

Container transport inside the port area and to the hinterland

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Container Transport Inside the Port Area and to the Hinterland

Qu Hu

Delft University of Technology

Container Transport inside the Port Area and to the Hinterland

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology

by the authority of the Rector Magnificus, Prof. dr. ir. T.H.J.J. van den Hagen,
chair of the Board for Doctorates

to be defended publicly on,
Monday 1 July 2019 at 10.00 o'clock

by

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Printed in the Netherlands

Dedicated to my wife, Xiao Liang.

Preface

In September 2014, when I first came to the Netherlands, I could hardly imagine what my life would be in the coming years. Now, when I look back, I must admit that those times are most precious and memorable. I am sincerely thankful to those delightful or frustrating moments as well as the people who accompanied and helped me.

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Qu Hu

Delft, March 2019.

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Chapter 1

Introduction

This thesis focuses on the optimization of the container transport in the port area and from the port area to the hinterland by using rail. In this chapter, concepts involved in the studied transport chains such as inter-terminal transport (ITT), terminal operations and railway transport to the hinterland are introduced. The studied problem in the thesis is described in Section 1.2 and the research questions are presented in Section 1.3. In Section 1.4 and 1.5, the contribution of this thesis to science and the outline of the thesis are given, respectively.

1.1 Container transport in the port area and from the port to the hinterland by rail

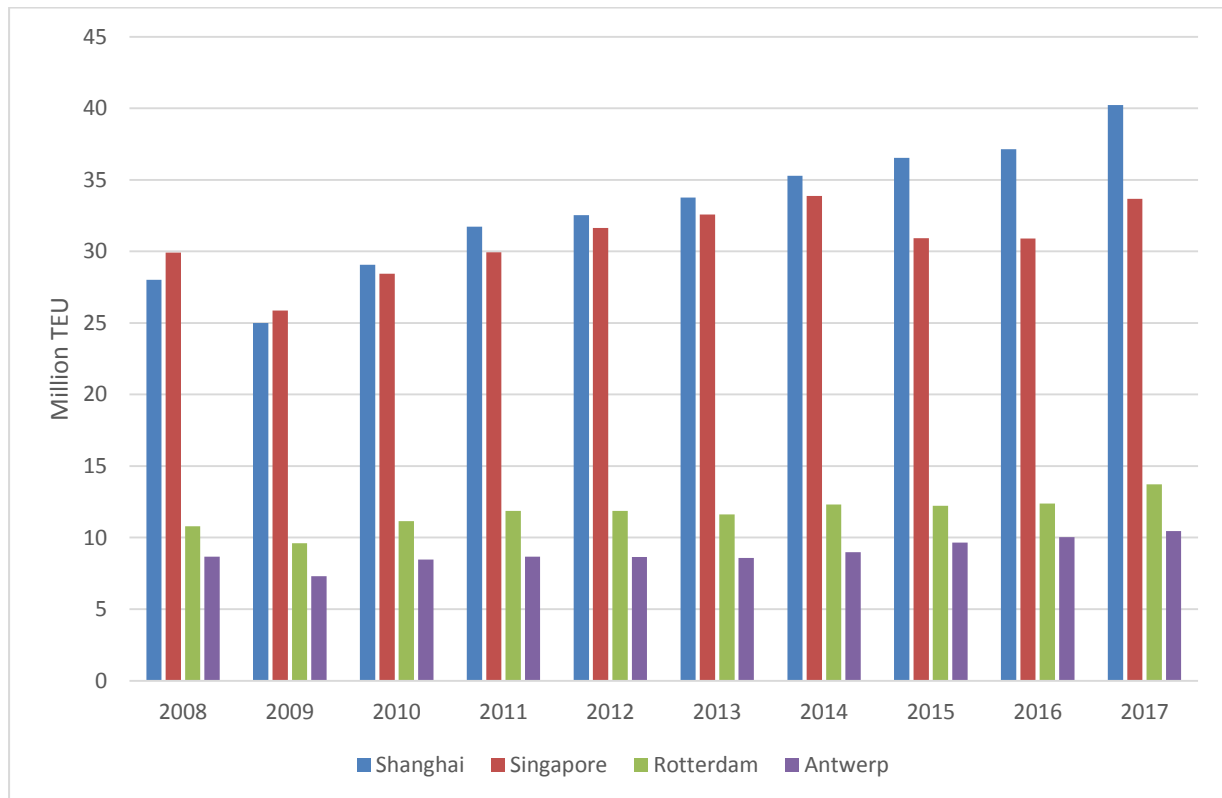


Figure 1.1 Number of handled containers in port of Shanghai, Singapore, Rotterdam and Antwerp

Based on data from Shanghai International Port, 2018; Maritime and Port Authority of Singapore, 2018; Port of Rotterdam, 2018; Port of Antwerp, 2018

Container ports play an important role in containerized transport. In the last decade (2008-2017), the throughputs of major ports around the world have increased considerably. Figure 1.1 shows the throughputs of two largest ports in Asia (Shanghai and Singapore) and two largest ports in Europe (Rotterdam and Antwerp). In 2017, 40.2 million twenty-foot equivalent unit (TEU) containers were handled in Shanghai port: the number rose by 44% compared with the throughput of 2007. During the same time period, the throughput of Rotterdam, Antwerp and Singapore port increased by 27%, 21% and 13%.

The growth of containerized transport puts pressure on both container ports and hinterland transport. The major container ports are expanding to handle the increasing transport demand and different terminals and service centers are located in the port area and connected with different modalities such as road, railway and waterway (see Figure 1.2 as an example case for the Port of Rotterdam). Advanced equipment and scheduling methods are used to ensure the fast and efficient transshipment both inside and between terminals. For example, in Rotterdam port, automated guided vehicles (AGVs) are used to move containers from the quay to the stacks inside the terminal; barge, truck and shuttle train are used to transport a container be-

tween different terminals before leaving the port. Multiple actors, such as the port authority, terminal operators, shipping companies, freight forwarders, etc., may get involved in the transport in the port area. Numerous operations, e.g., ITT, (un)loading, inner-terminal transport, stacking, etc., are performed in the port area, which significantly affects the efficiency of the transport chains.

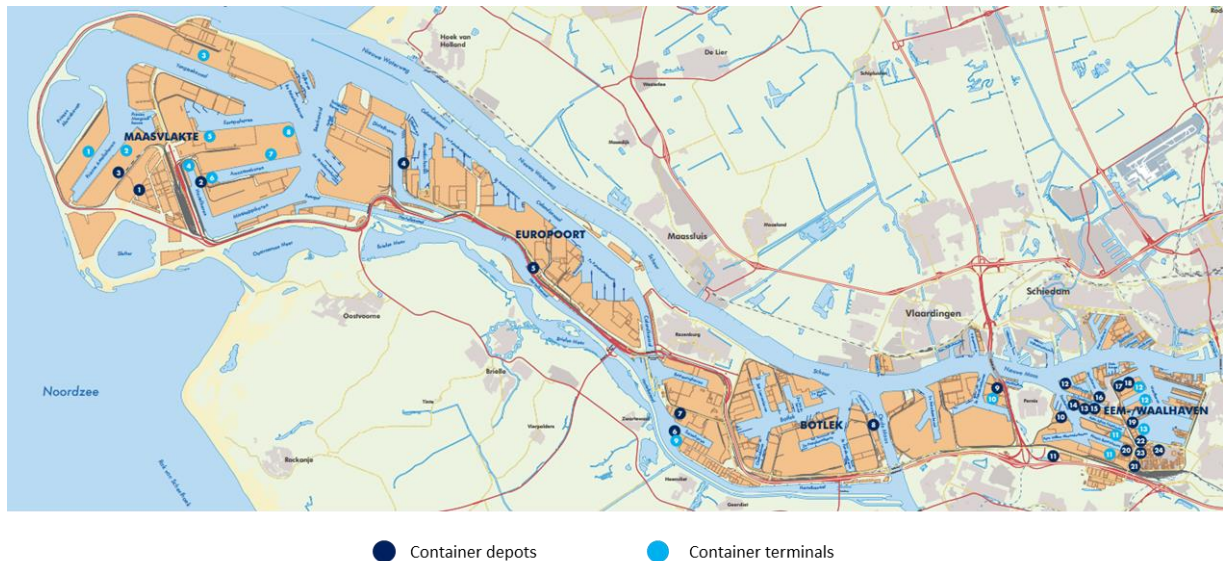


Figure 1.2 Container terminals and depots in Rotterdam port (Source: Port of Rotterdam)

In terms of the hinterland transport, multiple transport modes can be used. From Rotterdam port, inland shipping, railway and road transport are provided to move containers to destinations in the hinterland. Inland shipping and railway provide efficient and environmental friendly options for long-distance transport. Road transport is fast and flexible for the short distance delivery. Currently, 40% of the goods leaving the Rotterdam port by truck remain in the Rotterdam region and only 10% of the goods are delivered outside the Netherlands. Trucks suffer from significant delays on the motorway to and from Maasvlakte 2, Rotterdam. Thus, it is beneficial to reduce road haulage and facilitate the growth of railway and inland shipping. For example, in order to reduce road transport, contractual agreements are made with terminals located on Maasvlakte 2 to transport containers via inland shipping and railway (Maasvlakte 2, 2014).

Nowadays, more than 250 weekly intermodal rail services connect Rotterdam port with hinterland destinations: a train from Rotterdam port could reach the German border within three hours. However, the efficiency of the container transport is not only affected by the hinterland railway services, but is also influenced by the transshipment inside the port area. Therefore, it is worthwhile studying these two problems in an integrated way.

1.2 Problem statement and research scope

This thesis focuses on the container transport process starting from when containers are released in the port until containers are unloaded onto trains heading to the hinterland. In this

process, containers are handled inside terminals as well as moved between terminals in the port area. Several key processes can be identified and are discussed below.

1.2.1 Inter-terminal transport

ITT refers to the container movement between terminals and service centers in the port area (Duinkerken et al. 2006, Heilig and Voss 2017). Usually, the ITT network involves several terminals connected by multiple transport modes, and a fleet of different types of vehicles, e.g., trucks, barges, and trains, moving containers between the terminals (Tierney et al., 2014, Schepler et al., 2017). The ITT concept was first studied by Ottjes et al. (1994): a simulation model was proposed to study the multiple terminals planning considering container exchange between them. With the expansion of the ports, several ITT systems with multiple modes were designed and evaluated. For example, Duinkerken et al. (2006) study an ITT system with Automated Guided Vehicles (AGVs), Automated Lifting Vehicles (ALVs) and Multi-Trailer System (MTS). Li et al. (2017a) and Li et al. (2017b) focus on waterway transport: inland barges are used to carry ITT containers. Moreover, multiple terminal handling operations, such as loading/unloading (Caris and Janssens, 2009) and stacking (Zhen et al., 2016) are considered when scheduling the ITT system.

ITT is critical for the transport chain because it connects not only terminals but also operations inside large port areas. When delays occur in the ITT, the operations in the rail yard, e.g., train loading, and train departure, will be affected as well. However, the ITT is usually studied without considering the hinterland transport and terminal operations. To fill these research gaps, this thesis focuses on the container transport between terminals and railway transport inside the port and from the port to the hinterland, see Figure 1.3. The studied transport system involves different types of terminals, different types of ITT fleet and terminal operations including landside (un)loading and the railway hinterland transport.

1.2.2 Railway connection of the container terminals in the port area

In the port area, two types of container terminals have rail connections inside the terminal (also called on-dock): the first one is the railway terminal with road connection (RTR) and the second one is the maritime terminal with both road and rail connection on-dock (MTRR). In RTRs and MTRRs, containers from the maritime and road transport sectors can be transhipped to rail directly. Other terminals, which have no rail connection, are defined as maritime terminal with road connection rail off-dock (MTR). In an MTR, containers must be moved to a RTR or MTRR before being able to leave the port area.

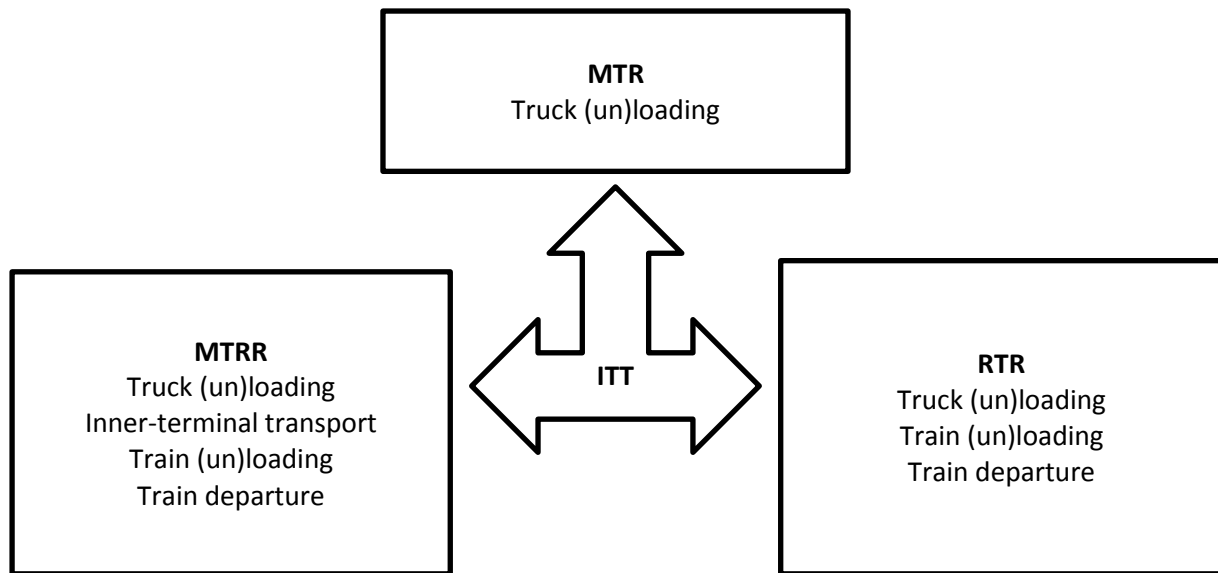


Figure 1.3 Terminals and problems considered in this thesis

1.2.3 Terminal handling

Terminal handling involves (un)loading, stacking, inner-terminal transport shunting, etc. Usually, after arriving at the terminal, a container will be unloaded from the deep-sea vessel and then loaded onto a vehicle which moves the container to the storage yard. The container will be stacked in the storage yard before another vehicle picks it up and sends it to the rail yard. In the rail yard, containers are loaded onto the trains heading to the hinterland according to the loading plan and railway timetable.

When handling a set of containers, the maximum number of cranes that can be used to serve a vessel or a train is usually given. Each crane can move the container in a certain area, which means the moving area of the crane should be determined. The loading and unloading problem can be seen as scheduling the crane movement to exchange containers between storage area, truck and train/vessel (Kim and Park 2004, Corry and Kozan 2006, Froyland et al. 2008). Each handling operation is split into several tasks, such as lift and drop off, and assigned to crane movements. In this thesis, we study the landside handling in maritime and railway terminals while the quayside handling operations are not taken into account.

1.3 Overarching research questions

The main objective of this thesis is to formulate and optimize the most critical operations at the interface between a railway network and a container port, including different types of container terminals and service centers, to improve container transportation in terms of cost and time. To achieve this objective, we consider the following research questions:

Research question 1: What kind of ITT system is needed to improve the transport efficiency and how to reduce the ITT related costs in both infrastructure planning (e.g., terminal and network layout) and operations (e.g., terminal operation scheduling and vehicle dispatching)?

Designing and constructing of an ITT system requires cooperation between stakeholders such as the port authority, terminal operators, freight forwarders and logistics providers. Numerous strategic and tactical problems, e.g., the provider of the ITT, the ITT fleet size and fleet configuration, the service network of ITT, should be determined to reduce cost in construction and guarantee the efficiency. On the operational planning level, methodologies should be developed to coordinate the handling operation inside the terminals and transport operations between terminals to minimize delay and reduce the operational costs.

To answer this question, the following sub-questions are considered in Chapter 2:

- What problems should be considered in ITT system planning?
- Which actors should be involved in the ITT and how to balance the responsibility and cost between them?
- What methodologies can be used in the ITT system planning?

Research question 2: How to formulate and optimize the connection between the railway system and the ITT system?

This thesis focuses on an ITT system connected with railway hinterland transport. In the studied system, containers from different terminals will be collected by the ITT vehicles and then sent to rail yards. Therefore, two important sub-systems must be investigated: the ITT system that connects terminals inside the port area and the hinterland railway transport system that moves containers from the port area to their destinations in the hinterland. In the ITT system, vehicle and container flow must be scheduled; and in the hinterland railway system, containers are loaded onto train and trains leave the port area according to the timetable. In order to coordinate the operations in both sub-systems, we consider the following sub-questions in Chapter 3:

- How to mathematically model the ITT operations and railway terminal operations?
- How to optimize the ITT delivery and hinterland railway delivery at the same time?
- To what degree the delay ITT will impact the entire transport process?

Research question 3: How to quantify and optimize the performance of different ITT system and railway hinterland transport strategies?

In the port area, a fully-coordinated planning may not be realized because the actors involved could have conflicting interests. Therefore, some facilities may not be shared among some terminals and the ITT network could not cover all terminals. Moreover, train formation strategies and railway timetable also affect the container delivery, which should be investigated. The following sub-questions are studied in Chapter 4:

- How to mathematically formulate the ITT operations, railway terminal operations and other maritime terminal operations?

- How would the different ITT connections, train formation strategies and railway time-tables affect the container delivery performance?

