Combining models of a transportation chain in ports

Analysing interaction between processes to improve design and planning of freight transportation

L.A. van de Water

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Master Thesis

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Preface

This report represents the conclusion of my master degree in Transport and Planning at the faculty of Civil Engineering and Geosciences at the Technical University of Delft. The report is the result of a research into the possibility of combining models related to interaction between processes and subsystems along a transportation chain with a focus on the optimisation of ports. The research subject has been put together with and performed at RoyalHaskoningDHV, however, it was given framework in cooperation with my thesis committee. Researching interaction not only requires insight in operations of infrastructure as well as terminals, but also in optimisation and modelling of freight transportation. This multidisciplinary combination proved to be a challenge, but equally motivating. I managed to quickly acquire a good understanding of the operations, which enabled me to set-up two simulation models of a reasonable quality. I found the research very interesting and have enjoyed learning more about freight transportation in general as well as in detail

First of all, I would like to thank my thesis committee for the productive meetings, their support and feedback: Prof. R.A. Zuidwijk, Dr. R.M.P. Goverde, Dr. ir. F. Corman, ir. P.B.L. Wiggenraad and ir. C. van der Hoog. With their help I managed to formulate a large and complex problem into a manageable subject for my thesis. Their feedback allowed me to improve the theoretical background of the research study. I would especially like to thank my daily supervisor ir. C. van der Hoog of RoyalHaskoningDHV; by always asking the right questions and being available he helped me in improving the quality of the report as well as my personal skills.

During the set-up and simulation of models I was assisted by modelling experts of RoyalHaskoningDHV: ir. D. Koopman and ir. T. van de Sande. I want to thank them, but also their colleagues, for their assistance and availability for questions; with their help and expertise I managed to set-up and combine two models with a high level of detail in a rather short time.

Furthermore I would like to thank Daniel Mooijman and Martin de Winter from the EMO dry-bulk Terminal for their perspectives on the subject and feedback on the models. Without their help it would not have been possible to verify and validate my results.

Finally I want to thank my family and friends for their continuous support during my complete study and especially those who reviewed and provided feedback for my master thesis. I would like to give special thanks to Else for her patience and unconditional support.

Laurence van de Water

Delft, July 2015

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Summary

Introduction

Growth of transportation volumes combined with increased competition in the transportation market has led to an increase in the demand for optimisation instead of expansion of transportation systems. Due to separate optimisation approaches in order to protect their competitive position, stakeholders in ports tend to respond reactive to developments outside their own subsystem. These separate approaches can have negative effects on the functioning of the total transportation chain or system. Integration of the separate microscopic subsystems provides valuable insight in the interaction of systems along a transportation chain.

Ports consist of a large number of subsystems and are therefore ideal to analyse the integration of subsystems for optimisation purposes. As ports depend on their accessibility, the cooperation between the systems is important for the competitive position of a port.

This research study analyses the possibility to combine models in order to represent a larger part of a transportation chain of a port. It focuses on optimisation for strategic and tactical planning purposes and is limited to observing processes inside a port. The study focuses at the technical aspect of combining models; organisation and implementation are not taken into account. This thesis provides a hypothetical concept and methodological approach for combining models, which are tested in a case study. The following research question is formulated:

> *How can the two worlds of terminals and infrastructure be combined in a single modelling environment?*

Current approach of optimisation

Optimisation of terminals and infrastructure are approached differently, since the main characteristics of the processes are different. Terminals are normally optimised for providing transhipment at low costs for high volumes and to act as a buffer in the transportation chain process. Optimising terminals often involves the acceptance of simplifications to reduce complexity and costs. However, when optimising a system, it must be considered in what manner simplifications and a limited internal focus are justified or if interferences of other operations have to be taken into account.

Infrastructure operations are optimised to provide transportation capacity as a stable and robust system compared to costs. Due to the size of infrastructure networks and interaction with other operations, simplifications are always required. However, these simplifications affect the stability and robustness of a system and thereby affect the efficiency of a hinterland connection.

For ports, different optimisation approaches can be recognised, which can generally be categorized in (sub) system and transportation chain approach. The (sub) system approach focuses on optimising a specific system in the port within its own boundaries and takes other influences only limited into account. On the other hand the transportation chain approach focuses on optimising and tuning different processes along a transportation chain on a more macroscopic level. Both approaches have their own strengths, but lack detailing or do not cover all influential aspects. Combining both methods can provide insight in interferences due to interaction of operations at a microscopic level.

Modelling of ports

Combining multiple models along a transportation chain of a port environment requires representation of terminal and infrastructure operations together in a single modelling environment. The basis for modelling terminal and infrastructure operations is different. Multiple methods are capable of combining both in a single environment.

A large microscopic model can be used for representing a larger part of a transportation chain into a single model, but requires simulation software packages to represent all aspects of the different types of processes. Add-ones provided by simulation software packages are subject to simplifications and contain a lower level of detail, which leads to an undesirable unbalance in the representation of different processes.

Representation of a larger part of a transportation chain can also be achieved by combining models developed in different simulation software packages through the exchange of data. The exchange of data can be conducted via multiple communication methods: offline communication, real-time communication and a hybrid method.

Offline data exchange between models limits communication to exchanges before or after the simulation, which makes it only suited for observing specific behaviour for specific conditions and scenarios (figure 1). Models combined by offline communication are run in succession. The output of the first model is processed into the input for the next model. This method is the least complex and expensive method and can provide insight into interaction of processes and sensitivities of parameters. However, the communication method still requires simplifications and thereby limits the application.

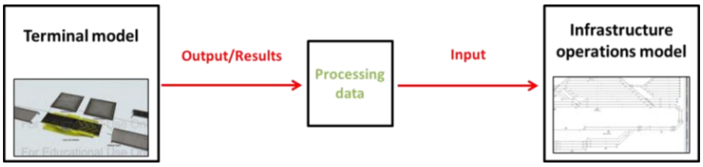

Figure 1: Example of combining models by offline and one directional data-exchange

Real-time data exchange allows the combined models to communicate and intervene during simulation, which requires models to be run simultaneously (figure 2). The communication between different simulation software packages often involves different server-based communication tools with different protocols connected to a database. Communication is conducted via the exchange of status messages and commands. Real-time communication allows for more interaction and requires fewer simplifications, but is more complex than other methods.

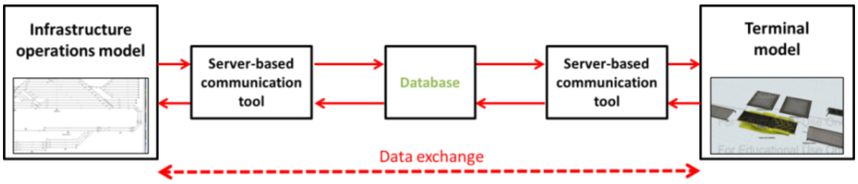
Infrastructure operations model
Server-based communication tool
Database
Server-based communication tool
Terminal model
Data exchange

Figure 2: Impression of a combination of models with real-time data exchange applied to a port

The hybrid method consists of one model communicating real-time with a database and the other model representing an offline script. This method requires the scripted model to represent parameters by offline communication, but is less expensive and complex. It also provides the ability to intervene during the simulation, which is preferable for some applications.

Characteristics of models

The set-up of models is dependent on the objective of the research study and simulation and by the choice of simulation software packages. The main objectives of representing a larger part of a transportation chain can be categorized by: costs, capacity, stability and robustness. Multiple simulation software packages are currently available, however these are dedicated to logistical or traffic simulation. To support integral decisions with regard to the optimisation of a transportation chain, an integrated modelling environment for both types of simulation has to be provided.

Hypothetical concept and methodological approach

The hypothetical concept states that combining models can provide insight and representation of a larger part of a transportation chain through which influences and interactions can be measured. Using existing simulation models of subsystems of ports can be a cost-efficient alternative to the set-up of large microscopic models from scratch. Combining models requires a comprehensive modelling environment, which can be provided by a combination interface. A methodological approach is presented which describes how to combine models with a combination interface.

Case study introduction and model set-up

To test the hypothetical concept, it is applied to a case study analysing the interference due to interaction of infrastructure operations. The case study combines a model of the EMO dry-bulk terminal, representing the loading process with a transportation model representing the local rail infrastructure operations (figure 3). Reasons for choosing this specific case study are based on simplicity, stability of the system and product demand, sufficient size of transportation volumes and availability of operational and infrastructural data.

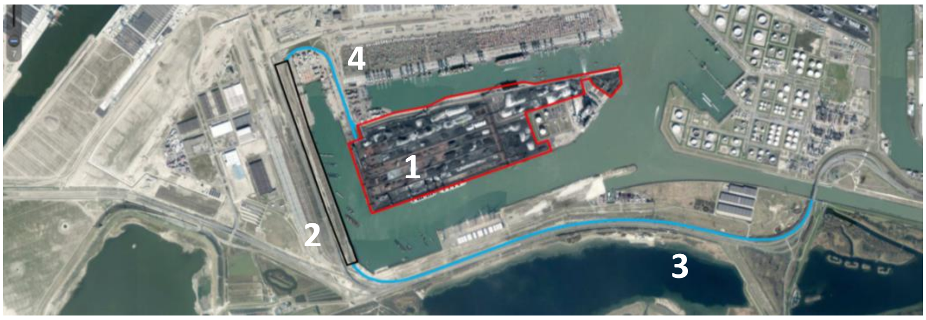

Figure 3: Impression of the location (source: edited picture from Google Earth), 1) EMO dry-bulk terminal, 2) Maasvlakte East railway yard, 3) Port Railway Line and 4) private sidings

The goal of the case study is to prove models can be combined and can provide insight into interaction of infrastructure operations. The interaction of infrastructure operations focuses on interference of train operations. To be able to focus on its goal, all other influences are neglected besides a variable loading time. Variety in the loading time provides insight in the interaction and thereby in the added value of combining models. Depending on the available resources, the models are combined by offline data exchange.

The terminal model is developed in FlexSim representing the loading process for several common train compositions. The infrastructure operations are modelled in OpenTrack in order to represent rail operations at the terminal and the railway yard connecting it to the Dutch Railway System. A combination interface connects the two models and exchanges a variable loading time as a distribution. Simulation runs are performed based on the representation of a normal day under normal weather and operational conditions.

Case study results

The case study results show the loading time distributions, which allow discussing the reliability of data exchange and the interference due to interaction of infrastructure operations.

Loading time distributions

The loading time distributions are determined for four common train compositions by the combination interface (figure 4). In the curve of the distributions two characteristic shapes can be recognised, which are related to the set-up of the terminal model. Also disturbances are observed which can be related to the large variations in start-up delays.

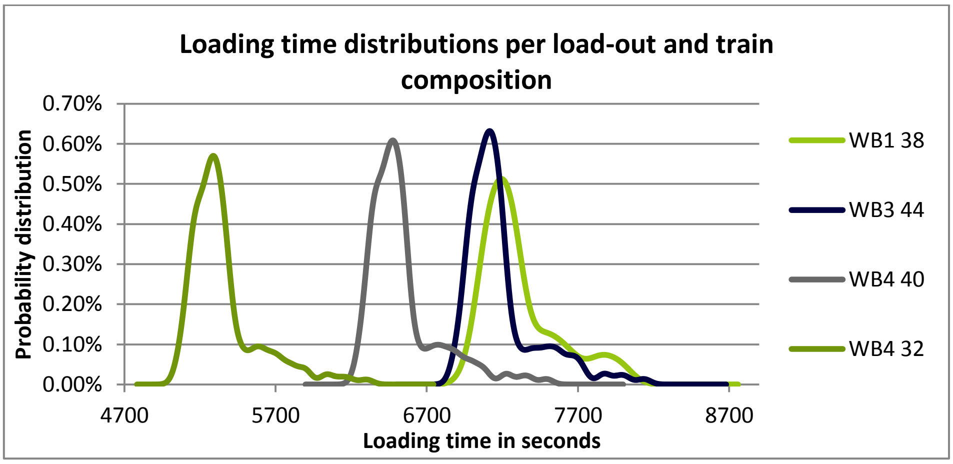

Figure 4: Probability distributions for the loading times for the relevant train compositions

Correctness data exchange

The correctness of the data exchange is tested by comparing the loading time distribution based on data of the terminal model with its representation based on results of the infrastructure model. Small deviations are observed but the representation is sufficient for the goal of this case study; to prove that models can be combined and interference can be measured.

Interference due to interaction of infrastructure operations

The determination of interferences is performed by visualisation and quantification of comparing turn-around times at different locations in the model with the loading time. Visual comparison starts with determining delays by scatterplots per train (figure 5) and is followed by determining if delays lead to behavioural changes by plotting the distributions for the relative turn-around times (figure 6).

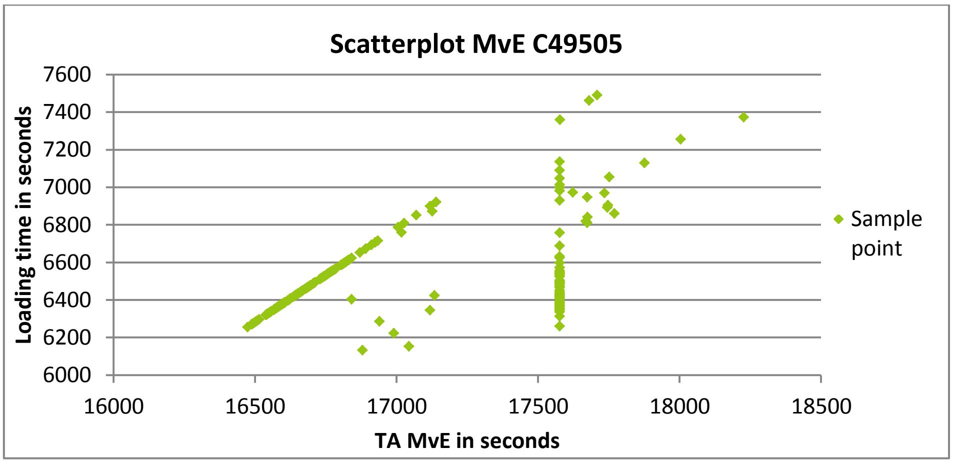

Figure 5: Scatterplot showing delays comparing the loading time with the turn-around time at the railway yard

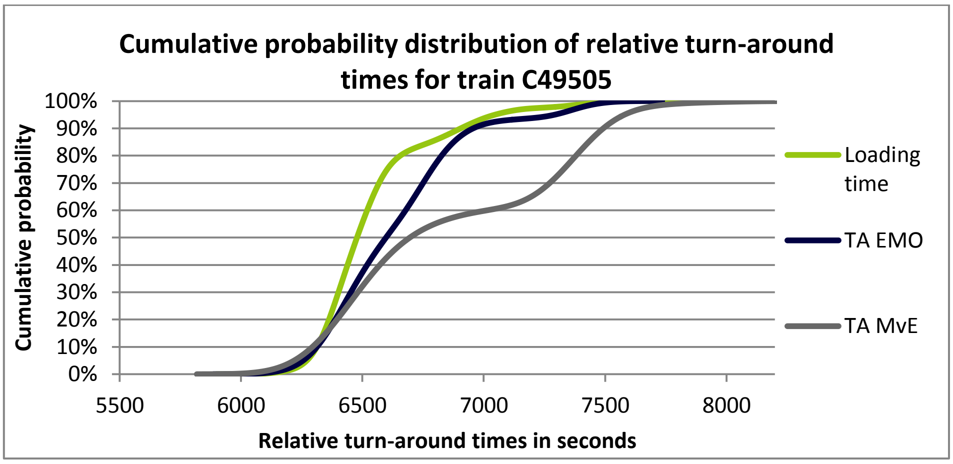

Figure 6: Cumulative probability distribution of relative turn-around times for train C49505

The effects of the delays are quantified per train and focus on differences between the following aspects: quartiles, dispersion width and standard deviation. Since the interference varies per train and is highly related to the planning of operations, the results conclude with the observation of the effects of all trains together. Though an analysis of the total set of trains an average delay per train and per day is observed. Overall an average delay of 181 seconds per train and an average delay of 2254 seconds per day can be observed. Much larger increases can be observed at the average dispersion width (+39.5%) and average standard deviation (+48.1%).

Case Study conclusion

The case study application of the hypothetical concept proves that models can be combined for the purpose of measuring interference and interactions between subsystems in a transportation chain. The combination interface was able to exchange improved representations of the loading time.

Analysis of the visualisation and quantifications of the results per train shows delays caused by the interference of other trains, which is consistent with observations during simulation. Plotting the relative turn-around times shows difference in the behaviour of trains. Quantification of the delays provides an improved insight in the size and variations of delay. Through observation of the results for the total system, the average delay per train is relatively small compared to the total turn-around time. However, the dispersion width and standard deviation have a substantial increase and thereby negatively affect the functioning of the system.

Conclusions

The hypothetical concept of combining models has proven to be a helpful tool for the analysis of interactions of processes. It allows for the representation of a larger part of a transportation chain in ports. Interferences due to interactions between models in a transportation chain can be visualized and quantified. An improved insight in the size and variation of delays can improve the design and planning of terminal or infrastructure operations. However, the complexity and applicability of the concept is dependent on the chosen communication method between the models.

Since it is expected that the transportation market and its competition will keep growing, optimisation of transport systems will become even more interesting. Together with increasing technological development, combining models will become more available and the design and planning of operations in ports can become more efficient.

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1 Introduction

The last couple of decades a rise is observed in the optimisation of transportation chains at a macroscopic level. However, operators and local governments in ports tend to respond reactive to developments in processes of subsystems influencing the total chain and other chains. This is related to the fact that in practice these processes and systems are managed and optimized separately by different stakeholders. These stakeholders tend to limit their view to the performance and boundaries of their own system. Combined with a competitive market, this behaviour leads to a fragmented and shielded approach in operating and optimising the transportation chain. An integrated approach to the transportation chain can reduce this fragmentation and improve design and planning, resulting in more efficient operations.

The research focuses on the technical problem of integrating different parts of a transportation chain by combining simulation models. This chapter provides an introduction into freight transportation in ports and optimisation by modelling and concludes with a description of the research and thesis outline.

1.1 Freight transportation in ports

This increase of demand in transportation volume has led to an increased number of freight transport operators, lower prices and interweaving of transportation routes. In the last couple of decades the overall production of goods has shifted from western countries to developing countries and has led to an increase in transport distances and an overall improvement of the worldwide transportation network. Globalisation has turned intercontinental transport networks into the drive of economic growth worldwide. In order to increase efficiency and lower transportation costs, intercontinental freight flows are bundled as much as possible as illustrated in figure 1.1. The volume of transported commodities has increased due to developments in technology, which allows bundling transportation streams in order to achieve more efficiency.

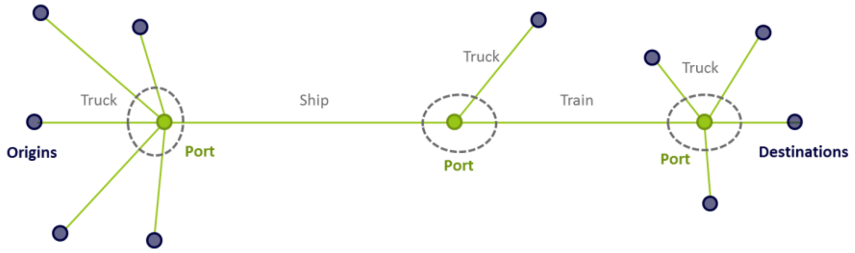


Figure 1.1: Example of bundling of transportation and the position of ports in a transportation chain

Besides increased efficiency, bundling has made intercontinental transportation really complex since the transportation of a product from origin to destination now involves a large number of different stakeholders and numerous sub-processes and subsystems. In order to reduce complexity and avoid administrative delays, in practice sub-processes of the transportation chain within a port are often approached separately by the different stakeholders. The transportation of a single product along a chain has become more fragmented and sub-processes along the chain are dependent on external processes of other chains.

Ports

In the transportation chain of a certain good, most stakeholders and sub-processes are located at ports. This makes ports the most suitable location for researching integration of processes and subsystems. The quality of a port is based on the quality of its accessibility, and hereby the internal and external infrastructure. Port authorities are in charge of the management of ports. These authorities are normally owned by local and national governments and can be categorized in different types. This research focuses on a seaport with intercontinental (long-distance) connections. The two main components of a seaport are terminals for transhipment and infrastructure.

Terminals of seaports are characterised by the processes of several main parts that take place internally; the transhipment process itself, the maritime arrival process and the hinterland transportation process. Their main goal is to tranship goods at low costs and act as a buffer in the transportation process. Different types of goods require different ways of transportation and each way of transportation requires its own type of terminal. The main types of products are intermodal transport, dry-bulk, liquid-bulk and piece goods. The open market and variety of products result in a large number of terminals in a port using the same infrastructure for transportation to the hinterland.

Transportation into the hinterland can be performed by different modes. This research study focuses on the transportation by rail, however keeps applicability to all modes in mind. Most rail transportation networks are operated as an open market and thereby contain a mix of stakeholders. An increase in transport operators providing transportation services is observed in the last decade and competition in the rail sector contributes to the fragmentation along transportation chains. With this increase in stakeholders involved in rail freight transportation, it becomes difficult for the infrastructure operations manager to meet the interests of all stakeholders.

A characteristic of the transportation sector is that it is quite competitive, which makes optimisation of transportation a popular subject. At the moment the most common and advanced technique for optimisation of freight transportation is the use of modelling and running simulations.

Optimisation by modelling

Transhipment terminals can be optimised in different ways, but is always focussed on its main goal and owners' interests. In most cases the optimisation of a terminal focuses on the efficiency in the transhipment process within the terminals physical boundaries. However, a more realistic approach is to optimise the terminal as a node of a larger transportation chain. The main difference between the two optimisations is to which extent external but influential elements are taken into account when defining the goal, scope and boundaries of the optimisation. Nevertheless, as more maritime and hinterland connections are taken into account, the optimisation process becomes more complex and inefficient. For instance, at a seaport the variance in arrival times of ships and that of trains have a totally different magnitude, which makes integration of optimisations inefficient.

Since the benefits of integration are unknown and integration of these processes is complex and expensive, optimisation of terminals is often simplified to its own physical boundaries and the most expensive internal process is the basis for optimisation. This simplification has effects on the optimisation of the efficiency of terminals and on processes outside the scope of the optimisation due to decisions based on efficiency inside the terminal. The effects on processes outside of the scope have lately started to get recognized and are generally answered with a short-term response.

Sometimes even a large overcapacity of other parts of the process is accepted in order to guarantee ongoing operations. However, the processes and functioning of the (sub) systems are sensitive for external influences and this can create a wrong impression of reality. By integrating succeeding processes along a transportation chain, the different processes can be tuned and the total chain optimised.

1.2 Research outline

Since the dynamic behaviour of transportation in ports is complex and consists of many aspects, the research study must include a clear focus and boundaries in order to reach its goal. This chapter describes the focus of the research study by discussing the problem statement, the scope and the structure of the report.

1.2.1 Problem Description

The problem can be defined as:

> *The response to most developments in the transport system inside ports is reactive, due to the fact that the focus lies onto optimising terminals or infrastructure by separate simulation models instead of optimising a total chain process. This behaviour may lead to inefficient planning and operations of freight transportation.*

In order to research solutions for this problem in the described complex setting, the set-up of the research needs to be feasible. Therefore, a tight definition and scope are important. In the next paragraphs the research framework is explained.

The goal is defined as:

> *The goal is to create a comprehensive modelling environment for combining multiple simulation models into a representation of a transportation chain in a port.*

The research question is stated as:

> *How can the two worlds of terminals and infrastructure be combined in a single modelling environment?*

1.2.2 Research scope

To analyse interaction between optimisation models in ports, the research scope is bound to the interaction between a terminal model and its hinterland infrastructure operations within a single transportation chain. This study considers infrastructure operations to be all operations required for the transportation of goods from the terminal into the hinterland by a certain mode. Terminal operations are considered to be all operations required for the transhipment of goods inside the terminal's physical boundaries.

In a transportation chain, ports are the location where transportation networks come together and bundling occurs. Therefore, ports are the ideal location to observe this behaviour at a microscopic level. The problem of combining models is not limited to technical aspects, it is highly influenced by the way ports and transportation networks are organised. However to keep the research feasible and manageable, this study is focussed on technical aspect of combining different models.

The theoretical concept of combining models is applied to a case study. In order to ensure the wide applicability of the theory, the boundaries in which the case study is applied are separately discussed in the case study scope described in chapter 4.

Models representing a terminal are normally bounded by physical boundaries and take external influences into account to a certain extent. Infrastructure models often exclude operations at terminals and their connections, as the processes are really complex to implement in a single model. The scope of this study includes a terminal as well as infrastructure and its connection within a port, as can be seen in figure 1.2.

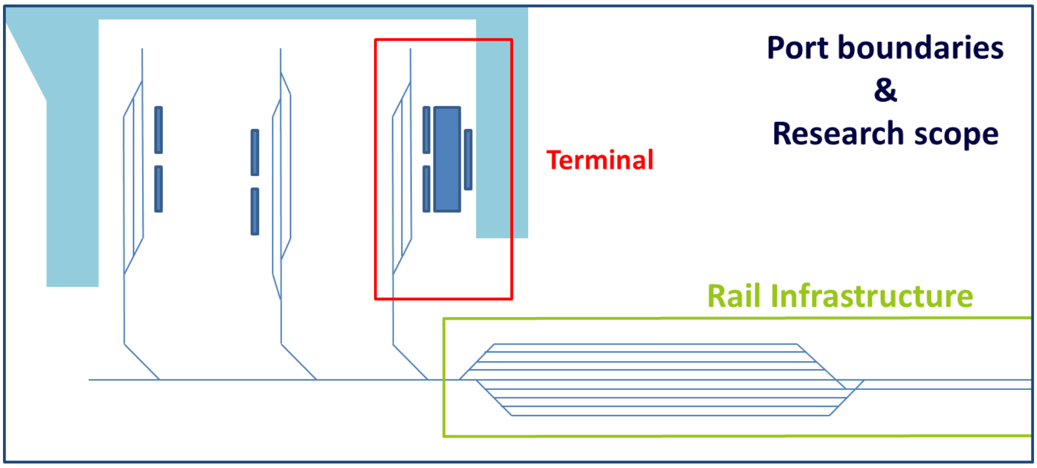


Figure 1.2: Illustration of the project scope compared to the terminal and rail infrastructure

1.2.3 Report structure

The structure of the report, besides the introduction and conclusion, is divided in three parts: analysis of theory, hypothetical concept and case study. In order to keep the hypothetical concept widely applicable, the analysis of theory and hypothesis are approached in a general manner. The goal of the case study is to test the hypothetical concept and thereby focuses on the application to a specific case. Figure 1.3 provides an impression of the report structure and the connections between the chapters.

The analysis of the theory is presented in chapter 2 and goes into chain management, optimisation of ports, modelling, simulation and the combining of models. Chapter 3 describes the hypothetical concept of combining existing models and its methodological approach. An introduction to the case study, the model set-up, simulation and validation is explained in chapter 4. Results and conclusions of the case study are discussed in chapter 5. Conclusions and recommendations of the research study are provided at the end of the report in chapter 6.

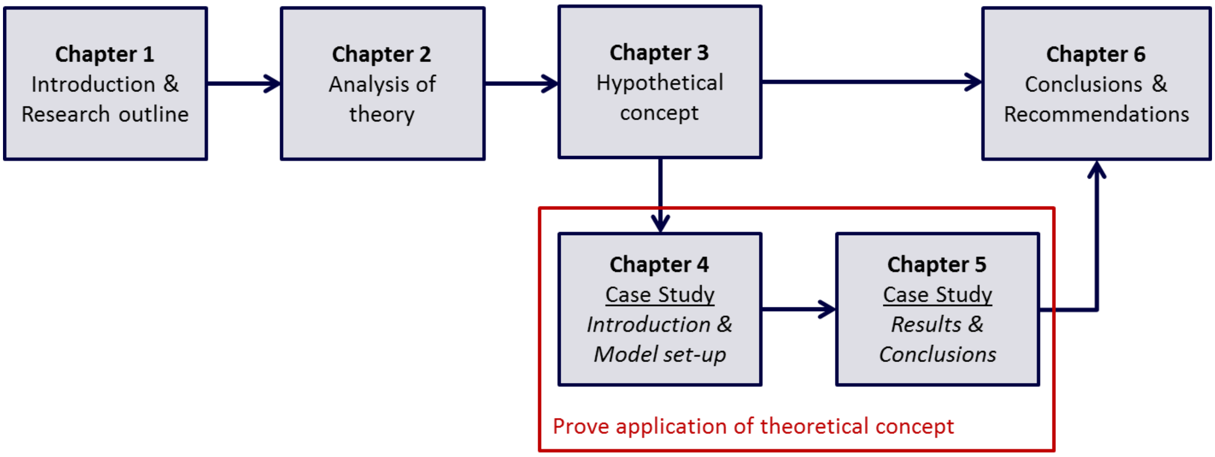

Chapter 1
Introduction & Research outline
Chapter 2
Analysis of theory
Chapter 3
Hypothetical concept
Chapter 6
Conclusions & Recommendations
Chapter 4
Case Study
Introduction & Model set-up
Chapter 5
Case Study
Results & Conclusions
Prove application of theoretical concept

Figure 1.3: Report structure

MSC
MOL
BERGE BULK
SAFETY FIRST
NO SMOKING

2 Optimisation by modelling in ports

The optimisation of terminals and infrastructure operations are approached differently since freight transportation at terminals and over infrastructure is operated and organised in different ways. To be able to create a comprehensive modelling environment for combining the worlds of terminals and infrastructure, more insight in optimisation by modelling in ports is required.

This chapter discusses the current approach, modelling and relevant characteristics and aspects of optimising freight transportation in ports. First, the current approaches of optimisation are introduced and then methods are described for modelling a larger transportation chain into a single modelling environment. Also insight is given into the main objectives of freight and rail transportation modelling and characteristics of simulation software packages.

2.1 Current approach

In ports different type of processes can be found which are optimised differently. For instance, logistical and transportation processes. Increasing competition in the transportation market has freight transportation operators striving for an increase in efficiency by optimisation, instead of the more expensive option to expand the systems. As a result this provides opportunities for innovations. Currently these processes are almost always optimised separately, as combined optimisation is complex and expensive. As the design and planning of both processes are highly related, optimising these in a single model can provide valuable insight in the interaction between the processes.

In the past decade simulation by modelling techniques has proven its additional value and has made it a popular research subject. However, simulations are not yet used to their full potential and their improvements can lead to more accurate and correct representation of reality. Improved models, when applied correctly, can lead to increased optimisation and thus to improvements in efficiency of the transportation chain.

To combine the different worlds of terminals and infrastructure for optimisation purposes, some background information and basis for these optimisations is provided. First a brief introduction is given in the practice of operating terminals and infrastructure, then the different optimisation approaches and techniques are discussed.

2.1.1 Optimisation of transhipment terminals

Optimisation of transhipment terminals can be performed in different ways, for different goals and are often subject to simplifications to reduce complexity and costs. However, these simplifications can in some cases provide a wrong impression of reality.

The main goal of terminals in ports is to tranship goods at low costs. Terminals also act as a buffer between the different capacity and frequency of the modes in the transportation process (Rodrigue, 2013). Each product type has its own type of terminal, based on the way of transhipment and transport. Most terminals of seaports are characterised by their main internal processes; the transhipment process itself, the maritime arrival process and the hinterland transportation process.

As transhipment volumes grow bigger and bigger, ports and transhipment terminals grow with them and a higher capacity at hinterland connections is required.

Most of the larger terminals are private companies owned by holdings of transport companies that transport the same type of products. However, in the last decade a trend can be observed of freight forwarders and supply chain managers taking ownership of the global transportation process. This trend results in profitability of ports becoming of even less importance compared to efficiency of a port based on its position in the transportation chain.

Terminals are optimised in different ways due to different goals, processes and interests. In most cases the optimisation of a terminal focuses on throughput versus costs efficiency in the transhipment process within the physical boundaries of the terminal. However, the terminal can also be optimised as a node that is part of a larger transportation chain. The two optimisations differ in which elements are taken into account when defining the scope and thereby which sub-process is the main focus of the optimisation.

In practice many simplifications for optimisations are accepted to reduce complexity and costs. Often this results in the most expensive internal terminal process becoming the basis for optimisation. For the optimisation of these processes, simulation models are used which are primarily and only focussed on these processes. However these simplifications often provide a limited insight into the different processes and causes of variances affecting the stability of the terminal and individual processes. To guarantee ongoing and stable operations of the terminal, often a large but expensive overcapacity of specific processes is accepted.

This approach raises the question in which cases simplifications are justified and whether the model provides an acceptable representation of reality. To reduce simplifications and to research the causes of variances in operations, more processes of hinterland connections influencing the terminal's operations should be included when optimising a terminal. However, these processes and characteristics are part of a shared infrastructure system and are dependent on operations outside the transportation chain. Including these processes makes the optimisation process more complex and influences the terminal's operations only indirectly.

The fact that these influences are only indirect does not mean that the functioning and capacity of the terminal cannot be substantially affected by other operations. For instance, a limited availability of capacity at the hinterland connection can limit the throughput of a terminal. This interaction between terminals and infrastructure operations can cause interference of operations and affects the capacity, stability and robustness of a terminal. Interferences do not only occur at situations where capacity is fully used, but can already be caused by a capacity demand of different operations at the same time. Relating this to a total port with multiple terminals that are using the same infrastructure, means that there could be dynamic interference between operations at different terminals.

2.1.2 Optimisation of infrastructure operations

Optimising infrastructure operations of hinterland connections is primarily focussed on planning operations that are subject to a large number of influences and variations. Simplifications are used to reduce the complexity of operations, but limit the representation of daily operations.

Optimisation of infrastructure operations are focussed on the provision of transportation capacity compared to costs, stability and robustness of operations. Hinterland freight connections are operated on a smaller time horizon and in practice large variances in arrival and departure times in the maritime connection of a port can be observed. This results in the requirement of large buffers at terminals or flexibility of hinterland connections. As the amount of freight transportation operators and their competition at the hinterland connections increases, it becomes difficult for the infrastructure operations manager to plan and manage flexibility in infrastructure operations at the lowest costs.

Infrastructure operations can be performed by different modes, each with their own characteristics. To provide an impression in the optimisation of infrastructure operations, more insight is given into rail freight transportation. Appendix A provides a brief description of the organisation of rail transportation in Europe.

Rail freight transportation

Planning of rail infrastructure operations is normally handled by composing a yearly timetable based on the requested train capacity. In the planning of timetables for rail freight transportation several phases can be recognised based on time-horizons: strategic (long-term), tactical (medium-term) and operational (short-term) planning (Siefer, 2008). Since this research focuses on optimisation of design and planning of operations, it concentrates on strategic and tactical planning. Optimisation of operational planning has a different approach and is not further discussed.

Strategic planning is focussed on design and long-term development. It is used to calculate predictions of transportation volume, market growth and changes in the demand of capacity and to plan infrastructure adaptations related to these predictions.

Tactical planning focuses on planning of operations by the effective allocation of existing resources to improve the performance of the whole system (Marin, 1996a). In reality it forms the basis for the yearly timetable and policies for operational management. For instance, in the Netherlands the process of creating a yearly timetable and to divide the capacity on the railway network takes normally twelve months. Setting-up a timetable starts with the development of a basic-hour pattern and publication of pre-arranged paths. Based on requested train paths, a design timetable is developed, which is followed by a response period before the final timetable is determined.

For instance, in the Netherlands the capacity is determined by train paths or time slots (Keyrail, n.d.). Freight transport operators must request train paths or time slots in advance by a path catalogue of available slots provided by the operations manager. Train paths can also be requested on a shorter term, but can then only be provided when the path is available. The planning of the timetable is a complex and time costly process and is highly related to the planning of infrastructure. Some of the freight train routes use infrastructure

> shared with passenger trains, which makes the planning of freight train services highly dependent on passenger train services.
>
> Since the last decade infrastructure and operations managers are striving to separate passenger and freight traffic by developing dedicated lines. However, separation requires large investments and is therefore only applied at railway lines with a high intensity of mixed traffic. This development is beneficial for the exploitation of railway operations, as traffic with different characteristics is separated. Separation of traffic leads to higher throughput for passenger traffic as well as freight traffic. However, a variety of train characteristics still exists within freight traffic, which leaves room for optimising the planning of rail freight traffic.

The size of most infrastructure networks in ports and the combination of many stakeholders with variations in their operations, inevitably cause the need for simplifications when optimising infrastructure operations in practice. Since the demand in freight varies regularly the requirements to the infrastructure operations change also, such as the required capacity and planning. This makes it hard to determine an optimal state for a transportation network. In practice, parts of the networks are often optimised separately in order to reduce complexity and investments. However, separating optimisation can lead to a loss in detail and representation of indirect influences. Since most stakeholders involved are protective of their operational data, due to competitiveness of the market, the required input data or boundary conditions that are available are either inaccurate or assumptions. Especially all the effects of malfunctions in other parts of the system are hard to represent in the infrastructure operations, as their behaviour is often subject to unknown or large variance.

By simplifying the optimisation of infrastructure operations in ports, only generic insight is created in the capacity at a static state and not in the stability, robustness or dynamic interaction between transportation services in the total system. As the intensity and number of transport operators active on the infrastructure increases, the stability and robustness of the system depends on more variances. This undesirably reduces the reliability of the system. Reliability in combination with speed and pricing is the basis of the competitive position of the mode.

For instance at a rail transportation network in a port, observations show that transport operators reserve extra capacity in the form of time-slots in order to cope with variances in demand. Since not all time-slots are used, the transport system is used inefficiently. Combined with large variances, the daily handling of operations often differs heavily from the original planning.

2.1.3 Optimisation of ports

As discussed in the introduction, nowadays freight transport routes are part of a much larger international network and freight is transported by several modalities and by different operators before it reaches its destination. With all these different stakeholders pursuing their own interests and goals, different optimising methods are developed for optimising different parts of a transportation chain or system.

The different methods can be divided into two main categories in optimisation approaches: the (sub) system and the transportation chain approach. Both methods have proven their value in practice. Each method has its own goal and characteristics, but makes them almost exclusively applicable to specific cases.

(Sub) System Approach

System optimisation is most often performed from the point of view of operators within the transportation process, who only strive to optimize their own part of the transportation chain. For instance: a terminal operator optimises the processes taking place on the area of the terminal and takes influencing processes into account as (often simplified) boundary conditions. It focuses only on the interests of the client and optimises only the relevant subsystem, process or set of processes of the supply chain. These actors are normally commercial parties involved in the transportation process and gain direct benefits from the optimisation.

Transportation Chain Approach

Optimisation of the total transportation process tends to focus on the transportation of a product from the origin to the destination; it focuses on optimising the total supply chain and the general interest. Research institutes, universities and governments usually perform this optimisation. Their interest does not lie in the direct gain of personal benefits. Instead they try to improve the optimisation on a higher level. Goods in intercontinental transportation travel large distances and are involved in a large amount of subsystems, processes and external influences along its way. To keep the optimisations manageable and decrease the complexity, most optimisations are approached from a macroscopic level.

Neither approach covers all the aspects of a transportation network, nor the detailing to realistically approach the transportation system. This makes them applicable for very specific research goals, as the models tend to operate on a different level of detail. The approaches tend to not match or clash when representing individual interests of different stakeholders versus the general interest. In practice this has led to less cooperation between different stakeholders in optimising freight transportation and a fragmented approach to optimisation. As the amount of stakeholders involved still increases, this problem becomes more and more complex.

Combined with competitive reasons, commercial companies along a transportation chain are focussed on optimising the system only inside their own company boundaries. However, the functioning and optimisation of their system is dependent on the other systems and processes in the transportation chain. This means that often only small optimal working subsystems can be observed. An optimal situation for all stakeholders involved in the transportation of a good is not obtained. Both approaches have their own benefits and have proven their value in optimisations in practice.

A combination of the two approaches would provide valuable insight in the different subsystems influencing each other. This combined approach integrates different subsystems in a transportation chain and thereby provides the possibility of optimising a larger part of the transportation chain on a microscopic level. However, due to the large amount of stakeholders involved, such an approach makes the optimisation by modelling process really large and complex. Combined with unknown benefits and the amount of time and costs required to set up such an optimisation, it becomes an inefficient approach.

This trend is consistent with another trend that can be observed at fast developing ports: the shortage of research capacity needed for network optimisation. Network optimisation costs a lot of time and money. With the fast developments of ports, this research capacity is required for the planning of adaptations and expansions to the system. However, optimisation can have unmistakeable value for the planning of ports. For instance, it can lead to the improvement of the functioning of the overall system by improving the cooperation of subsystems in the transportation chain. Results of these improvements are only visible on the long-term, which often leads to postponing this kind of optimisation to a later stadium. Meanwhile the system is not functioning optimally and new investments to adapt are often necessary.

Chain process management

The increase in chain management is good for the reliability and efficiency of transportation by tuning the different processes along a chain. However, chain management focuses on the processes of a single chain and takes external and influential operations not into account or only to a certain extent. Since not all influences are taken into account, there is still room for improvement. The application of chain management in freight transportation has proven to be valuable and has increased rapidly in the last decade. As the scope of the research study focuses on the design and planning for the whole system, additional detail of the transportation chain approach is provided by discussing chain process management.

Due to the bundling of transportation routes, the transportation of a good is influenced by its own chain as well as other processes in the bundled transportation chains. That means that in order to be able to further optimise a transportation chain by modelling, all transportation processes which can affect the transportation chain and their dynamic behaviour have to be taken into account. Taking all these influential processes into account is really complex for larger ports. The investments required to build a large model do not weigh up to the expected benefits. However, as long as the benefits and influence on other processes are not clear, there is the possibility that taking all influential processes into account can be of value for planning and increasing the efficiency of operations.

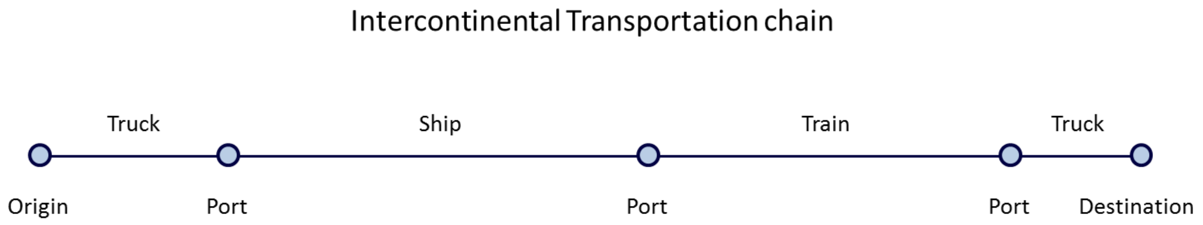


Figure 2.1: Example of an intercontinental transportation chain

Chain management in transportation tries to optimise the transportation of a specific type of good along its route through terminals and over infrastructure. Looking at a simple example of an intercontinental transportation chain, different processes along the transportation route can be recognized. These different processes can generally be characterized by its main function: storage, transhipment or transportation. Storage inserted in the transportation chain is normally used to act as a buffer between processes to filter out irregularities. In practice the storage is often used to split the transportation chain in several pieces for optimisation. This has led to a fragmented approach, which takes the effects of the external processes only limited into account. Transhipment is the process in loading and unloading modalities or storages. Transportation is the process of bringing the good from one point to another.

In these processes several stakeholders can be identified, such as the factory selling the products (origin), the client (destination), trucking companies, ports, shipping companies and train operators. Each of these stakeholders applies optimisation to their own processes and has their own interests to represent. Most transhipment terminals are commercially operated and are either owned by a larger transportation company or operate as a private company. Most parts of the infrastructure of a port are owned and managed by organisations in service of national governments, but commercial companies perform the operations. Infrastructure located inside terminals is owned and managed by terminal operators. This already shows that organisation of transportation in a port is rather complex and part of the reason behind the non-optimal functioning of the system. However, the organisation is not relevant for the technical aspect of combining models and therefore not further taken into account in the main report.

2.2 Modelling

With the increase in freight traffic and the complexity of transportation systems, such as in ports, modelling larger (parts of) transportation chains or systems with a high level of detail becomes more and more interesting to provide insight in and tune processes and systems of a network. To model a larger part of a transportation chain of a system, several methods are possible each with their own characteristics and application. This chapter provides a brief introduction into transportation modelling and discusses different methods.

