximum speeds in the real ITT system to reduce the investment costs and prevent congestion problems.

When the reliability of the model is considered it can be concluded that all possible interactions between vehicles and processes such as the handling of containers have been modelled. The model has been verified by solving a small problem such that the model behaviour could be analysed by the researcher and did not show strange behaviours. Because there is no existing ITT system anywhere in the world the model cannot be validated using data from such systems. The results of AGVs are compared with the results presented in [6] and showed comparable values from which we can conclude that that the model is able to determine reliable results. Also the outcomes for other vehicle types show reasonable results and therefore it is expected that the model is considered reliable for uncongested systems and single load vehicles. It is also expected that the results are reliable for MTSs and barges under the assumption that enough containers are available at a single terminal to load a MTS or barge without waiting for containers.

For future research it is recommended to compare this research with the results from [13] who developes a simulation tool able to analyse the vehicle requirements determined in this paper. Also systems related to ITT could be used to validate the results of this model such as internal transport systems in terminals or factories. It is important to realise that the optimizing character of the model presents the optimal vehicle requirement and therefore the results might deviate from the real situation when the planning algorithm is not as smart as the model. This asks for a planning algorithm which incorporates optimization in its planning.

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Appendix B

Demand scenario 1

Participant	ECT Delta Terminal	Euromax Terminal	APM MV1 Terminal	Rotterdam World Gateway	APM MV2 Terminal	T3	T4	ECT Delta barge Feeder terminal	Delta Container Services	Common Rail Terminal	Rail Terminal West	Rotterdam Container Terminal Hartelhaven	Common Barge Service Center	Kramer Delta depot	Van Doorn Container depot	Empty depot MV1	Empty depot MV2	Customs
ECT Delta Terminal	x	3905	2580	3096	3572	3096	2560	397	119	66687	62559	47754	39795	7107	9645	12183	25787	9662
Euromax Terminal	3696	x	1907	2288	2640	2288	0	293	88	52080	48855	37294	31078	5550	7532	0	20138	7546
APM MV1 Terminal	2293	1790	x	1419	1638	1419	1174	182	55	34402	32272	24635	20529	3666	4975	6285	13303	4984
Rotterdam World Gateway	2818	2201	1454	x	2013	0	1443	224	67	41283	38727	29562	24635	4399	5970	7542	15963	5981
APM MV2 Terminal	3326	2598	1716	2059	x	2059	1703	264	79	0	44685	34110	28425	5076	6889	8702	0	6902
T3	2818	2201	1454	0	2013	x	1443	224	67	41283	38727	29562	0	4399	5970	7542	15963	5981
T4	2273	0	1173	1407	1623	1407	x	180	54	34138	32024	24446	20371	3638	4937	6236	13200	4946
ECT Delta barge Feeder terminal	321	250	165	198	229	198	164	x	8	5293	4965	3790	3158	564	765	967	2047	767
Delta Container Services	95	74	49	59	68	59	49	8	x	1588	1489	1137	948	169	230	290	614	230
Common Rail Terminal	100031	78120	51603	61924	0	61924	51206	7939	2382	x	0	0	0	8026	10893	13759	0	0
Rail Terminal West	93838	73283	48408	58090	67027	58090	48036	7447	2234	0	x	0	0	7529	10218	12907	27321	0
Rotterdam Container Terminal	31836	24862	16423	19708	22740	19708	16297	2527	758	0	0	x	0	10370	14074	17778	37630	0
Common Barge Service Center	26530	20719	13686	16423	18950	0	13581	2106	632	0	0	0	x	8642	11728	14815	31358	0
Kramer Delta depot	13198	10307	6808	8170	9427	8170	6756	1047	314	4322	4054	5584	4653	x	0	0	0	0
Van Doorn Container depot	17911	13988	9240	11088	12794	11088	9169	1422	426	5865	5502	7578	6315	0	x	0	0	0
Empty depot MV1	22625	0	11672	14006	16161	14006	11582	1796	539	7409	6950	9573	7977	0	0	x	0	0
Empty depot MV2	47889	37399	24705	29646	0	29646	24515	3801	1140	0	14711	20262	16885	0	0	0	x	0
Customs	9662	7546	4984	5981	6902	5981	4946	767	230	0	0	0	0	0	0	0	0	x