1.4 Contributions of the thesis

The main contributions of this thesis are as follows:

- We review the existing research of the ITT and identify the research gaps. The literature review focuses on the planning objectives, actor responsibility and methodology used in the ITT system planning. The results will reveal that the integration between ITT and terminal operations requires further study to improve both the ITT, terminal operations and hinterland transport.
- We will present a mathematical model to formulate the container transport between terminals and heading to the hinterland. The model integrates ITT and the rail yard operation for hinterland rail transport.
- A tabu search algorithm which is capable of solving large-scale instances of the container and vehicle flow optimization both inside the port area and to the hinterland will be developed. Then, we derive simplifications for strategic decision making regarding the relationship between bottlenecks within ITT and the connection to railway links, as well as fleet size, loading rate, allowed delay of trains, handling times, and traverse time within the port area.
- We will discuss the relationship between ITT optimization and railway hinterland transport performance, and analyze to what degree the intersection, empty movements and fleet size in ITT could affect the performance of the ITT delivery.
- We will further develop the mathematical model so that different terminal handling operations can be formulated. Before leaving the port area, containers are not only transport between terminals, but also handled inside the terminal. The container (un)loading and transshipment operations are considered in the developed model.
- We also discuss how the ITT network connection, train capacity and railway timetable will affect the railway transport to the hinterland. We will analyze the performance of different ITT networks as connections may not exist between competing terminals. Meanwhile, different configurations of train capacity and railway timetable also result in different transport performances.

1.5 Thesis outline

- Chapter 2 presents a literature review of studies focusing on ITT planning. We examine 77 scientific journal papers to identify what kind of objectives should be achieved in ITT system planning, which actors should be involved, and what methodologies can be used.
- Chapter 3 presents a mathematical model for the planning of container movements in the port area, integrating the ITT of containers (within the port area) with the rail freight formation and transport process (towards the hinterland). A tabu search algorithm is proposed to solve the problem. The practical applicability of the algorithm is tested in a realistic infrastructure case and different demand scenarios.
- Chapter 4 investigates the problem of optimizing inter-terminal movements of containers and vehicles within the port area in order to achieve an integrated and effective transport within the port and towards the hinterland. Containers from different port terminals are first moved to a rail yard and then delivered to the hinterland by rail. Various vehicle types and the handling operations inside the terminals are considered in the model.
- Chapter 5 states the main conclusions of this thesis and presents recommendations for future research.

Chapter 2

Literature Review into Planning of Inter-Terminal Transport

Nowadays, the major ports around the world usually consist of multiple terminals and service centers which are often run by different operators. Meanwhile, inland terminals have also developed to reduce port congestion and improve transport efficiency. The integrated planning of ITT between the seaport and inland terminals helps in providing frequent and profitable services, but also could lead to higher overall planning complexity. Moreover, the ITT system usually involves multiple stakeholders with different or even conflicting interests. Although an increasing number of studies have been conducted in recent years, few studies have summarized the research findings and indicated the directions for future research regarding ITT. This chapter provides a systemic review of ITT planning: we examine 77 scientific journal papers to identify what kind of objectives should be achieved in ITT system planning, which actors should be involved, and what methodologies can be used to support the decision-making process. Based on the analysis of the existing research, several research gaps can be found. For example, the multi-modality ITT systems are rarely studied; cooperation frameworks are needed in the coordination of different actors and quantitative methodologies should be developed to reflect the different actors' financial interests.

2.1 Introduction

The continued growth of containerized transport volumes necessitates an expansion in scale and accessibility of container ports, as well as an improvement in their throughput productivity. Consequently, major ports such as Shanghai and Rotterdam are investing in an increasing number of interconnected terminals of different types (deep-sea terminals, barge terminals, railway terminals, and empty depots) and sizes. Meanwhile, multiple types of terminals have been developed in the hinterland and these terminals are connected by different combinations of modalities (road, rail, barge, and sea).

The development of the multi-terminal system increases the complexity of the transport process. Ideally, after arriving at a terminal in a port, export containers should be transferred to deep-sea transport and import containers could be transported to the hinterland destination directly. In reality, containers are often moved between several terminals in the seaport. Firstly, the implementation of intermodal transport requires transshipment between modalities, which can only be achieved by inter- and/or intra-terminal transport. Secondly, freight consolidation operations are performed in certain terminals. For example, feeder vessels are used to gather containers from multiple maritime terminals in a port area to a barge service center, where containers are loaded onto inland vessels and sent to the hinterland.

Therefore, the ITT could lead to several planning problems such as terminal location, freight consolidation, container inventory, coordination between terminal operations and transport, etc. Moreover, multiple stakeholders are involved in the planning, which makes it complex to balance their different interests.

This chapter reviews the studies of ITT in the port area and in the hinterland, seeking to identify research gaps. Problems related to ITT have been studied and reviewed from different perspectives. For example, the optimal location for a hub terminal was studied by Racunica and Wynter (2005); Jeong et al. (2007) investigated the freight and vehicle flow in an inland transport network; Vis and De Koster (2003) reviewed the transshipment operations in container terminals. In their research, ITT was seen as the connection between different modalities, but the ownership of the ITT system and the organization of the ITT service were not discussed.

Heilig and Voss (2017) reviewed the ITT between maritime terminals. The authors first discussed where ITT is required in the port area and then addressed several objectives of an efficient ITT system. The authors analyzed the approaches used in the literature and proposed several important research topics for further research.

Apart from ITT between maritime terminals, ITT in the hinterland also influences the transport process. According to Notteboom and Rodrigue (2005), the growth of port terminals and functional areas is limited by several local constraints, e.g., land use and environmental factors, thus, some seaport functions are moved to the hinterland. At the same time, the change of the production system and consumption market also favors the extension of port

functions to the hinterland with multiple inland terminals, which could better serve the regional market. Therefore, apart from the ITT in the port area, we also discuss the connection between terminals in the seaport and in the hinterland.

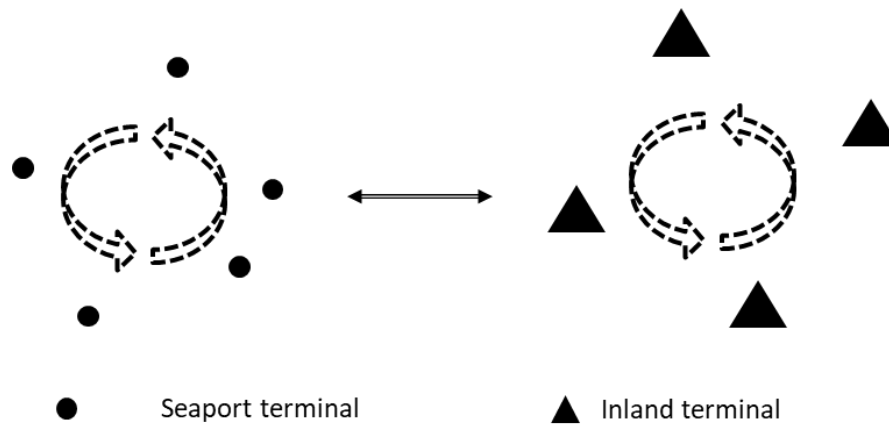


Figure 2.1 Schematic representation of an ITT network

A schematic representation of the ITT network studied in our research is shown in Figure 2.1. The ITT network consists of several terminals in the seaport and its hinterland. In the seaport, the terminals are interconnected, then, the seaport terminals are connected to multiple inland terminals (direct connections are excluded in the search). The ITT differs from general transport as ITT service always involves one or multiple intermediate terminals between the origin and destination terminals. In the view of freight bundling (see Janic et al., 1999 and Kreutzberger, 2010 for introductions of different bundling networks), ITT network could be a line network, a hub-and-spoke network, a trunk line with collection and distribution network or a mix of these networks.

In this chapter, we seek to answer the question of what kind of ITT system is needed and which stakeholders should be considered in ITT planning. We also extend the literature review into the hinterland of port areas and analyze the differences between ITT in port areas and hinterlands. Thus, this chapter identifies research gaps of ITT in:

- (1) Planning problems and objectives in the ITT system;
- (2) ITT stakeholders responsibilities in ITT system planning and the coordination between different actors;
- (3) Methodologies and theories used in ITT system planning.

This chapter is organized as follows: in Section 2.2, the search strategy is discussed; in Section 2.3, we analyze the search result; in Section 2.4 and 2.5, we review the research related to ITT and in Section 2.6, we conclude the review and propose suggestions for further research.

2.2 Materials and methods

To analyze the transport between terminals from a comprehensive perspective, we performed a literature search for studies have been published in scientific journals using Scopus, Web of Science, ScienceDirect and Google Scholar databases. To ensure the robustness of the search, different combinations of search strings (see Table 1) were used to identify relevant research and the search field was set as title, keywords and abstract. It is notable that Google Scholar will search these keywords in full text (Google, 2019) and result in a large number of papers. According to Google (2019), the search results will be ranked based on the relevance, thus, when the number of search result is larger than 100, only the first 100 journal paper will be selected and analyzed. A similar searching process can be found in Brakewood and Watkins (2019).

Table 2.1. Search strings, databases and search results

Keywords	Database	Number of search results	Duplicates removed	Title and abstract	Final result	
Inter-terminal transport AND	Scopus	13	29	406	87	77
	Web of Science	12				
	ScienceDirect	6				
	Google Scholar	22				
Container transport AND multi terminal	Scopus	11	34			
	Web of Science	7				
	ScienceDirect	6				
	Google Scholar	34				
Freight transport AND multi terminal	Scopus	20	24			
	Web of Science	9				
	ScienceDirect	3				
	Google Scholar	24				
Container transport AND seaport	Scopus	25	115			
	Web of Science	29				
	ScienceDirect	9				
	Google Scholar	100				
Freight transport AND seaport	Scopus	44	150			
	Web of Science	25				
	ScienceDirect	8				
	Google Scholar	100				
Container terminal AND transport AND network	Scopus	66	176			
	Web of Science	62				
	ScienceDirect	25				
	Google Scholar	100				

The search was conducted in March 2019, and 528 papers were retrieved from the databases. After removing the duplicates, 406 papers remained. Then we checked the title and abstract of these papers which reduced the number of papers to 87. We read these papers in full and checked the bibliographies for additional literature (snowballing). In the end, 77 papers were included in our research. We do indeed neglect the grey literature (such as reports written in the framework of European research project for instance) because our focus is on scientific papers.

In the searching and checking process, we selected papers based on the ITT definition given in the Introduction: 1) the transport network covers terminals in the seaport and its hinterland; 2) the transport process always involves intermediate terminals. Therefore, we excluded these studies on single terminal or port, studies on point-to-point transport, studies focusing on inland transport networks without seaport connections, or the studies covering transport between multiple seaports.

2.3 Descriptive analysis on search results

2.3.1 ITT in the port area and in the hinterland

Both port network and inland networks have been studied by the 77 papers. 30 of these studies focus on ITT operations in port areas (further referred as port ITT) and 47 papers focus on planning ITT system in an inland transport network (further referred as hinterland ITT). Table 2.2 demonstrates the geographical focus of both port ITT and hinterland ITT. We can find that most of the studies are based on the European network and only European and Asian port ITT systems have been studied.

Table 2.2. Geographical focus of reviewed papers

Geographical Focus	Port ITT	Hinterland ITT
Unknown/conceptual	8	8
Europe	17	16
Asia	3	5
North-America and Europe	-	1
North-America	-	1
Latin-America	-	1
Pacific (Australia)	-	1
Total	28	33

Among the 22 port ITT studies with a specific geographical focus, 15 of them investigate the terminals in Maasvlakte 1&2, Rotterdam port. Other port ITT networks have been studied include the port of Hamburg, Antwerp, Singapore, and Tianjin. Hinterland ITT systems in the

hinterland of Rotterdam, Antwerp, and Campanian region, Italy have been investigated more intensively as there are 19 papers focusing on these areas.

2.3.2 Research level of the ITT problem studied in the literature

Generally, studies can be classified into three categories: strategic, tactical and operational. A strategic study usually focuses on long-term decisions such as infrastructure layout and fleet configuration. A tactical study focuses on planning problems with a weeks- or months-long duration, such as barge rotations and train timetables. An operational study aims at solving problems that occur on a daily basis, such as vehicle routing and crane scheduling. In this review, we classify the reviewed papers by their planning horizons as either strategic or tactical/operational studies because some operations such as barge (un)loading in multiple terminals may take several days and some tactical problems such as vessel rotation planning are interrelated with terminal handling operations.

Most of the port ITT studies focus on tactical and operational problems while most hinterland ITT studies are on the strategic level. Among the 30 port ITT research, apart from the 2 literature survey papers, 8 papers are strategic focusing on terminal design, ITT fleet, and information system, and 20 papers are tactical/operational focusing on berth allocation, barge rotation, and land vehicle routing, see Figure 2.2.a. Among the 47 hinterland ITT research, there are 2 literature survey papers, 30 strategic research focusing on terminal design and terminal allocation, and 15 tactical/operational research focusing on barge rotation, and service network design, see Figure 2.2.b.

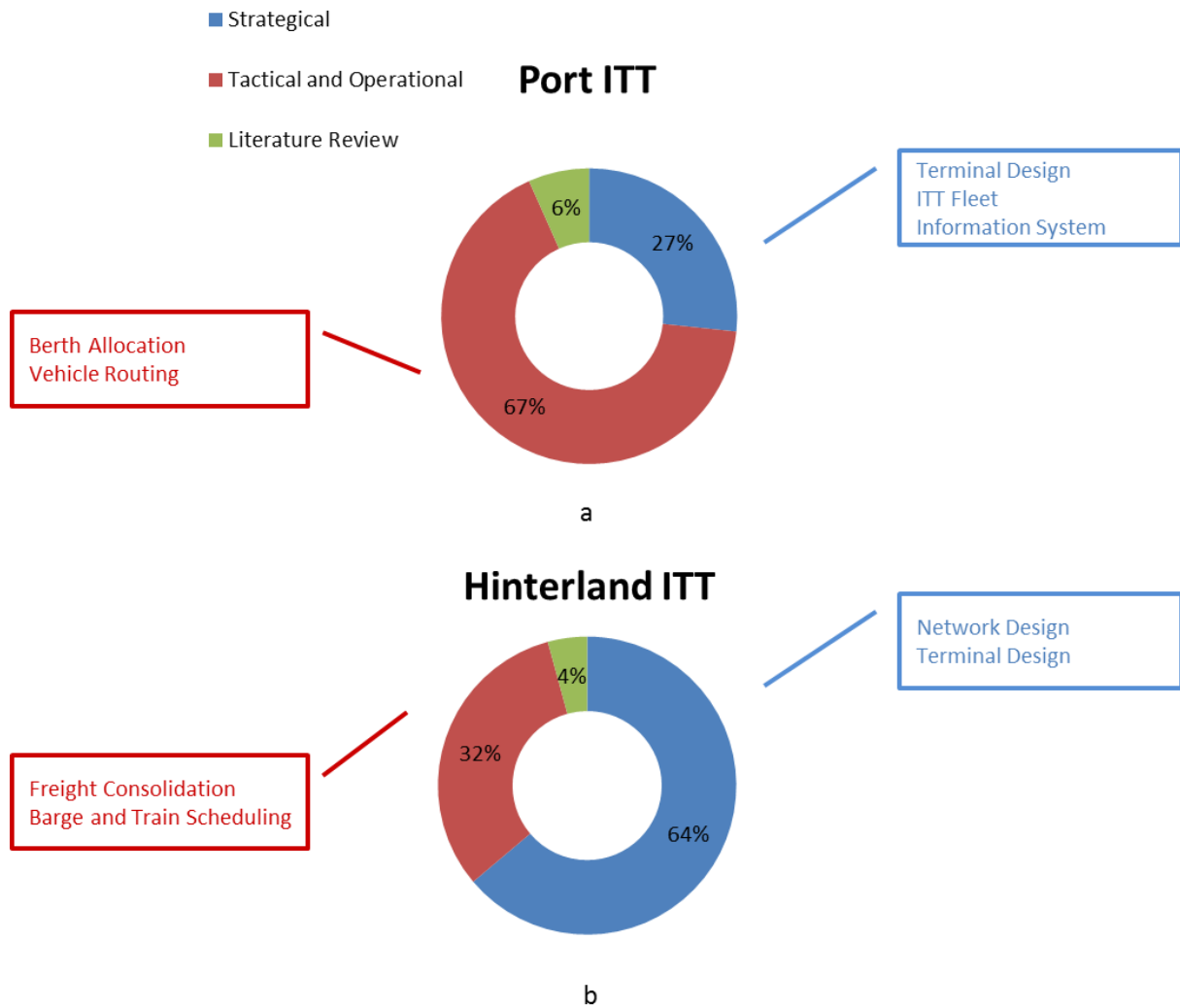


Figure 2.2. Research levels of port ITT (a) and hinterland ITT (b)

2.3.3 Distribution by year of publication

We selected 30 port ITT papers and 47 hinterland ITT papers and these papers were published between 1999 and 2019. We noticed that the number of port ITT studies remained relatively small in the before 2015. However, in 2016 and 2017, 14 papers were published, which accounts for almost half of the total number, see figure 2.3.

