A Simio simulation model for the evaluation of Inter Terminal Transport systems at Maasvlakte 1 and 2 in 2030

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ect Europe Container Terminals

Challenge the future

A Simio simulation model for the evaluation of Inter Terminal Transport systems at Maasvlakte 1 and 2 in 2030

by

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Preface

This report is the result of my master thesis in completion of the Master Civil Engineering (Track Transport & Planning) at the Delft University of Technology. This thesis has been conducted at Europe Container Terminals. I would like to thank different people that supported me during my master thesis (and the previous years of my study).

First of all, I would like to thank my daily supervisor, Bart Wiegmans. I would like to thank him for his available time to answer all my questions and his critical view during my project. I would also like to thank the rest of the thesis committee for the useful feedback and advices during the meetings. Thanks to Rudy Negenborn for providing the input data that I used during my research and thanks to Alexander Verbraeck for all the help building my simulation model.

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Finally, I would like to thank my family and friends who supported me during my thesis and during the previous years of my studies.

Marloes Brands
Delft, January 2015

Summary

The Maasvlakte port area in Rotterdam is located in the Netherlands. There are 14 container terminals and empty container depots located within this area, some are existing and some will be built in the near future. At container terminals containers are being transhipped between different modalities. At empty container depots, empty containers are being stored for a certain time.
The container terminals are sharing the same customs facility and empty container depots. Transport between the container terminals and these facilities has to be organised. It is also possible that containers arrive at one container terminal, but have to depart from another container terminal. This transport between different terminals and depots is called Inter Terminal Transport (ITT). This ITT has to be organized in the future. The main question of this research is:
Which transport system is most appropriate for Inter Terminal Transport between the terminals and depots at Maasvlakte 1 and 2 in 2030 and why?

Previous studies were performed to determine the most appropriate transport system for ITT. This study includes a new simulation model to compare the ITT systems, in which the most up-to-date information can be used for the generation of new ITT container demand scenarios. The minimum percentage of on-time containers is set as a constraint, which was not done in previous researches. In this way a fair comparison can be made of the ITT systems and they can be evaluated using multiple criteria.

In this research the AGV, ALV, and MTS will be compared. The AGV and ALV are automated vehicles, have a capacity of 2 TEU, and are expected to drive with a speed of 40 km/h in 2030. The ALV is able to load and unload containers by itself. The MTS is a manned vehicle, has a capacity of 10 TEU, and is expected to drive with a speed of 30 km/h in 2030. These ITT systems will be compared for three different economic growth scenarios (defined by the Port of Rotterdam): low growth, high oil prices, and European trend. An existing container generator (which is made in an earlier project) is used to create a table with containers. Each containers has the following properties: start time, origin (terminal/depot), delivery time, destination (terminal/depot), and size in TEU. The amount of generated containers for ITT differs per economic growth scenario:

- Low growth scenario: 0.70 million containers/1.17 million TEU per year
- High oil prices scenario: 0.78 million containers/1.29 million TEU per year
- European trend scenario: 0.99 million containers/1.66 million TEU per year

The list of containers from the generator is used as input for a simulation model. For this research a dynamic, discrete-event stochastic model has to be built. Multiple simulation software packages exist that are able to build such kind of model, but a choice has to be made. Based on the availability of the programs at the university, the costs, and the user friendliness, Simio is chosen.
Containers arrive at the terminals using their start time and origin property. Containers are labelled as urgent when their latest departure time (delivery time minus the expected loading, unloading and transport time) is within 1 hour, otherwise the containers are labelled as non-urgent. The containers are sorted in different waiting areas; for each destination a separate waiting area is created. Those waiting areas are divided in two parts: the urgent part and the non-urgent part. The containers are virtually sorted by means of their latest departure time; the containers that must depart first are in front of the waiting area (FEFO).
The containers are loaded on the ITT vehicles using the terminal equipment (except for the ALV). Each terminal has its own type and number of terminal equipment. Only (urgent and/or non-urgent) containers with the same destination are loaded on the same vehicle. The ITT vehicles depart when they are fully loaded or when a certain time limit is reached.
A dedicated road for ITT vehicles will be constructed. 3-way crossings and crossings with rail or public road are located within the ITT network, where vehicles can be delayed.

When vehicles arrive at their destination terminal, the terminal equipment unloads the vehicle (except for the ALV). For each terminal this is the same terminal equipment that is also used for loading the ITT vehicles.
After unloading, the ITT vehicles are empty again and determine their next transport assignment. It is checked if there are containers waiting at the current terminal or another close terminal (using a predefined list of terminals), starting from the closest to the most far away terminal. If there are urgent containers waiting, the vehicle drives to that terminal (and takes non-urgent containers from the current terminal with that terminal as destination if possible). If there are no urgent containers waiting, all the terminals are checked to see if there are non-urgent containers waiting, starting from the closest terminal (the current terminal) to the most far away terminal. If non-urgent containers are found, the ITT vehicle drives to that terminal. If no containers are found, the ITT vehicle waits and repeats the process of searching containers.

It is by far the most important task to deliver the containers on time. Therefore a minimum percentage of 95% on-time containers is used, to get a fair comparison between the ITT systems. The number of vehicles is changed as input, until the minimum number of needed vehicles is found to achieve 95% on-time containers. This minimum number of needed vehicles per ITT system per scenario is shown in Table 0-1.

Table 0-1: Needed number of vehicles per ITT system per scenario to reach 95% on time containers

	AGV	**ALV**	**MTS**
Low growth	34 AGVs	24 ALVs	14 MTS-trucks, 90 trailers
High oil prices	39 AGVs	27 ALVs	16 MTS-trucks, 105 trailers
European trend	53 AGVs	34 ALVs	20 MTS-trucks, 130 trailers

The AGV needs clearly the highest number of vehicles, then the ALV, and the MTS needs the lowest number of vehicles. The difference between the AGV and ALV can be declared by the fact that the ALV has the ability to load and unload itself. The capacity of the MTS is 5 times as large as the capacity of the automated systems. This is a clear advantage, because it needs less vehicles than the automated systems, though, the MTS has a lower vehicle speed and has to wait longer during loading and unloading.
The automated systems can reach percentages of on-time containers close to 100%, but the MTS can reach only approximately 97%, because of its long loading and unloading time due to its high capacity.

The output of the simulation model is used for a Multi Criteria Analysis (MCA). The MCA is used to evaluate the different ITT systems, based on two criteria: total costs and sustainability.
The total costs of the three ITT systems are very comparable. For the low growth and high oil prices scenario the total costs of the AGV and MTS are equal. The total costs of the ALV are 4% higher than for the AGV or MTS. For the European trend scenario the MTS has the lowest costs. For this scenario the costs of the AGV are 6% higher than the costs of the MTS, and the costs of the ALV are 7% higher than the costs of the MTS. The vehicle costs of the MTS are much lower than the automated systems, but the personnel costs are on the other hand much higher.
The sustainability of the ITT systems is measured by the electricity usage. The electricity usage of the automated systems is 99% to 166% higher than the electricity usage of the MTS. The ALV uses approximately 25% more electricity than the AGV.

Independent on the weighing factors of the MCA the MTS would have the highest score. The MTS has the lowest costs for each of the scenarios and is the most sustainable ITT system. The difference between the MTS and the automated systems is relatively small looking at the total costs but there is a significant difference looking at the sustainability. The difference between the score (of the MCA) of the MTS and the automated systems depends on how important sustainability is considered by the decision makers. The higher the importance of sustainability is considered, the higher the difference of the score between the MTS and the automated systems will be. Eventually, the MTS will receive in all cases the highest score. Therefore the MTS is considered as the most appropriate ITT system for each of the economic growth scenarios. The input data did not contain large flows from and to empty depots, but in reality these flows will be present. This causes that the amount of ITT flows will be larger, which probably causes that the MTS scores better on total costs, because the MTS scores better on total costs with the highest volume of ITT in the European trend scenario compared to the other two scenarios. Next to this, the MTS is probably a safe option to choose, because for the AGV and ALV large developments are assumed according to the vehicle speed in contrast to the MTS.

It is recommended that future research will be done on different fields. It is interesting to see what happens if the ITT flows are divided differently over the ITT network, and if the large flows from and to the empty depots are taken into account. It is interesting to model multiple years instead only 2030, to find out at which moment it is best to implement a new system. It can be investigated if combinations of ITT systems are more appropriate. Another dispatching method can be used to see if a decrease in the number of vehicles can be reached. It is important to know if there are important decision criteria (and their corresponding weighing factors) missing in the MCA, according to the decision makers. This can have an influence on the results of a MCA. It is also interesting to see what the amount of extra costs is to achieve percentages of on time containers close to 100%. It can be considered if the extra on time delivery of the containers can outweigh the extra costs.

Summary (Dutch)

De Maasvlakte is een havengebied in Rotterdam, gelegen in Nederland. In dit gebied bevinden zich 14 container terminals en lege container depots. Sommige hiervan zijn bestaand, anderen worden in de nabije toekomst gebouwd. Op containerterminals worden containers overgeladen tussen de verschillende modaliteiten. Op lege container depots worden lege containers opgeslagen voor een bepaalde tijd.
De containerterminals delen dezelfde douane-faciliteit en lege container depots. Vervoer tussen de containerterminals en deze voorzieningen moet worden georganiseerd. Het is ook mogelijk dat containers op een terminal aankomen, maar vanuit een andere terminal moeten vertrekken. Het transport tussen de verschillende terminals en depots heet Inter Terminal Transport (ITT). Dit ITT moet in de toekomst worden georganiseerd. De centrale vraag van dit onderzoek is:
Welk transportsysteem is het meest geschikt voor Inter Terminal Transport tussen de terminals en depots van Maasvlakte 1 en 2 in 2030 en waarom?

Er zijn eerder onderzoeken uitgevoerd om het meest geschikte transportsysteem te vinden voor ITT. Dit onderzoek bevat een nieuw simulatiemodel om de ITT systemen te vergelijken, waarin de meest up-to-date informatie gebruikt kan worden voor het genereren van nieuwe scenario’s voor de vraag van ITT containers. Een minimum percentage van het aantal containers dat op tijd komt wordt ingesteld als randvoorwaarde/beperking, wat niet gedaan is in eerdere onderzoeken. Op deze manier kan een eerlijke vergelijking van de ITT systemen gemaakt worden en kunnen ze worden geëvalueerd op basis van meerdere criteria.

In dit onderzoek worden de AGV, ALV, en MTS vergeleken. De AGV en de ALV zijn geautomatiseerde voertuigen, hebben een capaciteit van 2 TEU, en zullen naar verwachting in 2030 met een snelheid van 40 km/u rijden. De ALV is in staat om zelf containers te laden en te lossen. De MTS is een bemand voertuig, heeft een capaciteit van 10 TEU, en zal naar verwachting in 2030 met een snelheid van 30 km/u rijden. Deze ITT-systemen zullen worden vergeleken voor drie verschillende economische groeiscenario's (gedefinieerd door het Havenbedrijf Rotterdam): lage groei, hoge olieprijzen en Europese trend. Een bestaande container generator (die al in een eerder onderzoek gemaakt is) wordt gebruikt om een tabel met containers maken. Elke container heeft de volgende eigenschappen: starttijd, herkomst (terminal/depot), aflevertijd, bestemming (terminal/depot) en de grootte in TEU. Het aantal ITT-containers dat wordt gegenereerd, verschilt per economische groei scenario:

- Lage groeiscenario: 0.70 miljoen containers/1.17 miljoen TEU per jaar
- Hoge olieprijs scenario: 0.78 miljoen containers/1.29 miljoen TEU per jaar
- Europese trend scenario: 0.99 miljoen containers/1.66 miljoen TEU per jaar

De lijst van containers van de generator wordt gebruikt als input voor een simulatiemodel. Voor dit onderzoek moet een dynamisch, discrete verandering, stochastisch model worden gebouwd. Er bestaan meerdere simulatiesoftware pakketten waarmee het mogelijk is om zo’n soort model te bouwen, maar een keuze moet gemaakt worden. Op basis van de beschikbaarheid van de programma’s op de universiteit, de kosten en de gebruiksvriendelijkheid is Simio gekozen.
Containers komen aan op de terminals aan de hand van hun starttijd en herkomst. Containers worden bestempeld als urgent wanneer hun laatste vertrektijd (aflevertijd minus de verwachte tijd voor laden, lossen en transport) binnen 1 uur is, anders worden de containers als niet-urgent bestempeld. De containers worden gesorteerd in verschillende wachtrijen; elke bestemming heeft een eigen wachtrij. Deze wachtrijen zijn verdeeld in twee delen: het urgente dringende gedeelte en het niet-urgente gedeelte. De containers worden virtueel gesorteerd op hun laatste vertrektijd; de containers die als eerste moeten vertrekken staan vooraan.
De containers worden geladen op de ITT-voertuigen met het terminal materieel (behalve de ALV). Elke terminal heeft zijn eigen soort en aantal terminal materieel. Alleen (urgente en/of niet-urgente)

containers met dezelfde bestemming worden geladen op hetzelfde voertuig. De ITT-voertuigen vertrekken wanneer ze volledig zijn geladen of wanneer een bepaalde tijdslimiet is bereikt.
Er wordt een aparte weg voor uitsluitend ITT gebouwd. Binnen het ITT-netwerk bevinden zich 3-richting kruispunten en kruisingen met het spoor of de openbare weg, waar voertuigen vertraging op kunnen lopen.
Wanneer voertuigen op hun terminal van bestemming aankomen, worden de voertuigen door het terminal materieel gelost (met uitzondering van de ALV). Voor elke terminal is dit hetzelfde terminal materieel dat ook wordt gebruikt voor het laden van de ITT voertuigen.
Na het lossen zijn de ITT-voertuigen weer leeg en bepalen zij hun volgende transport opdracht. Er wordt gecontroleerd of er containers staan te wachten op de huidige terminal of een andere dichtbij zijnde terminal (een vooraf gedefinieerde lijst van terminals), vanaf de dichtstbijzijnde tot de terminal het meest ver weg. Als er urgente containers staan te wachten, rijdt het voertuig naar die terminal toe (en neemt niet-urgente containers vanaf de huidige terminal mee met die terminal als bestemming indien dit mogelijk is). Als er geen urgente containers staan te wachten, worden alle terminals gecontroleerd of er niet-urgente containers staan te wachten, beginnende bij de dichtstbijzijnde terminal (de huidige terminal) tot de terminal het meest ver weg. Als er niet-urgente containers worden gevonden, rijdt het ITT-voertuig hier naar toe. Indien geen containers worden gevonden, wacht het ITT-voertuig en wordt het proces van containers zoeken herhaald.

Het is verreweg de belangrijkste taak om de containers op tijd leveren. Daarom wordt een minimumpercentage waarbij 95% van de containers op tijd komt gebruikt, zodat een eerlijke vergelijking tussen de ITT-systemen gemaakt kan worden. Het aantal voertuigen wordt gewijzigd tot het minimum aantal benodigde voertuigen wordt gevonden waarbij 95% van de containers op tijd komt. Het minimum aantal benodigde voertuigen per ITT-systeem per scenario wordt getoond in Tabel 0-1.

Tabel 0-1: Aantal benodigde voertuigen per ITT-systeem per scenario voor 95% containers op tijd

	AGV	**ALV**	**MTS**
Lage groei	34 AGV’s	24 ALV’s	14 MTS-trucks, 90 trailers
Hoge olieprijzen	39 AGV’s	27 ALV’s	16 MTS-trucks, 105 trailers
Europese trend	53 AGV’s	34 ALV’s	20 MTS-trucks, 130 trailers

De AGV heeft duidelijk het meest aantal voertuigen nodig, dan de ALV en de MTS heeft het laagste aantal voertuigen nodig. Het verschil tussen de AGV en ALV kan worden verklaard door het feit dat de ALV de mogelijkheid heeft om zelf containers te laden en te lossen. De capaciteit van de MTS is 5 keer zo groot als de capaciteit van de geautomatiseerde voertuigen. Dit is een duidelijk voordeel, omdat de MTS minder voertuigen nodig heeft dan de geautomatiseerde systemen, hoewel de MTS een lagere voertuigsnelheid heeft en langer moet wachten bij het laden en lossen.
De geautomatiseerde systemen kunnen percentages dicht bij 100% containers op tijd bereiken, maar de MTS slechts ongeveer 97%, vanwege de lange laad- en lostijd door de hoge capaciteit van het voertuig.

De output van het simulatiemodel wordt gebruikt voor een Multi Criteria Analyse (MCA). De MCA wordt gebruikt om de verschillende ITT-systemen te evalueren, op basis van twee criteria: totale kosten en duurzaamheid.
De totale kosten van de drie ITT- systemen zijn zeer vergelijkbaar. Voor het lage groei scenario en het hoge olieprijzen scenario zijn de totale kosten van de AGV en MTS gelijk. De totale kosten van de ALV zijn 4% hoger dan voor de AGV en MTS. Voor het Europese trend scenario heeft de MTS de laagste kosten. De kosten van de AGV zijn 6% hoger dan de kosten voor de MTS en de kosten van de ALV zijn 7% hoger dan de kosten van de MTS. De voertuigkosten van de MTS zijn veel lager dan voor de geautomatiseerde systemen, maar de personeelskosten zijn daarentegen veel hoger.

De duurzaamheid van de ITT-systemen wordt bepaald door het elektriciteitsgebruik te meten. Het elektriciteitsverbruik van de automatische systemen is 99% tot 166% hoger dan het elektriciteitsverbruik van de MTS. De ALV gebruikt ongeveer 25% meer elektriciteit dan de AGV. Onafhankelijk van de gebruikte weegfactoren in de MTS, zal de MTS de hoogste score krijgen. De MTS heeft de laagste kosten voor elk van de scenario's en is het meest duurzame ITT systeem. Het verschil tussen de MTS en de geautomatiseerde systemen is klein wanneer gekeken wordt naar de totale kosten, maar er is een significant verschil wanneer gekeken wordt naar de duurzaamheid. Het verschil tussen de score (van de MCA) van de MTS en de geautomatiseerde systemen hangt af van hoe belangrijk duurzaamheid wordt geacht door de besluitvormer. Hoe belangrijker duurzaamheid wordt geacht, hoe hoger het verschil tussen de score van de MTS en de geautomatiseerde systemen. Uiteindelijk zal de MTS in alle gevallen de hoogste score krijgen. Daarom wordt de MTS als het meest geschikte ITT-systeem beschouwd voor elk van de economische groei scenario's. De input van het simulatiemodel bevat geen grote stromen van en naar lege container depots, maar in werkelijkheid zijn deze stromen aanwezig. Dit veroorzaakt dat de hoeveelheid ITT groter is, wat waarschijnlijk veroorzaakt dat de MTS beter scoort op de totale kosten, omdat de MTS beter scoort op totale kosten voor het hoogste volume van ITT in het Europese trend scenario in vergelijking met de andere twee scenario's. Daarnaast is de MTS waarschijnlijk een veilige optie om te kiezen, omdat voor de AGV en ALV grote ontwikkelingen worden verondersteld voor de voertuigsnelheid in tegenstelling tot de MTS.

Het wordt aanbevolen dat toekomstig onderzoek wordt gedaan op verschillende gebieden. Het is interessant om te zien wat er gebeurt als de ITT-stromen anders worden verdeeld over het ITT-netwerk en als de grote stromen van en naar de empty depots mee worden genomen. Het is interessant om meerdere jaren te modelleren in plaats van alleen 2030, om erachter te komen op welk moment het het beste is om een nieuw systeem te implementeren. Het kan worden onderzocht of combinaties van ITT-systemen meer geschikt zijn. Een andere methode voor het bepalen van de volgende opdracht van de voertuigen kan worden gebruikt om te zien of een afname van het aantal voertuigen kan worden bereikt. Het is belangrijk om te weten of er belangrijke besliscriteria (en de bijbehorende weegfactoren) missen in de MCA volgens de besluitmakers. Dit kan een impact hebben op de resultaten. Het is ook interessant om te zien wat de extra kosten zijn om percentages dicht bij 100% containers op tijd te bereiken. Er kan worden bepaald of het extra percentage containers dat op tijd afgeleverd wordt zwaarder weegt dan de extra benodigde kosten.

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List of abbreviations

AGV	Automated Guided Vehicle
ALV	Automated Lifting Vehicle
ASC	Automated Stacking Crane
ECT	Europe Container Terminals
ITT	Inter Terminal Transport
MTS	Multi Trailer System
MCA	Multi Criteria Analysis
QC	Quay Crane
RQ	Rail Crane
SC	Straddle Carrier
TEU	Twenty feet Equivalent Unit

1 Introduction

In this introduction first the problem statement/background will be given. After this, the research questions will be discussed and the research methodology will be explained. Finally the report structure is given.

1.1 Problem statement/background

The Maasvlakte port area in Rotterdam is located in the Netherlands. There are 14 container terminals and empty container depots located within this area. At container terminals containers are being transhipped between different modalities. At empty container depots, empty containers are being stored for a certain time.

Next to the existing container terminals, at Maasvlakte 2 two new terminals will be built: APMT2 (5) and Rotterdam World Gateway (3). The existing ECT Euromax terminal (2) at Maasvlakte 1 is able to expand at Maasvlakte 2. All the terminals and depots at Maasvlakte 1 and 2 are shown in Figure 1-1.

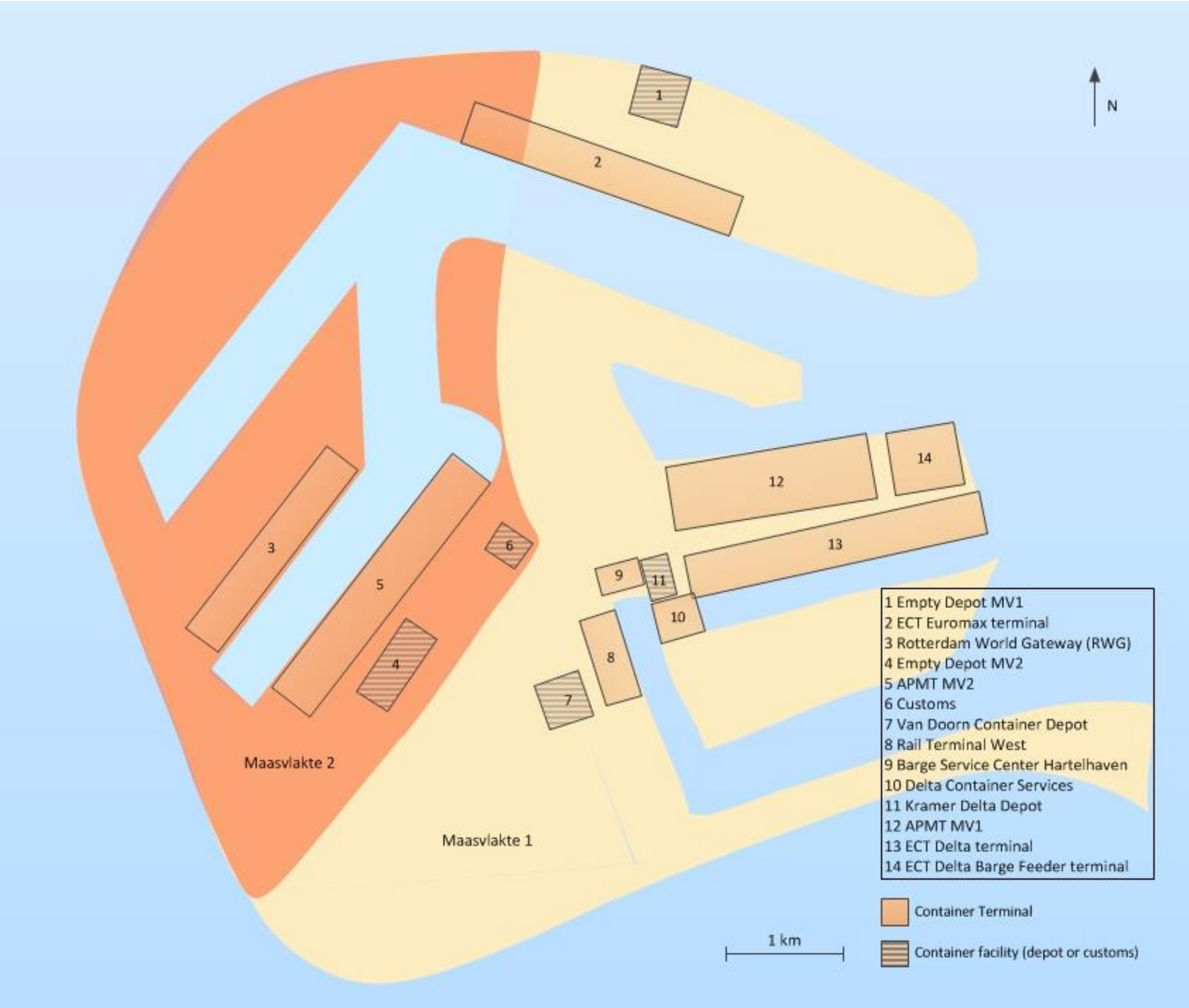

Figure 1-1: Terminals and depots located at the Maasvlakte (Duinkerken & Negenborn, 2014)

The container terminals are sharing the same customs facility and empty container depots. Transport between the container terminals and these facilities has to be organised. It is also possible that containers arrive at one container terminal, but have to depart from another container terminal. This transport between different terminals and depots is called Inter Terminal Transport (ITT).

In the future the Inter Terminal Transport between the terminals (and depots) at Maasvlakte 1 and 2 has to be organised. It is predicted that this transport will be organised until 2020 by using 3 TEU trucks that drive on the public road, but at a certain moment this option will no longer suffice. For 2030 it must be investigated what the most appropriate ITT system is.

1.2 Research questions

For this research a main question and multiple sub questions are determined. On the basis of the sub questions the main question can be answered. The main question of this research is:

Which transport system is most appropriate for Inter Terminal Transport between the container terminals and depots at Maasvlakte 1 and 2 in 2030 and why?

First it will be determined which ITT systems will be evaluated in this research. The choice of the simulation program will be explained and the simulation steps will be described. The system will be analysed and the inputs and the outputs of the system will be determined. A simulation model will be made to generate output data. The process steps in the simulation model are described, including the way in which they will be modelled. After the description of the simulation model, the input values will be discussed and the future scenarios will be described. Per scenario the total amount of Inter Terminal Transport varies. Finally, per future scenario it can be determined which ITT system scores highest using a Multi Criteria Analysis.

On the basis of the following sub questions the above described steps will be followed:

- *Which ITT systems will be compared in this research?*
- *Which simulation program will be used in this research and which simulation steps will be followed?*
- *What are the inputs and outputs of the system?*
- *Which process steps can be distinguished and how will these be modelled?*
- *What are the input values that will be used in the simulation model and which future scenarios will be modelled?*
- *Which ITT system scores highest per future scenario, based on a Multi Criteria Analysis?*

With the outcomes of the sub questions, the main question can be answered. It can be determined which of the ITT systems is the most appropriate alternative in this research.

1.3 Research methodology

To compare different ITT systems for Inter Terminal Transport between the different terminals and depots at Maasvlakte 1 and 2, a Multi Criteria Analysis will be used. A MCA is a scientific evaluation method to make a choice between multiple alternatives, in this case the different ITT systems. When a MCA is used, not all the criteria have to be expressed in costs. This means that not only costs have to be taken into account and the ITT systems can be evaluated based on multiple criteria.

A simulation model will be used to gather input data that will be used in the MCA. For example, the needed number of vehicles can be determined using the simulation model and therewith the vehicle costs. Simulation is a decision analysis and support tool. With a simulation model it is possible to compare and evaluate different ITT systems for Inter Terminal Transport (under the same circumstances). It is very impractical and expensive to test those ITT systems in reality, so a simulation model will be used to mimic the reality. The model is an appropriate way to make the processes and the complex interactions within the system clearly visible. Queues can be observed and bottlenecks can be identified. By changing the input variables it becomes directly visible what happens in the system.

1.4 Report structure

Chapter 1 gives an introduction of the research subject. In chapter 2 the literature (on Inter Terminal Transport) has been reviewed and the gap in the literature is defined. In this chapter also the simulation program is chosen. In chapter 3 the system will be analysed and a conceptual model is made. The inputs and the outputs of the system will be determined. The process steps are described and the way of modelling those process steps. In chapter 4 the experimental setup of the simulation model will be given. Afterwards a MCA will be performed. Finally, in chapter 6 the conclusions and recommendations of the research will be discussed.

2 Literature review

In this chapter first literature of transport systems for hinterland transportation and internal terminal transport is reviewed. Then a description of Inter Terminal Transport is given and the possible transport systems are listed. For the case study Maasvlakte, previous researches about modelling ITT are reviewed and the focus of this research is stated. Finally, a simulation program is chosen for modelling Inter Terminal Transport at the Maasvlakte.

2.1 Literature review of transport systems for hinterland transportation

Hinterland transportation deals with larger transport distances than Inter Terminal Transport, but there are comparable aspects. Literature about hinterland transportation can be used for the research about ITT.

Choice for bundling of containers
A dilemma which is part of the hinterland transportation is the choice for intermodal transport or not. It is possible to choose a combination of modalities, where barges and trains are mostly used for the main transportation and trucks are used for pre- and end haulage. Trucks are used for single modality transportation. The choice between bundling of containers by using barges or trains, or transporting a very low amount of containers at once by using trucks (which can carry at maximum 3 TEU) has to be made. (Frémont & Franc, 2010) (Wiegmans & Konings, 2013) When bundling is chosen, containers must change modality, and pre haulage or end haulage also has to be provided. For ITT the choice for bundling can also be made. It must be investigated if direct bundled transport from the origin to the destination is possible and no pre haulage and end haulage is required, or only bundled transport between central points is done and pre haulage and end haulage is required.

Traffic congestion
Hinterland transportation requires just-in-time transport operations, but congestion makes this more complicated. The advantage of rail and inland waterway transport is that it doesn't suffer (much) from congestion, while road transport does suffer. Inter Terminal Transport might possibly have to deal with congestion, when a large amount of vehicles has to be used. In this case bundling of containers might be more advantaged, but the size of the effect of congestion has to be investigated first.

Environmental impact
The attention to environmental awareness and regulations is growing. The transport sector causes much pollution, so the environmental impact of transport systems is of large importance for the policy makers. More sustainable transport systems are therefore desired. (Bergqvist & Egels-Zandén, 2012) At this moment this is applied to hinterland transportation, but for the choice of a new ITT system the environmental impact could be of large importance too.

2.2 Literature review of transport systems for internal terminal transport

The analysis of internal terminal transport can be used to get more insight in which transport systems can possibly be appropriate for Inter Terminal Transport. Internal terminal transport can be described as the transport between the quay and the stacking area of a container terminal. The transport distances are much smaller than the distances for ITT. The loading and unloading of the vehicles compared to driving is proportionally larger for internal terminal transport than for ITT.

Number of vehicles
Two different types of vehicles are considered in the research of Vis and Harika for transport between the quay and the stacking area; the AGVs and the ALVs. (Vis & Harika, 2004) Both can be used with no impact on the unloading times of the vessel, but there is a difference in the number

of vehicles that must be used. 38% more AGVs than ALVs are required to fulfil the transport demand.
Yang et al. made a simulation model to determine the needed number of vehicles used at an automated container terminal. (Yang, et al., 2004) The ALV and the AGV are being compared. In the model, where 3 quay cranes and 12 stacking cranes were used, at least 50% more AGVs have to be used compared to the number of ALVs. The ALV scores better on productivity than the AGV, because the waiting time at the buffer areas at the quay crane is reduced. (Yang, et al., 2004)
Bae et al. compare single-load AGVs and ALVs for the internal terminal transport. (Bae, et al., 2011) The dispatching strategy of Briskorn et al. is used for the simulation. (Briskorn, et al., 2006) The cycle times of the ALV are considerably shorter than the AGV, because of the reduction in waiting times at the quay cranes. In some cases ALVs can reach the same productivity level as the AGV by using 70% less vehicles. This is caused by the fact that AGVs have more waiting time at the buffer areas and the stacking areas.
The researches show that more or less 50% more single-load AGVS are required compared to ALVs to perform the same internal terminal transport operations at the same service level. The difference can be explained by the waiting times of the AGVs during the loading and unloading of the vehicle. Each research used other characteristics of terminals, so the findings are assumed to be sufficiently robust. It is questionable if the difference between the required number of vehicles between the ALV and the AGV is still so large for Inter Terminal Transport at Maasvlakte 1 and 2. The travelling distances for ITT are much larger than the distances for internal terminal transport, so the share of travelling compared to the share of loading and unloading becomes larger. The difference between the AGV and ALV is caused by the waiting times for the loading and unloading of containers. With a smaller share of (un)loading in the process it is expected that the difference in the needed number of vehicles between the AGV and ALV becomes smaller.

Influential factors on the number of vehicles
Vis and Harika conclude that the size of the buffer area at the quay cranes has an influence on the average number of vehicles required. Less vehicles are needed when there is a larger buffer area. When twin-load AGVs are used instead of single-load AGVs, the number of vehicles can be reduced with a small amount of vehicles. Lower cycle times of the quay cranes result in the use of more vehicles. (Vis & Harika, 2004)
Bae et al. states that the AGV can reach the same productivity level as the ALV by adding more vehicles despite traffic congestion. When the throughput of the quay cranes is extremely high, the AGVs are not able to meet the demand in this case, independently on the number of vehicles. The AGVs have an underperformance, which is mainly caused by the too long waiting times at the ASC. (Bae, et al., 2011)
In the research of Yang et al. it is stated that the number of vehicles is inversely proportional to the speed of the vehicles, until a point where the minimum number of vehicles remains constant. (Yang, et al., 2004)
These researches show that there are multiple influential factors on the required number of vehicles: the size of the buffer area, the cycle times of the crane, traffic congestion and the speed of the vehicles. The influential factors of internal terminal transport can also have an impact on ITT. It has to be considered if these factors are taken into account in this research.

Choice of modality
In the case study of the research of Vis and Harika ALVs are the best alternative when the investment costs of the vehicles are taken into account. The choice between ALVs and AGVs is influenced by the layout of the terminal (buffer area) and the technical aspects of the equipment (quay crane and vehicle), when the investment costs are taken into account. (Vis & Harika, 2004)
Yang et al. states that a reduction of costs is possible when a mix between AGVs and ALVs is being used. (Yang, et al., 2004)

Bae et al. only compared the productivity of the vehicles and gives the recommendation that the choice between ALVs and AGVs must be made by taking the investment and maintenance costs into account. (Bae, et al., 2011)
Not all the researches made an evaluation based on costs. For ITT, the costs (but also other criteria) will be evaluated. It will be taken into account that the choice for the ITT system depends on the case study to which it is applied, it depends on the layout and the technical aspects of the equipment.

2.3 What is Inter Terminal Transport and which ITT systems can be used?

Inter Terminal Transport (ITT) is described as the transport between different terminals and depots within a port area. For instance, it is possible that a container changes from modality (and has to depart from another terminal) or has to be stored in an empty container depot. (Tierney, et al., 2013)

For example, Maasvlakte 1 in Rotterdam already consists of multiple container terminals and depots. With the construction of Maasvlakte 2, the port area will be increased and new terminals will be built. The terminal use a common infrastructure with respect to customs activities and container depots, which requires ITT. Next to that, the transport between the terminals also has to be provided by means of ITT.

A transport system must be chosen to handle the ITT containers. To make a choice for the most appropriate ITT system, a trade-off between costs and performance must be made. There are three main decision problems in transport operations:

- type of vehicles
- number of vehicles
- routing and dispatching of the vehicles

To solve these three problems, the assumptions that must be made depend mostly on the type of vehicle that will be used. (Carlo, et al., 2014) Therefore, the possible transport systems will be discussed.

AGV

Automated guided vehicles (AGVs) are vehicles with a capacity of 2 TEU that are able to travel unmanned in a specific area. Figure 2-1 shows the AGV. In Figure 2-2 the ITT process of AGVs is shown.

Figure 2-1: Automated Guided Vehicle (Europe Container Terminals, 2007)

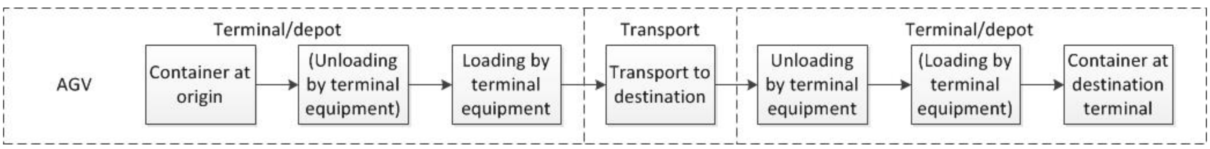

Figure 2-2: ITT process of AGVs (Author, 2014)

Automated systems require high investments, so these are only used when labour costs are high. (Steenken, et al., 2004) AGVs need terminal equipment to load and unload the vehicle.

ALV

Automated lift vehicles (ALVs) are comparable to AGVs. They also have a capacity of 2 TEU and can drive unmanned in a specific area. In Figure 2-3 an ALV is shown and Figure 2-4 shows the ITT process.

Figure 2-3: Automated Lift Vehicle (Terex, n.d.)

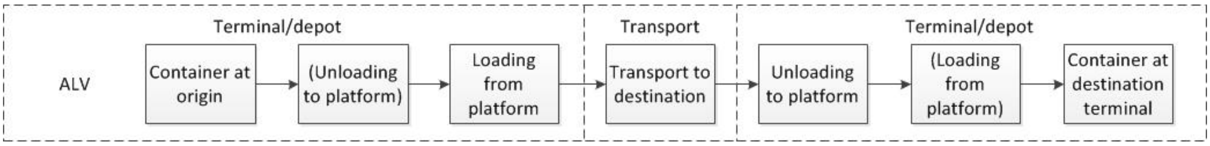

Figure 2-4: ITT process of ALVs (Author, 2014)

ALVs do not need terminal equipment to load and unload the vehicles, in contradiction to AGVs. These vehicles are able to lift the containers themselves for loading and unloading. This is a large advantage, because the vehicles do not have to wait until the terminal equipment becomes available.