Modelling ports

In science modelling seems to be one of the best methods for understanding and solving problems. A large variety of models can be found in practice, each with its own application. The current development in computer programming has provided the opportunity to work with larger optimisation models that have a higher grade of detail and shorter running times. These optimisation models approach a more realistic representation of large and complex transportation networks. Modelling, often in combination with computer programming, is currently a wide applied method used for optimisation of freight transportation.

Most models in ports are used for analysing and improving designs (strategic) and planning (tactical) of operations at terminals or infrastructure. Optimisation of transportation at a strategic and tactical level can be modelled in the same type of model and normally is done so. Models focussed on the optimisation of execution (operational) of transportation involve a different modelling paradigm and are therefore modelled by a different type of model. Optimisation of transportation at an operational level is not part of the scope and not further discussed.

Optimisation models focussed at the design and planning of operations normally consist of elements describing the actual infrastructure or equipment and elements that describe the operations of freight traffic. On the basis of the physical infrastructure or equipment, the models in ports are divided in two general categories: infrastructure operation models and terminal operation models. Another category that can be identified in ports is models that are describing the manufacture or processing of products and are highly related to terminal logistic models, but these are outside of the scope of the research.

Terminal operation models are commonly optimised by discrete-event modelling of the logistical processes or systems of a supply chain. Most logistical models are focussed on the transportation of goods and consist of processors, carriers and buffers. Logistical models can be applied on all systems where transportation is involved, however, most are applied in supply chains and industry. In ports, logistical models represent the transhipment processes of a terminal.

Modelling infrastructure operations consists of development of an infrastructure model and a description of the behaviour of traffic. The infrastructure model consists of a set of nodes and links representing the local infrastructure of one or more modalities. Its main goal is to provide a reproduction of reality for the planning and evaluation of operations and infrastructure.

To represent a larger part of transportation chains or networks in detail, both terminal and infrastructure operations should be represented in a single model. Such a model can be developed by different methods based on its goal and level of detail. In general a distinction can be made between large microscopic models and combining models by offline or real-time exchange of data.

2.2.1 Large microscopic models

To represent interaction between different parts of a transportation chain or network, a large microscopic model containing the different parts of the chain or network can be developed in a single model. However, modelling different processes with different characteristics and interaction in a single modelling environment is complex and requires a large amount of time and investments.

Setting-up a large microscopic model for the optimisation of the design and planning of a port, requires a simulation software package that can represent all different aspects of a port. It must provide the possibility to represent different types of processes at a high level of detail, for instance in ports logistical as well as transportation processes. Since logistical and transportation processes are modelled by different basic principles, these are normally modelled in dedicated software packages and are difficult to represent in a single software package at the same level of detail.

In practice, several dedicated simulation software packages provide add-ons which can represent other type of processes of a transportation chain or network. For instance, terminal simulation models can also represent train operations (FlexTerm, n.d.). However, most of these additions are developed as an extra service for customers and are not part of the main intention of the developers. As developers are normally not specialised in the development of these additional processes, these often lack detail and contain many simplifications compared to dedicated simulation software packages. This results in a limited representation of other processes and unbalanced level of detail between the modelled processes.

Setting-up a large microscopic model from scratch requires a lot of time and financial means as it requires time for modelling, the acquisition of input data and the verification and validation of the model. When comparing current simulation software packages that are representing the logistical as well as the transportation processes to existing dedicated software packages, one must conclude that that setting up a large microscopic model in a single software package is inefficient and that there is a lot of potential for processes to be represented more accurately.

2.2.2 Combining models by offline data exchange

Another option to set up a large model consisting of terminal and infrastructure operations is to combine models representing different parts of a transportation chain or network. The models are combined by exchanging data, which can be performed by two different communication methods: offline and real-time communication. This chapter discuss combining models by an offline exchange of data. The following chapter discusses combining models by a real-time exchange of data.

The method combines multiple models developed in different, but more suitable, simulation software packages and can represent a larger system by exchanging data. Due to the fact that data is exchanged more directly, loss in detail can be reduced through which the representation of interaction between the models becomes more accurate. More than two models can be combined, however, a certain structure and simulation order is required. In studies where a large amount of variables is involved, a large amount of different scenarios are possible.

Combining models with offline data exchange means that the models can only communicate before or after a run of simulations; communication or intervention during the run itself is not possible (figure 2.2). Since data cannot be exchanged during simulation, the exchanged parameter must be represented by the model beforehand and cannot be dependent on data obtained during the simulation of the other model. For instance, a terminal model featuring multiple loading stations exchanging loading times cannot be subject to other operational influences of the other loading stations. Being subject to other operational influences would require data exchange during simulation and the need for the loading time to be represented in a single parameter. This means that one model's output is the other model's input, which sometimes requires processing the data into comprehensible input. The fact that the parameter must be representable by a single model often requires simplifications, or is only applicable for the representation of a certain scenario for a limited time window.

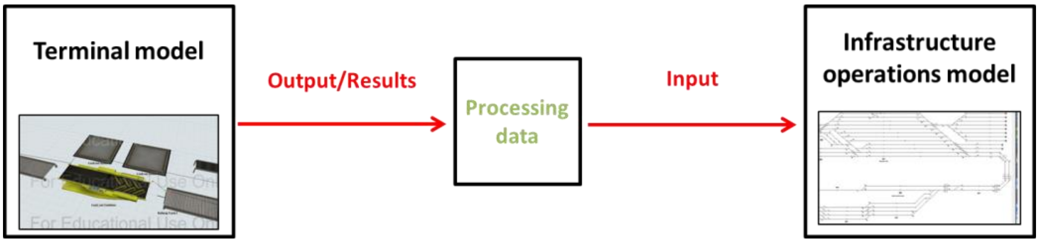


Figure 2.2: Example of combining models by offline and one directional data-exchange

Combining models with offline communication is suited for observing the behaviour under predefined conditions for a certain scenario. Data can be exchanged between the models in one or both directions depending on the requirements of the research. One directional exchange of data is the easiest way. Exchange of data in both directions requires a more complex and time intensive iterative way of running models and creates an uncertainty in case an optimum is reached, especially when multiple parameters are exchanged.

Compared to other methods discussed in this chapter, combining models with offline communication is the least complex and expensive method to gain insight into interaction between processes and sensitivities of parameters. However, the applicability of combining models by offline data exchange is limited due to predetermined exchangeable data. It thereby limits the amount of interaction represented in the model. As the combination of models with offline communication still requires quite some simplifications, its representation of dynamic behaviour affecting capacities, stability and robustness is also limited.

2.2.3 Combining models by real-time data exchange

As explained in chapter 2.2.2, combining models by real-time exchange of data can represent a larger part of a chain or system and consequently allows for reduction of loss in detail and a representation of interaction between processes. However, this method is distinctively different from combining models by offline data exchange. It is further described in this chapter.

Combining models by real-time data exchange means that the combined models run simultaneously and communicate during simulation. Interaction between processes can be represented rather realistic as the exchange of data between the models influences multiple parameters and processes directly and operations can be adjusted. Synchronizing simulations of models developed in different software packages is rather difficult due to computation and communication times. This can result in a long simulation time, which is not preferable as a large number of runs are necessary for statistical correctness.

The method of combining models by real-time data exchange requires both simulation packages to provide the opportunity to communicate real-time. Communication between different simulation software packages is normally based on status messages and commands in different protocols by server-based communication and an external data sheet (figure 2.3). The server-based communication systems are set-up separately of the simulation packages and require additional software and licences. The development of real-time communication between the models is difficult and requires advanced programming skills. This technology of real-time communication is rather new and is still being further developed. Therefore it is limited in its application and functions; current server-based communication tools cannot exchange all types of data and can limit the accuracy of parameters.

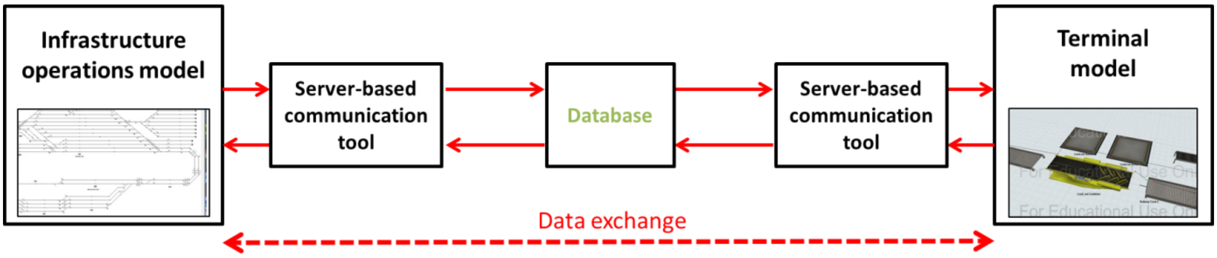

Infrastructure operations model
Server-based communication tool
Database
Server-based communication tool
Terminal model
Data exchange

Figure 2.3: Impression of a combination of models with real-time data exchange applied to a port

Real-time communication can also exchange data in a single direction or both directions. However, only in both directions is worth being performed. When data is only exchanged in one direction, the data exchange can also be performed before simulation and real-time communication shows no additional benefits compared to offline communication.

The advantage of real-time data exchange to other models is, that influential behaviour of different processes in a chain or network can be researched with a high level of detail. Because models combined with real-time communication have the opportunity to react and adapt to events during the simulation, more insight is created in capacity, stability and robustness of a system. Compared to large microscopic models, a combination of models by real-time data exchange can represent each process in the best suitable software package and consequently requires less simplifications or investments.

2.2.4 Hybrid method

The two methods of combining models can also be combined into a hybrid method which uses offline, as well as real-time communication. This hybrid method is a simplified version of the other methods and focuses on analysing infrastructure operations.

The hybrid method (figure 2.4) is especially applicable for combining multiple terminal models to an infrastructure operations model. Compared to real-time communication, the hybrid method does not require a simultaneous simulation of the models. It only requires a single server-based communication tool, which allows intervention in the simulation of infrastructure operations. A comparison of the method to offline communication provides the possibility to approach infrastructure operations more realistically, since it is not limited to predetermined planning.

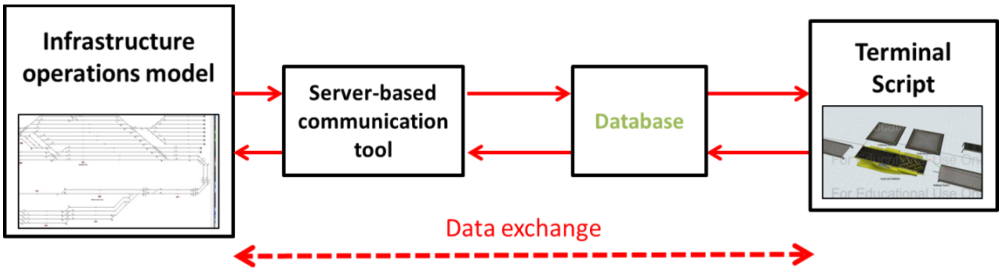

Infrastructure operations model
Server-based communication tool
Database
Terminal Script
Data exchange

Figure 2.4: Method of real-time communication letting one simulation starting the other and waiting for response

The method works through the interruption of the infrastructure operations model at specific events (for instance arrival at a certain station) and sends a message to the database. This incoming message in the database starts up a script representing the loading process. When finished, it exports the required data back to the database. This data is then imported in the infrastructure operations model, after which the simulation run is continued.

The hybrid method is simpler, requires less software and programming and is easier to set-up compared to the other methods of combining models. However, the method is limited in the exchangeability of parameters. It requires simplifications, as the terminal model must be able to be represented in a script and therefore must be independent of other processes. The script can only obtain information provided by the main model. This method can be preferred over the other methods as it is less complex and requires fewer investments. It can provide a more realistic representation of infrastructure operations compared to offline communication.

2.3 Characteristics of models

Freight transportation can be optimised for different objectives and by different approaches. Due to the versatility of optimisations in ports it is preferable to define objectives and choose a type of simulation software package. Objectives for the optimisation of a larger part of a transportation chains in ports mainly focus on an increase in capacity, stability, robustness or reduction of costs. In general two different simulation software types can be observed in port optimisation: logistical and traffic simulation.

2.3.1 Objectives

To be able to optimise freight transportation by modelling, the purpose of the optimisation and model is often described in objectives or parameters. The decision of which objective or parameter is the most important in an optimisation depends on the goal and the initiator of the optimisation. Increased efficiency based on costs is often the goal of optimisations in freight transportation, but efficiency can be represented by (a combination of) different parameters. Also multiple parameters can be the subject of an optimisation, for instance the optimisation of throughput compared to robustness of a terminal. However, it can also be a model's objective to only create insight in a system, processes or behaviour. Common specific objectives for freight transportation in ports can be divided in four categories: costs, capacity, stability and robustness.

Parameters can be expressed in different units and might therefore behave differently in simulation models. Most parameters are strongly related to other parameters, some can even be composed from other parameters. For instance, speed can be composed from distance and travel time.

Costs

Costs are normally the most important factor in transportation of goods, due to the competitive character of the transportation sector. Not all stakeholders involved in transhipment and transportation operate commercially. However, cost-benefit analyses are the most common applied type of analysis in planning transportation operations and designs of infrastructure. Since most of the stakeholders operate between different boundaries, optimisation of costs tends to focus on subsystems and not on the whole transportation chain. As this research study focuses on the improvement of designs and operational planning of a transportation chain, optimisation of costs is not taken into account.

Capacity

When transporting a good from origin to destination, the capacity of the transportation system is one of the main parameters to optimize. Capacity consists of a certain transportation volume over a certain period of time and is highly related to the speed of transportation. Most stakeholders benefit from higher speeds in the transportation process as their equipment becomes available sooner for the new shipments of goods. Speed also plays an important role in the pricing of transportation. Some customers are willing to pay extra for faster transportation, while others are willing to wait longer for a lower price. Many parameters are related to the modelling capacity of a freight transportation system, such as throughput and speed. The fact that increasing the throughput and speed of a transportation chain is beneficial for all stakeholders involved makes capacity of transportation a suitable objective for combining models.

Throughput

Capacity of a transportation system is normally expressed in throughput. Throughput can be perceived as a type of speed, since it represents a quantity of transport volume that is transported through a (sub) system in a certain amount of time. The throughput of a transportation chain is dependent on all processes along the chain and often limited by the lowest throughput of subsystems. Optimisation of this parameter should involve all processes along the chain at once.

Speed

Capacity is highly related to speed. Within in the field of freight transportation, different speeds can be recognised. Speed can be categorised as transportation speed or operational speed. Transportation speed observes the time over distance in a transportation chain, operational speed observes the speed of transportation modes in the system. Transportation and operational speeds are related to distance, travel time, transport volume and frequency. Since every separate process has its own values of these parameters, optimisation of these parameters can be performed separately for each process or for the total transportation chain.

Stability

Stability of the system or subsystems represents if and how well the transport system can cope with irregularities such as delays. The stability is important for the reliability of the system and supports the planning of timetables. Stability can be determined by analysing the sensitivity and robustness of the operational system and timetable (Goverde, 2007).

Because the total system consists of several subsystems, the stability of the overall system is dependent on the stability of each of the subsystems. Therefore in a transportation chain it is important that all subsystems are stable to create a reliable overall system. If the total system is instable, it is important to determine which subsystem is instable. Improving the stability of the total system is beneficial for all stakeholders, since the functioning of subsystems is highly dependent on that of the infrastructure. Therefore, stability of the model is an important aspect to take into account when optimising freight transportation.

Robustness

Measurement of the stability of a freight transportation system is best approached through determination of the robustness of the system. Robustness of a system is best determined through the capacity consumption of a process or system. In railway systems, the consumption capacity of a certain part of the system is measured and visualized through the compression method (Pachl, 2008). The compression method virtually compresses the blockage time stairways of a timetable without changing the sequence of trains for a certain time period. The consumption of capacity can be determined by the time the system is blocked based on this compression. This principle can also be applied to other transportation systems in ports when considering the time a system is in-use or available.

2.3.2 Simulation software packages

Nowadays, a variety of simulation software packages is available for modelling processes and systems in ports. Terminal and infrastructure operations are normally modelled in different software simulation packages due to different modelling paradigms. This raises the question how both modelling paradigms can be combined for the simulation of multiple types of port operations.

In the last decade, a large variety of simulation packages have become available, each with their own purpose, application width, strengths and weaknesses. For commercial reasons simulation software packages are primarily focussed on a specific type of system or combination of processes, such as logistics or traffic simulation. As simulation of combined paradigms is limited in practice, it is not interesting for commercial software developers to create a single microscopic simulation software package capable of simulating logistics and traffic. The fact that the design and planning of terminals and infrastructure operations are approached separately supports the assumption that there is no demand for a simulation model for combined paradigms.

Simulations are the act of recreating reality in order to analyse behaviour of a system or process (Siefer, 2008). To be able to perform simulations, a model is required that the system or process describes. Computer programming has provided the possibility to simulate almost all processes or systems, which has made it an ideal technique to study the behaviour of the traffic and logistics. Most common benefits of simulation models are analysed through behaviour of systems and alternatives and through the prediction of growth. Running simulation models require a lot of time; in order to be statistically firm the model needs to run a large number of simulations (Siefer, 2008).

Logistics simulation

Several different types of logistics simulation software packages exist and their goal is to approach realistic logistical process behaviour. Most of these software packages are not specifically developed for modelling terminals, but focus on wide applicability in the field of modelling logistical processes. Logistics simulation models are able to represent traffic processes. However, representation of mode-characteristic behaviour of traffic is complex and different from behaviour of logistical processes. Therefore the simulation of other than logistical processes is simplified and does not provide the same level of detail as a traffic simulation model.

Traffic simulation

Multiple simulation software packages for traffic optimisation are available of which some have a high level of detail and can approach traffic behaviour realistically. However, the representation of traffic behaviour is complex and therefore traffic simulation models are often dedicated to single-mode traffic. The complexity of these models makes it difficult to implement behaviours of other type of processes. Because traffic simulation is mostly applied by infrastructure operators and timetable managers, who focus on internal processes, the inclusion of other processes at a high level of detail in the simulation software package does not weigh up to the costs.

Conclusion

Both types of simulation models are better at realistically approaching their core processes than other type of processes. To support integral decisions for a larger part of a transportation chain, a single model is required that can simulate logistics as well as traffic behaviour. This can be achieved by integrating both modelling paradigms into a single environment, but such an environment with the detail of separate simulation models is not yet available in a single simulation software package.

3 Combining models along a transportation chain

This chapter discusses the hypothetical concept of combining transportation models and provides a methodological approach of how models can be combined. The models are combined into a microscopic representation of a larger part of a transportation chain or network in ports. The hypothetical concept also discusses aspects related to the set-up of a combination of models.

3.1 Hypothetical concept of combining transportation models

Combining models can provide an improved representation and understanding of a larger part of a transportation chain. A combination of models provides the possibility to measure influences and interactions of subsystems onto the chain process and the way parts of a transportation chain influence each other. Including these influences can lead to more accurate models, more precise results and better representation of parameters and objectives such as capacity, stability and robustness. Improvements in design and planning should lead to a reduction of the static and fragmented behaviour towards developments in ports. The following aspects are important in setting up a combination of models and are generally discussed in this chapter: goal and scope, communication method, combination structure, models and organisation.

As the number of optimisation models for terminals and infrastructure in ports increases, the question is raised if a combination of existing models can be an efficient alternative for the set-up of large microscopic models from scratch. A combination of models also provides the possibility to model processes in different and more suitable software packages, instead of trying to fit all processes of a transportation chain into a single software package. Especially for modelling operations of terminals or infrastructure, dedicated software packages focus only on either application or the other. Using a single simulation software package to represent all processes in a transportation chain would require more simplifications and leads to a loss of detail. However, different models are built in different modelling paradigms and to be able to create cooperation, a comprehensive modelling environment needs to be provided.

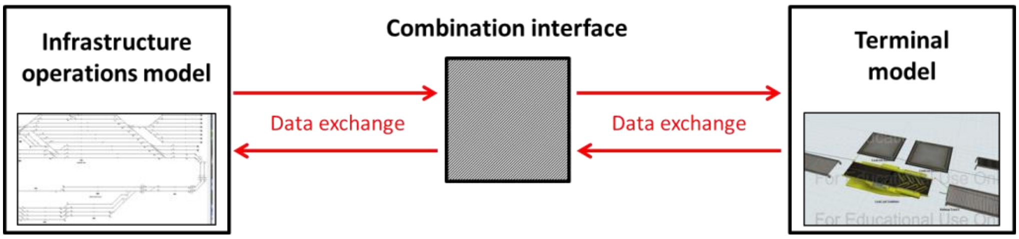


Figure 3.1: Example of a comprehensive modelling environment for a single combination of a terminal and infrastructure operations model

This comprehensive modelling environment can be created through the implementation of a combination interface between every two combined models to perform the data exchange (figure 3.1). The goal of the combination interface is to exchange input and output between the models and when required to process output of one of the models into comprehensive input for the other model. This seems rather simple, but the different communication methods and the variety of exchangeable data can make the combination interface really complex.

Goal and scope

Since the requirements and thereby composition of the combination interface differs per application, it is important to clearly define the goal of the combination of models. This is especially important in the case of combining existing models, as the objective of utilizing existing models and combining the models can differ. This can result in wrongful acceptance of simplifications and level of detail applied in the existing models and consequently provides an incorrect representation of the transportation chain. For instance researching the sensitivity of a system involves different simplifications and requires different data to be exchanged than researching the effects of variances in train arrival times. The required representation of processes and objective is determined from the goal and the scope of the model and processed in parameters and data. Most common objectives for using a combination model are capacity, stability and/or robustness.

Communication method

The combination interface can execute communication between the models in different ways. Since this study focuses on design and planning applications, input or output can be exchanged by offline or real-time communication and in single or both directions. Which communication method is used depends on the goal and scope of the study, but also the degree to which matter simplification is accepted or allowed.

Offline communication can be applied to cases which do not require intervention during simulation and all exchanged data or parameters can be put in beforehand. This requires the models to be run one at a time for predefined scenarios; the models cannot be run simultaneously. The data exchange can be performed in single or both directions, but running simulations with data exchange in both directions requires a more complex iterative approach of running models. A combination interface with offline communication can be interpreted as a black box model, as it just translates output into comprehensible input between two specific models.

Offline exchange of data can be performed manually or automated. In this case study a few steps are performed manually due to required advanced programming skills. By running the models for different scenarios, the behavioural aspects of the models can be observed. The way the data is processed affects the correctness of the total model and therefore should be done accurately, however, this requires a lot of time. In order to check if the sample size for creating the distributions is correct, the distributions must be validated.

The method of offline exchange of data in this case study requires three steps: running the terminal model multiple times, processing of data into distributions and running the infrastructure operations model after importing the distributions. Different scenarios can be simulated in order to measure the sensitivity or effects of the system to variances in certain parameters.

Real-time communication between the models provides the possibility to run the models simultaneously and adapt the operations during the simulation based on intermediate output. This communication method should be used when multiple dependent parameters are exchanged and the goal is to measure their interaction. However, it also requires a much more complex combination interface consisting of server-based communication tools suitable for the used simulation packages.

Combination structure

Combining more than two models requires a structure defining which model represents which processes and where the different models are combined. As this research focuses on ports, this structure is limited to a combination of infrastructure operations and terminal models. In order to model the processes in the most suited model, the boundaries should ideally be located at the loading and unloading process of the mode operating at the infrastructure. Working with existing models, use of the ideal location for combination is not always possible. This means that it is inevitable that models overlap or lack representation of processes. Only observing the transportation chain inside a port does not mean that other processes outside the port do not influence the model. In order to ensure the model's correct representation of reality, these processes need to be taken into account as boundary conditions.

In the case of overlapping representation of processes, it is required to dedicate each overlapping process to one of the models. This redefines the boundaries of the combinable models and this redefinition is dependent on the existing models. An analysis of the transportation chain must give insight in existing models and their characteristics. In case of lacking representation of processes, the processes must be added to the models or represented in the combination interface. For overlapping processes an analysis must provide insight in which process is best represented in which model, based on level of detail and output-input combination between the two models. Situations without a clear distinction are possible. In this case the user can indicate a preference in which model the process is described. However, each combination of models is different and should be approached as a unique case.

Besides overlap and a lack of process representation, existing models will inevitably have differences in level of detail. As differences in level of detail can influence the outcome, sensitivity analyses of the parameters are required.

As multiple models are combined, the definition of a main model to which the other models are connected is recommended. Based on the goal of the research, the main model should be the model that provides the required results for the total research. The macroscopic structure of a transportation chain provides a logical overview of the different processes along the chain. By combining the macroscopic structures of transportation chains inside ports at shared infrastructure or terminals, an ideal combination structure for a port can be created.

Models

The hypothetical concept can be applied to any modality. It even allows for the possibility to combine multiple infrastructure models with different modalities as long as the models are directly or indirectly connected to each other in the macroscopic structure. Even infrastructure models are available, which are able to simulate multiple modalities in one model, such as Villon (Adamko, 2008). However, these simulation models are often quite complex and often lack level of detail and wide applicability of data processing compared to single modality models. To reduce complexity and keep the research manageable, it is advised to use a single modality, if possible, taking into account the goal of the research.

Organisation

For the implementation and application of combining models, the cooperation of each stakeholder is required. The combination of models requires input data and insight in the processes along the transportation chain. Stakeholders are known to be reluctant to share data due to its value to competitors and thus can be a risk for the future development of their company. The benefits of taking other processes into account are not clear and therefore do not weigh up to the risks involved. However, it is observed that there is a shared interest between stakeholders, which provides the possibility to exchange data and work together in a combined model. This can be achieved by creating an organisational structure that protects interests and competitive positions of each stakeholder.

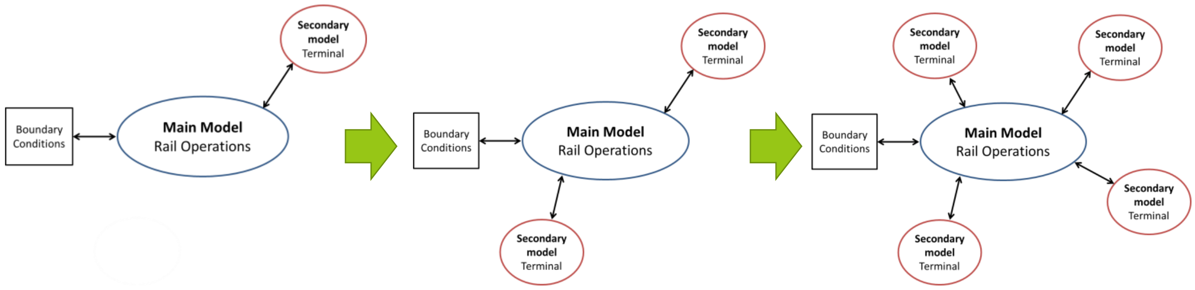
Since the research study focuses on the technical aspect of combining models, the organisation of combining models is not important and therefore not further taken into account. A possible organisation structure in which the hypothetical concept can be realised is presented in appendix A.

3.2 Methodological Approach

The methodological approach describes which steps need to be taken to apply the hypothetical concept in reality. By keeping the approach generic, the methodological approach is applicable for cases with existing models as well as newly set-up models. The steps of the general approach can be divided into four main parts:

1. **Set-up combining models**
2. **Combination structure**
3. **Simulation, verification and validation**
4. **Evaluation combination of models**

When combining more than two models, it is recommended to create each combination interface, one at a time, and to verify the correct working of the model in between (figure 3.2). For the actual combining of the models, step two has to be repeated for every added model. Step one, three and four can be performed for the total model at once.


Boundary Conditions
Main Model Rail Operations
Secondary model Terminal
Boundary Conditions
Main Model Rail Operations
Secondary model Terminal
Secondary model Terminal
Boundary Conditions
Main Model Rail Operations
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Secondary model Terminal

Figure 3.2: Example of combining more than two models

Most of the models that are being combined are microscopic simulation models that describe subsystems within a port. The combination model focuses on a single modality and connects models of subsystems to a main infrastructure model. During the process of combining the different models, the goal and the scope have to be kept in mind to ensure the correctness and effectiveness of the research. If several actions within the research do not support the goal or do have influence in processes within the scope, the actions have to be checked to be necessary for the development of the combination model. For instance, at all times the combined models and processes have to be ensured to be congruent, thus to be of the same “level of resolution”. If not, parts of the model can be left out and are not necessary to take into account in the scope. It is necessary to determine if adaptations to the existing models are required and if exchanging data is efficient and effective.

3.2.1 Set-up combining models

As a preparation and due to different methods of combining models, the outline of the research in which models are combined needs to be defined. An outline helps focussing on the goal and ensuring that all relevant factors are taken into account/correctness of the model.

The following steps have been determined as a preparation for setting up the combination of models.

1. **Goal**
   A definition of the goal of a combining models study provides insight in why models should be combined and which processes or parameters are involved. When combining models it is really important to determine a clear goal as it determines which processes need to be taken into account and is the basis for accepting simplifications. Generic goals of combining models are not preferred due to difficulties in deciding which influences to take into account. For instance a generic goal could be “improving insight into all interactions in a transportation chain”. It is difficult do decide however, which influences should and should not be implemented in the model in order to reach the goal.

2. **Scope**
   The scope defines which processes of a transportation chain are taken into account to which level and which processes are actually modelled. Similar to the goal of combining models, it is important to clearly define which processes are taken into account and which are not.

3. **Analysis of processes and transportation chain of the scope**
   By analysing the transportation chain inside the scope, insight is provided in the availability and characteristics of existing models and used simulation packages. This information is required for determining which communication method is used for exchanging data between the models and composition of the total model structure. Adaptation of the scope might become necessary.

4. **Communication method/assumptions/simplifications**
   The most suited communication method must be chosen. This decision should be based on the goal of the model, exchanging requirements, analysis of existing models, used simulation packages and availability of funds and time. Possible simplifications required for the communication method, must be determined and defined.

5. **Effects of simplifications**
   To ensure that the goal and quality of the total model are not compromised, a small analysis to the effects of the simplifications is performed.

6. **Dividing processes over models**
   As multiple models are combined to describe a single transportation chain, the processes must be divided over the model to determine which process is best represented in which model. This division is based on the ideal division, the characteristics of the simulation packages and the characteristics of existing models. The ideal division, in case of newly developed models, would have the models that are being combined meet at the loading process. When existing models are used, boundaries of the models need to be redefined to solve the problem of overlapping or lacking representation of processes.

3.2.2 Combination structure

The combining structure explains the composition of the actual combination of separate simulation models. This approach describes which actions have to be taken to set-up a combination of models applied to transportation by infrastructure and terminals in ports. It is assumed that the models combined already consist of all input data besides the exchangeable data. The steps in this main part of the approach are the actual combining of models and are repeated per combination of two models.

7. **Combination interface and exchanging data set-up**
   Set-up of the combination interface based on previous set requirements and results of analyses. Due to the fact that every combination of models is unique, the best way must be determined on the user's preferences, communication method and simulation packages involved. For instance, a combination interface with offline communication can be set-up in spread-sheet software like Microsoft Excel as it only converts data output of a model into input, but a model with real-time communication can require a XML-based database to communicate with.

8. **Simulation outline**
   In the simulation outline is defined for each model how the running of simulations is performed, under which conditions and for how many runs. Especially the amount of runs is important as it affects the statistical correctness of the results.

9. **Verification data exchange**
   In order to ensure correct data exchange by the combination interface, the communication between each combination of two models should be verified separately. This verification reduces wrong representations of parameters and makes detecting of errors easier.

3.2.3 Simulation, verification and validation

The third step is the actual running of simulation, analysing and validating the results, as described in the following.

10. **Verification combination of models**
    In the case of combining more than two models, the possibility exists that the data exchange between any two models functions correct, but does not do so for the total system. This is the case if for instance, a parameter is exchanged through multiple combination interfaces and one of the interfaces cannot correctly process the variations of the parameter determined in another interface. To prevent these incorrect representations, the combination of models must be verified as a total system.

11. **Simulation**
    The next step is running simulations: offline communication requires running each model separately; real-time communication provides the possibility to run the models simultaneously.

12. **Analysis of results**
    Running the combination of models provides results in the form of data and observations, which needs to be processed and analysed for determining conclusions about the goals.

13. **Validation**
    Validation of the model ensures the correct representation of the processes in the transportation chain. Preferably validation is performed by comparing results with reality data, however not for all applications is data available. In that case validation must be performed by reviewing the total model with experts.

3.2.4 Evaluation combination of models

After the combination model is verified and validated, the functioning of the model needs to be compared to the current approach and the goal of the application. Since different methods are available and each is suited for certain applications, a comparison can show the added value of combining models compared to other approaches. The added value of the combination model is found in “lessons learned” by comparing results of the current and new approach while observing interaction and keeping the amount of work into account. The so gained experience can help interpreting results, show improvements to the model and improve the method of combining models.

The comparison of the results should be focussed on the main parameters (for instance capacity or stability) of the transportation system and research study by visualisation and quantification. To be able to analyse the benefits of just the combination of existing models, the combination model should be compared to the same infrastructure model applied in the combination model. The comparison possibly also requires data of the terminal(s), which should be included in the way it is provided now in the current approach and circumstances.

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4 Case Study: Introduction and Model set-up

The hypothetical concept discussed in the previous chapter is applied with the goal to prove that combining models can provide insight in the interactions of operations in a transportation chain. Application is performed by a case study of the loading process of coal and iron ore trains at the EMO dry-bulk terminal in the port of Rotterdam in the Netherlands. It tests if combining models for representing a larger part of a transportation chain is possible and usable for determining interference due to interactions of infrastructure operations. This case study was chosen from several options, mainly based on its chain process, infrastructure and operations. The chapter starts with an introduction to the case study and is followed by the set-up of the models.

4.1 Introduction EMO dry-bulk terminal and Maasvlakte East

This chapter provides a brief introduction to the case study of loading trains at the EMO dry-bulk terminal and discusses the boundaries in which the hypothesis is applied. The introduction goes into the decision, scope and chain process of the case study.

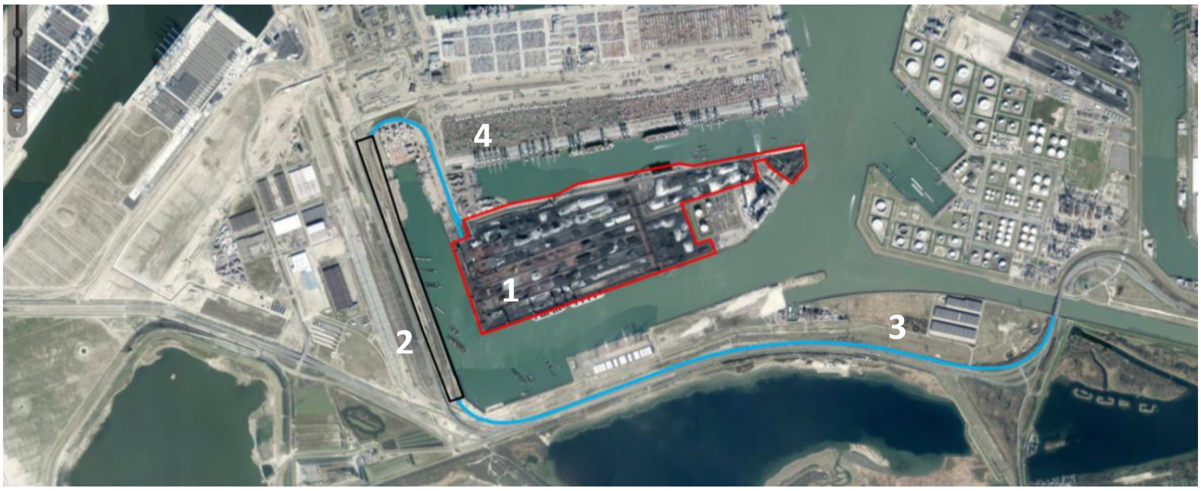

Figure 4.1: Impression of the location (source: edited picture from Google Earth), 1) EMO dry-bulk terminal, 2) Maasvlakte East railway yard, 3) Port Railway Line and 4) private sidings

The EMO dry-bulk terminal (figure 4.1) is an import terminal located near the North Sea at the Maasvlakte in Rotterdam, Netherlands. It has a surface area of 170 hectares and handled 22 million tonnes coal and 12 million tonnes iron ore in 2014[1]. The coal and iron ore's main destination is Germany, which is transhipped to barges and freight trains. For the loading of freight trains the terminal is provided with three automated load-outs, a large belt conveyor system and seven stacker/reclaimer combinations. A total loading time of 3 hours is assumed and reserved for loading coal trains and 3.5 hours for iron ore trains. However, in practice large deviations can be observed and the characteristics of the load-outs make it seem theoretically possible to load a train in a shorter time.

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[1] www.emo.nl

The EMO dry-bulk terminal is connected to the Dutch railway system by the Maasvlakte East railway yard and Port Railway Line. Primarily the railway yard is used for coal and iron ore trains from the EMO terminal, but is also connected to a steel and container terminal and used for the storage of wagons and locomotives. The Port Railway Line is used by a large variety of freight trains and connects all rail terminals south of the Maas with the hinterland. The railway yard and Port Railway Line are provided with a catenary system, but the private sidings and terminal are not. This requires for electrical powered trains to switch locomotives at the railway yard.

4.1.1 Why Maasvlakte East and EMO dry-bulk terminal?

Since microscopic simulation of rail freight transportation is rather complex, the decision for which case study to use was mainly based on simplicity with keeping the goal of the research study in mind. The complexity of the transhipment and transportation processes is mainly dependent on the type of freight. Based on complexity, dry-bulk transportation is preferred above intermodal/container or liquid bulk transportation. The chain process of dry-bulk transportation is assumed to be rather simple, due to the fact that trainsets are used which do not often change of composition (less shunting movements) and all freight has the same destination. It also seems to be a rather stable system, no large increase or decrease expected in the demand of coal and iron ore. However, for this case study a substantial part of the coal demand is used for generating electricity and therefore the coal demand is subject to a trend due to climate changes between seasons.

After a short analysis of possible case studies, the EMO dry-bulk terminal was determined to be the best option. The decision for this decision was based on the availability of operational and infrastructural data and the conditions of the location and total chain process. Data of the infrastructure and operations is mostly available by the different stakeholders; for instance technical drawings with the measurements of the total rail infrastructure of the Netherlands are available at ProRail.

The size in demand, transport volume and frequency of trains of this case study provide a system and chain process large enough for observing behavioural changes and capacity constraints in the daily chain process as well as individual processes. The infrastructure and location of the terminal and railway yard provide an almost dedicated coal and iron ore transportation before entering the Port railway line’s infrastructure. This reduces the amount of other rail processes that should be taken into account and therefore reduces the complexity of the simulation models. However, by taking a part of the Port Railway Line into account, the effects of other operations at the main line on the chain process can be observed. For instance, iron ore trains are much heavier than intermodal trains and this affects the acceleration and deceleration and thereby affects the scheduling of trains. However, this case study focuses on loading and turn-around times and other train operations are not taken into account.

4.1.2 Scope

The scope of the case study focuses on the testing the hypothesis for a certain application, analysing infrastructure influences at the turn-around times of the loading process of trains, and defines the boundaries in which the case study is performed. Since loading processes at the terminal are largely influenced by other processes and to avoid extreme complexity, the case study is limited to the transhipment and transportation of coal and iron ore by rail. This means that other operations at the rail infrastructure are not part of the scope and thereby neglected. For testing the applicability of the hypothesis, this simplification is acceptable for this case study but it must be kept in mind when observing results and comparing it to reality.

The scope includes the EMO dry-bulk terminal, Maasvlakte East railway yard, Port Railway Line and private sidings. Not the total length of the Port Railway Line is taken into account, it is observed from kilometre 32.9 to 40.1. The observed chain process of transportation and transhipment of coal and iron ore is bounded by the same physical boundaries.

4.1.3 Chain process

The chain processes represented in the case study of coal and iron ore trains are generally the same, however characteristics of elements differ at a microscopic level. Stakeholders involved in the chain process optimise the chain process differently; however most efforts are put in the development of a constant daily or weekly process. Table 4.1 provides an example of the general steps made in the chain process inside the port for the arrival, loading and departure of a coal or iron ore train at the EMO dry-bulk terminal. To give an impression of the time duration of the general steps of the chain inside the port, average values are provided. The values for station delays are based on summation of reference values of ProRail and travel times are provided by simulations made in the OpenTrack model. A more detailed description of the chain process can be found in appendix B.

Table 4.1: Impression of steps in the chain process of coal or iron ore trains at the EMO dry-bulk terminal

Process/Handlings	Approximate duration
Entering Port Railway Line	-
Arrival at Maasvlakte East	-
Station delay at Maasvlakte East	45 minutes
Departure Maasvlakte East and entering EMO terminal	11 minutes
Station delay at Emo Terminal and loading of wagons	211 minutes
Departure EMO terminal and entering Maasvlakte East	13 minutes
Station delay at Maasvlakte East	62 minutes
Entering Port Railway Line and leaving port	-

4.2 Model set-up and Simulation

To test the hypothesis at the case study, two models and a combination interface have to be set-up representing different parts of the chain process. This chapter discusses the set-up and simulation of the different models based on offline communication. First the outline of the combined model is discussed and after that the set-up of the two base models and combination interface.

4.2.1 Combined model and Simulation outline

Before the set-up of the separate models is discussed, the framework in which the models are set-up and simulated are explained. The case study focuses on influences of the infrastructure on the turn-around times of the loading process of trains at the EMO dry-bulk terminal, which means that the main objective of the total model is to determine loading times with and without the use of infrastructure. By observing only the loading times for normal conditions, the influences of the infrastructure and thereby the additional value of combining models is determined.

The case study consists of two models, one representing terminal operations and the other rail infrastructure operations. Based on quality and availability of software packages and expert assistance, the terminal is chosen to be modelled in FlexSim and the rail infrastructure in OpenTrack. The communication method applied to the models is offline, since real-time communication between the software packages requires unavailable server-based software packages.

OpenTrack is a microscopic object-oriented simulation model for railway networks and operations using a mixed discrete/continuous simulation process (OpenTrack, n.d.). The software package was developed at the Swiss Federal Institute of Technology and has developed into a high detailed modelling tool with a wide application in the railway sector. OpenTrack provides the possibility to import and export data and can be modified relatively easy (Nash, 2004).

FlexSim is a discrete event simulation model that is widely used for simulation processes in manufacturing, warehousing, healthcare, mining and other logistics (FlexSim, n.d.). The simulation package has a wide applicability in several sectors and a strong visualisation of the simulated processes. It is commonly used in evaluating alternatives in development projects. Railway operation can be simulated in FlexSim, but simplified and it does not provide the same level of detail for this application as OpenTrack.

The hypothesis states that combining existing models reduces costs and time in comparison with setting up a large microscopic simulation model from scratch. In order to completely understand all processes in the chain process, their characteristics and analyse the effects of communication method, the decision was made to set-up new base models for the study. This is underpinned by the fact that this research study is performed at the Technical University of Delft and unavailability of existing detailed models for the chosen software packages.

Scope

To focus on measuring only the influence of the infrastructure to the turn-around times of the loading process, the combined model is simulated for normal conditions at a normal single day. However, to measure infrastructure influences, a substantial intensity of traffic at the infrastructure is required. Based on operational data of April 2015[2] a Wednesday is the best representation of a normal busy day at the terminal. Therefore the combined model represents operation on a normal Wednesday under normal operational and weather conditions, malfunctions are neglected

For the same reason only variances in the loading times are taken into account, other processes in the transportation chain are represented by a constant value. These values are based on reference values provided by ProRail (Samuel, 2011) and verified by experts of dry-bulk terminals and railway operations[3]. The chain process described in the case study is taken into account, a more detailed description of the different steps in the chain process of loading trains and their reference value can be found in appendix B.

Input for the models is mainly based on technical specifications of the elements of the terminal and infrastructure or based on operational data provided by the EMO dry-bulk terminal. In the model set-up the input and its origin is discussed per element. To focus on its goal, the output of the models is limited to loading and turn-around times.

Set-up of the combined model and base models

The goal of the combination of simulation models is to describe the chain process of coal or iron ore rail transportation within a port. As new base models are set-up, a decision must be made which processes are simulated in which model. This decision is based on which simulation package can represent a combination of processes the best. By combining the processes per simulation package into sub-chains, two process chains are developed for each of the simulation package.