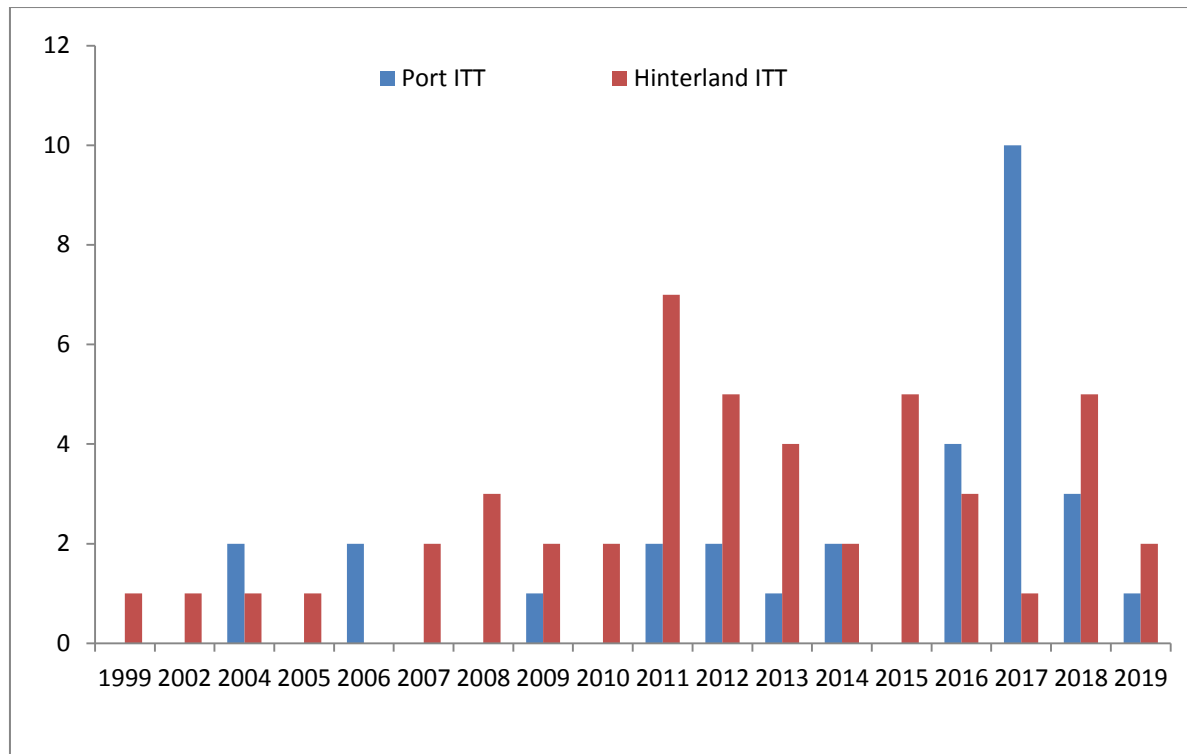


Figure 2.3. Distribution of journal papers by year of publication

2.3.4 Analysis of important research institutes and groups

Several institutes and research groups have a great influence on the study of ITT. Among the 30 port ITT studies, 17 of them are conducted by researchers from Delft University of Technology (the Netherlands), University of Twente (the Netherlands), Erasmus University Rotterdam (the Netherlands) and University of Hamburg (Germany). Five research institutes and groups, i.e., Delft University of Technology (the Netherlands), Erasmus University Rotterdam (the Netherlands), Italian National Research Council (Italy), Chalmers University of Technology (Denmark) and Beijing Jiaotong University (China) can be identified involved in 15 of the 47 hinterland ITT studies.

Delft University of Technology has been the most influential research institute for both port and hinterland ITT studies by publishing 10 studies in port ITT and 7 hinterland ITT studies. Especially, two research groups from Delft University of Technology have been considerably productive: the department of Maritime Transport Technology has published 8 papers in port ITT, while the department of OTB- Research for the built environment has been involved in 6 hinterland ITT studies.

2.4 Port ITT

This section reviews the port ITT studies and analyses the planning problems, actors involved and methodologies used in decision making. As it is shown in Figure 2.1, the port ITT studies discuss the seaport terminal operations and the transport between these seaport terminals. We

reviewed 30 papers and analyzed the planning problems covered, the stakeholders involved and the methodologies used in these papers.

2.4.1 Port ITT planning problems

Port ITT strategic planning problems: terminal design and fleet configuration

The terminal layout could affect the port ITT demand. In some cases, if terminals are connected with all modalities and have enough handling capacity, the port ITT demand could be reduced. Ottjes et al. (2006) compare three terminal configurations: compact configuration, dedicated configuration, and combined configuration. The compact and dedicated configurations are two extreme situations where all terminals are either connected with multiple modalities or with a single modality. The combined configuration represents the planned layout of the Rotterdam Maasvlakte terminals: both compact and dedicated terminals exist. The results show that the number of ITT vehicles in use in the dedicated configuration is two times larger than in the compact configuration. Evers and De Feijter (2004) investigate whether each terminal should be equipped with the facility to handle feeders (decentralized ship service) or the feeders should be handled in a single service center (centralized ship service) to reduce the ship service time. The results show that the centralized service can reduce the vessel average in-port time while using the same number of ITT vehicles.

Choosing the proper ITT fleet could also reduce the ITT related costs. Different transport modes have different advantages and limitations. Generally, road transport is widely used because it provides the fastest delivery with flexibility. But Gharehgozli et al. (2017) point out that some special vehicles, such as multi-trailer system (MTS), require a private road, and some vehicles, such as Automated Guided Vehicle (AGV) and Automated Lifting Vehicle (ALV) require a private road as well as a control system. Waterway transport is the most economical transport mode but requires a longer transport time. Barges are usually used to transport containers among several terminals in a port. But the handling and waiting time is relatively long and highly affected by the rotation plan (Douma et al. 2011). Railway transport has a lower transport cost compared to road transport and a higher transport speed compared to waterway transport. However, rail transport also requires complicated handling operations and long handling time, which lead to high ITT costs (Hansen, 2004).

Information systems play a fundamental role in the ITT planning. Both centralized and decentralized systems have been studied. Heilig et al. (2017a) introduce the usage of a centralized communication system with a cloud-based server and a mobile application. The core of this platform is routing optimization, which includes fixed vehicle costs, variable vehicle operating costs and penalty costs for late delivery. The result of the optimization is presented by a WebApp to enable the ITT provider to monitor the position of their trucks and to interact with drivers by sending and receiving messages. The truck drivers, in turn, use a MobileApp, which collects GPS information and displays their optimized sequence of transport orders. In reality, a centralized communication system may be hard to achieve because both terminal

operators and transport providers compete with each other, and sharing information could be unacceptable (Douma et al., 2011). Therefore, a multi-agent scheme is tested in Douma et al (2009), Douma et al. (2011), and Douma et al. (2012). In the scheme, different levels of information exchange are examined: 1. no information, i.e., barges visit the terminals according to the shortest path; 2. yes/no, i.e., a barge can ask whether a certain arrival time is acceptable to the terminal operator; and 3. waiting profiles, i.e., terminals give barges information about maximum waiting time a barge has to wait for every possible arrival time. The results indicate that the waiting profiles work well compared to a centralized system.

Four major research gaps can be identified in the strategic planning. Firstly, the layout of terminals should be further evaluated considering infrastructure investment and potential ITT cost. Coordinated terminal and ITT infrastructure design may reduce the ITT demand, or meet the ITT demand with minimal service cost and time. Nevertheless, ITT demand reduction could be infeasible in practice: the construction of a compact terminal or centralized ship service center may increase the investment for the terminal operator.

Secondly, the future study may pay more attention to the detailed data collection or estimation of port ITT demand between different seaport terminals. Currently, most research makes assumptions on the transport demands between different types of seaport terminals, e.g., 1% of the total transshipment containers in deep-sea terminals will use the ITT system (Gharehgozli et al., 2017). If the demand data is not available in planning for the future ITT network, estimation should be made based on the overall planning of terminal type, terminal layout, terminal capacity, and coordination between terminal operators and transport operators. We noticed that in De Lange (2014) and Gerritse (2014), transport demand between terminals is estimated based on the terminal capacity, port throughput, and the potential growth. The estimation could be further improved based on the realistic development of terminals. Moreover, some European research projects, e.g., ETIS Plus, has developed models and tools to forecast transport demand for large-scale network work. These methodologies could be used in ITT demand estimation.

Thirdly, there is no integrated analysis of integrated multiple-mode ITT systems. Existing literature focusses on the performance evaluation of one transport mode and finding the ITT fleet configuration with the best performance: minimal number of vehicles needed, highest delivery punctuality, etc. For example, Duinkerken et al. (2006) compare three road-based ITT systems (with AGV, ALV, and MTS, respectively) among the Maasvlakte terminals considering the lateness delivery rate. Future research should investigate the integrated ITT fleet with rail, road and waterway vehicles.

Lastly, further research is needed to investigate the dynamics of the information systems when coordinating vehicles with and without appointments. The performance of the information system is only guaranteed when all users have access to the system and follow the instruction of the system. As indicated by Giuliano and O'Brien (2007): the truck appointment system has little impact on the truck waiting time at the terminals because few trips are per-

formed with an appointment and terminal operators give no priority to the trips scheduled with an appointment.

Port ITT tactical and operational planning problems: berth allocation and vehicle routing

Tactical and operational planning usually aims at reducing the ITT timespan or costs. Several operations may affect the ITT timespan: transport, handling, storage, etc. The potential costs related to the ITT operation includes vehicle energy consumption cost, vehicle hiring cost, (crane, reach stacker, etc.) handling cost, storage cost, lateness delivery cost, etc.

To improve the ITT planning, existing research has tackled different problems. Some research focuses on the allocation of deep-sea vessels to different terminals and quays. When a deep-sea vessel visits one terminal and some discharged containers should be loaded onto another vessel or train in another terminal and some export containers in another terminal must be loaded onto this vessel. ITT is needed to move the containers between terminals. Additionally, containers waiting for the ITT must be stored in the terminal yard, which leads to extra storage cost. A proper assignment of deep-sea vessels may reduce the costs caused by ITT movements. Zhen et al. (2016) study the terminal assignment for the vessel considering fuel consumption, ITT and storage cost. Hendriks et al. (2012) study a berth allocation problem among multiple terminals with an objective to minimize the quay crane operation cost and ITT cost. A comparison with a realistic allocation constructed by PSA Antwerp shows that a small modification can reduce almost 25% of the number of crane operations and more than 3% of the ITT cost.

Routing of ITT vehicles has also been studied. For the ITT barge and train, it is important to determine which terminals the vehicle should visit or stay. In some cases, trains and barges may visit multiple terminals for ITT movements. Caballini et al. (2014) and Caballini et al. (2016) study the rail cycle in the port aimed at minimizing the queuing time in multiple yards. Li et al. (2017a) use the inland vessel in ITT: when a vessel arrives at a terminal, both hinterland and ITT containers will be loaded and unloaded to/from the vessel. The objective of this research is to find the optimal vessel rotation plan with minimal travel time. Li et al. (2017b) also aim to minimize the travel time in the port. In their research, possible disturbance such as terminal equipment failure and sudden closing of terminals are also taken into consideration. For road vehicles, the routing problem has been studied considering fuel costs, delay costs, emission costs, etc. For example, Jin and Kim (2018) study the truck routing in Busan port with delivery time windows. A trucking company's profit from moving containers is maximized in the research while the truck usage cost and delay penalty are taken into account. Heilig et al. (2017b) extend the ITT truck routing optimization considering the emissions. Trucks are used to pick up and deliver containers, and all containers must be delivered. A multi-objective model is proposed to minimize the fixed vehicle hiring cost, vehicle traveling cost, lateness delivery penalty, and emission cost. Additionally, the depot at which the vehicle starts and ends its route also affects the ITT cost. Hu et al. (2018) and Hu et al. (2019) study the ITT

vehicle routing problem integrated with railway transport to the hinterland and terminal operations.

Although considerable efforts have been made to tackle the port ITT tactical and operational planning, there are some questions to be further investigated. Firstly, railway ITT is rarely studied. Port terminals usually have rail yard on dock or rail connection to rail terminals, but it is not clear how to use these facilities in ITT to realize the benefit. Secondly, the ITT should be studied integrated with terminal operations especially the loading and unloading of the large capacity vehicles such as trains and vessels. Therefore, the objective of ITT should not only focus on the delivery of ITT demand but should also take the upstream and downstream transport into consideration.

2.4.2 Port ITT stakeholders

Four types of actors could affect the port ITT planning have been discussed in the literature: the port authority, terminal operators, transport operators (could be a freight forwarder or a carrier), and the third party ITT provider. Hendriks et al. (2012) and Lee et al. (2012) focus on the situation when a terminal operator controls multiple terminals, then, the ITT fleet can be shared as a way to balance the transport demand and handling capacity among these terminals. In this case, the terminal operator will act as the central decision maker and an optimal ITT fleet and operation plan can be determined based on the terminal operator's interest.

The transport operator, such as the barge operator, may also provide ITT service. For example, Douma et al. (2011) and Li et al. (2017a) study the cases that a barge visits multiple terminals in the port. In Li et al (2017a), the barge operator makes a rotation plan and could decide how much extra ITT container the barge could transport.

A third party ITT provider is usually assumed to provide ITT service. For example, Hu et al. (2018) propose a truck-based ITT system connecting 18 terminals in a port area. Duinkerken et al. (2006) compare different types of vehicle used in the shared ITT system in Maasvlakte, Rotterdam. In this case, the ITT provider will dispatch the vehicle considering all terminals' transport demand.

Two research gaps can be identified respect to the actors involved. Firstly, the coordination between terminal operators and multiple transport operators must be further studied. Jacobsson et al. (2018) investigate the coordination between terminal operators and road hauliers regarding the road hauliers' access to seaport terminals. The authors also point out that the communication between different hauliers should be further studied.

Secondly, when multiple ITT providers are involved, it is not clear how to share the responsibilities in facility investment, operation organization, or the revenue from the ITT service. As in the case of Jin and Kim (2018), the several trucking companies could work in a collaborative way by sharing transport orders and capacities, however, the share of the revenue still

remains to be investigated. Further research is needed to clarify the cost and benefit for different actors in investing and using the ITT.

2.4.3 Methodologies and theories used in port ITT planning

Simulation, mathematical programming and case study have been used in the existing research. Simulation tools are widely used to evaluate the performance of different terminal layout and fleet configuration. For example, Ottjes et al. (2006) simulate a multi-terminal system with different factors such as ITT infrastructure, sea berth length, stacking capacity, etc.; Duinkerken et al. (2006) test the performance of ITT systems with MTS, AGV, and ALV respectively. Mixed integer programming (MIP) is usually used to formulate the ITT operations, such as vehicle routing and crane scheduling, and find the optimal plan. For example, Hendriks et al. (2012) propose a MIP model aimed at balancing the quay crane workload for unloading vessels over terminals while minimizing the ITT cost; Schepler et al. (2017) present a MIP model taking into account feeder vessels, inland waterway barges, trains and trucks routing among multiple terminals and aimed at minimizing the weighed turnaround time. A case study research can be found in Hansen (2004). The author analyses the main characteristics of train services and railway facilities of container terminals at seaports and presents an innovative automated rail inter-terminal transport system.

Theories such as queuing theory, control theory, and game theory have been used in the literature. Queuing theory is applied to reflect the relations between different subsystems considering the potential disturbance. For example, Caballini et al. (2014) focus on port rail operations including container transport between the stacking yard and the internal rail yard in a maritime terminal, train loading and shunting at the internal yard, train traction between the internal yards and to the external yards. The number of containers changing their states (e.g., moved from storage yard to internal rail yard) is restricted by the productivity of the terminal resource using queueing theory. The queues' length is determined by the arrival rates, initial conditions and service rate of terminal resources. Similar research can be found in Caballini et al. (2016) and Mishra et al. (2017).

Some other researchers also investigate the integration of control theory with optimized planning. Zheng et al. (2016) and Zheng et al. (2017) study the control of waterborne AGVs used in ITT. In Zheng et al. (2016), the online model predictive control optimizations for smooth tracking is integrated with a mixed-integer quadratic programming problem considering distance-to-go and time-to-go at each sampling step. Then, in Zheng et al. (2017), the authors consider the control of the waterborne AGV fleet integrated with an optimization model to minimize the weighted sum of waterborne AGV deployment cost, energy consumption, emissions, total travel time, and delivery delay.

Gharehgozli et al. (2017) integrate simulation and game theoretical methods to find the optimal ITT service with different providers. In that research, coalitions of terminal operators and transport scenarios are first defined; then, a simulation is used to determine the number of

vehicles needed to meet the transport demand; next, game theoretic concepts are used to determine stable coalitions and to divide costs and benefits for each transport mode fairly between the stakeholders; lastly, the annualized investments in ITT infrastructure are compared with the cost savings that can be realized.

Two research gaps can be identified in methodologies and theories in port ITT planning: firstly, the financial interests of actors were rarely considered. Actors such as the port authority and transport operators may be involved, but their benefit of investing in the ITT system is not clear. Therefore, a methodology that could reflect both the costs and savings for different actors should be further developed. Secondly, the ITT operations should be more precisely formulated. Several simplifications have been applied in modeling the ITT operations like container handling time, transport time and costs. For example, it could be hard to accurately estimate the productivity of shunting yards; in Caballini et al. (2014), Caballini et al. (2016), and Mishra et al. (2017), only homogeneous vehicle capacity was considered and no congestion was taken into account. These simplifications and assumptions keep the problem solvable but may result in losing accuracy.

2.5 Hinterland ITT

This section reviews the research of hinterland ITT. The focus is put on the transport between seaport terminals and multiple inland terminals, and the terminal operations in both seaport and inland terminals, see Figure 1. The 47 reviewed studies mainly focus on maximizing the transport volume while reducing the related costs by using properly designed networks and terminals. Stakeholders such as port authority, terminal operator and transport operators are involved in the hinterland ITT planning. Optimization models, case studies and simulation systems are used in these papers.

2.5.1 Planning problems

Hinterland ITT strategic planning: network design and terminal development

On a strategic level, the existing research covers three important topics: determination the network design, such as the location of the hub terminal and the function of terminals, evaluation of the network and service performance, and impediments in network development.

In terms of network design, hub-and-spoke networks have been intensively studied and implemented to increase the service frequency and reliability. Cost factors, including terminal development cost, transport costs, and terminal handling costs, are widely considered in the network design. The location of the hub terminal is crucial to reduce the cost of the ITT network. Racunica and Wynter (2005) propose a model to formulate the hub-and-spoke network for intermodal freight transport on dedicated or semi-dedicated freight rail lines. Both the hub terminal development cost and transport cost are taken into consideration. Limbourg and Jourquin (2009) focus on a rail-road hub-and-spoke network, where pre- and post- haulages are performed by road transport and inter-hub haulage is performed by rail. The research aims

at finding the optimal hub terminal locations on the European transport network with the lowest transport and transshipment costs. Konings et al. (2013) investigate the location of the terminal as well as the impact of using different vessel size, vessel type, service frequency, etc. The authors conclude that a hub-and-spoke network can be used to improve the barge transport connecting Rotterdam port and its hinterland.