Appendix C

Demand scenario 2

Participant	ECT Delta Terminal	Euromax Terminal	APM MV1 Terminal	Rotterdam World Gateway	APM MV2 Terminal	T3	T4	ECT Delta barge Feeder terminal	Delta Container Services	Common Rail Terminal	Rail Terminal West	Rotterdam Container Terminal Hartelhaven	Common Barge Service Center	Kramer Delta depot	Van Doorn Container depot	Empty depot MV1	Empty depot MV2	Customs
ECT Delta Terminal	x	4239	0	2688	3102	2688	2223	0	0	57907	53453	0	26855	0	7925	10011	21189	4575
Euromax Terminal	3981	x	2053	1971	2275	1971	0	316	95	45223	41744	25633	20972	4560	6189	0	16548	3573
APM MV1 Terminal	0	1912	x	1213	1399	1213	1003	0	0	29873	27575	0	13854	0	4088	5164	10931	2360
Rotterdam World Gateway	2338	1826	1206	x	1336	0	958	186	56	28678	26472	16255	13300	2892	3925	4958	10494	2266
APM MV2 Terminal	2752	2149	1420	1363	x	1363	1127	218	66	0	30544	18756	15346	3337	4529	5720	0	2614
T3	2338	1826	1206	0	1336	x	958	186	56	28678	26472	16255	0	2892	3925	4958	10494	2266
T4	1892	0	976	937	1081	937	x	150	45	23714	21890	13442	10998	2391	3246	4100	8678	1874
ECT Delta barge Feeder terminal	0	264	0	168	193	168	139	x	0	4596	4242	0	2131	0	629	794	1682	363
Delta Container Services	0	78	0	50	57	50	41	0	x	1379	1273	781	639	139	189	238	505	109
Common Rail Terminal	70775	55272	36511	35051	0	35051	28984	5617	1685	x	0	0	0	5973	8107	10240	0	0
Rail Terminal West	65331	51020	33703	32354	37332	32354	26755	5185	1556	0	x	0	0	5514	7483	9452	20008	0
Rotterdam Container Terminal	0	20972	0	13300	15346	13300	10998	0	639	0	0	x	0	0	10480	13238	28020	0
Common Barge Service Center	21972	17159	11335	10881	12556	0	8998	1744	523	0	0	0	x	6318	8574	10831	22925	0
Kramer Delta depot	0	6841	0	4338	5005	4338	3587	0	209	3982	3676	0	4212	x	0	0	0	0
Van Doorn Container depot	11888	9284	6133	5887	6793	5887	4868	943	283	5404	4989	6987	5716	0	x	0	0	0
Empty depot MV1	15016	0	7746	7437	8581	7437	6149	1192	358	6827	6302	8825	7221	0	0	x	0	0
Empty depot MV2	31784	24822	16396	15741	0	15741	13016	2523	757	0	13338	18680	15284	0	0	0	x	0
Customs	4575	3573	2360	2266	2614	2266	1874	363	109	0	0	0	0	0	0	0	0	x

Appendix D

Demand scenario 3

Participant	ECT Delta Terminal	Euromax Terminal	APM MV1 Terminal	Rotterdam World Gateway	APM MV2 Terminal	T3	T4	ECT Delta barge Feeder terminal	Delta Container Services	Common Rail Terminal	Rail Terminal West	Rotterdam Container Terminal Hartelhaven	Common Barge Service Center	Kramer Delta depot	Van Doorn Container depot	Empty depot MV1	Empty depot MV2	Customs
ECT Delta Terminal	x	4239	0	2688	3102	2688	2223	0	0	0	50110	0	0	0	7925	10011	21189	4575
Euromax Terminal	3981	x	2053	1971	2275	1971	0	316	95	0	39133	17374	0	4560	6189	0	16548	3573
APM MV1 Terminal	0	1912	x	1213	1399	1213	1003	0	0	0	25850	0	0	0	4088	5164	10931	2360
Rotterdam World Gateway	2338	1826	1206	x	1336	0	958	186	56	0	24816	11018	0	2892	3925	4958	10494	2266
APM MV2 Terminal	2752	2149	1420	1363	x	1363	1127	218	66	0	28634	12713	0	3337	4529	5720	0	2614
T3	2338	1826	1206	0	1336	x	958	186	56	0	24816	11018	0	2892	3925	4958	10494	2266
T4	1892	0	976	937	1081	937	x	150	45	0	20521	9111	0	2391	3246	4100	8678	1874
ECT Delta barge Feeder terminal	0	264	0	168	193	168	139	x	0	0	3977	0	0	0	629	794	1682	363
Delta Container Services	0	78	0	50	57	50	41	0	x	0	1193	530	0	139	189	238	505	109
Common Rail Terminal	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	0	0	0
Rail Terminal West	61245	47830	31595	30331	34997	30331	25081	4861	1458	0	x	0	0	11487	15590	19692	41682	0
Rotterdam Container Terminal	0	14215	0	9014	10401	9014	7454	0	433	0	0	x	0	0	19054	24069	50945	0
Common Barge Service Center	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0
Kramer Delta depot	0	6841	0	4338	5005	4338	3587	0	209	0	7658	0	0	x	0	0	0	0
Van Doorn Container depot	11888	9284	6133	5887	6793	5887	4868	943	283	0	10393	12703	0	0	x	0	0	0
Empty depot MV1	15016	0	7746	7437	8581	7437	6149	1192	358	0	13128	16046	0	0	0	x	0	0
Empty depot MV2	31784	24822	16396	15741	0	15741	13016	2523	757	0	27788	33963	0	0	0	0	x	0
Customs	4575	3573	2360	2266	2614	2266	1874	363	109	0	0	0	0	0	0	0	0	x