Comparing the two simulation packages, OpenTrack is better in describing the behaviour of trains and FlexSim in the transportation and processing of products. FlexSim can describe train behaviour by the RailAPI (FlexSim, 2008). However, due to its complexity and small range of application and functions of the RailAPI cannot match with OpenTrack at representing train behaviour. OpenTrack lacks the option to describe all processes involved in loading a train without simplification of the total process by the use of statistics.

This specific case, the loading of coal and iron ore trains, requires the trains to move at a very low speed. In OpenTrack it is not possible to enter speeds below 1 kilometre per hour and in FlexSim the describing of train behaviour becomes unnecessary complex. Therefore it is logical to dividing the process chains at the process of loading the train at the load-out of the terminal. By this the train behaviour with a speed above one kilometre per hour is simulated in OpenTrack and the lower but constant speed while loading the wagons is simulated in FlexSim. Therefore the OpenTrack model includes the total chain process of appendix B with the exception of the loading process, which is represented in the FlexSim model.

To keep the base models as simple as possible, non-influencing parts of the process chain are excluded from the model. For instance, the size of the stock yard is so large that the processes of unloading ships onto the terminal have almost no effects on the loading process. Therefore the ship-stack part of the process chain is neglected at representing the process of loading the wagons.

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[2] Daily operational data available at EMO Pl@n (Europees Massagoed Overslag BV., n.d.)

[3] T. van der Sande and D. Koopman, engineers at RoyalHaskoningDHV

The terminal has three different load-outs with its own characteristics influencing each other by the rail infrastructure connecting them to the railway yard. In order to represent the dynamic effects of the different loading operations, all three load-outs are taken into account. In practice the operations at the load-outs are influenced by each other due to the shared conveyor system and stacker/reclaimer. However, this makes the FlexSim and combination interface really complex and for simplicity reasons it is assumed that the loading processes are not influenced by each other and the load-outs can be represented by three separate FlexSim models.

In this set-up one process overlaps processes which are simulated by the different models: the locating of the reclaimer to the specific stack. This process can already start when an empty train is at the railway yard, is assigned an arrival track, is called in to the terminal and the stacker/reclaimer combination is available for its next loading task. This process is only included in the FlexSim model and the start-up time is reduced by the averaged time of the processes between the train leaving the railway yard to locating the first wagon underneath the load-out. By simulating the loading processes individually and not the total terminal, the complexity and duration of the simulation is reduced.

The next three chapters discuss the set-up of the different models in detail: the terminal model (FlexSim), combination interface and the infrastructure operations model (OpenTrack). After the set-up two chapters go into validation and simulation of the models.

4.2.2 Terminal model: Wagon loading process

A step-by-step explanation is provided of setting up the three FlexSim models, each representing one of the load-outs of the EMO dry-bulk terminal. The goal of the models is only to determine a distribution for the time duration of the total loading process for different train compositions. These models are named after their load-out; WB1 (iron-ore), WB3 (coal) and WB4 (coal). This chapter first describes the scope, assumptions and variables related to the model, followed by discussing the set-up of the main parts

Scope

The scope of the models includes the processes from the reclaiming at the stack to the load-out on the terminal terrain. The models are used to determine a distribution for the total loading time under normal conditions for a day with normal operations. The three models each represent one of the load-outs and its connection to the reachable stacks within the physical boundary of the EMO dry-bulk terminal. Compared to OpenTrack, detailed train behaviour is complex to represent in FlexSim. Therefore all processes involving train behaviour are excluded from the model and are represented in the OpenTrack model. Trains in FlexSim are represented by a *flowitem* travelling a conveyor system at a constant speed.

The total stack capacity of the EMO dry-bulk terminal is large compared to the daily transport volume of coal and iron ore. Since this research study observes the behaviour of the loading processes and rail traffic over a single day, the stacks are assumed to be unlimited for this duration. When assuming the endless supply of coal, the processes between ship and stack can be neglected.

Because the model is focussed on its functionality, i.e. to reduce simulation time and complexity, the model uses standard objects of the FlexSim library as much as possible. For this case study all objects of the loading process are simple and all of them can be represented by a standard item of the library. At each object is described by which standard item it is represented.

Assumptions

The assumptions made setting up the models explain in which matter reality is simplified. These assumptions are generally divided into three types: general assumptions, model assumptions and assumptions related to parts of the model. This chapter explains the general and model assumptions; the assumptions related to parts of the model are described later on in the model set-up.

The general assumptions are made to fit the case study within the theory of connecting simulation models by offline communication. For this case study the offline communication and thus one-way data exchange requires that the loading process at a load-out can be represented by a general model for all possible conditions. This means that the model needs to be independent of other processes outside the model and all input needs to be able to be put in beforehand.

For the case study this means that each load-out needs to be represented by its own model. Representing the load-outs in one model requires input of arrival of the trains and other processes at the terminal. This is not possible by offline communication since it requires input variables from the OpenTrack model which simulates the train traffic (variable arrival times). However the different load-outs use the same belt conveyor system and stacker/reclaimer-combinations and therefore the loading processes are actually dependent on each other. To be able to represent the chain process by offline communication, it is assumed that the load-outs are independent and can be modelled in a separate FlexSim model.

Independency of the models also means that the start- and end-position and the availability of the stacker/reclaimer combination and the availability of the stacks cannot be taken into account. However the stacker/reclaimer combinations are also used for other operations at the terminal; using the start- and end-positions correctly requires a simulation of all operations related to the stacker/reclaimer combinations of the terminal. The effects of neglecting a specific start- and end-positions compared to a positioning time with a random length, can lead sometimes to a larger and sometimes to a shorter positioning time, resulting in an average delay of zero for all the operations combined. Therefore the specific position of the stacker/reclaimer combination can be neglected and is taken into account as a random start-position. This also requires the assumption that the stacker/reclaimer combination is always available for load-outs at any time and that all load-outs can operate simultaneously.

Other assumptions are directly related to the set-up of the models and are mainly required for simplicity reasons and in order to keep the focus to the main purpose of the model. These model assumptions are related to the scope and mentioned before:

- The model represents operation on a normal Wednesday under normal operational and weather conditions, malfunctioning of parts are neglected
- Detailed behaviour of trains is neglected and the loading process of a wagon can be represented by certain speed over a certain distance
- The capacity of the stacks on the terminal are unlimited and provide an endless supply of coal or iron ore

Simulation

Since the simulation is run under normal conditions and train compositions and operations differ, train compositions related to the load-out have to be assumed. Based on data of April 2015 the following train compositions are defined: WB4 with 40 wagons, WB4 with 32 wagons, WB3 with 44 wagons and WB1 with 38 wagons. The effects of this assumption are rather small as this are the most common train compositions per load-out and the two coal load-outs are generally the same[4].

Simulation is run for the total duration of the loading time, it automatically stops when finished. The required amount of runs for the simulation is determined by the combination interface representing the loading time and can be found in chapter 4.2.3 *Combination interface*.

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[4] See chapter 4.2.2 Terminal model, *Load-outs* page 42

Overview model

The main parts of the FlexSim model representing the loading of the wagons are the products coal and iron ore, the stacks and stock yards, the wagons, the load-out, the belt conveyor system, the stacker/reclaimer combination and export data. An overview of the model for load-out WB4 (coal) is provided in figure 4.2, all main parts are represented by standard objects from the FlexSim library. The model is set-up from the load-out to the stacker/reclaimer combination, since the load-out has a lower capacity than the conveyor system and the stacker/reclaimer combination and is therefore determinative for the total system. This chapter gives a detailed description for the set-up of the main parts.

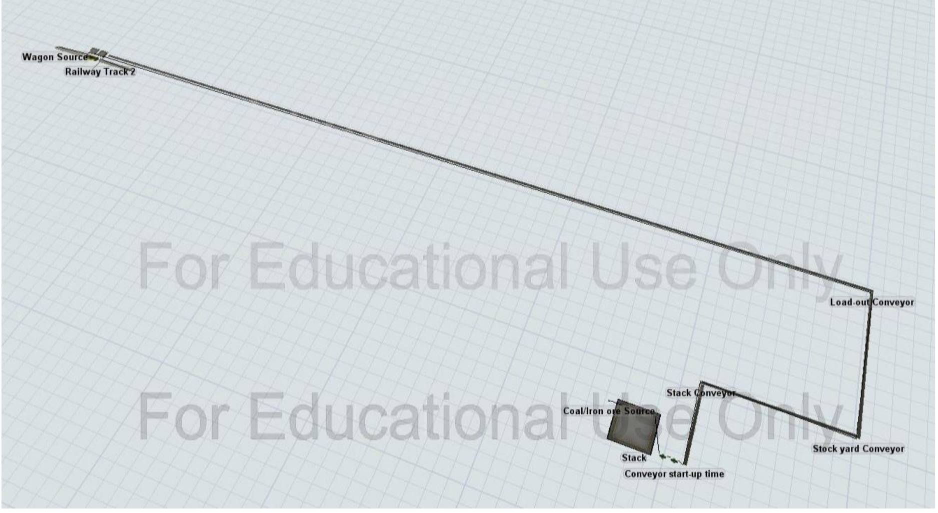

Figure 4.2: Overview FlexSim model of load-out WB4, the load-out at the left-top is connected by the belt conveyor system with the stacker/reclaimer combination at the bottom-right

Products: Coal and Ore

The products which are loaded on the terminal are coal and iron ore. In order to determine throughput and flow values from data, a value for the density is required. The bulk density is determined from reference values of the stacker/reclaimer combination: for coal 0.70 - 1.00 tonnes per cubic meter and iron ore: 1.70 – 3.10 tonnes per cubic meter.

Due to the fact that the density of coal and iron ore is dependent on many factors, it is hard to represent realistically a density in such a model when all circumstances are taken into account. For instance, the density is not only dependent on the moisture content and granular size but also on client preferences per trainload. The case study assumes operations under normal weather and operational conditions; therefore it is assumed that an average can represent the density in the model.

The fact that the load-out measures loads per wagon on weight accurately (Klein Gunnewiek, 2008) and is limited by a maximal volume, underpins this assumption. Compared to the total weight of the train, the effects of these deviations are small and its effects limited. FlexSim is a discrete object simulation package, therefore bulk is not represented continuous flow, but as discrete unit (packages) of bulk. Based on these characteristics and simplicity reasons, the model uses packages 0.5 tonnes with standard measurements. As long as each package represents 0.5 tonnes of product, the measurements do not have any effect on the model and the bottom surface is set to 1 by 1 meter.

- **Coal:** The average of the density of coal is 0.85 tonnes per cubic meter, which means that in FlexSim a package of coal is 0.588 cubic meter. The measurements of each package are set to 1 x 1 x 0.588 meter (length x width x height)
- **Iron ore:** Iron ore has an average of 2.40 tonnes per cubic meter and the measurements of a package of 0.5 tonnes are set to 1 x 1 x 0.208 meter

Stacks and stock yards

The stacks and the stock yards are the storage locations of the products on the terminal. The stock yards are sections containing a row of stacks and are reachable from both sides by stacker/reclaimer combinations. Stacks are considered a certain pile of coal or iron ore. As explained the stacks are assumed to be unlimited, all stacks are used for both products and available at all times. Figure 4.3 shows the layout of the stock yards in the terminal.

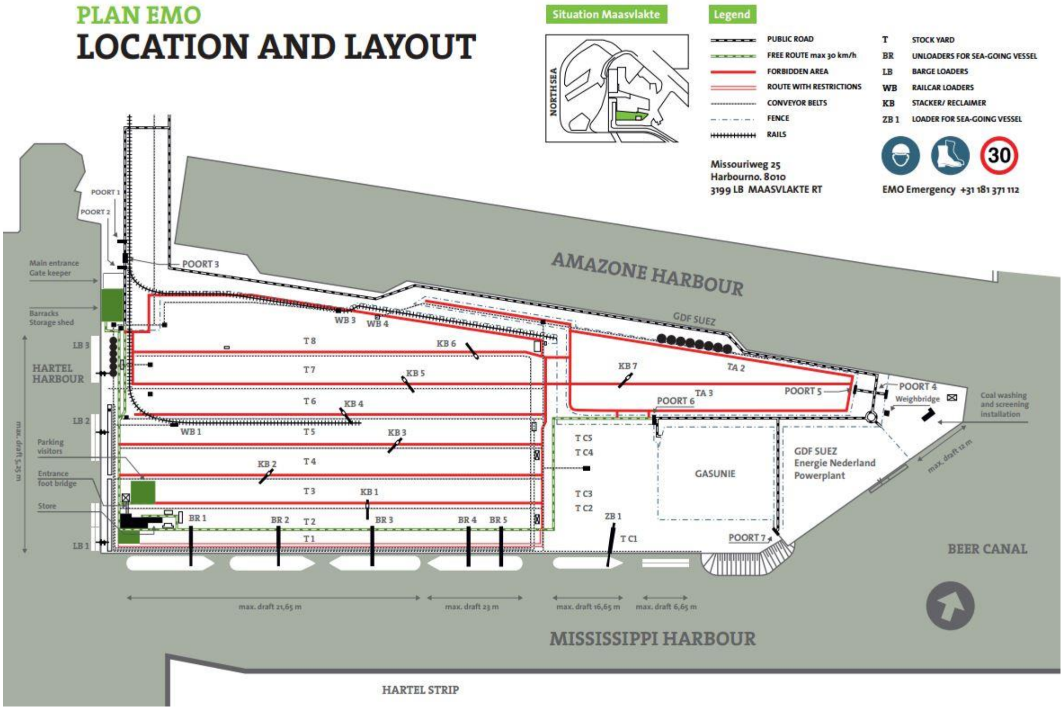
PLAN EMO
LOCATION AND LAYOUT
Situation Maasvlakte
NORTH SEA
Legend
PUBLIC ROAD
FREE ROUTE max 30 km/h
FORBIDDEN AREA
ROUTE WITH RESTRICTIONS
CONVEYOR BELTS
FENCE
RAILS
T STOCK YARD
BR UNLOADERS FOR SEA-GOING VESSEL
LB BARGE LOADERS
WB RAILCAR LOADERS
KB STACKER/ RECLAIMER
ZB 1 LOADER FOR SEA-GOING VESSEL
30
Missouriweg 25
Harbourno. 8010
3199 LB MAASVLAKTE RT
EMO Emergency +31 181 371 112
POORT 1
POORT 2
POORT 3
Main entrance Gate keeper
Barracks Storage shed
LB 3
HARTEL HARBOUR
LB 2
Parking visitors
Entrance foot bridge
Store
LB 1
max. draft 5,25 m
WB 3
WB 4
WB 1
T 8
T 7
T 6
T 5
T 4
T 3
T 2
T 1
KB 6
KB 5
KB 4
KB 3
KB 2
KB 1
BR 1
BR 2
BR 3
BR 4
BR 5
AMAZONE HARBOUR
GDF SUEZ
KB 7
TA 2
TA 3
POORT 6
POORT 5
POORT 4
Weighbridge
Coal washing and screening installation
T C5
T C4
T C3
T C2
ZB 1
T C1
GASUNIE
GDF SUEZ Energie Nederland Powerplant
POORT 7
max. draft 12 m
BEER CANAL
max. draft 21,65 m
max. draft 23 m
max. draft 16,65 m
max. draft 6,65 m
MISSISSIPPI HARBOUR
HARTEL STRIP

Figure 4.3: Schematic plan of EMO dry-bulk terminal, stock yards are represented by T1-T8, source: www.emo.nl

Wagon

Several types of wagon are used for the transportation of coal and iron ore at the EMO dry-bulk terminal. However the differences between the types are rather small and the types are generally the same. Therefore it is assumed that the most common used type at the terminal can be used as a representative for all wagons. In the FlexSim model the wagons are represented as a *flowitem* which can be loaded with the specifications of the type of wagon.

The most common type of wagon for coal transportation is the Falns-type for coal transportation and Faals- or Falrrs-type for iron ore transportation. There are different versions of the Falns coal-wagon type, each with small difference in its measurements and characteristics. The representative coal wagon-type for this case study is chosen to be Falns^{183}. Wagon types of Faals and Falrrs are almost the same, but the Falrrs consists of a set of two wagons of the type Faals which are connected by a fixed coupling rod. Since this characteristic has no effect on the model, the Faals^{151} type is chosen to represent the iron ore wagon. The characteristics of both wagon-types are described in table 4.2.

Table 4.2: Specifications of coal wagon Falns^{183} and Faals^{151}, source www.gueterwagenkatalog.rail.dbschenker.de

Characteristics	Coal wagon Falns^{183}	Ore wagon Faals^{151}
Length over buffers	12.54 m.	15.05 m.
Width	3.14 m.	3.068 m.
Height	4.300 m.	4.007 m.
Mass	25 tonnes	35 tonnes
Loading Capacity	64.5 tonnes/85 m3	100 tonnes/ 70 m3
Max. axle load	22.5 tonnes	25 tonnes **(22.5 tonnes)***
Wheel arrangement**	2´2´	3´3´
Max. speed empty	120 km/h	120 km/h
Max. speed loaded	100 km/h	100 km/h
Loading opening	11.594 m. x 1.856 m.	12.76 m. x 2.238 m.

*: permitted axle load of infrastructure along the route (Keyrail, 2012), **: UIC-notation

In practice the maximum axle load of the wagons can also be limited by the maximum loading class allowed on the infrastructure (Samuel, 2011). The lowest loading class along the route of the train is determinative and for this study is the Port Railway Line's maximum loading class of D4 (Keyrail, 2013). However the maximum axle load is less or equal to loading class D4 and therefore does not have any effects on the model.

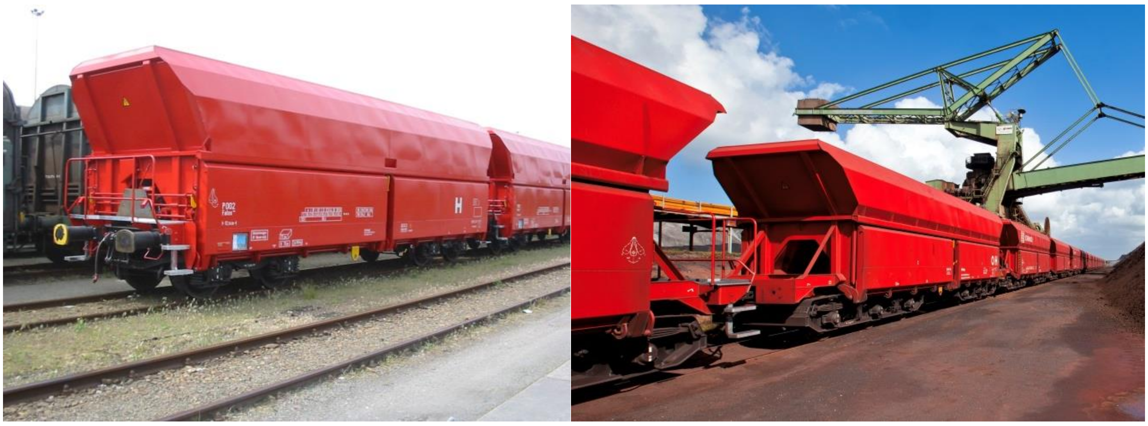

Figure 4.4: On the left a coal wagon of the type Falns^{183}, source www.wikipedia.nl, on the right a picture of the iron ore wagon Falrrs^{152}, source EMO dry-bulk terminal

The maximum loading capacity of the coal wagon is 64.5 tonnes per cubic meter, but in practice the actual loading volume is slightly lower. This is deliberately done in order not to overload the wagons, which requires manual labour and a lot of time to unload the overweight and is punishable by high fines. When observing departure data from the EMO dry-bulk terminal[5], an average of loading weight of a coal train divided by the total amount of wagons is 64.1 tonnes per wagon. Since the model works with packages of 0.5 tonnes and for simplicity reasons, an actual loading weight of 64.0 tonnes per coal wagon is assumed. The same approach is used for the iron ore wagon and its results can be found in table 4.3.

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[5] The EMO dry-bulk terminal provides departure and loading data on their website (Europees Massagoed Overslag BV, n.d.)

Table 4.3: Loading weights of wagons in model

Loading weight	Coal wagon Falns[183]	Ore wagon Faals[151]
Maximum loading weight	64.5 tonnes	100.0 tonnes
Average loading weight	64.1 tonnes	98.7 tonnes
Assumed loading weight	64.0 tonnes	98.5 tonnes
Amount of packages	128	197

Load-out

The load-out is the machine that actually loads the product into the wagons while the wagons travel at a continuous low speed while being loaded. In this case study the load-outs are provided with a storage bunker and a weighing bunker which automatically weighs the load required per wagon. The loading process is automated; it can detect the position of a wagon with a detection system, and is controlled from the terminal control centre. The load-out is set-up in FlexSim (figure 4.5) as a combination of two queues and a combiner. The two queues represent the storage and weighing bunker, the combiner represents the process of loading the product into the wagon. The process time of the combiner represents the time it takes for a wagon to travel underneath the load-out while it is being loaded.

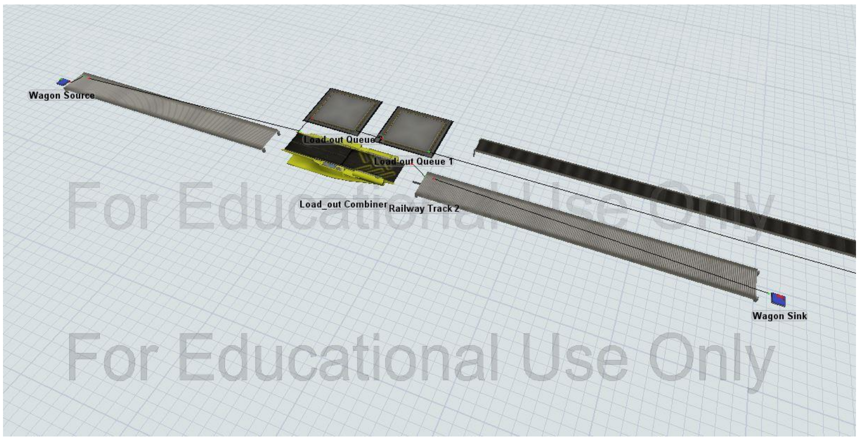

Figure 4.5: Representation of the load-out in FlexSim

As explained before, the theoretical loading capacity of the load-out is less than the theoretical reclaiming capacity of the stacker/reclaimer combination and therefore determinative for the size of the flows of the loading system. The technical specifications of the load-outs are available at the EMO website and can be found in table 4.4, other required information was provided by RoyalHaskoningDHV. Load-outs WB3 and WB4 are generally and thereby assumed the same, load-out WB1 has a different design but works in the same manner. The relevant amount of wagons differ per load-out, for instance the trains for load-out WB1 normally have 38 or 36 wagons. Since the research study observes the chain process under normal operational conditions, only the standard train compositions are observed[6].

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[6] See chapter 4.2.2 Terminal model, *Simulation* page 38

Table 4.4: Load-out specifications by EMO, source www.emo.nl

	Coal (WB3, WB4)	Iron ore (WB1)
Loading capacity	Max. 2,750 ton/h	Max. 3,600 ton/h
Trains	Max. 16 trains/day	Max. 6 trains/day
Weight bunkers	2 x 80 ton	2 x 60 ton
Wagon loading capacity	65 ton	100 ton
Train capacity	2,750 ton	4,000 ton

Coal load-out WB3 and WB4

Assuming that the loading capacity is the dump capacity of the loading shaft, a representative value for the loading time per wagon can be calculated. It is assumed that each single wagon travels at a certain constant speed underneath the load-out, because detailed train behaviour is not part of the scope of the FlexSim model. The loading capacity of the load-out of 2,750 tonnes per hour (0.7639 tonnes per second) and a wagon capacity of 64.0 tonnes, results in a loading time of 83.8 seconds per wagon volume. However the load-out can only load the wagon while the wagon's loading opening is fully underneath the loading shaft. Since the total length of the wagon is larger than the wagon's loading opening, the time it takes for a wagon to travel underneath the load-out is longer than the loading time per wagon's volume. The actual distance over which the wagon travels while it is loaded can be based on the loadings opening length minus twice the half of the width of the loading shaft.

Based on schematic drawings of the coal load-out WB3 provided by RoyalHaskoningDHV, the width of the loading shaft just above the wagon is approximately 4.40 meters. The loading opening length of the coal wagon Falns[183] is 11.954 meters, which lead to an actual distance travelled during the loading process of 7.55 meter. This length divided by the loading time of a wagon's volume of 83.8 seconds gives a wagon speed at maximum loading capacity of 0.090 meters per second. Based on this speed, a wagon needs a minimum of 139.3 seconds to travel underneath the load-out.

However the speed of the EMO shunting robot pulling the wagons underneath the load-out is not so accurate that the loading process can be performed with a constant speed of 0.090 meter per second while being influenced by the increasing loading weight of the wagons. In order to describe the variance in loading times per wagon without describing detailed train behaviour of the EMO shunting robot, the accuracy of the shunting robot for low speeds must be assumed. The EMO dry-bulk terminal has four shunting robots available with minor differences in characteristics, but for simplicity reasons the robots are assumed to have the same characteristics.

There is not much information available about the accuracy of these shunting robots; however an article by one of the shunting robot's developers provides a measured minimum speed of 0.05 meters per second (Vollert, 2011). Based on these values, a variance of 0.005 meters per second is assumed which is likely by EMO dry-bulk terminal. Since the calculated loading time is based on maximum loading values, it is the minimum loading time. With a variance of 0.005 meters per second, the loading time varies between 139.3 and 156.8 seconds with a mean of 148.05 seconds. Due to the fact that there is a clear minimum and a standard variance is assumed, a triangular distribution is chosen to represent the loading time in the FlexSim model.

Another aspect that cannot be neglected is the required time for loading the weighing bunker, which takes bases on available data about 10 seconds. The filling of the weighing bunker is done in the intervals between the actual loading process of the wagons. Since these intervals are between 55.5

and 73.0 seconds, the loading of the weighing bunker has only effect on the first wagon to load. The value is rather small and therefore a constant value of 10 seconds is assumed and represented by a processor.

The load-out is represented in the FlexSim model by two queues, a processor and a combiner. By assuming the combiner length as the length of a single wagon, the process time is equal to the loading time of a single wagon. The queues, processor and the combiner for WB3 and WB4 have the following specifics:

- **Queue 1**
    - max load: 300 tonnes[7] (600 packages)
- **Processor 1**
    - Process time: 10 seconds
    - Capacity: 128 packages
- **Queue 2**
    - max load: 64.0 tonnes (128 packages)
- **Combiner**
    - Process time: triangular distribution (min. 139.3 seconds, max. 156.8 seconds, mean 148.05 seconds)
    - Combination of 1 *flowitem* “coal wagon” and 128 packages of coal
    - Length: 12.54 meter, width: 5 meter

Iron ore load-out WB1

Iron ore load-out WB1 has a different design than the coal load-outs WB3 and WB4. Therefore it is necessary to determine the loading capacity for this specific design. Load-out WB1 is different from WB3 and WB4 since it has two loading shafts and loads both compartments of the wagon at the same time, which results in a shorter loading time. However this only affects the method that the loading time is approached for each compartment and therefore the approach is not explained in detail.

The loading capacity of load-out WB1 is 3600 tonnes per hour, which is 1 ton per second. Loading one compartment of a Faals[151] iron ore wagon, with half of the loading openings length, takes 49.25 seconds. Each of the loading shafts has a width of 2.04 meters, which results in an actual distance travelled during loading process of 4.34 meters. This results in a maximum wagon speed of 0.09 meters per second and a minimum travel time per wagon underneath the load-out of 167.2 seconds. Assuming the same shunting robot and thus same variance in speed, the maximum travel time is 188.1 seconds and a mean of 177.65 seconds.

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[7] Based on article of Klein Gunnewiek, 2008

The objects representing load-out WB1 have the following specifics:

- **Queue 1**
    - max load: 300 tonnes[8] (600 packages)
- **Processor**
    - Process time: 10 seconds
    - Capacity: 197 packages
- **Queue 2**
    - max load: 98.5 tonnes (197 packages)
- **Combiner**
    - Process time: triangular distribution (min. 167.2 seconds, max. 188.1 seconds, mean 177.65 seconds)
    - Setup time: 0 seconds
    - Combination of 1 *flowitem* “coal wagon” and 197 packages of coal

Train track

Train track is included in the model for providing a continuous input of wagons in the load-out and for visual monitoring of the functioning of the model, however does not have any effect on the results. The train track is represented by a conveyor system (figure 4.5). The width of the conveyor is set to the width of the *flowitem* representing the wagon; 3.14 meters.

Belt conveyors

The belt conveyor system is the system of connected belt conveyors transporting the products from the stacker/reclaimer combination to the load-outs. All belt conveyors have generally the same specifications, operate at a constant speed and have a higher capacity than the maximum demand of the load-out. In practice the conveyor system is started up after the first wagon is located at the load-out. This is done in order to prevent that the conveyor system must be shut down in situations where the wagon is not yet available for loading. Based on this, the continuous running of the system and for simplicity reasons, the acceleration and deceleration of the conveyor system are neglected. The belt conveyors at the terminal have a width of 1800 millimetre and a speed of 4.5 meters per second. Lengths of the different parts of the conveyor system are measured in Google Earth.

Throughput

The throughput of the belt conveyor system depends on the demand of the load-out, which is regulated at the input provided by the stacker/reclaimer combination. This throughput can be regulated accurately and is tuned so the loading process at the load-out is not interrupted. Since the model works with packages, the spacing distance should be tuned to the throughput required for the minimum loading time per wagon. In the model this may cause for a full storage bunker when loading the last wagons of the train, however this does not affect the results since acceleration and deceleration are not taken into account. In practice the input of the conveyor system would be reduced.

The required amount of coal per wagon is 64.0 tonnes and the minimum loading time is 139.3 seconds per wagon, but minus 10 seconds for the process time of the loading of the weighing bunker. This means that the belt conveyor system has to supply at least 0.495 tonnes per second. With a speed of 4.5 meters per second, the required minimum spacing distance between coal packages of 0.5 tonnes is rounded down 4.54 meters. Rounded down is required to ensure the required throughput.

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[8] Based on article of Klein Gunnewiek, 2008

The spacing distance for iron ore wagons is different due to a different required throughput. With a loading capacity of 98.5 tonnes, a minimum loading time of 167.2 seconds and 10 seconds process time, the supply needs to be 0.627 tonnes per second. This leads to spacing distance of rounded down 3.58 meters.

Conveyor length

The total length the packages have to travel along the conveyor system to the load-out is dependent on which stack at which stock yard is being reclaimed. Once the system is running continuously, after the first wagon is loaded, the length has no influence on the total loading time. However the conveyor system is only started up when the first wagon is located at the load-out, which affects in a start-up delay for the loading of the first wagon.

To represent this start up time, due to the length difference, a processor with a setup-time distribution is added to the model. Since the minimum and maximum length of the conveyor is clear and the start- and end-position of the stacker/reclaimer combination is neglected, a triangular distribution is chosen to represent this start-up time. Due to the synchronous simulation of the model, the model cannot represent negative values (cannot go back in time). This means that in the model represents the minimum length of belt conveyors in order to ensure a positive time delay. In the model the belt conveyors are named by which part of the terminal it grants access: load-out conveyor, stock-yard conveyor, stack conveyor and reclaimer conveyor. Using different routes leads to a difference in length of the stock yard conveyor and the stack conveyor; the other two are always used over its total length.

Table 4.5: Conveyor lengths per load-out in meters

	WB1	WB3	WB4
Shortest length to stacker/reclaimer combination	260	1000	790
Lengths to other stock yards	100, 200, 300, 335, 400	170, 340, 350, 450, 550	115, 215, 270, 315, 415, 515
Variable distance along stock yards	1200	1200	1200
Reclaimer conveyor length	50	50	50
Minimum length	310	1050	840
Maximum length	1910	2800	2555
Difference	1600	1750	1715
Difference in time*	355.6 s.	388.9 s.	381.1 s.

*: in seconds and based on the conveyor speed of 4.5 seconds

Load-out WB4

The difference in length of the conveyor system is 1715 meters. Since the conveyor system has a speed of 4.5 meters per second, the start-up time varies between 0 and 381.1 seconds and has a mean of 190.55 seconds. The time delay should only affect the first package, after that the flow of packages is continuous. In order not to affect the continuous running of the model, time delay is set to different setup time for a number of items which is larger than the amount of packages loaded per train. The process time of the conveyor is chosen so it does not affect the required throughput of the system, which is already regulated by the spacing distance of the belt conveyors.

The processor for the start-up delay for WB4 has the following characteristics:

- Setup time: *Different time* ***for*** *Nth item* [N = 6000, time Nth item = triangular distribution (min. 0 seconds, max. 381.1 seconds, average 190.55 seconds), time other = 0, start = 1]
- Process time: 0.2
- Maximum capacity: 1 package

The start-up delay of the conveyor systems of the other load-outs are approached in the same way and only differ in the setup-time. The setup-time for load-out WB1 and WB3 are:

- **Load-out WB1**
    - Setup time: *Different time* ***for*** *Nth item* [N = 8000, time Nth item = triangular distribution (min. 0 seconds, max. 355.6 seconds, average 177.8 seconds), time other = 0, start = 1]
- **Load-out WB3**
    - Setup time: *Different time* ***for*** *Nth item* [N = 6000, time Nth item = triangular distribution (min. 0 seconds, max. 388.9 seconds, average 194.45 seconds), time other = 0, start = 1]

The belt conveyor system in the FlexSim model:

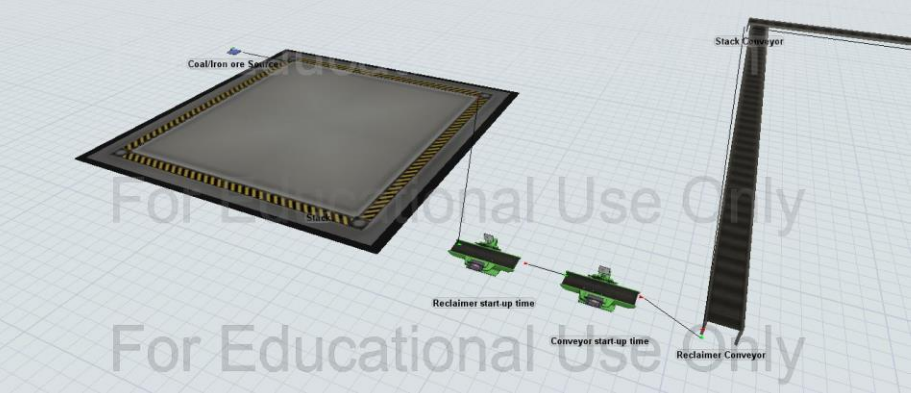

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Figure 4.6: Representation of the stacker/reclaimer combination and conveyor system setup-time delays by processors in the FlexSim model

Stacker/Reclaimer combination

The function of the stacker/reclaimer combination in the model is to reclaim the stacks and load it onto the conveyor system. Some assumptions about modelling the stacker/reclaimer combination are already defined: the start- and end-position is neglected, available at all time and each stack can be reached and used for coal or iron ore with an unlimited supply. Each stacker/reclaimer combination travels by its own tracks along the stock yards not influenced by other stacker/reclaimer combinations. Different types of stacker/reclaimer combinations are used at the EMO dry-bulk terminal, but are generally the same and meet the demand of the load-out. The specifications of the representative stacker/reclaimer combination KB6 are:

- Reclaiming capacity (for coal and iron ore) nominal: 3875 tonnes per hour
- Reclaiming capacity (for coal and iron ore) maximal: 4500 tonnes per hour
- Travel speed: 3-30 meter/minute

In practice the stacker/reclaimer combination is also used for stacking and reclaiming for ship loading. The stacker/reclaimer combinations can move up to 1200 meters along the stock yards and has a reach of 50 meters with a maximal speed of 0.5 meters per second. This means that, when travelling at maximum speed, it can take between 0 and 2400 seconds to locate the stacker/reclaimer combination to its position dependent on which stack is being reclaimed. Keeping the assumptions in mind, the positioning of the stacker/reclaimer combination can be represented by a start-up time delay for a random start-position.

However in practice the process of positioning the stacker/reclaimer combination can already start at the time a train is assigned an arrival track. This assigning is normally done at the time the train is ready to depart the railway yard and the terminal's control centre grants permission to enter the tracks to the terminal. Therefore the start-up time delay can be reduced by the time interval from the train departing the railway yard to the first wagon being available for loading at the load-out.

In order to determine this time interval, information is required from the simulation of the train traffic at the terminal. Since the models communicate offline, a non-variable and representative value for this interval has to be assumed. This can be done by analysing this interval during simulation in the OpenTrack model. During this interval the train travels from the railway yard to the terminal, where the shunting locomotive is uncoupled, the EMO shunting robot is coupled and the train is positioned at the load-out. For the coupling and uncoupling in OpenTrack, reference values of 3 minutes are used. Analysing the data of random runs in OpenTrack provides an average of 12 and 5 minutes for the travelling to the terminal and locating the first wagon respectively. The total interval time is 23 minutes.

Since different locomotives are used for travelling to the terminal and the distance towards the load-out can differ, these values are rather inaccurate compared to the rest of the model. Unfortunately this is where the offline communication (one-way) meets its limits, since a general representation of these intervals and thereby a simplification is required. Despite the inaccuracy, it is assumed that these values are usable for the model.

The start-up time delay is represented by a distribution, but needs to take the interval time into account. A clear minimum and maximum is known and therefore a triangular distribution combined with the interval reduction seems to be the most suitable. In theory this would not be correct since negative values would incorrectly reduce the total loading time. However, the model in run synchronously (i.e. cannot go back in time) and therefore all negative values become zero and are applied correctly.

The maximum capacity and process time of the processor was chosen so it does not influence other processes in the chain process. The stacker/reclaimer combination start-up time delay is represented by a processor with the following characteristics and is for all three load-outs the same:

- Setup time: *Different time **for** Nth item* [N = 8000, time Nth item = triangular distribution (min. -1380 seconds, max. +1020 seconds, mean -180 seconds), time other = 0, start = 1]
- Process time: 0.2 seconds
- Max. capacity: 1 package

Export data

To be able to determine a distribution for the total loading time, the FlexSim model has to export data related to the loading time of the wagons. The combiner exports the start- and finish-time for every wagon to a table in FlexSim, which can be exported to Excel. From this data the loading times for the relevant number of wagons can be determined. By running different streams, a dataset of different loading times for a certain number of wagons can be created.

Also the correct working of the model as a continuous process can be checked by analysing the start- and the finish-times per wagon. Since the wagons are coupled, the finish-time of loading a wagon should be equal to start-time of the next wagon.

The loading times are composed of triangular distributions and constant values. Since there is a clear minimum and maximum at every triangular distribution, the theoretical minimum and maximum loading time can be determined. In the following tables the approach of the minimum and maximum times is described.

Table 4.6: Approach of minimum and maximum values for total loading time in seconds

	WB1		**WB3**		**WB4**	
	Min.	Max.	Min.	Max.	Min.	Max.
Start-up time Reclaimer	0	1020	0	1020	0	1020
Start-up time conveyor variance	0	355.6	0	388.9	0	381.1
Start-up time conveyor constant	68.9	68.9	233.3	233.3	186.7	186.7
Process time bunkers	10	10	10	10	10	10
Loading first load	157.1	157.1	129.3	129.3	129.3	129.3
Loading time per wagon	167.2	188.1	139.3	156.8	139.3	156.8

Table 4.7: Minimum and maximum values for total loading time for relevant amount of wagons in seconds

	WB1		**WB3**		**WB4**			
Number of wagons	38	36	44	40	44	40	39	32
Min. Time for loading	6589.6	6255.2	6501.8	5944.6	6455.2	5898.0	5758.7	4783.6
Max. time for loading	8759.4	8383.2	8680.7	8053.5	8626.3	7999.1	7842.3	6744.7

Verification

Multiple test-runs are performed with the terminal model for verification. Some minor adaptations and recalculations were necessary, but eventually led to the presented model. Validation of the model is presented in chapter 4.2.5 *Validation*.

4.2.3 Combination interface (loading times)

The goal of the combination interface is to exchange data between the two simulation models by offline-communication. Raw data from the simulation runs needs to be processed and checked before it can be transformed into a distribution. In the case of offline-communication a spreadsheet application is sufficient for these tasks, since it is less complex and requires no programming skills.

This chapter goes into the combination interface set-up specifically for this case study: the exchange of loading times at a terminal. The steps taken in setting up the interface are discussed in short: the scope, processing raw data and first wagon check, distribution approach and amount of runs.

Scope

The scope of the combination interface is limited to the processing of the raw FlexSim data into loading time distributions. Scopes and assumptions of the FlexSim and OpenTrack model also apply to the combination interface and affect the structure of the combination interface. For instance the assumption that the loading processes at the load-outs are not dependent on each other, due to the assumptions made in the FlexSim model, decides that the loading time of each load-out is determined separately and can be represented by a single distribution.

Processing of data and first wagon check

The first step is to sort the data in order to simplify the processing of the data in the next steps, each load-out processed in a separate Excel-file. Per wagon in the first column the start time and in the second column the finish time of the loading process is presented.

In order to check the correctness of the FlexSim model, the data can be checked by comparing the finish and start times of succeeding wagons. Since the wagons are coupled, these times should be the same. If these times are not the same, the throughput at the conveyor system is not correct. This can be checked for every succeeding wagon, however the throughput is tuned to the shortest loading time and therefore only the first couple of wagons need to be checked. If the first wagons are correct for a large number of random runs, it is assumed that the throughput is correct for the load-out and the wagons succeed without an interval. A simple formula is used to check these quickly for the first wagons; the throughputs of the FlexSim models seem to be correct.

After the start and finish times are checked, the finish times of the relevant amounts of wagons are selected and sorted from low to high. The relevant amounts of wagons are:

- WB1: 38 wagons
- WB3: 44 wagons
- WB4: 40 wagons and 32 wagons

Distribution approach

From the processed data a distribution for the total loading times is determined and used as input for the OpenTrack model. Since the loading times are composed of multiple different triangular distributions and constants, especially the partially negative but synchronously modelled distribution, it cannot be represented by a standard distribution.

An empirical approach gives a step-wise function and a most direct representation of the data, however requires a large dataset and is complex to import all values in OpenTrack. A suitable alternative is a Kernel Density Estimation, which approximates a smooth line between the data-points and allows the user to input a minimum, maximum and number points to calculate. This provides the opportunity to choose a step size when importing the distribution into OpenTrack.

The Kernel Density Estimation can be determined quickly in Excel by using the Kernel add-in developed by the Royal Society of Chemistry (Royal Society of Chemistry, 2015). To check if this approach is correct, the Kernel Density Estimation is visually compared to the Empirical approach for every load-out and relevant amount of wagons. As can be seen in figure 4.7, the Kernel Density Estimation fits the Empirical approach well and the approach is assumed to be correct.

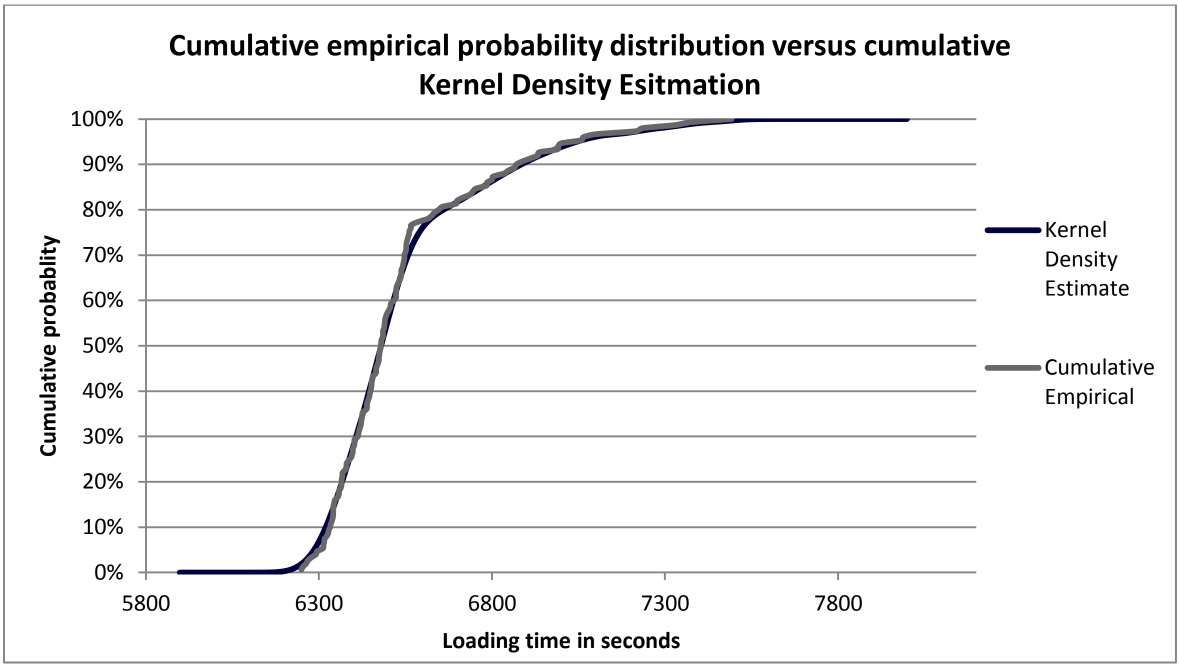

Figure 4.7: Cumulative Empirical versus Kernel Density Estimation for WB4 with 40 wagons

A minor deviation and angle can be observed around 75 percent, which is presumed to be related to the positioning time of the stacker/reclaimer combination. This positioning time is in most cases zero, but can be rather large in other cases. Since the deviation is rather small, it is assumed that the Kernel Density Estimation fits the distribution correctly.