The function of terminals may also influence the cost of the ITT network. Dry ports can be seen as special inland hub terminals with seaport terminal functions which could relieve port congestion and reduce freight transport emission (Roso and Lumsden, 2010, Hanaoka and Regmi, 2011, Meers et al., 2018). Therefore, hinterland ITT network with dry ports has also been discussed with transport cost, terminal operation cost, and other factors, such as societal benefits and users' choice preference. For example, Iannone and Thore (2010) investigate the situation that parts of ports operations are moved to inland dry ports and a lower total costs (transport costs, inventory holding costs, terminal and customs operation costs) can be achieved. Iannone (2012a) studies the transport system in the Campanian region, Italy, which includes two interports. The author claims that the customs facilitation between seaports and interports could be conducive to expand the hinterland of the Campanian seaports and improve the competitiveness of the regional logistics system.

Apart from network design, existing studies also evaluated the performance of hinterland ITT regarding system performance, sustainability, resilience, etc. For example, Konings and Priemus (2008) analyze the barge transport connecting seaport and hinterland. The authors point out that visiting multiple terminals with small handling volumes in the port is time-consuming and negatively affects terminal productivity. The authors also argue that direct transport from seaport to destination terminal is less attractive due to the small transport volume and waterway restrictions. Janic et al. (1999) evaluate the sustainability of rail-based ITT with 20 indicators including network size, frequency, terminal time, etc. Suggestions are made to make a network "promising", e.g., routes should cover a wide spectrum of distances, from extremely short to extremely long, and frequency should be sufficient to serve expected demand, regular, and available as needed.

Awad-Núñez et al. (2015) assess the sustainability of the location of a dry port taking into account 17 different types of factors, which are related to the environment, economic, social, accessibility and location, would influence the sustainability of the dry port. The authors proposed a multi-criteria decision analysis framework: weighting these factors with expert scoring and using an artificial intelligence model based on Bayesian network to reduce the arbitrariness of the weights.

Chen et al. (2017) evaluate the resilience of the port-hinterland transport network by simulating how the transport process would recover after unconventional emergency events which could damage the transport facilities. Recover activities such as using an adjacent dry port and rail shuttle, transporting by road, and waiting for temporary repair are respectively tested in the study.

Meanwhile, several impediments have been identified by the existing research. Roso (2008) investigates the development of the dry port in Sydney and points out that the infrastructure construction (rail and road), land use, environmental and institutional impediments are the common impediments in dry port development. Iannone (2012a,b) argues that policymakers could improve the port-interport system with more adequate regulations and more effective and intelligent organizational schemes and regional logistics marketing initiatives. Jeevan et al. (2018) conduct a survey for Malaysian dry port stakeholders to examine the influential factors of Malaysian dry port operations. The results indicate that improving the information system is most important for dry port operations, and modernizing and upgrading current capacity in dry ports should be included as one of the main agenda items.

One research gap can be identified in hinterland ITT network strategic studies: the external effects of these transport modalities and services. Several external effects such as emissions, accidents, and congestions have been studied with single-modal transport systems, but are often neglected in multimodal transport system with different vehicles, terminals, and trans-shipment operations. Bektaş et al. (2018) review the role of operational research in green transport and point out that the methodologies and tools can be developed to consider the dynamics of the energy consumption based on traffic conditions, infrastructure, and other external influences. Future research should find ways to internalize these costs.

Hinterland ITT tactical and operational planning: transport network design

In a tactical and operational level, the existing studies have been focused on the service network designing, i.e., providing profitable transport service with a given infrastructure network. To reduce the hinterland ITT cost and maximize the profit for the transport operators, the following topics have been discussed.

The first research topic is freight flow consolidation. Different consolidation networks have been studied and their economic performances have been evaluated. Trip and Bontekoning (2002) discussed the possibility to integrate small transport flows into the intermodal system at an inland rail terminal. The authors could find a feasible solution with feeder trains to bundling freight flow from outside the economic core areas but point out that it could be hardly profitable to run the feeder trains. Jeong et al. (2007) consider the European rail system as a hub-and-spoke network, the freight flow could go through any number of hub(s). The authors develop a mathematical model to determine which hub(s) to use to reduce total costs including transport cost, handling delay-time cost at hubs, waiting time costs, consolidation costs, etc. Konings (2007) points out that the barge operator could improve its productivity and hence gain substantial additional revenue if the number of terminal visits in the port could be reduced. A similar conclusion can be found in Caris (2011), the authors propose a consolidation network that inland vessels only visit one or several hub terminals in the port area of Antwerp. The results show that by reducing the visiting terminals, the turnaround time of inland shuttle services can be reduced; sea terminals may operate more efficiently.

Another important research topic is the rotation plan of barges and trains, i.e., which terminals barges and trains should visit and what operations should be performed in these terminals. For inland waterway transport, the vessel may visit multiple terminals along the river. The rotation plan is made to maximize the operator's revenue based on transport demand, transport cost and container handling cost, see Zheng and Yang (2016). An et al (2015) study the barge transport between the seaport and several inland waterway terminals. The authors assume that the barge service is provided between the seaport terminal and any inland waterway terminal. Besides the fuel cost and container handling cost, the authors also consider a terminal entering cost and a fixed route cost due to the waterway condition. In the optimal solution, both direct transport, service between seaport terminal and an inland waterway terminal, and transport covering multiple terminals are provided. Maras (2008) and Maras et al. (2013) also investigate the barge routing along the inland waterway, aiming at maximizing the profit of the barge company considering shipping cost, terminal handling cost, and empty container related cost.

For railway transport, Lupi et al (2019) identify the railway path from seaport to its hinterland with a proposed a cost function, considering travel time and service cost per train. Crainic et al. (2015) mathematically formulate the rail shuttle service connecting seaport terminals and dry ports. With a given fleet, the proposed model could help the operator to find the optimal service plan. Van Riessen et al. (2015) focus on intermodal transport from port terminals to the hinterland. The authors propose a model aimed at generating a weekly schedule for both self-owned and subcontracting intermodal transport fleet with the lowest transport cost, transfer cost, and delay penalty.

Additionally, Fazi and Roodbergen (2018) discuss how would demurrage and detention fees affect the container transport from seaport to inland terminals. It is assumed that by charging demurrage and detention fees, shippers will be motivated to move containers out of the seaport. However, the research shows that these charges will negatively affect the transport cost and dwell time; meanwhile, these charges also limit the usage of barge transport. The authors also suggest that a combined demurrage and detention charges, which applies a single free period for both demurrage and detention, could result in shorter dwell time.

Several research gaps can be identified in the hinterland ITT tactical and operational planning. Firstly, integration and collaboration between multiple terminals and vehicles are rarely studied. Feng et al. (2015) investigate the communication between the terminal and barge operator, a mediator is proposed to coordinate multiple barges and terminals. Similar research is needed to coordinate multiple terminals and vehicles: schedule terminals' handling operation plan and the vehicles' routings. Secondly, freight consolidation and vehicle scheduling are rarely studied with a multi-modality fleet. With the integration and cooperation between different transport operators, it is possible that there is an intermodal transport operator who provides multi-modal transport. Therefore, further research on multi-modality transport could help the intermodal operator provide more competitive service. Thirdly, rail service between the sea-

port and dry port is rarely studied in tactical or operational level. As mentioned in Crainic et al. (2015), decisions must be made such as service area, freight assignment to operated service, the schedule of the service, etc. Given the diversity of the dry port in terms of location and operations, further research is needed to provide deeper insight into the feeder service organization.

2.5.2 Hinterland ITT Stakeholders

Generally, three types of actors have been discussed in the hinterland ITT literature: policy-maker, transport operator (freight forwarder and/or carrier), and terminal operator. The policymaker could be a regional or national government agency that provides subsidy, determines the land use, making regulations or owns the infrastructure; the freight forwarders organize the transport in cooperation with terminal operators and transport operator, who runs a fleet of transport vehicles. Specially, in the railway transport system, there could be an infrastructure manager who is responsible for infrastructure construction and maintenance. In the intermodal transport system, the transport between seaport terminals and inland terminals can be performed by seaport terminals, inland terminals and a third party (Veenstra et al., 2012). Shipping lines sometimes are involved in the inland transport by cooperation with inland terminals (Wilmsmeier et al., 2011). Inland transport operators are also crucial, for example, barge container carriers in fact control about half of Rhine terminals (Notteboom and Konings, 2004). Kotowska et al. (2018) point out that, to improve the quality of hinterland connections, the seaport authorities usually cooperate with inland ports, acquire shares in inland ports, or invest in inland terminals operating as dry ports. The Rotterdam Port Authority possesses, for example, the Wanssum Intermodal Terminal, located in the southeast of the Netherlands, and Alphen aan den Rijn, located 60 km away from Rotterdam.

Despite the diversity in stakeholders involved, policy makers should play a leading role in the strategic planning of hinterland ITT. While investing a new terminal or expanding an existing terminal, the policy maker should make decisions on a more comprehensive perspective. For example, in the development of two inland intermodal terminals connected to Botany port in Sydney, several impediments from different actors can be identified. The truck companies are strongly against any actions that could reduce the road transport share, and the sea port's proposal for solving port congestion was charging the truck companies a higher fee in peak hours (Roso, 2008). Roso et al. (2009) point out that a win-win cooperation is possible. If an inland intermodal terminal is properly implemented, the money saved at the sea ports can be used to subsidize the rail shuttle service. The road transport share may be reduced but the road transport operators could have a lower operation time at the terminals. . Ng et al. (2013) point out that the institutional framework and multiple governmental agencies negatively affect the integration of dry port and seaport in Brazil. Bask et al. (2014) analyze the development of two sea port-dry port systems and identify financial support from policy makers in both cases.

Several research gaps can be found in the coordination between actors: firstly, the conflicting interests between different policy makers are rarely studied. For example, Jeong et al. (2007) study the European railway network and indicate that the national governments have little interests in investment that could promote international transport because the benefits may only be achieved outside the country. Therefore, the investment and benefit analysis should be further studied from policy makers' perspective. Secondly, although the cooperation between transport and terminal operators is critical in providing hinterland ITT service, few studies investigate how to balance their interests. Van Riessen et al. (2015) investigate the European Gateway Services provided by Europe Container Terminals (ECT), who runs three terminals in the port of Rotterdam. In that case, the ECT works as an intermodal network planner, transporting containers between the port and hinterland terminals. However, the service could involve multiple operators, for example, Rodrigue and Notteboom (2012) point out that some railway operators provide direct shuttle service on the spoke of a competitor's established hub-and-spoke network, and Iannone (2012b) indicates that some sea port terminals and freight forwarders are reluctant to cooperate with inland terminals to prevent losing their core activities. Therefore, the relationship and cooperation between operators should be further studied.

2.5.3 Methodologies used in ITT operation planning

Mathematical modeling, case study, and simulation have been used in hinterland ITT planning. Mathematical modeling is widely used in infrastructure network planning and service network planning to identify the optimal network with the lowest investment and operation cost. For example, Iannone and Thore (2010) optimize the container import flow in the Campania region in Southern Italy. The authors formulate the transport process using a MIP model aiming at minimizing the transport cost, inventory cost, terminal operation cost, and customs operations cost. Limbourg and Jourquin (2009) propose an integer programming model to find optimal locations for European transfer terminals embedded in a hub-and-spoke network. Alfandari et al. (2019) formulate the barge rotation problem with a MIP model to determine which terminal to visit and which container to transport. To reflect the different actors preference in choosing services in the network, Vasconcelos et al. (2011) use a Logit choice model to determine the proportion that a specific service is chosen. Meng and Wang (2011) introduce user equilibrium constraints in their model. Moreover, fuzzy variables are used to characterize the uncertainties in the system, such as transport and operation time (Yang et al., 2016, Wang et al., 2018).

Case studies and conceptual studies are used to demonstrate the experience obtained in the network development process and service network planning. For example, Hanaoka and Regmi (2011) analyze the development of the intermodal transport system with dry ports in five Asian countries. The authors discuss the modality of the transport systems, ownership of the dry ports and summarize the lessons learned from each case. Similarly, Jeevan et al. (2018) analyze the influential factors of dry port operations in Malaysia based on the data ob-

tained from online-survey. Trip and Bontekoning (2002) discuss the possibility to organize freight consolidation in Valburg terminal. A bundling plan is made based on the transport volume, operational capacity and railway timetable to demonstrate that the consolidation is possible.

In the methodology aspect, two research gaps can be identified: firstly, powerful algorithms are needed. The size of the ITT network keeps growing with the development of the inland terminals, and at the same time, the integration in transport and logistics problems are becoming more important (Speranza, 2018). The collaboration of different operators, dynamics in the demand, operation time and cost should also be considered in the ITT planning. This trend can be already seen in software, such as Nodus (proposed by Jourquin and Beuthe, 1996), which could solve large-scale transport problem multiple modes and handling operation (Jourquin, 2016). Further extensions could cover more factors in the ITT system. Meanwhile, some factors in the planning problem, such as the cost discount for scale economies in freight consolidation (Racunica and Wynter, 2005), cannot be accurately formulated by linear functions. In Liu et al.,(2019), the authors minimize the intermodal transport system cost considering scale economies with a non-linear and discontinues objective function. The problem is solved by a hybrid heuristics with a small network. Therefore, methodologies and algorithms that could precisely formulate the system and handle large-scale network should be further studied.

Secondly, empirical analysis methodologies are needed to quantitatively discuss the cost and benefit of any investment and activities for policymakers. Existing research mainly focuses on maximizing single decision maker. The empirical analysis is needed to demonstrate the benefits to regional, national governments and international organizations.

2.6 Discussion on the review

Based on the 77 papers, we can find that the number of studies on port ITT planning is relatively small but increases over the last years. Meanwhile, the academic community pays special attention to the ITT network in Rotterdam port as half of the port ITT research focuses on this area.

The hinterland ITT, especially the European network, has been more intensively studied. The port ITT research aims at developing an efficient transport network with the lowest ITT costs. Five major ways to reduce the port ITT costs can be identified in the existing research: 1) properly designing of the terminal layout; 2) choosing an efficient ITT fleet; 3) improving the information system; 4) better assignment of the deep-sea vessels to terminals; 5) and optimizing the routing of ITT vehicles. On the other hand, the hinterland ITT studies focus on relieving port congestions and providing better connections in terms of service coverage, frequency, and price. Compared with the port ITT studies, more strategic problems, such as the network layout, the terminal's location, and function, have been discussed in the hinterland ITT sys-

tem. Moreover, considerable efforts have been taken to optimize the barge transport between the seaport and several inland waterway terminals.

The responsibilities of port ITT stakeholders are relatively clear in the existing research, the terminal operator could run an ITT service on a self-owned network; the transport operator could transport ITT containers if these operations are profitable, and the port authority is also assumed to act as a third party ITT provider. However, the situation is more complicated in the hinterland. The existing research shows that the multiple policy makers, such as location government, national government, and international organizations, are involved in the hinterland ITT. These policy makers play a significant role as they not only determine the network layout, subsidize the infrastructure construction, but also get involved in the transport and terminals operations.

According to the review, mathematical modeling and simulation tools are widely used in both port and hinterland ITT studies to find the optimal freight flow, vehicle route, and terminal scheduling. Queueing theory and game theory have been used in port ITT studies to investigate the relationship between different subsystems and actors. Control theories are also studied in the dispatching the port ITT vehicles. Conceptual and case studies are more often used in hinterland ITT to summarize the development trend and lessons can be learned in different cases. User equilibrium theory and logit model have been used to reflect different actors behavior in the hinterland ITT.

Meanwhile, some research gaps can be identified in port and hinterland ITT, see Table 2.3. In terms of the strategic planning, multi-mode ITT system is rarely investigated in the port ITT system; studies discussing the port ITT transport demand and its relation with network and terminal design are rare, while a considerable number of research papers and projects can be found focusing on the hinterland ITT. Moreover, how to optimize the port ITT operations with different types of information systems should be further investigated. External effects of ITT system have been studied in the port and hinterland, however, more comprehensive analysis based on a multi-modality system is needed for the hinterland ITT.

On the tactical and operational level, the scheduling of the rail service and the integrated planning of transport and terminal operations should be further studied in both port and hinterland ITT. Moreover, as the hinterland ITT may involve more terminal, transport operators and more complicated networks, the coordination between multiple operators and the fleet scheduling considering freight consolidation should be further studied.

The coordination between terminal and transport operators should be further studied in both port and hinterland ITT, a trusted party or cooperation framework is needed to balance various benefits. Especially, the multiple policymakers' interests in the hinterland ITT system should be further investigated. Moreover, future research should help to identify the costs and benefits of organizing the ITT in the port area.

In the methodology perspective, quantitative methodologies are needed to reflect different actors' financial interests as the existing research mainly uses conceptual and case studies in the analysis. Some simplifications and assumptions in mathematical modeling in port ITT, such as handling operation time and disturbance, should be further studied and more precisely formulated. Moreover, powerful algorithms are needed to deal with the increasing problem size and handle the non-linear factors in the problem.

2.7 Conclusion

This chapter reviews ITT in the port area and in the hinterland to answer the **Research Question 1**, i.e., what kind of ITT system is needed to improve the transport efficiency and how to reduce the ITT related costs in both infrastructure planning and operations. The review results demonstrate that strategic planning problems, such as the layout of the terminal and network, the ITT fleet and the information system as well as the tactical and operational planning problem, such as vessel berth allocation and ITT vehicle routing, will affect the cost of the ITT system. Meanwhile, multiple actors are involved in the planning of ITT system, therefore, planning approaches are needed to coordinate their planning targets.

In the following chapters, we put our focus on the integration of ITT system and the railway hinterland transport system. We mathematically formulate and optimize the connection between ITT and railway system in Chapter 3 and evaluate the performance of different strategies used in the integrated ITT-railway system in Chapter 4.