MTS

A Multi Trailer System (MTS) is a set of at maximum 5 trailers with a capacity of 10 TEU, which is being pulled by a manned MTS-truck. In Figure 2-5 a MTS is shown and in Figure 2-6 the ITT process of MTSs is shown.

Figure 2-5: Multi Trailer System (Europe Container Terminals, 1999)

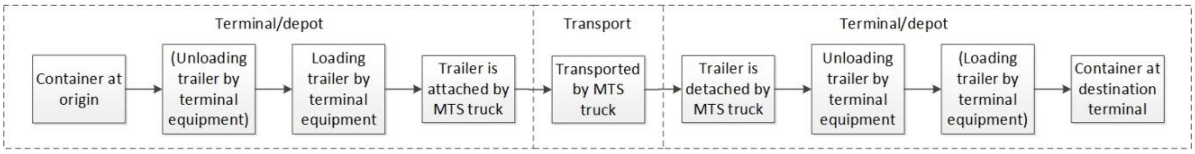

Figure 2-6: ITT process of MTSs (Author, 2014)

MTSs were designed to increase the efficiency for transporting container over a few kilometres (between different terminals). The MTS-truck connects to the trailers, transports it and then disconnects. This means that the containers can be unloaded while the MTS-truck is fulfilling its next transport assignment.

Barges

It is possible to transport a large amount of containers at once by using barges. Figure 2-7 shows a barge and Figure 2-8 the ITT process of barges is shown.

Figure 2-7: Barge (Europe Container Terminals, 2011)

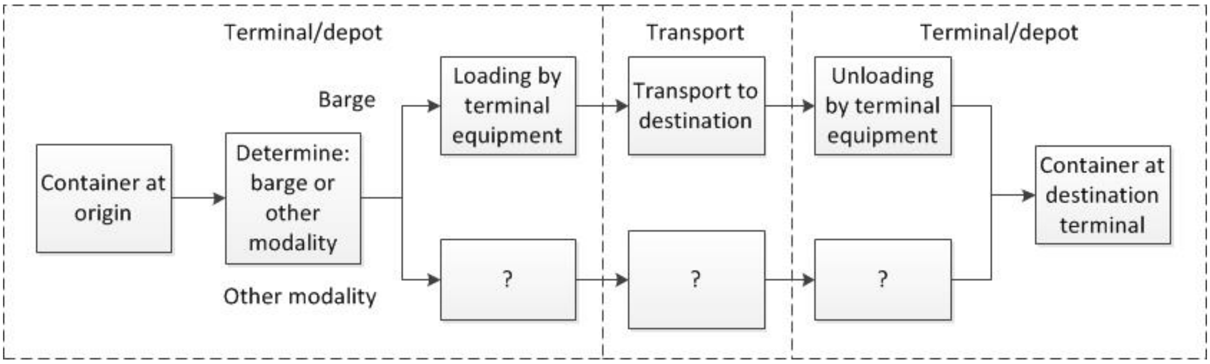

Figure 2-8: ITT process of barges (Author, 2014)

Barges travel slowly and it takes long to load and unload the barges, but there are also advantages compared to road vehicles. Barges have a high capacity (they can carry mostly more or less 50 containers), the distances between terminals by water can be shorter than by road, and they experience less congestion. (Tierney, Voß, & Stahlbock, 2013) Barges must be used in combination with other vehicles, because barges are not able to deliver containers, which have a short time period between arrival and departure, on time.

Train

Trains are not mentioned in earlier researches about ITT, but they can transport also a large amount of containers at once. Regular trains are not appropriate for this kind of transport, because they are very long and it takes a long time to turn the train (switching the locomotive). It is possible to use CargoSprinters. Figure 2-9 shows a CargoSprinter and Figure 2-10 shows the ITT process.

Figure 2-9: CargoSprinter (Windhoff, n.d.)

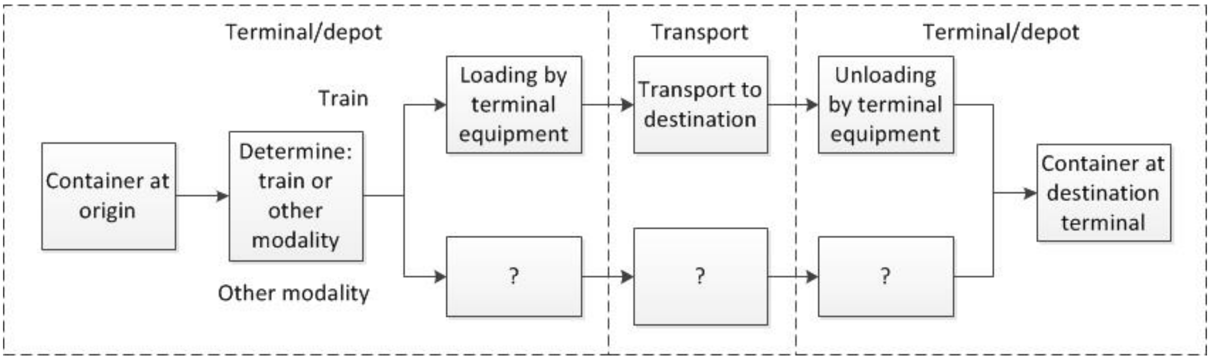

Figure 2-10: ITT process of trains (Author, 2014)

These trains can carry up to 26 TEU and are operated by a push-pull configuration, so they can easily drive in two directions. The trains must be used in combination with another modality, because they are not able to transport the urgent containers in time.

Overview of possible ITT systems

In Table 2-1 all the ITT systems are shown. Their capacities, advantages, disadvantages, and their requirement to be combined with another modality is given.

Table 2-1: Overview of possible ITT systems

ITT system	Capacity	Advantages	Disadvantages	Combination with other modality?
AGV	2 TEU	No personnel needed High transport speed	High investment costs	No
ALV	2 TEU	No terminal equipment needed No personnel needed High transport speed	High investment costs	No
MTS	10 TEU	Bundling of containers	Medium transport speed	No
Barge	50 TEU	Bundling of containers	Slow transport speed Combination with extra modality needed	Yes

Train	26 TEU	Bundling of containers	Slow transport speed Combination with extra modality needed	Yes

(Author, 2014)

2.4 Case study: Modelling Inter Terminal Transport at the Maasvlakte

In this study choices had to be made on the different research elements of ITT at the Maasvlakte. The ITT network is defined, different demand scenarios of ITT containers are developed, the ITT systems which will be compared are chosen, and influential factors are defined. In Table 2-2 an overview is given of the chosen research elements of this study. This table also gives an overview of previous researches with their choices on the different research elements.

Table 2-2: Overview of different researches about ITT at the Maasvlakte

Research	Network	ITT demand	ITT systems	Influential factors
This research	Maasvlakte 1 and 2: 14 separate terminals and depots	3 new scenarios	AGV, ALV, MTS	Congestion of vehicles Terminal equipment Vehicle speed Prioritization of containers
Duinkerken et al.	Maasvlakte 1: 11 nodes (marine terminals and empty depots)	1 scenario: 1.4 million container per year	AGV, ALV, MTS	/
Tierney et al.	Maasvlakte 1 and 2: 8 terminals	4 demand scenarios: 500, 1000, 1500 and 2000 in a 10 hour period	AGV, ALV, MTS + combination of barge with AGV, ALV or MTS	Congestion of vehicles Prioritization of containers
Nieuwkoop	Maasvlakte 1 and 2: 5 groups of clustered terminals	3 scenarios: 1.42, 2.15 and 3.34 million TEUs per year	AGV, ALV, MTS, combination of barge and truck	Vehicle speed
Schröer et al.	Maasvlakte 1 and 2: 18 separate terminals and depots	3 scenarios: 1.42, 2.15 and 3.34 million TEUs per year	AGV, ALV, MTS, combination of barge and truck	Congestion of vehicles Terminal equipment Vehicle speed Prioritization of containers

(Author, 2014) (Duinkerken, et al., 2007) (Tierney, et al., 2013) (Nieuwkoop, 2013) (Schroër, et al., 2013)

Duinkerken et al. made a simulation model for comparing the transportation systems for Inter Terminal Transport. (Duinkerken, et al., 2007) Tierney et al. made a mathematical model (a novel integer programming model) for analysing Inter Terminal Transport in new and expanding sea ports. (Tierney, et al., 2013) This model assists ports in analysing the impact of new infrastructure, the placement of terminals, and ITT vehicle investments. Nieuwkoop used the research of Tierney et al. to develop a deterministic cost flow model. (Nieuwkoop, 2013) Tierney et al. minimized the costs with a fixed number of vehicles. The largest difference between the two models of Tierney and Nieuwkoop is that the model of Nieuwkoop optimizes the number of vehicles by minimizing the cost of delays and the cost for adding an extra vehicle. This model is able to calculate the optimal vehicle configurations for different ITT systems. Schroër et al. used these optimal vehicle configurations in his discrete event simulation model to compare the different ITT systems. (Schroër, et al., 2013)

This research
In this research different ITT systems are evaluated. The output of a stochastic, dynamic, discrete-change simulation model is used as input for a Multi Criteria Analysis to evaluate the different systems, based on different criteria.

Each of the research elements, mentioned in Table 2-2, will be discussed in the following sections. The choices of the previous researches are described and the choice for this study is explained.

2.4.1 Maasvlakte ITT networks

Duinkerken et al. made a simulation model from the terminals at Maasvlakte 1, consisting of 11 nodes. These nodes consist of the marine terminals and empty depots at the ECT peninsula, a barge service centre, a rail service centre, a rail terminal, and DistriPark. In the research of Tierney et al. 8 terminals at Maasvlakte 1 and 2 are taken into account. Nieuwkoop used 5 groups of clustered terminals and depots at Maasvlakte 1 and 2. These terminals are located next to each other or have an internal connection. This research states that this has a small effect on the number of required vehicles and it sometimes performs better than transporting containers between individual terminals. This is in contrast to Schroër et al., who used 18 separate terminals and depots. When there are more terminals, more empty trips are required and the vehicle capacity can be used less optimal. This phenomenon can be observed especially by vehicles with a large capacity, such as MTS, because these vehicles have to wait longer before the vehicle is fully loaded. Using bundled terminals causes that there are more containers waiting for transport at one node and that there are more containers with the same destination node.

This research
For this research the Inter Terminal Transport between all the terminals and depots at Maasvlakte 1 and 2 will be investigated. The terminals and depots are shown in Figure 1-1. Separate terminals will be used, because the containers must be transported to the terminals and not to a central point between the terminals. When there would be a central point, there must be extra transport to the terminals.

2.4.2 Demand of ITT containers at the Maasvlakte

In Duinkerken et al. only 1 scenario is used for the demand of ITT containers. It is assumed that 1.4 million containers per year must be transported, equal to 27,277 containers per week (on average). Daily fluctuations are applied. Tierney et al. models 4 demand scenarios in a 10 hour period: 500, 1000, 1500, and 2000 containers. Three different demand scenarios (which are developed by Jansen) are used in the research of Nieuwkoop. (Jansen, 2013) These scenarios consist of 3.34, 2.15, and 1.42 million TEUs of ITT per year. One of the scenarios is a high demand scenario; a common barge and rail terminal will be built and all the ITT movements will be done by the new ITT system (so the current ITT system of ECT will be replaced). Another scenario uses the same assumptions, but a reduced demand is applied. The last scenario does not include a common barge and rail terminal, and the current ITT system will not be replaced. The same future scenarios are used in the research of Schroër et al.

This research
The used demand scenarios in the different researches are based on different assumptions. In this research, these scenarios are evaluated and 3 new, (more) realistic scenarios are developed. The scenarios differ on the amount of ITT containers, but the underlying assumptions are the same for each scenario. This is further explained in chapter 4.1: Scenario definition and Appendix C: Scenario definition.

2.4.3 Specific characteristics of ITT systems at the Maasvlakte

Duinkerken et al. compares the MTS, ALV, and the AGV. A distinction is made between AGVs at the landside and the waterside. Tierney et al. modelled AGV, ALV, MTS, and all these ITT systems combined with barges. The number of vehicles is varied (50, 100, 150, and 200 vehicles) and for every ITT system the combination with 2 barges is investigated. Nieuwkoop searches for the optimal number of vehicles per scenario for the AGV, ALV, MTS, and a combination of barge and truck. Schroër et al. use the same ITT systems as Nieuwkoop.

In Duinkerken et al. the non-performance is determined per ITT system when the number of vehicles is being varied. Even with extreme high numbers of vehicles, the performance of the MTS system remains clearly poorer than that of the AGV and the ALV systems. This difference can be explained by the batch type work method of the MTS.

In the study of Tierney et al. a penalty for late delivery is assumed. MTSs seem to have the smallest penalty. Although they have slow loading capabilities, they have two key advantages over AGV and ALV. MTSs can carry more containers, so less MTSs are needed to service large amounts of demands and they travel faster than AGVs and ALVs. There is a large gap of the penalties between the MTS and the AGV and ALV. When barges in combination with these transport modes are being used, this gap becomes much smaller.

These two researches do not conclude that the same type of ITT system is the most appropriate. It is possible that this could be explained by the fact that Duinkerken et al. only uses Maasvlakte 1 and Tierney et al. uses Maasvlakte 1 and 2. For longer distances the MTS could be more appropriate.
In Nieuwkoop 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. This results in the number of vehicles that is shown in Table 2-3.

Table 2-3: Required number of vehicles per vehicle type per scenario

	ALV	**AGV**	**MTS**	**Barge**
Scenario 1	51	65	16 trucks +76 trailers	41 trucks and 2 barges
Scenario 2	33	42	12 trucks + 59 trailers	22 trucks + 3 barges
Scenario 3	24	32	9 trucks + 42 trailers	17 trucks + 2 barges

(Nieuwkoop, 2013)

In Schroër et al. it is stated that it is the most important task of the vehicles to deliver the containers on time. Containers that not arrive on time are labelled as non-performance. When the ITT configurations from Nieuwkoop are put in this model, the non-performance per configuration is shown in Table 2-4.

Table 2-4: Non-performance and average lateness of late containers per configuration per scenario

Scenario	**Configuration**	**Non-performance [%]**	**Average lateness for late containers [hour]**
1	51 ALVs	18.3	7.67
	65 AGVs	41.5	37.24
	16 MTSs	40.7	78.18
	41 trucks + 2 barges	98.6	261.49
2	33 ALVs	11.2	6.10
	42 AGVs	39.4	20.83
	12 MTSs	26.7	13.75

	22 trucks + 3 barges	98.5	444.17
3	24 ALVs	2.5	0.60
	32 AGVs	21.7	3.83
	9 MTSs	19.3	3.69
	17 trucks + 2 barges	98.7	353.85

(Schroër, et al., 2013)

In the research of Schröer et al. the barge configurations have a very high non-performance rate and almost every container is delivered weeks later. Schröer et al. think that this is caused by the fact that in the research of Nieuwkoop barges were modelled in a non-realistic way. (Schroër, et al., 2013) This made it possible that containers can be transported separately (by a segment of a barge) and barges do not have to wait until they are full, which is not possible in reality.
The simulation model first makes an estimation if it is possible to deliver the container on time by barge. If not, the container will be transported by truck. Because the average available time in the simulation model is 8 hours before the container has to be delivered, the barge is most of the time too slow. Trucks are then used as an alternative, but in the simulation model there is a large shortage of trucks.
In the simulation model barges make a round trip between all the terminals, which are located next to the water. These barges have low loading rates, even when they sail between two terminals with the highest exchange of containers. If the available time for delivery is higher, this would result in a higher loading rate of the barges. Changing the barge route in such way that barges only sail between terminals with a high container exchange could have potential.
MTSs were also modelled in a non-realistic way (just like the barges) by Nieuwkoop, which causes the same effect as earlier described for the barges. Next to this, the bundled terminals cause that MTSs would have to wait less long before they are fully loaded.
Also the ALV and AGV were not correctly modelled by Nieuwkoop. An unlimited terminal equipment capacity was assumed in this model, but this would make the AGV work the same as the ALV because the AGV then never has to wait until the terminal equipment is available. In the simulation model of Schroër et al. the difference is modelled.

This research
The articles find different ITT systems that are most appropriate for ITT. Tierney describes that the MTS performs the best and Nieuwkoop and Schroër et al. prefer the automated systems. The difference can be explained by the fact that Tierney used a fixed number of vehicles and that the number of vehicles was not optimized. Nieuwkoop did the optimization, but the results of non-performance were extremely high in the model of Schroër et al. Therefore a model must be made where the level of non-performance for each ITT system is acceptable, otherwise the ITT systems cannot be compared. The number of vehicles is changed until a minimum percentage of on time containers is reached. New demand scenarios will be used and the network will look differently, so it is still needed to compare different ITT systems, but it can be decided which ITT systems to include in the research.

In the research of Duinkerken et al., Tierney et al., and Schroër et al. the AGV, ALV and MTS seem to have potential. Therefore these ITT systems will be taken into account in this research. Trucks will be disregarded, because it is expected that the total costs will be far too high. Trucks can carry a small amount of containers, and need drivers. Therefore the number of vehicles will probably be high and this results in high personnel cost.

In the research of Schroër et al. barges were used to transport large amounts of containers at once. However, a very small amount of containers were actually transported by the barges. The transport by barge is always prioritized, unless the barge cannot deliver a container on time. Then the containers are transported by road. To determine if the containers will be transported by barge the

expected delivery time is calculated on forehand (using the release time and the expected transport time) and compared with the actual delivery time. The low use of barge for the transportation of containers could be explained by the round route the barge is sailing, but even when the barges sail only between two terminals that exchange the most containers, the barges have very low loading rates. This is caused by the average time that is available for the transport of containers is equal to 8 hours. The barges have very low sailing speeds, 12 km/h, and the mooring time is already 30 minutes. When the loading and unloading time is added and extra buffer time is added, the expected transport time by barge often exceeds the available time for transport. Another disadvantage from barges is that the barges cannot reach every terminal by water. Sometimes there is a problem that when terminals can be reached (like the rail terminal west), the barges must sail a large detour.
The transport demand input in this research will be different than in the research of Schroër et al., but the average time of containers that is available before departure will probably be comparable. Therefore it is assumed that the barges won't be a feasible solution.

As an alternative, rail can be investigated. When normal trains are used, it takes a long time to turn the train (switching the locomotive). It is possible to use small trains, called CargoSprinters. These can carry up to 26 TEU and are operated by a push-pull configuration, so they can easily drive in two directions. They do not use the quay and the existing rail infrastructure can be used. Trains have a higher average speed and they need less time to enter the terminal. The deep sea terminals already have a connection to the rail network, but it is possible to make extra connections at the other terminals and depots. Because the short time that is available before delivery, the trains will follow a predetermined route, but the train only stops at terminals that exchange a lot of containers. The train is just like the barge a modality that transports a large amount of containers at once. It is therefore the best to use these trains only between terminals that exchange a large amount of containers. For the rest of the ITT another modality must transport the containers. Therefore the train will be combined with trucks, ALV, or AGV. Trucks could be a good alternative. When the trains transport most of the containers, the trucks only transport a small amount of containers. No new infrastructure is needed and if a low amount of trucks is needed the personnel costs won't be extremely high. Trains in combination with ALV or AGV can be investigated, because the automated vehicles can transport all the other containers that not will be transported by the trains. Because of their low capacity and high speed they will be able to transport the containers fast without long waiting times, especially important for urgent containers.
Trains in combination with MTS is not a good option to take into account. When a part of the containers will be transported by train, a part of the containers is left for the transport by MTS, so it is desirable that a much lower amount of MTS-trucks and trailers will be used compared to the situation in which only MTS-trucks (and trailers) will be used. This lower amount of vehicles causes the problem that it is much more difficult to have an empty trailers at the terminal from which new transports originate. This is especially the case for urgent containers (which probably will not be transported by the train because of time pressure). This problem can only be solved when a larger amount of MTS-trucks (and trailers) will be used, but this also entails higher costs. It is expected that these costs will be too high.
There is potential for using trains in combination with other modalities, but because of time limit it is excluded from this research. It is recommended that more research about these ITT systems will be done.

2.4.4 Influential factors on the ITT process when modelling ITT at the Maasvlakte

There are multiple factors that have an influence on the ITT process. These include the congestion of the vehicles, the vehicle speeds, the terminal equipment and buffer areas, and prioritization of containers. Each of these factors will be discussed separately.

Duinkerken et al. do not take congestion into account. Tierney et al. modelled congestion by putting a capacity restriction on each arc. Four road intersections were modelled and three waterway intersections. Nieuwkoop describes that congestion does not have a significant influence on the ITT system with these demand scenarios. Schroër et al. made a built-in traffic model for congestion and delay at intersections and crossings with rail and public road. At the intersections, FIFO (only one vehicle can enter an intersection at a time) has larger mean vehicle delays compared to the priority algorithm (multiple vehicles can cross the intersection at the same time), but the difference in non-performance is very small. Crossings with rail or public road would have a significant impact on the system. It is possible that the ITT vehicles have to wait at a crossing with trains or vehicles at the public road. The experiment has included five intersections.

Both in the research of Nieuwkoop and Schröer experiments were done to see if a change in vehicle speed has a large influence on the results. These experiments show that the vehicle speed of the automated vehicles has a large effect on the non-performance. Nieuwkoop states that when the vehicle speed is lower, the vehicle requirements increase. Schröer states that when vehicles drive with a lower speed, more vehicles are needed and more congestion at the intersections will arise.

The literature about terminal transport shows that the size of the buffer area affects the number of AGVs required. This result is particularly significant for twin-load AGVs and multiple-load yard trucks. (Carlo, et al., 2014) In the research of Schröer this has been determined by the busiest scenario. The number of required terminal equipment is calculated based on the number of containers that must be handled. Each terminal has an overcapacity of terminal equipment, which causes that the ITT systems do not have to cope with large delays at the terminals.

Prioritization of containers takes place in the previous researches for minimizing the late delivery of containers. Tierney et al. minimized the container delivery delay and penalized late container delay by using three penalty functions for demands, representing low, medium, and high priority containers. (Tierney, et al., 2013) Schröer made a distinction between urgent and non-urgent containers. (Schroër, et al., 2013)

This research
Congestion at intersections and crossings with rail and public road will be taken into account in this research. The experiments in the research of Nieuwkoop and Schroër et al. show that this has a large impact and that the vehicles can experience large delays. This is especially the case when the volume of ITT containers gets larger.
Vehicle speeds of the AGV and ALV could have a large impact on the results. If needed, experiments will be done to see the impact of the vehicle speeds.
It has to be determined what is realistic for the terminal equipment and the buffer areas. This means, how realistic is it that vehicles experience delays because of the amount of terminal equipment or the size of the buffer areas?
Prioritization will also be taken into account in this research, because then the chance that containers arrive too late will be lowered.

2.4.5 Costs and benefits of the different ITT systems

In the research of Duinkerken et al. it is concluded that the robotized ITT (AGV and ALV) achieves the best service level at the lowest costs. Their service level rapidly increases to a plateau level if their number increases. The level of this plateau depends on other bottlenecks in the system, for example limited transfer cranes, or peaks in the demand for transport. The MTS solutions seem to converge slower to a somewhat lower plateau.
Tierney et al. does not compare the ITT systems based on costs. The authors recommend that the costs of building new infrastructure and/or purchasing new types of vehicles versus the improvements in port efficiency and reduction in delays must be analysed.

Nieuwkoop performed a Multi Criteria Analysis in his research (using the criteria total costs, punctuality, feasibility, sustainability, and flexibility) and this analysis shows that the AGV is the best vehicle type for the ITT system.
The conclusion in the research of Schroër et al. is that the ALV configurations are the best configurations, because they have by far the lowest non-performance and lateness values for each of the 3 scenarios.

This research
This research will evaluate the ITT systems on an extensive way. A Multi Criteria Analysis will be done, comparing the different ITT systems, which have the same minimum percentage of on-time delivery of containers.

2.5 Choice of simulation program to model Maasvlakte ITT

The simulation model must be suitable for the type of problem that will be modelled. Models can be classified in different ways. To decide which type of model will be used, a choice between different classes of models is made. Then the choice for an appropriate software package is explained.

2.5.1 Static versus dynamic

A static model represents a system at a particular time, or when time plays no (active or meaningful) role. In a dynamic model time does play an essential role. Queuing-type systems are nearly always dynamic models, because arrivals and service times take place over (simulated) time. In this case, the ITT is also a queuing-type system. The arrivals and service times take place over time in the model, therefore a dynamic model is a proper model.

2.5.2 Continuous-change versus discrete-change

In dynamic models, there is a difference between continuous-change and discrete-change models. State variables describe the state of the system at any point in (simulated) time. The state variables of the queuing system in this research include for instance the length of the queue, the arrival times of containers/MTSs, and the status of the servers (SCs, etc.).

Continuous-change means that the state variables can continuously change over time. In a discrete-change model the state variables can only change at instantaneous, separated, discrete points over time. In this research, the state variables can only change at the times of occurrence of discrete events, like arrivals or the loading of containers.

2.5.3 Deterministic versus stochastic

In deterministic models, all the input variables are fixed, non-random constants. In stochastic models, there are variables, which are not fixed constants, but random draws from probability distributions. For example, the service times of the terminal equipment are not fixed and the time and duration of the closure of crossings with rail or public road are not fixed. Therefore a stochastic model, which uses random draws from probability distributions, is appropriate.

2.5.4 Simulation software package

For this research a dynamic, discrete-change stochastic model has to be built. Multiple simulation software packages exist that are able to build such kind of model: Simio, Arena, ExtendSim, Promodel, Flexsim, Simul8. All these packages can be used for the described problem, but a choice has to be made.
Based on the availability of the programs at the university, the costs, and the user friendliness Simio is chosen. It is the only available program with a licence from the university and could be used without costs. Next to this Simio is a very user friendly program, because no programming skills are needed. Simio uses the latest in-software development. It has intelligent objects and has a new

object-based paradigm. Simio objects are created using simple graphical processes that require no programming. Simio is thus a very user-friendly package. With Simio it is also possible to make (2D and 3D) animations and Simio is applicable to ports. (Kelton, et al., 2011)

3 System analysis and simulation model development

A conceptualization of the ITT system will be made and the system will be analysed. First the conceptual modelling method is explained, after which a description of objects and processes is made. Then inputs and outputs of the simulation model are listed. Finally, the simulation model development is described.

3.1 Conceptual modelling of the system

First the choice of the conceptual modelling method will be discussed. Then a description of the objects will be given and finally a description of processes will be given.

3.1.1 Choice of conceptual modelling methodology

When making a conceptual model of the system, a distinction between conceptual modelling methodologies must be made. The methodology should be chosen in the context of the task to which it is applied. (Agarwal, et al., 1996) A distinction between a task that is function strong or data strong can be made. A task is *"function strong when it can be conceptualized almost entirely in terms of the operations it performs and data strong when it can be specified predominantly in terms of the data upon which it acts."* (DeMarco, 1982) When the distinction between operations and data is made, there are two methodologies that fit well; the process-oriented methodology and the object-oriented methodology (Constantine, 1989). The difference between those two methodologies is as follows:

- Using the process-oriented methodology*," the function and procedure are primary and the data are only secondary. Functions and related data are either conceived as independent, or data are associated with or attached to the functional components."* (Constantine, 1989)
- Using the object-oriented methodology, "*the data are considered primary and the procedures are secondary. Functions are associated with related data."* (Constantine, 1989)

The object oriented approach has some advantages in comparison with the process-oriented approach. The object oriented approach has "*expressive power, provides a good data abstraction and encapsulation, the resultant software is reusable, and the modelling technique has an inherently modular nature, which facilitates extensibility and maintainability.*" (Agarwal, et al., 1996) Proponents of the object oriented approach contend that it is a more natural method for the analyst. (Agarwal, et al., 1996)

In this research, the task is the Inter Terminal Transport. When looking at ITT, it has to be considered if the data or the procedures are primary. The containers contain a lot of information. The determination of the next transport assignment of a vehicle depends on the available information. The process cannot be determined on forehand, but it is dependent on the available data (of the containers). For example, a vehicle will only drive to a terminal where containers are waiting for transport. The information about the waiting containers is needed to determine this, and the next step of the process depends on the data. This means that an object-oriented methodology is most suitable for the simulation of ITT. This fits in well with the fact that Simio will be used for the simulation and is an object-oriented simulation tool.

A description of the objects will be made, by distinguishing different object classes and by describing their attributes and operations.

3.1.2 Description of objects of ITT

An object class describes the general characteristics applying all individual instances. The information and functionality of the different objects does not differ within an object class. In this situation the different object classes can be determined, because all the instances are the same.

Each container is an object class, each different ITT system can be seen as an object class, each different kind of terminal equipment is an object class, and an intersection is a separate object class.

These ITT systems will be simulated in the model:

- MTS-truck (+ trailers)
- AGV
- ALV

These different types of terminal equipment will be used at the terminals:

- SC
- ASC
- RS
- RC
- QC

(Duinkerken & Negenborn, 2014)

Table 3-1, Table 3-2, Table 3-3, and Table 3-4 show the different object classes and indicate whether the class is active or passive. Active objects can perform operations, sometimes make decisions, undergo operations of other active objects and determine the system behaviour. Passive objects often undergo operations from active objects and influence the decisions of active objects. The attributes and operations are shown per object class. The attributes of the object classes are equal to the properties of these object classes.

Table 3-1: Attributes and operations of object class container

Container
Passive
Attributes
Origin
Start time
Destination
Delivery time
Size in TEU

Table 3-2: Attributes and operations of object classes within the category ITT systems

ITT systems			
Trailer (of MTS)	**MTS-truck**	**AGV**	**ALV**
Active	Active	Active	Active
Attributes	*Attributes*	*Attributes*	*Attributes*
Speed	Speed	Speed	Speed
Clear time factor	Clear time factor	Clear time factor	Clear time factor
Capacity in TEU	Trailer coupling time	Capacity in TEU	Capacity in TEU
	Trailer decoupling time		Unloading time
			Loading time
Operations	*Operations*	*Operations*	*Operations*
Transporting containers	Attaching trailers	Transporting containers	Transporting containers

Waiting until loaded	Transporting trailers	Waiting until loaded	Unloading to platform
Waiting until unloaded	Detaching trailers	Waiting until unloaded	Loading from platform
	Waiting for new assignment	Waiting for new assignment	Waiting for new assignment

Table 3-3: Attributes and operations of object classes within the category terminal equipment

Terminal equipment				
SC	**ASC**	**RS**	**RC**	**QC**
Active	Active	Active	Active	Active
Attributes	*Attributes*	*Attributes*	*Attributes*	*Attributes*
Loading time	Loading time	Loading time	Loading time	Loading time
Unloading time	Unloading time	Unloading time	Unloading time	Unloading time
Operations	*Operations*	*Operations*	*Operations*	*Operations*
Loading containers	Loading containers	Loading containers	Loading containers	Loading containers
Unloading containers	Unloading containers	Unloading containers	Unloading containers	Unloading containers

Table 3-4: Attributes and operations of object class intersection

Intersection	
3-way crossing	**Crossing with rail or public road**
Passive	Passive
Attributes	*Attributes*
Time to cross	Time to cross
	Green light time
	Red light time

3.2 Inputs and outputs of the simulation model

First the inputs of the simulation model are given. Then the outputs of the model will be discussed, using the criteria that will be used in the MCA. An overview of the inputs and outputs of the simulation model is shown in Figure 3-1.

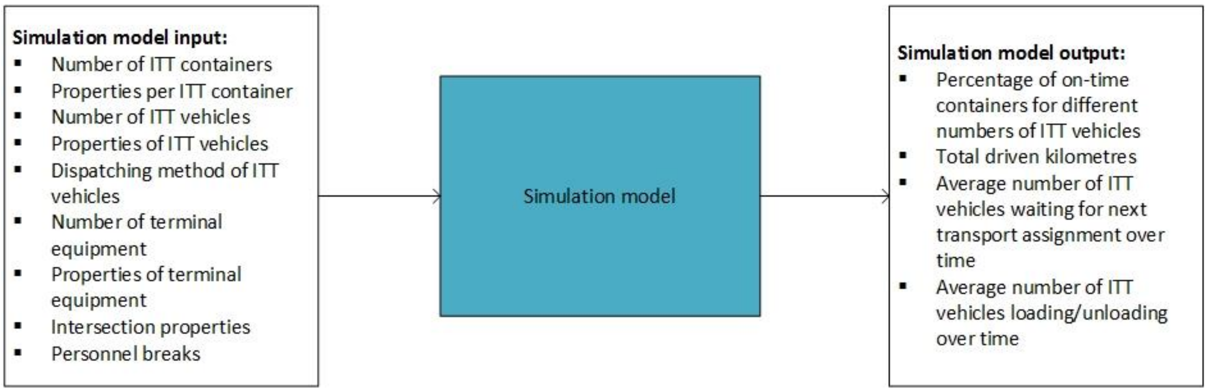

Figure 3-1: Inputs and outputs of the simulation model (Author, 2014)

3.2.1 Inputs of the simulation model

Two different kinds of variables can be distinguished from the input variables; the instrument variables and the external variables. External variables are non-controllable (and are not in the scope of this research), but the instrument variables can be influenced by the decision maker. (Delft University of Technology, 2006)

Instrument variables:

- Number of ITT containers
- Properties per ITT container
- Number of ITT vehicles
- Properties of ITT vehicles
- Dispatching method of ITT vehicles
- Number of terminal equipment
- Properties of terminal equipment
- Intersection properties
- Personnel breaks

External variables:

- Extreme weather conditions
- Failure of vehicles/equipment

3.2.2 Outputs of the simulation model

To evaluate the different ITT systems by the use of a MCA, the ITT systems must be comparable. This is possible on different ways:

- Setting a minimum level on the on-time delivery of containers
- Minimize the waiting times of the ITT systems
- Minimize the driving distances
- Minimize the number of vehicles
- Minimize occupancy rate of the vehicles
- Etcetera

The on-time delivery of containers is the key performance indicator (output variable) of Inter Terminal Transport. (Europe Container Terminals, 2014) Therefore it is stated that the percentage of on-time containers (containers that arrive at their destination before their delivery time) for every ITT system must achieve a minimum level. The determination of this minimum percentage for this research is explained in section 4.2: Scenario definition. To achieve this percentage, a certain number of vehicles is necessary, see Figure 3-2.

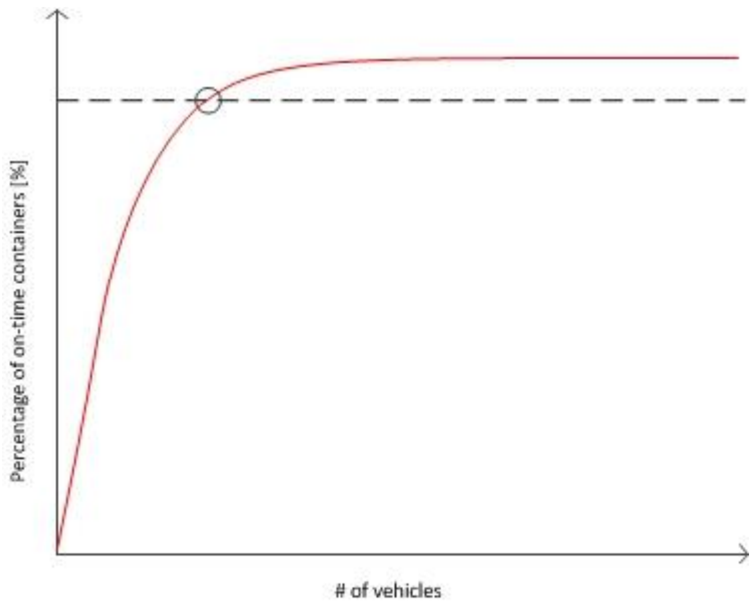

Figure 3-2: Relation between the percentage of containers that arrive on-time and the number of vehicles

After the needed number of vehicles per ITT system is determined, the different ITT systems will be evaluated using a Multi Criteria Analysis (MCA) (see section 4.5). This MCA uses the following criteria:

1. Total costs of the ITT system
   a. Fixed costs
      - Vehicle costs
      - Infrastructure costs
      - Software costs
   b. Variable costs
      - Maintenance and repair costs of the vehicles
      - Maintenance of the infrastructure
      - Maintenance contract of the software
      - Personnel costs
      - Energy consumption costs
      - Overhead costs

(Wiegmans & Konings, 2013)

2. Sustainability of the ITT system

(Europe Container Terminals, 2014)

For each of the criteria of the MCA it is determined which output of the simulation model is required.

Total costs of the ITT system

The vehicle costs can be determined using the needed number of vehicles. An estimation of the infrastructure costs has to be made. The maintenance and repair costs of the vehicles depend on the total number of driven kilometres. The total number of driven kilometres therefore has to be measured. The maintenance of the infrastructure and software has to be estimated. The personnel costs depend on the number of vehicles. During quiet periods less personnel has to be deployed (for manned vehicles), so the average number of vehicles that is waiting (for a next transport assignment) will be measured. The energy consumption costs also depend on the total driven kilometres of the ITT vehicles. The overhead costs will be estimated for each of the ITT systems.

(The MTS is modelled as if the MTS truck is always coupled to the set of trailers. This means that the MTS truck has to wait when the containers are loaded on the trailers. In reality the MTS truck can uncouple and already transport a loaded set of trailers. To make a good estimation of the decreased needed number of MTS trucks the average number of coupled MTSs that are loading/unloading over time has to be measured.)

Sustainability of the ITT system
It is assumed that electrical vehicles will be used in 2030. Therefore the sustainability will be measured by the electricity usage of the vehicles. Using the speed of the vehicles, the electricity usage per kilometre can be calculated. The driven kilometres must be measured to calculate the total electricity usage of the vehicles.

Conclusion output variables
An overview of the output variables:

- Percentage of on-time containers for different numbers of ITT vehicles
- Total driven kilometres
- Average number of ITT vehicles waiting for next transport assignment over time
- Average number of ITT vehicles loading/unloading over time

3.3 Simulation model development

In this chapter first the network will be described. Then the arrival of containers and the loading process are explained. The modelling of the intersections is discussed and the unloading of the ITT systems and the determination of their next transport assignment. A detailed description of the simulation model is given in Appendix A: Detailed description of simulation model.