Amount of runs

Since the Kernel Density Estimation uses the FlexSim data to determine a representative distribution, a minimum sample size is required for a correct representation. The minimum sample size can be checked by comparing results for the Kernel Density Estimations with different sample sizes and determining an allowed deviation. Tests were performed with sample sizes of 120 and 150 random runs. When comparing the distributions of different sample sizes, deviations are observed related to the deviation seen in the comparison between the Kernel Density Estimation and Empirical approach (figure 4.7).

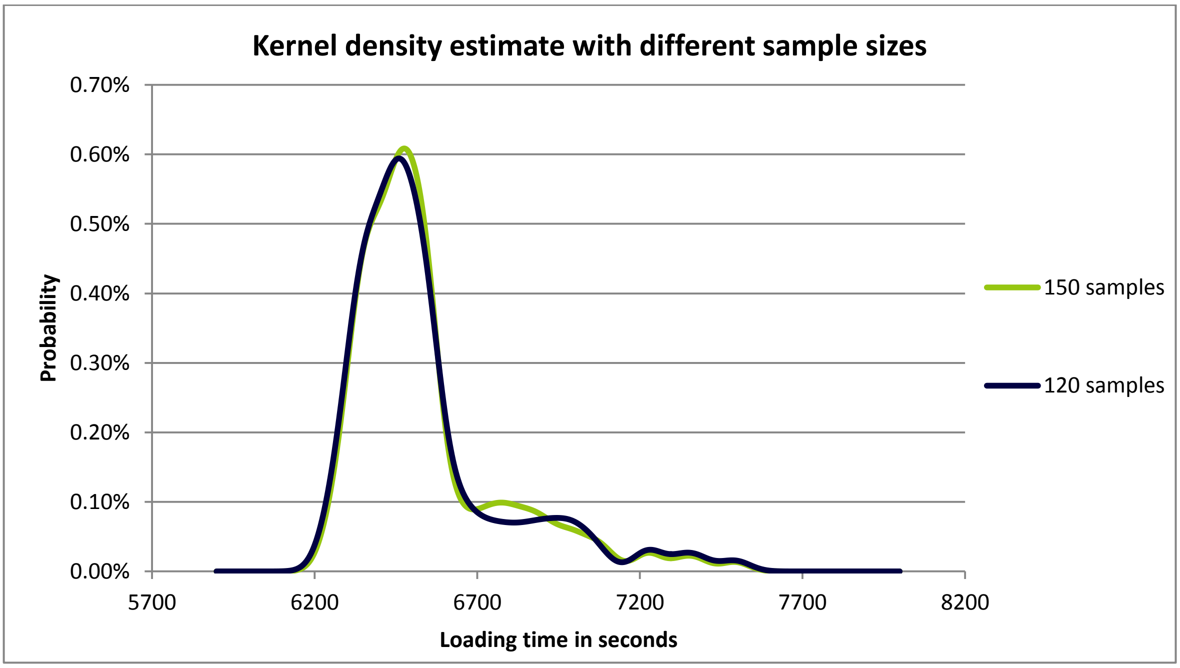

Figure 4.8: Kernel Density Estimation for WB4 and 40 wagons, based on 150 and 120 samples

To analyse the effects for the input data of OpenTrack, the sample sizes are compared for the step size of the OpenTrack input data. In consultation with OpenTrack expert D. Koopman engineer at RoyalHaskoningDHV a step size is chosen of four percent based on the goal and characteristics of the simulation. The Kernel Density Estimation determines the probability for a certain amount of points; in this case 1000 points are determined. To determine the input distribution for OpenTrack, the point nearest to the optimal step size are used. This sometimes leads to a slightly larger or smaller step size, but has limited effects to the simulation and is therefore accepted.

The analysis between the sample sizes with the OpenTrack step size provided a maximal difference of 1.1 percent on the loading times between 120 and 150 runs. Therefore it is assumed that the amount of 150 runs is acceptable for the FlexSim model in this case study; more runs will not give a substantial difference in accuracy. If a larger step size is required, it is better to decrease the step size for the input in OpenTrack.

4.2.4 Infrastructure operations model (OpenTrack)

The goal of the OpenTrack model is to recreate the infrastructure on a terminal and its connection in order to observe the combination of train traffic and the loading process with focus on dynamic loading time. The microscopic model consists of the infrastructure and traffic at the EMO dry-bulk terminal, Maasvlakte East railway yard and a part of the Port Railway Line. First the chapter describes the scope and assumptions, second the chapter goes into a detailed description of the set-up of the model.

Scope

The OpenTrack simulation model represents the rail infrastructure and its operations within the scope of the case study in order to simulate all the processes in the chain process involving train behaviour. It focuses on the effects on the loading capacity of the terminal due to a variable loading time and infrastructure restrictions. Since the case study is observed for normal conditions, malfunctioning of rolling stock or infrastructure is not taken into account. The physical boundaries of the model include the terminal, private sidings, the Maasvlakte East railway yard and a part of the Port Railway Line. In order not to include other irrelevant processes the Port Railway Line is taken into account from the Maasvlakte East railway yard to the next railway yard in both directions. Because the focus of the model is to measure the effects of the variable loading time at the EMO dry-bulk terminal, other trains travelling at the Port Railway Line are not taken into account.

Assumptions

General assumptions related to the scope and total case study are briefly discussed in this chapter, other assumptions directly related to parts of the model are discussed later on. The general assumptions made are:

- The model represents operation on a normal Wednesday under normal operational and weather conditions, malfunctioning of parts are neglected
- The chain process of the loading of coal and iron ore trains is not affected by other trains; therefore these do not have to be modelled
- The arrival of trains is assumed right on time, waiting times for early arrivals are neglected
- The load-outs at the terminal are assumed to be available at all time for the loading of trains, therefore trains only have to wait at the railway yard for the availability of the track underneath the load-out

Simulation

The simulation is run with 200 random runs and from 02:00 till 04:20 the next day. This time-window is chosen in order to represent the total train services at a normal Wednesday. Advised by OpenTrack expert D. Koopman based on his experience, the preferred minimal amount of samples is 300 to receive accurate results. However, OpenTrack is limited to 200 random runs and in order to gain more runs, multiple days have to be simulated. Since this case study focuses on proving that a combination of models can provide insight into interaction between operations and not on the accuracy of interaction, the limited amount of runs is accepted but taken into account when observing the results.

Overview of the model

The required proceedings, assumptions and data to set up the model are explained by the following steps: Infrastructure, Rolling stock, Routes, paths and itineraries, Courses/Services and timetable, Distributions and Test-run validation. Other basic steps that are required for setting up a model in OpenTrack but are not related to the case study are not elaborated. The main infrastructure components are: EMO dry-bulk terminal, private sidings, the Maasvlakte East railway yard and a part of the Port Railway Line.

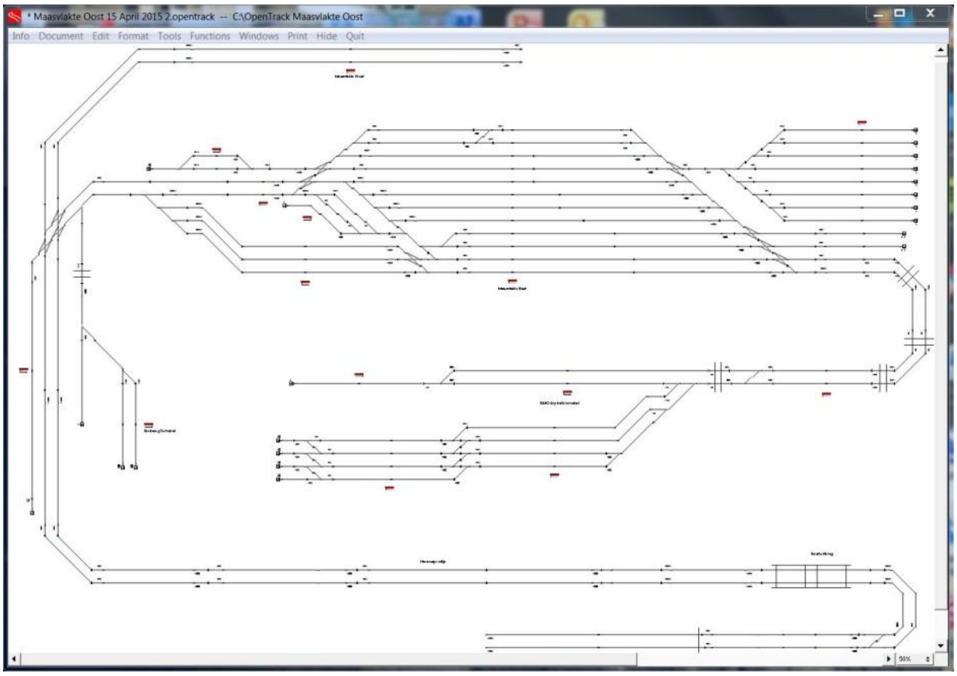
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Figure 4.9: OpenTrack model of the Maasvlakte East railway yard and the EMO dry-bulk terminal

Infrastructure

In order to set-up an OpenTrack model, all infrastructure located in the scope of the case study must be drawn and its characteristics defined. Based on this infrastructure operations can be defined and simulations can be performed. The main parts of the infrastructure for this case study are discussed: layout, train protection system, stations and crossings. Figure 4.9 provides an impression of the infrastructure of the OpenTrack model.

Layout

The layout in OpenTrack is created with nodes and links, called edges, in colon graph and link-orientated[9]. Characteristics and measurements of all physical track elements are provided by the OBE-drawings[10] of ProRail, accessible by RoyalHaskoningDHV. The OBE-drawings provide the location and some characteristics of track elements with an accuracy of one meter. These elements are for instance the length, slopes and maximum speeds of edges, type of (insulated) joints and signals. However, the OBE-drawings normally cover only the infrastructure which is property of ProRail; most private sidings and terminal tracks are not included in the drawings. In the scope of the case study parts of the infrastructure are private sidings or terminal tracks and are not included in the OBE-drawings. Therefore the measurements of the private sidings and the EMO terminal were measured in Google Earth, when done precisely the track elements can be measured with an accuracy of also one meter.

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[9] More information about colon graph: *Railway Timetable & Traffic,* page 45-46 (Radtke, 2009)

[10] OBE-drawings are up-to-date design drawings of the Dutch railway infrastructure managed by ProRail.

The layout of the tracks is a schematic representation of the tracks at the EMO dry-bulk terminal, Maasvlakte East railway yard and the Port Railway Line. In order to create practical working conditions the track alignment was fitted into a single screen. For instance in figure 4.9 the top is in reality the West and not all curves are actually curves in reality. Lengths of elements in the model are kept in ratio as much as possible and angles are kept at 45 degrees. Based on the scope the tracks at the container terminal of the Kramer Group are not taken into account, the Steinweg steel terminal is included in the model but not part of the scope. Instead of modelling the whole Maasvlakte West railway yard, only two tracks are added to be able to simulate traffic but exclude complex irrelevant processes. At the boundary of the scope at the Port Railway Line, two sections are added where trains can enter and leave the model.

The OBE-drawings provide the maximum speed at each section; 80 kilometres per hour at the Port Railway Line and 40 kilometres per hour at the Maasvlakte East railway yard. In the drawings also a restriction is added for the private sidings towards the terminal of 30 kilometres per hour while riding on sight. However in practice the train normally travels at a lower speed since it is rather long and heavy, is pushed onto the terminal while being controlled from the first wagon and also requires stopping at a manual crossing. Therefore the maximum speed of the private sidings is set to 20 kilometres per hour and the terminal’s maximum speed to ten kilometres per hour.

Train protection system

After the track layout, the train protection system is added to the infrastructure in order to control the traffic in the model as in reality. The Port Railway Line and Maasvlakte East railway yard are operated by ERTMS level 1 (Keyrail, 2013), the private sidings and terminal traffic is controlled by the terminal’s control centre. At the private tracks/terminal infrastructure no signalling system is used and is operated on sight. However in order to recreate realistic train traffic, OpenTrack requires to use virtual signals to be able to control operations and create general routes at the terminal and private sidings. These virtual signals are mainly positioned around switches in order to create sections as long as possible. Required for shunting movements, some signals provide the opportunity to enter an occupied block. Virtual signals are also applied to the locomotive and wagon storage locations at the Maasvlakte East, which are also uncontrolled and operated on sight in reality.

The ERTMS Level 1 signalling system at the Port Railway Line uses balises for communication from the traffic operator to the train. Due to the fact that the model is only used to simulate normal conditions, trains travel the Port Railway Line only at the right-hand side. Therefore the model is simplified by implementing only the balises in the relevant travelling direction without influencing the results. Since OpenTrack already communicates with the train at signals, balises at signal positions are also neglected.

Stations

In order to set up a timetable between locations, stations and their station areas have to be defined in the model. Since the model represents freight traffic and shunting operations without real stations, the location of stations must be chosen based on operational and timetable requirements. The main locations for stations are the Maasvlakte East and the EMO dry-bulk terminal.

At the Maasvlakte East a distinction is made between tracks for arrival and departure of trains and tracks for the storage of wagons and locomotives, each combination of tracks set as a station. The EMO dry-bulk terminal has separate stations for the coal and iron ore load-outs and for each has an arrival/departure and loading track. Besides these logical locations, also stations were located on at the boundaries of the model and around the railway yard for shunting movements.

Crossings

The infrastructure within the scope of the case study contains five crossings, all located at private sidings connected to the Maasvlakte East. In the case study two types of crossings can be identified; crossings with automatic or manual warning lights. Engineer J. Bos of RoyalHaskoningDHV, an expert in the field of crossing protection systems, advised on how to simulate these in OpenTrack based on their application in reality. Due to low speeds and low intensity of traffic at the crossing, the automatic controlled crossings do not affect operations and are implemented as normal automated crossings. The manual controlled crossing requires train drivers to leave the train and press a button to close the crossing. This process was implemented by setting all routes over the crossing with a reservation time of 20 seconds and a reservation distance at five meters.

Rolling stock

OpenTrack requires for simulating traffic a database of engines and compositions of trains. RoyalHaskoningDHV provided an engine database of all engines and their characteristics currently active at the Dutch railway system. Besides the database, the EMO dry-bulk terminal has shunting robots operational as traction during the loading process.

At the EMO dry-bulk terminal four shunting robots are in service, all with different types and characteristics. Characteristic data of these shunting robots is limited, therefore one of the robots is chosen as representative. Two types of shunting robots, the Vollert DR300 and Bemo BRD300, are quite similar and the OpenTrack engine is based on these. The shunting robot was added to the database based on its characteristics; weight of 130 tonnes, traction force of 300 kilo newton and a representative speed-traction diagram made in consultation with an OpenTrack expert of RoyalHaskoningDHV.

In order to set-up courses for the simulation, the compositions of trains have to be defined. The relevant train compositions travelling to the EMO dry-bulk terminal have different compositions, but have many similarities. Since also the FlexSim model assumes representative types of wagons, representative compositions of trains are assumed with these types of models. The models and their characteristics can be found in the set-up of the FlexSim model and in table 4.2.

Four representative train compositions can be identified in train traffic under normal conditions at the terminal and the railway yard, generally categorized by the type of product and transport operator. Due to shunting movements and connections of trains, it is required to assign also trains only consisting of shunting locomotives and trains without engines and only consisting of trailers. The trailers arrive in the model empty and a difference in load is added at the terminal during the loading process.

The four representative train compositions are:

- DB Schenker: iron ore train with two BR189 locomotives and 38 Faals-wagons
- DB Schenker: coal train with two BR189 locomotives and 44 Falns-wagons
- RheinCargo: coal train with one Class66 locomotive and 40 Falns-wagons
- Captrain: coal train with a single BR189 locomotive and 32 Fals-wagons

The shunting locomotives are:

- Multiple combinations of two DE6400 locomotives for DB Schenker trains
- A single V100 locomotive for Captrain trains
- Four single EMO shunting robots for shunting wagon sets at the terminal

Routes, paths and itineraries

Before a train can travel from one station to another in OpenTrack, the total set of its movements has to be defined in an itinerary. These itineraries are composed of a set of paths or shunting moves, paths are composed of a set of routes which are assigned from one signal to the next. All relevant routes, shunting moves, paths and itineraries for the traffic at the Port Railway Line, the railway yard and the terminal are set in the model.

In freight traffic variances in arrival and departure times can be observed and handling of daily operations varies more compared to passenger traffic. These variances lead to different arrival and departure tracks, but also in the routes of shunting locomotives. This case study observes the operations under normal operations and for different loading times, however due to these variances representable routes cannot be determined and an assumption for the routes in normal operations is required.

OpenTrack provides the possibility to set-up alternative itineraries, however the large variance in loading time and other train movements require a very large number of alternative itineraries; one for each possible loading time. This is underpinned by the fact that shunting moves require intervention by assigning a different route when a train arrives at another track. Since offline communication does not allow intervention during the simulation, each train service is represented by a single set of succeeding itineraries applicable to all possible loading times.

In reality the shunting locomotives at the Maasvlakte East railway yard handle several trains per day and thereby their itineraries should be related. However due to the variety in loading times these itineraries of different train services can overlap, which means that in some cases the shunting locomotive is not yet available for the itinerary of next train service. Since intervention during the simulation is not possible, it is assumed that a train service can be represented by a single set of itineraries which is only used for this specific train service and that there is an unlimited supply of shunting locomotives available. The effects of these assumptions are limited, because test-runs show that these overlaps do not occur often and overlaps only occur for a short time. Since in reality extra shunting locomotives are available at the railway yard, used in case of malfunctioning locomotives, it is assumed that these effects can be neglected. This assumption is also applied to the EMO shunting robot.

The amount of tracks at the railway yard and the train schedule allows to assign each train composition an own arrival and departure track and thereby ensures the suitability of the itineraries with the variance in loading time. In this way other processes are influences as less as possible, which is compliant with reality as trains are routed over the tracks which are available at the railway yard at that specific time.

The representative train compositions have each a set of itineraries representing the total chain process it follows through the model. For shunting moves and connections, several routes allow entry in occupied sections. Route reservation times are set to nine seconds for sections involving switches and to zero for sections without switches, which is normal values for the Dutch railway system. All route release times are set to three seconds. Besides the manual crossing explained at Layout, another exception is the arrival in the train protected area.

Courses/Services and timetable

After the itineraries are defined in the model, the next step to set-up representative traffic is to define courses/services and a timetable. Courses/services combine a certain train compositions with an itinerary and a timetable in order to plan operations.

In this case study multiple courses are necessary to describe a single train service due to connections for shunting moves. Connections are used for joining and splitting of trains, but also allow trains to wait for arriving, passing or departing trains. A set of courses representing a train service is identified by its train number; the set of courses all have the same trailer-set but different locomotives providing traction to the train service. The train services for the case study can be found in table 4.8, which is based on average terminal data of a normal Wednesday in April 2015.

Table 4.8: Train services at EMO dry-bulk terminal for a normal Wednesday in April 2015

Train number	**Product**	**Transport operator**	**Loading block** Start	End	**Amount of wagons**	**Traction**
49507	Coal	Captrain	13:40	16:40	32	BR189
47709	Coal	RheinCargo	20:30	23:30	40	Class66
49505	Coal	RheinCargo	6:50	9:50	40	Class66
49525	Coal	RheinCargo	10:15	13:15	40	Class66
48701	Coal	DB Schenker	13:40	16:40	44	2x BR189
48729	Coal	DB Schenker	03:25	06:25	44	2x BR189
48745	Coal	DB Schenker	17:05	20:05	44	2x BR189
48711	Iron Ore	DB Schenker	20:00	23:30	38	2x BR189
48713	Iron Ore	DB Schenker	0:00	3:30	38	2x BR189
48715	Iron Ore	DB Schenker	4:00	7:30	38	2x BR189
48717	Iron Ore	DB Schenker	8:00	11:30	38	2x BR189
48719	Iron Ore	DB Schenker	12:00	15:30	38	2x BR189
48721	Iron Ore	DB Schenker	16:00	19:30	38	2x BR189

Since each train-service requires different shunting movements, the total process of the arrival, shunting, loading and departure of a coal or iron ore train requires multiple courses. For instance OpenTrack advises in the case of uncoupling one locomotive and coupling another, to use a new course for representing the new train. In some cases this was necessary for connecting the coupled locomotive at the right side of the train as trains are pushed onto the terminal.

In general the traction of the train is determinative for the amount of shunting movements, because the non-electrified private sidings from the railway yard to the terminal require diesel-powered traction. Trains with BR189 traction, an electrical-powered locomotive, require an extra switch at the railway yard compared to trains with Class66 traction, which is a diesel-powered locomotive. In this case study trains with BR189 traction require seven courses per train service, train with Class66 traction require four courses. Courses are set-up representing a realistic service made for trains within the scope, each with its own timetable tuned to the start of the loading block and succeeding courses for shunting purposes. The following two tables present a representative set of courses for a train service with BR189 and Class66 traction.

Table 4.9: Representative set of train courses for the train service with BR189 traction: iron ore train IO48715

Train courses	Movements
IO48715 Hvs - Mve	Movements from the main line to the railway yard
IO48715 Emo	Internal movement at the terminal during the loading process
IO48715 Emo –Mve	Movements from the terminal to the railway yard
IO48715 Emo Robot	Internal movements at the terminal for connecting purposes
IO48715 Mve – Emo	Movements from the railway yard to the terminal
IO48715 Mve – Hvs	Movements from the railway yard to the main line
IO48715 Shunt	Internal movements at the railway yard

Table 4.10: Representative set of train courses for the train service with Class66 traction: coal train C49505

Train courses	Movements
C49505 RC Hvs - Mve	Movements from the main line to the terminal and back again
C49505 RC Emo	Internal movement at the terminal during the loading process
C49505 RC Emo Robot	Internal movements at the terminal for connecting purposes
C49505 RC Emo Robot End	Internal movements at the terminal for disconnecting purposes

In the timetable the load difference after the loading of the wagons is added, as well as all required connections for coupling and uncoupling trains. Connections were also added for trains waiting during the variable loading process.

Distributions

Since OpenTrack only allows entering speeds in round numbers, the loading process must be implemented as a distribution for the station delay. A distribution is entered into the distributions menu as a piecewise linear function for each load-out and amount of wagons. The piecewise linear function represents the loading time distribution determined from the FlexSim data with a certain step size.

For the case study the distribution is applied to the station located at the load-out and a step size of four percent is used, more information about the step size can be found in the combination interface set-up. By defining in the timetable that a certain distribution has to be used at a station stop, its station delay is randomly chosen from the defined distribution. Implementing the loading time as a station delay, neglects the time costs from the positioning of the wagon underneath the load-out. Since this action is performed automatically at very low speeds, it is assumed that these effects can be neglected.

Verification

After the data exchange and set-up of the infrastructure operations model, the functioning and correctness of the model is checked by multiple test-run verifications. Observing simulation runs shows errors resulting in deadlocks of traffic for a substantial amount of random runs. The cause of these errors is found in interference of other trains during the connecting of two courses, which seemed to be rather sensitive to punctuality. Observations showed that these are caused in most cases by a train unintentionally entering an occupied track, which is caused by the required allowance of entering occupied track necessary for shunting operations at the terminal or railway yard.

These deadlocks mainly occur at two points in the model: the entrance of the EMO dry-bulk terminal and the entrance of the Maasvlakte East railway yard at the side of the Port Railway Line. In reality the rail operations these errors can occur due to malfunctioning of rolling stock, however these are not intended to be modelled in this case study as malfunctions are not part of the scope. In order to run the model for all random loading times, adaptations are required to solve these deadlocks.

The following six changes are made to several train services and infrastructure:

1. The arrival of train service C49505 of RheinCargo at the EMO dry-bulk terminal is modelled ten minutes earlier to avoid crossing, and thereby avoid interference with, joining trains of the IO48715 service at the iron ore tracks. This crossing led to a failed connection and eventually a deadlock at the entrance of the terminal. Observations revealed that this error only occurs at very short loading times of the IO48715. Effects of the changed arrival time are considered minimal due to a low intensity and interference with other trains in the original state of the model. From arrival data of the EMO dry-bulk terminal can be determined that these variations are normal for operations.

2. The arrival of train service C49525 of RheinCargo at the EMO dry-bulk terminal is modelled five minutes later for the same reasons as the C49505 service. Effects are also considered minimal.

3. The arrival of train service C49507 of Captrain at the EMO dry-bulk terminal is modelled five minutes later for the same reasons as the C49505 service, however it crosses the IO48717 and IO48719 service. Effects are also considered minimal.

4. The route of the observed crossing trains at the entrance of the EMO dry-bulk terminal is provided with a release time of 32 seconds. This release time is based on the length and the speed of the crossing trains. For almost all cases the crossing train now waits before entering the terminal and does not unintentionally enters an occupied track. This is consistent with behaviour in reality and therefore an accepted adaptation.

5. The storage of the BR189 locomotive of the Captrain service C49507 during the loading process is changed to a non-electrified track, which is not possible in reality. Using the non-electrified track was necessary due to required connections at the railway yard and station locations chosen earlier in the set-up of the model. Since its travel time is rather short, crosses a limited amount of other train services and its adapted route passes by the correct station before going to or coming from the non-electrified track, the effects of this change is assumed to be limited and acceptable.

6. The IO48715 is provided with a ten second station delay at the Maasvlakte East railway yard while making several shunt moves and crossing different trains. This is necessary for shunting locomotives crossing routes while being allowed to enter occupied tracks for connecting purposes. The effects of this adaptation are limited and therefore acceptable.

These adaptations have resulted in a decrease of random runs with errors. However still runs with errors are observed; four runs show complete deadlocks and eight runs show errors with the last train failing its connection. Resolving these errors require larger adaptations, while discarding these runs is assumed to lead to smaller effects. A reduction of the sample size by twelve does not influence the results much, as it does not reduces the preferred sample size for a train service under 300 random runs with the exception of the Captrain service.

4.2.5 Validation of models

Due to offline communication and observing the loading process under ideal conditions, it is incorrect to validate the model on available data. Therefore the model is validated based on reviews with experts in the field of rail freight transportations and dry-bulk terminals.

During the model set-up expert assistance was provided by RoyalHaskoningDHV and the assumptions and models were regularly reviewed and adapted. After the set-up the models and first results are discussed and the models were found sufficient representative when considering the goal of the research. Set-up of the terminal model was assisted by T. van de Sande MSc, Dry Bulk & Logistics consultant at RoyalHaskoningDHV. The set-up of the infrastructure model in OpenTrack was assisted by D. Koopman MSc, Advisor Rail at RoyalHaskoningDHV.

The model of the dry-bulk terminal, chain process and first test-results were discussed with D. Mooijman MSc, Business Analyst & Developer at the EMO dry-bulk terminal. In his opinion the model gives a fair representation of the loading process at the terminal and values of loading times are generally comparable with reality. A remark to the model is that the effect of the assumption that the load-outs can be modelled independently should not be underestimated. In reality the stacker/reclaimer combinations are also used for stacking processes and lead to large start-up delays for the loading process. However, improved operational information management also provides more accurate arrival data and provides the possibility to start the positioning of the stacker/reclaimer combination at an earlier time.

4.3 Offline versus real-time communication

The fact that the case study is performed with offline communication provides a limited picture of the applicability of the hypothesis of combining models. As described in the model set-up, several assumptions required for offline communication have distinct effects on the results and applicability of the created model. In order to provide a complete picture of the potential of combining transport simulation models, this chapter discusses a comparison between and applicability of offline and real-time communication while focussing on the case study and based on the lessons learned.

4.3.1 Comparison

Comparing the methods of communication provides insight in which method can be used for different goals. The main difference between offline and real-time communication is the limitation for offline communication that intervention during simulation is not possible. This means that all input data must be predefined into a single scenario and variables must be represented by a distribution or constant. Resulting in the limitation that dependencies between models are restricted to two. However, one dependency is preferred as two dependencies require an iterative process of running the two models, not knowing when and if an optimum is reached.

Since this iterative process is complex and not preferred, the best application of offline communication seems to be with a single dependency between models and for analysing a single parameter. Simulations with offline communication with the case study showed that tuning train operations with a variable loading time is difficult without intervention.

Real-time communication on the other hand provides the possibility to intervene during simulation. Therefore combined models with real-time communication can have multiple dependencies and approach reality with less simplifications and more detail. However, setting up these models is really complex, it requires high investments and actual benefits of real-time communication are not known.

4.3.2 Applicability of methods

The matter in which either communication method can be applied is determined by its restrictions and characteristics, but is most dependent on the goal of the research. As described earlier offline communication is restricted to its application, but is less complex and requires less investments like server-based software packages. Therefore combining models with offline communication is more suitable for some cases than real-time communication. However, these cases are restricted to independency of other processes in the transportation chain or cases where neglecting of this dependency is acceptable.

Looking at the applied case study, examples of applications of combined models with offline communication are:

- Analysis of effects of variances of a single parameter dependent on one model, such as loading times
- Analysing the effects of a certain scenario, such as malfunctioning of a wagon
- Static behaviour bottleneck analysis

Real-time communication can in theory be used for every application and in any requested detail. However, every research is bounded by available time and funding and therefore the models are bound to a certain level of detail. Examples of applications with real-time communication are:

- Analysis of dependencies between load-outs
- Capacity and stability analysis of a terminal or infrastructure
- Analysis of influences of multiple terminals or implementation of other processes at a terminal
- Analysis of resilience to random malfunctions (with intervention)
- Test short-time planning of infrastructure operations

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5 Case Study: Results and Conclusion

By analysing the results of the turn-around and loading times, possible influences of infrastructure operations at the loading times are tried to be measured. The models provide results for the loading time and turn-around times at certain locations in the infrastructure model. As the results focus on measuring any interference, most results are presented in seconds to provide also insight in small variations. This chapter discusses the loading time distributions, correctness data exchange and interference due to interaction of infrastructure operations. The chapter finalizes with a conclusion describing what these results mean for the case study.

5.1 Loading time distributions

This chapter discusses the determined loading time distributions by the combination interface from data of the FlexSim terminal model. The fact that the models are combined with offline communication is taken into account when analysing the results provided by the FlexSim terminal model and the combination interface. This paragraph discusses the results, correctness of the data exchange and provides a brief conclusion of the determined loading time distributions.

Results combination interface

The combination interface provides four probability distributions for the relevant amount of wagons at the three load-outs. How these distributions are determined is described in chapter 4.2.3 *Combination interface*. The distributions are determined for a normal Wednesday under normal conditions and are presented in figure 5.1 and table 5.1.

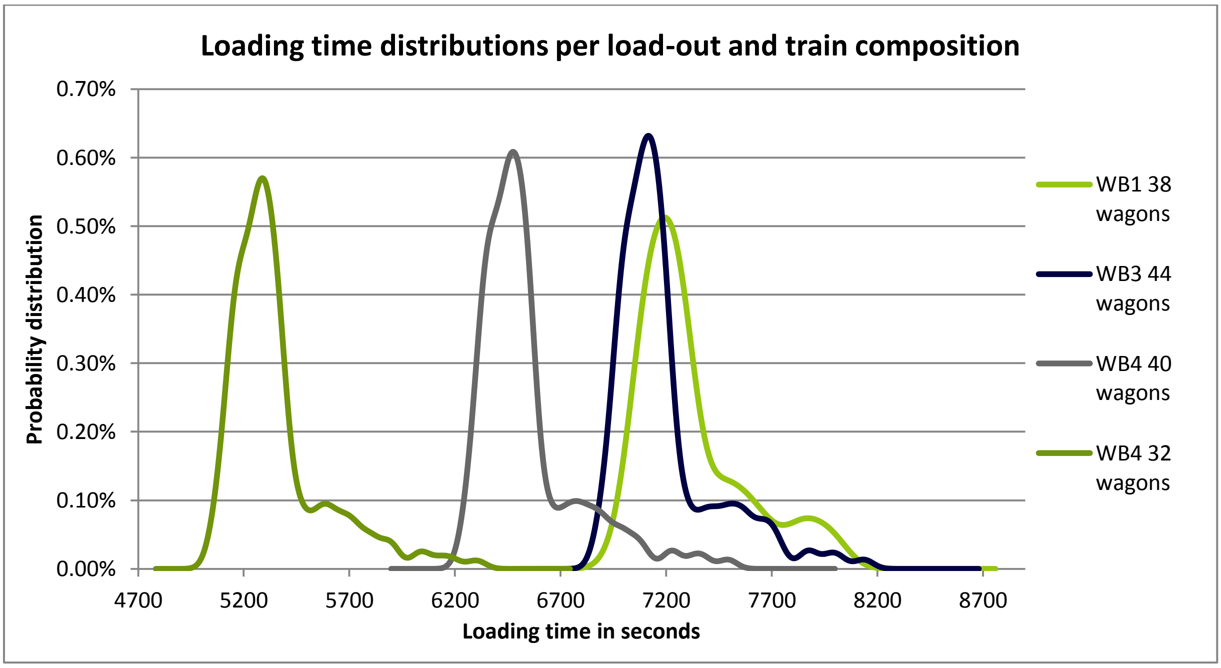

Figure 5.1: Probability distributions for the loading times of the relevant train compositions at the three load-outs

The total loading times vary between 1.3 and 2.4 hours for the different load-outs and train compositions and the medians of the different distributions are located near the peaks. All areas underneath the distributions represent 100%, but are different due to a different step size determined by the Kernel Density Estimation. This does not affect the results and is purely based on the dispersion width divided by the number of steps.

Table 5.1: Step size, minimum, median and maximum values of loading time distributions in seconds

	WB4 40	WB4 32	WB3 44	WB1 38
Step size	2.10	1.96	2.18	2.17
Minimum	5898	4784	6502	6590
Median	6481	5296	7128	7243
Maximum	7999	6745	8681	8759

From the graph can be determined that all four loading time probability distributions have generally the same shape, but are shifted to each other due to the difference in amount of wagons to load. The shape of the distributions can be divided in two characteristic parts; a large parabolic peak in the middle and a low declining slope at the right side of the peak. These shapes are consistent with the composition of the FlexSim terminal model and the characteristic parts of the distributions can be explained by the different parts of the terminal. The large peak is the result of the loading of the wagons; it is a summation of 32, 38, 40 or 44 identical triangular distributions and should approach a normal distributed shape. The low declining slope is the result of the start-up delays of the stacker/reclaimer combination and the conveyor system.

Besides the two characteristic parts also small turbulences can be observed, mainly in the declining slope of load-out WB3 and WB4. Comparing these with the distribution of load-out WB1, shows that the cause of the disturbances must he located in the different size of the input values as the rest of the models is generally the same. Therefore the disturbances are assumed to be caused by a combination of the start-up delays and distance to the nearest stack. It is likely that these disturbances are reduced when increasing the sample size of simulations with the FlexSim model.

Another characteristic for all four distributions is the distance between the theoretical and measured minimum and maximum. For instance, looking at the WB4 and 40 wagons distribution, a theoretical minimum of 5898 is observed, however based on the data the Kernel Density Estimation determines that 6104 still has a chance of 0.00% of occurring. This can be explained by the amount of distributions in FlexSim which influence the loading times at the terminal; 32 to 44 distributions for the loading per wagon and two additional distributions for the start-up delays of the conveyor system and positioning of the stacker/reclaimer combination. The chance that all wagons of a train are loaded at the theoretical minimum or maximum loading time, or values near the minimum or maximum, is extremely small. As in practice the speed and traction force of the EMO shunting robot varies much due to the increasing load during the loading process, this behaviour seems to be a correct representation of reality.

Correctness data exchange

To determine the correct data exchange between the models, results of the loading time in OpenTrack are compared to the original distribution determined in FlexSim. Results of the loading time in OpenTrack are summed per train composition and processed into a Kernel Density Estimation. These distributions are visually compared for their correct representation by plotting the distributions in the same graph. In the case of deviations, the deviations must be quantified in order to determine if these are acceptable or the representation of the loading time has to be improved. Visual comparison for this case study is presented for the worst fit of the loading time distributions determined in FlexSim and OpenTrack. The worst fit is train composition WB4 with 40 wagons and is presented in picture 5.2; the other three distributions are presented in appendix C. Since both distributions are determined with the same minimum, maximum and amount of steps in the Kernel Density Estimation, the area underneath the distributions should be the same.

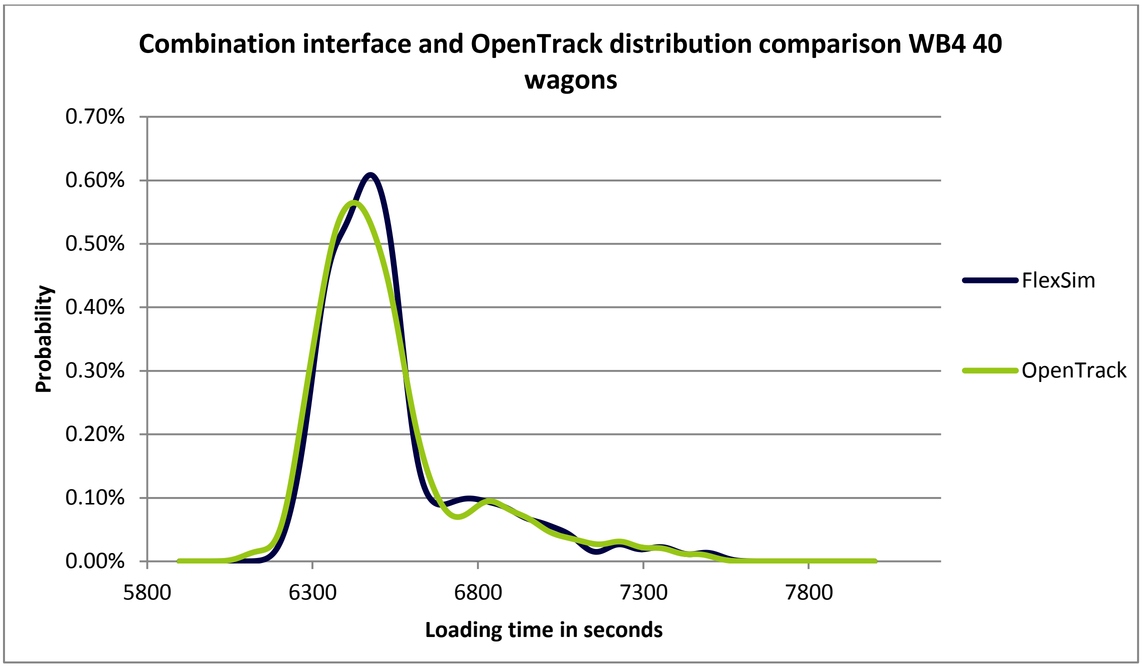

Figure 5.2: Comparison of distributions of FlexSim and OpenTrack for WB4 with 40 wagons

Comparing the distributions for the train composition WB4 with 40 wagons provides an overall decent representation of the loading time. However, visual comparison provides a major deviation at the peak of the distribution and several smaller deviations at the declining slope. By quantifying the values for the peaks of the distributions (table 5.3), the size of the deviation can be analysed. The quantification is based on analysing values provided by the Kernel Density Estimations.

Table 5.2: Peak comparison loading time distribution represented by FlexSim and OpenTrack

FlexSim		**OpenTrack**	
6474	0.61%	**6425**	0.57%

Analysing the data of the deviation at the peak, a deviation around 0.04% can be observed and a shift of approximately 51 seconds. This means that the distribution in OpenTrack gives for some random runs a lower loading time for this train composition. The cause of these differences in loading time is related to the step size of 4% used for importing the distribution into OpenTrack. This step size is larger than the smallest step size determined by the Kernel Density Estimate for the loading time of the FlexSim model and therefore causes loss of detail when exchanging the distribution. However, the goal of the study is to combine models and to provide insight in interferences, not the accuracy of interferences. Combined with other inaccuracies throughout the model, these deviations are accepted.

In case the goal of a case study requires more accuracy, it is advised to reduce the local step size of the OpenTrack representation of the distribution. A sensitivity analysis can provide insight in the effects of the differences and should be the basis for accepting a certain inaccuracy.

Conclusion loading time distributions

The determined distributions provide a reasonable representation of the loading time per train and show sensitivity for start-up delays. However, these distributions are based on simplifications and restrictions to offline communication. In reality the loading process is dependent on more processes and it is likely that the representation of the distribution's declining slopes is more complex. Since these start-up delays can have positive and negative effects and only in rare cases lead to really large variations, the used approach is acceptable for the accuracy of the used models when observing a normal Wednesday under normal conditions. The accuracy of the distributions can and should be improved to reduce disturbances by increasing the sample size in a next research step.

Analysing the distribution for the loading time per train itself shows its sensitivity to start-up delays. This means that a more stable and predictable loading time can be obtained by reducing these start-up delays and thereby the variation of the distribution. Since adaptations to the terminal are expensive, reduction of the start-up delays can be best obtained by reducing the start-up delay for locating the stacker/reclaimer combination. This can be improved by bringing forward the time a train is dedicated to an arrival track at the terminal. However, this requires much more coordination with the other processes at the terminal and therefore should be approached with real-time communication and a model of the total terminal.

Comparisons of the results of the combination interface and OpenTrack distributions show a reproduction of the distribution which is accurate enough for the specific goal of this case study. However, for a more detailed research of loading times or working with complex distributions in OpenTrack, more accuracy is required. This can be achieved by applying a smaller step size for implementation in OpenTrack.

5.2 Interference due to interaction infrastructure operations

Visualisations and quantifications of interference are determined by analysing the arrival and departure times provided by the model. The visualisations are used to determine delay occurrence based on the dataset. After the determination of delays, the distribution for each train is visualised to determine differences in behaviour. The next step is the quantification of the individual results of each train in order to improve insight in the size of interferences. To conclude, the individual results are analysed as a set to determine the interference at the total system.

Interference due to the interaction of infrastructure operations is measured by comparing turn-around times at different locations in the model to the variable loading time. The case study focuses on interference and ignores all other influences; all measured interference should only be caused by interaction with other operations of the infrastructure. Since interference can be measured in different ways, the method of analysing the results and measuring interference is discussed. The analysis of the interference is discussed by the following steps:

1. Visualisation of interference
2. Interference quantification
3. Conclusion

Determining turn-around times

The turn-around times to observe interference are determined from comparing arrival and departure times at certain parts of the model for each train. Comparing the turn-around times of multiple locations provides insight in where interference occurs and combined with observations can reason the cause of delays. Since the only other variable in the model is the loading time, without interference of trains the turn-around times should show behaviour identical to the loading times.

The loading time data and distributions are used as reference values for comparing turn-around times for determining interference. To be able to compare the turn-around times with the loading time, the turn-around times without any interference are determined in the model. By reducing the turn-around times with their zero-interference turn-around time, the difference between the turn-around time and loading time should be the interference. The zero-interference turn-around times without the loading time are presented in table 5.3.