Table 2.3 Research gaps in port and hinterland ITT studies

Port ITT		Hinterland ITT	
Strategic	Tactical and Operational	Strategic	Tactical and Operational
- Infrastructure investment and potential ITT cost should be studied in an integrated way. - Port ITT demand is rarely studied. - Integrated multi-modality systems should be further investigated. - Dynamics of the information systems should be considered in ITT planning.	- Organization of rail ITT system is rarely studied. - The ITT operations should be formulated taking into account upstream and downstream transport and terminal handling operations.	External effects should be investigated and formulated based on a multi-modality ITT system.	- Integration between multiple terminals and vehicles has received less attention. - Freight consolidation and vehicle scheduling are rarely studied with a multi-modality fleet. - Seaport-dry port rail service is rarely studied.
Stakeholders		Stakeholders	
- Stakeholders and ways to coordinate terminal operator and multiple transport operators should be further studied. - Stakeholders' share of responsibility revenue is rarely investigated.		- Conflicting interests between different policymakers are rarely studied. - Stakeholders and ways to coordinate terminal operator and transport operator should be further studied.	
Methodologies		Methodologies	
- Quantitative methodologies are needed to reflect different actors' financial interests. - ITT operations should be more precisely formulated.		- Quantitative methodologies are needed to reflect different actors' financial interests. - Powerful algorithms are needed to handle the large-scale planning problems and non-linear factors	

Chapter 3

Optimization of Integrated ITT and Hinterland Rail System

Transport demand for containers has been increasing for decades, which places pressure on road transport. As a result, rail transport is stimulated to provide better intermodal freight transport services. This chapter investigates mathematical models for the planning of container movements in a port area, integrating the inter-terminal transport of containers (ITT, within the port area) with the rail freight formation and transport process (towards the hinterland). An integer linear programming model is used to formulate the container transport across operations at container terminals, the network interconnecting them, railway yards and the railway networks towards the hinterland. A tabu search algorithm is proposed to solve the problem. The practical applicability of the algorithm is tested in a realistic infrastructure case and different demand scenarios. Our results show the degree by which internal (ITT) and external (hinterland) transport processes interact, and the potential for improvement of overall operations when the integrated optimization proposed is used. Instead, if the planning of containers in the ITT system is optimized as a stand-alone problem, the railway terminals may suffer from longer delay times or additional train cancellations. When planning the transport of 4060 TEU containers within one day, the benefits of the ITT planning without considering railway operations account for 17% ITT cost reduction but 93% railway operational cost growth, while the benefits of integrating ITT and railway account for a reduction of 20% in ITT cost and 44% in railway operational costs.

This chapter is an edited version of the article:

Hu, Q., Corman, F., Wiegmans, B., and Lodewijks, G. (2018). A Tabu Search Algorithm to Solve the Integrated Planning of Container on An Inter-terminal Network Connected with A Hinterland Rail Network. *Transportation Research Part C: Emerging Technologies*, 91, 15-36.

3.1 Introduction

Containerized transport is increasingly important in global trade. In order to satisfy growing container transport demand, major container ports aim to extend their scale. The increasing size of container ports enables a higher throughput; however, it also leads to another problem: efficiently connecting the container terminals in a port to the hinterland transport service network. Currently, road transport accounts for more than 75% of the freight inland movement in Europe (Eurostat Database, 2014). Although road transport provides faster, reliable, and flexible transport, it has several disadvantages including congestion and negative environmental impacts such as emissions and noise nuisance. Thus, it is beneficial to reduce road haulage and facilitate the growth of railway and inland shipping. In order to achieve the modal shift away from trucks, containers from deep sea terminals should be moved to railway yards or inland shipping berths. This movement could be via inter-terminal transport (ITT).

This gives rise to the following two operational problems: first, moving and rearranging container flows around the multiple terminals, and the railway yards, by using available transport vehicles; second, scheduling loading the container trains and determining their departure time. An inter-terminal transport network is used for the former issue; effective operations are critical for reducing the impact of delays generated outside of the network (by incoming vessels), in the terminal operations, as well as in the transport part. Currently, this is a hot topic, and clear point of improvement, as according to the Rotterdam Port Authority, over 40% of vehicles coming to or from Maasvlakte 2 experience a considerable delay. When delays occur within the ITT network, downstream operations, e.g., train loading in the railway yard, will be affected and may result in extra cost: trains could be delayed or even cancelled.

Previous research on the ITT network operations focused mostly on the design and dimensioning perspective (how many vehicles, which types); moreover, previous research neglected the integration of ITT and hinterland transport. In this chapter, we tackle the problem of planning ITT movements, in an integrated perspective: we determine an operational plan, some hours to some days in advance, describing which containers (i.e. demands) should be moved at what time from their origin terminal to their destination terminal, using which vehicles. Some of the containers are to be loaded onto trains, whose loading process and departure process (once the relevant containers are available, depending on the ITT process) have to be considered as well.

In order to solve the above-mentioned problem, we first use a time-space graph to formulate the vehicle routing and container transport problem in an ITT network. Second, railway links to the hinterland are connected to the ITT network and the railway terminal operations are integrated with ITT. To find good solutions within a limited time horizon, we propose a tabu search algorithm. The algorithm is tested with different transport demand volumes. The scientific contributions of this chapter include the following:

- We present a mathematical model integrating container and vehicle movement in ITT and rail yard operation for hinterland rail transport.
- We develop a tabu search algorithm capable of solving large-scale instances of the problem.
- We investigate the practical applicability of using the algorithm for decision support in a realistic ITT case with a realistic demand scenario.
- We derive simplifications for strategic decision making regarding the relationship between bottlenecks within ITT and the connection to railway links, as well as fleet size, loading rate, allowed delay of trains, handling times, and traverse time within the terminal area.

The remaining part of this chapter is organized as follows. Section 3.2 presents a literature review on ITT, VRP, and terminal operations. Section 3.3 provides basic information on ITT. Section 3.4 explains how to mathematically model the problem with a time-space graph. In Section 3.5, we present the tabu search, and in Section 3.6, we report and analyze our results. Section 3.7 provides conclusions and presents further research.

3.2 Literature review on ITT, VRP, terminal operations

3.2.1 Vehicle routing problems

The ITT problems studied in this chapter is very similar to vehicle routing problems (VRP), as they relate to shipment containers with given release and due times, on a given network. Dantzig and Ramser first formulated VRP in 1959. VRP evolved from then into a series of problems related to finding optimal delivery routes between a depot and several customers. Parragh et al. (2008a) and Parragh et al. (2008b) present a detailed survey about the transport problem between multiple origins and destination nodes. According to Parragh et al. (2008b), the ITT problem in our research is a VRP with Pickups and Deliveries (VRPPD). Specially, the ITT problem deals with multi-commodity demands. Each Container in the ITT system has its origin terminal, destination terminal, and a time window to pick-up and deliver. Similar formulations can be found in Battarra et al. (2009), Rodríguez-Martín and Salazar-González (2012), and Cattaruzza et al. (2014). Battarra et al. (2009) study a VRP with a central depot and multiple customer locations. Different types of commodities should be sent to these customers. Rodríguez-Martín and Salazar-González (2012) consider the pick-up and deliver among multiple costumer locations. Multiple commodities are considered and each commodity has its own origin and destination. In Cattaruzza et al. (2014), two types of commodities that cannot be loaded into a same vehicle are considered. In our problem, vehicles visit pickup points to collect containers and deliver them to delivery points. When compared with a typical VRPPD or multi-commodity flow problem, this chapter deals with specific issues of the ITT network in terms of connectivity, density of vehicles, amount and dynamics of demand, and moreover not only optimizes the delivery routes inside the port area, but also takes into con-

sideration related railway operations. The train loading and departure plan is made according to the result of the VRPPD and reducing the delay and rescheduling cost are included in the objective of VRPPD. We briefly review the works which relate particular aspects of research for ITT networks and operations.

3.2.2 Inter-Terminal Transport

There has been growing attention on ITT recently. Heilig and Voß (2017) provide a literature overview on ITT and indicate that a collaborative planning is needed to integrate the intra- and inter-terminal operations. Following this reasoning, our research studies the integration of the ITT and hinterland railway transport to reduce the costs in both segments. Several optimization models have been proposed to study the ITT. Tierney et al. (2014) propose the first fully defined mathematical model of ITT using a time-space graph. The objective is to minimize tardiness of container delivery. In the time-space graph, nodes represent terminals and intersections, and weighted arcs represent connections. To reflect loading/unloading time in the real world, long-term nodes and long-term arcs are introduced. Based on the graph, the authors present an integer-programming model to solve the ITT problem. In this model, 4 terminals and 2 intersections are taken into account and the planning horizon is 8 hours with a time step of 5 minutes. Nieuwkoop et al. (2014) develop the time-space model to find an optimal vehicle configuration with minimized delays. Here, we also use a time-space model, which is similar to the model presented by Tierney et al. (2014), but we extend the model to study a more complicated problem integrated with hinterland railway transport operations. We use the same transport network presented by Nieuwkoop et al. (2014) in the case study presented. Instead of searching for the optimal vehicle configuration in ITT, we focus on investigating the best ITT delivery and train loading and departure plan to reduce the total operational cost and delay cost. Heilig et al. (2017a) and Heilig et al. (2017b) study the ITT truck routing and the emission reduction. It is indicated that reducing the empty trips of the truck can reduce emissions. In our research, we optimize the container delivery based on fixed fleet size, which ensures that the reduction of the empty trips will improve our objective.

3.2.3 Railway operations

In terms of railway terminal operations, Boysen et al. (2012) present an exhaustive review of railway terminal operational problems and challenges. Much research has focused on the train loading and unloading problem. Most researchers use a mixed-integer programming (MIP) model to describe the loading and unloading process. Corry and Kozan (2007) propose an assignment model for dynamically assigning containers to slots on a train at an intermodal terminal. Li and Wang (2008) use a simulation based algorithm to find the optimal deployment of forklifts and container trucks when (un)loading container trains. Anghinolfi (2011) proposes a planning procedure for serving freight transportation requests in a railway network with horizontal handling equipment. Although operations in railway terminal are intensively studied, few studies investigate the coordination between railway terminals and ITT in an in-

tegrated manner. Caballini et al. (2014) present a planning approach to optimize railway operations in seaport terminals by adopting a queue-based discrete-time model of the considered system.

The integration of different topics of optimization within railway chains is drawing increasing attention, see for instance the papers discussed in Corman et al. (2016). One key point of our approach is the integration with railway operations. In fact, to ensure timely delivery of containers to their end destination, we argue that integration of the delivery process, for railway, is a needed and relevant extension.

3.3 The ITT network with railway links and transport operations

In our research, we study the container transport process from the moment containers are released at terminals, until they are delivered to their destinations in another terminal inside the port area, or in the hinterland. We target overall cost reduction, which is made up of several contributions. In the ITT part, we reduce the vehicles' travelling cost and containers delay cost by arranging vehicles' routes and containers' delivery order with the information about when and where the container is released and should be delivered. In the railway operation part, any container that is delayed cannot be loaded on time on the train and might affect the train departure plan. Costs are related to delays penalties, as well as increased costs when the train loading rate is low. If too many containers are late for a train, the train will be cancelled. Our research integrates all these processes to reduce the total operational cost and delay cost. This is of great importance for optimal exploitation of the available capacity in the ITT network, and to allow timely and cost-efficient departures of freight trains.

In this chapter, the mathematical model is generic and able to represent different layouts of ITT networks which consist of terminals, road connections and intersections. To address the studied problem more clearly, we use the transport network of Maasvlakte1&2 as an example case to analyze the optimal organization and operation of ITT. The road connections and transport demands between terminals in Maasvlakte1&2 were studied by Nieuwkoop et al (2014). In order to reduce the complexity and enhance the relationship between ITT and railway transport, we consider a schematic map of the ITT network (see Figure 3.1). We study the ITT and railway operations in this network during one day, with a time resolution of steps of one minute.

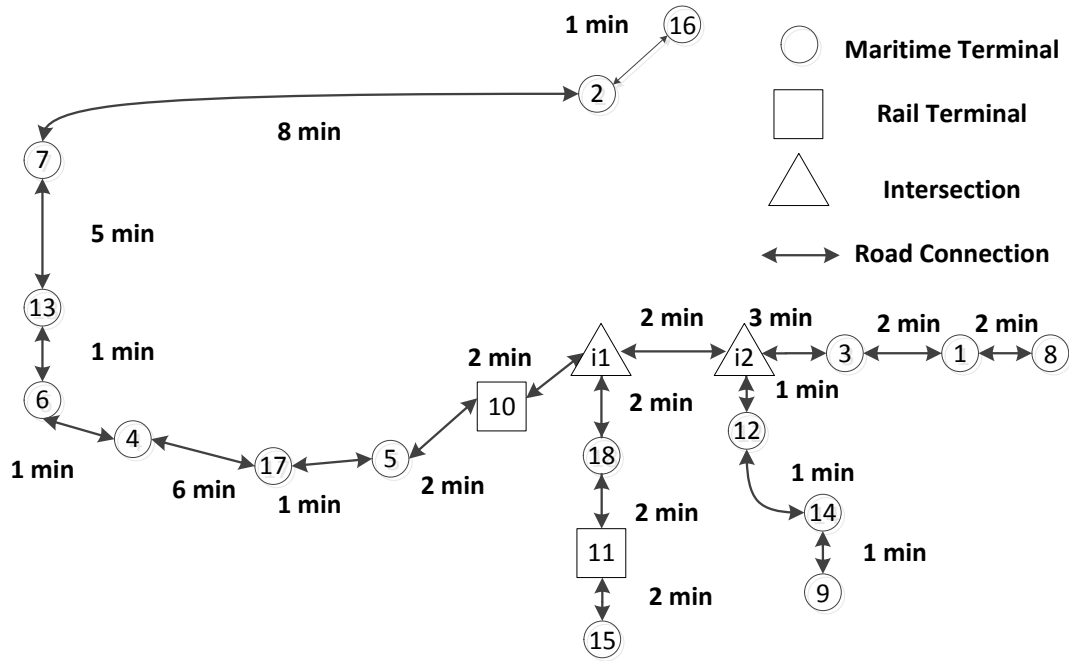


Figure 3.1 Schematic map of the ITT core road network at the Maasvlakte.

There are 20 nodes and 19 links that make up the ITT network. Among the 20 nodes, 18 nodes represent terminals and 2 nodes represent intersections (i1 and i2). We assume that the 18 terminals are connected by the road transport network. Terminal 10 and 11 are dedicated railway terminals that are connected to the hinterland railway network. Node i1 and i2 represent two three-way intersections. In the remainder of this section, we describe the nodes, links, and relevant operations in this system.

3.3.1 Nodes and links in the system: terminals, intersections, and road links

Terminal nodes

In the ITT network, two types of terminals are assumed, i.e., maritime and railway terminals. In this chapter, we assume that all terminals except 10 and 11 are maritime terminals. In a maritime terminal, containers are unloaded from the vessel using quayside cranes. The container is then moved to the storage area. Vehicles that transport the containers from the maritime terminal to their destination must access the end of the stacking blocks

Aside from the maritime terminals, we also consider railway terminals, i.e., 10 and 11. In a typical railway terminal, vehicles can use the driving lane next to the railway tracks and cranes are used to handle containers between trains, the storage yard, and vehicles.

Intersections

Intersections may increase the traveling time of the vehicle in the network. In this chapter, only three-way intersections are used in the network. In order to identify the potential conflicts in an intersection, we add a dummy node 'O' to reflect the center of the intersection (see

Figure 3.2). Then, six directions can be found in that intersection, and three of them conflict, i.e., A-O-B, C-O-A, and B-O-C. While some vehicles can cross the intersection without blocking other vehicles' routes, only a limited number of vehicles can cross the dummy node O in one time step without lowering their speed.

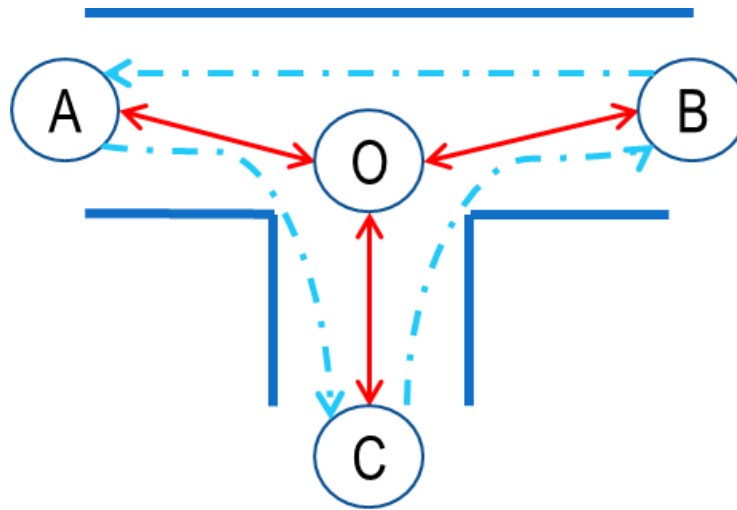


Figure 3.2 Schematic diagram of a three-way intersection

Links in the system: road transport network

The above-mentioned 18 terminals are connected by a road network as shown in Figure 3.1. If a container is required to be moved from one terminal to another, the container will enter the ITT network. We define the transport demands as tasks. Each task consists of 1 or 2 TEU containers with given origin terminal, destination terminal, and a delivery time window. Specifically, any transport task can only be picked up from its origin terminal after the release time, and it should be delivered to its destination before the due time.

3.3.2 Assumptions for the operations in the nodes, intersections, and links

Handling operations in maritime and railway terminals

In maritime and railway terminals, we assume a container can be loaded onto a vehicle immediately after its release time. We also assume that if there is more than one task available in a terminal, the task with the earliest due time will be transported first.