The road network of Duinkerken et al. can also be used for this research, shown in Figure 3-3. (Duinkerken & Negenborn, 2014) The road will be a dedicated road, only for Inter Terminal Transport. This road does not exist yet, so have to be built in the future. All the roads are bidirectional and have one lane for each direction. It is not allowed for vehicles to overtake.

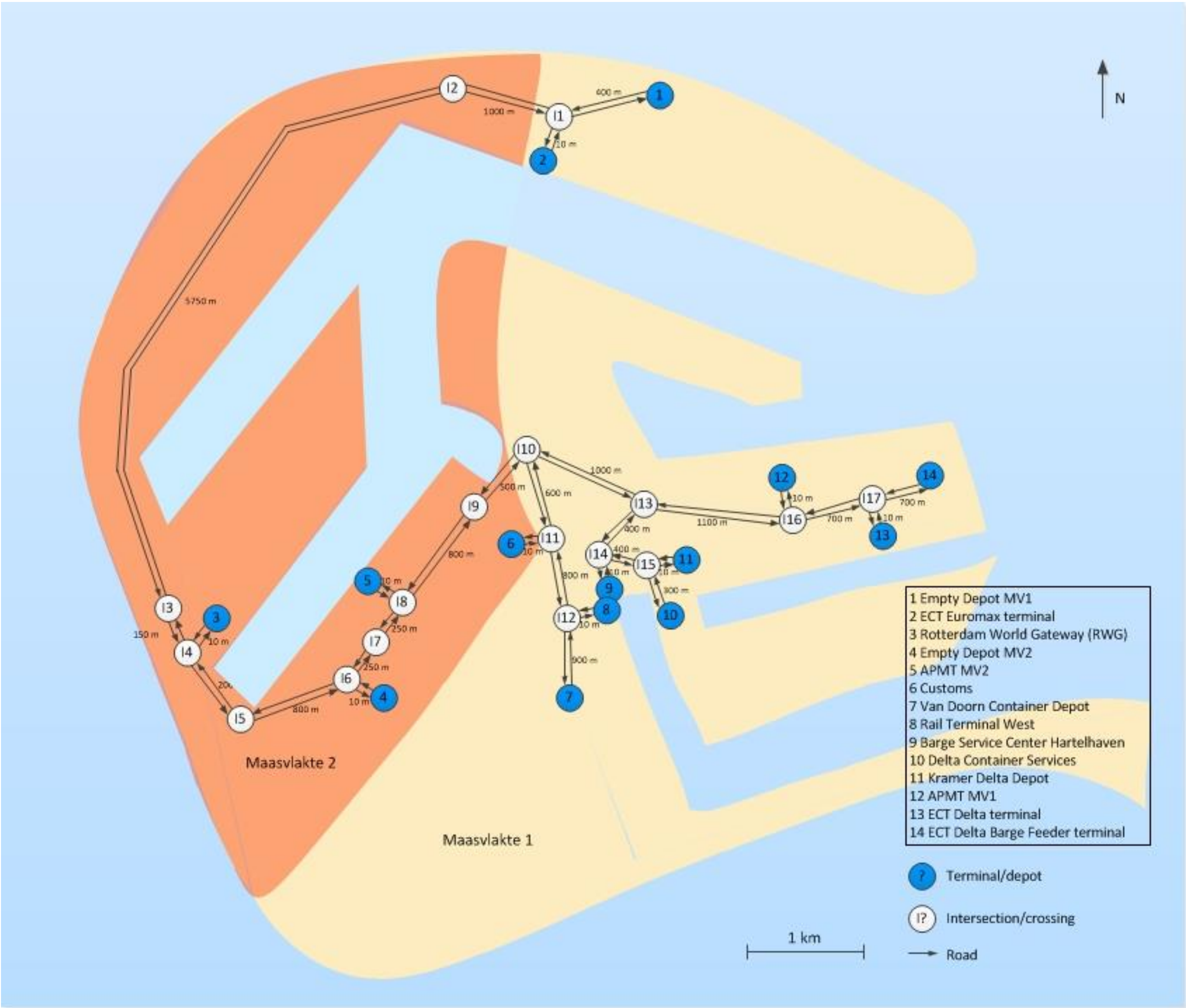

Figure 3-3: Road network (Duinkerken & Negenborn, 2014)

3.3.1 Process step 1: Arrival of containers at the terminals/depots

The containers are modelled as the entities that must be transported. A data table with all available containers will be made. Each container has the following properties:

- Start time
- Origin
- Delivery time
- Destination
- Size in TEU

At a certain point in time, the start time, a container will be created at its origin terminal/depot. At each terminal/depot the containers are put in different waiting areas, see Figure 3-4. Each destination terminal/depot has a separate waiting area. The waiting area per destination is divided in two separate waiting areas: an urgent waiting area and a non-urgent waiting area. Containers are labelled as urgent when their latest departure time is below a certain value, above this value the containers are non-urgent. The latest departure time is equal to the delivery time minus the transport time (without any delays at intersections) and the expected loading and unloading time. (The transport time can be calculated by dividing the distance with the vehicle speed. The expected loading and unloading time depends on the terminal equipment per terminal.) The containers are sorted in the (urgent and non-urgent) waiting areas by means of their latest departure time (the containers that must depart first are in the front of the waiting area).

When a container arrives at a terminal/depot, it is checked if the container is urgent or not. If the container is urgent, it will be put in the urgent waiting area. The non-urgent containers are put in the non-urgent waiting area. When a non-urgent container becomes urgent, that means, the latest departure time of that container is below a certain value, the container will be removed from the non-urgent waiting area and transferred to the urgent waiting area. (In reality the container stays at the same location, the waiting areas are virtual waiting areas that are only used in the simulation model.)

For the current ITT at the Delta terminal prioritization of containers is also done. (Europe Container Terminals, 2014) Containers that must depart urgently are transported first and have priority over other containers. This causes that all the containers have the largest chance of arriving on-time. In previous researches on ITT, prioritization of containers also takes place, as explained in section 2.4.4.

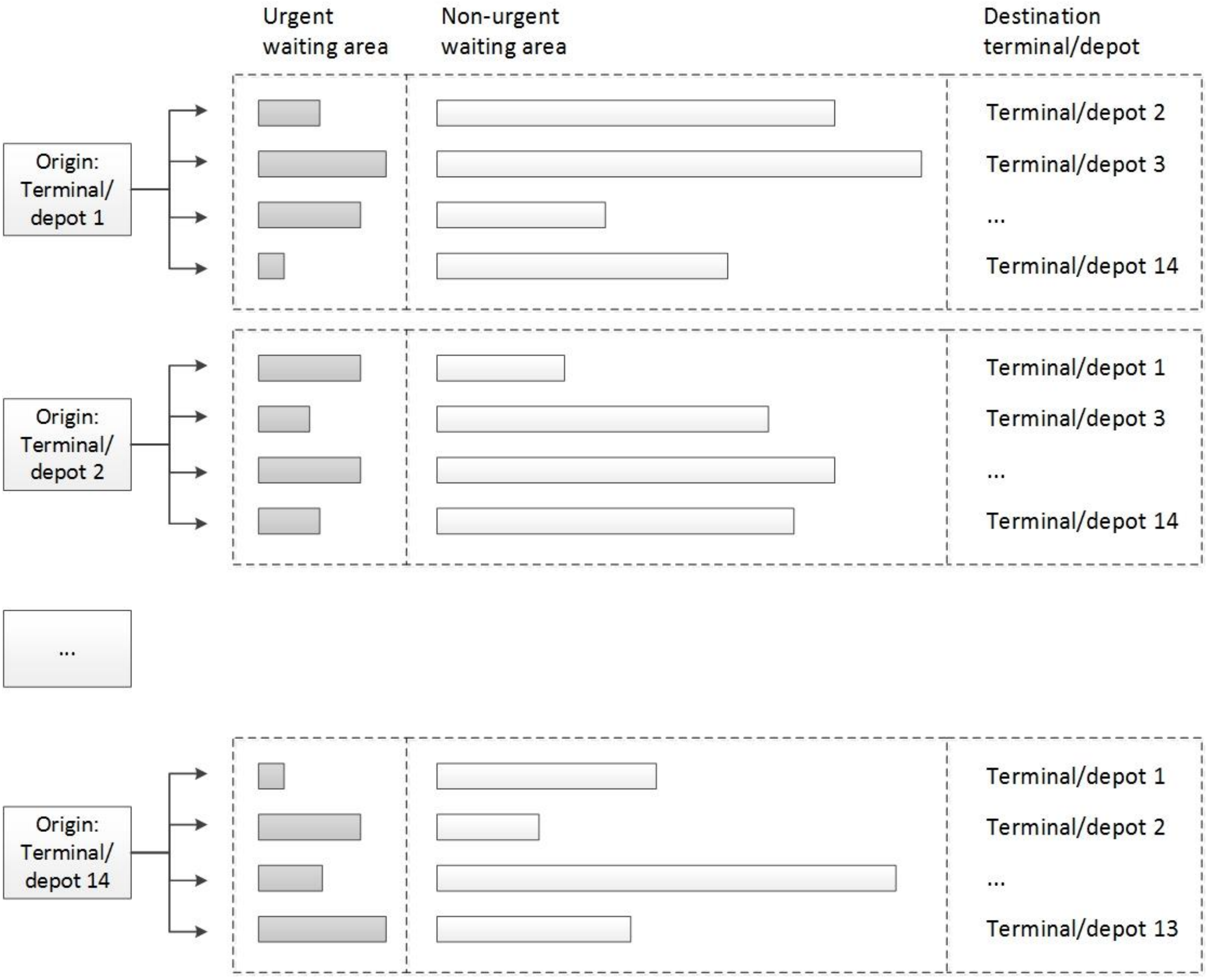

Figure 3-4: Arrival of containers

3.3.2 Process step 2: Loading process of containers on the ITT systems

At a terminal/depot vehicles arrive. The process of loading these vehicles is shown in Figure 3-5.

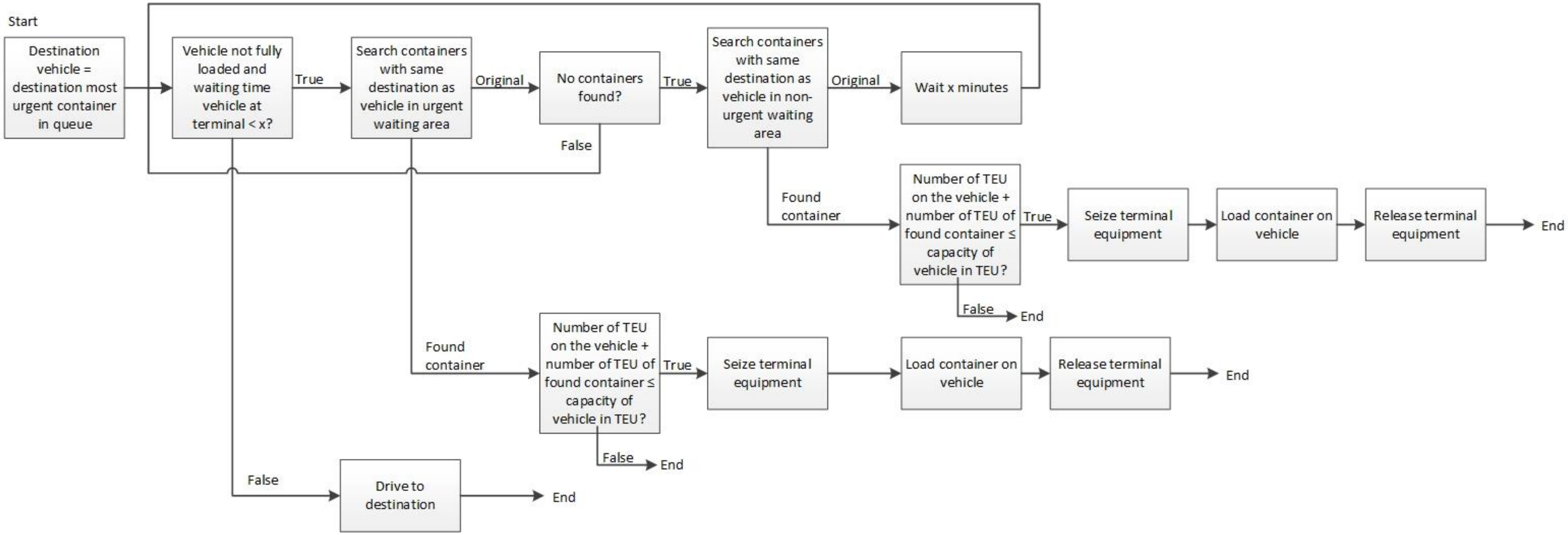

Figure 3-5: Loading process of the vehicles

When an empty vehicle arrives, the destination of the vehicle is determined by searching the most urgent container waiting at this terminal. This is possible by comparing the first available container per destination. The container with the latest departure time, that is first in time, is selected. The destination of this container will be assigned to the vehicle and the destination node of the vehicle will be set. (According to the process of the simulation model in Figure 3-5 there is a check if the vehicle is already fully loaded or if a time limit is exceeded, but this is never the case at this moment when the vehicle is still empty and has just arrived.) Then containers with the same destination will be searched in the urgent waiting area. (The current ITT at the Delta terminal also takes only containers with the same origin and destination per ITT vehicle (Europe Container Terminals, 2014).) If there are containers found, it is checked if the number of TEUs on the vehicle summed with the number of TEUs of the found container is smaller or equal to the capacity of the vehicle. When this is the case, the container will be removed from the waiting area and loaded on the vehicle by the terminal equipment (except for the ALV, because they can load by themselves). It will be checked if the vehicle is fully loaded or if a certain time limit after arrival of the vehicle is exceeded. When this is not the case, the non-urgent waiting area will be searched and found containers are loaded on the vehicle (if the sum of TEUs loaded on the vehicle and the TEUs of the containers is smaller or equal than the vehicle capacity in TEUs). The process continues until the vehicle is fully loaded or until the vehicle has exceeded the time limit. Then the vehicle will depart to its destination terminal.

3.3.3 Process step 3: Intersections and crossings at the ITT infrastructure

In the road network there are intersections. There are some 3-way crossings and there are crossings with rail or public road. The 3-way crossing do not have traffic lights, but the crossings with rail or public road do have traffic lights.

3-way crossing

At a 3-way crossing vehicles from different sides arrive. First the simulation model is run with no delay at the intersections. For each combination of scenario and ITT system the number of vehicles crossing an intersection is counted. The chance that a vehicle meets another vehicle (or the safety margin around the vehicle) at the intersection is calculated and a probability distribution for the waiting time is determined.

Crossing with rail or public road

A timer is set with a random interval time. This interval is based on a probability distribution and represents the interval between the trains which are passing by or the vehicles on the public road that cross. The crossing is modelled as a node, where vehicles entering that node have to wait until the timer event has elapsed for a certain time period.

3.3.4 Process step 4: Unloading of the ITT systems and new transport assignment of the ITT systems

At the destination terminal the containers are unloaded by the terminal equipment (except for the ALV, because they can unload by themselves). At each terminal, the same terminal equipment is used for loading and unloading, but the type of equipment can differ per terminal. An unloaded container is virtually transported to the sink, where the containers are removed from the system. The vehicle waits until all containers are unloaded. The vehicle fulfilled its transport assignment and must determine which container(s) will be next for transport. This process is shown in Figure 3-6.

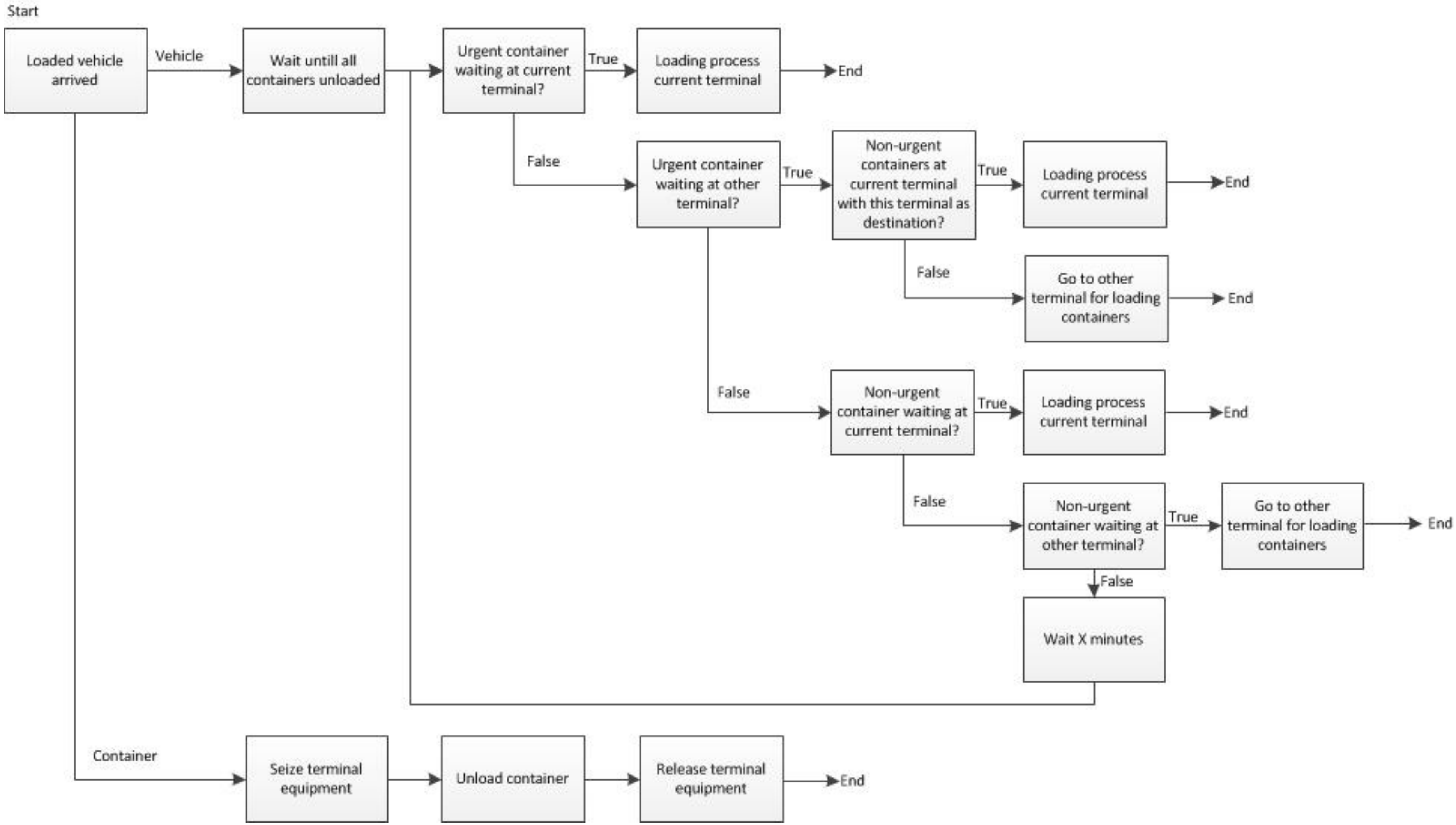

Figure 3-6: Determining next transport assignment of ITT vehicles

First it will be checked if there is an urgent container at the current terminal. Then the surrounding terminals are checked, starting from the closest to the most far away terminal. This will not be checked for all the terminals, because otherwise the vehicles drive very long distances for picking up the containers. Depending on the input data, for each terminal must be decided which surrounding terminals will be checked. For each urgent waiting area it is checked what the number of TEUs waiting is divided by the capacity of the vehicle in TEUs. The outcome is summed for all the waiting areas. Then the number of vehicles driving to the current terminal and the number of vehicles loading at the current terminal is subtracted. If a positive non-zero value remains, there are still urgent container(s) waiting for transport at this terminal. If at a terminal urgent containers waiting for transport are found, the vehicle must go there, but first will be determined if there are non-urgent containers at the current terminal with this terminal as destination. These can be taken already, while driving to this terminal for the next transport assignment. If there are no non-urgent containers with the certain terminal as destination, the vehicle will drive empty to the terminal.
When it appears that there are no urgent containers waiting for transport the non-urgent waiting areas of the terminal are searched. Also the same decision logic can be used here. The closest to the most distant terminal can be searched for non-urgent containers. If the vehicle does not find a new transport assignment, the vehicle must wait for x minutes and can then start searching for a next transport assignment again.

The MTS is a more difficult system than the AGV and the ALV. Containers are loaded on trailers and trailers are being pulled by the MTS-truck. The MTS-truck can couple and decouple from the trailers. In the time the trailers are being loaded, the MT-truck can fulfil another transport assignment. When there are (urgent) containers located at a terminal waiting to be loaded on a trailer, but there is no empty trailer, a MTS-truck must transport this trailer first from another terminal to that terminal. This requires a more complex way of modelling.
When the above logic is used, the MTS is modelled as if it is always coupled to the trailers. This causes that the number of MTSs found in the simulation model is too high, because normally the MTS-truck can uncouple and execute a new transport assignment, while the trailers are being loaded and unloaded by the terminal equipment. An estimation of the number of required MTSs and trailers has to be made, using the outcomes of the coupled MTS. Originally it was planned to also model a lower bound on the number of needed MTSs by modelling an unlimited amount of trailers, but this is excluded from the research. For an uncoupled variant an extra step has to be added to the process: first the containers are loaded on the (set of) trailers, and then the (set of) trailers are coupled to the MTS-truck. When the same logic is applied, the MTS-truck looks where (sets of) loaded trailers are to determine its next transport assignment. This can be done when a loaded set of trailers is available for transport; a set of trailers is fully loaded or when a container becomes urgent, the set of trailers (on which this containers is loaded) must become available after a certain time limit for transportation by the MTS-truck. There are some limitations using this logic, such as reduced information and a shortcoming during the period of loading compared to the coupled variant.
Using the uncoupled variant, the MTS-trucks do not know if there are urgent containers waiting at the terminals, only until the moment a loaded trailer is ready for transport. This means that the MTS-truck has less information compared to the coupled variant. During the period that a (not fully) loaded trailer (with (an) urgent container(s)) is available for transport, no extra containers can be loaded on the vehicle. Using the coupled variant, containers can be loaded during that period. Those limitations cause that no lower bound will be reached. This is further explained in Appendix B: Variant of the MTS-trucks with decoupling of MTS and trailers.

4 Experimental design of simulation model and Multi Criteria Analysis

For the experimental design of the simulation model, first the scenario definition and model set-up will be discussed. After this the validation and verification of the simulation model will be discussed. The model application and result analysis will be explained and finally the MCA will be performed. An overview of the components and the connections between them is given in Figure 4-1.

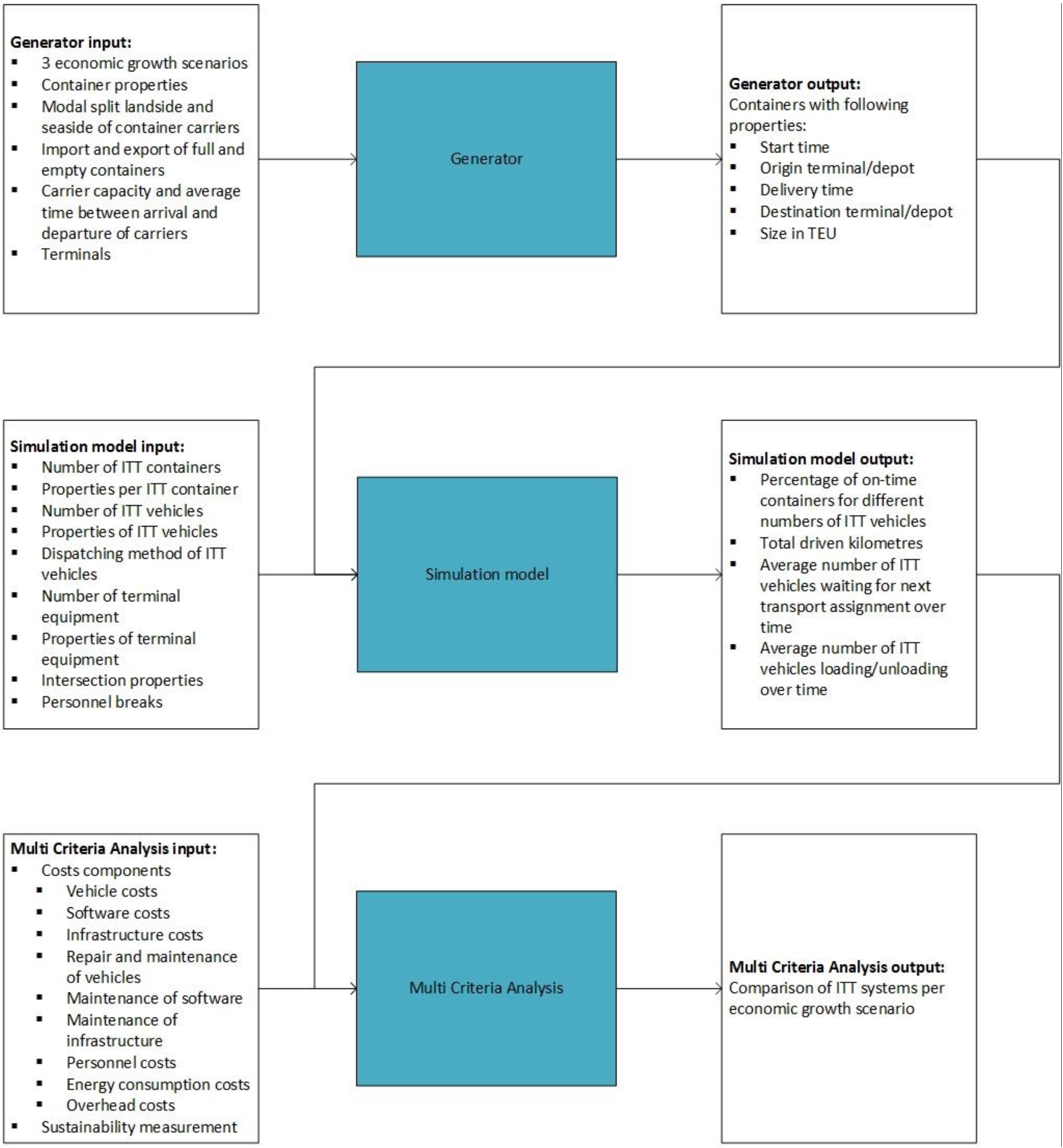

Figure 4-1: Overview of the components of this research and the connections between them (Author, 2014)

4.1 Scenario definition

Three different future scenarios for 2030 will be developed. A generator will be used for the generation of ITT containers. Three different transport demand input files will be created, based on the different future projections. The working of the generator will be explained and the economic growth scenarios are discussed. Finally the generator input variables and the generator output/transport demand input of the simulation model are discussed.

Working of generator

The generator of de Lange et al. will be used in this research (de Lange, et al., 2014). This generator is not the first one made for generating ITT containers. The following problems were earlier identified in previous studies. Gerritse made a generator to indicate possible future scenarios, but the scenarios were limited and the calculations were based on averages. (Gerritse, 2014) This is good indication of future demand flows of ITT, but not a specific scenario with visible peaks and peak durations. The FAMAS study links container arrival to the arrival of container carriers, but the container departure is not linked to the carrier departure. (FAMAS.MV2 2000-2002, 2000) The generator of de Lange et al. is able to link the arrival and departure of the containers to the container carrier, which creates a dynamic and more realistic time window for the future ITT scenarios. (de Lange, et al., 2014)

All the containers receive an arrival and departure modality. The generator creates batches of containers by linking them to container carriers. The size of the terminal determines the chance that containers arrive at that terminal. If the departure modality is also located at the arrival terminal, no ITT is needed. If the departure modality is not located at the terminal, the terminal must be transported to another terminal by means of ITT. The size of the terminals determines the chance that a container will depart over there.

There are different variables that can be changed in the generator, like the modal split, and the import and export ratio of full and empty containers. These variables are set at the same value for the different scenarios. There is much uncertainty about the economic prospects and it is not clear which of the four economic projections of Port Vision 2030 must be used. (Port of Rotterdam Authority, 2011) This will therefore be the only variable that will be changed. The bandwidth of the future ITT volume can be described with the projections. When only the ITT differs between the scenarios, it is possible to see which ITT system is the most appropriate per amount of ITT. The division of containers between the terminals will stay the same and only the size of the flows will change.

Economic growth scenarios

The Port of Rotterdam has determined four economic growth scenarios: low growth, high oil prices, European trend, and global economy. These scenarios are shown in Figure 4-2.

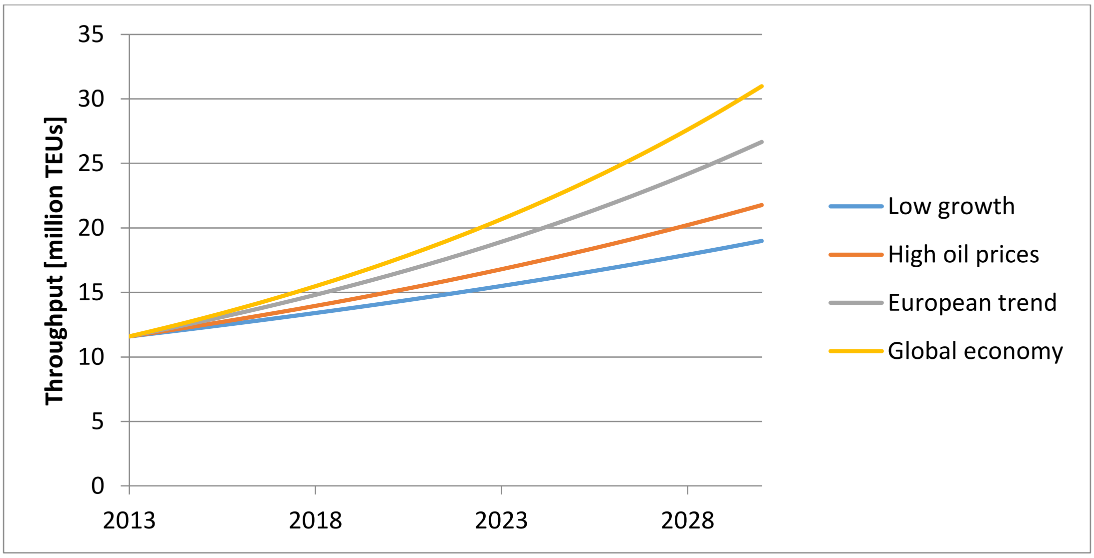

Figure 4-2: Economic growth scenarios (Port of Rotterdam Authority, 2011)

These scenarios were made in 2008. At this moment data until 2013 is known, so the updated information is used to have a critical view on the growth scenarios. The global economy scenario is considered to be too optimistic. The last years the growth was far below the global container growth and it is not expected that the growth in Rotterdam reaches the level of the global growth. This means that the container port traffic would almost need to triple from 2013 until 2030 with an average growth percentage of 5.95%. Therefore the global economy scenario is not taken into account in this research.

The other scenarios are considered as more realistic scenarios and will be taken into account. As the container traffic in this area is still recovering from the crisis (in 2013 there was still a decrease of 0.1%), it is possible that the growth will stay minimal and that the low growth scenario will be followed. The scenario with the high oil prices is assumed to be the most realistic, because it assumes a moderate growth and a strict environmental policy. Much more attention is and will be paid to the sustainability of industry and logistics. The European growth scenario can also be seen as a realistic scenario, because it follows the existing policy and a moderate growth. The European growth scenario and the low growth scenario show the upper and lower bound of the estimation of the future.

Generator input variables
The chosen values of the variables that can be changed in the model, like the modal split, and the import and export ratio of full and empty containers are explained in Appendix C: Scenario definition. The output of the generator consists of a large table with a list of containers. Each container is assigned with a start time, origin (terminal/depot), delivery time, destination (terminal/depot), and size in TEUs. Three of those tables will be created; one for the low growth scenario, one for the high oil prices scenario, and one for the European trend scenario.

Generator output/transport demand input
For a period of 22 days ITT containers have been generated. One day warming up period is enough to divide the vehicles over the network (actually a few hours is already enough), because then already hundreds of containers are transported. (Verbraeck, 2014)
The generator uses a weekly pattern. It is best to let this pattern return three to six times. Because of the computer run time, three weeks/21 days is chosen to be the simulation time. (In total 9 combinations of scenario have to be run. For each combination first the number of vehicles has to be found, and then multiple replications have to be done. Therefore it is desirable that the computer run time per run is as short as possible.)
The month September will be used for the simulation, this is the second busiest month per year (9% of the containers are handled during this month). At airports it is required that the systems must be able to handle a 'busy day'. (Transportation Research Board / National Research Council, 2002) A busy day is specified as the second busiest day of an average week of the busiest month. In this research the busiest day of an average week of the second busiest month (9% (busiest month) * 25% (average week) * 21% (second busiest day) = 0.473% of the yearly volume) is approximately equally busy as the second busiest day of an average week of the busiest month (10% (busiest month) * 25% (average week) * 19% (second busiest day) = 0.475% of the yearly volume).
When the month September reaches the required level of on-time containers, it is assumed that this is sufficient. During the busiest month, a few days (the busiest days of the average weeks) extra equipment will be deployed. This causes a large cost reduction, because otherwise the whole year there is an overcapacity of equipment and only a few days during the busiest month it is actually required. (During the busiest period there is a cost increase.)

All the assumptions are the same for the three scenarios, so there is no difference in the way the containers are divided over the terminals and depots. There is only a difference in the amount of containers per scenario. This amount of containers is generated per scenario for a period of two months:

- Low growth scenario: 46,096 containers/76,476 TEU in 22 days (0.70 million containers/1.17 million TEU per year)
- High oil prices scenario: 51,265 containers/85,077 TEU in 22 days (0.78 million containers/1.29 million TEU per year)
- European trend scenario: 65,579 containers/108,828 TEU in 22 days (0.99 million containers/1.66 million TEU per year)

In Appendix C: Scenario definition, three OD-matrices are shown with the exact number of containers to and from each terminal and depot.

Most of the ITT containers are originating from and/or going to the container terminals. Large terminals have relatively more ITT moves than smaller terminals, because the size of the terminals determines the chance that containers/container carriers arrive or depart from the terminal. Also a large flow to and from the customs is generated, because 0.25% of the full ITT containers has to go to customs. The ITT move of those containers is therefore split up in two parts; from their origin terminal to customs and from customs to their destination terminal.

There are very low moves to and from empty depots. This is caused by the fact that only empty containers, that already have an ITT move between two terminals, will be stored in an empty container depot if they are longer than 120 hours/5 days at the port. The available transport time for the ITT move will then be divided in two, and the ITT move is separated in two parts. A very small amount of containers stay longer than 5 days at the port, so the amount of empty container moves is also very low.
In reality, shipping companies give orders to transport (a certain amount of) empty containers from a terminal to an empty depot or vice versa, because they must pay for containers that are stored longer than a certain time in the stack. These orders are not taken into account by the generator, so in reality there would be more ITT moves.

At some terminals there is no balance between the incoming and outgoing ITT containers. It is noticeable that for three terminals in the west of the network significantly more containers have the terminals as destination than origin, and for three terminals in the east this exactly the opposite. This unbalance between in incoming and outgoing containers must be taken into account for the determining the next transport assignment of the vehicles.

The data of the start time of the containers shows clearly a weekly pattern, see Figure 4-3. For instance, in the weekends less containers arrive at the terminals.

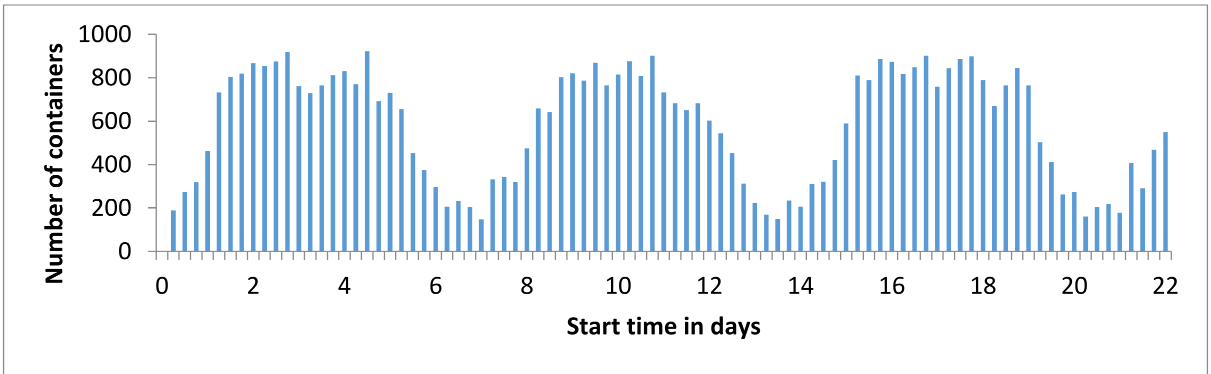

Figure 4-3: Weekly pattern of start times of containers for scenario high oil prices (Author, 2014)

There is a lot of time pressure on a part of the ITT containers, see Figure 4-4. More or less 20% of the containers has an available transport time lower than 1 hour and more or less 27% of the containers has an available transport time lower than 2 hours. The available transport time is the time between the delivery time and the start time.