Appendix E

AGV verification results

	1	2	3	4	5	6	7	8	9	10	11	12
C1	3	0	2	3	0	0	5	0	3	3	0	5
C2	0	1	0	0	0	1	0	1	1	1	1	0
V	2	1	1	2	2	1	0	0	0	0	0	0
A^T	1	0	0	0	0	0	1	0	0	0	0	0
	0	1	0	0	0	0	0	1	0	0	0	0
	0	-1	1	0	0	0	-1	0	1	0	0	0
	-1	0	0	0	1	0	0	-1	0	1	0	0
	0	0	0	1	-1	0	0	0	-1	0	1	0
	0	0	-1	0	0	1	0	0	0	-1	0	1
	0	0	0	0	0	-1	0	0	0	0	-1	0
	0	0	0	-1	0	0	0	0	0	0	0	-1

Appendix F

ALV verification results

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
C1	4	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	2	2	0	0	0	0	2	0	0	0	0	0	0	0
V	2	0	0	0	0	0	0	1	1	2	2	0	0	1	0	0	0	0	0	0	0
A^T	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	0	-1	0	0	1	0	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0
	0	0	0	-1	0	0	0	0	1	0	0	0	0	-1	0	0	1	0	0	0	0
	-1	0	-1	0	0	0	1	0	0	0	1	0	0	0	-1	0	0	1	0	0	0
	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	-1	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	-1	0	0	1	0
	0	0	0	0	-1	0	0	1	-1	0	0	1	0	0	0	0	0	-1	0	0	1
	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	-1	0	0
	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	-1	0
	0	0	0	0	0	-1	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	-1

Appendix G

MTS verification results

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
C	0	0	2	0	0	0	0	4	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tr	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tu	0	0	1	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A^T	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	-1	0	-1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0
	0	0	0	0	-1	0	-1	0	0	0	0	1	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0
	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	-1	0	0	0	0	1	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0
	0	0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0
	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	-1	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1
	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1

Appendix H

ALV and barge verification results

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
C	1	0	0	0	1	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	40	0	0	0	0	0	0	0	0	0	40	0	1	0	0	0	0	1	1	0	0	0	1	1	0	0	0	0	1	0	0	0
A^T 1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	-1	1	0	0	0	0	0	0	-1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	-1	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	-1	0	0	0	0	-1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
21	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
22	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0
31	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	0
32	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1
41	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
42	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
V	1	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0
A^T 1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	-1	1	0	0	0	0	0	-1	0	1	0	0	0	0	0
12	-1	0	0	0	0	1	0	0	0	-1	0	1	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	1	0	-1	0	0	0	0	-1	0	1	0	0	0
22	0	0	-1	0	0	0	1	0	0	0	0	-1	0	1	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	1	0	-1	0	0	0	0	0	-1	0	1	0
32	0	0	0	-1	0	0	0	1	0	0	0	0	0	-1	0	1
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	-1	0
42	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	-1
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
B	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0
A^T 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
5	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0
14	0	0	0	-1	0	0	0	0	0	0	1	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0
15	-1	0	-1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	-1	0	0	1	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	-1	0	0	1	0	0	0	0
25	0	0	0	0	-1	0	0	0	1	0	-1	0	0	0	1	0	0	0	0	0	0	-1	0	0	1	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	-1	0	0	1	0
35	0	0	0	0	0	-1	0	0	0	1	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	-1	0	0	1
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	-1	0
45	0	0	0	0	0	0	-1	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1