Based on the simulation model and its scope, the best locations to observe and measure turn-around times are the railway yard and the terminal. Since the route duration between the railway yard and the Port Railway Line are constant and reserved at once, extra delay due to occupied routes (interference) is included in the departure time of the train. Therefore the arrival and departure times at the railway yard and the terminal can be used to determine the turn-around times. The two turn-around times are determined by:

- *Turn-around time of the railway yard Maasvlakte East (TA MvE):* from the arrival of a train at the railway yard from the Port Railway Line to its departure from the railway yard to the Port Railway Line
- *Turn-around time of the EMO dry-bulk terminal (TA EMO):* from the arrival of a train at the terminal from railway yard to its departure from the terminal to the railway yard

Table 5.3: Zero-interference turn-around times without loading time

Train number	Train composition	TA EMO	TA MvE
49507	WB4 32 wagons	2712	10530
47709	WB4 40 wagons	5547	10219
49505	WB4 40 wagons	5547	10219
49525	WB4 40 wagons	5547	10219
48701	WB3 44 wagons	2556	10083
48729	WB3 44 wagons	2556	10083
48745	WB3 44 wagons	2556	10083
48711	WB1 38 wagons	2780	10281
48713	WB1 38 wagons	2780	10281
48715	WB1 38 wagons	2780	10281
48717	WB1 38 wagons	2780	10281
48719	WB1 38 wagons	2780	10281
48721	WB1 38 wagons	2780	10281

5.2.1 Visualisation of interaction

To visualize the interaction of trains and determine if there is any interference in operations, the turn-around times are plotted in graphs. First the interaction is observed for delays by scatter plots and then the behaviour of the turn-around times is observed based on their cumulative probability distributions.

Scatter plots

Scatter plots can be used for observing delays at specific locations of the route of a train. In the case of no interference, the only variable is the loading time and the turn-around times; the travel times and station delays of the train would be constant. Under this condition plotting the loading time to a turn-around time in a scatter plot, all dots should be aligned along a straight line. For instance when delays occur, the turn-around time with reference to a certain loading time is longer and therefore should be located not on the line. Two characteristic scatter plots are presented and explained for the trains C47709 and C49505, scatterplots of the other trains can be found in appendix D.

First the scatterplots for train C47709 are presented for the characteristic case of no interference; all sample points are approaching a line. This indicates that almost no delays occur and observations of simulations confirm this behaviour.

Figure 5.3 presents the scatterplot for the combination of the loading time data and turn-around time data measured at the EMO dry-bulk terminal. The sample points are almost aligned in a straight line and a much higher density can be observed at the lower loading time values. This indicates that there is a higher chance on a lower combination of loading and turn-around time at the EMO dry-bulk terminal for the C47709 train. The scatterplot is consistent with the related distribution of the loading time presented in chapter 5.1 *Loading time distributions.*

The scatterplot in figure 5.4 describes the relation to the turn-around time at the Maasvlakte East railway yard and shows identical behaviour to the scatterplot in figure 5.3. Based on the same observations, no delay occurrence can be observed.

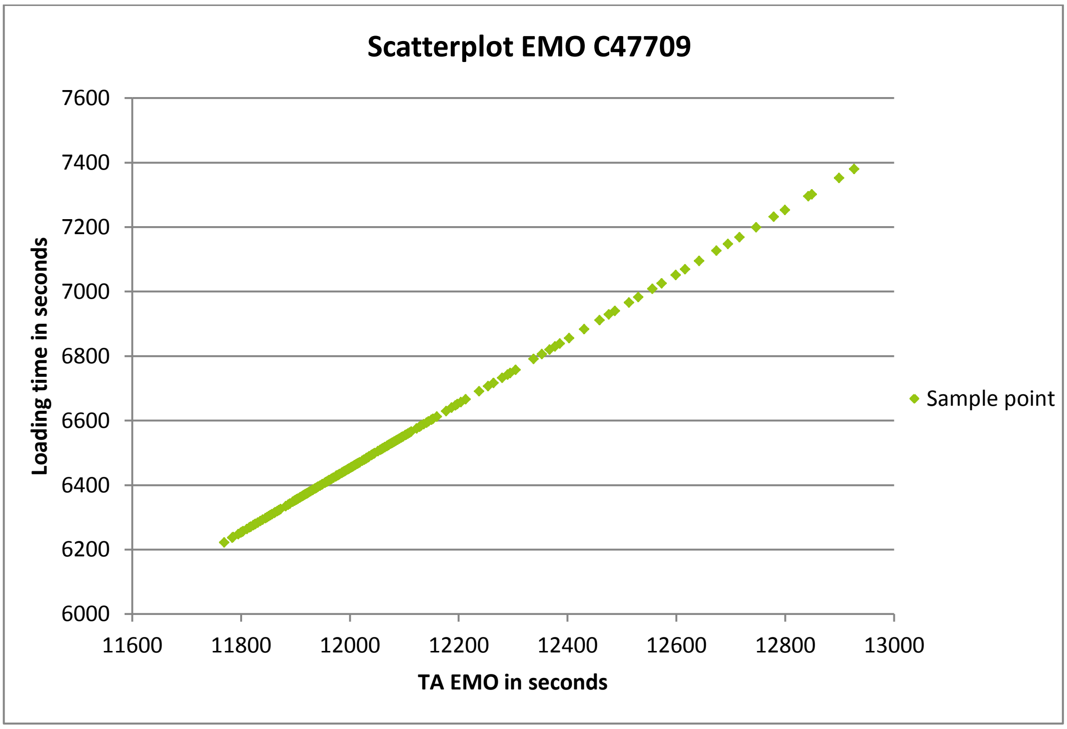

Figure 5.3: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the C47709 train

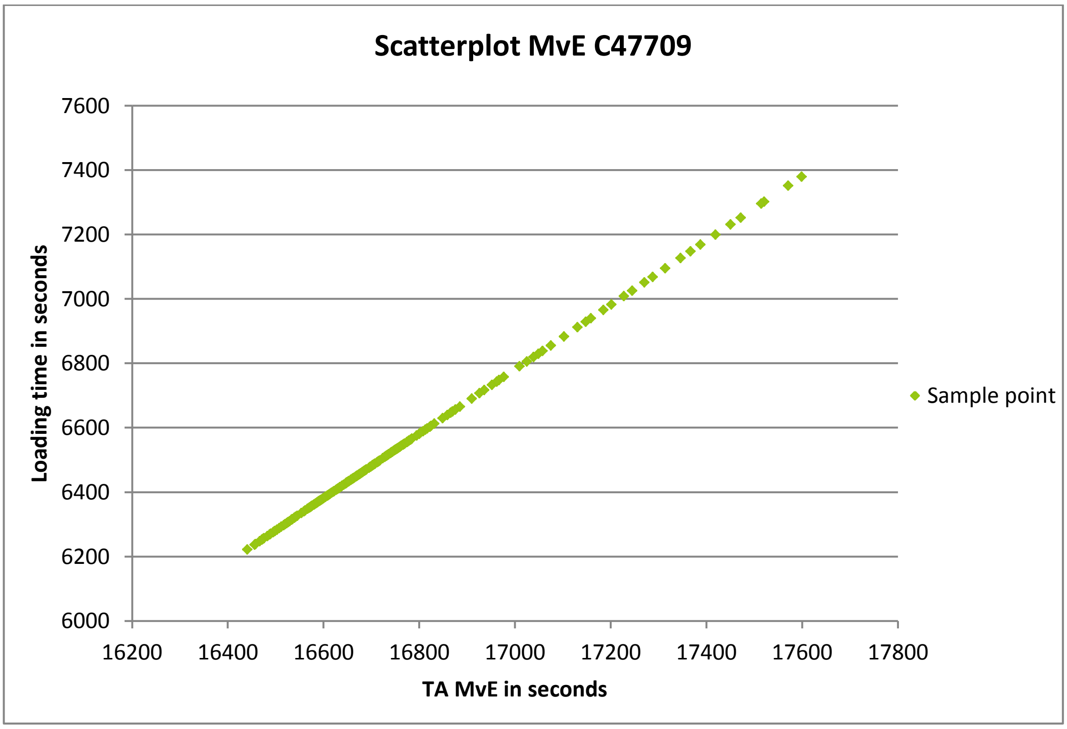

Figure 5.4: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the C47709 train

The scatterplots in figure 5.5 and 5.6 of train C49505 both show multiple sample points located outside the straight line, indicating the occurrence of delays. In figure 5.5 the scatterplot for the C49505 train is presented for the combination of the loading and turn-around time at the EMO dry-bulk terminal. Two patterns of delays can be recognised, one around 6500 second and the other around 7000 second loading time. The first pattern is an area with random scatter of sample points, indicating a variable delay for random trains. The second pattern shows a more vertical line, indicating that trains wait until a certain time.

The model neglects all other influences and only a variable loading time and interference are taken into account, therefore the delays must be caused by interference due to crossing trains. This means that incoming trains should be arriving exactly on time in the case without interference and that outgoing trains are always subject to variances of the loading time. Combining these facts with the delay patterns observed indicates that the pattern with trains waiting until a certain time should be related to incoming trains. This also means that delay patterns with random scatter are related to outgoing trains, which seems to be consistent with observations during simulation. However observations also show that trains can be affected by interference of multiple trains, arriving as well as departing trains. Therefore it is not correct to state that a delay is caused by an incoming or outgoing train, but can give an impression of the cause of delays.

In reality trains do not arrive exactly on time and daily operations are subject to large variances. However these results give insight in the characteristic behaviour of delays for every train and provide the possibility to take targeted actions to reduce interference and delays. By comparing the turn-around times at different locations, the delays can be related to a certain location of the infrastructure.

The scatterplot in figure 5.6, describing the combination of loading and turn-around time for the Maasvlakte East railway yard, shows also two locations of delay occurrence. Compared to the scatterplot of the loading and turn-around time at the terminal, even a more distinctive vertical line, as well as a large gap in the no-delay-line can be observed. This strongly indicates another train crossing the C49505 train and forces it to wait for departure for a certain set of loading times. The appearance of a gap indicates that all loading times located in this interval subject to a delay until a certain time. This means that there is a structural delay for some loading times, probably related to an incoming train. These structural delays can be reduced by changing the timetable of the incoming train. Based on the amount of the delays, a change in the “behaviour” of the train is expected.

Observation of the scatterplots indicates the occurrence of delays for most of the trains simulated in the model. Since not all trains are subject to delays and delays show large variations, the total interference at the system can only be analysed by observing the total set of trains.

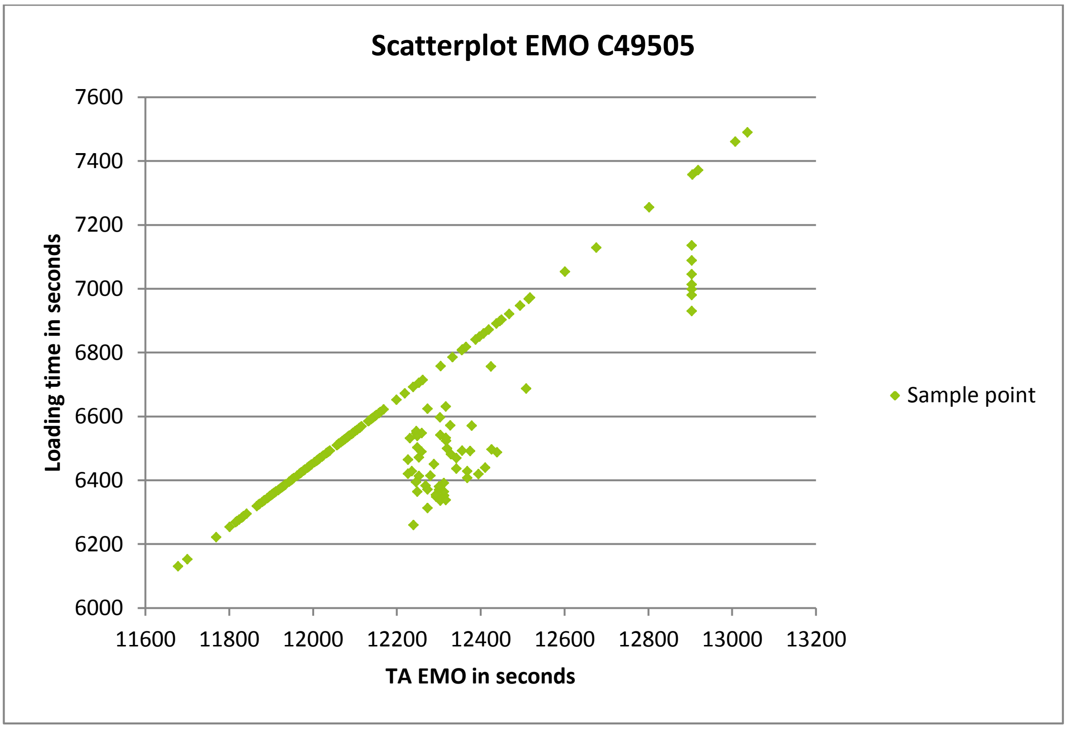

Figure 5.5: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the C49505 train

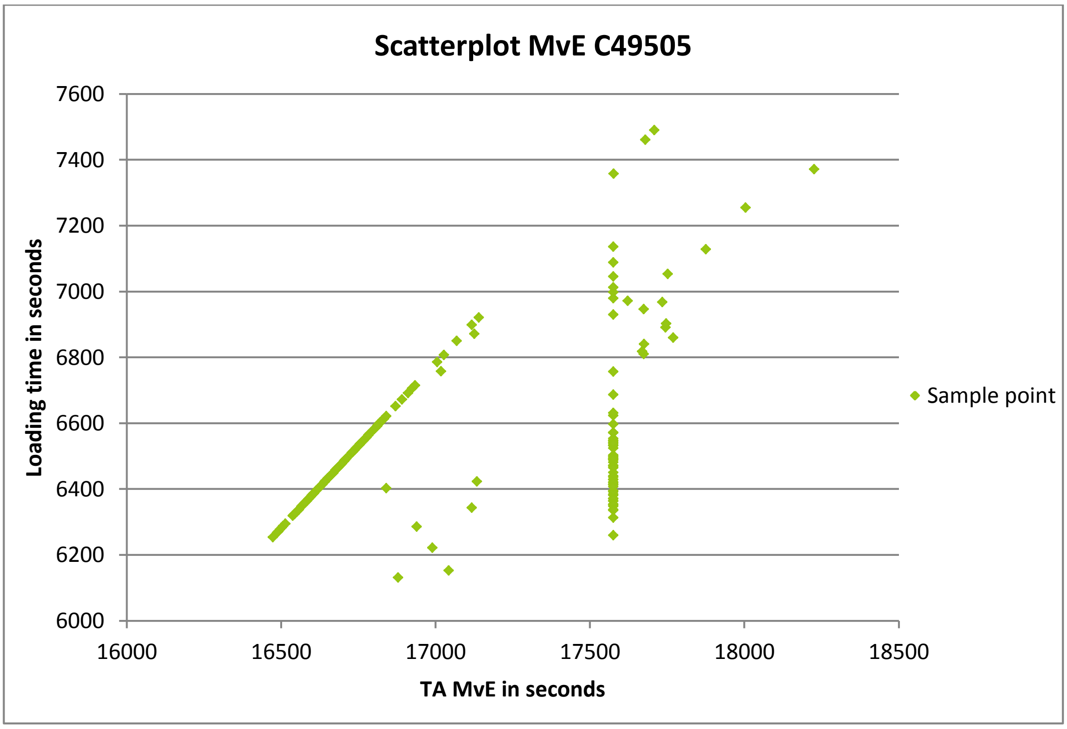

Figure 5.6: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the C49505 train

Cumulative probability distributions

The scatter plots in figure 5.5 and 5.6 show the fact that delays occur for a certain train. To analyse if these delays have a substantial influence on the behaviour of trains in the model, the cumulative probability distributions of the trains are compared to the distribution of the loading time. Comparing the distributions of the different turn-around times per train give insight into different behaviour due to interference of trains.

The turn-around times are processed into distributions in the same manner the combination interface does with the loading time. This means that distributions are determined by a Kernel Density Estimation, but without a minimum and maximum due to an unknown maximum turn-around time. To simplify the comparison, the distributions of the turn-around times are shifted to the distribution of the loading time. Shifting the distributions requires reducing the turn-around times with the minimal turn-around time without the loading time. For instance the turn-around time at the Maasvlakte East is reduced by the station delays and by the minimum travel times. In the case that the turn-around distributions are located right of the loading time distributions, the area between the lines represents the total delay of the train over all simulation runs.

A perfect fit of the three distributions can be observed when looking at the cumulative probability distributions for the C47709 train in figure 5.7. The shape of the distributions is consistent with the loading time distribution determined in the terminal model. The turn-around time distributions do not show a difference in behaviour. The minimum and maximum values of the turn-around distributions are slightly smaller compared to the loading time distribution, which is logical as the chance that these loading times occur is very small.

The curve of the loading time distribution of the C47709 train is consistent with the distribution determined in the terminal model (figure 5.8). Comparing the relative turn-around distributions of train C49505 with the loading time distribution shows distinctive differences in shapes. The curves of the relative turn-around distributions are located to the right of the loading time distributions, which indicates an average longer loading time and delay occurrence. This means that the delays caused by interference have a substantial effect on the behaviour of the train, which is consistent with the expectations of the scatterplots of train C49505 in figure 5.5 and 5.6.

The shape of the relative turn-around distribution of the terminal is relatively similar to the shape of the loading time distribution, however shows an increase in time in the mid-section of the distribution. The shape of the relative turn-around distribution of the railway yard shows more differences compared to the loading time. It makes a shift to the right at the top of the distribution, which is consistent with the delays observed in the scatterplot. The area between the loading time distribution and turn-around time distribution of the railway yard is relatively large, which means that the total delay of this train is large. These observations are consistent with the observed behaviour in the related scatterplots.

It can be concluded that operations for a single train are influenced by the operations of other trains and therefore nothing can be concluded for the total infrastructure operations. All distributions have to be determined in order to analyse which trains are interfered and which are not. Analysing the total set of trains together can provide the possibility to conclude the effects of interference between infrastructure operations in a transport system. The distributions of the other trains are presented in appendix D.

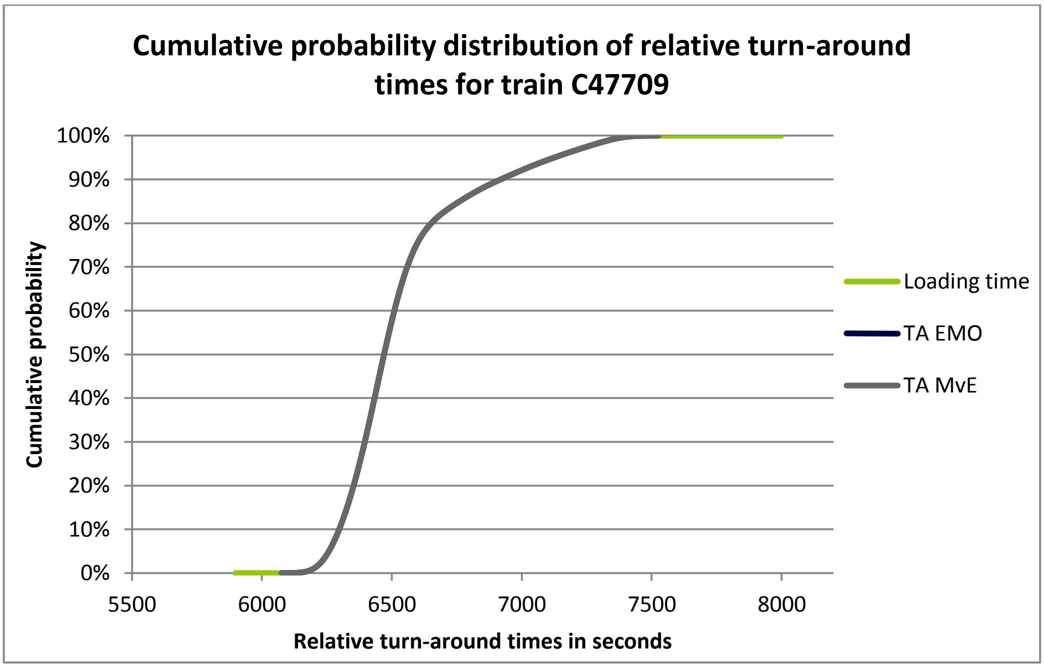

Figure 5.7: Cumulative probability distribution of relative turn-around times for train C47709

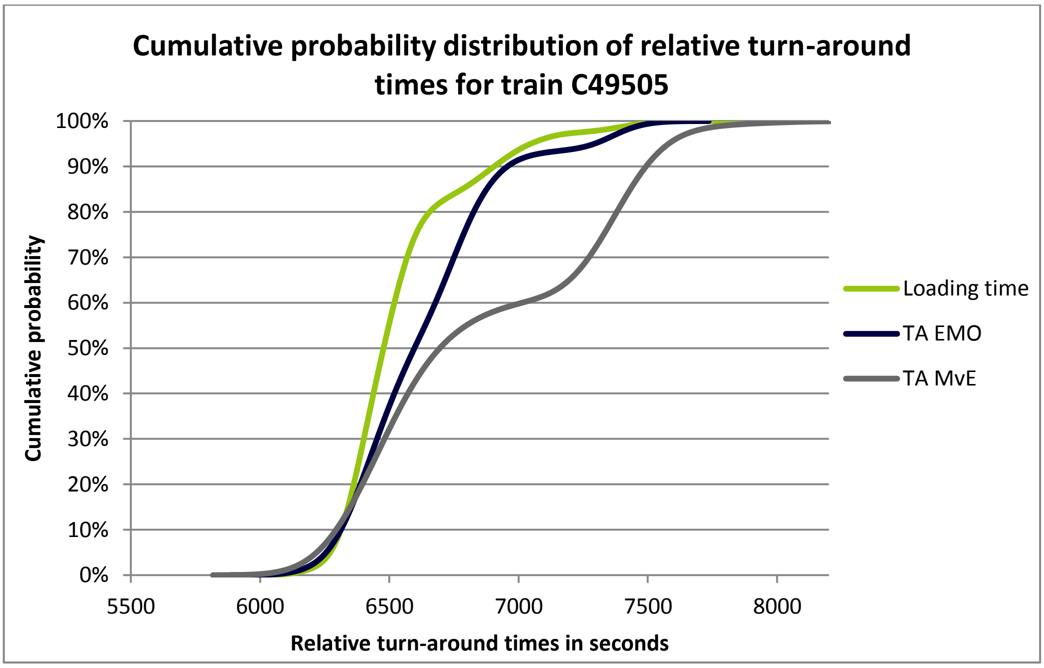

Figure 5.8: Cumulative probability distribution of relative turn-around times for train C49505

5.2.2 Interference quantification

The insight in the interference effects can be improved by quantifying the interference. First, the individual effects of interference by infrastructure operations are presented for a single train and then the effects for all trains at the total system are discussed. Individual effects are presented for train C49505 as delays are clearly visible, the individual effects of other trains are determined in the same way and can be found in appendix D.

Train C49505

The quantification of the effects per train focuses on differences in three aspects: quartiles, dispersion width and standard deviation. Specifications of these three aspects for the C49505 train are presented in the following three tables.

Observing the quartiles determined from the cumulative probability distributions of chapter 5.2.1 provides insight in the shift of the turn-around distributions related to the loading time distribution. To minimize the effects of the fixed minimum and maximum loading time and thereby an unfair comparison, the observed minimum is taken at 1% and the maximum at 99%. The quartiles based on the distributions are presented in table 5.4.

Table 5.4: Quartiles of relative turn-around times for train C49505

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6174	6147	-0.4%	6089	-1.4%
Q1	25%	6382	6421	+0.6%	6438	+0.9%
Median	50%	6479	6597	+1.8%	6696	+3.4%
Q3	75%	6603	6786	+2.8%	7329	+11.0%
Maximum	99%	7425	7469	+0.6%	7797	+5.0%

From the quartile data can be concluded that the largest difference can be found around Q3, which indicates a higher chance on larger turn-around times (TA). The median shows a minor increase of 3.4%, which means that on average the train C49505 has a delay of 217 seconds measured at the Maasvlakte East railway yard (MvE). This increase in average turn-around time also means that the train is longer present in the local system and therefore more interference with other trains is possible. Comparing the quartiles at turn-around time distribution for the EMO dry-bulk terminal and the Maasvlakte East railway yard, it can be observed that the most delays must occur at the railway yard or its connection with the terminal.

The maximum value of the turn-around time increases, indicating that also trains with a high loading time can be subject to delays. A minor decrease can be observed at the minimum value, but this should mean that trains with a short loading time can reduce their travel times or station delays. Analysing the dataset of results, it is observed that the lowest relative turn-around time measured is not lower than the minimum of the loading time. Therefore it can be concluded that the decreased minimum is likely caused by the low sample size related to the method of determine the distributions. To improve the insight into the changes in minimum and maximum, the dispersion widths of the dataset are analysed. The dispersion widths for the dataset of train C49505 are presented in table 5.5.

Table 5.5: Dispersion width for train C49505

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6131	11678	6131	16473	6254
Maximum	7490	13037	7490	18226	8007
Dispersion width	1359	1359		1753	

Comparing the dispersion widths of the C49505 train at the different locations, an increase can be observed in the dispersion width between the turn-around times of the railway yard and the terminal. The dispersion width increases with 29.0%, which means that larger variances are possible in the system due to the delays. To improve the insight in these variances, the standard deviation of the dataset is analysed. The standard deviations for the different turn-around times based on the sample data are presented in table 5.6.

Table 5.6: Standard deviation for train C49505

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
49505	241	275	460	219	90.7%

Comparing the standard deviations, a substantial increase can be observed between standard deviation of the turn-around time at the terminal and the railway yard. This increase means that larger deviations are more likely to occur at the turn-around time of the railway yard compared to the loading time or terminal turn-around time. These observations of the dataset are consistent with the distributions of train C49505 presented in figure 5.8.

The combination of these results shows that the operations of train C49505 are mainly subject to delays between the terminal and railway yard. Since all other influences are neglected, these delays must be caused by interference of other operations at the infrastructure. Observations during simulations confirm interaction with other trains and delay occurrence.

Special observations in individual results

Before analysing the total set of trains, some special behavioural observations of the individual results of the other trains presented in appendix D are discussed. Some trains show a decrease in dispersion width and standard deviation, which indicates an improvement of the stability of the system. This behaviour is caused by delays only affecting the lower loading times and thereby compressing the dataset into a smaller region.

A number of trains show very large delays. Observations during simulation show that these delays are longer as the train has to wait for shunting moves. Due to limitations of the infrastructure at the railway yard, shunting moves use and cross incoming and outgoing tracks.

Train C49507 shows completely different behaviour comparing the turn-around time at the railway yard with the loading time. Analysing the model shows that different behaviour is caused by the amount of crossing trains and the fact that C49507 always waits instead of the crossing train. Because the train arrives at the railway yard at the busiest time of the day, this behaviour is considered to be possible in reality and therefore not discarded.

Total set of trains

The results for the total set of trains are analysed to determine the effects for the total system. As already determined most delays occur at the railway yard or its connection to the terminal. Therefore the total effects are observed for the turn-around time of the railway yard compared to the loading time. The total effects are measured by comparing the individual results of the differences in percentages presented in appendix D, which are presented in table 5.7.

Table 5.7: Percentage differences for all trains comparing the loading time with the turn-around time of the railway yard based on individual results presented in appendix D

Train number	Median difference In seconds	 In percentage	Dispersion width Difference in percentage	Standard deviation Difference in percentage
49507	872	+16.5%	+158.0%	+278.9%
47709	0	0.0%	0.0%	0.0%
49505	217	+3.4%	+29.0%	+90.7%
49525	526	+8.1%	+24.1%	-13.5%
48701	122	+1.7%	+8.9%	+46.3%
48729	42	+0.6%	+48.2%	+122.0%
48745	58	+0.8%	+27.6%	+9.4%
48711	42	+0.6%	-3.9%	-8.0%
48713	-2	0.0%	0.0%	+0.7%
48715	222	+3.1%	+17.0%	-11.7%
48717	147	+2.0%	+41.0%	+46.0%
48719	48	+0.7%	+16.5%	+16.4%
48721	64	+0.9%	+147.4%	+48.5%

Comparison of the results for all trains in table 5.7 show that some trains are subject to large delays while others are not. Observations during simulations show that often the same trains suffer delays, which underpins that delays caused by interferences are highly related to planning of operations.

The results of the medians show an average increase in relative turn-around time of 2.9%. Observing the actual results, the average delay per train is 181 seconds and the total delay for all trains in one day is 2254 seconds due to interference of trains. Delays result in an increase in transportation time and costs, which means that the average delay is related to the cost efficiency of the system. In a system without interference the delay would be zero and therefore reduction of the average delay is preferable for improving the cost efficiency.

The differences in dispersion width show an average increase of 39.5% and the differences in standard deviation an average increase of 48.1%. This means that the deviations in the turn-around time are larger and larger deviations occur more likely compared to the loading time. Larger variations are undesirable for operations as it reduces the stability and reliability of the system.

Observing the results of the different trains show very large increases in standard deviations and dispersion widths compared to the increase in medians. This means that the average turn-around time is not much longer than without interference, however most of the trains are subject to longer and larger deviations in turn-around times.

It must be kept in mind that these results are determined from a dataset with only 188 samples. Observing a larger dataset can improve the accuracy of the results. Due to the low sample size it is possible that the results are not statistically significant, however it does provide proof that combining models can determine and measure interference due to interaction in the transportation chain.

5.2.3 Conclusion interference

The visualisations and quantifications of individual and total set of results show interference, and observations confirm that these are caused by interaction of train operations. Scatterplots comparing the loading time with turn-around times per train show delays occurrence for some trains. The delays show distinctive behaviour: the delays are scattered in a small area or are located on a line, sometimes combined with a gap in the no-delay-line. Analyses of the case study results show that these delays must be caused by crossing trains, compliant with observations during simulation. Delays can be related to incoming or outgoing trains, but since most trains are subject to interference of multiple trains a single train cannot be appointed as cause.

Processing the result data into distributions provides a representation of the difference in behaviour of individual trains due to the occurrence of these delays. Most distributions show an increase in the chance of higher turn-around times, which is consistent with the observations of the scatterplots.

By quantifying the results, the insight in the effects of the interference is improved. The results are quantified for every individual train and for the trains al a total set. Quantification is based on quartiles, dispersion width and standard deviation determination. Analysing the individual results show that some trains are not affected at all and some trains have large increases, especially in the standard deviation. This means that is not correct to determine interference of operations by analysing individual trains, but should be determined by analysing the total set of trains.

Analysing the total set of trains an average delay of 181 seconds per train is observed comparing the turn-around time of the railway yard to the loading time. Due to delays overall the trains have large increases of 39.5% in dispersion width and 48.1% in standard deviation. The increase in dispersion width and standard deviation negatively influence the stability of the system, as larger deviations are more likely to occur.

The average delay is considered rather small compared to the turn-around time from the train's origin to destination, but combined with large deviations the effects can become considerably important. Especially in the case of a larger intensity, more interference is expected and the average delay can have a large increase. Reducing the average delay can have positive effects for the efficiency of the system, reducing the standard deviation and dispersion width improves the stability.

5.3 Conclusions Case Study

Application of the developed concept to the case study proved that a combination of models can provide valuable insight into the interference due to interaction of infrastructure operations. The case study proved that a terminal and rail infrastructure model can be combined by a combination interface for representing a larger part of a transportation chain in a port. Due to availability of resources, the case study was limited to offline communication and therefore required a substantial amount of simplification. However, the model was sufficient for the specific goal of the case study, which was to prove that a comprehensive modelling environment can be created with the purpose of analysing transportation operations in a port's chain process.

The case study has shown that interference due to interaction of infrastructure operations can be made measureable and a fairer representation of the loading time by distributions can be provided. These results show that the system could operate more efficient and that the hypothetical concept can be used to optimise tactical or strategic planning. For instance, combining these results with a bottleneck analysis provides insight in where infrastructure measures could reduce the interference.

The loading time distributions for different load-outs and train compositions are determined and exchanged by a combination interface. These distributions give a fair representation for this specific case study. However, if required these distributions could easily be improved by enlarging samples sizes and locally reducing step sizes. Validation by reviewing of the terminal model showed that certain assumptions can have large effects and thereby decrease the representation of the model, but are inevitable with offline communication.

Analysing the results and their relation to the model set-up showed that interference due to interaction of infrastructure operations are highly related to the planning of the train operations. The case study assumed a static state in which trains arrive always on time and results show that not all trains are subject to delays. Therefore measuring interference of a system requires analysing the operations of the total set of trains in the system in relation to the planning of operations. In reality this would be almost impossible due to the large amount of interferences between all trains operating at the railway system. However, the hypothetical concept provides insight in the effects of terminal operations on the infrastructure operations and in fragile points in the timetable of train operations.

Application of the case study has shown that terminal and transport operators can improve the stability and reliability of the transportation chain by decreasing interference and delays. This interference and delays can be decreased by adapting the planning of operations or infrastructure. For instance a bottleneck analysis can be performed to determine which infrastructure measures have to be taken to reduce interference between train operations.

6 Conclusions and recommendations

In this chapter the conclusions and recommendations of the research study are presented. First the conclusions are discussed for the research study and hypothetical concept, followed by the recommendations.

6.1 Conclusion Research Study

The conclusions are divided in conclusions for combining models, offline and real-time communication and their effects to freight transportation in ports.

Combining models

Combining transportation models in ports can be a helpful approach when researching interaction between processes of a transportation chain and can provide a fairer representation of parameters. Application of this concept improves insight and understanding of operations along a transportation chain by quantifying interferences between processes. This can improve designs, planning and efficiency of operations.

The case study application proves that a combination of models can represent a larger part of a transportation chain by offline communication and can visualize and quantify interferences of interaction between processes. Offline-communication limits the analysis by required simplifications and only a static state for normal conditions was observed. The application at the case study provided an improved representation of loading times at terminals and an average delay per train caused by interference. It can be concluded that in order to reduce interferences in the system, the total set of trains needs to be observed, and that these interferences are highly related to the planning of operations.

Offline and real-time communication

The applicability and complexity of the method in practice is highly related to the applied communication method between the models. During the comparison of the communication methods, offline communication provided a distinct difference in application through the limitation of only exchanging single model dependent parameters. This limitation makes offline compared to real-time communication based models less complex and less expensive. However, it can have large effects on the results and approximation of reality. Nevertheless, offline communication can provide valuable insight into observation of a specific part or a single parameter of a transportation chain.

Real-time communication on the other hand can provide insight into the dynamic behaviour of operations due to multiple dependencies along a transportation chain. Combining models with real-time communication is much more complex and expensive. It gives however a fairer picture of the stability and capacity of a transportation network or system. Besides this, it can also provide a more correct and detailed representation of parameters required for optimisation of separate parts of the transportation chain.

Effects to freight transportation in ports

In a time where the optimisation of a system becomes more interesting than the expansion of a system due to technical innovations, the concept of combining models becomes more important as more insight into the cohesion of operations is required. Since the benefits for the different stakeholders are unclear and the required investments are high, it is likely that the application of this technique in practice will take some time. However, as transport volumes and the demand to freight transportation networks worldwide increase, research into the application of combined models will continue and possibly accelerate the implementation of the concept.

Implementation of the concept of combining models can at first be a helpful tool optimising terminals, infrastructure and transportation chains. As its application increases and technology develops, it becomes possible to connect a larger number of models. Combining more and more models into a transportation network provides the possibility to create large microscopic model and increases efficiency at intercontinental as well as local transportation.

6.2 Recommendations

The recommendations derived from the research, results and conclusion are divided in the recommendations for future research and case study.

Research Study

Recommendations related to the research study of combining models are mainly focussed on the expansion of the analysis to benefits and applications of the hypothetical concept. The main recommendation is to perform a case study of combining models by real-time exchange of data to analyse the effects and benefits of this communication method. Combining models by real-time data exchange is much more complex, but can provide an even more realistic representation of interference thanks to the interaction of operations. The method of real-time data exchange also allows for the possibility to improve the analysis into the dynamic behaviour of capacity or to increase the amount of exchangeable interdependent processes.

Besides researching the technical aspects of combining models, it is recommended to research how the concept can be implemented in reality. The implementation of the concept in practice is complex due to the manner in which the transportation sector is organised.

As a final recommendation, it is advised to research the possibility of combining models outside the scope of ports. Since the case study has proven that the method of combining models can be applied and be beneficial in some cases, other large systems could be improved by the same concept. Not only in the transportation sector, but potentially in other fields where modelling is used for optimisation purposes.

Case Study

To prove the application of the hypothetical concept and to provide insight in its potential, the concept was applied to a simplified case study. Since numerous improvements to the simplified case study are possible, only the most important recommendations are discussed. The recommendations for the case study, based on the analysis of the system and observations during simulation, can be divided in two types: recommendations within case study scope and within hypothetical concept.

Case study scope

Due to the fact that the case study was used to prove the application of the hypothetical concept, more simplifications were accepted than when the case study was analysed for a real optimisation of the terminal. The following recommendations can improve the accuracy or application of the case study.

- *Improving the representation of the positioning of the stacker/reclaimer combination*

  The simplification at the start-up delay of the stacker/reclaimer combination can have large effects; possibly another approach can give a better representation and thereby improve the accuracy of the loading time distribution.

- *Sensitivity analysis of exchanged parameters*

  To ensure the correct representation of the exchanged data, a sensitivity analysis must provide insight into the effects of loss of detail in the communication process. This analysis provides more insight into whether the representation is sufficient or must be improved.

- *Performance of a bottleneck analysis*

  By combining the delay results with occupancy of sections, bottlenecks can be discovered. Bottlenecks and delays are the basis for infrastructural adaptations to improve the system.

- *Planning optimisation analysis*

  By analysing the effects of planning at interferences due to interaction, possibly planning principles for rail freight transportation can be determined. These principles can improve the planning of operations as interferences are reduced.

Real-time data exchange applications

Even though the case study is performed with offline communication, real-time data exchange can provide more insight into interaction and dependencies of processes in a transportation chain. Recommendations for combining models by real-time data exchange are presented.

- *Capacity analysis*

  Real-time data exchange allows for the possibility to determine the dynamic capacity of the terminal affected by the interference due to interaction of operations. To determine the maximum capacity, real-time communication is required to compress operations.

- *Malfunction effects analysis*

  The research study did not include malfunctioning of parts of the transportation chain, however it was clear that malfunctions can have large effects on operations. By analysing the effects of malfunctions, insight is provided in the negative effects. This can help determine which measures are suited for managing and minimizing the effects of malfunctions.

- *Research effects of planning of external operations*

  By including external railway operations in the model, more insight is created in interactions along the transportation chain. The best method to include these operations is by real-time communication, because it provides the possibility to represent traffic more realistically as it enables the model to react on variances during operations.

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List of abbreviations

EMO	European dry bulk goods and transhipment company (*Europees Massagoed Overslag BV*)
Hvs	Port Railway Line (*Havenspoorlijn*)
MvE	Maasvlakte East railway yard
TA EMO	Turn-around time measured by the arrival and departure time at the EMO dry-bulk terminal
TA MvE	Turn-around time measured by the arrival and departure time at the Maasvlakte East railway yard
NS	Dutch Railway Company (*Nederlandse Spoorwegen*)
DB Schenker	German freight transport operator which is part of the Deutsche Bahn Group

List of definitions

Betuweroute	Dedicated freight railway line in the Netherlands which is a hinterland connection to Germany
Hinterland connections	Transport connections towards a region lying inland from a port
Infrastructure	All elements required for the transportation of goods
Infrastructure operations	All activities at infrastructure for the transportation of goods
Load-out	Loading facility for loading train wagons with bulk goods
Logistics simulation	Representation realistic behaviour of logistical processes for experimental testing
Maasvlakte	Location in the port of Rotterdam
Mode	A mean of transportation, such as rail, road and inland waterways
Optimisation	The act of improving something, such as a process of system
Port Railway Line	Railway line connection terminals in the port with the Dutch Railway System, such as the Betuweroute
Robustness	The ability or otherwise of a system or component to withstand model errors, parameter variations, or changes in operational conditions (Hansen, 2008)
Stability	The ability of a system or component to compensate for delays and return to the desired state (Hansen, 2008)
Stacker/reclaimer	Facility that stacks or reclaims bulk products
Terminal	A facility where ships are (un-)loaded in a port
Terminal operations	All activities within the boundaries of a terminal
Traffic simulation	Representation realistic behaviour of traffic for experimental testing
Transhipment	The shipment of goods to an intermediate destination, used to change means of transportation
Transportation	The movement of goods from one place to another by means of a vehicle
Transport capacity	Maximum amount of goods that can be transported by a certain system
Transportation chain	Succeeding processes in bringing a product from its origin to its destination

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C. Case Study Results: Data exchange
D. Case Study Results: Individual results of interference

A. Organisation of transportation in ports

This appendix provides insight into two aspects of the organisation of transportation in ports in relation with this master thesis. The first aspect discusses the organisation of rail transportation in Europe, and especially the Netherlands. The second aspect describes a possible organisational structure in which implementation of the hypothetical concept should be possible.

A.1 Organisation of rail transportation

The organisational structure of the rail sector is determinant for the operational set-up and thereby influences the handling of operations. In 1991 the European Union introduced the First Railway Directive, which demanded changes in the structure of the European railway sector. This directive had to make sure that the European railway network allowed open access for operations by companies other than those that own the infrastructure. The First European Directive was followed by a second and a third version of the directive, which formed the railway sector into what it is now.

Before the introduction of the directive, a railway company had a national monopoly on owning and managing railway infrastructure and exploiting railway transport services. After the introduction, the companies were split up and different companies were formed for infrastructure management, passenger train services, freight train services, train maintenance and infrastructure engineering. As a result of the introduction of this new legislation, new commercial train service operators were allowed access on the national railway infrastructure and nowadays there is a variety of private freight transport operators active throughout Europe. A much slower adaptation can be observed in other fields of the railway sector, as a result of political decisions in the amount of liberalisation and a more conservative climate in these parts of the sector.

The new structure, that should provide a more liberal market, was mainly focussed on separating the infrastructure management from transport and other operations. In practice this led to the placing of all parts of the company into separate companies located under a holding company. In the decade after the reorganization, some of these companies merged or sold. Many studies were conducted and models were introduced to describe the organisational structure and roles of the different stakeholders involved in the railway sector. For instance, the TRAIL model and layer model (Schaafsma, 2001).

Organisation in the Netherlands

To give an impression of the developments and increased complexity in the organisation of rail transportation in Europe, this part of the chapter goes into the organisational developments in the last two decades in the Netherlands.

The organisational structure of rail transport in the Netherlands was reorganised in 1995 due to the changed European legislation, which led to separation of the main railway operations of the Dutch Railways company (NS) into new private companies. Before the reorganisation, all railways related activities in the Netherlands were part of one company: The Dutch Railways (NS).

The rail operations were split up into passenger and freight transportation. The passenger transport operation part is the Dutch Railways (NS) as it is known now, not only containing rail operations but also related services. The freight transport operation part of the Dutch Railways (NS) merged after 5 years with DB Cargo, a German rail freight operator which is currently known as DB Schenker and is the largest rail freight operator in Europe. Since the reorganization, more rail freight operators started services in the Netherlands and now a variety of freight transport companies can be found on the Dutch rail infrastructure.

The infrastructure managing part is currently assigned to holding company Railinfratrust B.V., containing three former Dutch railway parts: NS Railinframanagement, Railned and NS traffic control. The holding company is owner of the public rail infrastructure in the Netherlands and all of its shares are property of the Dutch State. It is currently known as ProRail.

Currently, the main rail freight corridor of the Netherlands is the Betuweroute, operational since 2007. The Port of Rotterdam is connected to the Betuweroute by the Port Railway Line, which was heavily improved in the last two decades. New investments in the port railway must remove bottlenecks and thereby improve the capacity needed for the expected demand of freight transport from the Maasvlakte 2. The many capacity expanding projects for the Maasvlakte 2 and the short realisation time available, have led to prioritising of projects and a short term vision for developments in the rail sector. Together with uncertainties in the growth of the demand of freight transport due to economic instability, the long term effects of infrastructural developments are complex and thus hard to predict.

Roles of stakeholders

The new structure of the railway sector, separate companies with different owners, has led to an increase in the amount and characteristics of stakeholders involved in freight transportation. All of these stakeholders have their own interests and strive for optimizing their own companies. In order to prevent a limited image, and thereby an unrealistic view of freight transportation, all the stakeholders and their interests have to be identified by their role in the transportation process. The stakeholders are categorized in 4 main types and several sub-types based on their main activity. In chapter 6 the relevant stakeholders of the case study will be identified.