Train formation in railway terminals

In a railway terminal, a certain number of trains are planned every day with different departure times and capacity of loaded containers. We determine a train's actual departure time based on the following criterion: if a train is not fully loaded at its planned departure time, this train will be delayed. In this chapter, we set a fixed buffer time for each train, so only delays within the buffer time are allowed. Boysen et al. (2010) also point out that trains could only be profitable if full trains are moved. In the case of a train not being fully loaded at the end of

the buffer time, the train with a loading rate higher than η (for instance 75% or 80% of capacity) will depart; otherwise, the train will be cancelled.

In this chapter, we use a mid-range time horizon (one day), thus we could not estimate the actual transport time for the containers in the second day. Moreover, containers left at the terminal will influence the container transport in the second day, which may lead to extra cost. Therefore, in order to calculate the delay cost, we assume that the containers that miss their connecting trains will be transported into the hinterland by truck instead. A similar assumption can be found in Behdani et al (2014). Future research could focus on longer time horizons and the possibility of determining the frequency of unit trains.

Intersection transport operation: congestion

Given the short travel time in ITT network, e.g., the average travel time of the links in Figure 3.1 is 2.4 minutes, the delay time caused by intersection is more significant than in a larger transport network. Our research also shows that the intersection waiting time will increase if more ITT vehicles are used or more containers are moved. In order to manage the congestion within intersections, we set S to limit the number of vehicles entering the intersection. We assume that the capacity of the intersection equals 2 vehicles per time step (1 minute).

In this chapter, we assume that when a vehicle cannot enter an intersection immediately due to the capacity, this vehicle could: (1) wait a time step before entering the intersection; (2) change the transport task it performs to change its route. In the first solution, the vehicle could spend the waiting time in a terminal before the intersection, which could provide extra buffer time for terminal operation in realistic situations. But this solution always results in longer waiting time. In the second solution, a new vehicle route can be found entering intersections in less busy time. The quality of these two solutions for intersection congestion will be evaluated and the better solution will be selected by our model.

More detailed models that take the intersection capacity into consideration could be studied in the future to formulate the real world better. For example, the bottleneck model in Arnott et al. (1990) and Knockaert et al.(2016) provide a promising way to formulate the influence caused by intersection congestion.

Transport on the links

In general, there are several vehicles which are regularly used for the transport of containers between terminals: manned trucks, normally with a capacity of 2 TEU; multi trailer systems (MTSs), which pull up to five chassis; automated guided vehicles (AGVs), which transports one 40 ft container or two 20 ft containers with speeds of up to 20 km/h at existing maritime terminals; automated lifting vehicles (ALVs), which are able to lift a container on a platform decoupling the loading/unloading operation between the crane and the vehicle.

In Duinkerken et al. (2006), which compare the ITT systems with AGV, ALV and MTS, the travel time of the vehicle is calculated without considering congestion. In this chapter,

manned trucks with a capacity of 2 TEU are used as vehicles in the ITT network. The average speed of the truck is set to 30 km/h, and the traverse time of each link is shown in Figure 3.1. We also assume that no congestion happens on the links.

Given the size of the ITT network, the distance between a truck's starting location and the vehicle's first task could be very short; we made another assumption that the trucks' routes always start from the first task and end at the last task, therefore, there is no vehicle movement at the beginning or end of the planning horizon. A similar assumption is made by Heilig et al. (2017): the trip to the first location is not counted as an empty trip and the trip return to the initial location is not considered in the objective function. Empirically, this gives no significant variation in objective function.

3.4 Mathematical model for the ITT and railway terminals

3.4.1 Mathematical model

We construct an integer linear programming model for integrated terminal operations, which extends the ITT model presented by Tierney et al. (2014). We first extend their approach with the formulation of intersections in the ITT network. Then, the railway loading operations are integrated into the model, which reveal the interaction between ITT and the hinterland transport. Moreover, we use the extended model to study a more complicated problem with a larger transport network including railway yard and railway operations, a longer planning horizon, and smaller time steps. The original paper pointed out all of these dimensions as key drivers of complexity.

The model used in this chapter is based on a constrained multi-commodity flow model over a time-space network, with additional side-constraints for operations at terminals. The result of the model is a description of all movements of (i) containers, (ii) ITT vehicles, and (iii) railway vehicles over time, such that demands are satisfied. The inputs include: 1) a description of an ITT network with terminals, intersections, and roads modeled as a series of nodes and arcs, and distances required to move from each of them to any other; 2) a set of demands characterized by different numbers of containers that have to be shipped from pre-specified origins to destinations at the intended release-delivery time, each of which has a due date time and associated costs for late delivery; 3) the properties of the network and the vehicles, (i.e., the vehicle carrying capacity, and vehicle transverse time) and the characteristics of the railway services, in terms of capacity, destination, and planned departure time; and 4) a planning horizon $t = 1, \dots, T$, where all movements must take place, T is the length of the planning horizon. The granularity of time is in minutes.

Parameters

The following parameters are used in our model.

N	Set of nodes in the base graph
N^{ter}	Set of nodes representing terminals
N^{int}	Set of nodes representing intersections
N^{Rail}	Set of nodes representing railway terminals
A	Set of arcs in the time-space graph
A^{mov}	Set of non-stationary arcs
A^{sta}	Set of stationary arcs
V	Set of vehicles
Θ	Set of tasks
$V^{TrainHin}$	Set of trains
$f_{i,j}$	Traverse time of arc (i, j)
o_θ	Origin node of task θ
d_θ	Destination node of task θ
r_θ	Release time of task θ
u_θ	Due time of task θ
Dem_θ	Number of containers of task θ
$c^{traverse}$	Travelling cost of vehicles in ITT network
c^{Road}	The cost for road transport from terminal to hinterland
c^{Rail}	The cost for railway transport from terminal to hinterland
S	Capacity of intersection
U	Carrying capacity of ITT vehicles
H_φ	Capacity of a train φ
P_φ	Planned departure time of train φ
Δ	Longest delay time of trains
D_φ	The transport distance between railway terminals and destination in the hinterland of train φ
δ	Value of time for one container
η	The minimal loading rate
β	Penalty coefficient for the trains not fully loaded

Let N be the set of nodes. The subsets N^{ter} and N^{int} refer to the terminal and intersection nodes respectively. Two adjacent nodes $i, j \in N$ identify an arc (i, j) , which refers to the

possibility of moving from one node (location) to another one at a given time. Each arc $(i, j) \in A$, is associated with a traverse time $f_{i,j}$. To model the moving and idle status of vehicles and containers, two types of arcs are considered, i.e., stationary arcs and non-stationary arcs (subsets A^{sta} and A^{mov}). Vehicles and containers on a stationary arc do not move in space, but stay at the same node during the given time step. Vehicles and containers on a non-stationary arc are moving from one terminal to another; the arcs connect two different locations at different times. Let V be the set of vehicles. Each vehicle $v \in V$ has a carrying capacity U and a transport cost $c^{traverse}$ per time unit. Let θ denote the transport tasks to be served and Θ denote the set of tasks. Each task is associated with a number of containers Dem_θ in TEU, an origin node $o_\theta \in N^{ter}$, a destination node $d_\theta \in N^{ter}$, an earliest release time r_θ and an intended delivery time u_θ . If a task's destination is a railway terminal in the ITT network, then it will be further associated with a final destination in the hinterland, and a planned train which delivers this task to its final destination.

In railway terminals, a set of trains $V^{TrainHin}$ are planned to depart at a pre-determined departure time P_ϕ . D_ϕ denotes the transport distance of train ϕ . If the number of containers loaded on a particular train $\phi \in \Phi$ does not reach the train's loading capacity H_ϕ , the train risks departing partially loaded. In this case, we assume the train will be delayed until the loading rate is increased. The value of time δ is used to reflect the delay cost per unit time for one container. Thus, we can convert a container's delay time into a cost. We also assume that there is a minimal loading rate η : a train will only depart if its loading rate reaches η within the longest allowed delay time Δ . Otherwise, the train will be cancelled. If a train departs without being fully loaded, there will be a penalty cost for the train usage, a coefficient β is introduced to model the penalty cost.

Road transport to the hinterland is used for containers that are unable to be transported by trains because of a delay on the ITT network, or because a train has been cancelled. Transport costs typically increases in this case because road transport cost per kilometer from terminal to hinterland c^{Road} are higher than railway transport cost per kilometer c^{Rail} .

Variables

Four types of integer variables are used to formalize the temporal and spatial movements of vehicles, containers and the departure of trains, respectively. Let variables $x_{i,j,t}$ indicate the number of ITT vehicles travelling on arc (i, j) at time t . Variables $y_{i,j,t,\theta}$ represent the number of containers for task θ delivered on ITT arc (i, j) at time t . Specifically, if a demand is destined to a train ϕ , i.e., its containers are planned to be loaded on train ϕ , then $y_{i,j,t,\phi}$ represents the number of containers for train ϕ delivered on ITT arc (i, j) at time t . The variable $l_{t,\phi}$ represents the total number of containers loaded on the train $\phi \in V^{TrainHin}$ at its actual

departure time. Therefore, $l_{t,\varphi}=0$ holds at any time before/after a train's departure time or when a train is cancelled. Variables $w_{i,\varphi,t} \in \{0,1\}$ express the fact that train φ departs from terminal i at time t or not.

Objectives

The overall objective is to minimize operating costs of the entire logistics system. This consists of three main cost factors: 1) maintaining punctuality of tasks to minimize the loss of the containers' delay costs; 2) decreasing operational costs of ITT vehicles; and 3) minimizing operational costs in railway terminals.

The former two are represented as delay costs of containers in equation (3.1) and the transport costs of vehicles in equation (3.2). In equation (3.1), the delay cost of the containers that cannot reach their destination before due time will be summed up. Specifically, a container's arrival time to its destination can be presented as $t + f_{i,d_\theta}$, t is the time when the container is in node i , d_θ is the destination of the container, and f_{i,d_θ} is the time to move the container from i to d_θ . The delay time can then be calculated through $t + f_{i,d_\theta} - u_\theta$. Equation (3.2) calculates the total cost caused by the movement of the vehicles.

$$Z_1 = \sum_{\theta \in \Theta} \sum_{(i,d_\theta) \in A^{mov}} \sum_{u_\theta < t + f_{i,d_\theta} \leq T} (t + f_{i,d_\theta} - u_\theta) \cdot \delta \cdot y_{i,d_\theta,t,\theta} \quad (3.1)$$

$$Z_2 = \sum_{(i,j) \in A^{mov}} \sum_{\min(r_\theta) \leq t \leq T} c^{traserve} f_{i,j} \cdot x_{i,j,t} \quad (3.2)$$

The cost for railway terminals includes several components because different stakeholders have different interests in railway transport. Usually, customers, e.g., the importer of the containers, hire a freight transport operator to coordinate and organize the hinterland transport from the port to the hinterland, see Wiegmans et al. (2014) and Ducruet and Van der Horst (2009) for the description of the roles of freight transport operators. The customers want their cargo to be delivered as soon as possible, but the transport operators hope they can make full use of the trains. This will result in tradeoff objectives in the transport system.

In this chapter, we assume that the cost of dedicated railway terminals is represented by equations (3.3), (3.4), and (3.5). First, if a train is delayed, all containers loaded on that train will be delayed, so there will be a penalty cost Z_3 for the railway delay. Second, road transport will be used to deliver the containers that miss connecting trains and from the cancelled trains, so there will be an extra transport cost Z_4 . Third, if a train leaves the terminal without being fully loaded, there will be a penalty for loss of potential train capacity Z_5 .

$$Z_3 = \sum_{\varphi \in V^{TrainHin}} \sum_{i \in N^{Rail}} \sum_{t \in T} l_{t,\varphi} \cdot \delta \cdot (t - P_\varphi) \quad (3.3)$$

$$Z_4 = \sum_{\varphi \in V^{TrainHin}} \sum_{i \in N^{Rail}} (H_\varphi - \sum_{t \in T} l_{t,\varphi}) \cdot (c^{Road} - c^{Rail}) \cdot D_\varphi \quad (3.4)$$

$$Z_5 = \beta \cdot \sum_{\varphi \in V^{TrainHin}} \frac{H_\varphi - \sum_{t \in T} l_{t,\varphi}}{H_\varphi} \quad (3.5)$$

Equation (3.3) reflects that if a train departs with delay, then it will lead to a delay cost for the containers loaded on that train. Equation (3.4) establishes the extra transport cost from railway terminal to the hinterland. When a train is fully loaded, $\sum_{t \in T} l_{t,\varphi} = H_\varphi$, there is no extra transport cost. When a train departs but there are containers that miss the train, the $H_\varphi - \sum_{t \in T} l_{t,\varphi}$ missed containers will be transported by road. When a train is cancelled, all containers on that train, i.e., H_φ , will be transported by road. Equation (3.5) reflects the penalty cost when a train is not fully loaded.

The integrated ITT can be formulated as following:

$$\min(Z_1 + Z_2 + Z_3 + Z_4 + Z_5) \quad (3.6)$$

subject to:

$$\sum_{(o_\theta, j) \in A} y_{o_\theta, j, r_\theta, \theta} = Dem_\theta, \forall \theta \in \Theta \quad (3.7)$$

$$\sum_{(i, j) \in A} y_{i, j, t - f_{i, j}, \theta} = \sum_{(j, k) \in A} y_{j, k, t, \theta}, \forall \theta \in \Theta, t \in T \quad (3.8)$$

$$\sum_{(i, d_\theta) \in A} y_{i, d_\theta, T - f_{i, j}, \theta} = Dem_\theta, \forall \theta \in \Theta, j \in N \quad (3.9)$$

$$\sum_{i \in N^{ter}: (i, j) \in A} x_{i, j, t} = |V|, \forall t = \min(r_\theta), \forall \theta \in \Theta \quad (3.10)$$

$$\sum_{(i, j) \in A} x_{i, j, t - f_{i, j}} = \sum_{(j, k) \in A} x_{j, k, t}, \forall t \in T, \forall j \in N \quad (3.11)$$

$$\sum_{\theta \in \Theta} y_{i, j, t, \theta} \leq U \cdot x_{i, j, t}, \forall t \in T, (i, j) \in A^{mov} \quad (3.12)$$

$$\sum_{\theta \in \Theta} y_{i,j,t,\theta} \leq U \cdot x_{i,j,t}, \forall t \in T, i \in N^{int}, (i,j) \in A^{sta} \quad (3.13)$$

$$\sum_{(i,O) \in A^{mov}} x_{i,O,t} + \sum_{(O,j) \in A^{mov}} x_{O,j,t} \leq S, O \in N^{int}, \forall t \in T \quad (3.14)$$

On the ITT part, constraints (3.7)-(3.9) ensure the consistency of containers' movement for each demand at origin, intermediate, intersection, and destination node, respectively. Constraint (3.10) guarantees that vehicles depart from terminals at the earliest release time. For each node, constraint (3.11) forces the number of incoming vehicles to equal the number of outgoing vehicles at any time. In constraint (3.12), the number of containers delivered by a vehicle cannot exceed its carrying capacity. Constraint (3.13) is used to prevent containers from being stored at intersections. Constraint (3.14) ensures that the number of vehicles in the intersection at the same time step cannot exceed the intersection's capacity.

The departure time of a train depends on the number of containers loaded. Constraint (3.15) establishes the relationship between the number of loaded containers $l_{t,\varphi}$ and the number of containers transported to the railway terminal. Constraint (3.16) ensures that a train will not leave before it reaches the minimum required loading rate. In constraint (3.17), the number of containers loaded on a train is calculated only when a train departs. Constraint (3.18) guarantees that a train can only depart once. Constraint (3.19) ensures that a train cannot depart before the planned departure time.

$$l_{t,\varphi} \leq \sum_{j \in N^{Rail} : (i,j) \in A^{mov}} \sum_{r_\varphi \leq q \leq t} y_{i,j,q,\varphi}, \forall \varphi \in V^{TrainHin}, \forall t, q \in T, t < P_\varphi + \Delta - f_{i,j} \quad (3.15)$$

$$w_{j,\varphi,t} \leq \frac{\sum_{j \in N^{Rail} : (i,j) \in A^{mov}} \sum_{r_\varphi \leq q \leq t} y_{i,j,q,\varphi}}{\eta \times H_\varphi}, \forall \varphi \in V^{TrainHin}, \forall t, q \in T, P_\varphi \leq t < P_\varphi + \Delta - f_{i,j} \quad (3.16)$$

$$l_{t,\varphi} \leq H_\varphi \cdot w_{i,\varphi,t}, \forall \varphi \in V^{TrainHin}, i \in N^{Rail}, t \in T \quad (3.17)$$

$$\sum_{\varphi \in V^{TrainHin}} \sum_{i \in N^{Rail}} \sum_{P_\varphi \leq t \leq P_\varphi + \Delta} w_{i,\varphi,t} \leq 1, \forall t \in T \quad (3.18)$$

$$\sum_{\varphi \in V^{TrainHin}} \sum_{i \in N^{Rail}} \sum_{0 \leq t \leq P_\varphi} w_{i,\varphi,t} = 0, \forall t \in T \quad (3.19)$$

$$y_{i,j,t,\theta} = 0, \forall \theta \in \Theta, t < r_\theta, (i,j) \in A \quad (3.20)$$

$$x_{i,j,t} = 0, \forall t = \min(r_\theta), i \in N^{int}, (i,j) \in A \quad (3.21)$$

$$x_{i,j,t} = 0, \forall t < \min(r_\theta), (i, j) \in A \quad (3.22)$$

$$w_{i,\varphi,t} \in \{0,1\}, \forall i \in N^{Rail}, \varphi \in V^{TrainHin}, t \in T \quad (3.23)$$

Constraint (3.20) ensures that containers cannot be moved out of their origin nodes before the corresponding release times. Constraints (3.21) and (3.22), respectively, define the vehicle's original departure position, which cannot be an intersection, and vehicle departure times cannot be earlier than the earliest release time of tasks. Constraint (3.23) states the restriction of the variable $w_{i,\varphi,t}$.