Appendix I

Origin-Destination matrix

Origin-Destination matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	13.7	0.7	6.4	3.2	6.7	9.8	0.7	2.3	2.6	2.9	1.4	7.3	2.3	3.2	14.1	3.6	2.3
2	13.7	0	13.2	7.3	10.5	7	3.9	14.5	14.5	11.1	13.4	13.2	6.4	13.7	13.3	0.4	10.1	12.4
3	0.7	13.2	0	5.9	2.7	6.2	9.3	1.3	1.7	2.1	2.4	1.7	6.8	1.8	2.4	13.6	3.1	1.4
4	6.4	7.3	5.9	0	3.2	0.3	3.4	7.2	7.2	3.8	6.1	5.9	8.5	6.4	6	7.7	2.8	5.1
5	3.2	10.5	2.7	3.2	0	3.5	6.6	4	4	0.6	2.9	2.7	5.3	3.2	2.8	10.9	0.5	1.9
6	6.7	7	6.2	0.3	3.5	0	3.1	9.6	4.7	4.1	6.4	6.2	8.8	6.7	6.3	7.4	3.1	5.4
7	9.8	3.9	9.3	3.4	6.6	3.1	0	12.9	7.8	7.2	9.5	9.3	2.5	9.8	9.4	4.3	6.2	8.5
8	0.7	14.5	1.3	7.2	4	9.6	12.9	0	3	3.4	3.6	2.1	8.1	2.8	5.5	14.9	4.4	2.7
9	2.3	14.5	1.7	7.2	4	4.7	7.8	3	0	3.4	3.3	1	8.1	0.3	3.9	14.9	4.4	2.5
10	2.6	11.1	2.1	3.8	0.6	4.1	7.2	3.4	3.4	0	2.3	2.1	4.7	2.6	2.2	11.5	1	1.3
11	2.9	13.4	2.4	6.1	2.9	6.4	9.5	3.6	3.3	2.3	0	2.6	7	3.2	0.9	13.8	3.3	0.8
12	1.4	13.2	1.7	5.9	2.7	6.2	9.3	2.1	1	2.1	2.6	0	6.8	0.4	3.1	13.6	3.1	1.8
13	7.3	6.4	6.8	8.5	5.3	8.8	2.5	8.1	8.1	4.7	7	6.8	0	7.3	6.9	6.8	3.7	6
14	2.3	13.7	1.8	6.4	3.2	6.7	9.8	2.8	0.3	2.6	3.2	0.4	7.3	0	3.6	14.1	3.6	2.3
15	3.2	13.3	2.4	6	2.8	6.3	9.4	5.5	3.9	2.2	0.9	3.1	6.9	3.6	0	13.7	3.2	1.8
16	14.1	0.4	13.6	7.7	10.9	7.4	4.3	14.9	14.9	11.5	13.8	13.6	6.8	14.1	13.7	0	10.5	12.8
17	3.6	10.1	3.1	2.8	0.5	3.1	6.2	4.4	4.4	1	3.3	3.1	3.7	3.6	3.2	10.5	0	2.3
18	2.3	12.4	1.4	5.1	1.9	5.4	8.5	2.7	2.5	1.3	0.8	1.8	6	2.3	1.8	12.8	2.3	0

number	Terminals and service providers
1	ECT Delta Terminal
2	ECT Euromax
3	APMT Maasvlakte 1
4	Rotterdam World Gateway (RWG)
5	APMT Maasvlakte 2
6	Terminal 3
7	Terminal 4
8	ECT Delta Barge Feeder Terminal
9	Delta Container Services
10	Common Rail Terminal
11	Rail Terminal West
12	Barge Service Centre Hartelhaven
13	Common Barge Service Centre
14	Kramer Delta depot
15	Van Doorn Container Depot
16	Empty depot Maasvlakte 1
17	Empty depot Maasvlakte 2
18	Douane

Appendix J

Cost calculation

Vehicle cost (x1000)	AGV	ALV	MTS truck	MTS trailer
Investment	340	500	250	120
lifetime	10	10	8	10
Interest	0.05	0.05	0.05	0.05
Annuity	44	65	39	16
Maintenance/year	4.4	6.5	3.9	0.8
Insurance/year	0.66	0.75	1.16	0.31
Vehicle costs/year	**49.1**	**72.0**	**43.7**	**16.6**
Total vehicle costs	**491**	**720**	**437**	**166**

Infrastructure costs (x1000)	Regular	Automated
Road length (km)	15.7	
Lifetime	25	
Cost/m	1.2	
Interest	0.05	
Annuity road costs	**1300**	1300
Maintenance (6%)	**78**	78
Deapreciation (4%)	**52**	52
# crossings/km	0.5	
cost/crossing	500	
Interest	0.05	
Annuity crossing cost	**508**	508
Maintenance (6%)	**30**	30
Deapreciation (4%)	**20**	20
multiplication		1.5 x
Annuity total costs	**2490**	**3735**

Personnel cost (x1000)	MTS
cost/h	0.025
number of hours	8760
cost per MTS/year	**219**

Handling cost (x1000)	AGV	ALV	MTS truck
Cost/move	10	10	15
Total cost Sc1/year	**3340**	**3340**	**5010**
Total cost Sc2/year	**2150**	**2150**	**3225**
Total cost Sc3/year	**1420**	**1420**	**2130**