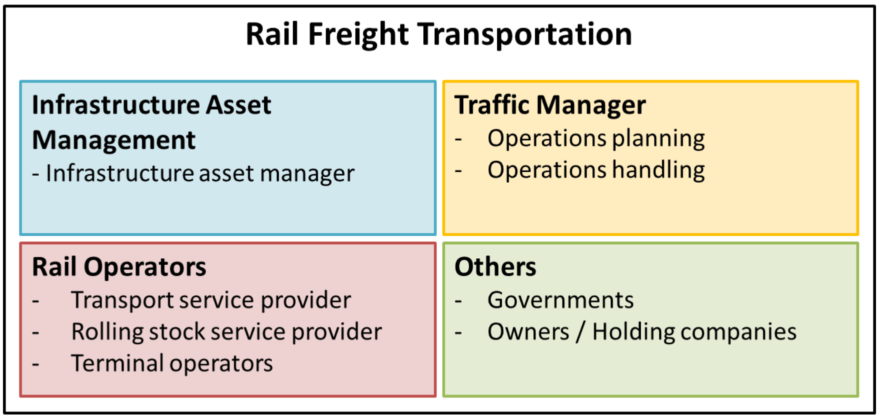
Rail Freight Transportation
Infrastructure Asset Management
- Infrastructure asset manager
Traffic Manager
- Operations planning
- Operations handling
Rail Operators
- Transport service provider
- Rolling stock service provider
- Terminal operators
Others
- Governments
- Owners / Holding companies

Figure A.9: Organisational structure of rail freight transportation

A quick scan of the current sector gives us the four main functions of stakeholders to make rail freight transport possible: *infrastructure asset manager, traffic manager*, *rail operators* and *others* such as owners or governments. In each of these main functions, one or more companies are active or provide services for these functions. Companies can also be involved in more than one main function and can represent different interests.

The relevant characteristics of the sub-types are presented in table A.1. The influence the stakeholders have in the sector are based estimated on a scale from 1 to 5, with 5 being the most influential stakeholder.

Table A.8: Characteristics of stakeholders, with influence on a scale of 1 to 5 (5 is most influential stakeholder)

Role stakeholders	Main activities	Main interests	Influence
Infrastructure asset management	Asset management of infrastructure	Optimization of infrastructure exploitation	4
Planning operations	Development of timetables	Providing and optimisation of long-term planning of operations	5
Operations Management	Managing/Handling traffic	Execution of timetable planning and minimizing irregularities	
Transportation service provider	Transportation of freight	Optimization of freight transportation: *low-costs per transported volume*	4
Rolling stock service providers	Providing rolling stock or maintenance	Optimization of services: *maximize occupancy rolling stock*	2
Terminal operators	Transhipment of freight	Optimization of throughput: *low-costs per transport volume*	3
Local, regional and national governments	Investments to ports and infrastructure	Improving economy and accessibility of the region	1
Owners and Holding Companies	Management of companies	Improving over-all profit	1

A.2 Organisational Structure for implementation hypothetical concept

The following structure is proposed as a basis for the organization of the combination model. For the application of such structure in practice, all stakeholders involved inside the scope should be given a position in the structure. The structure can be applied to combination of models with offline and real-time communication.

Management of the organisational structure should be assigned to a stakeholder that does not have a competitive position in the structure, benefits from the performance of the overall system and is directly involved with the other stakeholders of the structure. Based on these requirements, the manager of traffic and infrastructure and the port authority are the best candidates in ports to fulfil this position. Because both stakeholders represent different interests and primarily work on a different level and time horizon, a combination of both managing the model is even more desirable.

Since not all stakeholders involved in the development of the model are competitors, some of them have a different position with respect to the transportation process itself. To minimize the risks of data ending up at the competitors, competitive stakeholders should only be providing data and not managing the model. In order to protect the stakeholders, the exchange of data between the models must be shielded from competitors (figure A.2).

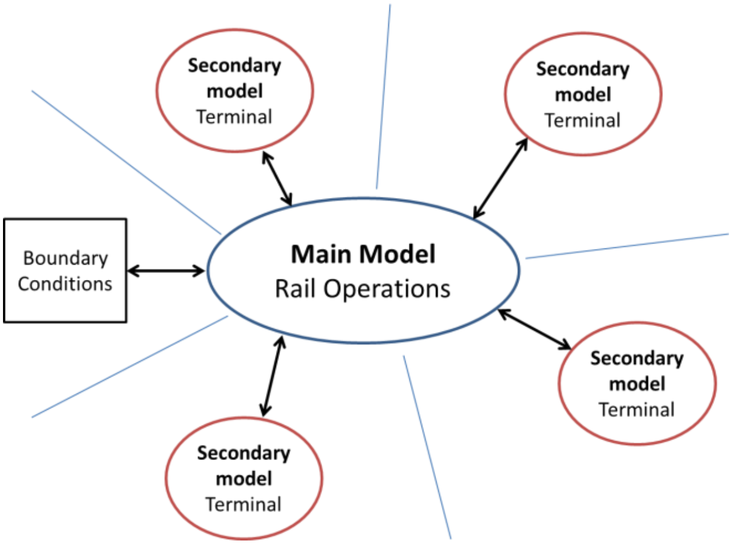

Figure A.10: Main (infrastructure) model and secondary (terminal) models and protection by shielding of data

The proposed structure (figure A.3) assumes a situation where the main infrastructure model of the combination model is managed by the operations manager and the port authority. Inside the structure the different stakeholders of rail freight transportation in ports can be recognised; the infrastructure manager, operations manager, transport operators and others.

The traffic manager handles daily traffic in the infrastructure network in cooperation with the involved transport operators. Their knowledge about operations and the functioning of the infrastructure system makes the operations manager the best fit for the set-up and management of the main infrastructure model.

The transport operators, divided in the different categories based on their field of work, are the main competitive stakeholders. Therefore the data streams towards the main infrastructure model must be separated and an interface may be necessary for the different models to communicate or process data.

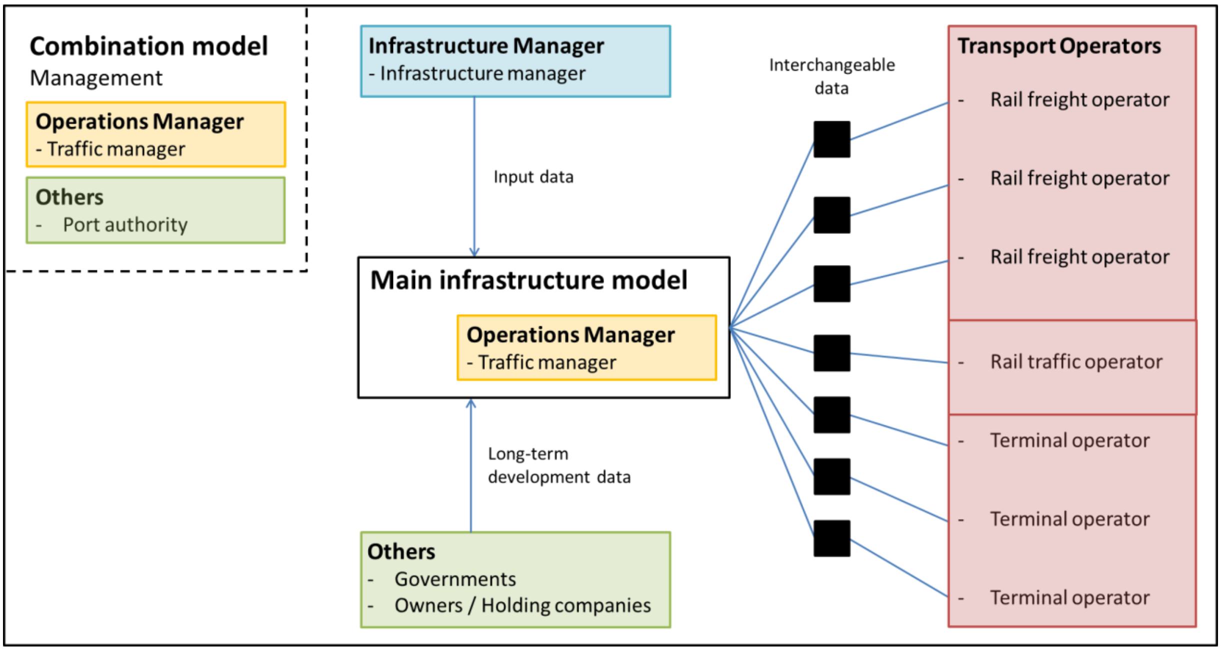
Combination model
Management
Operations Manager
- Traffic manager
Others
- Port authority
Infrastructure Manager
- Infrastructure manager
Input data
Main infrastructure model
Operations Manager
- Traffic manager
Long-term development data
Others
- Governments
- Owners / Holding companies
Interchangeable data
Transport Operators
- Rail freight operator
- Rail freight operator
- Rail freight operator
- Rail traffic operator
- Terminal operator
- Terminal operator
- Terminal operator

Figure A.11: Structure of combination model

The infrastructure manager, which in practice often is the same stakeholder as the operations manager, only provides input for setting-up the infrastructure model. Stakeholders defined as others only provide information of long-term developments of the port and its infrastructure and only provide input to the combination model.

Special interest groups, such as a transportation federation, are kept out of the structure as the combination model is not directly influenced by these groups. Any indirect influence is carried out through the involved stakeholders and therefore these groups can be left out.

B. Case Study: Chain process

Table B.1: Processes during the arrival, loading and departure of a coal train at the Maasvlakte East railway yard/EMO dry-bulk terminal using electric locomotives and related shunting processes

Process/Handlings	Average duration in minutes	Based on***
Maasvlakte East		
Arrival at Maasvlakte East railway yard	-	
Uncouple electric locomotives	3	A
Route electric locomotives to sidings (incl. route reservation and setting)**	-	
Arrival check of the train	30	A
Arrival of shunting locomotive from sidings (incl. route reservation and setting)**	-	
Coupling of shunting locomotive, reverse direction and small braking test	10	A
Report arrival and wait for availability at EMO	- (waiting)	
Route reservation/setting	1	A
From Maasvlakte East to EMO terminal		
Route to EMO	9	B
Close crossing	20 sec.	A
Enter terminal terrain	2	B
Release crossing**	-	
EMO terminal: loading train		
Arrival at terminal	-	
Uncoupling shunting locomotive	3	A
Coupling EMO Robot	3	A
Placing wagons underneath load-out	5	A
Loading process		
- *Locating reclaimer to specific stack***	-	C
- *Starting up conveyor system and loading load-out for first wagon*	-	C
- *Continuous loading of wagons*	-	C
Moving wagons from load-out	1	A
Moving wagons to departure track	3	B
Uncoupling EMO Robot	3	A
Coupling shunting locomotive	10	A
Optional departure check *	(45 min.)	A
From EMO terminal to Maasvlakte East		
Leaving terminal terrain	2	B
Close crossing	20 sec.	A
Release crossing**	-	
Route to railway yard	9	B
Announce arrival and permission for entering railway yard (protected area)	2	A
Maasvlakte East		
Route to designated track of Maasvlakte East railway yard	3	B
Uncouple shunting locomotive	3	A
Route shunting locomotive to sidings (incl. route reservation)**	-	
Arrival of electric locomotive from sidings (incl. route reservation and setting)**	-	
Couple electric locomotives, reverse direction and small braking test	10	A
Departure check	45	A
Route reservation	1	A
Departure of train of railway yard and entering of Port Railway Line	-	

***: transport operators using diesel powered locomotives prefer to do the departure check at the terminal and do not uncouple or couple at the railway yard**

****: can be executed parallel to earlier processes**

*****: A = based on reference values of ProRail (Samuel, S., 2011)**
B = based on results of simulations of the case study terminal and infrastructure operations models
C = variable parameter, normally assumed to be a total of 3 hours for coal trains and 3.5 hours for iron ore trains

C. Case Study Results: Data exchange

The correctness of the data exchange is analysed by comparing the loading time distribution determined in the combination interface and the loading time distributions retrieved from the infrastructure operations model. This comparison is made for each of the relevant train compositions: WB1 with 38 wagons, WB4 with 40 wagons, WB4 with 32 wagons and WB3 with 44 wagons.

WB1 with 38 wagons

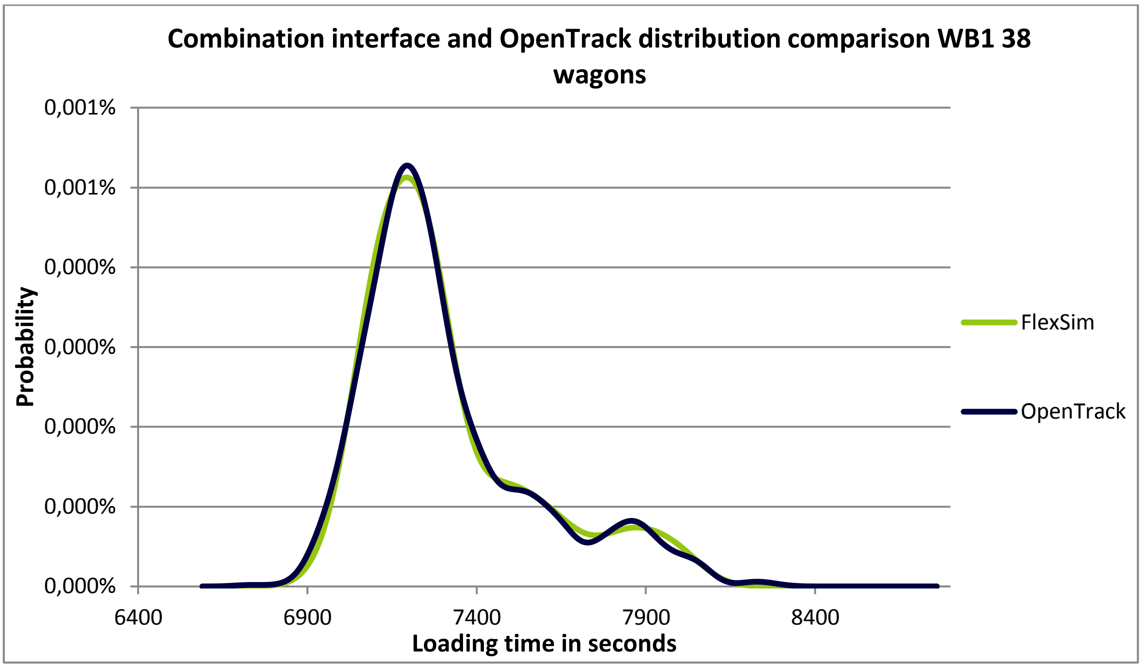

Figure C.1: Comparison of distributions of FlexSim and OpenTrack for WB1 with 38 wagons

WB4 with 40 wagons

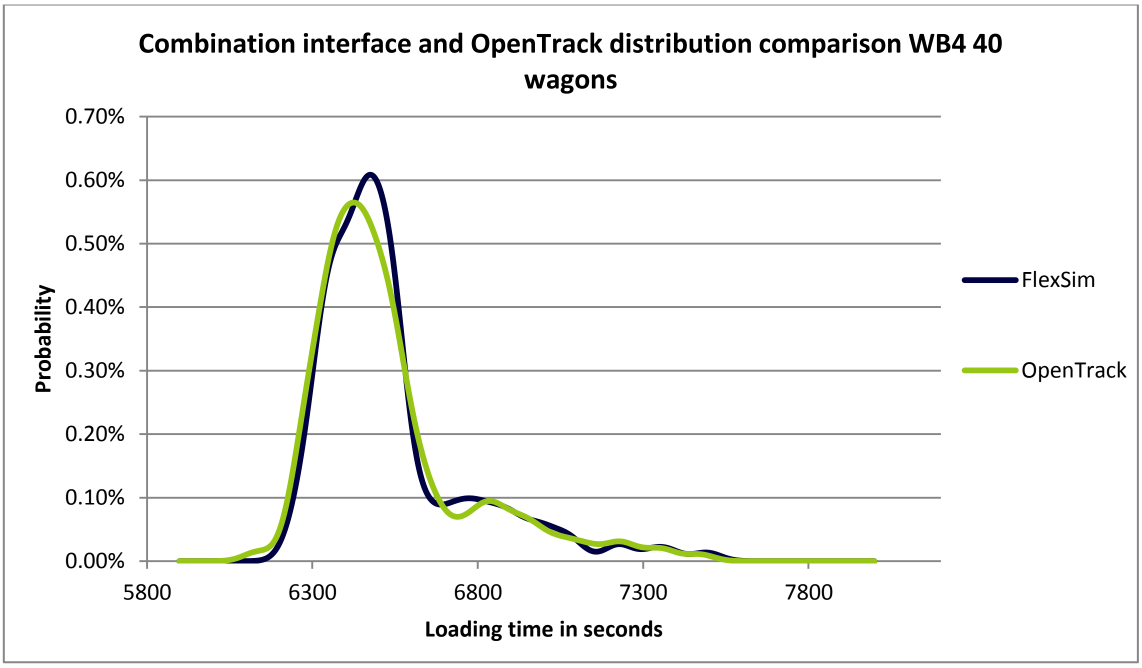

Figure C.2: Comparison of distributions of FlexSim and OpenTrack for WB4 with 40 wagons

WB4 with 32 wagons

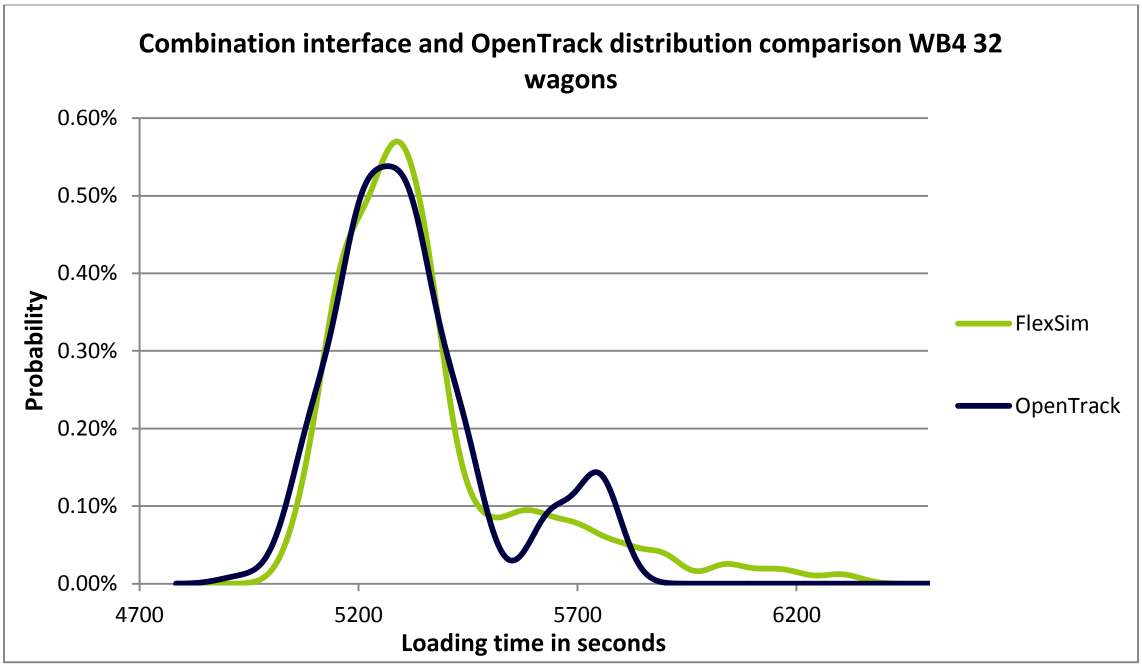

Figure C.312: Comparison of distributions of FlexSim and OpenTrack for WB4 with 32 wagons

WB3 with 44 wagons

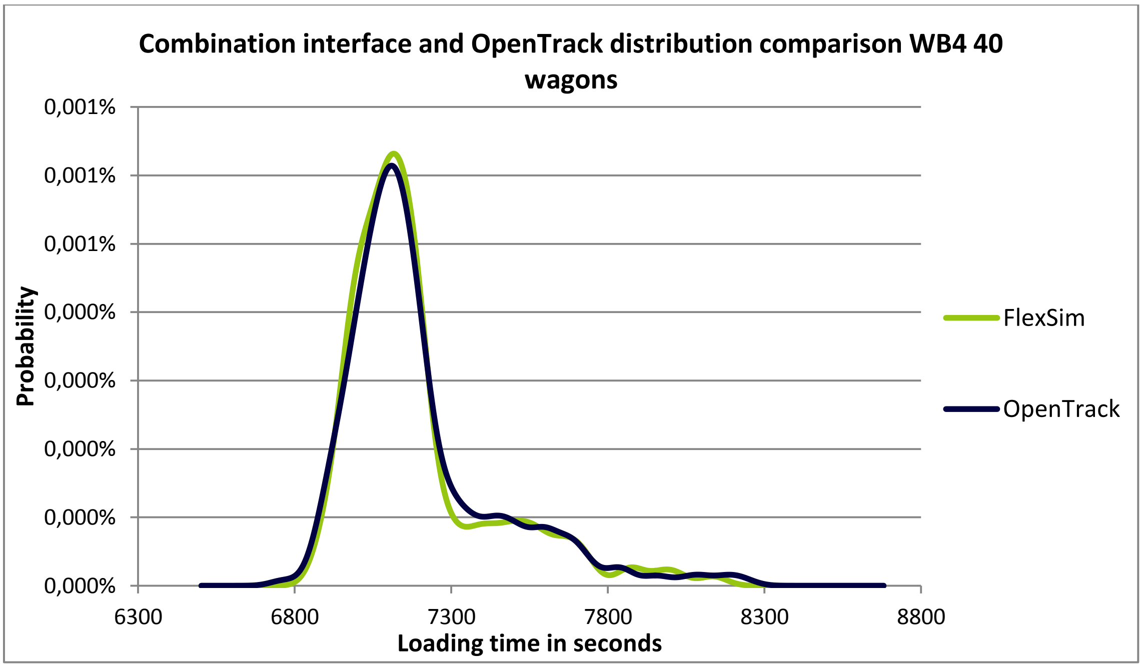

Figure C.413: Comparison of distributions of FlexSim and OpenTrack for WB3 with 44 wagons

D. Case Study Results: Individual results of interference

This appendix presents the individual results for all trains modelled in the case study. The individual results consist of:

- Two scatterplots determining the occurrence of delays by comparing the loading time with the turn-around time of a certain location
- Plotting the cumulative distributions of the Kernel Density Estimation for the loading time and each turn-around time. This comparison determines if turn-around times behave differently compared to the loading time
- Quartiles based on the distribution determined with the Kernel Density Estimation
- Dispersion width based on the determined dataset
- Standard deviation based on the determined dataset

The trains are: C49507, C47709, C49505, C49525, C48701, C48729, C48745, IO48711, IO48713, IO48715, IO48717, IO48719 and IO48721. A more detailed explanation of the trains can be found in 4.2.4 *Infrastructure operations model (OpenTrack).* More information about the determination and explanation of the results can be found in chapter 5.2 *Interference due to interaction infrastructure operations.*

C49507

Individual results for train C49507.

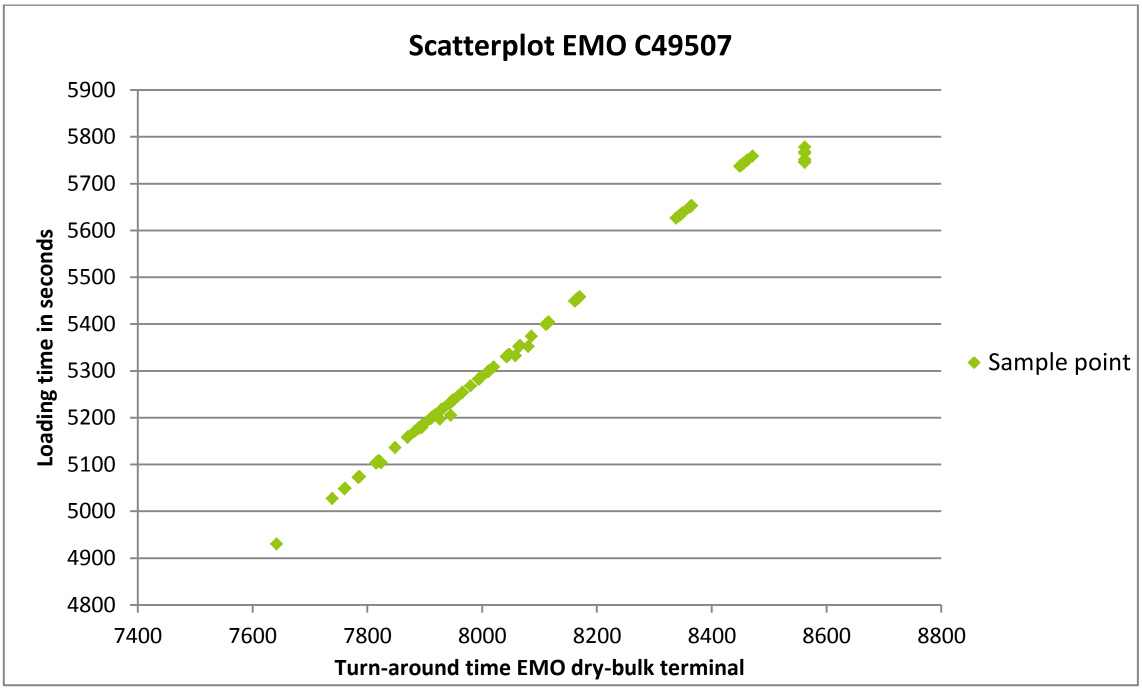

Figure D.1: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the C49507 train

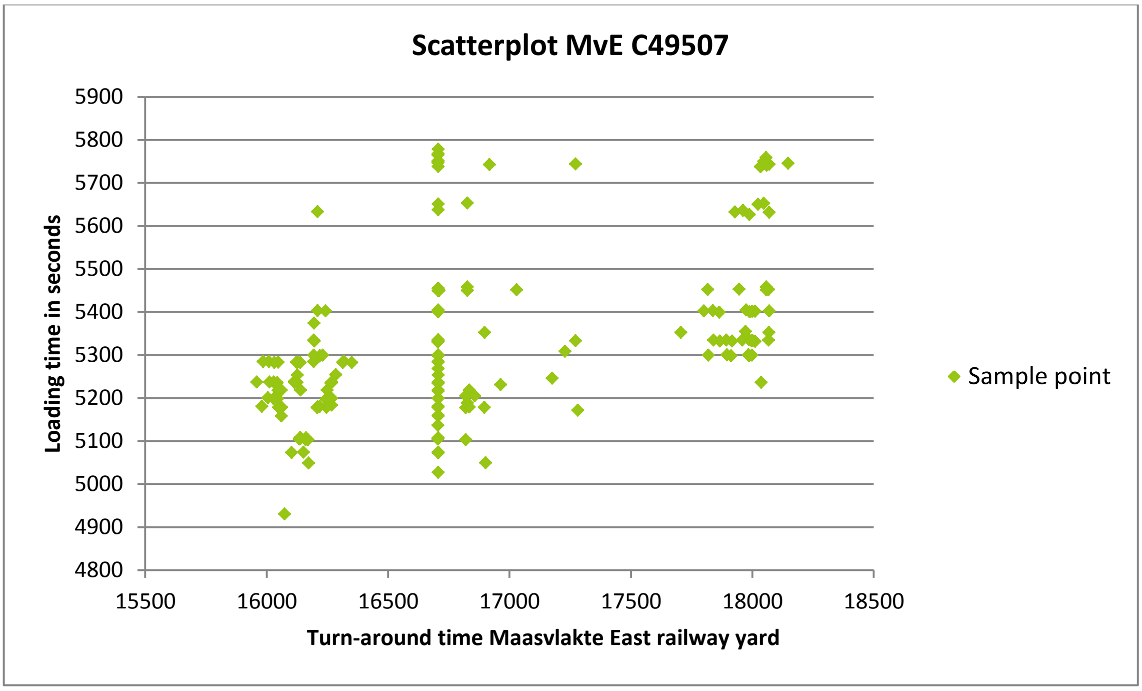

Figure D.2: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the 49507 train

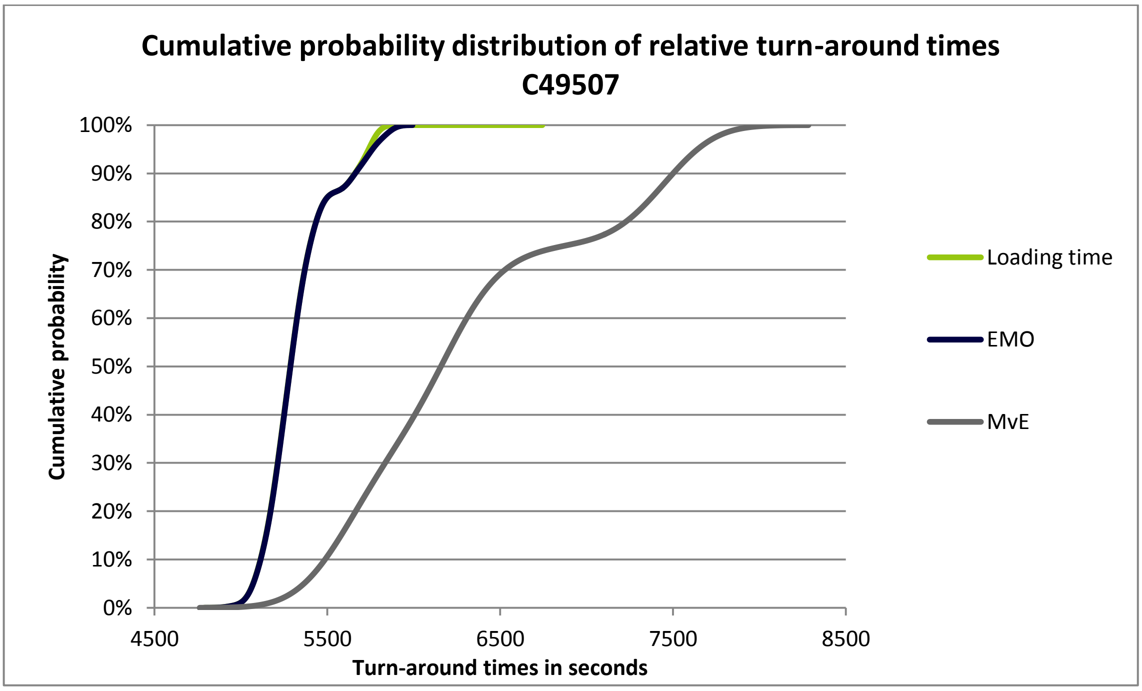

Figure D.3: Cumulative probability distribution of relative turn-around times for train C49507

Table D.1: Quartiles of relative turn-around times for train C49507

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	4996	4996	0.0%	5164	+3.4%
Q1	25%	5192	5194	0.0%	5749	+10.7%
Median	50%	5286	5287	0.0%	6158	+16.5%
Q3	75%	5398	5399	0.0%	6874	+27.3%
Maximum	99%	5806	5873	+1.2%	7858	+35.3%

Table D.2: Dispersion width for train C49507

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	4930	7642	4930	15959	5429
Maximum	5778	8562	5850	18147	7617
Dispersion width	848	920		2188	

The difference in dispersion width between the loading time and the TA MvE is +158.0%.

Table D.3: Standard deviation for train C49507

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
49507	186	193	704	518	+278.9%

C47709

Individual results for train C47709.

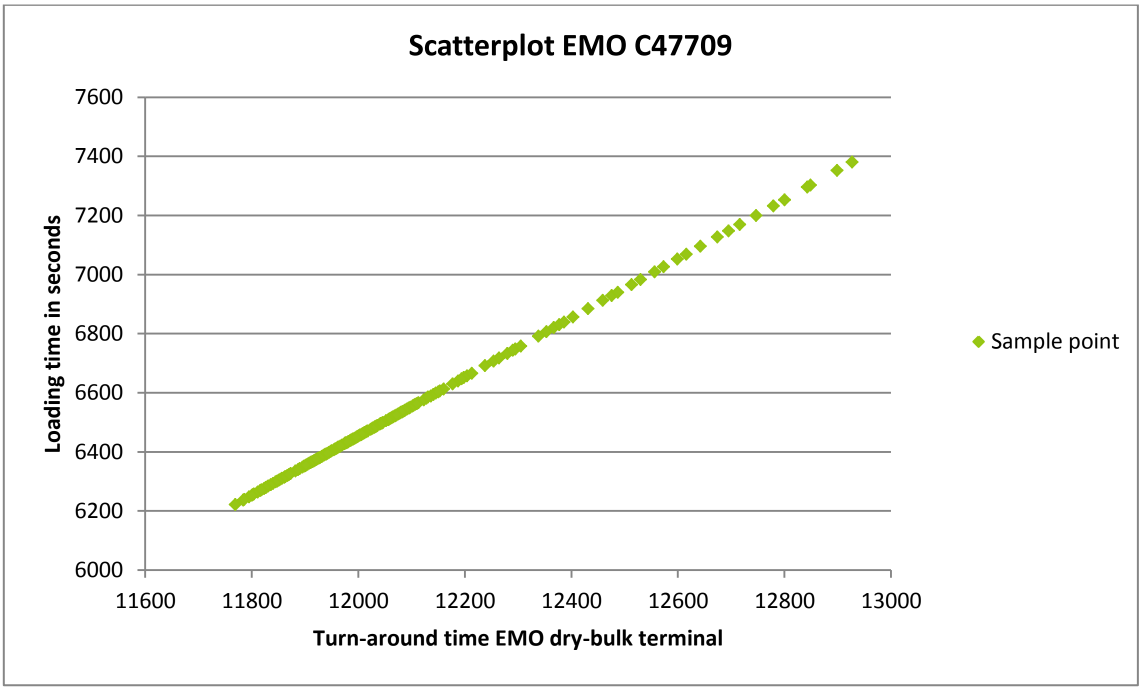

Figure D.4: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the C47709 train

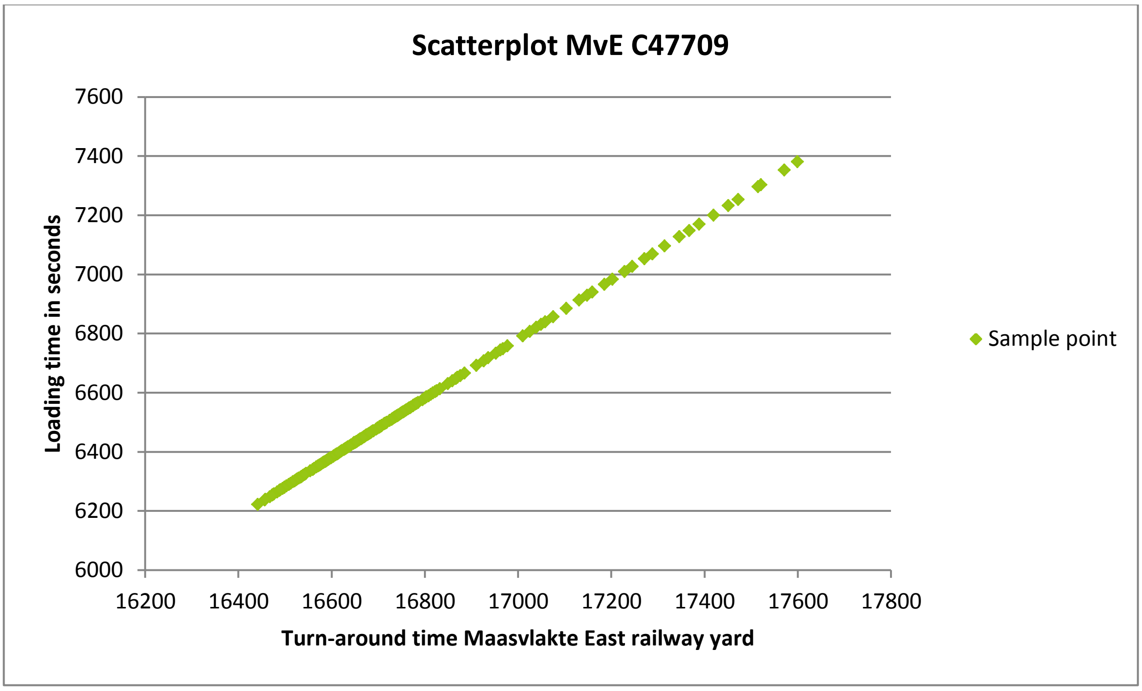

Figure D.5: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the C47709 train

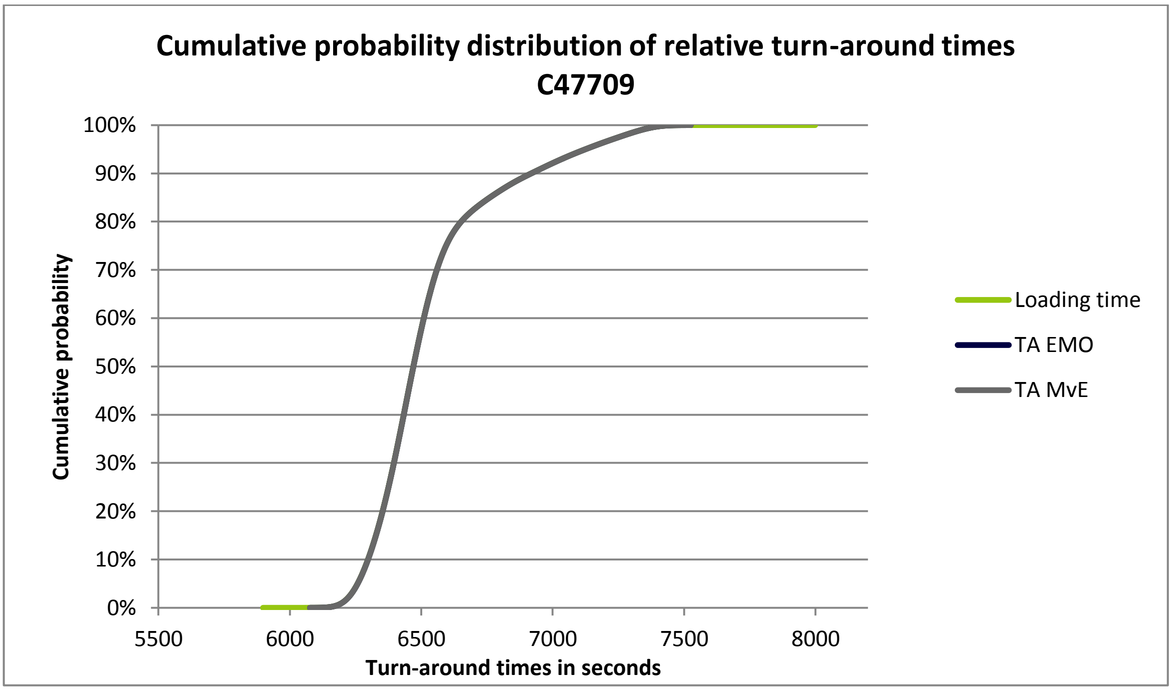

Figure D.614: Cumulative probability distribution of relative turn-around times for train C47709

Table D.4: Quartiles of relative turn-around times for train C47709

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6197	6198	0.0%	6198	0.0%
Q1	25%	6375	6375	0.0%	6375	0.0%
Median	50%	6470	6470	0.0%	6470	0.0%
Q3	75%	6594	6594	0.0%	6594	0.0%
Maximum	99%	7339	7338	0.0%	7338	0.0%

Table D.5: Dispersion width for train C47709

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6222	11769	6222	16441	6222
Maximum	7380	12927	7380	17599	7380
Dispersion width	1158	1158		1158	

The difference in dispersion width between the loading time and the TA MvE is 0.0%.

Table D.6: Standard deviation for train C47709

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
47709	246	246	246	0	0.0%

C49505

Individual results for train C49505.

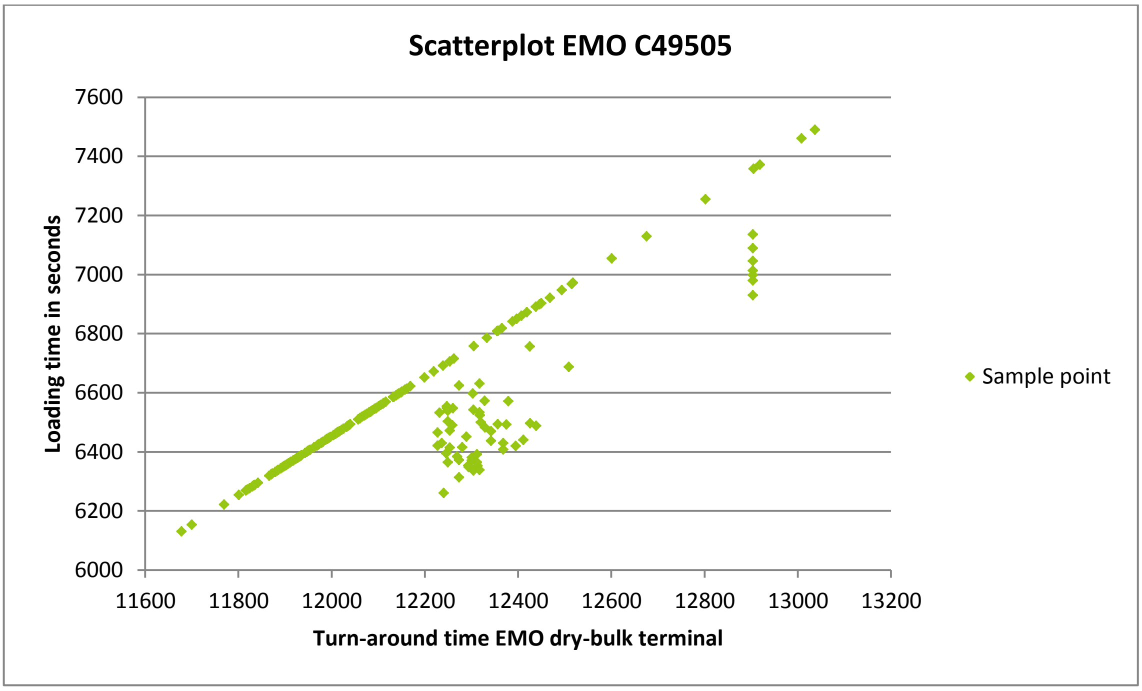

Figure D.7: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the C49505 train

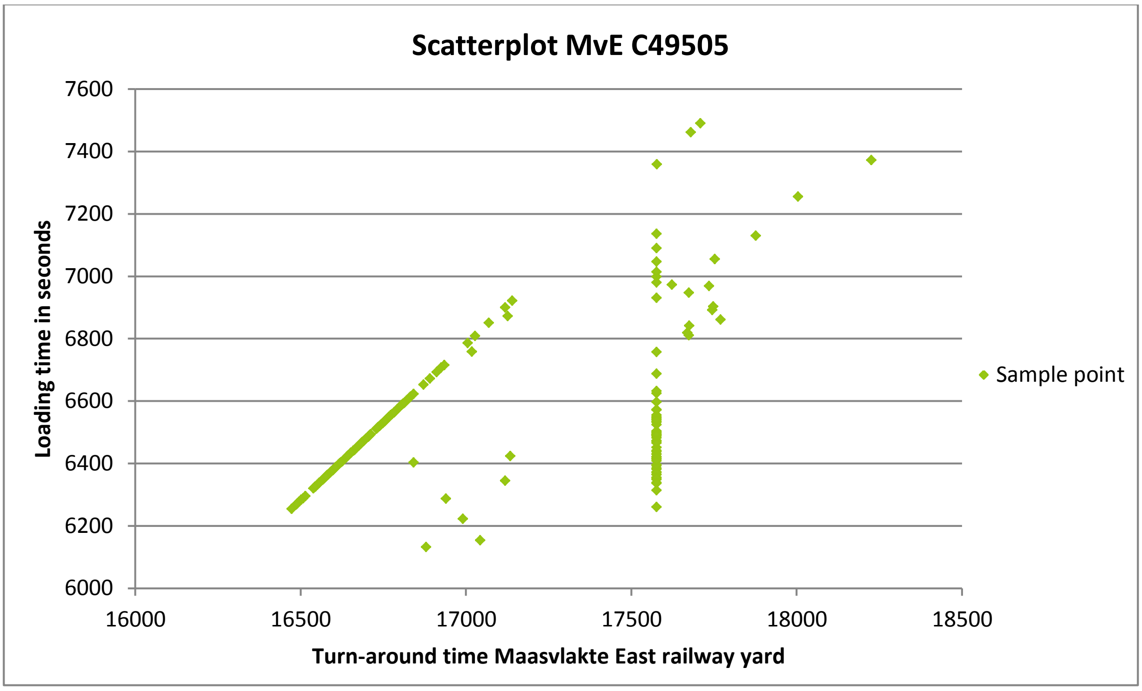

Figure D.8: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the C49505 train

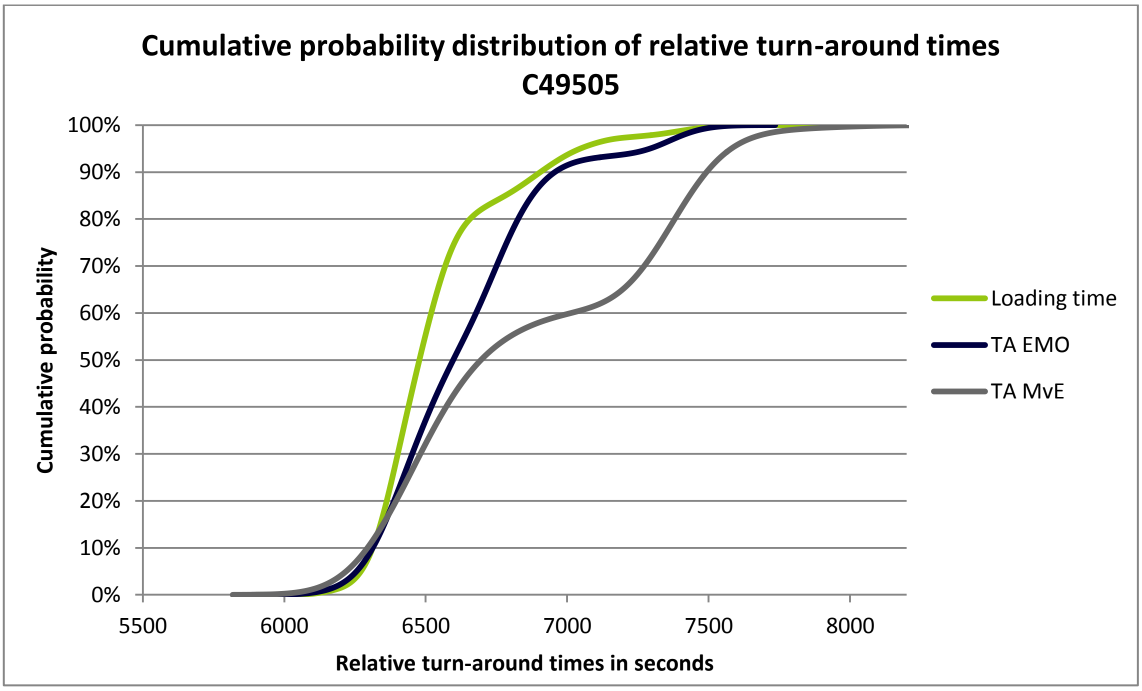

Figure D.9: Cumulative probability distribution of relative turn-around times for train C49505

Table D.7: Quartiles of relative turn-around times for train C49505

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6174	6147	-0.4%	6089	-1.4%
Q1	25%	6382	6421	+0.6%	6438	+0.9%
Median	50%	6479	6597	+1.8%	6696	+3.4%
Q3	75%	6603	6786	+2.8%	7329	+11.0%
Maximum	99%	7425	7469	+0.6%	7797	+5.0%

Table D.8: Dispersion width for train C49505

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6131	11678	6131	16473	6254
Maximum	7490	13037	7490	18226	8007
Dispersion width	1359	1359		1753	

The difference in dispersion width between the loading time and the TA MvE is +29.0%.