3.4.2 Illustration for time-space model

Table 3.1 Dataset of the simple example case

	Origin node	Destination node	Number of containers	Release time (unit: min)	Due time (unit: min)
task_1	T1	T2	2	1	4
task_2	T1	T3	2	2	5
task_3	T2	T3	2	3	6

For conceptual illustration, a simple network with three terminals and one intersection is shown on top of Figure 3.3. Terminal T3 is a railway terminal and it is connected to a hinterland destination. Table 3. 1 gives the information of three tasks: task_1 should be moved from T1 to T2; task_2 and task_3 will be first moved to T3 and then delivered to the hinterland by train. A train to the hinterland destination is planned to depart from terminal T3 at time step 6. Figure 3.3 gives a corresponding solution. Two vehicles are used to complete the tasks. The carrying capacity U of each vehicle is two TEUs.

In the solution illustrated in Figure 3.3, two vehicles are assigned to T1 at time step 1. The arc marked with 1Veh represent 1 vehicle is traveling on that arc. A vehicle's route can be represented by the nodes the vehicle visits, thus, the two vehicles' routes can be represented as {T1, i1, T2, i1, T3} and {T1, i1, T3}. Similarly, the movements of the containers are also marked on the arc: for example, 2C1 represents two containers of task 1 are on the marked arc. In the illustrated solution, both task_2 and task_3 are delivered to T3 before due time, therefore the train could depart on time.

improving move has to be chosen, the inverse of this non-improving move is forbidden for a certain number of iterations, i.e. it is tabu. The length of the tabu list determines how long moves are forbidden. In our case, we experimentally found that a more general concept of tabu moves is beneficial, namely forbidding some characteristic of any move performed, regardless it is improving or non-improving. This allows a richer diversification of the moves, which experimentally improves solution quality.

3.5.1 Representation of solutions

The solution of the integrated ITT model $S(x_{i,j,t}, y_{i,j,t,\theta}, l_{t,\varphi}, w_{k,\varphi,t}), \forall i, j \in N, k \in N^{Rail}, t \in T, \varphi \in \Phi$, namely the number of vehicles and containers on each arc of the time-space graph, contains redundant information, which makes it difficult to use in tabu search. In order to simplify the representation of the solution and to keep essential information at the same time, we use vehicle routes to represent the solution of the integrated ITT model. From the time-space network, assuming a vehicle will spend as little time as possible on the links, we derive the concept of a route $R_v, \forall v \in V$, i.e., the sequence of origin and destination nodes where containers are respectively (un)loaded from the vehicle. Based on the vehicle's route, the travelling time, waiting time of each vehicle and the delivery time of each container can be calculated, then the number of containers can be loaded on a train and the train's departure time can be determined.

3.5.2 Initial solution generation

Because the number of vehicles and transport demands are pre-determined, we generate the initial solution by assigning transport tasks to the vehicles. All tasks are chronologically ordered by their release time, tasks with the same release time are chronologically ordered by their due time. The vehicles are ordered by their index, i.e., 1, 2, 3... v . Based on the order of the tasks and vehicle, we use a typical greedy solution which assigns tasks to vehicles in a round-robin fashion. All vehicle routes will be determined by the sequence of the tasks and we will then have the initial solution.

The following strategies are used to generate the initial solution:

- S1 The first vehicle is assigned to the first task, the second vehicle is assigned to the second task until all the tasks are served.
- S2 The first vehicle is assigned to serve the first 10 tasks, the second vehicle is assigned to serve the second 10 tasks until all tasks are served.

3.5.3 Neighborhood structure

Generally, we can alter the sequence of any number of tasks in any vehicle's route or delete any number of tasks from one vehicle's route and insert to another vehicle's route. In this chapter we use 2-opt moves to find the neighbor solutions: choose one task per iteration, re-

move it from its original position in one vehicle's route and then insert it to another position in any vehicle's route.

In this chapter, we use the length of empty movement in each route to help create the neighbor solution. When fleet size and demand size are fixed, optimization of the routes with long empty movements would be likely to improve the objective function $Z_1 + Z_2$. We formulate the empty movement as follows:

$$Z_{Empty} = \sum_{(i,j) \in A^{mov}} \sum_{\min(r_{ij}) \leq t \leq T} f_{i,j} \cdot x_{i,j,t}, \forall y_{i,j,t} = 0 \quad (3.24)$$

So, the empty movement is the length of the arcs being traversed by a vehicle without carrying a container. In the time-space graph, if a non-stationary arc is traversed by a certain number of vehicles, i.e., $x_{i,j,t} \neq 0$, and there is no container on this arc, i.e., $y_{i,j,t,\theta} = 0$, then the empty movement will be $f_{i,j} \cdot x_{i,j,t}$. Based on this, we change the tasks' positions to reduce the length of empty movement in given routes. As shown in Figure 3.4.a, one task is deleted from the incumbent route and then inserted into a new position. Thus, a new solution is created as R'_v . In this case, $BE + FC < DE + BC$ would make less empty movements.

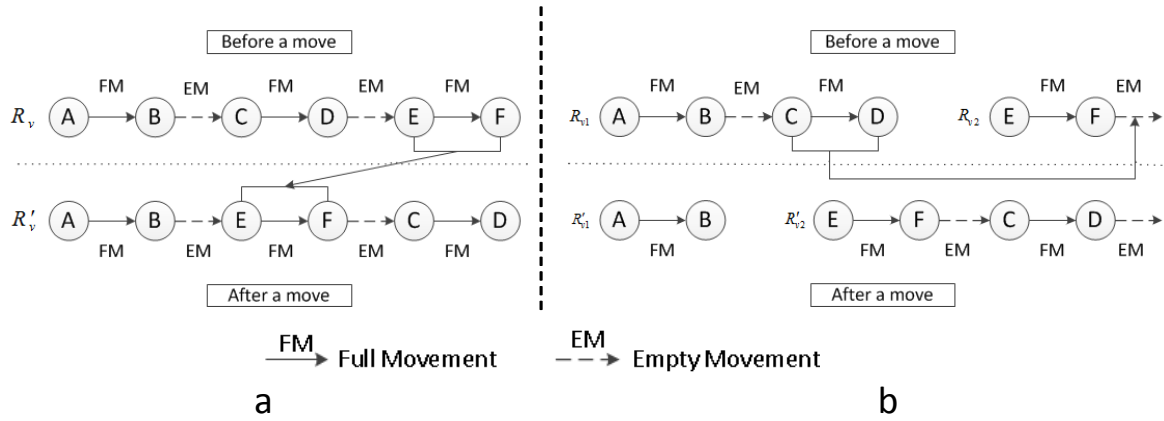


Figure 3.4 Change the order of tasks inside one route.

In another case, one task is deleted from one route and then inserted into another route, as shown in Figure 3.4.b. There are two new routes, R'_{v1} and R'_{v2} , that are created at the same time. In this case, $FC < BC$ would make less empty movements.

Based on the empty movement concept, we introduce the following neighborhoods:

N1 Randomly choose one task from the route with longest empty movement and insert it to a randomly chosen position.

N2 Find the task followed by the longest empty movement, then randomly choose a route and try to find the task which could reduce the empty movement best.

N3 A combination of N1 and N2, using N2 as far as there are moves in there, using N1 otherwise.

In the neighborhood N1, we start by choosing the route with the longest total empty movements. Then, a random task from that route will be selected and moved to a randomly selected position. N1 is the neighborhood containing all swaps between any two tasks of any two routes; as the neighborhood is very large, we randomly sample it when we need a small number of neighbors.

In the neighborhood N2, we try to reduce the longest empty movement. Some knowledge of the tasks is gained before changing the tasks. Specifically, we define connection as the movement required between unloading of a container at a terminal and loading of a container at a terminal along the route of a vehicle. Thus, the connection represents the sequence of two movements; “good” connections would result in smaller empty movements. Next, we build a best connection list according to the empty movement between any two tasks. The best connection list records empty movements between any two tasks. Based on this list, we find several potential best connecting tasks that connect to a certain target task with the shortest empty movement. Then, the release and due time of the tasks will be controlled to make sure the potential best connecting task’s due time is later than the target task’s release time. The potential best connecting task with the earliest due time is defined as the task connecting the best to the target task. After we find the longest empty movement in the incumbent routes, a best connecting task, which will reduce empty movement, is identified to make the change. For example, if BC in Figure 3.4.a is the longest empty movement, we will find the best connecting task of AB. If the best connecting task of AB is EF, then we will delete EF from its original position and insert it to the position adjacent to AB.

When using N2, it is possible that several tasks could reduce the longest empty movement in the same degree, then, we perform a random sampling. It is also possible that N2 could be empty under some circumstances, then the search will stop.

In the neighborhood N3, we use the same best connection list used in neighborhood N2 to reduce the empty movement. However, the best connection list in neighborhood N2 may be empty or too long to implement it thoroughly. Therefore, if the best connecting task does not exist or cannot be found in a certain number of iterations, a randomly chosen task will be used instead. The limitation of the iterations that search for the best connection is set to be equal to the neighbor size.

3.5.4 Tabu list and search strategies

In this chapter, one task is changed in each iteration, which means that in the solutions in the neighborhood, one or two vehicle routes will differ from their routes in the incumbent solu-

tion. After the swap, the generated solution will be considered for inclusion in the tabu list. Three tabu strategies are applied, and each of the lists could stop the algorithm visiting certain solutions.

- T1** The inverse of a non-improving move will be added to the tabu list.
- T2** The inverse of every move will be added to the tabu list.
- T3** The routes which have been changed are added to the tabu list.

With T1 and T2, a task is forbidden from being moved back to its original location. When using T1, if a move is implemented and the new solution is worse than the incumbent solution, then the inverse of this non-improving move will be added to the tabu list. This is a typical Tabu strategy; we studied and tested multiple strategies in preliminary analysis, and also consider strategies constraining more the solution space, with the aim to increase diversification of moves. Specifically, when using T2, the inverse of every move performed will be added to tabu list. With tabu list T3, the changed routes cannot be changed again in following iterations. For instance, task AB is the Nth task of route R1, in an iteration, it is moved to be the Mth task of R2. If T1 or T2 is applied, only the situation that AB is moved back to R1 and becomes the Nth task is forbidden. When T3 is applied, any task in R1 or R2 cannot be moved in the following iterations. If the newly generated solution is not forbidden by the tabu list, then this solution will be evaluated.

3.5.5 Move evaluation

In each iteration, a certain number of moves can be made in one neighborhood. Thus, we need to find the best move to improve the objective value. However, calculating the full objective of the model could be time consuming.

In order to find the best move quickly, we use the empty movement Z_{Empty} in equation (3.24) to evaluate the move. At each step, the total distance of empty movements will be computed, and the solution with the shortest empty movements will be implemented to approximate the value of the objective function. However, when Z_{Empty} cannot be further improved, it does not mean that the objective function (3.6) cannot be improved. Take the routes in Figure 3.4.b as an example, when the distance between B and C is 0, the Z_{Empty} of both routes is 0. Then Z_{Empty} cannot be improved, but the move shown in Figure 3.4.b may reduce the delay of task C-D, and therefore, improve the objective function (3.6).

3.5.6 The tabu search scheme

The tabu search scheme with T3 and neighborhood N3 is described as follows:

Algorithm Tabu Search

Input: An Initial Solution

Incumbent Solution = Initial Solution

Best Solution = Initial Solution

Best Value = Cost(Best Solution)

Incumbent Value = a large number

for ε iteration do

If $N2 \neq \emptyset$ do

calculate the empty movements in every non-tabu route

find the task followed by the longest empty movement: TASK

for π iteration do

choose a route and insert TASK into the route

find the solution with fewest empty movement:

temValue = Cost(temSolution)

Incumbent Solution = temSolution

Incumbent Value = temValue

else

calculate the empty movements in every non-tabu route

find the route with longest total empty movement: ROUTE

for π iteration do

Randomly choose a task from ROUTE: TASK

Randomly insert TASK to a non-tabu route

find the solution with fewest empty movement:

temValue = Cost(temSolution)

Incumbent Solution = temSolution

Incumbent Value = temValue

end if

if Incumbent Value < Best Value then

Best Value = Incumbent Value

Best Solution = Incumbent Solution

Update Tabu list

end if

end for

In the beginning of the search, an initial solution is generated and the objective value is calculated. Then the neighborhood N_2 is used to find a non-tabu solution, which reduces empty movement the most. If no neighbor solution can be found in N_2 , the neighborhood N_1 will be used. An iteration limit ε of 20000 is set to stop the algorithm.

3.6 Computational experiments

To assess the proposed algorithm, we present a test based on a simplified ITT road network of Maasvlakte 1&2. The tabu search algorithm is implemented in Java and executed on a PC equipped with an Intel I5 (3.5GHz) processor and 8 GB Ram.

3.6.1 Instance cases

The costs for ITT and railway operations are assumed to consist of five elements: ITT delay cost, hinterland railway transport delay cost, ITT vehicle transport cost, hinterland truck transport cost and penalty cost for train capacity loss. In this chapter, the delay cost is calculated based on the delay time and the containers' time value. Corman et al. (2017) give the value of time in container transport: $\delta=4(\text{€} / \text{hour})$. The transport cost is calculated according to Le (2016): the distance-dependent transport costs for road and railway are 0.2758 and 0.0635($\text{€} / \text{hour}$), respectively. For the penalty cost of the train capacity loss, we assume that $\beta=100$ so the penalty could be comparable to the other costs in the objective function. For the lowest loading rate η , we assume that all trains should be at least 75% -fully loaded before departure. The carrying capacity U of each vehicle in this case study is 2 TEUs.

Table 3.2 Demand cases used in the experiments

	Number of tasks	Number of containers (TEU)	Number of Rail-Oriented Containers (TEU)	Deadline of the last task (minutes)
Small demand cases	10	15	0	889
	20	34	0	895
	30	52	0	895
	40	69	0	895
	50	86	0	911
	100	168	0	911
Medium demand case	500	837	161	1440
Large demand case	2399	4060	747	1440

The following demand cases are generated.

- **Small demand cases.** These cases focus on ITT only while no planned trains are taken into consideration.

- **Medium demand case.** In this case, 500 tasks and 4 planned trains are handled within 24 hours.
- **Large demand case.** This case contains a realistic ITT demand: 2399 tasks and 12 planned trains are handled within 24 hours.

Small demand cases: 10 to 100 tasks without trains

We first generate a set of small test cases, which decrease the size of the problem by using small numbers of tasks and shorter planning horizons. Specifically, 4 trucks are used and all terminals in the network are maritime terminals. The small demand cases include six scenarios with 10, 20, 30, 40, 50 and 100 tasks respectively. In the smallest test case, 10 tasks (15 TEU containers) should be transported within the ITT network during 889 minutes and in the test case with 100 tasks, 168 TEU containers should be transported within the ITT network during 911 minutes, see Table 3.2.

Medium demand case: 500 tasks with 4 planned trains

We next consider a medium test case with 500 tasks in 24 hours. As shown in Table 3.2, 837 TEU containers have to be moved within the ITT network, and 161 of them are transported to the two railway terminals. We assume that 2 trains depart from each terminal respectively.

Large demand case: 2399 tasks with 12 planned trains.

Nieuwkoop (2013) presents an exhaustive transport network on Maasvlakte1&2 with detailed transport demands between terminals. In this chapter, we generate our large test cases based on Nieuwkoop (2013). As we use a planning horizon of one day, only the demands released and planned to be delivered within a time frame of one day are chosen.

We assume that 6 trains depart from each rail terminal respectively. Table 3.3 lists detailed information for each train. Every train has its planned departure time, a planned number of containers carried, and a transport distance. In this chapter, the capacity of the train is set at the number of containers planned to be loaded on that train.

Table 3.3 Instance of railway formation large demand case

Terminal 10			
Train	Planned Departure Time	Planned Containers Loaded (TEU)	Transport Distance (km)
1	11:00	68	50
2	15:00	56	140
3	17:30	62	200
4	20:30	69	50
5	22:00	55	140
6	24:00	55	200
Terminal 11			
Train	Planned Departure Time	Planned Containers Loaded(TEU)	Transport Distance (km)
7	12:30	66	50
8	16:00	69	140
9	18:00	55	200
10	20:30	64	50
11	22:30	67	140
12	24:00	69	200

Figure 3.5 shows the release time of the rail-oriented containers. Like the containers in the medium test case, containers here are also associated with a planned train to the hinterland. Most of the containers are available in the first half of the day and there are no containers released after 20:00.