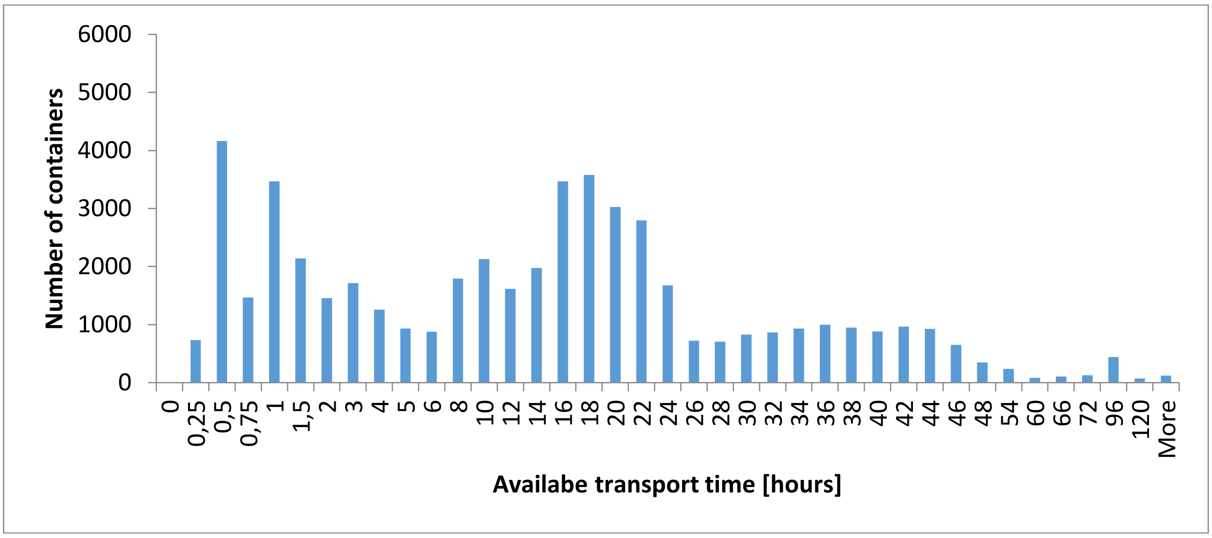

Figure 4-4: Histogram of the available transport time for scenario high oil prices (Author, 2014)

When these input data would be used, there are containers that are on forehand too late, because their available transport time is very low. This is considered to be not realistic. (Europe Container Terminals, 2014) At the current ITT system of Europe Container Terminals containers are deleted from the loading/unloading list when it is on forehand known they won't be able to arrive on time and will get a new delivery time and destination. Therefore the available transport time of all the containers is increased with one hour (one hour is added to the delivery time of the containers) and this data will be used in the simulation model.
Those increased available transport time matches better with the current available transport times of containers of the current ITT of ECT. (Europe Container Terminals, 2014) In this case all the available transport times are enlarged with 1 hour, but it is also possible to enlarge the available transport time of the containers of which it is on forehand known that they will be too late.

4.2 Model set-up

Not only the ITT containers and their properties are important for the simulation model, also a lot of other values must be determined. These include the properties of the ITT systems and the type and number of equipment per terminal. Input values for the intersections have to be determined and the personnel breaks are important for the manned vehicles. The minimum percentage of on-time containers, a threshold value for urgent containers, and the number of replications have to be determined.

A part of the input values of past researches (which are verified by Europe Container Terminals) will be used in this research as well and a part of the values is based on the data and expert view of Europe Container Terminals. An overview of all the input values for the simulation model is given in Appendix D: Input values of the simulation model. In this section the input values will briefly be discussed. This includes the input values of the ITT systems, the terminal equipment, the intersections, the personnel, and other simulation model input values.

4.2.1 ITT systems

The ITT systems have different properties, like the speed and the capacity. The proposed values of the research of Duinkerken and Negenborn are shown in Table 4-1. (Duinkerken & Negenborn, 2014) These values are verified by ECT and are considered realistic. (Europe Container Terminals, 2014)

Table 4-1: ITT system properties

	This research	Duinkerken & Negenborn
AGV		
Speed [km/h]	40	40
Capacity [TEU]	2	2
ALV		
Speed [km/h]	40	40
Capacity [TEU]	2	2
Container load time [min]	0.5	0.5
Container unload time [min]	0.5	0.5
MTS		
Speed [km/h]	30	30
Capacity [TEU]	10	10

(Duinkerken & Negenborn, 2014)

4.2.2 Terminal equipment

Each terminal has terminal equipment for the loading and unloading of the ITT systems. Only for the ALV no equipment is needed, because they are able to load and unload by themselves. The type of terminal equipment of the current and new terminals is known, but the ASCs are not able to load and unload a MTS. Therefore another type of equipment is assumed for these terminals. The type of equipment per terminal is shown in Table 4-2.

Table 4-2: Type of terminal equipment per terminal

Terminal number	Terminal	This research: equipment type	Duinkerken & Negenborn: equipment type
1	Empty depot MV1	RS	RS
2	ECT Euromax Terminal (when MTS used)	ASC SC/RS	ASC ASC
3	RWG (when MTS used)	ASC SC/RS	ASC ASC
4	Empty depot MV2	RS	RS
5	APM MV2 (when MTS used)	ASC SC/RS	ASC ASC
6	Customs	RS	RS
7	Van Doorn container depot	RS	RS
8	Rail Terminal West	RC	SC
9	Barge Service Center Waalhaven	QC	RS
10	Delta Container Services	QC	RS
11	Kramer Delta depot	RS	RS
12	APM MV1	SC	ASC
13	ECT Delta Terminal	SC	ASC
14	ECT Delta Barge Feeder Terminal	QC	SC

(Duinkerken & Negenborn, 2014)

The number of terminal equipment that will be used is calculated by the following formula:

$$\text{equipment}_{\text{required}} = \frac{\text{number of containers during simulation period}}{\text{length of simulation period / handling time per container}}$$

$$\text{equipment}_{\text{used}} = \text{round}(\text{equipment}_{\text{required}}) + 2$$

Based on the data of ECT, distributions for the loading time and unloading time per type of terminal equipment are determined. These are based on existing data (Europe Container Terminals, 2014). In Table 4-3 an overview is given.

Table 4-3: (Un)loading time per type of terminal equipment

Type of terminal equipment	This research: (un)loading time [min/container]	Duinkerken & Negenborn: (un)loading time [min/container]
ASC (automated stacking crane)	Triangular(2.5,0.5)	4
RS (reach stacker)	Triangular(3,1)	3
SC (straddle carrier)	Triangular(3,1)	3
RC (rail crane)	Triangular(2,0.5)	/
QC (quay crane)	Triangular(2,0.5)	4

(Duinkerken & Negenborn, 2014)

4.2.3 Intersections

There are two types of intersections; traffic lights and crossings. Per type the input values for the simulation model are discussed.

Traffic lights

Table 4-4 shows the values for the traffic lights. The proposed values of Negenborn and Duinkerken are verified by ECT (Europe Container Terminals, 2014). The crossing time of the ITT vehicles is considered realistic and will be used in this model as well. Negenborn and Duinkerken propose 18 minutes of green time for the traffic lights and 2 minutes of red light time (Duinkerken & Negenborn, 2014). The value of these numbers is considered as realistic, but the numbers are deterministic. In reality, the arrivals of vehicles at the public road or trains will not be equally divided over time, so a probability distribution is made for the green time, using the proposed values as the mean.

Table 4-4: Green and red time of traffic lights

	This research	Duinkerken & Negenborn
Green light time	Triangular(16,18,20)	18
Red light time	2	2

(Duinkerken & Negenborn, 2014)

3-way crossing

The chance that a vehicle meets another vehicle at a 3-way crossing is determined by the percentage the intersection is occupied by vehicles. This is the number of blocks during the simulation period times the block length, divided by the total simulation period. The block length (length that must be kept free around one vehicle) is equal to the intersection length summed with the vehicle length, divided by the vehicle speed summed with the time between two consecutive vehicles. From the 12 possible combinations of two vehicles at one intersection, only 6 of them are conflicting. Therefore the change that a vehicle meets another vehicle is divided by two.

When a vehicle has to wait, the waiting time is determined by the deceleration and acceleration time summed with a uniform chance between 0 and the waiting time of a full block length of the other vehicle. The waiting time per ITT system is shown in Table 4-5.

Table 4-5: Waiting time at 3-way crossings per ITT system

ITT system	Waiting time
AGV	8.9 + uniform(0,5.2)
ALV	8.9 + uniform(0,5.0)
MTS	10.3 + uniform(0,14.3)

4.2.4 Personnel

There are terminals that are using equipment that is manned. When personnel is employed, personnel breaks are provided for the employees. The current personnel breaks of ECT, shown in Table 4-6, are used in the simulation model for the terminals with the non-automated equipment, because it is expected that these will also be used in the future. (Europe Container Terminals, 2014) Not all the personnel has breaks at the same time, because then the whole ITT process (at that terminal) is paused. It is desirable that (urgent) containers always can be retrieved or delivered. One employee per terminal will have a late break, so these containers can be handled.

Table 4-6: Personnel breaks

Personnel break (normal)	Personnel break (late)
11.15h – 12.00h	12.00h – 12.45h
19.15h – 20.00h	20.00h – 20.45h
03.15h – 04.00h	04.00h – 04.45h

4.2.5 Other simulation model input values

There are other input values that must be set for the simulation model. Each of the input values will be discussed.

Determining next transport assignment: urgent containers at surrounding terminals
While determining the next transport assignment of the vehicles, first it is determined whether there are urgent containers at the surrounding terminals. Because of the unbalance of incoming and outgoing containers at some terminals, the search for urgent containers is adapted. Because there are significantly more containers with terminal 12 (APMT MV1), terminal 13 (ECT Delta terminal, and terminal 14 (ECT Delta Barge Feeder terminal), as origin than as destination, more vehicles have to be sent to these terminals. Therefore at terminal 6, 9, 10, and 11 it will also be checked whether there are urgent containers at these terminals. Table 4-7 gives an overview of the terminals which will be searched for urgent containers.

Table 4-7: Next transport assignment: searching for urgent containers at surrounding terminals

Terminal	Surrounding terminals
1	2
2	1,3
3	4,5
4	3,5
5	3,4,6
6	7,8,5,12,13,14
7	6,8

8	6,7
9	10,11,12,13,14
10	9,11,12,13,14
11	9,10,12,13,14
12	13,14
13	12,14
14	12,13

Minimum percentage of on-time containers

To compare the different ITT systems, they must achieve the same amount of containers that will be delivered on-time. This means that the maximum percentage of non-performance (containers that are delivered too late) must be determined. More or less 20% of the containers has less than 2 hours to be transported. This means that the ITT vehicles must quite fast pick up the containers. During the running of the simulation model it became visible that the MTS wasn't able to achieve much higher percentages of 95% on-time containers (in contradiction to the AGV and ALV), even when the number of vehicles increased. Therefore the minimum percentage of containers that must be delivered on-time is set to 95%.

Threshold value for labelling containers as urgent

A threshold value for labelling the containers as urgent has to be determined. When the latest departure time of a container is below this threshold value, the container becomes urgent. There needs to be enough time to pick up the containers by the ITT vehicles when they become urgent, but when the value is set too high, very much containers are labelled as urgent, which causes that the ITT vehicles travel further in total, because they first need to transport all the urgent containers. To meet this requirement, a value of 1 hour is used in the model.

Number of replications

It is not sufficient to run only one replication per experiment, because required accuracy in the output must be achieved. Therefore a method is used to determine the required number of replications. (Hoad, et al., 2007) The precision is defined as ½ width of the confidence interval, expressed as a percentage of the cumulative mean. A desired precision must be defined. Hoad et al. use a desired precision of 5%. In this simulation model also a desired precision of 5% will be used. For one output parameter the precision will be measured. In this case this will be the percentage of on-time containers. When the precision becomes less than or equal to the desired precision, x extra replications must be run. This is because it is possible that the precision converges to a level below the desired precision, and then diverges again. Hoad et al. advise that the value of the extra number of replications must be set to 5, because then the majority of premature convergence problems were solved during testing. (Hoad, et al., 2007)

4.3 Verification and validation of the simulation model

The simulation model is verified and validated. Verification is described as the determination if the simulation model performs as intended. Validation is defined as the determination whether the simulation model is an accurate representation of the system under study (Kleijnen, 1995).

4.3.1 Verification

The model verification is divided in two parts. During the model building verification is applied continuously to check whether there are programming errors. This is done by making a simplified model, where it is known how the model should behave. (Kleijnen, 1995) After the whole simulation model is built, extreme conditions testing is applied. (Sargent, 2007)

Check for programming errors using a simplified model

During the building of the simulation model in every step verification is applied, it is checked whether there are programming errors/bugs. First a simplification of the model was built, a model with only 2 terminals, to check whether the loading and unloading process worked as intended. Only a small amount of containers and vehicles were used in such a way that is was known what should happen.

Tests were done to check if the model behaves correctly. A few examples are summed below:

- Does the vehicle depart at the loading area when it is fully loaded or when the time limit is reached?
- Does the vehicle load non-urgent containers, when there are no more urgent containers?
- When the number of TEUs on the vehicle is capacity – 1, does the vehicle take only a 1 TEU container?
- Does the vehicle wait until all the containers are unloaded?
- Is the model working correctly when more vehicles are loading or unloading at the same time?
- Do the vehicles wait at crossings/intersections and do they pass after each other?

After the simple model was made, all the other terminals were added. The determination of the next transport assignment was tested by using a small amount of containers and vehicles. These test were executed:

- When there are more urgent or normal containers at different terminals, does the vehicle choose a container at the closest terminal?
- When there are normal containers at the current terminal, but urgent containers at another terminal, drives the vehicle to the right terminal?

Extreme conditions testing

When the simulation model is finished, extreme conditions testing is used to verify the model. It is stated that the model structure and outputs should be plausible for any extreme and unlikely combination of levels of factors in the system. (Sargent, 2007) This means that some variables are put to zero or to a very large value. The following tests were done to check to verify the model:

- If the available transport time is infinite (delivery time is infinity), then all the containers are expected to be delivered on time.
- If there is no delay at intersections, the vehicle speed is very high, the number of vehicles are very high, the number of terminal equipment is very high, and the loading and unloading times are zero, all the containers must be delivered on-time.

The results of the tests were equal to the expected results; 100% of the containers are delivered on time for both of the two tests. Therefore the simulation is verified.

4.3.2 Validation

Because there is no data for historic replay and the simulation is made for a non-existing system, expert validation is the only way for validation of the model. (Sargent, 2007) Experts were asked to check whether the model and/or its behaviour are reasonable. (Negenborn, et al., 2014) The input data for the simulation model is discussed and also the assumptions and processes in the simulation model. The limitations are given in this report. The results were checked, but because of an error, the number of vehicles was too high. An expectation on the number of vehicles was given. After the meeting, adjustments were done and new, more realistic, results were obtained, in line with the expectations.

4.4 Model application and result analysis

In total 3 ITT systems are modelled: the AGV, ALV, and MTS. There are 3 different future scenarios which are investigated. These future scenarios can be distinguished in the low growth scenario, the high oil prices scenario, and the European trend scenario. This means that for each scenario every ITT system is investigated and this results in (3*3=) 9 experiments (combinations of ITT system and future scenario). For each experiment the simulation model is run for three weeks (with a warm up period of 1 day). Multiple replications are run to achieve the required accuracy in the output results.

Results

Per economic growth scenario a graph is drawn for the different ITT systems. The number of vehicles versus the percentage of on-time containers is shown. Per ITT system it is shown how much vehicles are needed to achieve 95% on-time containers. Figure 4-5 shows this for the low growth scenario, Figure 4-6 for the high oil prices scenario, and Figure 4-7 for the European trend scenario.

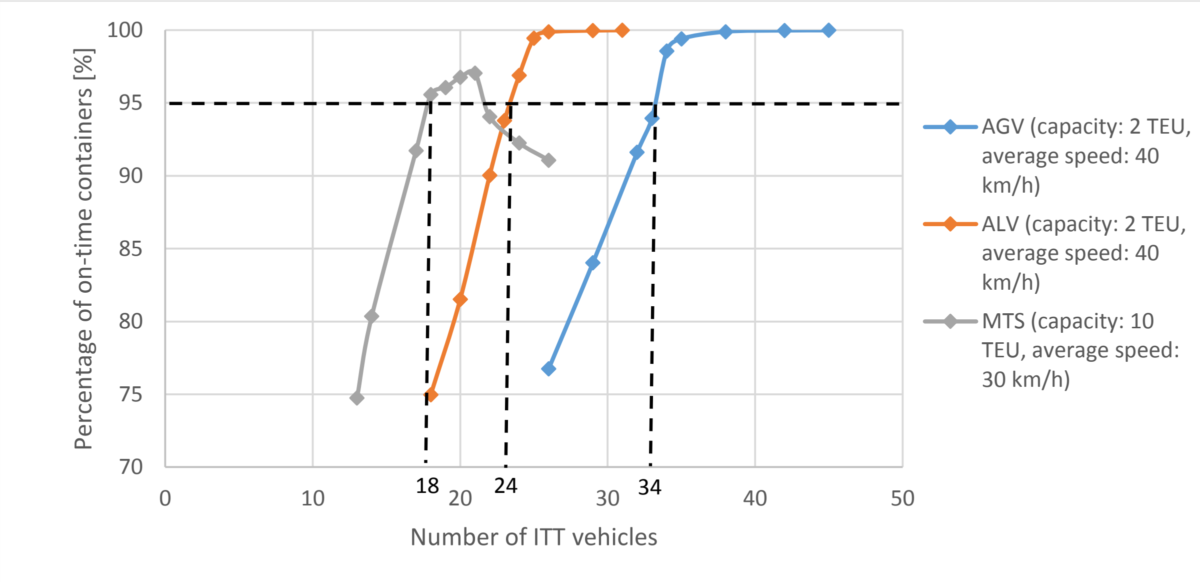

Figure 4-5: Number of vehicles versus the percentage of on-time containers for the scenario low growth (Author, 2014)

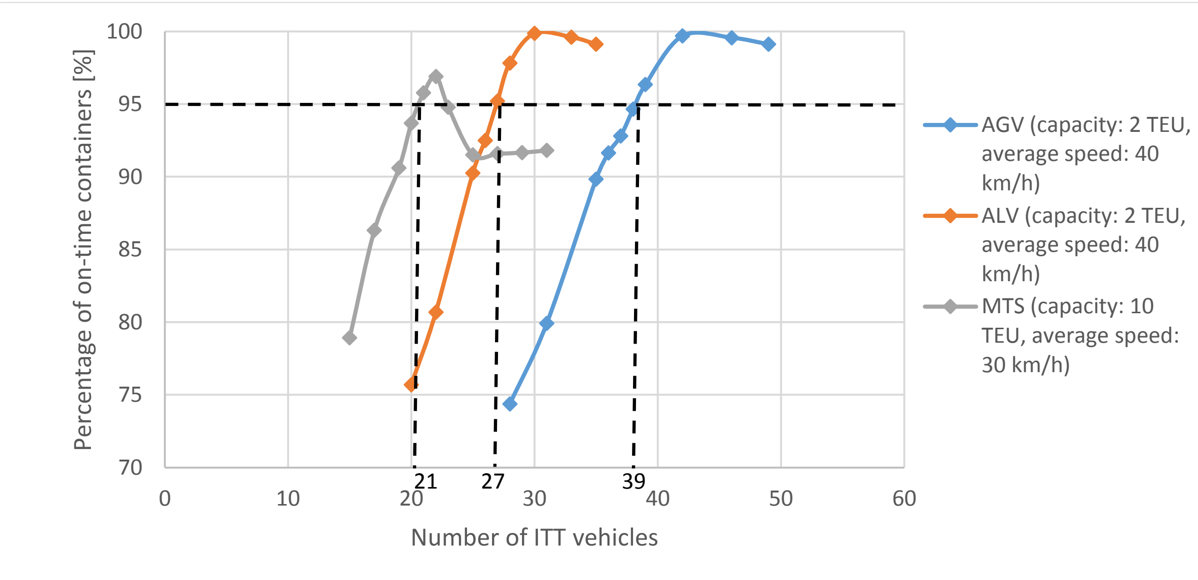

Figure 4-6: Number of vehicles versus the percentage of on-time containers for the scenario high oil prices (Author, 2014)

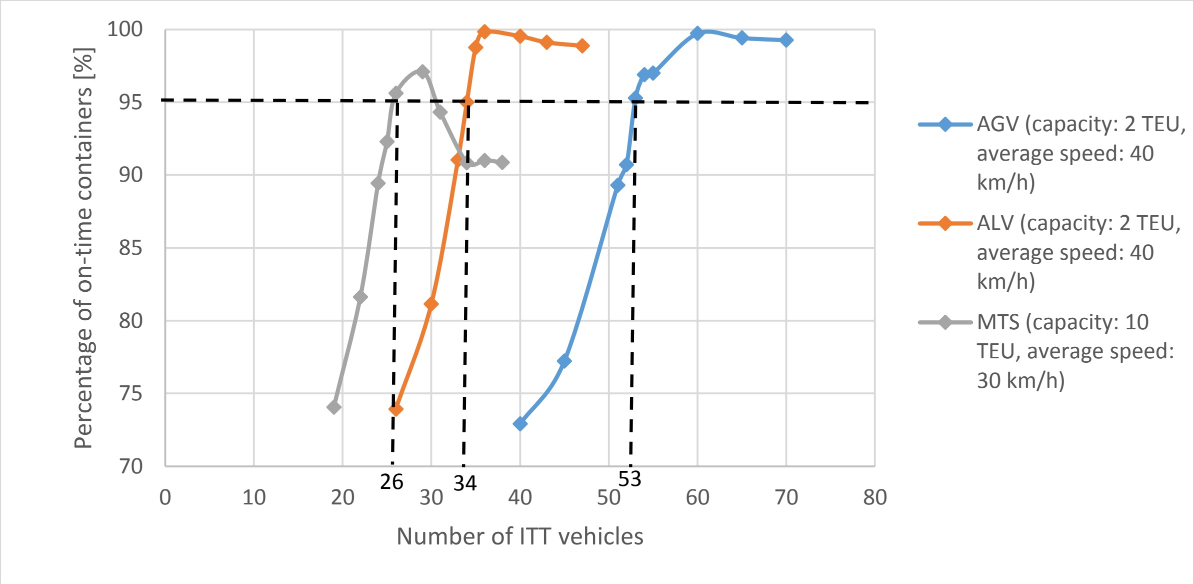

Figure 4-7: Number of vehicles versus the percentage of on-time containers for the scenario European trend (Author, 2014)

Result analysis

Figure 4-5, Figure 4-6, and Figure 4-7 shows that the MTS needs the lowest amount of vehicles. The ALV needs more vehicles, but less than the AGV. It is noticeable that the MTS cannot reach close to 100% on-time containers (only to approximately 97%), but the AGV and ALV can. The vehicle speed does not have an influence on the on-time delivery, see Figure 4-8. The vehicle speed only has an influence on the number of needed vehicles. The capacity of the vehicle has got an influence on the percentage of on-time containers, see Figure 4-9. Because of the high capacity of the vehicles, the time during the loading and unloading causes that not all the containers can be delivered on-time.

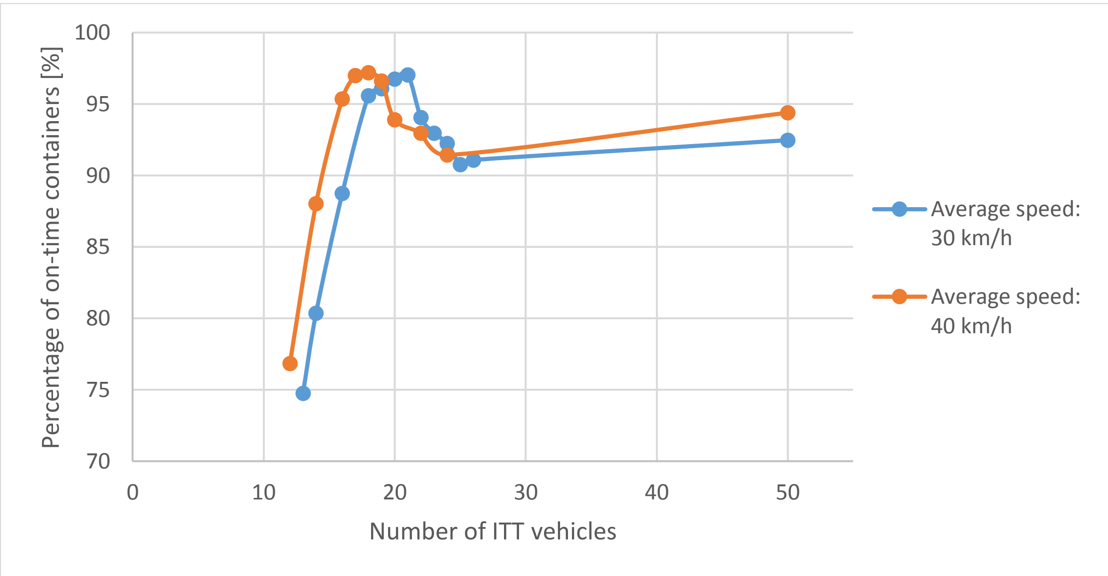

Figure 4-8: Percentage of on-time containers compared to the number of ITT vehicles with different average vehicle speeds of the MTS for the low growth scenario

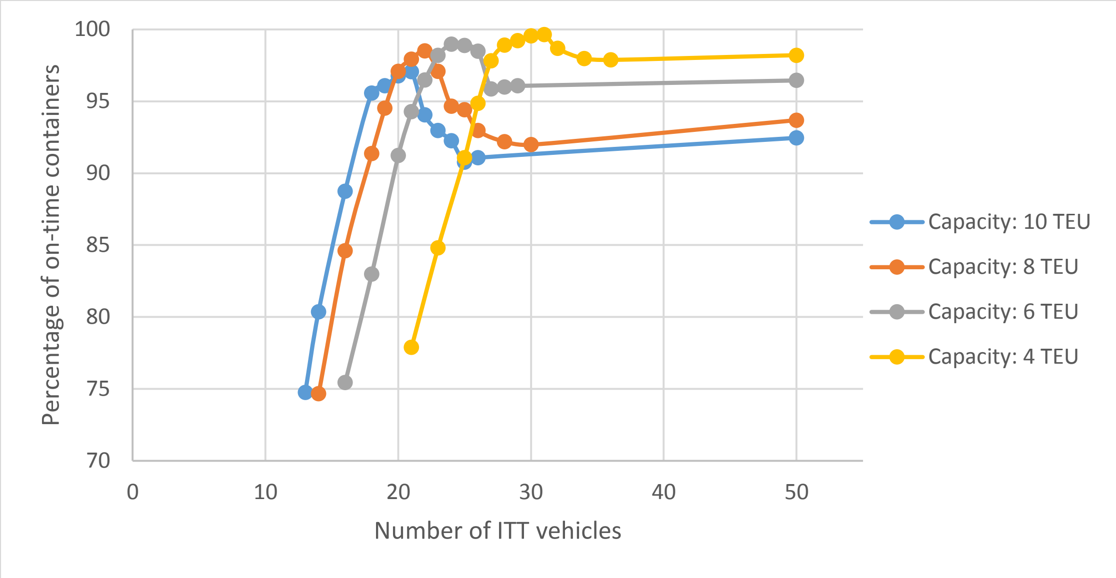

Figure 4-9: Percentage of on-time containers compared to the number of ITT vehicles with different vehicle capacities of the MTS for the low growth scenario

The MTS actually has a decrease in percentage on-time containers when more vehicles are added. Then the percentage of on-time containers stays with more vehicles equal to 91%. An analysis of the decrease is done, which is explained in Appendix E: Analysis of the decrease of on-time containers. When more vehicles are added, the average number of vehicles that is loading/unloading, the average number of vehicles that is waiting for a new transport assignment, and the average number of vehicles that is driving increase, and the total driven kilometres increase. In the loading process, a vehicle starts driving when it is fully loaded or when a time limit is reached (after 10 minutes). The increase in the average number of vehicles that is loading/unloading can be explained by the fact that more vehicles have to wait until the time limit is reached. More vehicles are used to transport the same amount of containers (the increase in average number of vehicles that are driving and the increase in driven kilometers), so probably more half loaded transports take place. Figure 4-9 shows the relation between the capacity and the decrease of the percentage of on-time containers. There is a lower decrease when the vehicle capacity is smaller. When a smaller capacity of the vehicles is modelled, the chance that vehicles drive fully loaded is higher. It happens less often that vehicles have to wait until the time limit is reached when loading the containers. This possibly causes that the size of the decrease also gets smaller. When this is the cause, the driver of the MTS knows in reality when there are no more containers to be loaded at a terminal, so the MTS can start driving. Then in reality this decrease does not take place and the percentage of on-time containers for a MTS with a capacity of 10 TEU stays around 97%.

Figure 4-10 shows that the average amount of vehicles driving for the MTS is much lower compared to the ALV and AGV and the MTS drives much less kilometres compared to the AGV and ALV, see Table 4-8. The minimum number of kilometres is calculated:

$$minimum\ number\ of\ kilometers = \frac{\text{distance between origin and destination terminal/depot} * \text{number of containers}}{\text{capacity of ITT vehicle}/_{\text{TEU} - \text{factor}}}$$

The minimum number of kilometres does not include empty rides, and the vehicles are always fully loaded. Table 4-8 shows the driven kilometres compared to the minimum number of kilometres needed. The ratio is higher for the MTS. This can be explained by the fact that the vehicles are not always fully loaded and more empty rides are needed. When there are in total less vehicles in the system, the chance that an empty ride needs to be performed (because the vehicles are not at the right location) is higher.

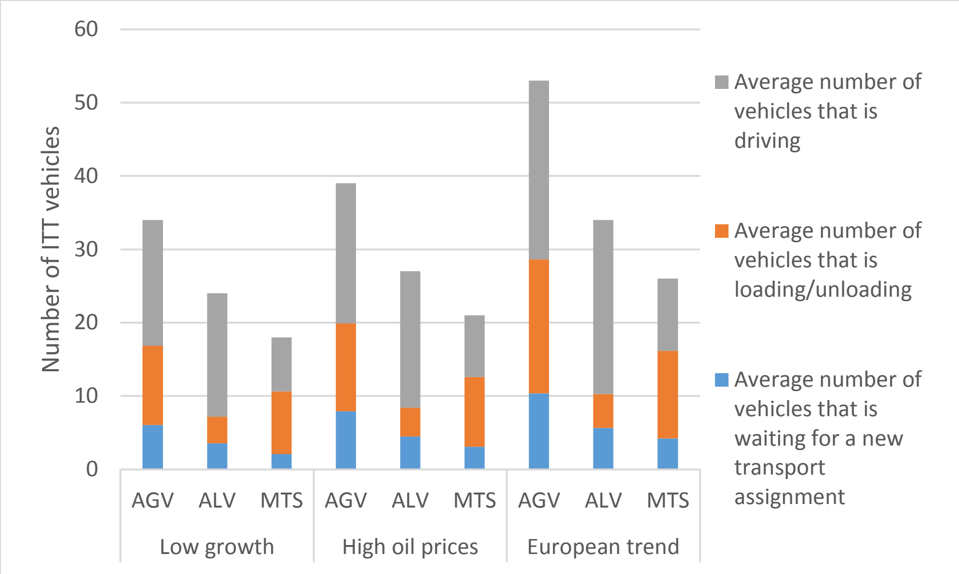

Figure 4-10: The division of driving, loading/unloading and waiting per ITT system per scenario (Author, 2014)

Table 4-8: Driven kilometers compared to minimum number of kilomters needed per ITT system per scenario

Economic growth scenario	ITT system	Driven kilometres	Number of times more than minimum number of kilometres needed (no empty and half-loaded rides)
Low growth	**AGV**	325,229	1.53
	ALV	319,333	1.50
	MTS	106,433	2.50
High oil prices	**AGV**	361,783	1.55
	ALV	352,740	1.51
	MTS	121,489	2.61
European trend	**AGV**	453,941	1.49
	ALV	449,911	1.48
	MTS	141,101	2.31

(Author, 2014)

The average number of vehicles that is driving is the same for the AGV and ALV, see Figure 4-10. The difference in the amount of vehicles can mainly be declared by the loading/unloading. The average amount of vehicles that are waiting (for their next transport assignment) is equal to 12% to 20% of the amount of ITT vehicles.

There are some properties of the vehicles that have the largest impact on the results:

- Ability to load and unload containers by the vehicle itself: The ALV needs a lower amount of vehicles compared to the AGV caused by this fact, because all the other vehicle properties are equal.
- Vehicle capacity: the capacity of the MTS is 5 times as large as the capacity of the ALV and AGV. The number of vehicles needed is lower than the number of vehicles needed for the automated systems, while the MTS has a lower vehicle speed and has to wait longer during loading and unloading (and is not able to load and unload the vehicles itself). The MTS is not able to deliver all the containers on-time. This can be explained by the vehicle capacity. The vehicle needs a lot time during loading and unloading.
- Vehicle speed: A lower vehicle speed causes that more vehicles are needed to reach the same percentage of on-time containers.

The MTS is modelled as it is always coupled, but in reality the MTS-truck can uncouple from the trailers. The amount of trailers that is needed is the same as the amount of the coupled variant, because the loading/unloading and driving takes the same time with an uncoupled variant of the MTS. The coupled MTS is 46% of its time loading or unloading (low growth scenario: 47%, high oil prices scenario: 45%, European trend scenario: 46%). Using an uncoupled variant of the MTS, the MTS can use the time when it is uncoupled to transport another trailer. The number of MTS-trucks cannot be decreased with 46%, because the MTS-trucks are not always at the right location when there are less MTS-trucks. This means that there are more empty rides. It is assumed that the number of MTS-trucks can only be decreased with half of the 46%. The needed number of vehicles per ITT system per scenario is given in Table 4-9.

Table 4-9: The needed number of vehicles per ITT system per economic growth scenario

Economic growth scenario	ITT system	Number of vehicles
Low growth	AGV	34
	ALV	24
	MTS	14 MTS-trucks, 90 trailers
High oil prices	AGV	39
	ALV	27
	MTS	16 MTS-trucks, 105 trailers
European trend	AGV	53
	ALV	34
	MTS	20 MTS-trucks, 130 trailers

(Author, 2014)

Comparison number of ITT vehicles with other researches

In Duinkerken et al. only 1 scenario is used for the demand of ITT containers. It is assumed that 1.4 million containers per year must be transported, equal to 27.277 containers per week (on average) and daily fluctuations are applied. In the European trend scenario of this research, which has the highest amount of containers, 0.99 million containers have to be transported, only 71% of the amount of Duinkerken. Duinkerken only takes the current ITT network of ECT into account, so the transport distances are on average smaller. Nine terminals (or sub terminals, the ECT Delta terminal is divided in different parts) are taken into account. Each terminal has one or more handling centres (an origin or destination of an ITT move). Much lower speeds of the ITT systems are used (AGV: 18 km/h, ALV: 14.4 km/h, MTS: 27.72 km/h (unloaded), 23.76 km/h (loaded)). Duinkerken states that even with high number of vehicles, the performance of the MTS system remains clearly poorer than that of AGV and ALV systems. This is a result of the batch-type work method of the MTS. The same conclusion can be drawn from this research when looking at the graphs of the number of vehicles versus the percentage of on-time containers. Table 4-10 shows the amount of vehicles of the research of Duinkerken and the number of vehicles of this research.

Table 4-10: Comparison of the amount of vehicles between the research of Duinkerken and this research (scenario European trend)

ITT system	Percentage of on-time containers	Number of vehicles in research of Duinkerken et al.	Number of vehicles in this research
AGV	99	122	59
ALV	99	60	36
MTS	99	18 MTS-trucks, 145 trailers	22 MTS-trucks, 145 trailers

(Duinkerken, et al., 2007) (Author, 2014)

The lower ITT demand of this research and higher speeds of the automated ITT vehicles are probably the main cause of the lower needed amount of vehicles in this research. The difference in speed of the MTS between the two researches is much lower and larger distances have to be driven for the ITT in this research compared to the research of Duinkerken et al., which causes that in this research more MTS-trucks are needed.

Only one scenario of the research of Schroër et al. has a comparable amount of ITT with this research. This scenario in the research contains 1.42 million TEUs of ITT per year and the high oil prices scenario of this research contains 1.29 million TEUs of ITT per year. The same vehicle speeds and capacities are used in the researches, but there are differences. In this scenario of the research of Schroër et al. the assumption is done that the current ITT of ECT will not be replaced. There are much more transports to and from the empty depots, and two new terminals at Maasvlakte 2 (which are not used in this research) will be built. The distribution of the ITT transports in the network is different, the distribution of the available transport times is different, and another method is used for determining the next transport assignment of the vehicles. The number of vehicles from Schroër et al. with the corresponding percentage of on-time containers is compared in Table 4-11 with the amount of vehicles of this research with more or less the same percentage of on-time containers, read from the graphs.

Table 4-11: Comparison of the amount of vehicles between the research of Schroër et al. and this research (scenario high oil prices)

ITT system	**Percentage of on-time containers**	**Number of vehicles in research of Schroër et al.**	**Number of vehicles in this research**
AGV	78.3	32	30
ALV	97.5	24	28
MTS	80.7	9	12 MTS-trucks, 75 trailers

(Schroër, et al., 2013) (Author, 2014)

The amount of vehicles is comparable. It is questionable if the relation between the number of vehicles and the percentage of on-time containers is comparable, because at this moment only one data point is compared.

4.5 MCA of different ITT systems

The Multi Criteria Analysis evaluates (for each economic growth scenario) the three different ITT systems. First the criteria are discussed. Then the ITT systems are compared per criterion. Finally, the results of the MCA are given.

4.5.1 Criteria

The Multi Criteria Analysis uses the following two criteria:

1. Total costs
2. Sustainability

The total costs of the ITT systems is by far the most important criterion. Costs determine whether a project is feasible and influence the decision makers the most.

It is assumed that all the vehicles will be electrical vehicles, because sustainability is getting more important. However, there is still a difference in the amount of electricity that is used by the vehicles. Sustainability is getting more important. For example, the new terminal APMT MV2 and RWG show that sustainability is one of their core values and want to be leading on the field of sustainability. (Rotterdam World Gateway, n.d.) (GMB, 2013) Therefore it is assumed that a new, sustainable ITT system at the Maasvlakte is of high importance. Costs are the most important factor, but sustainability has a quite considerable influence.