Table D.9: Standard deviation for train C49505

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
49505	241	275	460	219	90.7%

C49525

Individual results for train C49525.

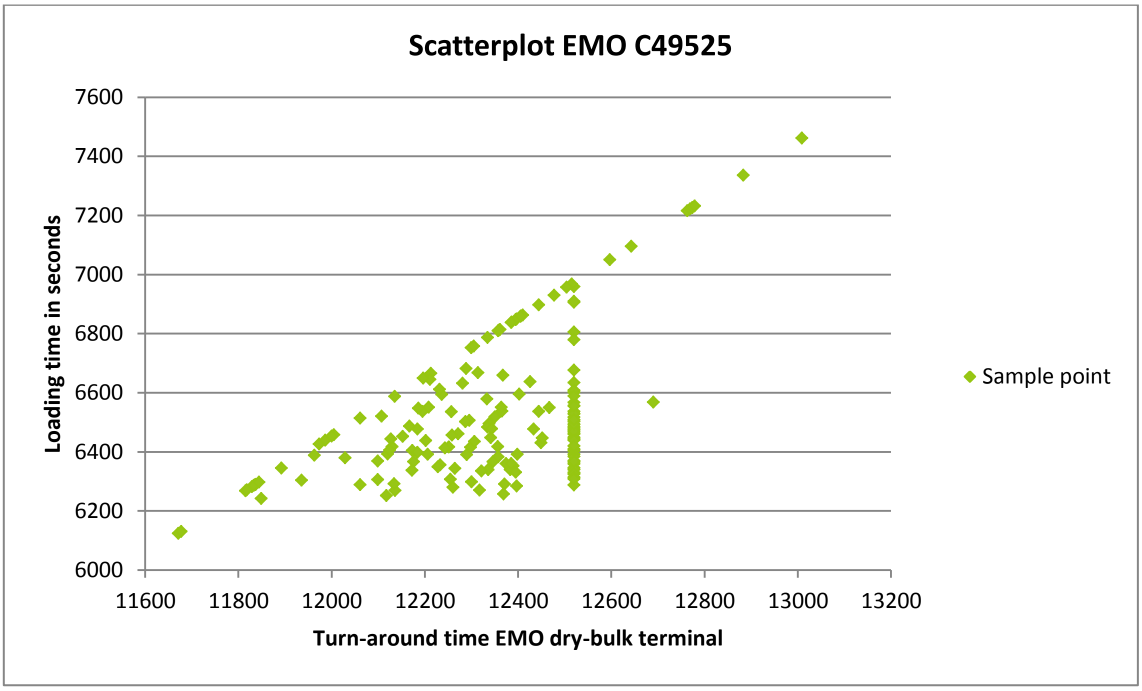

Figure D.10: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the C49525 train

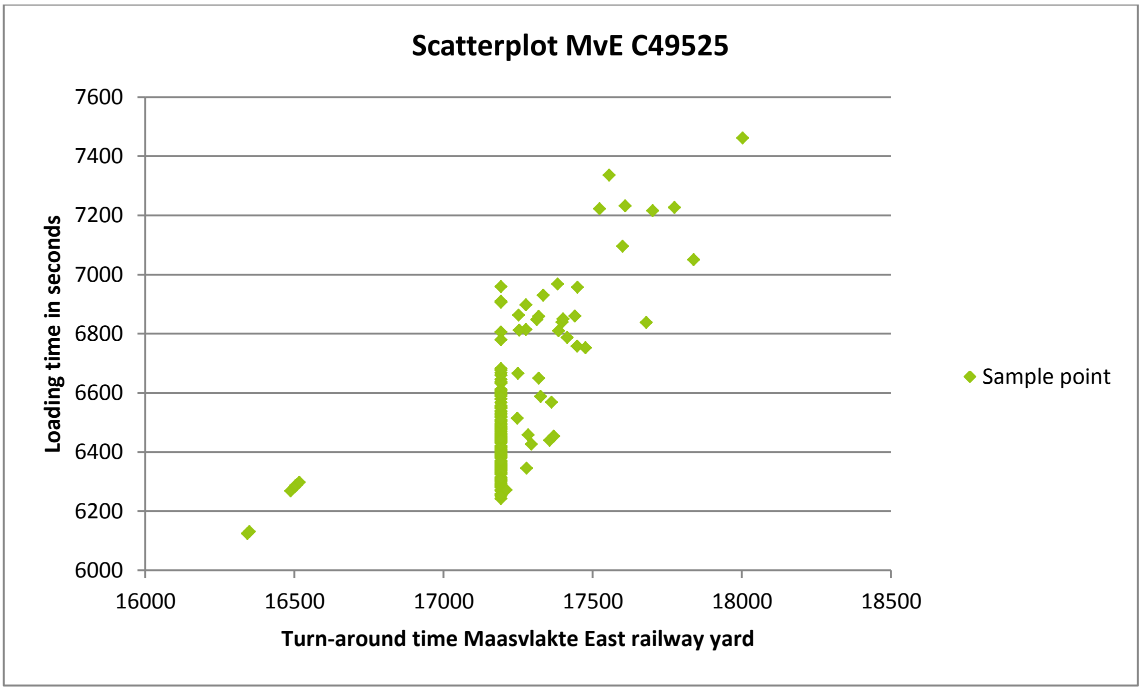

Figure D.11: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the C49525 train

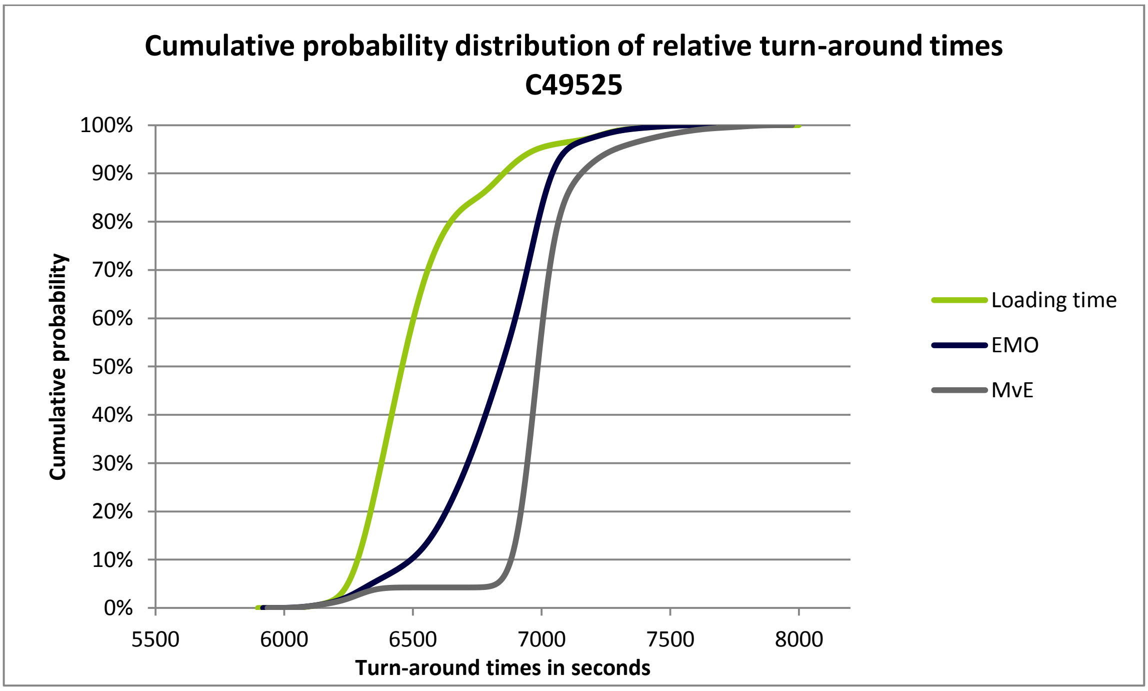

Figure D.12: Cumulative probability distribution of relative turn-around times for train C49525

Table D.10: Quartiles of relative turn-around times for train C49525

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6161	6170	+0.2%	6180	+0.3%
Q1	25%	6356	6675	+5.0%	6933	+9.1%
Median	50%	6460	6843	+5.9%	6986	+8.1%
Q3	75%	6594	6964	+5.6%	7045	+6.8%
Maximum	99%	7311	7321	+0.1%	7602	+4.0%

Table D.11: Dispersion width for train C49525

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6124	11671	6124	16343	6124
Maximum	7462	13009	7462	18003	7784
Dispersion width	1338	1338		1660	

The difference in dispersion width between the loading time and the TA MvE is +24.1%.

Table D.12: Standard deviation for train C49525

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
49525	231	222	199	-31	-13.5%

C48701

Individual results for train C48701.

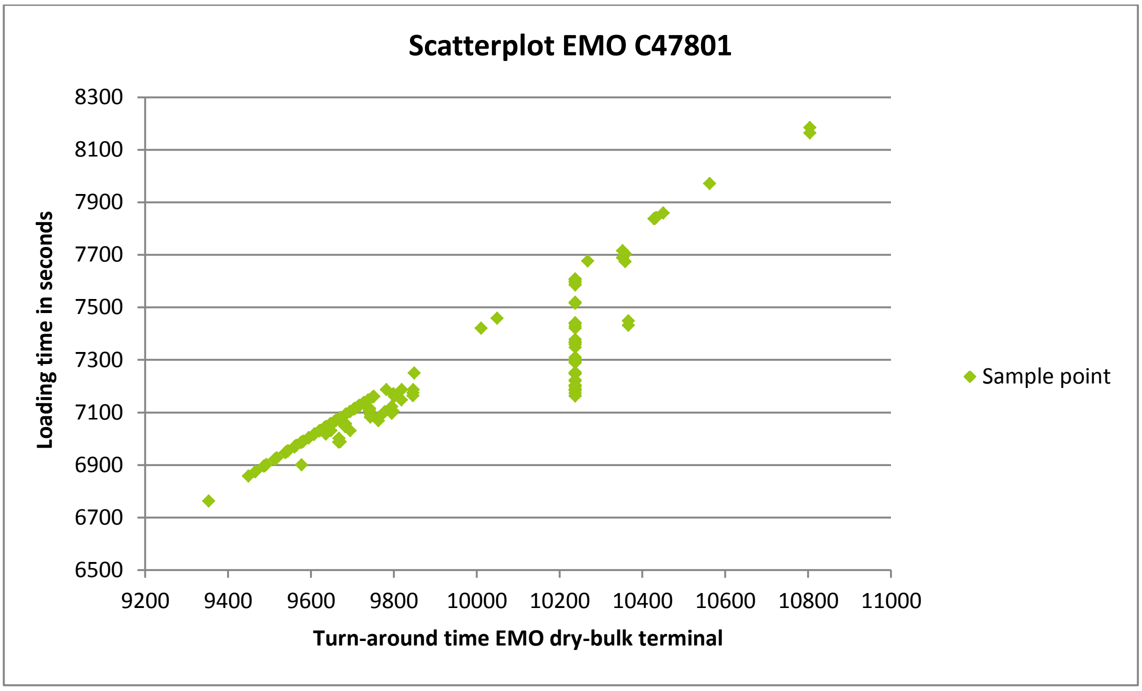

Figure D.13: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the C48701 train

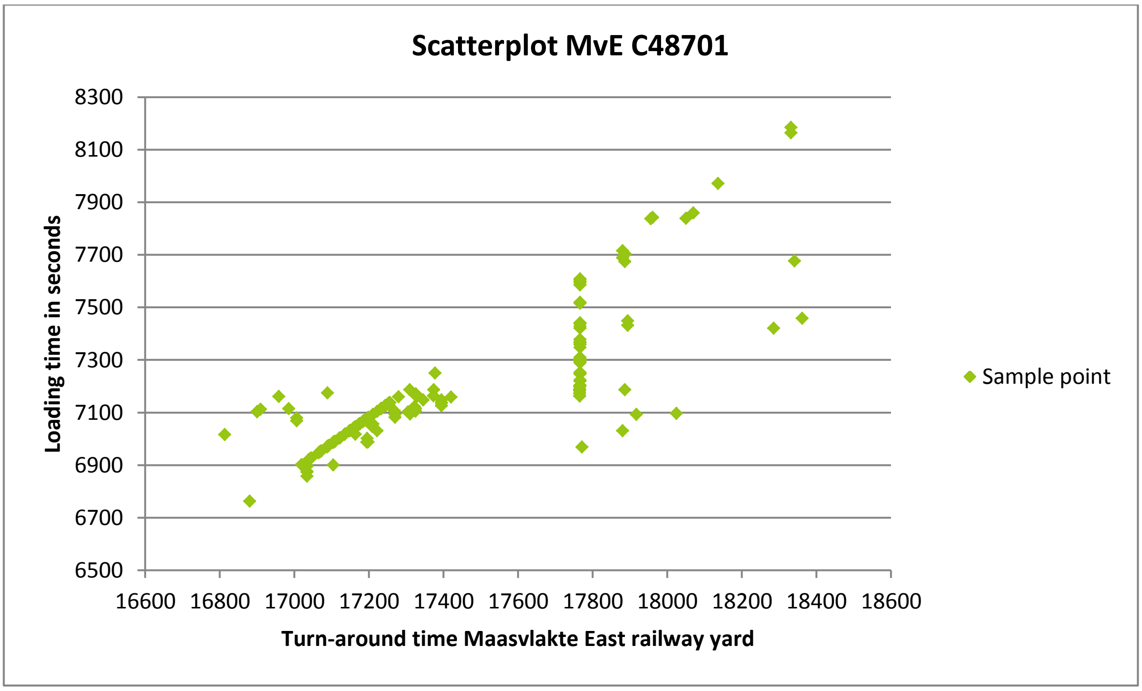

Figure D.14: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the C48701 train

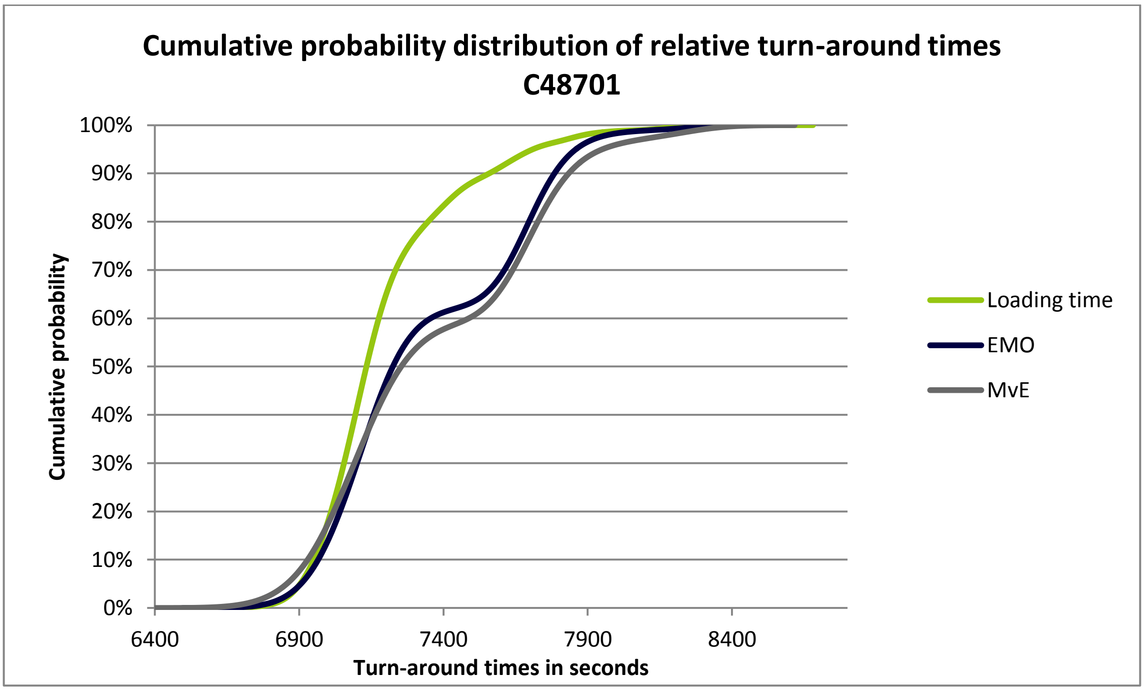

Figure D.15: Cumulative probability distribution of relative turn-around times for train C48701

Table D.13: Quartiles of relative turn-around times for train C48701

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6818	6798	-0.3%	6722	-1.4%
Q1	25%	7034	7071	+0.5%	7056	+0.3%
Median	50%	7132	7225	+1.3%	7254	+1.7%
Q3	75%	7280	7657	+5.2%	7684	+5.5%
Maximum	99%	8090	8132	+0.5%	8285	+2.4%

Table D.14: Dispersion width for train C48701

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6762	9353	6797	16813	6730
Maximum	8184	10804	8248	18362	8279
Dispersion width	1422	1451		1549	

The difference in dispersion width between the loading time and the TA MvE is +8.9%.

Table D.15: Standard deviation for train C48701

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
48701	244	318	357	113	+46.3%

C48729

Individual results for train C48729.

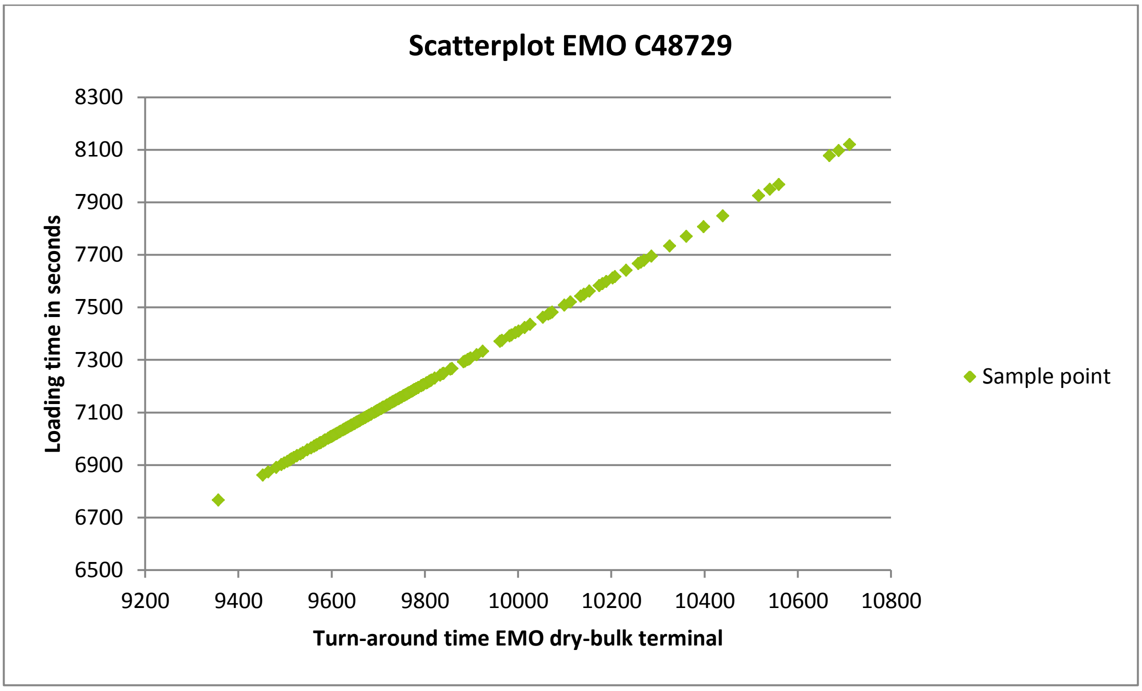

Figure D.16: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the C48729 train

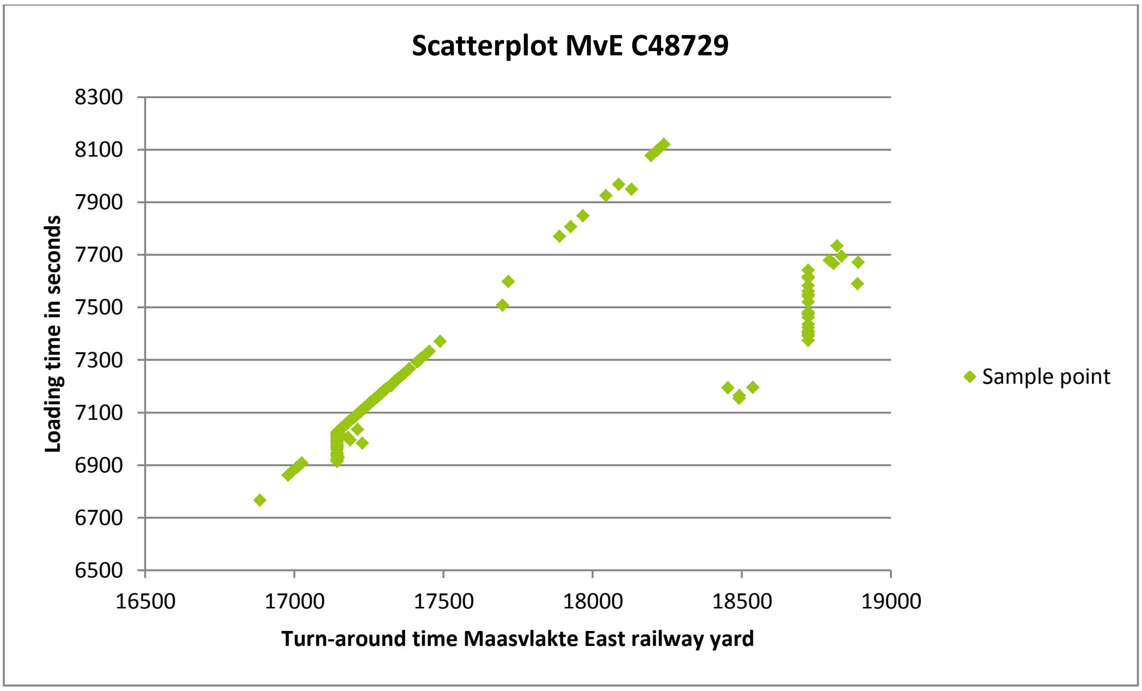

Figure D.17: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the C48729 train

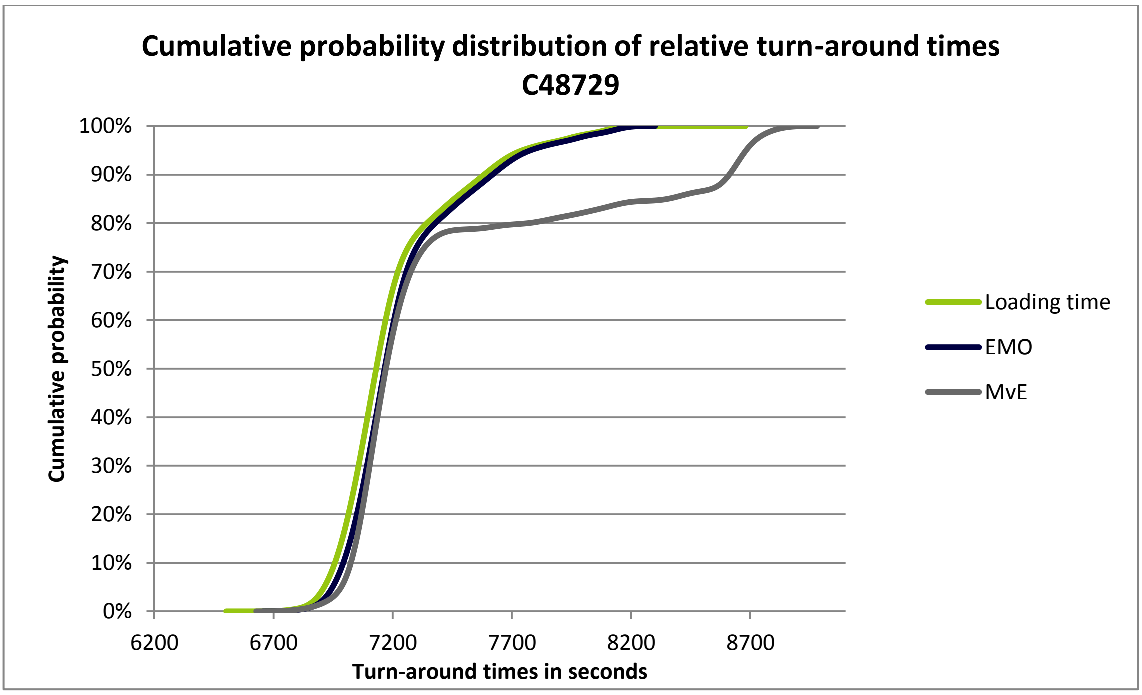

Figure D.18: Cumulative probability distribution of relative turn-around times for train C48729

Table D.16: Quartiles of relative turn-around times for train C48729

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6831	6866	+0.5%	6868	+0.5%
Q1	25%	7036	7072	+0.5%	7087	+0.7%
Median	50%	7130	7166	+0.5%	7172	+0.6%
Q3	75%	7265	7299	+0.5%	7334	+1.0%
Maximum	99%	8081	8116	+0.4%	8792	+8.8%

Table D.17: Dispersion width for train C48729

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6766	9357	6801	16884	6801
Maximum	8120	10711	8155	18890	8807
Dispersion width	1354	1354		2006	

The difference in dispersion width between the loading time and the TA MvE is +48.2%.

Table D.18: Standard deviation for train C48729

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
48729	253	253	562	309	+122.0%

C48745

Individual results for train C48745.

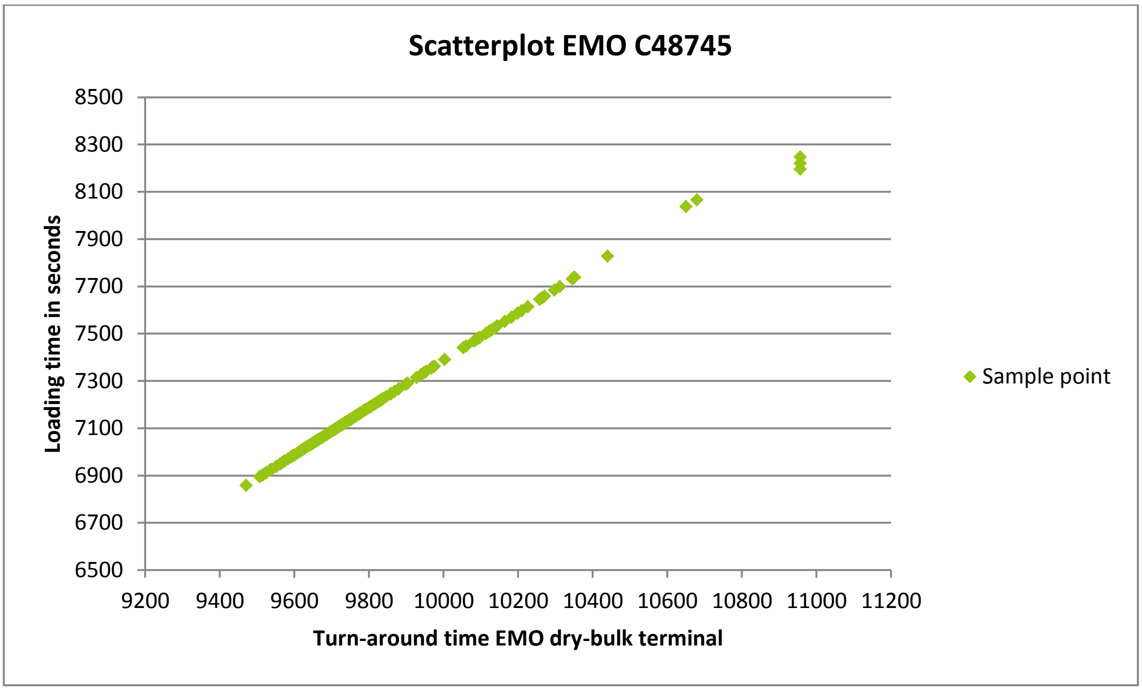

Figure D.19: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the C48745 train

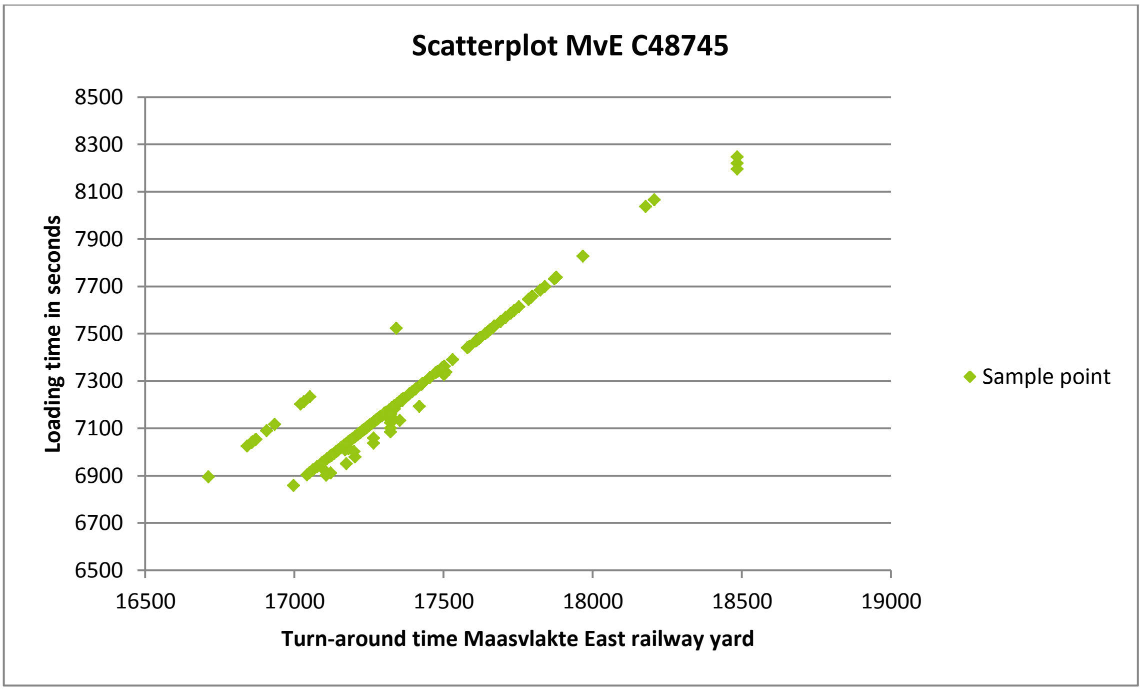

Figure D.20: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the C48745 train

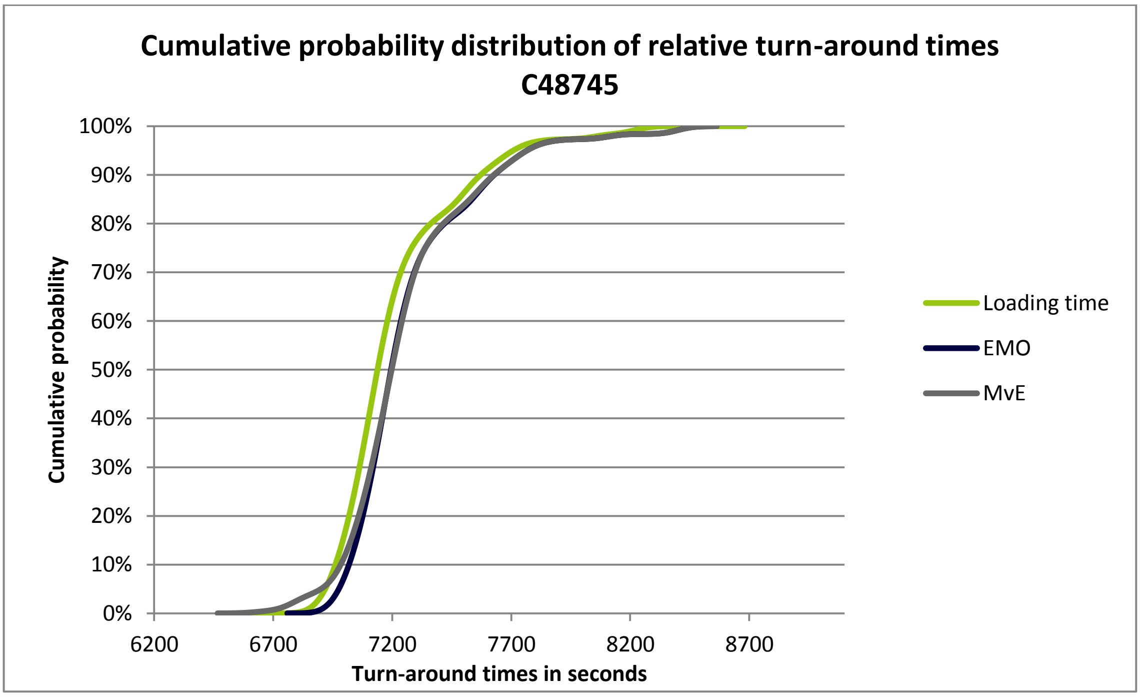

Figure D.21: Cumulative probability distribution of relative turn-around times for train C48745

Table D.19: Quartiles of relative turn-around times for train C48745

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6851	6910	+0.9%	6724	-1.8%
Q1	25%	7043	7099	+0.8%	7088	+0.6%
Median	50%	7139	7195	+0.8%	7197	+0.8%
Q3	75%	7280	7339	+0.8%	7338	+0.8%
Maximum	99%	8203	8384	+2.2%	8383	+2.2%

Table D.20: Dispersion width for train C48745

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6858	9471	6915	16712	6629
Maximum	8247	10957	8401	18484	8401
Dispersion width	1389	1486		1772	

The difference in dispersion width between the loading time and the TA MvE is +27.6%.

Table D.21: Standard deviation for train C48745

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
48745	256	264	280	24	+9.4%

IO48711

Individual results for train IO48711.

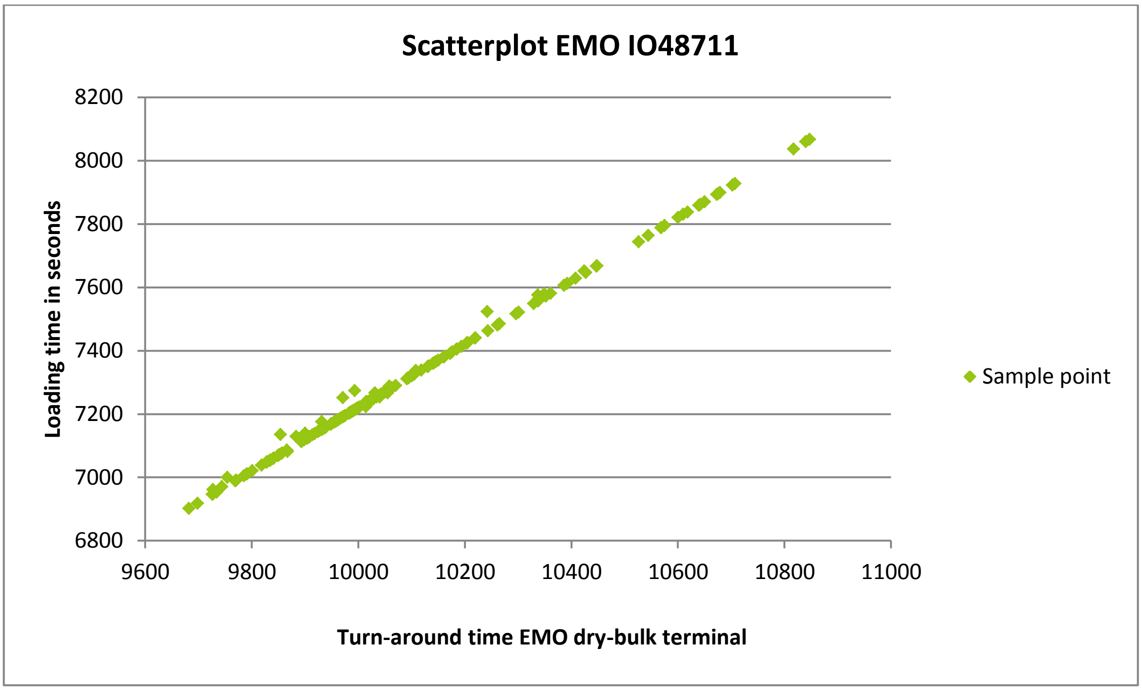

Figure D.22: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the IO48711 train

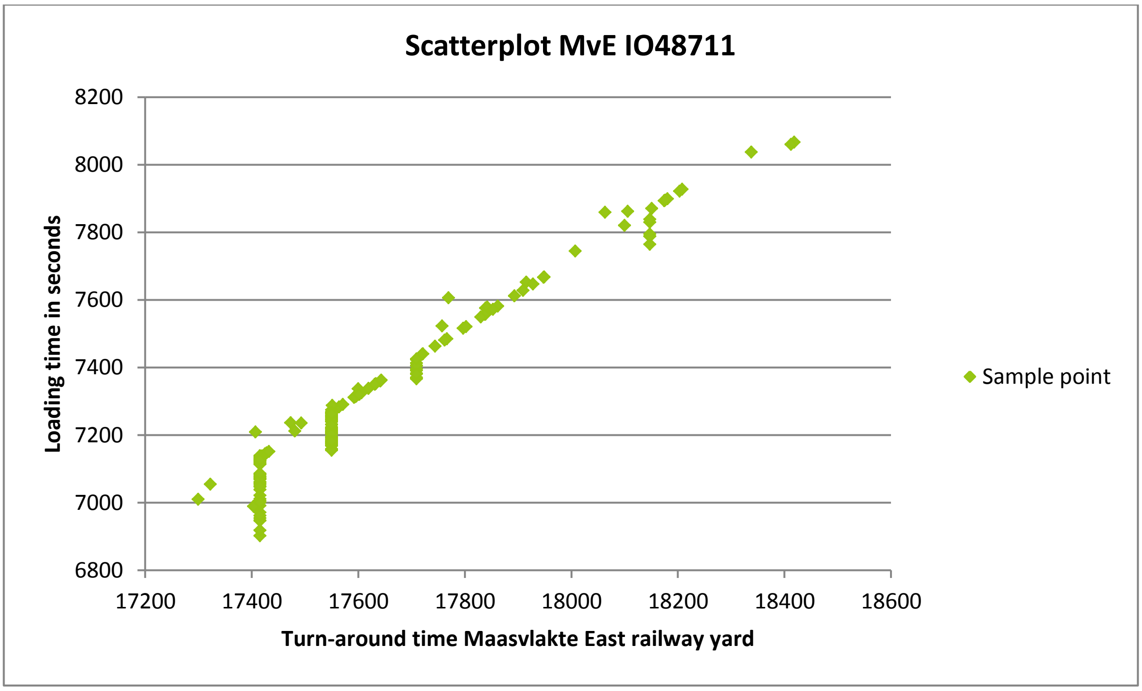

Figure D.23: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the IO48711 train

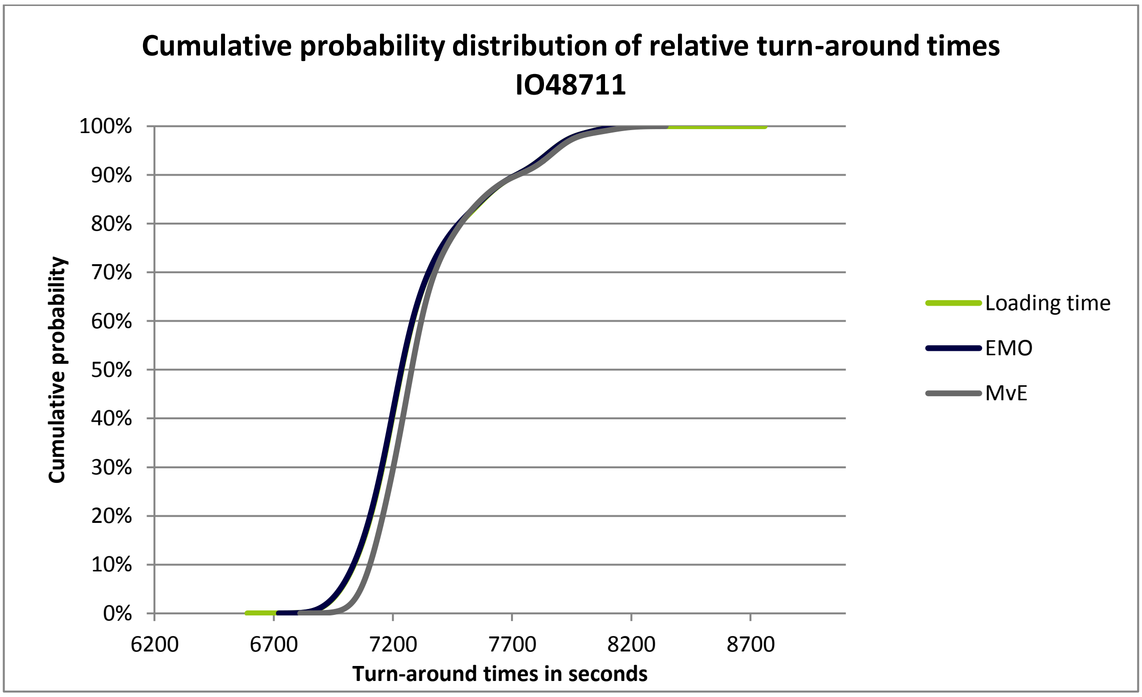

Figure D.24: Cumulative probability distribution of relative turn-around times for train IO48711

Table D.22: Quartiles of relative turn-around times for train IO48711

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6894	6891	0.0%	6998	+1.5%
Q1	25%	7133	7131	0.0%	7181	+0.7%
Median	50%	7237	7235	0.0%	7279	+0.6%
Q3	75%	7402	7401	0.0%	7422	+0.3%
Maximum	99%	8038	8040	0.0%	8086	+0.6%

D.23: Dispersion width for train IO48711

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6902	9682	6902	17299	7018
Maximum	8067	10847	8067	18418	8137
Dispersion width	1165	1165		1119	

The difference in dispersion width between the loading time and the TA MvE is -3.9%.