4.5.2 Criterion 1: Total costs

The total costs are determined per ITT system. The costs are divided in the following costs components:

- Fixed costs
  - Vehicle costs
    The purchase price of the different types of vehicles in 2010 is known (TBA, 2010). The expected price in 2030 is estimated using the CPI and the expected inflation.
    At this moment there are already battery-driven AGVs at the terminals of APM Terminals Maasvlakte II and RWG. (Maritiem Nieuws, 2012) (Nieuwsblad Transport, 2014). It is assumed that this trend will continue in the future and all the ITT vehicles will be battery-driven. The price is multiplied with an estimated factor for the extra costs. This factor is based on a research, in which an estimation is made of the prices in 2030 of a petrol/diesel car and the same car which is electrical driven (Element Energy Limited, 2011). It is assumed that one extra battery pack is needed per 3 vehicles.
    It is assumed that the automated vehicles will use GPS technology to determine their route. The extra costs of this system are added to the price. These costs are estimated using a research in which estimations are made of the price of the GPS system of a Google Car (USA Today, 2012).
    For each of the ITT vehicles the annuity payment is calculated.
  - Software costs
    The software costs are estimated using a previous research in 2010 in which 33 ALVs or 65 AGVs are used at the quay side of a container terminal (TBA, 2010). The same amount of costs is used in this research for the automated systems, but then converted to the price in 2030. For the MTS less software is needed, but a proper planning system for the containers is needed. It is estimated that this will be 75% of the price of the software system of the automated vehicles.
    For the software the annuity payment is calculated.
  - Infrastructure costs
    There is at this moment already discussion about the construction costs of a dedicated lane between the Port of Rotterdam, the terminals and a mediator. The expected construction costs are 80 million euros (Nieuwsblad Transport, 2014). These costs are also used in this research. It is assumed that these costs are equal for the AGV, ALV, and MTS, because the navigation technique of the automated vehicles is located in the vehicles, and not in the infrastructure.
    For the infrastructure costs also the annuity payment is calculated.
- Variable costs
  - Maintenance and repair costs of the vehicles
    The maintenance and repair costs are calculated looking at the driven kilometres of the different ITT vehicles. In a previous research these costs are determined for a truck. (Wiegmans & Konings, 2013) The tractor has repair and maintenance costs of €0.05/km and the trailer €0.02/km. In this research €0.07/km is taken for the AGV and ALV and €0.15/km for the MTS (and then converted to the price in 2030).
  - Maintenance contract of the software
    Also for the maintenance contract of the software an assumption is made. It is assumed that this is 5% of the annuity payment of the software. The same logic is applied; this is not one of the main cost components, so no more-detailed estimation is made.
  - Maintenance costs of the infrastructure

For the maintenance of the infrastructure it is assumed that this is equal to 5% of the annuity payment. Because this is not one of the main cost components, no more-detailed estimation is made.

- Personnel costs
  The AGV and ALV are automated systems, so they do not need drivers, but the MTS does. It is assumed that half of the waiting time per scenario, no drivers are needed.
  For all the ITT systems it is assumed that there needs to be security all the time. Two employees are employed the whole time. For the MTS there need to be employees that monitor if the ITT process is working correctly and intervene when needed.
  The loan of the employees at this moment is known. This is converted to the loan in 2030.
- Energy consumption costs
  The current electricity usage of an AGV with a speed of 21.6 km/h is known. (Mechatronica Machinebouw, 2013) It is expected that the AGVs and ALVs will drive 40 km/h in 2030. The use of electricity is not linear when the speed of the vehicles increases. Therefore the relation of the vehicle speed of a car compared to the electricity use is used to find the usage of the AGV with a speed of 40 km/h. (Tesla motors, 2008) When this is multiplied by the (expected) price of electricity (in 2030), the costs per kilometre are known for the AGV. It is assumed that the costs per kilometre of the ALV are 1.25 times as high as for the AGV, because its ability to load and unload the vehicles. It is assumed that the costs per kilometre of the MTS are 1.5 times as high as the AGV. The MTS has a lower speed (30 km/h), but has a much higher weight, especially when it is loaded. The energy consumption costs can be calculated by multiplying the costs per kilometre and the driven kilometres per year.
- Overhead costs
  This is a part of the costs of a company or organization that is spent to the organization itself. An investigation of the overhead of business service providers shows that there is a strong relation between the percentage of overhead and the average revenue per employee. (Huijben & Geurtsen, 2008) When an organization is wealthier, there will be more employees for assistance and the overhead percentage becomes larger. The overhead costs (as a percentage of the total revenues) differ a lot per sector/industry, from 2% to 38%. (From the 42 investigated sectors, 38 have a percentage between 10% and 30%.) The organization of the ITT system is assumed to be quite efficient and is assumed to be no very wealthy organization. Therefore the percentage of overhead is assumed to be 12% of the total revenues.

Figure 4-11 shows the total costs per ITT system per scenario. In Appendix F: Total costs of the ITT systems a detailed description of the different cost components is given.

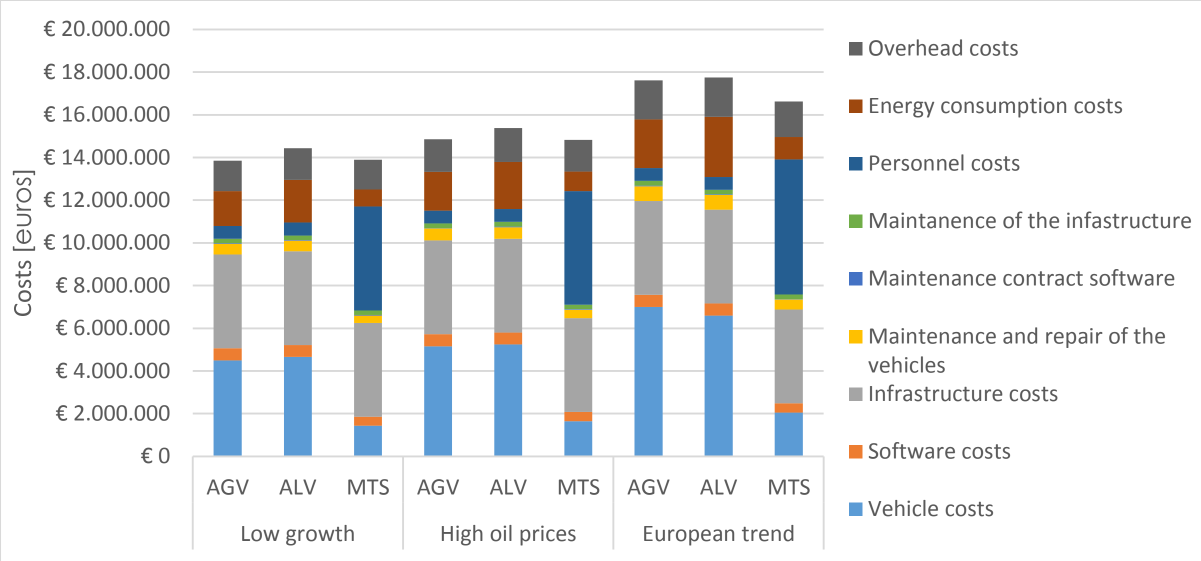

Figure 4-11: Total costs per ITT sytem per scenario (Author, 2014)

The vehicle costs, infrastructure costs, and personnel costs are the main cost drivers for the different ITT systems. The MTS clearly has the lowest vehicle costs, but also the highest personnel costs compared to the automated systems. For the low growth and high oil prices scenario the total costs of the AGV and MTS are equal. The total costs of the ALV are 4% higher than for the AGV or MTS. For the European trend scenario the MTS has the lowest costs. For this scenario the costs of the AGV are 6% higher than the costs of the MTS, and the costs of the ALV are 7% higher than the costs of the MTS.

4.5.3 Criterion 2: Sustainability

The electricity usage per year is used to determine the sustainability of the ITT systems. The electricity usage was already calculated for determining the energy consumption costs of the ITT systems (see section 4.5.2). Figure 4-12 shows the electricity usage. It is visible that the MTS has by far the lowest electricity usage, caused by the fact that the MTS has a much lower amount of driven kilometres. The electricity usage of the ALV is higher than the AGV, because the ALV needs to load and unload the containers by itself, which requires extra electricity.

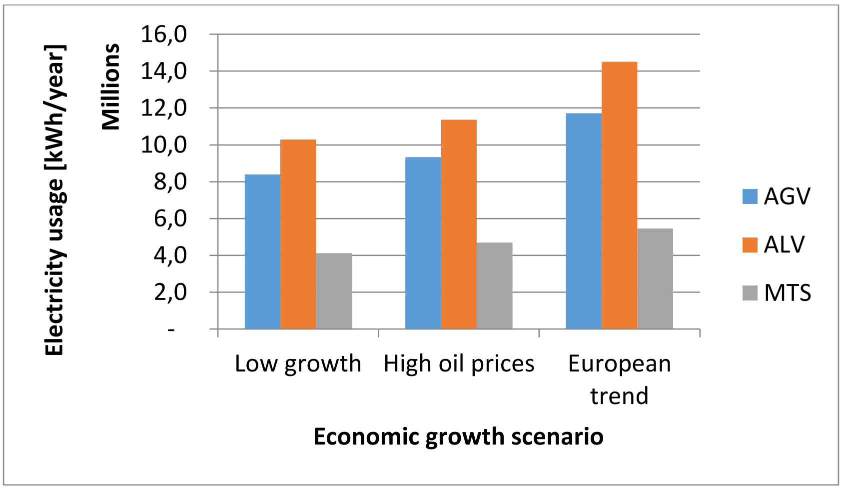

Figure 4-12: Electricty usage per ITT system per scenario (Author, 2014)

4.5.4 Results of MCA

Normally, for a MCA the different criteria receive a weighing factor to take the importance per criteria into account. However, in this case this is not necessary, because independent on the weighing factors the MTS would have the highest score. The MTS has the lowest costs for each of the scenarios (for the low growth and high oil prices equal to the costs of the AGV). The MTS is the most sustainable ITT system. The difference between the MTS and the automated systems is relatively small looking at the total costs (the largest difference is the difference between the total costs of the ALV compared to the MTS for the European trend scenario (7%), but there is a large difference looking at the sustainability. The electricity usage of the automated systems is 99% to 166% higher than for the MTS. The difference between the score (of the MCA) of the MTS and the automated systems depends on how important sustainability is considered by the decision makers. The higher the importance of sustainability is considered, the higher the difference of the score between the MTS and the automated systems. Eventually, the MTS will receive in all cases the highest score.

5 Conclusions and recommendations

First the conclusions will be given and then the recommendations and possibilities for future research are discussed.

5.1 Conclusions

In this research it is the goal to find the most appropriate ITT system is for Inter Terminal Transport between the container terminals and depots at Maasvlakte 1 and 2 in 2030.

The ITT network consists of 14 terminals and depots, located at Maasvlakte 1 and 2. The ITT systems AGV, ALV, and MTS are compared for three different economic growth scenarios:

- Low growth scenario: 0.70 million containers/1.17 million TEU per year
- High oil prices scenario: 0.78 million containers/1.29 million TEU per year
- European trend scenario: 0.99 million containers/1.66 million TEU per year

The input data is different than the input that is used in previous researches on ITT. In this research the most up-to-date information is used for the generation of new ITT container demand scenarios.

A simulation model is built to determine the needed number of vehicles per ITT system per economic growth scenario. It is by far the most important task to deliver the containers on time. Therefore a minimum percentage of 95% is used, to get a fair comparison between the ITT systems. In the previous researches on ITT no constraint was set on the on-time delivery of containers. Table 5-1 shows the needed number of ITT vehicles per ITT system per economic growth scenario to achieve the 95% on-time delivery.

Table 5-1: Needed number of ITT vehicles to achieve 95% on-time conatiners per ITTsystem per economic growth scenario

	AGV	ALV	MTS
Low growth	34 AGVs	24 ALVs	14 MTS-trucks, 90 trailers
High oil prices	39 AGVs	27 ALVs	16 MTS-trucks, 105 trailers
European trend	53 AGVs	34 ALVs	20 MTS-trucks, 130 trailers

For each scenario the MTS needs the lowest amount of vehicles (MTS-trucks), then the ALV, and the AGV needs the highest amount of vehicles. This can be explained by the fact that the MTS has a capacity which is five times larger than the capacity of the vehicles of the automated systems; though, the MTS has a lower vehicle speed and has to wait longer during loading and unloading. The ALV has an advantage compared to the AGV, because it is able to load and unload the vehicle by itself, and needs therefore less vehicles.
The MTS drives 2.9 to 3.1 times less kilometres compared to the AGV and the ALV, needs more half loaded and empty rides compared to the automated systems. When the minimum number of driven kilometres is calculated (sum of distance from origin to destination of all containers divided by the vehicle capacity), the MTS drives 2.5 times more kilometres and the automated systems drive 1.5 times more kilometres.
The automated systems can reach percentages of on-time containers close to 100%, but the MTS can reach only approximately 97%, because of its long loading and unloading time due to its high capacity.

The results of the simulation model are used as input for a Multi Criteria Analysis. The MCA evaluates the ITT systems on two criteria; total costs and sustainability.
The total costs of the three ITT systems are very comparable. For the low growth and high oil prices scenario the total costs of the AGV and MTS are equal. The total costs of the ALV are 4% higher than for the AGV or MTS. For the European trend scenario the MTS has the lowest costs. For this scenario the costs of the AGV are 6% higher than the costs of the MTS, and the costs of the ALV

are 7% higher than the costs of the MTS. The vehicle costs of the MTS are much lower than the automated systems, but the personnel costs are on the other hand much higher.
The sustainability of the ITT systems is measured by the electricity usage. There is a large difference looking at different ITT systems. The electricity usage of the automated systems is 99% to 166% higher than the electricity usage of the MTS. The ALV uses approximately 25% more electricity than the AGV.

Independent on the weighing factors of the MCA the MTS would have the highest score. The MTS has the lowest costs for each of the scenarios and is the most sustainable ITT system. The difference between the MTS and the automated systems is relatively small looking at the total costs but there is a significant difference looking at the sustainability. The difference between the score (of the MCA) of the MTS and the automated systems depends on how important sustainability is considered by the decision makers. The higher the importance of sustainability is considered, the higher the difference of the score between the MTS and the automated systems. Eventually, the MTS will receive in all cases the highest score. Therefore the MTS is considered as the most appropriate ITT system for each of the economic growth scenarios. The input data did not contain large flows from and to empty depots, but in reality these flows will be present. This causes that the amount of ITT flows will be larger, which probably causes that the MTS scores better on total costs, because the MTS scores better on total costs with the highest volume of ITT in the European trend scenario compared to the other two scenarios. Next to this, the MTS is probably a safe option to choose, because for the AGV and ALV large developments are assumed according to the vehicle speed in contrast to the MTS.

5.2 Recommendations

First the recommendations concerning the simulation model input are discussed. Then recommendations concerning the simulation model, and finally concerning the MCA.

5.2.1 Recommendations concerning the simulation model input

It is questionable if the current division of the containers between the different terminals and depots is realistic. Are there shipping companies making alliances and to which terminals are they going? In this research only the amount of ITT containers is changed, but not the division between the terminals. It is interesting to see what happens if the division is changed, for example a large flow to and from the ECT Euromax terminal, which is located far from the other terminals. Will the MTS still be the most appropriate ITT system? What happens with the needed number of vehicles? Can the ITT systems reach the same percentage of on-time containers?

In this research it is assumed that no barge service centre and common rail terminal will be built. At this moment it is not known if these are going to be constructed, but if so, this has a large influence on the amount of ITT containers and the division of the containers over the terminals.

In this research the ITT systems are compared for 2030. It is possible to generate data input files for multiple years. Then it can be found out at which moment it is best to implement a new system.

There is only a very small amount of ITT moves from and to the empty depots in the input data. This is caused by the fact that orders of shipping companies to store empty containers are not included. These orders most of the time consist of significant amounts of containers, so in reality there will be more ITT containers.

For containers that have to go to customs, two separate ITT moves are created. In reality, the containers stay on the trailer and will be driven through the gates of the customs, so this is actually one ITT move. In the simulation model the containers are unloaded and loaded, but this is not necessary.

5.2.2 Recommendations concerning the simulation model

Assumptions are made for the arrival time, delivery time, and no distinction is made between full and empty containers. It is assumed that it does not mind if containers arrive early. In reality, this is different. At some rail or feeder terminals, the containers are unloaded from the ITT vehicles and put directly on the train/feeder. When the train or feeder isn't there yet, this is not possible. Also for the feeders there are loading plans, because of the stowage of the vessels. For some terminals it is not desirable that ITT containers arrive very early, because then they have to be longer in the stack.
The containers have a delivery time property. This departure time is the time it needs to be at the destination terminal. In reality there is some extra time, because during the loading of the vessels containers still can arrive and it does not matter if the containers arrive a bit late.
There is no distinction made between full and empty containers. Actually, for empty containers it is not as important as for full containers that they have to be delivered on time. When empty containers are brought to empty container depots, it does not mind if they arrive late, because there are no consequences (maybe only paying a small amount for the extra time in the stack at the terminals). When an empty container arrives too late and is not able to be loaded on the container carrier, the consequences are smaller than for full containers, because there are no goods arriving too late at their destination.

For this simulation model a unique way of determining the next transport assignment is developed. However, there is optimization possible. The dispatching strategy for all the ITT vehicles is not optimal at this moment. When these strategies are modelled in a more optimal way, the needed number of vehicles can probably be lower.
Vehicles drive to the closest terminal or depot where urgent or normal containers are waiting. No distinction is made between the numbers of containers that are waiting at the terminals/depots. Especially for the MTS this is important, because of its high capacity. When only a very small amount of containers is waiting, the vehicles drive not fully loaded. It could sometimes be better to drive to another terminal where more containers are waiting.

For the ITT systems there are some recommendations for the speed of the automated vehicles, the uncoupling of the MTS, and the combination with rail. The speed of the AGV and ALV is set to 40 km/h, so a large development in the next years of the vehicles is assumed. When this will not be achieved, the AGV and ALV probably perform differently. It has to be investigated if more vehicles are needed to achieve the same percentage of on-time containers (and the total costs are higher) and it has to be investigated if the ITT systems can reach percentages close to 100%.
The time that is needed for changing battery packs is not taken into account. It is not known how long it takes and on how many locations it will be possible to change battery packs.
The MTS is only modelled coupled, while in reality it is possible for the MTS-trucks to uncouple from the trailers. An upper bound of the needed number of MTS-trucks is determined and an estimation of the decrease of MTS-trucks for the uncoupled variant. A better estimation can be made when this variant will be modelled.
The ITT system combination of rail with another modality is not modelled, but there could be potential of bundling containers by using rail for ITT. It is recommended that more research will be done. Appendix G: Combinations of ITT systems gives some information about modelling the combination of ITT systems. It is still questionable if it possible to use small trains in practice, because of fixed driving schemes. This should also be investigated.

The results of the simulation model show that there is a decrease in the percentage of on-time containers when more vehicles are added. An analysis is done to find out what the cause is of this phenomenon. The decrease possibly could be declared by the fact that the vehicles have more half loaded rides and must wait longer during the loading, because they have to wait until the time limit is reached. When a smaller capacity of the vehicles is modelled, the chance that vehicles drive fully loaded is higher. It happens less often that vehicles have to wait until the time limit is reached when loading the containers. This possibly causes that the size of the decrease also gets smaller. More research can be done to find out if the described cause is exactly the cause of the phenomenon. This can be done by modelling the loading of the vehicles differently. The vehicle has to start driving when there are no containers left at the terminal instead of waiting until the time limit is reached. Then it has to be checked if there is still a decrease in percentage of on-time containers.

Some simplifications are used in the simulation model, such as for the loading and unloading at terminals, and intersections. All the terminals are modelled as one location (node) where the containers must be transported to or from. It is possible that some distance has to be covered between the location where the containers are unloaded and the location where new containers are loaded. This takes extra time, which is not taken into account in this research.
In this research for each terminal one type and the number of terminal equipment is determined. This equipment is dedicated for ITT and does not perform other operations. Actually this is not the case for all the terminals. The terminal equipment also performs other (landside) operations. In reality, the number of equipment that can be used is larger, but only a part of their time is used for ITT. Only one type of equipment per terminal is used in this research, but there could be multiple types of equipment per terminal. When a terminal handles rail and other modalities, it is possible that rail cranes are used and another type of equipment. A better estimation of the loading and unloading times can be made when a better representation of the terminal equipment is made.
For the traffic lights distributions for the red time and green time are used and no distinction between day and night, and during the week or during the weekends is made.
3-way crossings are used in this model. For these crossings the possibility to cross another vehicle is determined, but no difference is made over time, so no distinction between quiet and busy periods is made.

5.2.3 Recommendations concerning the MCA

Some factors are not taken into account looking at the total costs. Some terminals use ASCs to load and unload the ITT vehicles, but for MTS this is not possible. This means that when MTSs will be used for ITT, these terminals need to do extra investments. This is an extra disadvantage of the MTS that is not taken into account in this research. For the ALVs platforms have to be built at all the terminals. Then the ALVs can load the containers on the platforms and unload the containers from the platforms. These extra costs are also not taken into account and are an extra disadvantage of the ALV that not is taken into account.
The number of vehicles is determined using the second busiest month. During the busiest month, it is possible that during a few days extra vehicles are needed, but these costs are not taken into account.

There are also some uncertainties for determining the total costs. It is not known how fast the ITT systems are developing. This could have an effect on the estimated costs of the vehicles. It is assumed that the vehicles are electric and are using GPS. It is assumed that the battery packs of the vehicles are changed (and an estimation of the needed amount of battery packs is made), but maybe in the future vehicles are charging themselves by using induction in the infrastructure instead of going to a charging station. The estimations and assumption have an impact on the estimated costs of the vehicles. More research can be done about the expectations of the future developments to get a better estimation of the costs.
A high speed of the vehicles is optimal looking at the operational aspects, but for energy consumption maybe it may not be optimal. Vehicles use disproportional more electricity looking at the energy consumption when higher speeds are used. It can be investigated what the effect would be on the results of the MCA when lower speeds of the vehicles are used.

Expectations are used for the MCA. However, the decision makers determine what is most important. The evaluation criteria of the MCA are based on the current expectations. It is possible that the decision makers find more criteria important, which can influence the results.
In this research it is stated that 95% on time containers is sufficient, but if the decision makers set a higher percentage as requirement, a new evaluation has to be done because extra investments are needed. The MTS is able to reach 97% on-time containers, but the AGV and ALV are able to reach approximately 100% on-time containers. For the MTS it is possible to use extra trucks to achieve a percentage close to 100%, because their average speed is higher and their average loading and unloading time is smaller. It is also possible to use smaller sets of trailers/a smaller capacity per MTS to reach a higher percentage of on-time containers. It also depends on the way the agreements are made with the shipping companies. Is it stated that a minimum percentage will be delivered on time or needs a fine to be paid for each container that arrives too late?

5.3 Future research

In this research the ITT systems are evaluated using different amounts of ITT containers, but it is interesting to see if the ITT systems behave in the same way when the ITT flows are divided differently over the different terminals and depots. It can be investigated if the number of needed vehicles and the percentage of on time containers changes.

The flows to and from the empty depots are not taken into account. Research can be done to see if the MTS still is the most appropriate ITT system.

Only the AGV, ALV, and MTS are evaluated in this research. It is possible that a combination of ITT systems brings opportunities. It can be investigated if a combination of ITT systems is more appropriate than the ITT systems used in this research.

In this research the ITT systems are compared for 2030. Actually it is interesting compare the ITT systems for multiple years to find out at which moment it is best to implement a new system.

The dispatching method in this research is not optimal. The effect of a more optimal dispatching method can be investigated to see if it is possible to achieve a lower amount of needed vehicles.

It is important to know if there are important decision criteria (and their corresponding weighing factors) missing in the research, according to the decision makers. This can have an influence on the results of a MCA.

It is interesting to investigate how large the amount of extra costs needed is to achieve on time percentages close to 100%. For the MTS probably extra trucks have to be used or smaller sets of trailers have to be used. It can be considered if the extra on time delivery of the containers can outweigh the extra costs.

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Appendix A: Detailed description of simulation model

In this chapter a detailed description of the simulation model is given. All the processes are shown and the steps of the processes are given.

The model consists of a main model and a sub model, the terminal/depot. Containers arrive at the different terminals/depots and the vehicles drive from terminal/depot to terminal/depot using the network of links and nodes. Vehicles automatically enter the sub model. In each sub model vehicles are loaded and unloaded by the terminal equipment. The terminal equipment is an object, a resource.

Vehicles and containers are modelled as entities. Entities are objects and they can have their own intelligent behaviour, have their own object properties and can move across the network of links and nodes. For example, the vehicles are able to determine the shortest route by itself. Entities are able to trigger certain events, for instance, a vehicle that enters a node. A token will be created at the start of the process. A token is a delegate of an object that executes the steps in a process. A token is created at the beginning of a process and is destroyed at the end of that same process. As the token moves through the process it executes the actions as specified by each step.

The properties of the objects can be recognized by the name "object.property". The model uses different state variables. State variables are variables that may be changed by assignment logic at discrete times during a model run. There are also tables that refer to state variables. When there is a reference to a table, this can be recognized by the name "table.column". The row is set on forehand or can be recognized by the number between brackets ("table[row].column").

Waiting areas and timers are used in the model and events can be fired. Statistics are gathered during the simulation period.

A.1.1 Process step 1: arrival of containers at the terminals/depots

All the containers are created at a source, see Figure A-1. The containers arrive at a certain time, specified in an arrival table. All the properties of the containers are assigned at the source and the containers are moved to the origin terminal of the container. At the terminal, the containers are placed in a normal waiting area. For each destination terminal of the containers a separate waiting area is created. When the containers get urgent, the containers are placed in an urgent waiting area, also divided in waiting areas per destination.

(Vehicles are also created at a source. The vehicles are divided over the terminals by probabilities. It is assumed that terminals that handle the most containers receive more vehicles.)

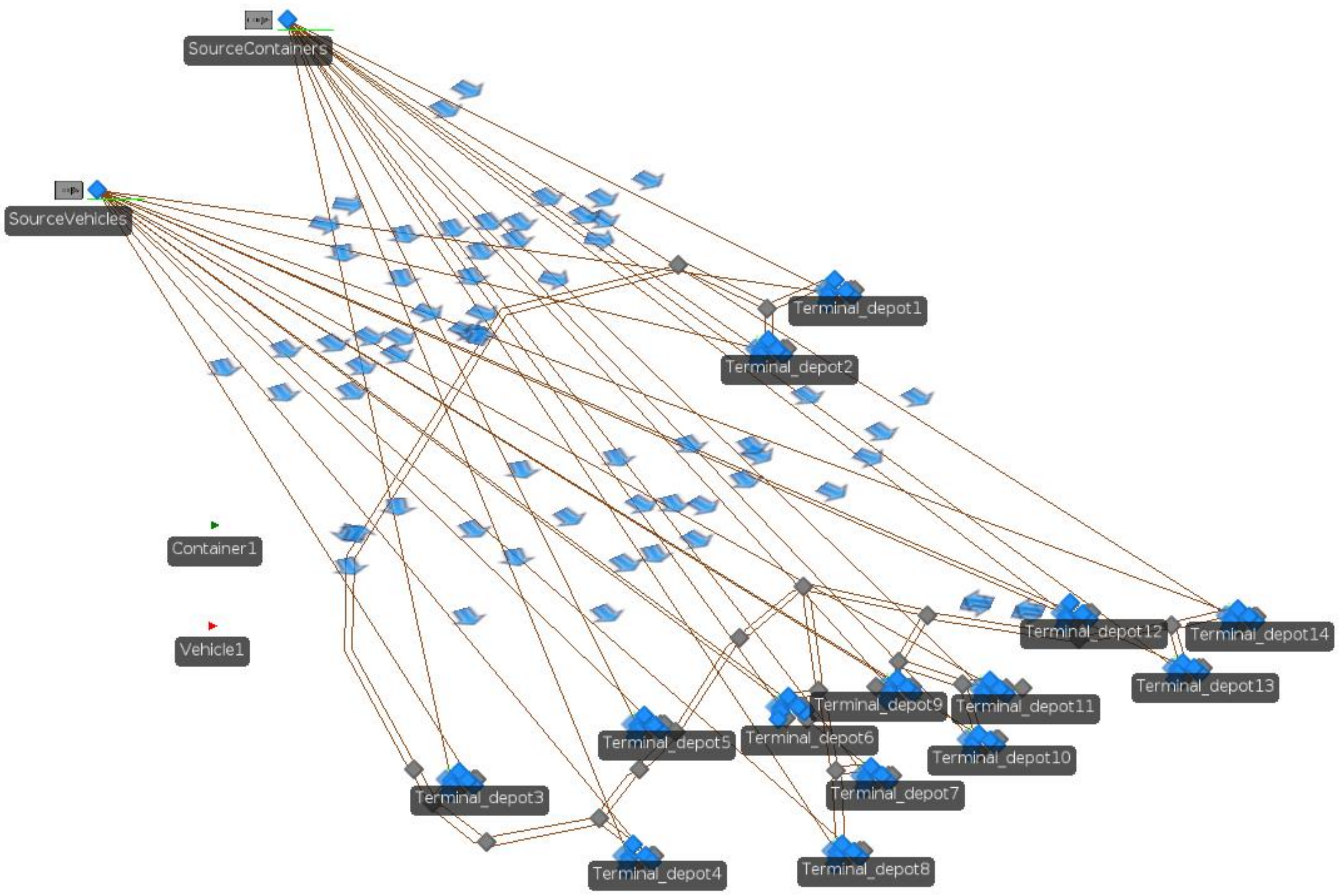


Figure A-1: Overview of the model (Author, 2014)

Source containers: Entity arrival logic

The entity arrival logic is based on a table, shown in Table A-1. The arrival time property is given by the Start time.

Table A-1: Container properties

Origin terminal	Origin node	Destination terminal	Destination node	Start time	Latest departure time	Delivery time	Number of TEU
5	Input_Containers@Terminal5	12	Input_Vehicles_Unloading@Terminal12	0,008333333	45,98691667	46,09533333	2
5	Input_Containers@Terminal5	6	Input_Vehicles_Unloading@Terminal6	0,024166667	3,823333333	3,888	2
…	…	…	…	…	…	…	…

(Author, 2014)

Source containers: State assignments before exiting

For assigning the properties of the containers, also Table A-1 is used. The following properties are assigned to the containers:

State variable name	Container.DestinationNode
New value	ContainerProperties.DestinationNode
State variable name	Container.DestinationTerminal
New value	ContainerProperties.DestinationTerminal
State variable name	Container.OriginNode
New value	ContainerProperties.OriginNode
State variable name	Container.OriginTerminal
New value	ContainerProperties.OriginTerminal
State variable name	Container.StartTime
New value	ContainerProperties.StartTime
State variable name	Container.LatestDepartureTime
New value	ContainerProperties.LatestDepartureTime
State variable name	Container.DeliveryTime
New value	ContainerProperties.DeliveryTime
State variable name	Container.NumberOfTEU
New value	ContainerProperties.NumberOfTEU

Output@SourceContainers: Routing logic

At the output of the source the containers are given an origin node.

Entity Destination node	Specific
Node name	Container.OriginNode

Insert containers in normal and urgent waiting area

At each terminal containers arrive. When the containers enter the first node (see Figure A-2), they will be placed in the waiting areas.

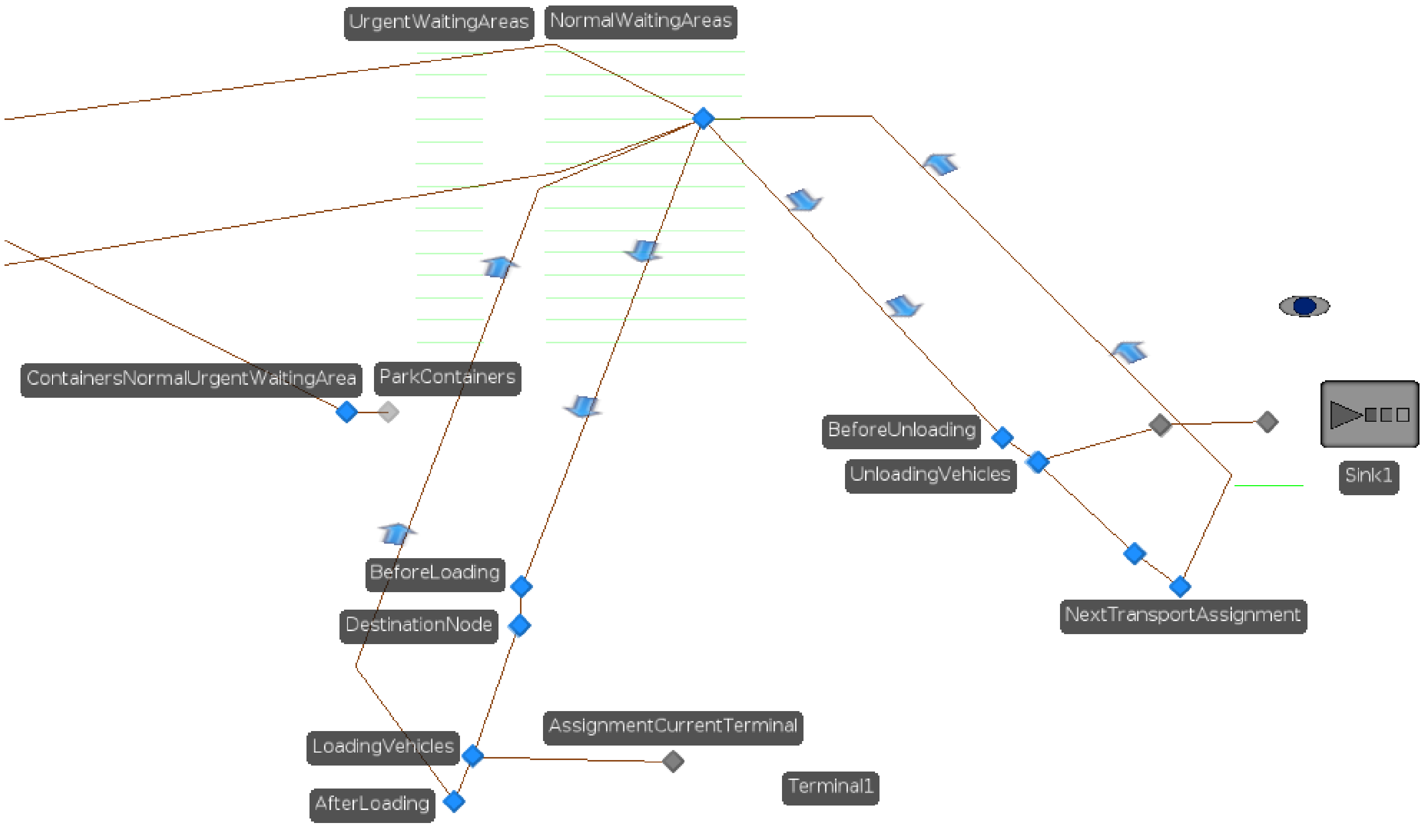


Figure A-2: Processes at different nodes of each terminal or depot (Author, 2014)

Figure A-3 shows the process of the placement of containers in the normal and urgent waiting areas.

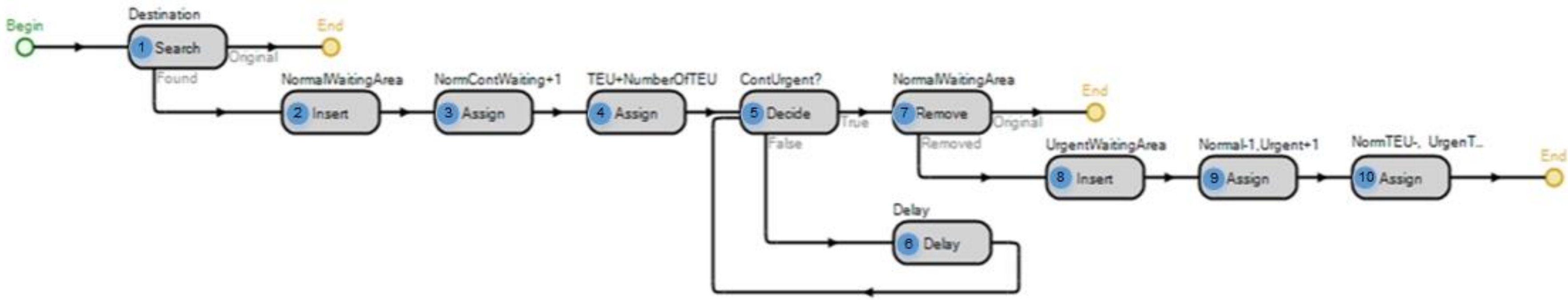


Figure A-3: Insert containers in normal and urgent waiting area (Author, 2014)

All the steps are shown and numbered. Table A-2 (TerminalLoading) is used for this process. Each step of the process is explained below:

Search	
Collection type	TableRows
Table name	TerminalLoading
Search type	Forward
Match condition	Container.DestinationTerminal == TerminalLoading.DestinationTerminal
Limit	1
Insert	
Queue state name	TerminalLoading.NormalWaitingArea
Assign	
State variable name	TerminalLoading.NumberOfNormalContWaiting
New value	TerminalLoading.NumberOfNormalContWaiting + 1
Assign	
State variable name	TerminalLoading.NumberOfNormalTEUWaiting
New value	TerminalLoading.NumberOfNormalTEUWaiting + Container.NumberOfTEU
State variable name	TerminalLoading.TEUAvailableForLoading
New value	TerminalLoading.TEUAvailableForLoading + Container.NumberOfTEU
Decide	
Expression	Container.LatestDepartureTimeHours - Run.TimeNow<=1
Delay	

Delay time	1 minute
Remove	
Queue state name	TerminalLoading.NormalWaitingArea
Insert	
Queue state name	TerminalLoading.UrgentWaitingArea
Assign	
State variable name	TerminalLoading.NumberOfNormalContWaiting
New value	TerminalLoading.NumberOfNormalContWaiting – 1
State variable name	TerminalLoading.NumberOfUrgentContWaiting
New value	TerminalLoading.NumberOfUrgentContWaiting + 1
Assign	
State variable name	TerminalLoading.NumberOfUrgentTEUWaiting
New value	TerminalLoading.NumberOfUrgentTEUWaiting + Container.NumberOfTEU
State variable name	TerminalLoading.NumberOfNormalTEUWaiting
New value	TerminalLoading.NumberOfNormalTEUWaiting - Container.NumberOfTEU

Table A-2: Information for loading at a terminal

Desti-nation termi-nal	Number of urgent TEU waiting	Number of normal TEU waiting	Normal waiting area	Urgent waiting area	Latest departure time first container in queue	TEU available for loading	Number of urgent containers waiting	Number of normal containers waiting
1	NumberOfUrgentTEUWaitingD1	NumberOfNormalTEUWaitingD1	WaitingAreaD1Normal.Queue	WaitingAreaD1Urgent.Queue	Math.If(NumberOfUrgentContWaitingD1 > 0, WaitingAreaD1Urgent.Queue.FirstItem.Container.LatestDepartureTimeHours, NumberOfUrgentContWaitingD1==0 && NumberOfNormalContWaitingD1 >0, WaitingAreaD1Normal.Queue.FirstItem.Container.LatestDepartureTimeHours, Infinity)	TEUAvailableForLoadingD1	NumberOfUrgentContWaitingD1	NumberOfNormalContWaitingD1
…	…	…	…	…	…	…	…	…
14	NumberOfUrgentTEUWaitingD14	NumberOfNormalTEUWaitingD14	WaitingAreaD1	WaitingAreaD1	Math.If(NumberOfUrgentContWaitingD14 > 0, WaitingAreaD14Urgent.Queue.FirstItem.Container.LatestDepartureTimeHours,	TEUAvailableForLoadingD14	NumberOfUrgentContWaitingD14	NumberOfNormalCo

			4Norma l.Queue	4Urgent .Queue	NumberOfUrgentContWaitingD14==0 && NumberOfNormalContWaitingD14 >0, WaitingAreaD14Normal.Queue.FirstItem.Container.LatestDepartureTimeHours, Infinity)			ntWaiting D14

(Author, 2014)

Park containers

When containers are put in a waiting area, the original entity stays at the network. While containers are waiting, they can still perform other operations. In this case this is not necessary. Therefore the containers are parked when they enter the next node, see Figure A-2. Figure A-4 shows the process.

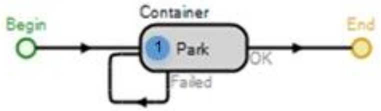


Figure A-4: Park containers (Author, 2014)

Only one step is performed and is explained below:

Park

Node name TX_ParkContainers

A.1.2 Process step 2: loading process of containers on the ITT systems → vehicles?

The ITT vehicles need to transport the containers. Therefore the containers need to be loaded on the vehicles. Before the loading of the vehicle some state variables need to be changed. Then the destination node of the vehicle is determined, the vehicle will be loaded and after the loading some state variables are changed.

Before loading of the vehicle

Before the loading of the vehicle some state variables are changed. In Figure A-5 the process before the loading of the vehicle is shown. This process is started when a vehicle enters the node, shown in Figure A-2.

Figure A-5: Before loading of the vehicle (Author, 2014)

This process only consists of one step:

Assign

State variable name	VehToTerminalX
New value	VehToTerminalX-1
State variable name	VehLoadingAtTerminalX
New value	VehLoadingAtTerminalX+1

Determining destination of the vehicle

First is checked if there are containers for loading and then the destination of the vehicle will be determined. Figure A-6 shows the process.

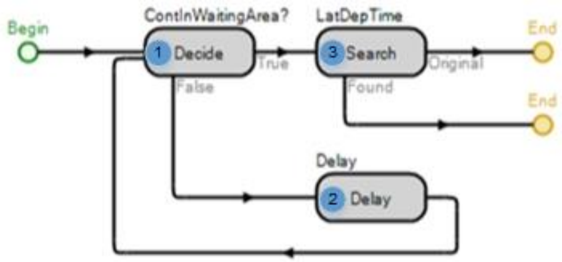


Figure A-6: Determining destination node of the vehicle (Author, 2014)

The steps of the process are numbered and are explained below:

Decide

Expression WaitingAreaD1Urgent.Queue.NumberWaiting>0 || WaitingAreaD2Urgent.Queue.NumberWaiting>0 || WaitingAreaD3Urgent.Queue.NumberWaiting>0 || WaitingAreaD4Urgent.Queue.NumberWaiting>0 || WaitingAreaD5Urgent.Queue.NumberWaiting>0 || WaitingAreaD6Urgent.Queue.NumberWaiting>0 || WaitingAreaD7Urgent.Queue.NumberWaiting>0 || WaitingAreaD8Urgent.Queue.NumberWaiting>0 || WaitingAreaD9Urgent.Queue.NumberWaiting>0 || WaitingAreaD10Urgent.Queue.NumberWaiting>0 || WaitingAreaD11Urgent.Queue.NumberWaiting>0 || WaitingAreaD12Urgent.Queue.NumberWaiting>0 || WaitingAreaD13Urgent.Queue.NumberWaiting>0 || WaitingAreaD14Urgent.Queue.NumberWaiting>0 || WaitingAreaD1Normal.Queue.NumberWaiting>0 || WaitingAreaD2Normal.Queue.NumberWaiting>0 ||

WaitingAreaD3Normal.Queue.NumberWaiting>0 || WaitingAreaD4Normal.Queue.NumberWaiting>0 ||
WaitingAreaD5Normal.Queue.NumberWaiting>0 || WaitingAreaD6Normal.Queue.NumberWaiting>0 ||
WaitingAreaD7Normal.Queue.NumberWaiting>0 || WaitingAreaD8Normal.Queue.NumberWaiting>0 ||
WaitingAreaD9Normal.Queue.NumberWaiting>0 || WaitingAreaD10Normal.Queue.NumberWaiting>0 ||
WaitingAreaD11Normal.Queue.NumberWaiting>0 || WaitingAreaD12Normal.Queue.NumberWaiting>0 ||
WaitingAreaD13Normal.Queue.NumberWaiting>0 || WaitingAreaD14Normal.Queue.NumberWaiting>0

Delay

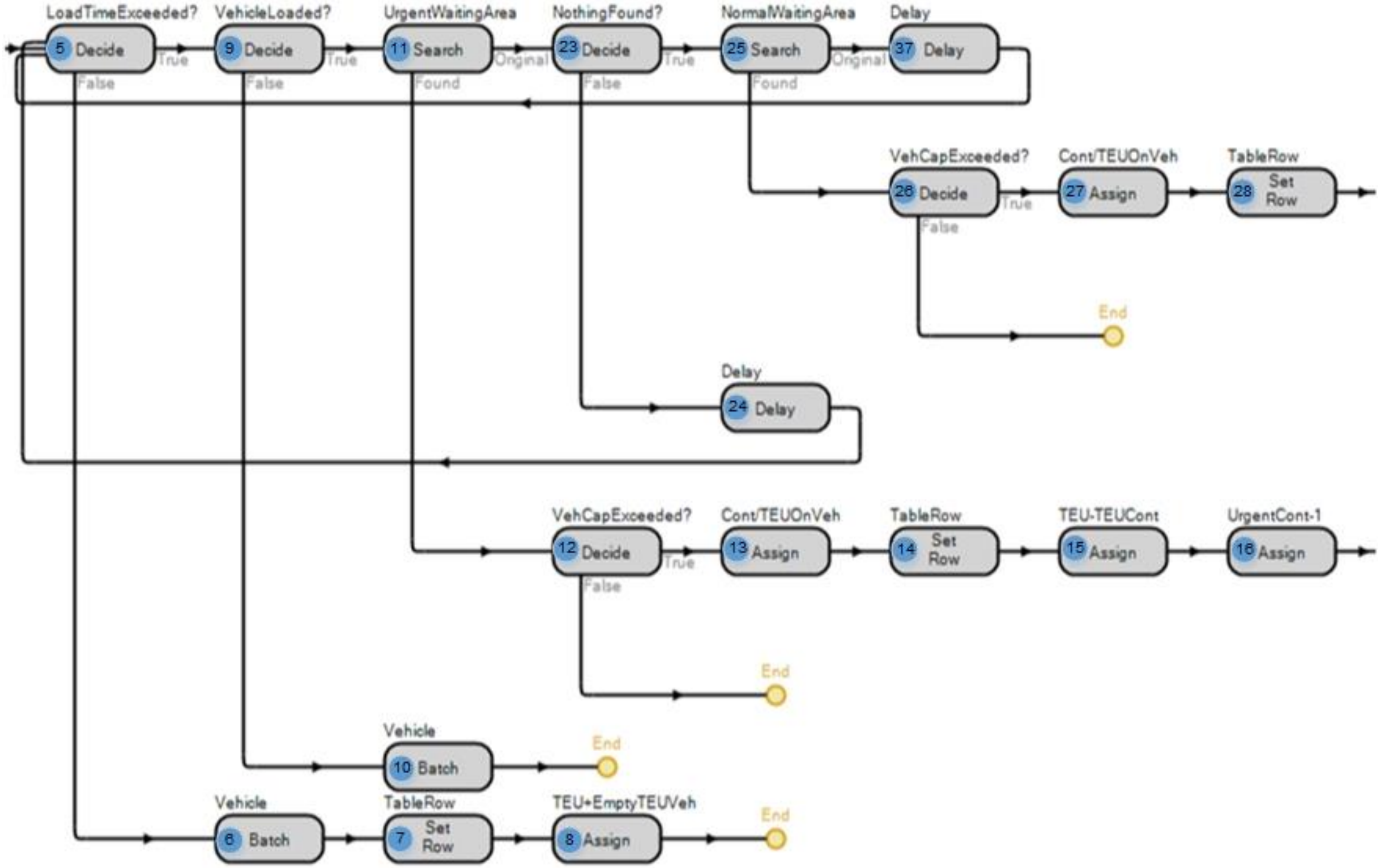
Delay time	20 seconds

Search

Collection type	Table rows
Table name	TerminalLoading
Search type	Minimize expression
Search expression	TerminalLoading.LatDepTimeFirstContainerInQueue
Limit	1
Save index found	Vehicle.IndexFound

Loading of the vehicle

The loading of the vehicle is quite an extensive process. The destination of the vehicle is known. Containers with the same destination are searched until the vehicle is fully loaded or until a time limit is reached. In Figure A-2 it shown when this process will be started (when the vehicle enters the node). Figure A-7 shows the process of loading of the vehicles. Table A-2 (TerminalLoading) is used for this process.


LoadTimeExceeded?
5 Decide
VehicleLoaded?
9 Decide
UrgentWaitingArea
11 Search
NothingFound?
23 Decide
NormalWaitingArea
25 Search
Delay
37 Delay
VehCapExceeded?
26 Decide
Cont/TEUOnVeh
27 Assign
TableRow
28 Set Row
End
Delay
24 Delay
VehCapExceeded?
12 Decide
Cont/TEUOnVeh
13 Assign
TableRow
14 Set Row
TEU-TEUCont
15 Assign
UrgentCont-1
16 Assign
End
Vehicle
10 Batch
End
Vehicle
6 Batch
TableRow
7 Set Row
TEU+EmptyTEUVeh
8 Assign
End
True
False
Original
Found

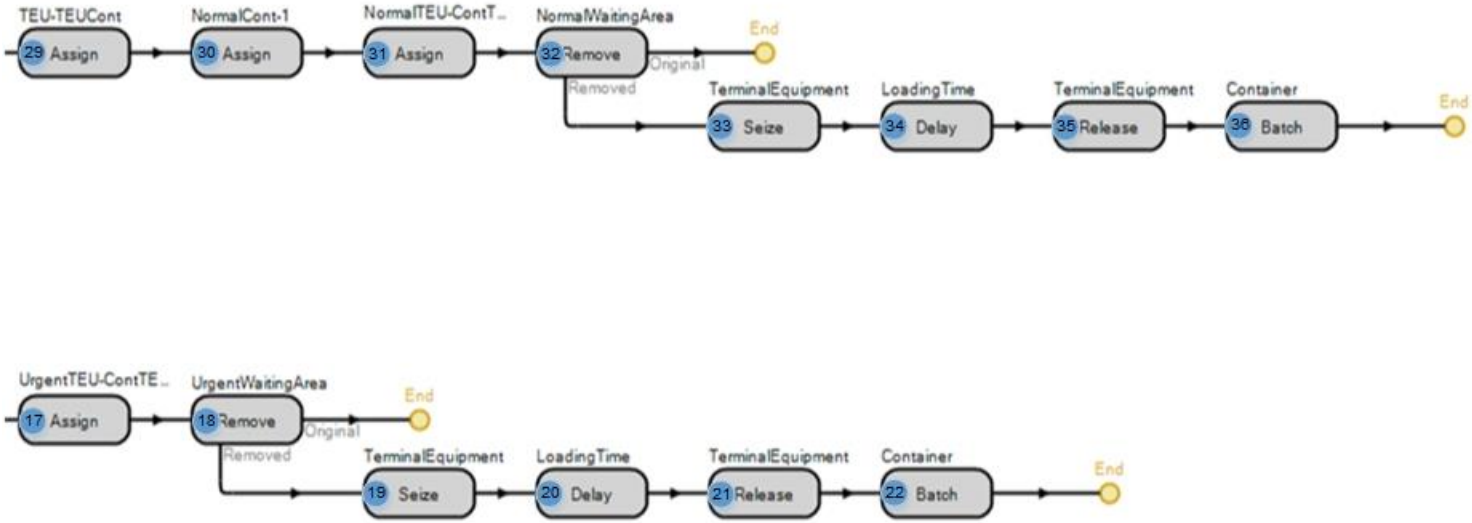


Figure A-7: Loading of the vehicle (figure consists of three parts) (Author, 2014)

All the steps of the process are numbered and are given below:

Assign	
State variable name	Vehicle.EmptyVehicleArrived
New value	TimeNow
Assign	
State variable name	Vehicle.DestinationTerminal
New value	TerminalLoading[Vehicle.IndexFound].DestinationTerminal
Set Row	
Table name	TerminalLoading
Row number	Vehicle.IndexFound
Assign	
State variable name	TerminalLoading.TEUAvailableForLoading
New value	TerminalLoading.TEUAvailableForLoading - Vehicle.CapacityTEU
Decide	
Expression	TimeNow - Vehicle.EmptyVehicleArrived <= 0.167
(false)	

Batch	
Batch logic name	BatchLogic1
Category	Parent
Set Row	
Table name	TerminalLoading
Row number	Vehicle.IndexFound
Assign	
State variable name	TerminalLoading.TEUAvailableForLoading
New value	TerminalLoading.TEUAvailableForLoading + (Vehicle.CapacityTEU - Vehicle.NumberOfTEU)
Decide	
Expression	Vehicle.NumberOfTEU < Vehicle.CapacityTEU
Batch	
Batch logic name	BatchLogic1
Category	Parent
Search	
Collection type	QueueState
Queue state name	TerminalLoading.UrgentWaitingArea
Search type	Forward
Limit	30
Save number found	Vehicle.NumberFound
Decide	
Expression	Vehicle.NumberOfTEU + Container.NumberOfTEU <= Vehicle.CapacityTEU
Assign	
State variable name	Vehicle.NumberOfTEU
New value	Vehicle.NumberOfTEU + Container.NumberOfTEU
State variable name	Vehicle.NumberOfContainers
New value	Vehicle.NumberOfContainers + 1
Set Row	
Table name	TerminalLoading
Row number	Vehicle.IndexFound
Assign	
State variable name	TerminalLoading.TEUAvailableForLoading
New value	TerminalLoading.TEUAvailableForLoading - Container.NumberOfTEU
Assign	

State variable name	TerminalLoading.NumberOfUrgentContWaiting
New value	TerminalLoading.NumberOfUrgentContWaiting – 1
Assign	
State variable name	TerminalLoading.NumberOfUrgentTEUWaiting
New value	TerminalLoading.NumberOfUrgentTEUWaiting - Container.NumberOfTEU
Remove	
Queue state name	TerminalLoading.UrgentWaitingArea
Seize	
Resource seizes	TerminalEquipment
Delay	
Delay time	LoadingTime_UnloadingTime_Equipment
Release	
Resource releases	TerminalEquipment
Batch	
Batch logic name	BatchLogic1
Category	Member
Decide	
Expression	Vehicle.NumberFound==0
Delay	
Delay time	5 seconds
Search	
Collection type	QueueState
Queue state name	TerminalLoading.NormalWaitingArea
Search type	Forward
Limit	30
Save number found	Vehicle.NumberFound
Decide	
Expression	Vehicle.NumberOfTEU + Container.NumberOfTEU <= Vehicle.CapacityTEU
Assign	
State variable name	Vehicle.NumberOfTEU
New value	Vehicle.NumberOfTEU + Container.NumberOfTEU
State variable name	Vehicle.NumberOfContainers
New value	Vehicle.NumberOfContainers + 1
Set Row	

Table name	TerminalLoading
Row number	Vehicle.IndexFound
Assign	
State variable name	TerminalLoading.TEUAvailableForLoading
New value	TerminalLoading.TEUAvailableForLoading - Container.NumberOfTEU
Assign	
State variable name	TerminalLoading.NumberOfNormalContWaiting
New value	TerminalLoading.NumberOfNormalContWaiting – 1
Assign	
State variable name	TerminalLoading.NumberOfNormalTEUWaiting
New value	TerminalLoading.NumberOfNormalTEUWaiting - Container.NumberOfTEU
Remove	
Queue state name	TerminalLoading.NormalWaitingArea
Seize	
Resource seizes	TerminalEquipment
Delay	
Delay time	LoadingTime_UnloadingTime_Equipment
Release	
Resource releases	TerminalEquipment
Batch	
Batch logic name	BatchLogic1
Category	Member

After loading of the vehicle

After the loading of the vehicles a state variable has to be changed and the vehicle must get an assignment to drive to its destination. (Vehicles are able to find the shortest route their selves.) The process is started when vehicles enter a node (shown in Figure A-2) and the process is shown in Figure A-8. Table A-3 (Destination_Table_Node) is used in this process.

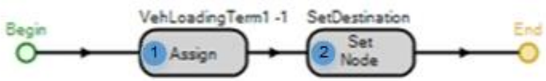


Figure A-8: After loading of the vehicle (Author, 2014)

The steps of the process are numbered and are given below:

Assign

State variable name	VehLoadingAtTerminalX
New value	VehLoadingAtTerminalX-1

Set node

Node name	Destination_Terminal_Node[Vehicle.IndexFound].DestinationNode

Table A-3: Destination terminal and destination node

Destination terminal	Destination node
1	T1_Unloading
...	...
14	T14_Unloading

(Author, 2014)

A.1.3 Process step 3: Intersections and crossings at the ITT infrastructure

There are two types of intersections at the ITT infrastructure: three-way crossings and traffic lights. At each intersection the there is a chance that the vehicles have to wait.

Three way crossing

There are multiple three way crossings in the model. When a vehicle enters a node of a three way crossing, the process will be started. Figure A-9 shows the process.

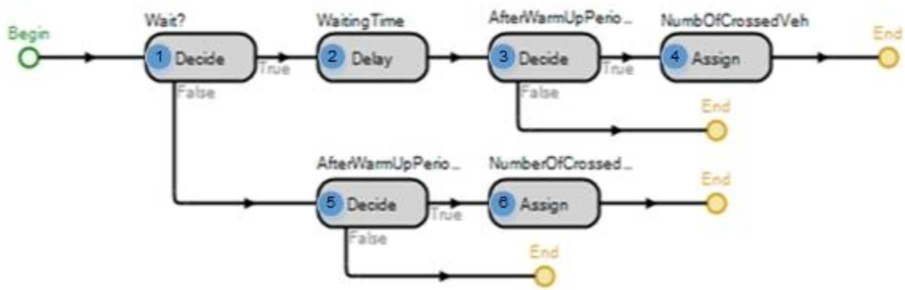


Figure A-9: Three way crossing (Author, 2014)

The steps of this process are numbered and are explained below:

Decide

Expression	Random.Uniform(0,1)<X
Delay	
Delay time	X+random.uniform(0,Y)
Decide	
Expression	Run.TimeNow>24
Assign	
State variable name	IX_NumberOfCrossedVehicles
New value	IX_NumberOfCrossedVehicles+1
Decide	
Expression	Run.TimeNow>24
Assign	
State variable name	IX_NumberOfCrossedVehicles
New value	IX_NumberOfCrossedVehicles+1

Traffic light

Also multiple traffic lights are located in the network. When the vehicles enter the node, where a traffic light is located, the process starts. Figure A-10 shows this process.

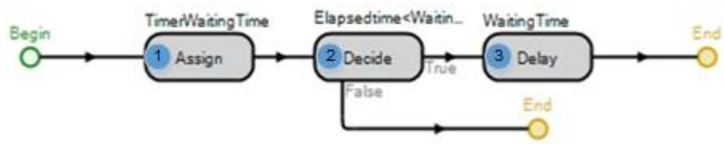


Figure A-10: Traffic light (Author, 2014)

The steps of this process are numbered and are explained below:

Assign	
State variable name	TimerIXWaitingTime
New value	2 minutes
Decide	
Expression	TimerIX.ElapsedTime<TimerIXWaitingTime
Delay	
Delay time	TimerIXWaitingTime-TimerIX.ElapsedTime

A.1.4 Process step 4: Unloading of the ITT systems and new transport assignment of the ITT systems → vehicles?

When the vehicles arrive at their destination, before the unloading some state variables have to be changed. Then the vehicles are unloaded and the vehicles determine their next transport assignment.

Before unloading of the vehicle

The process, shown in Figure A-11, will be followed before the unloading of the vehicles. In Figure A-2 it shown at which node this process takes place.

Figure A-11: Before unloading of the vehicle (Author, 2014)

The following steps are followed:

Decide

Expression	Vehicle.NormalTransportBeforeUrgentTransport==1

Assign

State variable name	VehToTerminalX
New value	VehToTerminalX-1

Assign

State variable name	Vehicle.NormalTransportBeforeUrgentTransport
New value	0

Unloading of the vehicle

When a vehicle enters the node of unloading the vehicles, see Figure A-2 , the process of unloading start. This process is shown in Figure A-12.

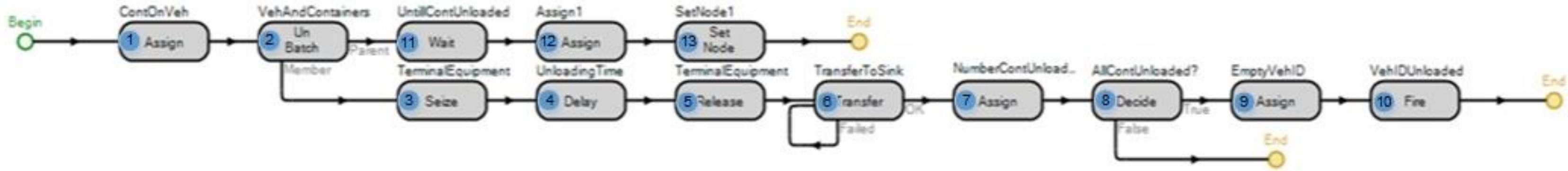


Figure A-12: Unloading of the vehicle (Author, 2014)

The process consists of the following steps:

Assign

State variable name	Vehicle.NumberOfContainersOnVehicle
New value	Vehicle.NumberOfContainers
UnBatch	
Quantity	Entity.BatchMembers
Entity object	Vehicle
Seize	
Resource seizes	TerminalEquipment
Delay	
Delay time	LoadingTime_UnloadingTime_Equipment
Release	
Resource releases	TerminalEquipment
Transfer	
From	FreeSpace
To	TX_ContainersToSink
Assign	
State variable name	Vehicle.NumberOfContainersUnbatched
New value	Vehicle.NumberOfContainersUnbatched+1
Decide	
Expression	Vehicle.NumberOfContainersUnbatched == Vehicle.NumberOfContainersOnVehicle
Assign	
State variable name	VehicleUnbatched
New value	Vehicle.ID
Fire	
Event name	AllContainersUnbatched
Wait	
Event name	AllContainersUnbatched
Event condition	Vehicle.ID == VehicleUnbatched
Assign	
State variable name	Vehicle.ID == VehicleUnbatched
New value	0
State variable name	Vehicle.NumberOfTEU
New value	0
State variable name	Vehicle.NumberOfContainers
New value	0

Set Node

Node name Node

Determining next transport assignment of the vehicle

After the unloading the vehicles can perform a next assignment. Figure A-2 shows the node at which this process is started and Figure A-13 the process. Table A-4 (TerminalXNextTransportAssignment) is used for this process.

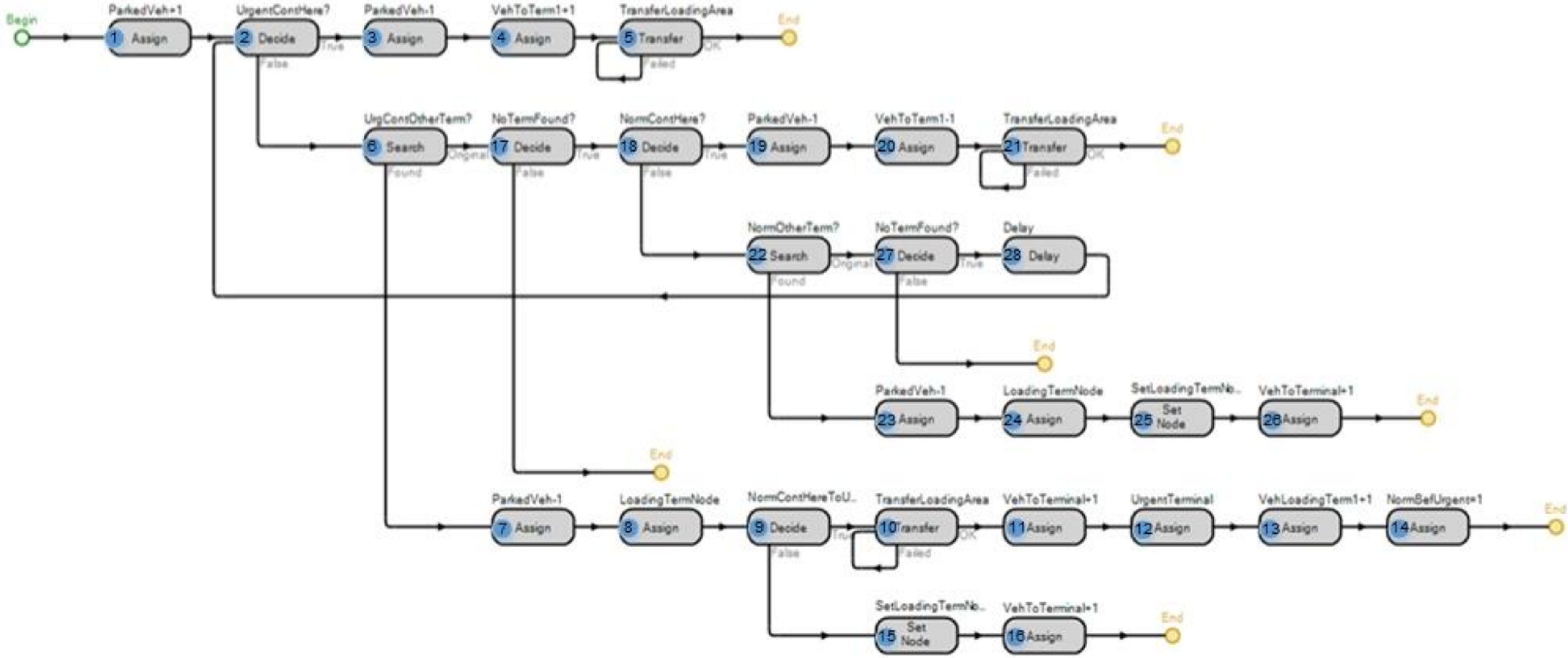


Figure A-13: Determining next transport assignment of the vehicle (Author, 2014)

The process consists of the following steps:

Assign

State variable name	NumberOfParkedVehicles
New value	NumberOfParkedVehicles+1
Decide	
Expression	TerminalXNextTransportAssignment[1].UrgentContainers>0
Assign	
State variable name	NumberOfParkedVehicles
New value	NumberOfParkedVehicles-1
Assign	
State variable name	VehToTerminal
New value	VehToTerminal+1
Transfer	
From	CurrentNode
To	TX_AssignmentCurrentTerminal
Search	
Collection type	TableRows
Table name	TerminalXNextTransportAssignment
Search type	Forward
Match condition	TerminalXNextTransportAssignment.UrgentContainers > 0
Starting index	2
Save index found	Vehicle.IndexLoadingTerminal
Save number found	Vehicle.NTA_NumberFound
Assign	
State variable name	NumberOfParkedVehicles
New value	NumberOfParkedVehicles-1
Assign	
State variable name	Vehicle.LoadingTerminalNode
New value	TerminalXNextTransportAssignment[Vehicle.IndexLoadingTerminal].TerminalNode
Decide	
Expression	TerminalXNextTransportAssignment[Vehicle.IndexLoadingTerminal].WaitingAreaNormal > 0
Transfer	
From	CurrentNode
To	TX_AssignmentCurrentTerminal
Assign	
State variable name	TerminalXNextTransportAssignment.VehToTerminal

New value	TerminalXNextTransportAssignment.VehToTerminal + 1
Assign	
State variable name	Vehicle.IndexFound
New value	TerminalXNextTransportAssignment.ClosestTerminal
Assign	
State variable name	VehLoadingAtTerminalX
New value	VehLoadingAtTerminalX+1
Assign	
State variable name	Vehicle.NormalTransportBeforeUrgentTransport
New value	1
Set Node	
Node name	Vehicle.LoadingTerminalNode
Assign	
State variable name	TerminalXNextTransportAssignment.VehToTerminal
New value	TerminalXNextTransportAssignment.VehToTerminal + 1
Decide	
Expression	Vehicle.NTA_NumberFound==0
Decide	
Expression	TerminalXNextTransportAssignment[1].NormalContainers>0
Assign	
State variable name	NumberOfParkedVehicles
New value	NumberOfParkedVehicles-1
Assign	
State variable name	VehToTerminalX
New value	VehToTerminalX+1
Transfer	
From	CurrentNode
To	TX_AssignmentCurrentTerminal
Search	
Collection type	TableRows
Table name	TerminalXNextTransportAssignment
Search type	Forward
Match condition	TerminalXNextTransportAssignment.NormalContainers > 0
Starting index	2

Save index found	Vehicle.IndexLoadingTerminal
Save number found	Vehicle.NTA_NumberFound
Assign	
State variable name	NumberOfParkedVehicles
New value	NumberOfParkedVehicles-1
Assign	
State variable name	Vehicle.LoadingTerminalNode
New value	TerminalXNextTransportAssignment[Vehicle.IndexLoadingTerminal].TerminalNode
Set Node	
Node name	Vehicle.LoadingTerminalNode
Assign	
State variable name	TerminalXNextTransportAssignment.VehToTerminal
New value	TerminalXNextTransportAssignment.VehToTerminal + 1
Decide	
Expression	Vehicle.NTA_NumberFound==0
Delay	
Delay time	0.5 minutes

Table A-4: Terminal X, determining next transport assignment

Closest terminal	Terminal node	Urgent containers	Normal containers	Vehicles to terminal	Vehicles loading at terminal	Number of normal containers waiting
1	T1_Loading	Terminal1.NumberOfUrgentTEUWaitingD1 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD2 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD3 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD4 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD5 / Vehicle.CapacityTEU +	Terminal1.NumberOfNormalTEUWaitingD1 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD2 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD3 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD4 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD5 / Vehicle.CapacityTEU +	VehToTerminal1	VehLoadingAtTerminal1	Terminal1.NumberOfNormalContWaitingD1

		Terminal1.NumberOfUrgentTEUWaitingD6 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD7 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD8 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD9 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD10 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD11 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD12 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD13 / Vehicle.CapacityTEU + Terminal1.NumberOfUrgentTEUWaitingD14 / Vehicle.CapacityTEU - VehToTerminal1 - VehLoadingAtTerminal1	Terminal1.NumberOfNormalTEUWaitingD6 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD7 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD8 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD9 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD10 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD11 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD12 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD13 / Vehicle.CapacityTEU + Terminal1.NumberOfNormalTEUWaitingD14 / Vehicle.CapacityTEU - VehToTerminal1 - VehLoadingAtTerminal1			
…	…	…	…	…	…	…

(Author, 2014)

Appendix B: Variant of the MTS with decoupling of MTS–truck and trailers

First it was also planned to define a lower bound of the number of required MTS-trucks. An unlimited amount of trailers can be put in the model. This means that there are empty rides if there are no (urgent) containers at the terminal, but no empty rides when there are too less empty trailers at a terminal. This means that the number of MTS-trucks would be in reality a bit higher. Unfortunately, it became clear that this variant was not possible to model (using more or less the original simulation model) because of the way the original model was set up.

The original model could be adapted in such a way that an extra batch step is added; first the containers and the empty trailers are combined to one batch, and then the MTS-truck with the loaded trailers are combined to a batch.

For the first batch step an extra threshold value must be set. When are the containers batched to the trailer and when is the trailer ready for transport? Of course this is possible when 10 TEU with the same destination is waiting, but when there are urgent containers these must be loaded on a trailer with a certain time limit. Otherwise, those containers will arrive too late when there is not enough TEU to load a vehicle completely.

Some limitations arise using this logic:

- The MTS-trucks do not know if there are urgent containers waiting at the terminals, only until the moment a loaded trailer is ready for transport. This means that the MTS-truck has less information compared to the coupled variant. In the coupled variant the MTS-trucks can anticipate on the urgent containers earlier. This means that the chance that urgent containers arrive too late is larger in this decoupling variant.
- During the period that the loaded trailer is set to be ready for transport, no extra containers can be loaded on the vehicle. This won't be a problem if all the trailers are fully loaded with 10 TEU, but this is a problem when the trailers are not fully loaded. This is in contradiction to the coupled variant. In that case, more containers are waiting at the waiting areas, and when the MTS-truck arrives, all the containers can be loaded on the trailer.
- The chance that MTS-trucks must transport urgent containers is quite high. This is caused by the input data. The input data is already adapted in such a way that all the containers have 1 hour more time for transport, there is still some time pressure on the containers. A container becomes urgent when the latest departure time is within one hour. Since approximately 20% of the containers has less than 2 hours and approximately 27% of the containers has less than 3 hours available for transport, MTS-trucks often have to transport urgent containers. This is especially the case with the extra batch step. (First the time limit must be reached before the containers and the trailer are batched. Then the MTS-truck knows that there are urgent containers waiting.)

  This problem is enlarged by the input data. The containers arrive in large amounts, but because the generator assumes that all the containers are unloaded by 1 crane, there is 2 minutes between every arrival of a container from a vessel or train. Not all these containers have the same destination, so the chance that there is a large amount of containers at a terminal with the same destination is small. Also the total amount of ITT containers is not that large for loading the trailers completely: on average there are 88 (scenario low growth), 98 (scenario high oil prices), and 125 (scenario European trend) containers per hour. This causes that the MTS-trucks mostly transport not fully loaded trailers. Because the other containers are not batched to groups of 10 TEU, the MTSs start transporting these containers only when they become urgent. In the coupled case, the non-urgent containers will be transported, independent on the case if there are enough containers.

Because of the found problems this variant is excluded from this research. Probably no lower bound will be found, as was originally intended. An estimation on the number of MTS-trucks and trailers will be made based on the coupled variant.

Appendix C: Scenario definition

In this chapter the (development of the) different future scenarios for 2030 are described. Per scenario the transport demand input must be generated. This input will be generated by using a computer generator. (de Lange, et al., 2014) The working of the generator will be explained, after which the variables that must be set for the input data are defined.

C.1 Generator input values

The generator creates different container carriers which carry a pre-set amount of containers. The modal split is used to define how much carriers of which modality are created. These container carriers will receive an arrival time at a terminal. Using the crane movement speed, all the containers are being unloaded after each other. The time when a container is being unloaded is called the start time of the container. The handling time of the containers (the time needed to unload all the containers) summed by the arrival time gives the departure time of the container carrier. The container carrier will have a fixed import and export amount, calculated using the carrier capacity. This amount of containers needs to be loaded and unloaded by the container carrier.
The origin of the container carrier is determined by looking at the terminals which handle the modality of that specific container carrier. The container carriers will be divided over these terminals, according to their percentage of the total terminal capacity of that certain modality. The origin of the container carrier will automatically be the origin of the containers at that container carrier.
The destination of the container is determined by the departure modality (using the modal split). It can be decided if ITT is needed. The terminal will be determined by looking at the terminals with the used modality and their percentage of the total terminal capacity. This terminal is the destination of the container.
A random generator is used to determine if the containers is 1 or 2 TEU, and is full or empty. Full containers have a chance to go via customs, also drawn by a random generator. The delivery time of the containers is determined by the departure time of the container carrier it departs with. The containers which have been waiting the longest, will be selected first. The delivery time of the containers is equal to the departure time of the container carrier minus the handling time of the container carrier. When a container is selected for customs, the ITT move is split in two parts: an ITT move from origin to customs and an ITT move from customs to destination. The available transport time (delivery time – start time) of the original move is also split in two and is assigned to the two ITT moves. When empty containers are above a certain time at the port, they will be stored in an empty container depot. The same process for splitting the ITT moves as for customs is applied.

There are different variables that can be changed in the model, like the modal split, and the import and export ratio of full and empty containers. In this research it is assumed that a good estimation of the different variables can be made and that the real values in the future won't be very different, so there won't be a large influence on the results. In contrast to this, there is much uncertainty about the economic prospects and it is not clear which of the four economic projections of Port Vision 2030 must be used. (Port of Rotterdam Authority, 2011) This will therefore be the only variable that will be changed. The bandwidth of the future ITT volume can be described with the projections. When only the volume of ITT containers differs between the scenarios, it is possible to see which ITT system is the most appropriate per amount of ITT. The division of containers between the terminals will stay the same and only the size of the flows will change.
The following variables have the largest impact on the results

- The chosen economic growth scenarios
- The chosen terminals and their corresponding capacity.

The chosen values of all the input parameters will be explained and the choice for these values will be discussed.