Table D.24: Standard deviation for train IO48711

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
48711	251	252	231	-20	-8.0%

IO48713

Individual results for train IO48713.

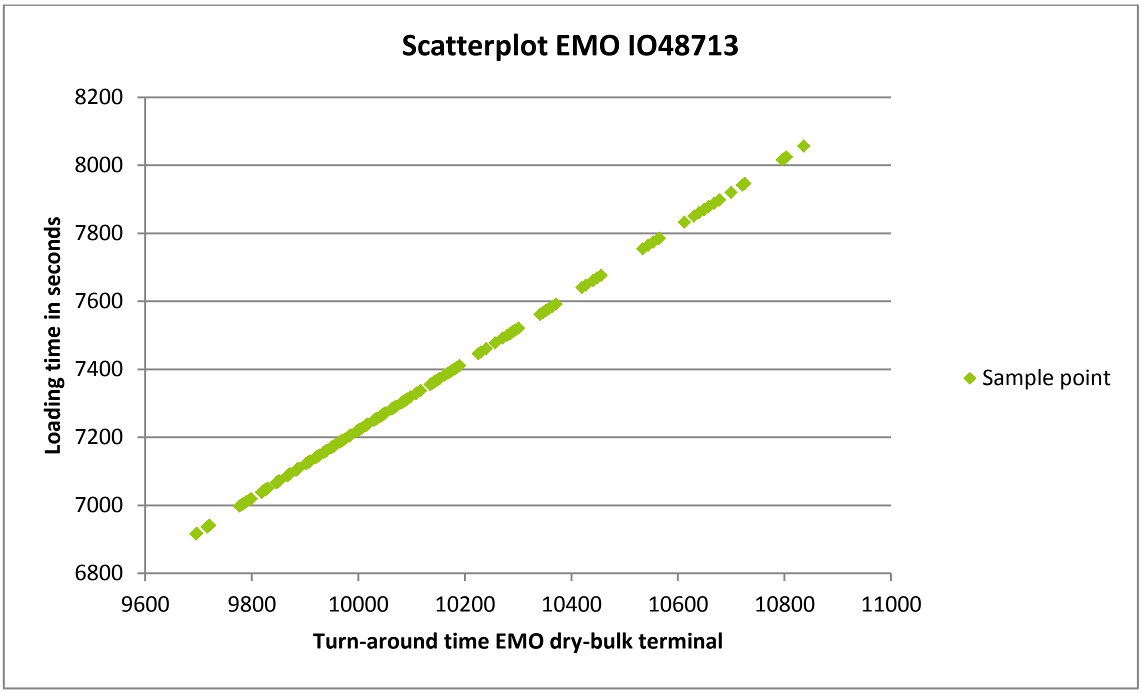

Figure D.25: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the IO48713train

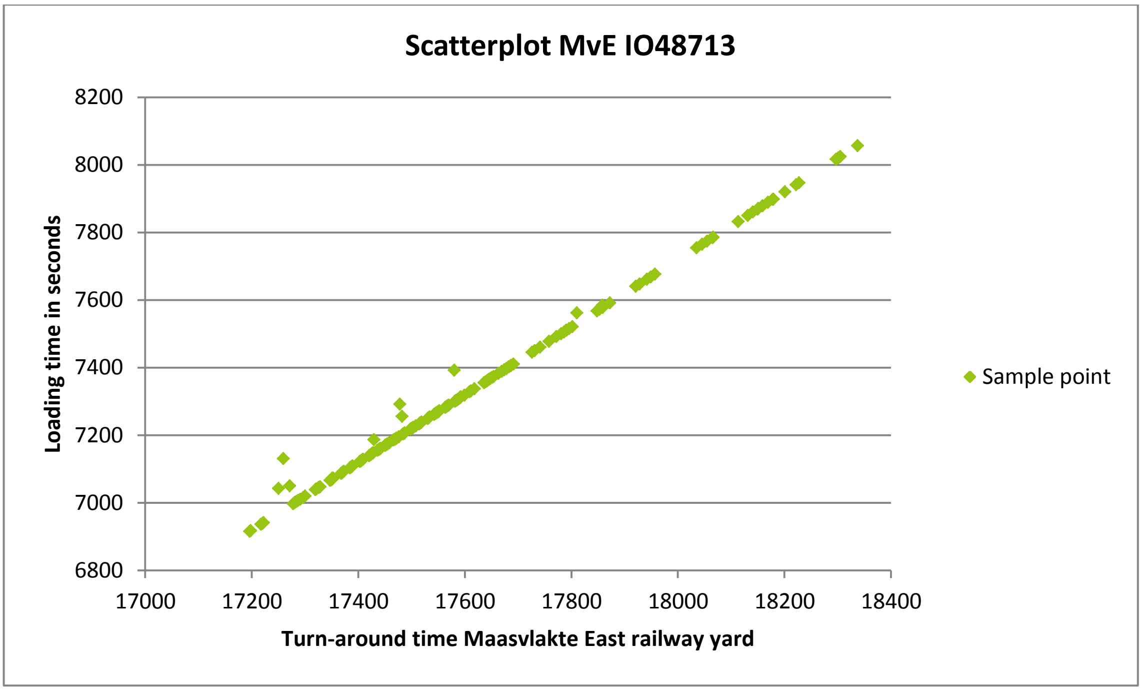

Figure D.26: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the IO48713 train

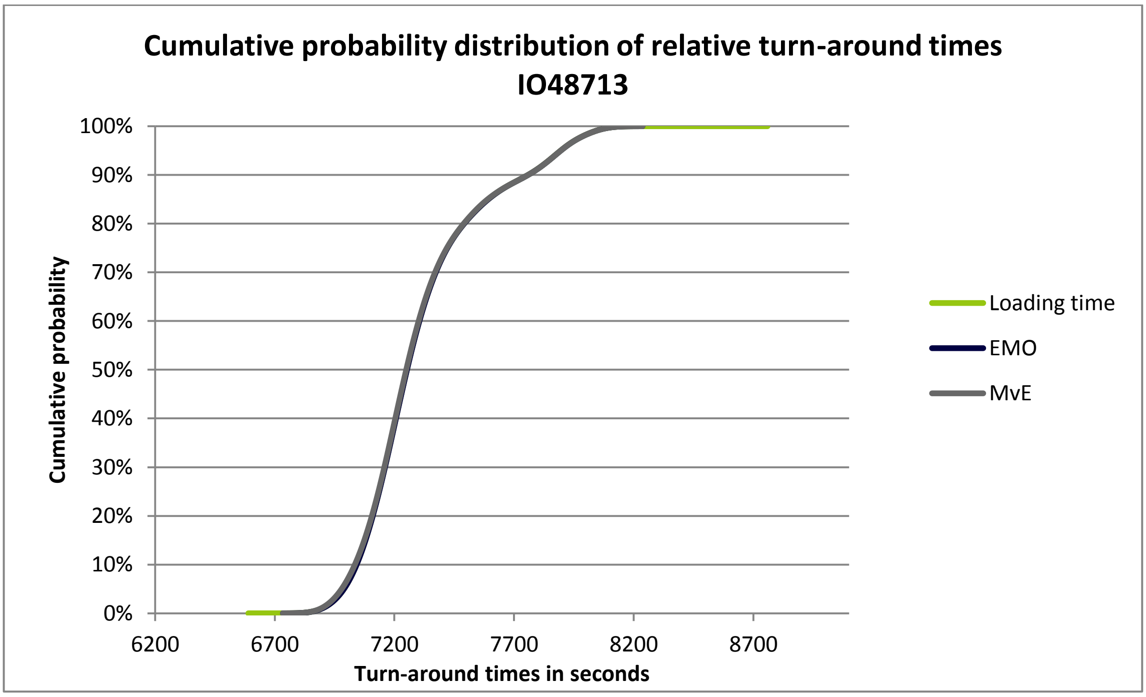

Figure D.27: Cumulative probability distribution of relative turn-around times for train IO48713

Table D.25: Quartiles of relative turn-around times for train IO48713

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6898	6898	0.0%	6892	-0.1%
Q1	25%	7137	7136	0.0%	7133	-0.1%
Median	50%	7252	7253	0.0%	7250	0.0%
Q3	75%	7421	7422	0.0%	7420	0.0%
Maximum	99%	8038	8040	0.0%	8040	0.0%

Table D.26: Dispersion width for train IO48713

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6915	9695	6915	17196	6915
Maximum	8056	10836	8056	18337	8056
Dispersion width	1141	1141		1141	

The difference in dispersion width between the loading time and the TA MvE is 0.0%.

Table D.27: Standard deviation for train IO48713

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
48713	257	257	259	2	+0.7%

IO48715

Individual results for train IO48715.

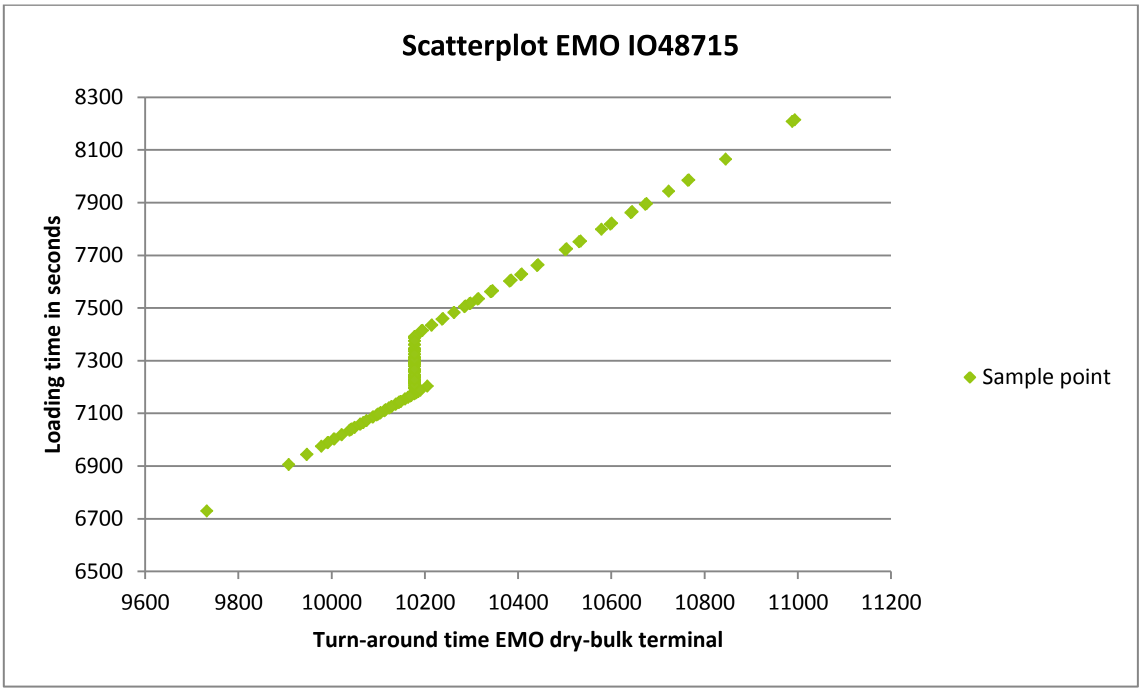

Figure D.28: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the IO48715 train

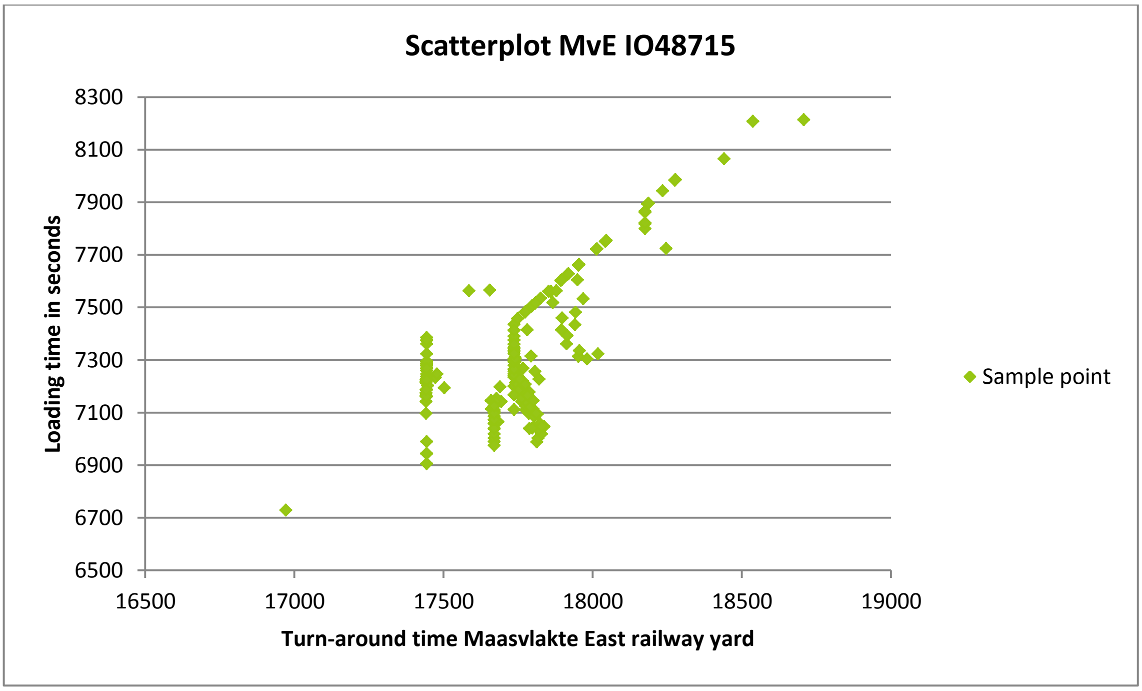

Figure D.29: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the IO48715 train

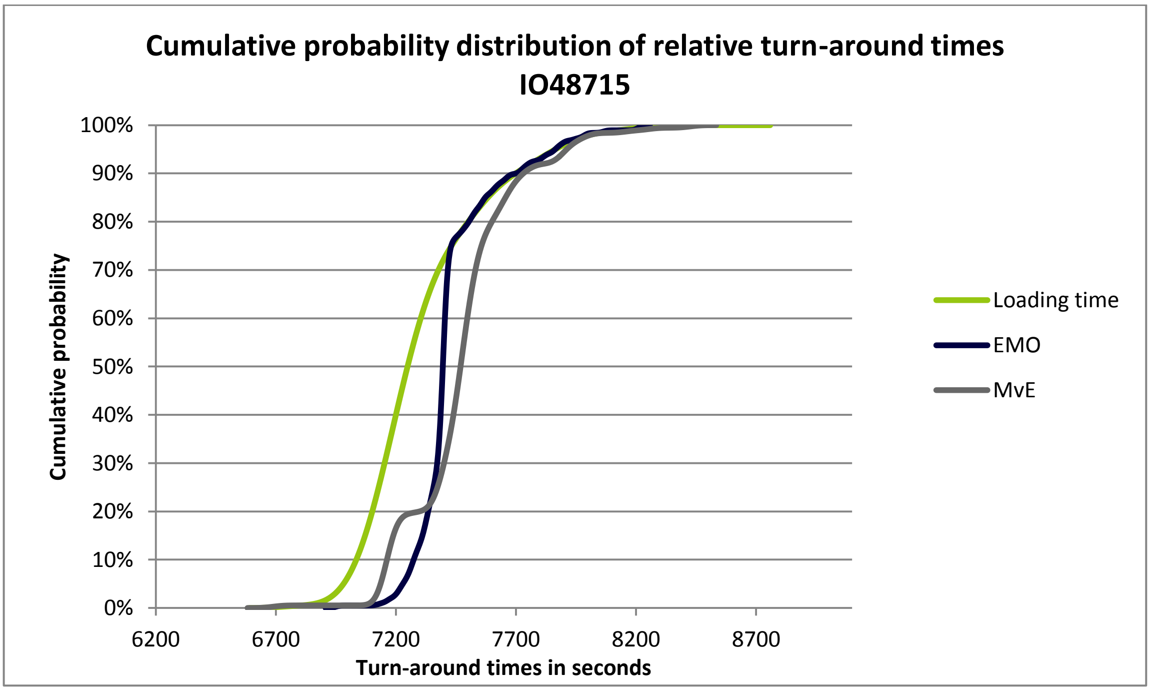

Figure D.30: Cumulative probability distribution of relative turn-around times for train IO48715

Table D.28: Quartiles of relative turn-around times for train IO48715

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6872	7140	+3.9%	7090	+3.2%
Q1	25%	7128	7356	+3.2%	7374	+3.4%
Median	50%	7248	7396	+2.0%	7470	+3.1%
Q3	75%	7432	7431	0.0%	7558	+1.7%
Maximum	99%	8140	8187	+0.6%	8220	+1.0%

Table D.29: Dispersion width for train IO48715

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6729	9732	6952	16971	6690
Maximum	8214	10994	8214	18708	8427
Dispersion width	1485	1262		1737	

The difference in dispersion width between the loading time and the TA MvE is +17.0%.

Table D.30: Standard deviation for train IO48715

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
48715	259	184	229	-30	-11.7%

IO48717

Individual results for train IO48717.

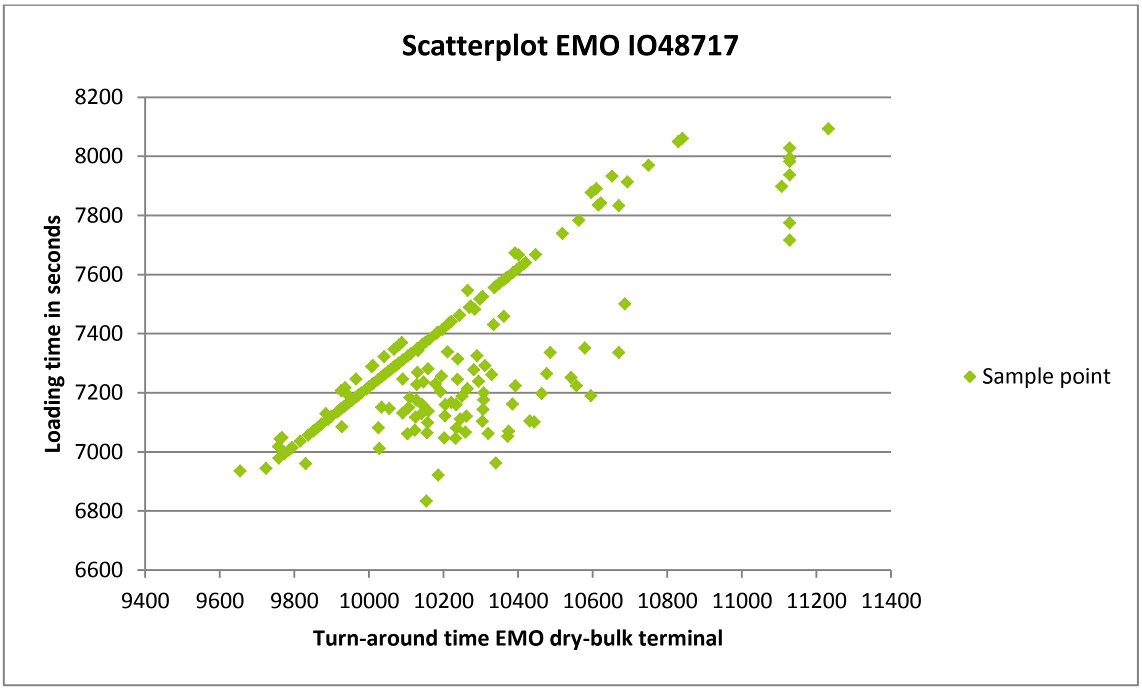

Figure D.31: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the IO48717 train

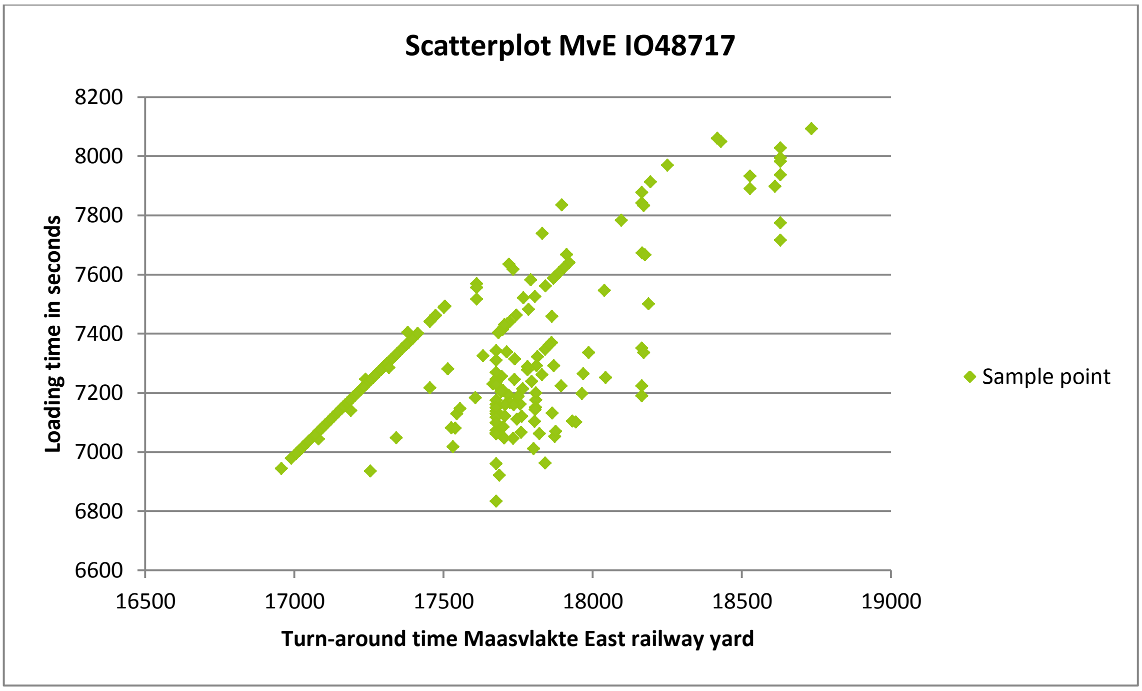

Figure D.32: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the IO48717 train

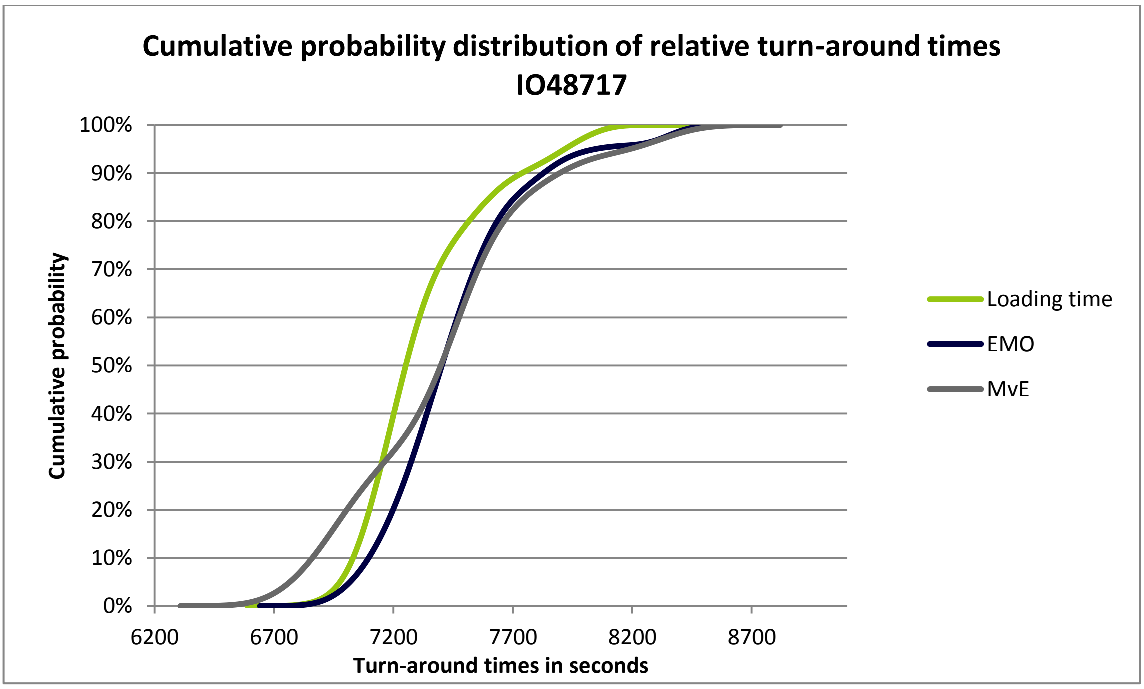

Figure D.33: Cumulative probability distribution of relative turn-around times for train IO48717

Table D.31: Quartiles of relative turn-around times for train IO48717

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6872	6897	+0.4%	6620	-3.7%
Q1	25%	7126	7238	+1.6%	7080	-0.7%
Median	50%	7252	7402	+2.1%	7399	+2.0%
Q3	75%	7441	7582	+1.9%	7602	+2.2%
Maximum	99%	8077	8417	+4.2%	8455	+4.7%

Table D.32: Dispersion width for train IO48717

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6833	9654	6874	16956	6675
Maximum	8093	11232	8452	18733	8452
Dispersion width	1260	1578		1777	

The difference in dispersion width between the loading time and the TA MvE is +41.0%.

Table D.33: Standard deviation for train IO48717

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
48717	265	301	387	122	+46.0%

IO48719

Individual results for train IO48719.

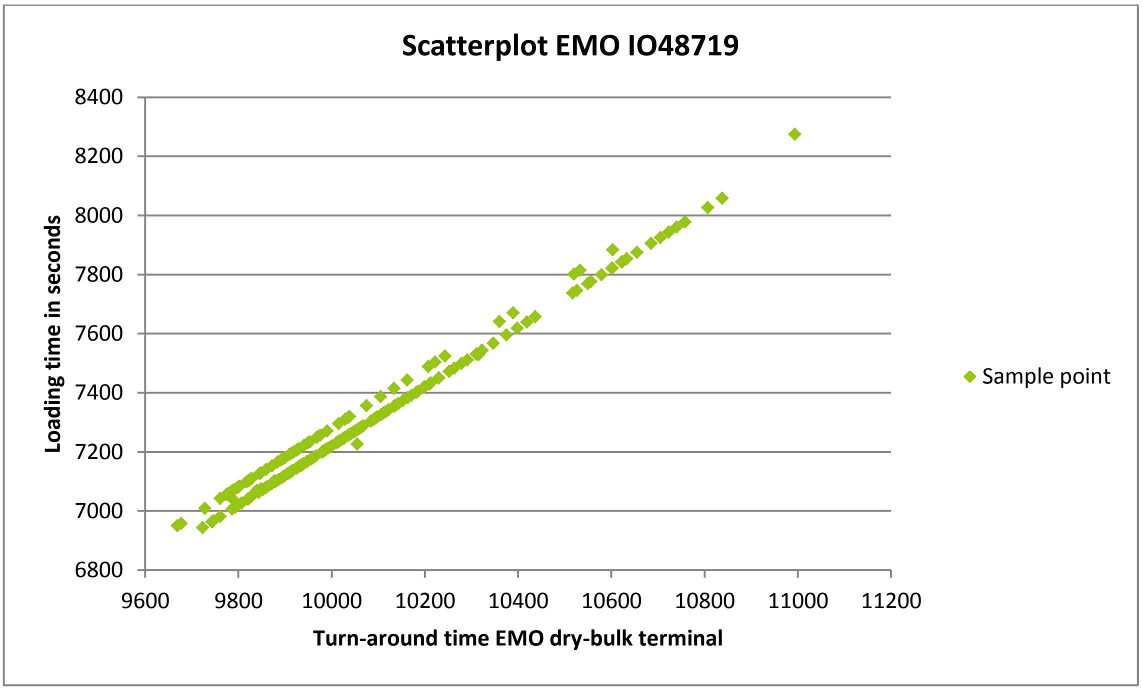

Figure D.34: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the IO48719 train

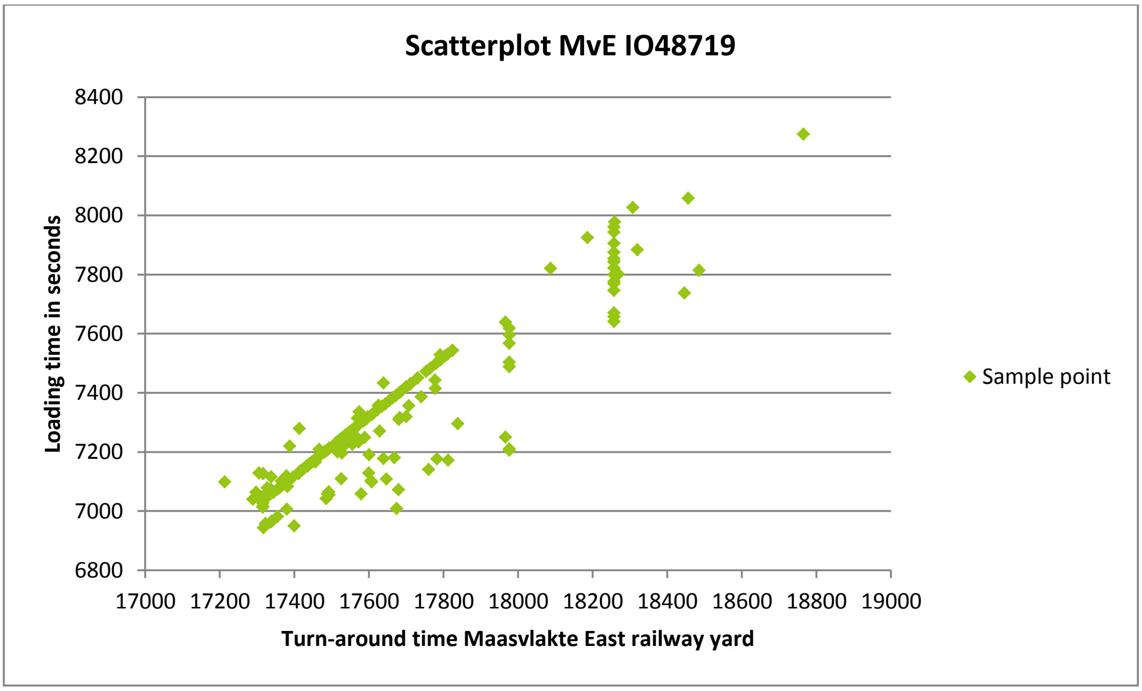

Figure D.35: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the IO48719 train

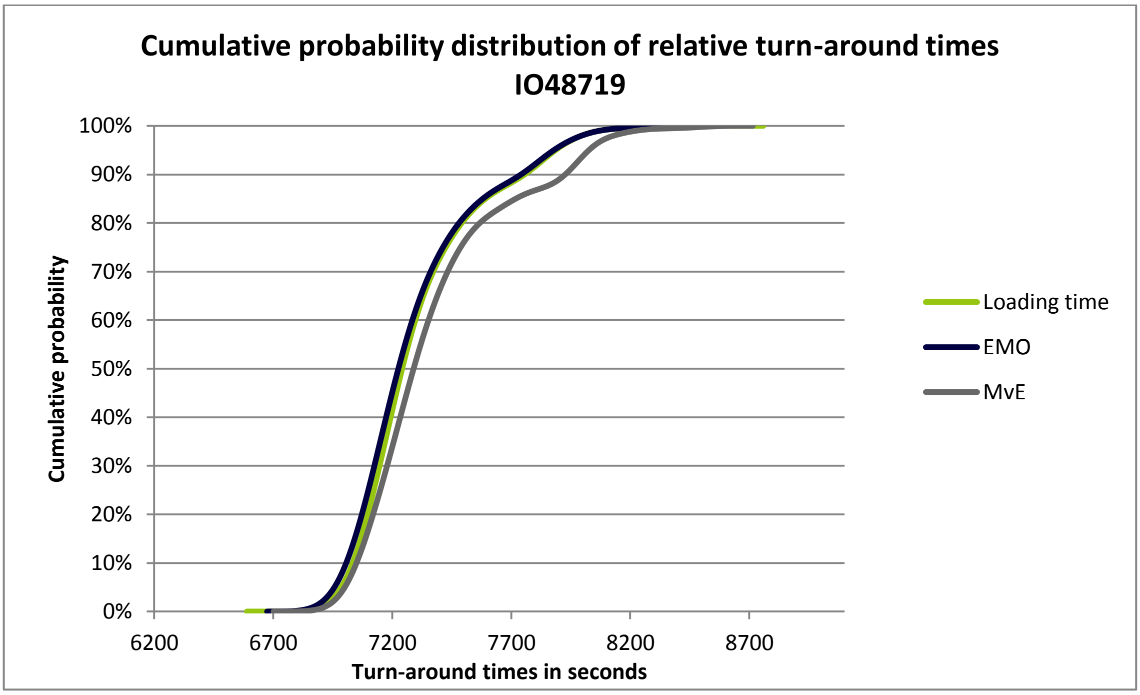

Figure D.36: Cumulative probability distribution of relative turn-around times for train IO48719

Table D.34: Quartiles of relative turn-around times for train IO48719

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6905	6871	-0.5%	6919	+0.2%
Q1	25%	7122	7099	-0.3%	7151	+0.4%
Median	50%	7241	7226	-0.2%	7290	+0.7%
Q3	75%	7424	7414	-0.1%	7487	+0.9%
Maximum	99%	8069	8072	0.0%	8225	+1.9%

Table D.35: Dispersion width for train IO48719

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6943	9669	6889	17213	6932
Maximum	8275	10994	8214	18765	8484
Dispersion width	1332	1325		1552	

The difference in dispersion width between the loading time and the TA MvE is +16.5%.

Table D.36: Standard deviation for train IO48719

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
48719	262	267	305	43	+16.4%

IO48721

Individual results for train IO48721.

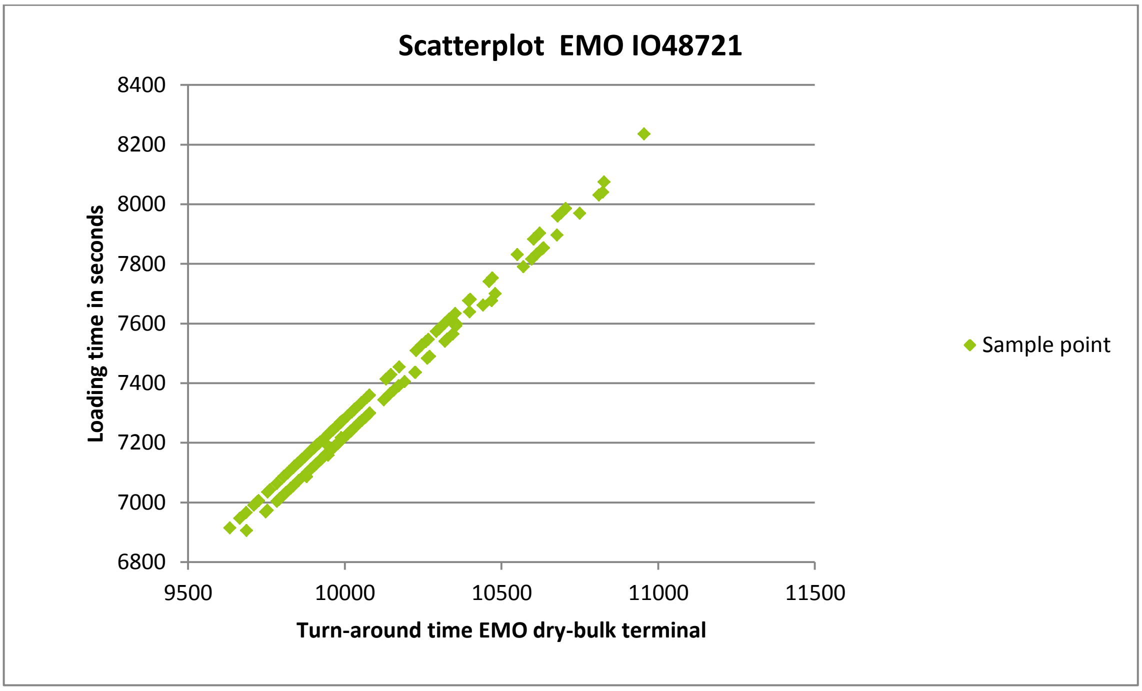

Figure D.37: Scatterplot of the loading time versus the turn-around time at the EMO dry-bulk terminal for the IO48721 train

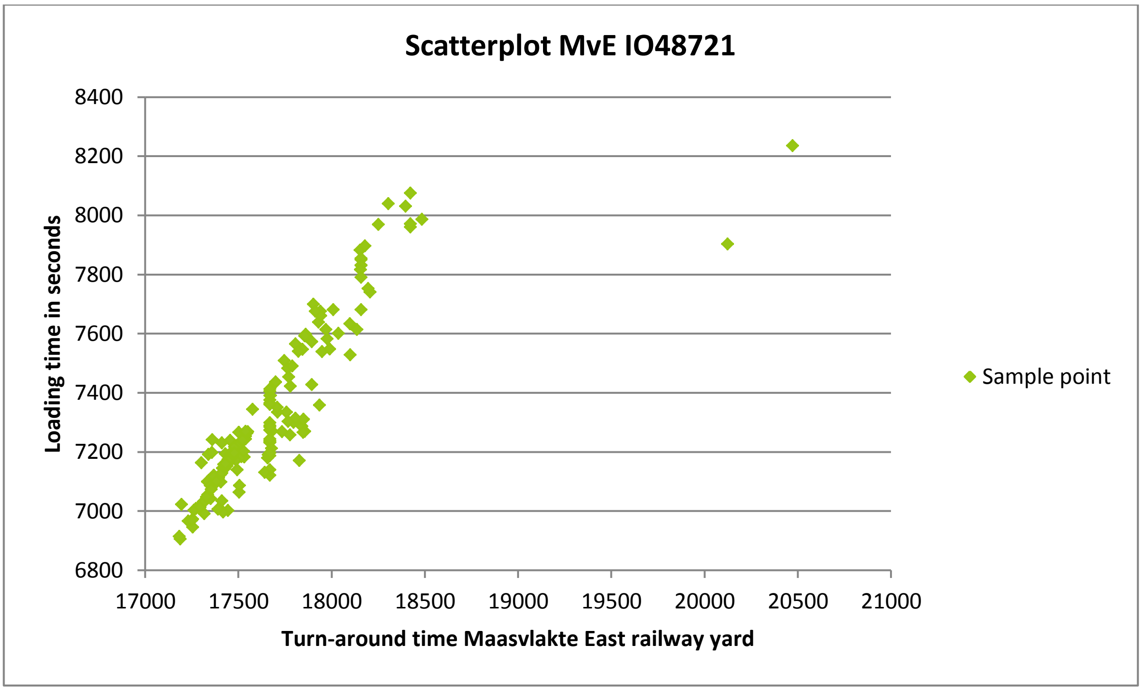

Figure D.38: Scatterplot of the loading time versus the turn-around time at the Maasvlakte East railway yard for the IO48721 train

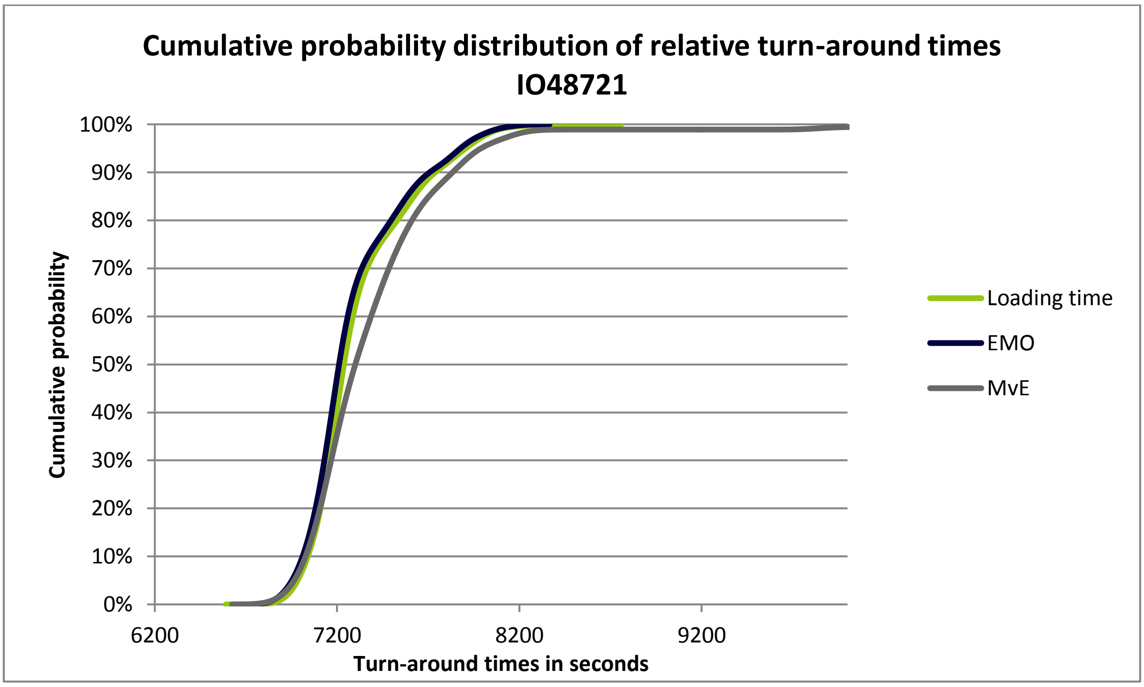

Figure D.39: Cumulative probability distribution of relative turn-around times for train IO48721

Table D.37: Quartiles of relative turn-around times for train IO48721

Quartiles	Percentage	Loading time	TA EMO	Difference in %	TA MvE	Difference in %
Minimum	1%	6894	6855	-0.6%	6854	-0.6%
Q1	25%	7135	7108	-0.4%	7135	0.0%
Median	50%	7237	7210	-0.4%	7301	+0.9%
Q3	75%	7432	7406	-0.4%	7539	+1.4%
Maximum	99%	8090	8074	-0.2%	20014	+147.4%

Table D.38: Dispersion width for train IO48721

Width	Loading time	TA EMO	Relative TA EMO	TA MvE	Relative TA MvE
Minimum	6906	9633	6853	17182	6901
Maximum	8236	10955	8175	20472	10191
Dispersion width	1330	1322		3290	

The difference in dispersion width between the loading time and the TA MvE is +147.4%.

Table D.39: Standard deviation for train IO48721

Train number	Std. dev. Loading time	Std. dev. TA EMO	Std. dev. TA MvE	Difference Std. Dev.	Difference in %
48721	266	266	396	129	+48.5%

Optimisation of freight transportation in ports is normally focussed on optimising separate subsystems instead of analysing transportation chains. Integration these separate subsystems can provide valuable inisght in the interaction between systems along a transportation chain. But how can the two worlds of terminals and infrastructure be combined in a single modelling environment?

The answer to the technical aspect of integrating these subsystems is given in this report. A method of integration is presented and demonstrated by a case study.

Laurence van de Water
Delft, July 2015

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TUDelft Railinfra Solutions Royal HaskoningDHV Enhancing Society Together