C.1.1 Economic growth scenario

There can be chosen between four different economic growth scenarios as input for the model: low growth, high oil prices, European trend, and global economy. These scenarios are shown in Table C-1. The throughput in 2013 was 11.6 million TEUs (International Transport Journal, 2014), which is equal to 116 million tonnes if the gross tonnes per TEU are equal to 10.0.

Table C-1: Throughput and average growth per economic growth scenario

Economic growth scenario	Million TEUs in 2030	Average growth from 2013
Low growth	19.0	2.94%
High oil prices	21.8	3.77%
European trend	26.7	5.02%
Global economy	31.0	5.95%

(Gerritse, 2014) (Port of Rotterdam Authority, 2011)

From the four economic projections only three projections will be used in the research. The global economy scenario is considered to be too optimistic. The last years the growth was far below the global container growth and it is not expected that the growth in Rotterdam reaches the level of the global growth. This means that the container port traffic would almost triple from 2013 until 2030 with an average growth percentage of 5.95%. These scenarios were actually developed with 2008 as baseline year. In that year the container throughput was equal to 112.3 million tonnes/11.23 million TEUs. This means that the throughput more or less remained the same. When the growth is equal each year, the growth from 2008 to 2030 must be 4.73%, but with the updated numbers from 2013 it must be 5.95%. So, the global economy scenario will not be taken into account in this research.

The other scenarios are considered as more realistic scenarios. As the container traffic in this area is still recovering from the crisis (in 2013 there was still a decrease of 0.1%), it is possible that the growth will stay minimal and that the low growth scenario will be followed. The scenario with the high oil prices is assumed to be the most realistic, because it assumes a moderate growth and a strict environmental policy. Much more attention is and will be paid to the sustainability of industry and logistics. The European growth scenario can also be seen as a realistic scenario, because it follows the existing policy and a moderate growth. The European growth scenario and the low growth scenario show the upper and lower bound of the estimation of the future.

C.1.2 Containers

There are some variables which relate to the containers, see Table C-2. The values gross tons per TEU and the TEU factor are set the same as in Gerritse. (Gerritse, 2014) Gerritse looked at the historical data of the average weight per TEU and the historical data of the TEU factor. The percentage of containers that will go to customs is researched in Diekman & Koeman and in this research the same value will be used. (Diekman & Koeman, 2013) The average time of a crane movement is determined by Duinkerken & Negenborn. (Duinkerken & Negenborn, 2014) The other variables are researched by de Lange. (de Lange, et al., 2014) These values are also used in this research. The minimal time for the storage of an empty containers was added, because of modelling difficulties. Some empty containers that were on the terminal one minute for departure were still sent to the empty depots. This parameter ensures that there will be no short stored empty containers from the ITT system. Only containers with an ITT move that are longer than 120 hours/5 days in the port are stored in between at an empty container depot. (5 days in the port means the time between the arrival of the origin container carrier and the departure of the destination container carrier, so the time that the container is located in the stack of a terminal is shorter.) This value is determined to be 5 days, because the storage in the stack is free for 4-5 days in the majority of the terminals at Le Havre. (Frémont & Franc, 2010) For Rotterdam it is assumed that this will also be more or less 4-5 days and it is assumed that containers that will stay longer will be sent to an empty depot.

Table C-2: Different values of container properties

Container property	Value
Gross tons per TEU	10
TEU factor	1.66
Percentage to customs	0.25%
Average time of crane movement	2 minutes/container
Minimal time for the storage of an empty container	120 hours

(Gerritse, 2014) (Diekman & Koeman, 2013) (de Lange, et al., 2014) (Frémont & Franc, 2010)

C.1.3 Run time of the generator

During the warming up period the vehicles and containers have to be divided over the network. The containers arrive directly at their origin, so this will be done automatically. The vehicles also have to be divided over the network. At the first day, hundreds of containers will be generated.
A few hours already would be enough to divide the vehicles over the network, but to be sure the period is long enough one day will be used. (Verbraeck, 2014)

There is a weekly pattern visible in the input data. It is best to let this pattern return three to six times. Because of the computer run time, three weeks is chosen to be the simulation time. (In total 9 combinations of scenario have to be run. For each combination first the number of vehicles has to be found, and then multiple replications have to be done. Therefore it is desirable that the computer run time per run is as short as possible.)
The month September will be used for the simulation, this is the second busiest month per year (9% of the containers are handled during this month). At airports it is required that the systems must be able to handle a ‘busy day’. (Transportation Research Board / National Research Council, 2002) A busy day is specified as the second busiest day of an average week of the busiest month. In this research the busiest day of an average week of the second busiest month (9% (busiest month) * 25% (average week) * 21% (second busiest day) = 0.473% of the yearly volume) is approximately equally busy as the second busiest day of an average week of the busiest month (10% (busiest month) * 25% (average week) * 19% (second busiest day) = 0.475% of the yearly volume).
When the month September reaches the required level of on-time containers, it is assumed that this is sufficient. During the busiest month, a few days (the busiest days of the average weeks) extra equipment will be deployed. This causes a large cost reduction, because otherwise there is the whole year an overcapacity of equipment and only a few days during the busiest month it is actually required. (During the busiest period there is a cost increase.)

C.1.4 Modal split

The modal split can be separated in the modal split of the land side and the sea side. The current modal split of the land side is given and it is expected that the modal split in 2030 is changed. The port of Rotterdam wants to change this modal split to the percentages shown in Table C-3. These values are also used in this research.

Table C-3: Modal split land side

	Truck	Rail	Barge
Current situation	48%	13%	39%

2030	35%	20%	45%

(Gerritse, 2014) (Port of Rotterdam Authority, 2011)

The modal split of the sea side at this moment is given. In the research of (Gerritse, 2014) it is assumed that the modal split will be the same in 2030, see Table C-4.

Table C-4: Modal split sea side

	Deep sea	Short sea	Transhipment
Current situation	60%	10%	30%
2030	60%	10%	30%

(Gerritse, 2014)

C.1.5 Import and export of full and empty containers

The import and export of containers can be divided in full and empty containers. The current situation contains 51% import and 49% full export containers. It is assumed that this won't change in the future, see Table C-5.

Table C-5: Import and export percentage of full containers

	Import	Export
Current situation	51%	49%
2030	51%	49%

(Gerritse, 2014)

The current situation of the import and export containers will be different in the future, see Table C-6. The import containers are expected to be 18%. At this moment there is 18% export of empty containers and it is estimated that this will be 21% in 2030. (Gerritse, 2014) This can be explained by the growing trade volumes with Asia.

Table C-6: Import and export percentage of empty containers

	Import	Export
Current situation	18%	18%
2030	18%	21%

(Gerritse, 2014)

C.1.6 TEU capacity and average time between arrival and departure

The capacities of the container carriers are needed as input for the model, shown in Table C-7. This value describes the number of TEUs handled on the terminal, not the number of TEUs that is on board of the carrier. The creator of the generator researched this topic using literature to find a good estimation of capacities of the container carriers. (The World Bank Group, sd) (de Lange, et al., 2014) The same values will be used as input, because the creator of the generator researched this subject with the same objective, finding the most realistic values for ITT. When the TEU capacity is divided by the TEU factor and multiplied by two times the crane movement speed the handling time is calculated. This is the average time between arrival and departure of a carrier. (de Lange, et al., 2014)

Table C-7: TEU capacity and average time between arrival and departure per modality

Modality	TEU capacity (number of TEUs handled on the terminal)	Average time between arrival and departure

Truck	2	0.5 hours
Barge	50	2.1 hours
Train	50	2.1 hours
Short sea vessel	600	24.6 hours
Deep sea vessel	1200	48.3 hours

(The World Bank Group, sd) (de Lange, et al., 2014)

C.1.7 Terminals

For the terminals at Maasvlakte 1 and 2 a distinction can be made between existing terminals (or terminals which are now being built) and terminals for which it is not sure if these will be built. This includes terminal 3 and 4 at Maasvlakte 2, a common rail terminal, and a common barge service centre.

The Port of Rotterdam wants to build a common barge service centre, but it is questionable if the terminal operators can find a compromise, because no one wants to pay the costs for the transport to and from this service centre. There is already a project concerning the barges, called Next Logic. Next Logic is based on three different aspects: neutral, integral planning, call optimization, and performance measurement. By assigning barges neutral and integral to terminal and depot slots, the demand and supply will be better matched and the reliability and predictability will be improved. By call optimization the number of calls will be decreased and the size of the average call size will be increased. This contributes to the optimization of the inland container transport chain. The performance measurement visualizes the performance of the supply chain, the individual parties in the chain, and the impact of the measures. It is assumed that Next Logic will be developed further and that no common barge service centre will be built.

It is realistic that there will be a common rail terminal, because the terminals are not able to load all the trains completely with their own containers. It is expensive to let the trains stop at every terminal, the trains must drive at predetermined time slots, and it takes a long time to turn the trains for a small distance. When the trains stop at a common rail terminal, the containers can be transported by means of ITT. However, when there will be a common rail terminal in the future, this will probably be the rail terminal west (RTW) and no new terminal will be built. Rail terminal west belongs to ECT, but then will be used for containers of different terminal operators.

This research will not include terminal 3 and 4. The existing terminals will have enough capacity, although for the European trend scenario all the terminals must use all their capacity to handle the volume. In reality, terminal 3 and 4 will possibly be built when it turns out that there is enough demand, but often the construction of those terminals is only finished when the existing terminals run already at full capacity. It is assumed that terminal 3 and 4 will be built after 2030.

The capacities of the terminals used by Gerritse do not match the capacities in this research. The difference is shown in Table C-8.

Table C-8: Capacities of terminals outside the Maasvlake and at the Maasvlakte

Outside Maasvlakte	**This research Capacity [million TEUs]**	**Gerritse Capacity [million TEUs]**
Uniport Multipurpose Terminals	1.2	1.2
Barge Center Waalhaven	0.2	0.2
Rotterdam Shortsea Terminals	1.44	1.45
ECT city terminal	1.15	1.15
Total	**3.99**	**4**

Maasvlakte		
2) ECT Euromax terminal	5	2.75
3) RWG	4	4.5
5) APMT MV2	4.5	4.5
8) Rail Terminal West	1.3	?
9) Rotterdam container terminal/ Barge Service Center Hartelhaven	0.5	0.5
10) Delta container services	0.15	0.15
12) APMT MV1	3.2	2.4
13) ECT Delta terminal	4.8	5.1
14) ECT Delta Barge Feeder terminal	0.8	0.33
Total	**24.25**	**20.23**
Total outside Maasvlakte & Maasvlakte	**28.24**	**24.23**

(Gerritse, 2014) (Port of Rotterdam Autohority, 2013) (Europe Container Terminals, sd) (Algemeen Dagblad, 2008) (Nieuwsblad Transport, 2011) (Vereniging van Rotterdamse terminal operators, sd) (Maasvlakte 2, sd) (Maasvlakte 2, sd) (Maasvlakte 2, 2010)

Gerritse uses two occupation rates of the terminals. The terminals at the Maasvlakte have an occupation rate of 85% and the terminals outside the Maasvlakte have an occupation rate of 45%. This is a lower rate than the Maasvlakte terminals, explained by the fact that the city terminals are further from the sea and smaller and thus less capable of taking advantage of economies of scale. This is predicted by the terminal operators as well. (van Schuylenburg, 2013)

In this research the same division of occupancy is used for the low growth and high oil prices scenario. The total capacity of the terminals is 26.94 million TEUs, but for the European trend scenario the total volume will be 26.7 million TEUs. Therefore it isn't possible to use the same occupation rates and all the terminals will run (almost) at full capacity.

Table C-9: Utilisation rates for the different scenarios per terminal

		Low growth		*High oil prices*		*European trend*	
Outside Maasvlakte	**Capacity [million TEUs]**	**Handled cargo [million TEUs]**	**Utilisation rate [%]**	**Handled cargo [million TEUs]**	**Utilisation rate [%]**	**Handled cargo [million TEUs]**	**Utilisation rate [%]**
Uniport Multipurpose Terminals	1.2	0.46	38%	0.53	44%	0.73	61%
Barge Center Waalhaven	0.2	0.08	38%	0.09	44%	0.12	61%
Rotterdam Shortsea Terminals	1.44	0.55	38%	0.63	44%	0.88	61%
ECT city terminal	1.15	0.44	38%	0.50	44%	0.70	61%
Total	**3.99**	**1.52**		**1.75**		**2.45**	
Maasvlakte							
2) ECT Euromax terminal	5	3.60	72%	4.14	83%	5.00	100%
3) RWG	4	2.88	72%	3.31	83%	4.00	100%
5) APMT MV2	4.5	3.24	72%	3.72	83%	4.50	100%

8) Rail Terminal West	1.3	0.94	72%	1.08	83%	1.30	100%
9) Rotterdam container terminal/ Barge Service Center Hartelhaven	0.5	0.36	72%	0.41	83%	0.50	100%
10) Delta container services	0.15	0.11	72%	0.12	83%	0.15	100%
12) APMT MV1	3.2	2.31	72%	2.65	83%	3.20	100%
13) ECT Delta terminal	4.8	3.46	72%	3.97	83%	4.80	100%
14) ECT Delta Barge Feeder terminal	0.8	0.58	72%	0.66	83%	0.80	100%
Total	**24.25**	**17.48**		**20.05**		**24.25**	
Total outside Maasvlakte & Maasvlakte	**28.24**	**19.00**		**21.80**		**26.70**	

(Author, 2014)

Concluding, all the terminals will be used in the model, except for the common barge service centre, the common rail terminal, and terminal 3 and 4.

The output of the generator consists of a large table with a list of containers. Each container is assigned with a start time, origin, delivery time, destination, and size in TEUs. Three of those tables will be created; one for the low growth scenario, one for the high oil prices scenario, and one for the European trend scenario.

C.2 Generator output/simulation model input

The output tables of the generator per scenario will be used as the input for the simulation model. The OD-matrices are given, then the weekly pattern is shown and the time pressure on the containers is discussed.

C.2.1 OD-matrices

Three OD-matrices are made for all the ITT containers that are generated (warm-up period and simulation period), one matrix per future scenario. The OD-matrix of the low growth scenario is shown in Table C-10, the high oil prices in Table C-11, and the European trend in Table C-12. All the assumptions for the generation of ITT containers are the same. There is only a difference between the amounts of containers per scenario. This means that there is only a difference in number of moves and not in the way they are divided over the terminals and depots.

A lot of containers are transported to and from the terminals. Large terminals have relatively more ITT moves than small terminals. Also the customs has to deal with a large amount of ITT containers. This is because 0.25% of the full ITT containers has to go to customs.

It is noticeable that only a very small amount of containers is transported from or to empty depots. This can be explained by the way the generator works. Only empty containers, which already have an ITT move between two terminals, can be stored in an empty depot. These containers will only be stored if they are longer than 120 hours/5 days at the port. The available transport time for the ITT move will then be divided in two, and the ITT move is separated in two parts. A very small amount of containers stay longer than 5 days at the port, so the amount of empty container moves is also very low. It is also possible that a truck delivers ITT containers at an empty depot and from there an ITT move is generated to a terminal, but this are also a low amount of ITT moves. In reality, shipping companies give orders to transport (a certain amount of) empty containers from a terminal to an empty depot or vice versa, because they must pay for containers that are stored longer than a certain time in the stack. These orders are not taken into account by the generator.

At some terminals there is no balance between the incoming and outgoing ITT containers. At the following terminals there are significantly more containers that have the terminal as destination than as origin:

- ECT Euromax terminal (2)
- Rotterdam World Gateway (3)
- APMT MV2 (5)
- Barge Service Center Hartelhaven (9)

The first three terminals are all located at the west side of the ITT network.

The following terminals have significantly more containers that have this terminal as origin than as destination:

- Rail Terminal West (8)
- APMT MV1 (12)
- ECT Delta Terminal (13)
- ECT Delta Barge Feeder Terminal (14)

The last three terminals are located at the east side of the network. The unbalance between incoming and outgoing containers must be taken into account for the dispatching strategy of the vehicles.

Table C-10: OD-matrix of the scenario Low growth

	1: Empty Depot MV1	2: ECT Euromax terminal	3: Rotterdam World Gateway (RWG)	4: Empty Depot MV2	5: APMT MV2	6: Customs	7: Van Doorn Container Depot	8: Rail Terminal West	9: Barge Service Center Hartelhaven	10: Delta Container Services	11: Kramer Delta Depot	12: APMT MV1	13: ECT Delta Terminal	14: ECT Delta Barge Feeder Terminal	
1: Empty Depot MV1	0	0	0	0	0	0	0	0	10	0	0	0	0	0	**10**
2: ECT Euromax terminal	11	0	387	0	429	2128	0	230	1069	18	0	378	486	70	**5206**
3: Rotterdam World Gateway (RWG)	0	443	0	11	441	1722	0	198	923	12	0	259	363	71	**4443**
4: Empty Depot MV2	0	0	0	0	0	0	0	0	14	4	0	0	0	0	**18**
5: APMT MV2	0	364	304	7	0	1761	0	190	863	7	0	242	376	100	**4214**
6: Customs	0	2149	1745	0	1786	0	0	26	142	23	0	1068	1548	97	**8584**
7: Van Doorn Container Depot	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
8: Rail Terminal West	0	711	588	0	650	74	0	0	5	4	0	475	717	16	**3240**
9: Barge Service Center Hartelhaven	0	483	396	0	506	96	0	10	0	0	0	300	429	3	**2223**
10: Delta Container Services	0	139	86	0	92	29	0	0	0	0	1	76	130	0	**553**
11: Kramer Delta Depot	0	0	0	0	0	0	0	0	12	93	0	0	0	0	**105**
12: APMT MV1	0	1121	912	0	1019	1113	0	241	499	8	2	0	211	41	**5167**
13: ECT Delta Terminal	0	2218	1695	0	1904	1679	0	498	961	8	11	283	0	77	**9334**
14: ECT Delta Barge Feeder Terminal	0	690	504	0	604	148	0	1	7	0	0	411	632	0	**2997**
	11	**8318**	**6617**	**18**	**7431**	**8750**	**0**	**1394**	**4505**	**177**	**14**	**3492**	**4892**	**475**	**46094**

(Author, 2014)

Table C-11: OD-matrix of the scenario High oil prices

	1: Empty Depot MV1	2: ECT Euromax terminal	3: Rotterdam World Gateway (RWG)	4: Empty Depot MV2	5: APMT MV2	6: Customs	7: Van Doorn Container Depot	8: Rail Terminal West	9: Barge Service Center Hartelhaven	10: Delta Container Services	11: Kramer Delta Depot	12: APMT MV1	13: ECT Delta Terminal	14: ECT Delta Barge Feeder Terminal	
1: Empty Depot MV1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
2: ECT Euromax terminal	1	0	390	0	472	2182	0	250	1038	14	0	449	525	67	**5388**
3: Rotterdam World Gateway (RWG)	0	436	0	2	439	1869	0	216	929	14	0	282	396	68	**4651**
4: Empty Depot MV2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	**2**
5: APMT MV2	0	536	464	0	0	2092	0	278	1131	12	0	313	506	162	**5494**
6: Customs	0	2211	1885	0	2121	0	0	27	191	16	0	1110	1773	131	**9465**
7: Van Doorn Container Depot	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
8: Rail Terminal West	0	696	565	0	663	53	1	0	10	5	0	441	664	22	**3120**
9: Barge Service Center Hartelhaven	0	523	429	0	488	122	0	12	0	1	0	288	471	2	**2336**
10: Delta Container Services	0	144	128	0	145	27	0	0	0	0	1	95	147	0	**687**
11: Kramer Delta Depot	0	0	0	0	0	0	0	0	0	97	0	0	0	0	**97**
12: APMT MV1	0	1375	1163	0	1275	1186	0	275	664	8	0	0	282	51	**6279**
13: ECT Delta Terminal	0	2362	1857	0	2171	1907	0	469	1050	17	3	316	0	59	**10211**
14: ECT Delta Barge Feeder Terminal	0	783	623	0	673	196	0	6	5	0	0	535	712	0	**3533**
	1	**9066**	**7504**	**2**	**8447**	**9634**	**1**	**1533**	**5018**	**188**	**4**	**3829**	**5476**	**562**	**51265**

(Author, 2014)

Table C-12: OD-matrix of the scenario European trend

	1: Empty Depot MV1	2: ECT Euromax terminal	3: Rotterdam World Gateway (RWG)	4: Empty Depot MV2	5: APMT MV2	6: Customs	7: Van Doorn Container Depot	8: Rail Terminal West	9: Barge Service Center Hartelhaven	10: Delta Container Services	11: Kramer Delta Depot	12: APMT MV1	13: ECT Delta Terminal	14: ECT Delta Barge Feeder Terminal	
1: Empty Depot MV1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	**2**
2: ECT Euromax terminal	3	0	540	0	630	2864	0	287	1545	16	0	564	687	117	**7253**
3: Rotterdam World Gateway (RWG)	0	488	0	1	529	2211	0	219	1099	16	0	325	479	84	**5451**
4: Empty Depot MV2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
5: APMT MV2	0	464	395	0	0	2410	0	244	1079	9	0	296	444	169	**5510**
6: Customs	0	2932	2276	0	2460	0	0	39	226	27	0	1519	2264	154	**11897**
7: Van Doorn Container Depot	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
8: Rail Terminal West	0	825	663	0	779	72	0	0	11	4	0	576	830	20	**3780**
9: Barge Service Center Hartelhaven	0	659	486	0	563	163	0	4	0	0	0	433	628	0	**2936**
10: Delta Container Services	0	258	172	0	201	47	0	6	14	0	24	142	221	0	**1085**
11: Kramer Delta Depot	0	0	0	0	0	0	0	0	0	94	0	0	0	0	**94**
12: APMT MV1	0	2175	1759	0	1989	1615	0	461	988	15	1	0	429	56	**9488**
13: ECT Delta Terminal	0	3256	2535	0	2835	2458	0	634	1464	17	1	416	0	106	**13722**
14: ECT Delta Barge Feeder Terminal	0	963	782	0	829	238	0	17	19	0	0	663	849	0	**4360**
	3	**12020**	**9608**	**1**	**10815**	**12078**	**0**	**1911**	**6445**	**201**	**26**	**4934**	**6831**	**706**	**65579**

(Author, 2014)

C.2.2 Weekly pattern

Figure C-1 shows a histogram of the start times of the containers from the generator. (Each bar represents the number of containers from 1/4th day.) The weekly pattern is clearly visible and the difference between the containers in the first month and the second month too. The weekly distribution will be 15% on Monday, 21% on Tuesday, 19% on Wednesday, 19% on Thursday, 19% on Friday and 4% on Saturday and Sunday.

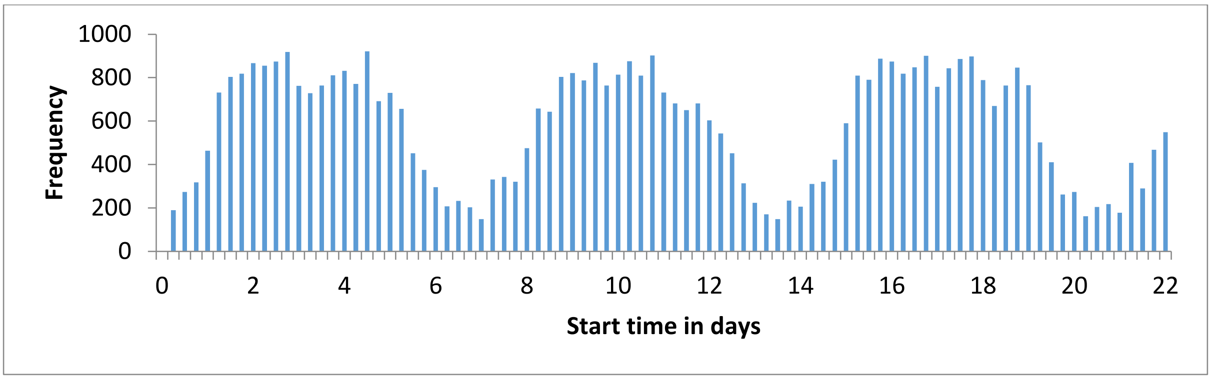


Figure C-1: Histogram of start times for the high oil prices scenario per 6-hour period (Author, 2014)

C.2.3 Time pressure of ITT containers

There is a lot of difference between the available transport times of the containers. The available transport time is the time between the start time and the delivery time of the containers. In Table C-13 the percentage of containers with an available transport time lower than 1 or 2 hours per scenario is shown. These percentages are quite high, so this means that there is a lot of time pressure on the ITT containers.

Table C-13: Percentage of containers with an available transport time lower than 1 or 2 hours per scenario

Scenario	Percentage of containers with an available transport time < 1 hour	Percentage of containers with an available transport time < 2 hours
Low growth	19.7%	26.5%
High oil prices	19.2%	26.2%
European trend	21.5%	29.4%

(Author, 2014)

To give an indication about the rest of the containers, Figure C-2, Figure C-3, and Figure C-4 show the available transport time divided in different categories per scenario.

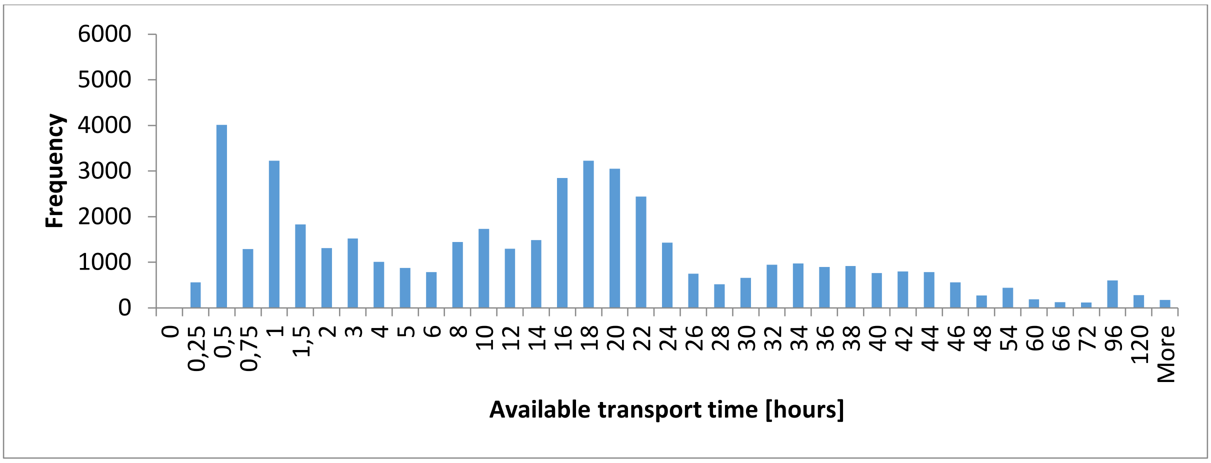


Figure C-2: Histogram of the available transport time for scenario low growth (Author, 2014)

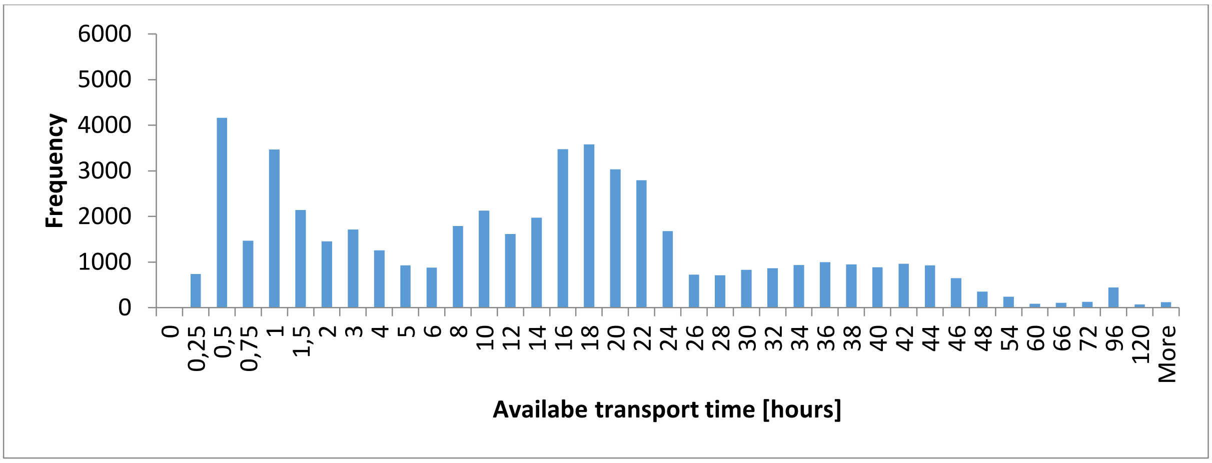


Figure C-3: Histogram of the available transport time for scenario high oil prices (Author, 2014)

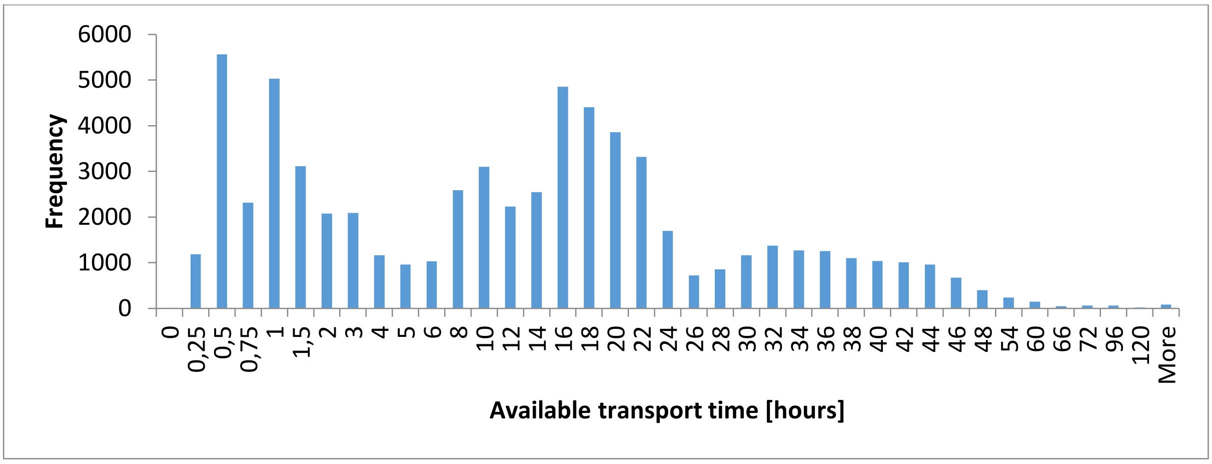


Figure C-4: Histogram of the available transport time for scenario European trend (Author, 2014)

When this input data would be used, there are containers that are on forehand too late, because their available transport time is very low. This is considered to be not realistic. (Europe Container Terminals, 2014) At the current ITT system at the Delta terminal of Europe Container Terminals containers are deleted from the loading/unloading list when it is on forehand known they won't be able to arrive on time and will get a new delivery time and destination. Therefore the available transport time of all the containers is increased with one hour (one hour is added to the delivery time of the containers) and this data will be used in the simulation model.

Appendix D: Input values of the simulation model

For the simulation model input values is necessary. In the project "Inter-terminal transport on Maasvlakte 1 and 2 in 2030 – Towards a multidisciplinary and innovative approach on future inter-terminal transport options" a set of parameters, their definitions, and proposed values has been made. (Duinkerken & Negenborn, 2014) A part of these values (which are verified by ECT) will be used in this research and a part of the values is based on the data and expert view of ECT.

D.1 ITT systems

The ITT systems have different properties, like the speed and the capacity. The proposed values of the research of Duinkerken and Negenborn are shown in Table D-1. (Duinkerken & Negenborn, 2014) These values are verified by ECT and are considered realistic. (Europe Container Terminals, 2014)

Table D-1: ITT system properties

ITT system	Speed [km/h]	Capacity [TEU]	ALV container load time [minutes]	ALV container unload time [minutes]
AGV	40	2		
ALV	40	2	0.5	0.5
MTS	30	10		

(Duinkerken & Negenborn, 2014)

D.2 Terminal equipment

Each terminal has terminal equipment for the loading and unloading of the ITT systems. Only for the ALV no equipment is needed, because they are able to load and unload by themselves. The type of terminal equipment of the current and new terminals is known, but the ASCs are not able to load and unload a MTS. Therefore another type of equipment is assumed for these terminals.

The number of terminal equipment that will be used is calculated by the following formula:

$$\text{equipment}_{\text{required}}=\frac{\text{number of containers during simulation period}}{\text{length of simulation period / handling time per container}}$$

$$\text{equipment}_{\text{used}}=\text{round}\left(\text{equipment}_{\text{required}}\right)+2$$

The OD-matrix is used to determine the amount of containers arriving and departing at a terminal and are summed. This is the number of container during the simulation period. The length of the simulation period is known and for the handling time per container the mean of the equipment type is used. The required equipment can be calculated. The used equipment in the simulation model is calculated by rounding the required number of equipment and adding two more. This causes that there will be a high capacity/an overcapacity of equipment. It is not desirable that the terminal equipment will be the bottleneck of the ITT process. (Europe Container Terminals, 2014) Therefore a high capacity is desirable, because then the ITT vehicles can be handled relatively fast.

In reality there is no dedicated equipment only for ITT. Most of the terminal equipment will be used for other landside operations (and sometimes for waterside operations). This means that in reality there is a larger amount of equipment that will be used for ITT, but that only a certain percentage of their time they are doing ITT operations.

It is also possible to use the real number of equipment that is available for ITT and the other operations and make an estimation of the probability distributions for the loading and unloading of the containers. This probability distribution can be different per terminal. This method can give a better representation of the reality, but no data is available of all the operations per terminal, so this would cause that an estimation would be made with a high uncertainty level. Especially for the not yet existing terminals and depots it is difficult to make an estimation. Therefore the above described method is used.

Table D-2 shows the number of containers to be handled per terminal and Table D-3 shows the type and number of terminal equipment per terminal. Because there is a different amount of ITT containers in the future scenarios, the number of terminal equipment differs. When MTSs are used in the model, at some terminals another type of equipment is used.

Table D-2: Number of containers to be handled per terminal during the simulation period

Terminal number	Terminal	Number of containers during simulation period: scenario low growth	Number of containers during simulation period: scenario high oil prices	Number of containers during simulation period: scenario European Trend
1	Empty depot MV1	21	2	5
2	Euromax Terminal	13524	14454	19273
3	RWG	11060	12155	15059
4	Empty depot MV2	36	4	2
5	APM MV2	11645	13941	16325
6	Customs	17334	19099	23975
7	Van Doorn container depot	0	2	0
8	Rail Terminal West	4634	4653	5691
9	Barge Service Center Waalhaven	6728	7354	9381
10	Delta Container Services	730	875	1286
11	Kramer Delta depot	119	101	120
12	APM MV1	8659	10108	14422
13	Delta Terminal	14226	15687	20553
14	DBF	3472	4095	5066

(Author, 2014)

Table D-3: Type and number of terminal equipment per terminal

Terminal number	Terminal	Equipment type	Average handling time equipment	Number of equipment: scenario low growth	Number of equipment: scenario high oil prices	Number of equipment: scenario European trend
1	Empty depot MV1	RS	3	2	2	2
2	ECT Euromax Terminal	ASC	2,5	3	3	3
	(when MTS used)	SC/RS	3	3	3	4
3	RWG	ASC	2,5	3	3	3
	(when MTS used)	SC/RS	3	3	3	3
4	Empty depot MV2	RS	3	2	2	2
5	APM MV2	ASC	2,5	3	3	3

	(when MTS used)	SC/RS	3	3	3	4
6	Customs	RS	3	4	4	4
7	Van Doorn container depot	RS	3	2	2	2
8	Rail Terminal West	RC	2	2	2	2
9	Barge Service Center Waalhaven	QC	2	2	2	3
10	Delta Container Services	QC	2	2	2	2
11	Kramer Delta depot	RS	3	2	2	2
12	APM MV1	SC	3	3	3	3
13	ECT Delta Terminal	SC	3	3	4	4
14	ECT Delta Barge Feeder Terminal	QC	2	2	2	2

(Author, 2014)

Based on the data of ECT, distributions for the loading time and unloading time per type of terminal equipment are determined. These are based on existing data. (Europe Container Terminals, 2014) In Table D-4 an overview is given.

Table D-4: Service times terminal equipment

Equipment type	**Loading time [minutes/container]**
ASC (automated stacking crane)	Triangular(2.5,0.5)
RS (reach stacker)	Triangular(3,1)
SC (straddle carrier)	Triangular(3,1)
RC (rail crane)	Triangular(2,0.5)
QC (quay crane)	Triangular(2,0.5)

(Europe Container Terminals, 2014)

When the loading process of vehicles takes place at a terminal or depot, vehicles will depart when the vehicle is fully loaded or when a time limit is reached. When the time limit is reached, the vehicle will depart not fully loaded. This time limit will be set to 10 minutes in the simulation model.

D.3 Intersections

There are two types of intersections in the ITT network: traffic lights and 3-way crossings. Traffic lights are used for crossings with rail or public road and at a 3-way crossing only ITT vehicles can cross.

D.3.1 Traffic lights

Table D-5 shows the values for the traffic lights. The proposed values of Negenborn and Duinkerken are verified by ECT. The crossing time of the ITT vehicles is considered realistic and will be used in this model as well. Negenborn and Duinkerken propose 18 minutes of green time for the traffic lights and 2 minutes of red light time. The value of these numbers is considered as realistic, but the numbers are deterministic. In reality, the arrivals of vehicles at the public road or trains will not be equally divided over time, so a probability distribution is made for the green time, using the proposed values as the mean.

Table D-5: Intersections

Type of intersection	Time to cross [seconds]	Intersection numbers	Green light time [minutes]	Red light time [minutes]
Traffic light	0	I2, I3, I5, I7, I9	Triangular(16,18,20)	2

(Europe Container Terminals, 2014)

D.3.2 3-way crossings

For the three way crossings (I1, I4, I6, I9, I10, I11, I12, I13, I14, I15, I16, and I17) first the number of vehicles is counted that crosses the intersection during a run with 95% on-time delivery. Then the chance a vehicle meets another vehicle (or the safety margin around the vehicle) at the intersection is determined. Therefore the block length (length that must be kept free around one vehicle) must be determined. The block length is equal to the intersection length summed with the vehicle length, divided by the vehicle speed summed with the time between two consecutive vehicles.

Table D-6: Block length per ITT system

ITT system	Intersection length [m]	Vehicle length [m]	Vehicle speed [km/h]	Time between two vehicles [s]	Block length [s]
AGV	20	15	40	2	5.2
ALV	20	13.7	40	2	5.0
MTS	20	82.5	30	2	14.3

(Author, 2014)

The chance that a vehicle meets another vehicle is determined by the percentage the intersection is occupied by vehicles. This is the number of blocks during the simulation period times the block length, divided by the total simulation period. From the 12 possible combinations of two vehicles at one intersection, only 6 of them are conflicting, see Figure D-1.

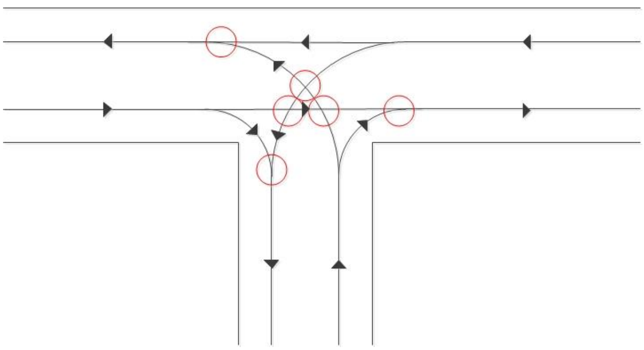


Figure D-1: Possible conflicts at a 3-way crossing (Author, 2014)

The chance that a vehicle meets another will therefore be divided by two. Table D-7 shows the chance that a vehicle has to wait at another vehicle per ITT system per scenario for each intersection.

Table D-7: Chance that a vehicle has to wait at a 3-way crossing

Intersection	Low growth			High oil prices			European trend		
	AGV	ALV	MTS	AGV	ALV	MTS	AGV	ALV	MTS

I1	2.28%	2.13%	1.91%	2.38%	2.32%	2.20%	3.13%	3.03%	2.71%
I4	4.33%	4.09%	3.59%	4.61%	4.52%	4.16%	5.97%	5.84%	5.25%
I6	4.10%	3.87%	3.37%	4.37%	4.28%	3.92%	5.69%	5.56%	4.96%
I8	5.92%	5.57%	4.79%	6.45%	6.31%	5.83%	8.31%	8.11%	7.18%
I10	6.88%	6.47%	5.51%	7.48%	7.29%	6.59%	9.75%	9.50%	8.13%
I11	4.36%	4.20%	3.68%	4.71%	4.61%	4.26%	5.90%	5.82%	5.06%
I12	1.02%	0.95%	1.07%	1.03%	1.00%	1.19%	1.24%	1.20%	1.36%
I13	4.97%	4.64%	3.84%	5.46%	5.30%	4.65%	7.38%	7.15%	5.99%
I14	1.56%	1.43%	1.20%	1.66%	1.62%	1.47%	2.25%	2.20%	2.03%
I15	0.19%	0.17%	0.19%	0.21%	0.20%	0.23%	0.31%	0.30%	0.31%
I16	4.40%	4.13%	3.34%	4.89%	4.75%	3.99%	6.64%	6.42%	5.08%
I17	3.12%	2.96%	2.20%	3.41%	3.33%	2.54%	4.42%	4.29%	3.02%

(Author, 2014)

A random uniform distribution is used in the model between 0 and 1. Each time the value is lower than the calculated change that a vehicle meets another vehicle, a vehicle has to wait at the intersection. The waiting time is determined by the deceleration and acceleration time, summed with the time the vehicle is stopped.

At this moment AGVs and ALVs drive with a speed of 6 m/s and accelerate and decelerate with 0.5 m/s^2. It is assumed that these vehicle will drive 11.1 m/s in 2030, so it is also assumed that a high difference in acceleration and deceleration will be achieved. Currently, for passenger cars 3.4 m/s^2 is a comfortable value for controlled braking. For trucks, the worst performance of a driver is 1.67 m/s^2, the best performance is 2.65 m/s^2, and when they use an antilock brake system it is 3.43 m/s^2. Because the AGV and ALV are automated systems, the performance of the driver does not have to be taken into account and 2.5 m/s^2 will be used in the simulation model. For the MTS, a somewhat lower value is used, 2.0 m/s^2. The time the vehicle has to wait is a uniform distribution between zero and the block length of the vehicle.

Table D-8: Waiting time per ITT system

ITT system	Acceleration/ deceleration [m/s^2]	Vehicle speed [km/h]	Acceleration/ deceleration time	Block length [s]	Waiting time [s]
AGV	2.5	40	8.9	5.2	8.9 + uniform(0,5.2)
ALV	2.5	40	8.9	5.0	8.9 + uniform(0,5.0)
MTS	2	30	10.3	14.3	10.3 + uniform(0,14.3)

(Author, 2014)

D.4 Personnel

There are terminals that are using equipment that is manned. When personnel is employed, personnel breaks are provided for the employees. The current personnel breaks of ECT, shown in Table D-9, are used in the simulation model for the terminals with the non-automated equipment, because it is expected that these will also be used in the future. (Europe Container Terminals, 2014) Not all the personnel has breaks at the same time, because then the whole ITT process (at that terminal) is paused. It is desirable that (urgent) containers always can be retrieved or delivered. One employee per terminal will have a late break, so these containers can be handled.

For the MTS, which needs drivers, no breaks are included in the model. Because the vehicles require a large investment, it is possible that the future owner of the system makes the personnel scheduling in such a way that the process always continues. Then the vehicles are optimally used and the ITT process will not get any delay. This maybe can cause a somewhat higher requirement of personnel.

Table D-9: Personnel breaks

Personnel break (normal)	Personnel break (late)
11.15h – 12.00h	12.00h – 12.45h
19.15h – 20.00h	20.00h – 20.45h
03.15h – 04.00h	04.00h – 04.45h

(Europe Container Terminals, 2014)

D.5 Next transport assignment: urgent containers at surrounding terminals

While determining the next transport assignment of the vehicles, first it is determined whether there are urgent containers at the surrounding terminals. Because of the unbalance of incoming and outgoing containers at some terminals, the search for urgent containers is adapted. Because there are significantly more containers with terminal 12 (APMT MV1), terminal 13 (ECT Delta terminal, and terminal 14 (ECT Delta Barge Feeder terminal), as origin than as destination, more vehicles have to be sent to these terminals. Therefore at terminal 6, 9, 10, and 11 it will also be checked whether there are urgent containers at these terminals. Table D-10 gives an overview of the terminals which will be searched for urgent containers.

Table D-10: Next transport assignment: searching for urgent containers at surrounding terminals

Terminal	Surrounding terminals
1	2
2	1,3
3	4,5
4	3,5
5	3,4,6
6	7,8,5,12,13,14
7	6,8
8	6,7
9	10,11,12,13,14
10	9,11,12,13,14
11	9,10,12,13,14
12	13,14
13	12,14
14	12,13

(Author, 2014)

D.6 Minimum percentage of on-time containers

To compare the different ITT systems, they must achieve the same amount of containers that will be delivered on-time. This means that the maximum percentage of non-performance (containers that are delivered too late) must be determined. More or less 20% of the containers has less than 2 hours to be transported. This means that the ITT vehicles must quite fast pick up the containers. During the running of the simulation model it became visible that the MTS wasn't able to achieve much higher percentages of 95% on-time containers (in contradiction to the AGV and ALV), even when the number of vehicles increased. Therefore the minimum percentage of containers that must be delivered on-time is set to 95%.

D.7 Treshold value for labbeling containers as urgent

A threshold value for labelling the containers as urgent has to be determined. When the latest departure time of a container is below this threshold value, the container becomes urgent. There needs to be enough time to pick up the containers by the ITT vehicles when they become urgent, but when the value is set too high, very much containers are labelled as urgent, which causes that the ITT vehicles travel further in total, because they first need to transport all the urgent containers. To meet this requirement, a value of 1 hour is used in the model.

D.8 Number of replications

It is not sufficient to run only one replication per experiment, because required accuracy in the output must be achieved. Therefore a method is used to determine the required number of replications. (Hoad, et al., 2007) The precision is defined as ½ width of the confidence interval, expressed as a percentage of the cumulative mean. A desired precision must be defined. Hoad et al. use a desired precision of 5%. In this simulation model also a desired precision of 5% will be used. For one output parameter the precision will be measured. In this case this will be the percentage of on-time containers. When the precision becomes less than or equal to the desired precision, x extra replications must be run. This is because it is possible that the precision converges to a level below the desired precision, and then diverges again. Hoad et al. advise that the value of the extra number of replications must be set to 5, because then the majority of premature convergence problems were solved during testing. (Hoad, et al., 2007)

Appendix E: Analysis of decrease in percentage of on-time containers

A decrease in the percentage of on-time containers can be observed for the MTS in all the scenarios after the maximum percentage of on-time containers is reached. (Also a very small decrease for the AGV and ALV can be observed.) This phenomenon was not expected, because normally an increase in capacity (number of vehicles) would not lead to a decrease in performance (on-time delivery). For the low growth scenario the MTS is analyzed to see what causes this phenomenon.

Table E-1 shows that the average number of vehicles that is loading/unloading increases, the average number of vehicles that is waiting, and the average number of vehicles that is driving increases when extra vehicles are added.

Table E-1: Average number of vehicles loading/unloading, waiting, and driving for different number of vehicles for the low growth scenario

Number of vehicles	Percentage of on-time containers	Average number of vehicles loading/unloading	Average number of vehicles waiting for next transport assignment	Average number of vehicles driving
18	95.58	8.52	2.08	7.40
19	96.07	8.64	2.54	7.82
20	96.76	8.80	3.01	8.19
21	97.05	8.96	3.46	8.58
22	94.06	8.99	4.18	8.83
23	92.96	9.10	4.81	9.09
24	92.25	9.15	5.43	9.42
25	90.77	9.22	6.24	9.54
26	91.08	9.23	6.93	9.84

The number of containers that has to be loaded/unloaded stays the same, independent on the number of vehicles. In the loading process, a vehicle starts driving after the loading process when it is fully loaded or when a time limit is reached (after 10 minutes). The increase in the number of vehicles that is loading/unloading can be explained by the fact that more vehicles have to wait until the time limit is reached.
The average number of vehicles that is waiting also increases. When extra vehicles are added, not all the vehicles are used for transporting the containers.
The average number of vehicles that is driving increases and the total driven kilometers also increase when more vehicles are added. This can possibly explained by the fact that the containers are divided over more vehicles, so more half loaded trips will take place. More vehicles are driving to transport the same number of containers.

Table E-2: Driven kilometers per number of vehicles for the MTS for the low growth scenario

Number of vehicles	Percentage of on-time containers [%]	Driven kilometers
18	95.58	106,433,436
19	96.07	112,408,882
20	96.76	117,828,704
21	97.05	123,474,384
22	94.06	126,999,754
23	92.96	130,908,169

24	92.25	135,525,255
25	90.77	138,860,194
26	91.08	141,742,218

The capacity of the MTS is changed to see if this has an effect on the decrease, see Figure E-1. When the capacity of the MTS is lower, higher percentages of on-time containers can be reached (because the vehicles have to wait less long during the loading and unloading) and the decrease after the maximum percentage of on-time containers gets lower. There is probably a relation between the capacity of the vehicles and the decrease.

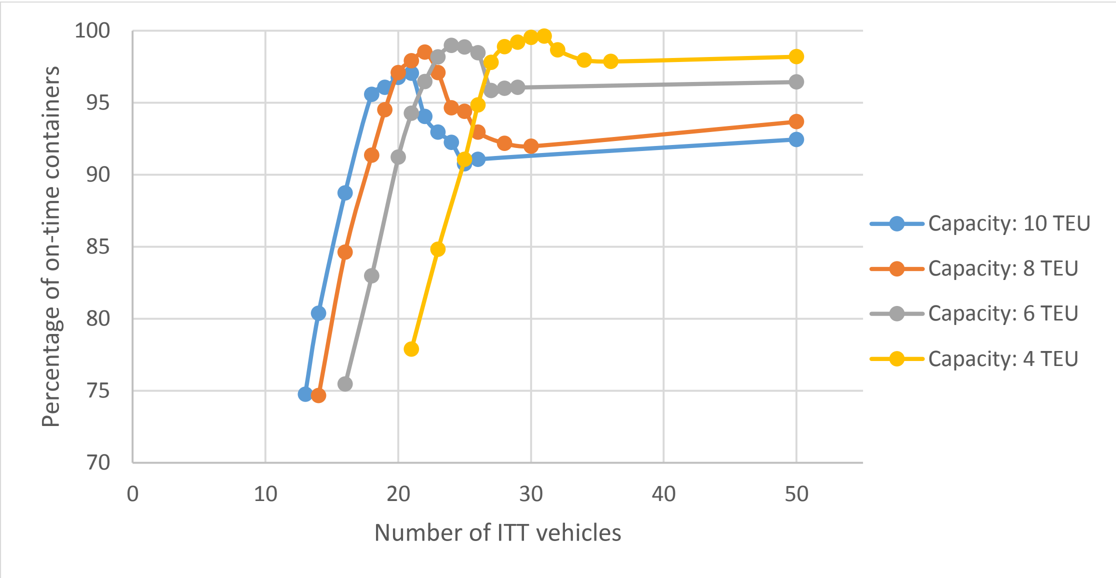


Figure E-1: Percentage of on-time containers compared to the number of vehicles for different capacities of the MTS for the low growth scenario

Above it was stated that the decrease possibly could be declared by the fact that the vehicles have more half loaded rides and must wait longer during the loading, because they have to wait until the time limit is reached. When a smaller capacity of the vehicles is modelled, the chance that vehicles drive fully loaded is higher. It happens less often that vehicles have to wait until the time limit is reached when loading the containers. This possibly causes that the size of the decrease also gets smaller. When this is the cause, the driver of the MTS knows when there are no more containers to be loaded at a terminal, so the MTS can start driving. Then in reality this decrease does not take place.

More research can be done to find out if the described cause is exactly the cause of the phenomenon. This can be done by modelling the loading of the vehicles differently. The vehicle has to start driving when there are no containers left at the terminal instead of waiting until the time limit is reached. Then it has to be checked if there is still a decrease in percentage of on-time containers.

Appendix F: Total costs of the ITT systems

The Multi Criteria Analysis is used to evaluate the different ITT systems, based on three criteria. First the weighing factors of the criteria will be discussed. Then the criterion 'total costs of the ITT systems' will be given. Then the criteria 'sustainability' and 'sensitivity to changes in the number of vehicles' will be discussed. Finally, the outcomes of the MCA will be given.

F.1 Total costs

An overview of the costs is given per scenario. Table F-1 shows the costs for the ITT systems of the low growth scenario, Table F-2 for the high oil prices scenario and Table F-3 of the European trend scenario.

Table F-1: Total costs of the ITT systems for the low growth scenario

		AGV	ALV	MTS	
Fixed costs	**Vehicle costs**			Trucks	Trailers
	Purchase price [€]	€ 691,799	€ 1,015,470	€ 354,014	€ 43,395
	Depreciation period [years]	7	7	7	12
	Rest value [% of purchase price]	10%	10%	10%	10%
	Interest [%]	6.0%	6.0%	6.0%	6.0%
	Present value [€]	€ 737,808	€ 1,083,004	€ 377,558	€ 45,552
	Annuity payment per vehicle [€/year]	€ 132,167	€ 194,004	€ 67,634	€ 5,433
	Number of vehicles	34	24	14	90
	Total annuity payment of vehicles [€/year]	**€ 4,493,687**	**€ 4,656,096**	**€ 946,875**	**€ 488,994**
	Software costs				
	Purchase price [€]	€ 3,157,407	€ 3,157,407	€ 2,368,055	
	Depreciation period [years]	€ 7	€ 7	€ 7	
	Interest [%]	6.0%	6.0%	6.0%	
	Annuity payment of software [€/year]	**€ 565,602**	**€ 565,602**	**€ 424,202**	
	Infrastructure costs				
	Construction costs of dedicated lane [€]	€ 80,000,000	€ 80,000,000	€ 80,000,000	
	Lifetime [years]	25	25	25	
	Interest [%]	2.6%	2.6%	2.6%	
	Total annuity payment of infrastructure [€/year]	**€ 4,391,893**	**€ 4,391,893**	**€ 4,391,893**	
Variable costs	**Maintenance and repair costs of the vehicles [€/year]**				
	Repair and maintenance costs [€/km]	€ 0.10	€ 0.10	€ 0.21	
	Driven kilometers per year [km]	5,162,361	5,068,776	1,689,420	
	Repair and maintenance costs [€/year]	**€ 496,077**	**€ 487,084**	**€ 347,882**	
	Maintenance contract software [€/year]	**€ 28,280**	**€ 28,280**	**€ 21,210**	
	Maintenance of the infrastructure [€/year]	**€ 219,595**	**€ 219,595**	**€ 219,595**	
	Personnel costs				
	Personnel costs per hour [€/hour]	€ 34	€ 34	€ 34	
	Number of driver hours needed per year [hours]	0	0	106,742	
	Driver costs per year [€/year]			€ 3,663,355	
	Number of other personnel costs per year [hours]	17,520	17,520	35,040	
	Other personnel costs per year [€/year]	€ 601,280	€ 601,280	€ 1,202,560	
	Personnel costs [€/year]	**€ 601,280**	**€ 601,280**	**€ 4,865,915**	
	Energy consumption costs				
	Electricity costs per kilometer [€/km]	€ 0.32	€ 0.39	€ 0.47	
	Driven kilometers per year [km]	5,162,361	5,068,776	1,689,420	
	Electricity cost [€/year]	**€ 1,629,968**	**€ 2,000,524**	**€ 800,128**	
	Overhead costs [€/year]	**€ 1,423,294**	**€ 1,486,170**	**€ 1,391,220**	
	Total costs [€/year]	**€ 13,849,675**	**€ 14,436,524**	**€ 13,897,913**	

(Author, 2014)

Table F-2: Total costs of the ITT systems for the high oil prices scenario

		AGV	ALV	MTS	
Fixed costs	**Vehicle costs**			Trucks	Trailers
	Purchase price [€]	€ 691,799	€ 1,015,470	€ 354,014	€ 43,395
	Depreciation period [years]	7	7	7	12
	Rest value [% of purchase price]	10%	10%	10%	10%
	Interest [%]	6.0%	6.0%	6.0%	6.0%
	Present value [€]	€ 737,808	€ 1,083,004	€ 377,558	€ 45,552
	Annuity payment per vehicle [€/year]	132,167	194,004	€ 67,634	€ 5,433
	Number of vehicles	39	27	16	105
	Total annuity payment of vehicles [€/year]	**€ 5,154,523**	**€ 5,238,108**	**€ 1,082,143**	**€ 570,493**
	Software costs				
	Purchase price [€]	€ 3,157,407	€ 3,157,407	€ 2,368,055	
	Depreciation period [years]	€ 7	€ 7	€ 7	
	Interest [%]	6.0%	6.0%	6.0%	
	Annuity payment of software [€/year]	**€ 565,602**	**€ 565,602**	**€ 424,202**	
	Infrastructure costs				
	Construction costs of dedicated lane [€]	€ 80,000,000	€ 80,000,000	€ 80,000,000	
	Lifetime [years]	25	25	25	
	Interest [%]	2.6%	2.6%	2.6%	
	Total annuity payment of infrastructure [€/year]	**€ 4,391,893**	**€ 4,391,893**	**€ 4,391,893**	
Variable costs	**Maintenance and repair costs of the vehicles [€/year]**				
	Repair and maintenance costs [€/km]	€ 0.10	€ 0.10	€ 0.21	
	Driven kilometers per year [km]	5,742,589	5,599,045	1,928,396	
	Repair and maintenance costs [€/year]	**€ 551,834**	**€ 538,040**	**€ 397,091**	
	Maintenance contract software [€/year]	**€ 28,280**	**€ 28,280**	**€ 21,210**	
	Maintenance of the infrastructure [€/year]	**€ 219,595**	**€ 219,595**	**€ 219,595**	
	Personnel costs				
	Personnel costs per hour [€/hour]	€ 34	€ 34	€ 34	
	Number of driver hours needed per year [hours]	0	0	120,044	
	Driver costs per year [€/year]			€ 4,119,882	
	Number of other personnel costs per year [hours]	17,520	17,520	35,040	
	Other personnel costs per year [€/year]	€ 601,280	€ 601,280	€ 1,202,560	
	Personnel costs [€/year]	**€ 601,280**	**€ 601,280**	**€ 5,322,443**	
	Energy consumption costs				
	Electricity costs per kilometer [€/km]	€ 0.32	€ 0.39	€ 0.47	
	Driven kilometers per year [km]	5,742,589	5,599,045	1,928,396	
	Electricity cost [€/year]	**€ 1,813,169**	**€ 2,209,808**	**€ 913,310**	
	Overhead costs [€/year]	**€ 1,531,269**	**€ 1,587,241**	**€ 1,481,722**	
	Total costs [€/year]	**€ 14,857,446**	**€ 15,379,847**	**€ 14,824,101**	

(Author, 2014)

Table F-3: Total costs of the ITT systems for the European trend scenario

		AGV	ALV	MTS	
Fixed costs	**Vehicle costs**			Trucks	Trailers
	Purchase price [€]	€ 691,799	€ 1,015,470	€ 354,014	€ 43,395
	Depreciation period [years]	7	7	7	12
	Rest value [% of purchase price]	10%	10%	10%	10%
	Interest [%]	6.0%	6.0%	6.0%	6.0%
	Present value [€]	€ 737,808	€ 1,083,004	€ 377,558	€ 45,552
	Annuity payment per vehicle [€/year]	132,167	194,004	€ 67,634	€ 5,433
	Number of vehicles	53	34	20	130
	Total annuity payment of vehicles [€/year]	**€ 7,004,865**	**€ 6,596,136**	**€ 1,352,679**	**€ 706,324**
	Software costs				
	Purchase price [€]	€ 3,157,407	€ 3,157,407	€ 2,368,055	
	Depreciation period [years]	€ 7	€ 7	€ 7	
	Interest [%]	6.0%	6.0%	6.0%	
	Annuity payment of software [€/year]	**€ 565,602**	**€ 565,602**	**€ 424,202**	
	Infrastructure costs				
	Construction costs of dedicated lane [€]	€ 80,000,000	€ 80,000,000	€ 80,000,000	
	Lifetime [years]	25	25	25	
	Interest [%]	2.6%	2.6%	2.6%	
	Total annuity payment of infrastructure [€/year]	**€ 4,391,893**	**€ 4,391,893**	**€ 4,391,893**	
Variable costs	**Maintenance and repair costs of the vehicles [€/year]**				
	Repair and maintenance costs [€/km]	€ 0.10	€ 0.10	€ 0.21	
	Driven kilometers per year [km]	7,205,405	7,141,451	2,239,700	
	Repair and maintenance costs [€/year]	**€ 692,403**	**€ 686,258**	**€ 461,194**	
	Maintenance contract software [€/year]	**€ 28,280**	**€ 28,280**	**€ 21,210**	
	Maintenance of the infrastructure [€/year]	**€ 219,595**	**€ 219,595**	**€ 219,595**	
	Personnel costs				
	Personnel costs per hour [€/hour]	€ 34	€ 34	€ 34	
	Number of driver hours needed per year [hours]	0	0	149,244	
	Driver costs per year [€/year]			€ 5,122,016	
	Number of other personnel costs per year [hours]	17,520	17,520	35,040	
	Other personnel costs per year [€/year]	€ 601,280	€ 601,280	€ 1,202,560	
	Personnel costs [€/year]	**€ 601,280**	**€ 601,280**	**€ 6,324,576**	
	Energy consumption costs				
	Electricity costs per kilometer [€/km]	€ 0.32	€ 0.39	€ 0.47	
	Driven kilometers per year [km]	7,205,405	7,141,451	2,239,700	
	Electricity cost [€/year]	**€ 2,275,040**	**€ 2,818,558**	**€ 1,060,747**	
	Overhead costs [€/year]	**€ 1,825,603**	**€ 1,841,040**	**€ 1,659,827**	
	Total costs [€/year]	**€ 17,604,561**	**€ 17,748,642**	**€ 16,622,247**	

(Author, 2014)

First the fixed costs will be discussed and then the variable costs.

F.1.1 Fixed costs

The fixed costs consist of the vehicle costs, the software costs, and the infrastructure costs. First the vehicle costs will be discussed, than the software costs, and finally the infrastructure costs.

Vehicle costs

The purchase price of the different ITT vehicles is known at this moment (TBA, 2010). An estimation of the purchase price in 2030 is estimated by using the CPI (to 2014) and the expected inflation until 2030. The vehicles are expected to be more expensive, because it is expected that a lot of innovations will be implemented. For instance, it is expected that all the ITT vehicles will be electrical vehicles. At this moment there are already battery-driven AGVs at the terminals of APM Terminals Maasvlakte II and RWG. (Maritiem Nieuws, 2012) (Nieuwsblad Transport, 2014). It is assumed that this trend will continue in the future and all the ITT vehicles will be battery-driven. The ratio between normal cars and electrical cars is compared to make an estimation of the purchase price of the electrical variant of the ITT vehicles. A research is done about the influences on the low carbon car market from 2020-2030. (Element Energy Limited, 2011) The different cost elements of different types of vehicles are compared for the period 2020-2030. The capex value of the petrol/diesel cars (conventional internal combustion engine vehicles) is compared to the capex value of the electric vehicles in 2030. The research shows that the electric vehicles (for all types of vehicles) are on average 1.28 times more expensive than the petrol/diesel cars in 2030. This ratio will also be used to estimate the purchase price of the electric ITT vehicles. These extra costs are needed for the battery packs. It is assumed that these battery packs will be changed during the operation. It is assumed that one extra battery pack is needed per 3 vehicles, so one third of the extra costs is added per vehicle.

The AGVs that drive at this moment at the quay side of the terminals are using transponders and sensors to determine their path. There is a lot of research for automated driving of cars, such as the Google Car. (USA Today, 2012) It is expected that AGVs also will have that kind of GPS technology, so no transponders etcetera are needed in the infrastructure. The price of the GPS system of a Google Car is at this moment $150,000. It is expected that the price of the system will drop during the years, because of the further development. A study of IHS Automotive shows that the price will drop to $5,000 in 2030 for such a system in the cars. (IHS, 2014) This price (more or less €4,000) is added to the purchase price of the automated ITT vehicles. The number of vehicles is determined using the simulation model and is used here.

For the fixed costs the annuity payment is calculated using the following formula:

$$C = \frac{PV}{\frac{1-(1+i)^{-n}}{i}}$$

In which,

C = annuity payment
PV = present value of investment
i = interest rate
n = depreciation period/lifetime

(Ross, et al., 2010)

An annuity is used, because then the yearly costs of the vehicles can be determined. It is assumed that the repayment is equal to the depreciation. The interest rate is assumed to be 6%, because it is assumed that the vehicles have to be purchased private.

The present value of the rest value of the purchase price of the vehicles is calculated using the following formula:

$$PV = \frac{C}{(1+i)^n}$$

In which,

PV = present value
C = future amount of money
i = interest rate

n = depreciation period
(Ross, et al., 2010)

Software costs
The software costs for the use of automated systems at the quay side of a terminal (using 33 ALVs or 65 AGVs with 1.2 million waterside moves) are estimated to be 2.3 million euros. (TBA, 2010) The same amount of costs is used in this research (but then converted to the price in 2030). For the MTS less software is needed, but a proper planning system for the containers is needed. It is estimated that this will be a quart of the price of the software system of the automated vehicles. For the software also the annuity payment is calculated and an interest rate of 6% is used, because it is assumed that the software also will be purchased private.

Infrastructure costs
There is at this moment already discussion about the construction costs of a dedicated lane between the Port of Rotterdam, the terminals and a mediator. The expected construction costs are 80 million euros. (Nieuwsblad Transport, 2014) These costs are also used in this research. It is assumed that these costs are equal for the AGV, ALV, and MTS, because the navigation technique of the automated vehicles is located in the vehicles, and not in the infrastructure. For the infrastructure costs also the annuity payment is calculated. It is assumed that the dedicated lane will be built very soon and will first be used for (3-TEU) trucks that are carrying out the ITT. The interest rate is set to the average Euribor rate of the past 15 years (Global rates, 2014), equal to 2.6%, because for earlier investments in the current port area and for new investments of Maasvlakte 2, the Port of Rotterdam could lend money with an interest rate, based on the three monthly Euribor rate. (Port of Rotterdam, 2012)

F.1.2 Variable cost

The variable costs consist of the maintenance and repair costs, the maintenance of the infrastructure, and the maintenance contract of the software. The personnel costs, energy consumption costs, and the overhead costs are also part of the variable costs.

Maintenance and repair costs
The maintenance and repair costs are calculated looking at the driven kilometres of the different ITT vehicles. In a previous research these costs are determined for a truck. (Wiegmans & Konings, 2013) The tractor has repair and maintenance costs of €0.05/km and the trailer €0.02/km. In this research €0.07/km is taken for the AGV and ALV and €0.15/km for the MTS (and then converted to the price in 2030).

Maintenance of the infrastructure
For the maintenance of the infrastructure it is assumed that this is equal to 5% of the annuity payment. Because this is not one of the main cost components, no more-detailed estimation is made.

Maintenance contract of the software
Also for the maintenance contract of the software an assumption is made. It is assumed that this is 5% of the annuity payment of the software. The same logic is applied; this is not one of the main cost components, so no more-detailed estimation is made.

Personnel costs
The AGV and ALV are automated systems, so they do not need drivers, but the MTS does. The needed number of MTSs is known, but there does not need to be that amount of drivers all the time. During the quiet periods, less MTS drivers are needed. An estimation is made based on the percentage of time the MTS is parked. In the low growth scenario, on average 2.1 of the 18 vehicles (12%) are parked. 3.1 of the 21 vehicles (15%) are parked in the high oil prices scenario and 4.2 of

the 26 vehicles (16%) are parked in the European trend scenario. Because the personnel works in shifts, it is assumed that not all the parked time can be used to decrease the number of drivers. It is assumed that half of the parked time per scenario, no drivers are needed.
For all the ITT systems it is assumed that there needs to be security all the time. Two employees are employed the whole time. For the MTS there need to be employees that monitor if the ITT process is working correctly and intervene when needed.
The loan of the employees at this moment is known. This is converted to the loan in 2030.

Energy consumption costs
The AGV uses at this moment 15 kWh/h with a speed of 21.6 km/h (or 6m/s). (Mechatronica Machinebouw, 2013) It is expected that the AGVs and ALVs will drive 40 km/h in 2030. The use of electricity is not linear when the speed of the vehicles increases. Therefore a graph, see Figure F-1, with the vehicle speed of a car compared to the electricity use is used to find the usage of the AGV with a speed of 40 km/h. (Tesla motors, 2008)

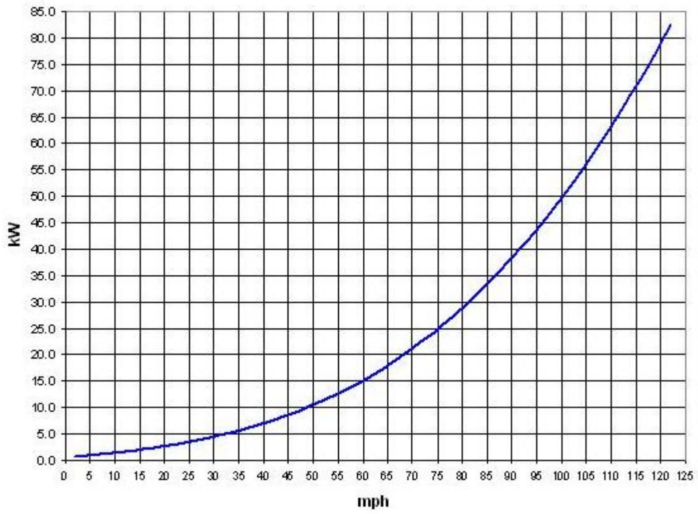


Figure F-1: Speed of a Tesla Roadster (mph) in relation to the electricity usage (kW) (Tesla motors, 2008)

A car drives 38 km/h when it has an electricity usage of 15 kWh/h. When the speed is multiplied by 40/21.6 the usage is equal to 65 kWh/h. This means that the average usage per kilometre is equal to (65/40=) 1.625 kWh/km. When this is multiplied by the costs for electricity (€0.14/kW) (Terex Port Solutions, 2014), the costs per kilometre are €0.23 for the AGV and ALV. This price is converted to the price in 2030. It is assumed that the costs per kilometre of the MTS are 1.5 times as high as the AGV and ALV. The MTS has a lower speed (30 km/h), but has a much higher weight, especially when it is loaded. The driven kilometres of each ITT system is known for a three week period in the second busiest month. In the second busiest month 9% of all the containers are handled, so the total driven kilometres per year are estimated by dividing the driven kilometres by 21/30*9%. The energy consumption costs can be calculated by multiplying the costs per kilometre and the driven kilometres.

Overhead costs
The rest of the costs consist of overhead costs. This is a part of the costs of a company or organization that is spent to the organization itself. The overhead costs are defined by the management board, management and secretarial support, the staff and organization, the IT, the communication, legal affairs and facility services.
An investigation of the overhead of business service providers shows that there is a strong relation between the percentage of overhead and the average revenue per employee. (Huijben & Geurtsen, 2008) When an organization is wealthier, there will be more employees for assistance and the

overhead percentage becomes larger. The overhead costs (as a percentage of the total revenues) differ a lot per sector/industry, from 2% to 38%. (From the 42 investigated sectors, 38 have a percentage between 10% and 30%.) The organization of the ITT system is assumed to be quite efficient and is assumed to be no very wealthy organization. Therefore the percentage of overhead is assumed to be 12% of the total revenues.

Appendix G: Combinations of ITT systems

Initially combinations of modalities also would be investigated, but this was excluded from the research because of time limit. However, some ideas about the modelling of the combination of ITT systems (train and AGV/ALV/truck) were created and are described in this appendix.

The train only runs between certain terminals that exchange a lot of containers, so only for certain OD-pairs containers can be transported by train. On forehand every container can get a property train or other modality. This is based on the next decision rule:
Delivery time – start time – expected transport time by train > X
If this is true, the containers will then be transported by train, else by another modality. The train has a predetermined route and on every terminal containers are loaded and unloaded. Also a distinction between urgent and non-urgent containers is made.

To take care that that there are (most of the time) enough spots on the train at the next terminal, the following rules can be applied (see Figure G-1):
Number of TEUs loading at current terminal <= number of empty spots on the train
Number of TEUs loading at current terminal <= number of empty spots in TEUs on the train + the number of TEUs with the next terminal as destination – the number of urgent TEUs at the next terminal. (If this value is negative, the number of TEUs loading at the current terminal is equal to 0.)
There are only not enough spots on the train at the next terminal when the number of urgent TEUs at the next terminal is larger than the number of empty spots in TEUs on the train + the number of TEUs with the next terminal as destination.

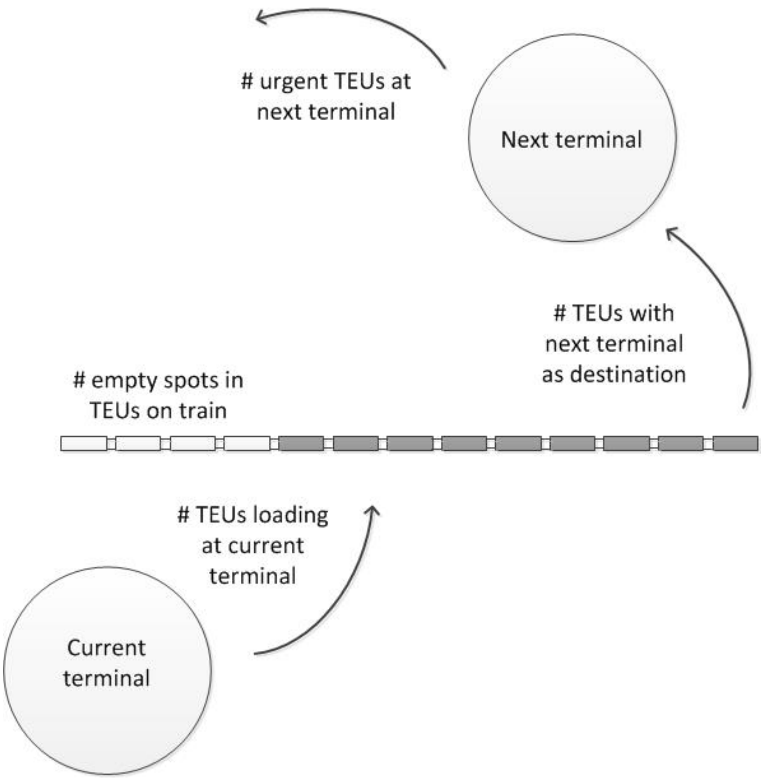


Figure G-1: Loading of containers on the train (Author, 2014)

It is assumed that containers do not need any pre or end haulage by another ITT system. The train stops at the origin or the destination terminal. The other ITT system also transports the containers directly from the origin to the destination terminal.

There are some challenges when modelling a combination of ITT systems:

- The determination of the number of terminals that are part of the train network must be determined. It is difficult to determine how much terminals is optimal.
- Also the route of the trains can have an impact on the containers that are transported. It has to be investigated to what extent the route has an impact on the ITT process.
- When a combination of ITT systems is used, it is far more difficult to determine the optimal number of trains and the number of vehicles of the other ITT system. Also the time schedule for the trains is important.
- When the trains make use of the national train network, it is possible that this brings some difficulties with the operators of the network. Trains normally have to follow a fixed schedule, so it is the question if this also holds for the ITT system. The ITT system can also not conflict with the trains coming from and going to the hinterland. This can cause extra delay in the ITT process.
- When the trains use the train network, it is possible that extra parts of rail network are constructed. This can have more intersections as a result, or the existing intersections become busier.