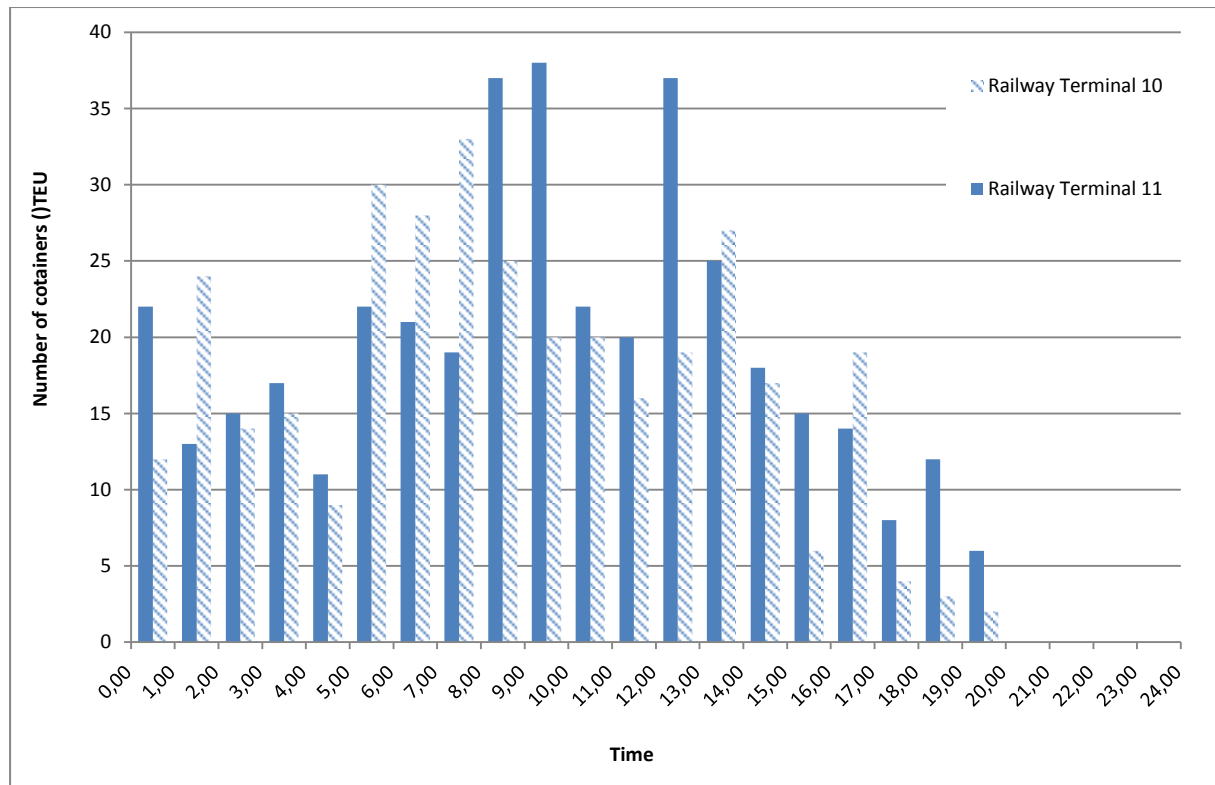


Figure 3.5. Release time of the rail-oriented containers

3.6.2 Assessment of tabu search components

In terms of the tabu search components, we test multiple configurations. To keep this chapter at a reasonable length, only some of the configurations, i.e., start solution S1 and S2; tabu list T1, T2 and T3; tabu length 2, 5, 10, and 15; neighbor size 2, 5, 8, and 10; and neighborhood N1, N2, and N3, are reported. When the tabu length is longer than 15 or the neighbor size is larger than 10, the computation time increases significantly.

S1 always provides a better initial solution than S2, and S1 also performs better than S2 at the end of the search. The tabu list T1 provides better performance than T2 and T3, see Figure 3.6. In the 20000 iterations, T2 has to update the tabu list after every iteration, while T1 updates the list for around 12000 times, which consumes less time and is efficient enough. In T3 too many potential solutions are forbidden and the algorithm needs more time to find a non-tabu solution.

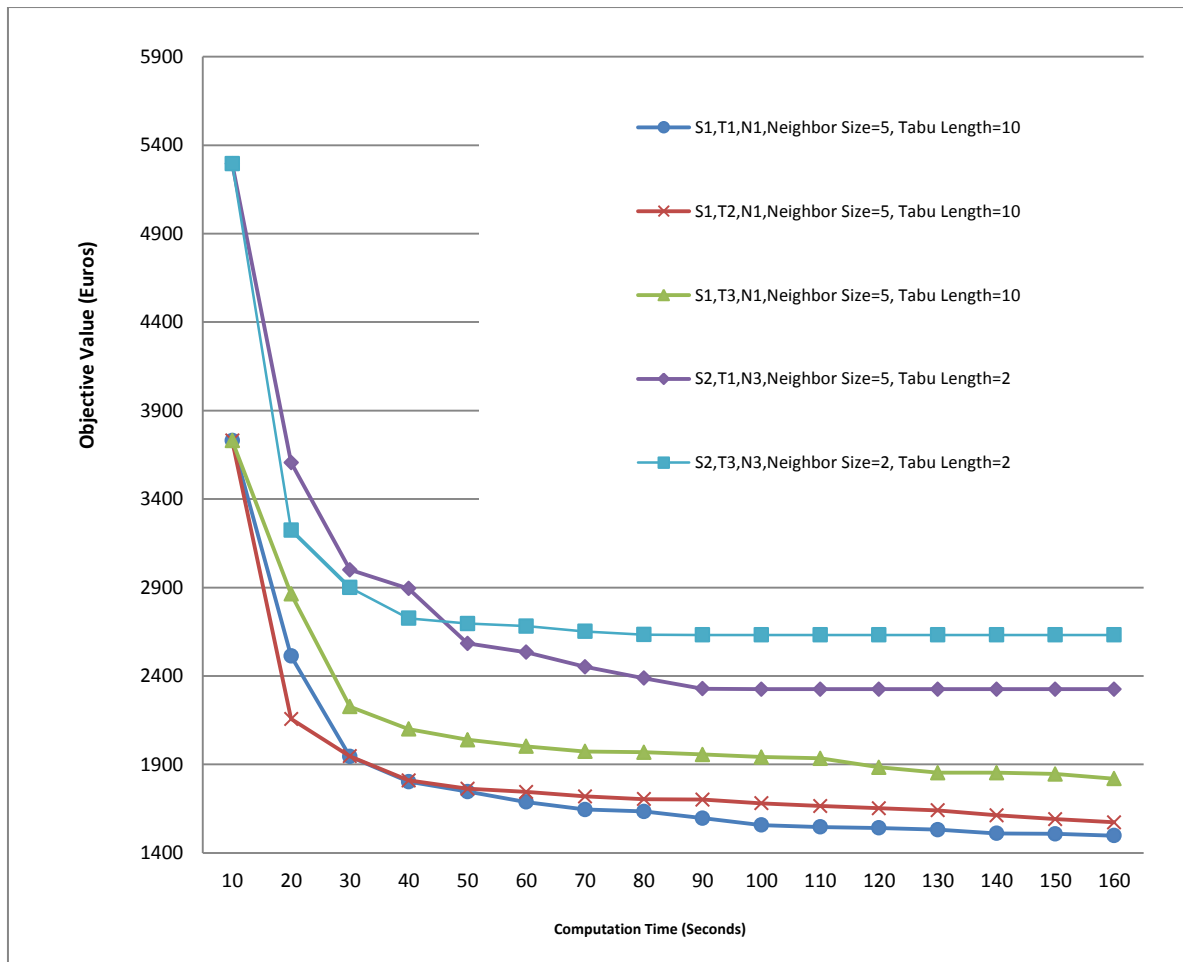


Figure 3.6. Performance of tabu search for a medium test case

Neighborhood N2 searches for the move that could largely reduce the longest empty movement, but it might also increase other empty movements at the same time. Therefore, N2 may give good solutions in the beginning of the optimization, but neighborhoods N1 and N3 will find better solutions in the end, see Figure 3.7.

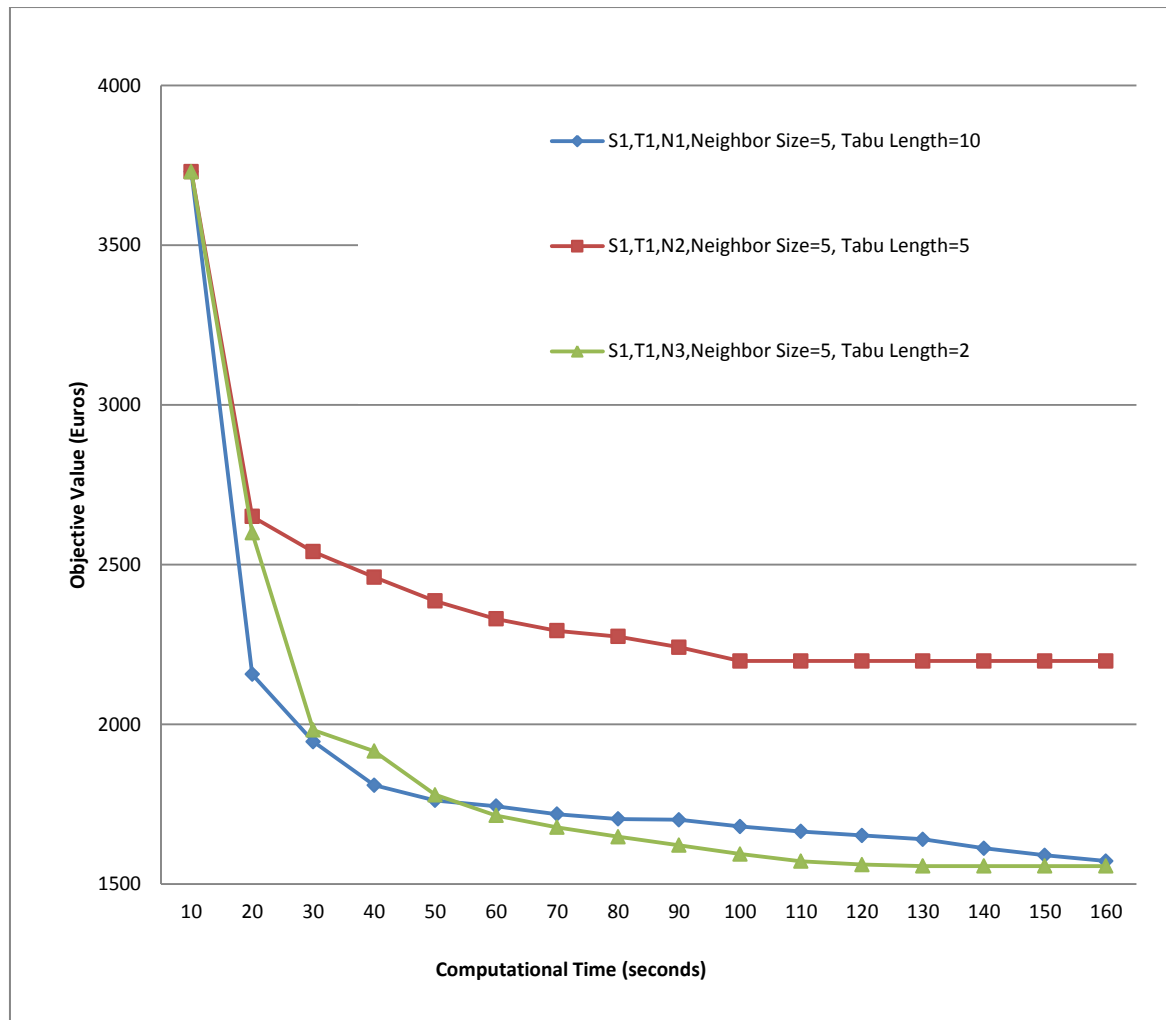


Figure 3.7 Performance of tabu search with different neighborhood structures.

For neighborhoods N1 and N3, the combination of neighbor size 5 and tabu length 2 performs best. In the following experiments, the configuration of N1, T1, S1, neighbor size 5, and tabu length 2 is used.

3.6.3 Tabu search performance compared with CPLEX and local search

In order to validate the proposed algorithm and evaluate its performance, we first make a comparison with CPLEX using small instances. Then, we test the tabu search solving larger problems and evaluate the performance by comparing it with a local search.

Comparison with CPLEX solutions using small demand cases

When solving the problem using CPLEX, because only the ITT part is studied, we use $Z_1 + Z_2$ as the objective functions, which means only the delay and travelling costs are taken into consideration. Variables and constraints related to railway operations are not considered in the model.

Table 3.4 Results of CPLEX and tabu search

Number of tasks	Computation time (second)		Objective value	
	CPLEX	Tabu search	CPLEX	Tabu search
10	4	6	178	178
20	22	250	359	365
30	1211	550	543	564
40	6044	600	749	783
50*	751*	710	890*	944
100*	6494*	980	1640*	1806

* because no optimal/feasible solution is obtained for the cases with 50 and 100 tasks within 5 hours, the lower bound and the computational time when the lower bound is found are provided.

Table 3.4 shows the comparison between the results obtained by CPLEX and by the proposed tabu search algorithm. If the scale of the problem is relatively small, CPLEX will provide optimal solutions with less computational time. However, when the scale of the problem increases, the computational time of CPLEX rises significantly. When the number of tasks is 40 plus, CPLEX will not be able to find a feasible solution within 5 hours. For 50 and 100 tasks, only a lower bound can be found within 751 seconds and 6494 seconds, respectively. The tabu search algorithm can handle much larger demand sizes and the computational time is still fast when more than 30 tasks are executed.

Table 3.5 Problem size when using CPLEX

Number of tasks	Planning horizon T (unit: minute)	Number of constraints	Number of variables	Computational time (unit: second)
10	100	62970	64457	4,03
10	200	124070	128257	11,11
10	300	185170	192057	731,68
30	100	174346	181617	--
30	200	341546	361417	1211,49
30	300	508746	541217	22953,86
50	1000	2761197	2960977	--
100	1000	5535807	5863877	--

Table 3.5 explains why CPLEX cannot handle large-scale problems. When solving a scenario with 10 tasks using 100 minutes as the planning horizon, the number of constraints that CPLEX has to deal with is 62970. The figure is 7 times larger when handling 30 tasks with a

planning horizon of 300 minutes. If we want to solve the problem with 100 tasks with a planning horizon of 1000 minutes, the number of constraints in CPLEX will be 5 million. So, it will be difficult to find the optimal solution in a reasonable computational time.

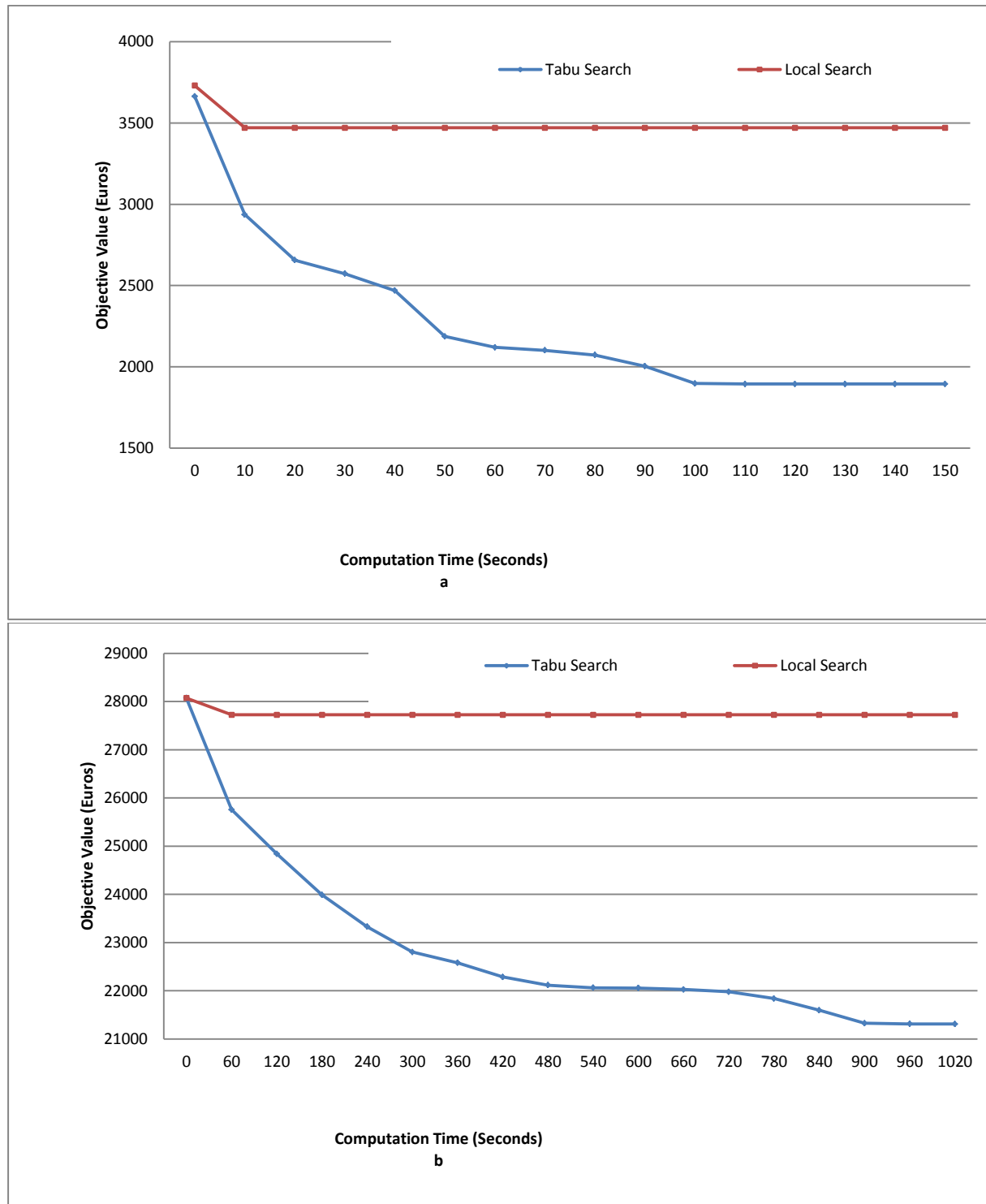


Figure 3.8 Performance of tabu search and local search for a medium demand case

Comparison with local search for medium and large demand cases.

In order to evaluate the performance of the tabu search, a local search algorithm is proposed as a benchmark. The local search algorithm also starts from one solution and then moves to a certain neighbor solution until no better solution can be found in the neighborhood. There is no algorithmic mechanism to escape local minima.

In the comparison, both the tabu search and local search use S1 to generate the initial solution and they both explore N1 to find neighbor solutions. T1 is used in the tabu search and the length of the tabu list is 2.

Figure 3.8.a shows the results of the test case of 500 tasks and 20 trucks. In the beginning of the test, the local search could give an improved solution, but after 10 seconds, the improvement of the local search stops, while the tabu search keeps improving. After 150 seconds, the best solution found by local search reduces the total cost by 7%, while the best solution found by tabu search reduces the total cost by 38%. Figure 3.8.b shows the results of the test case of 2399 tasks with 100 trucks. In the larger test case, tabu search also gives a better solution than local search: tabu search reduces the total cost by 24% while local search could only reduce the cost by 1%.

3.6.4 Integrated ITT and railway operation optimization

ITT and railway optimization in a medium demand case

To analyze the interactions between the ITT system and railway terminal operations, we first optimize the ITT only by using $Z_1 + Z_2$ as our objective. We review the medium and large demand cases in what follows.

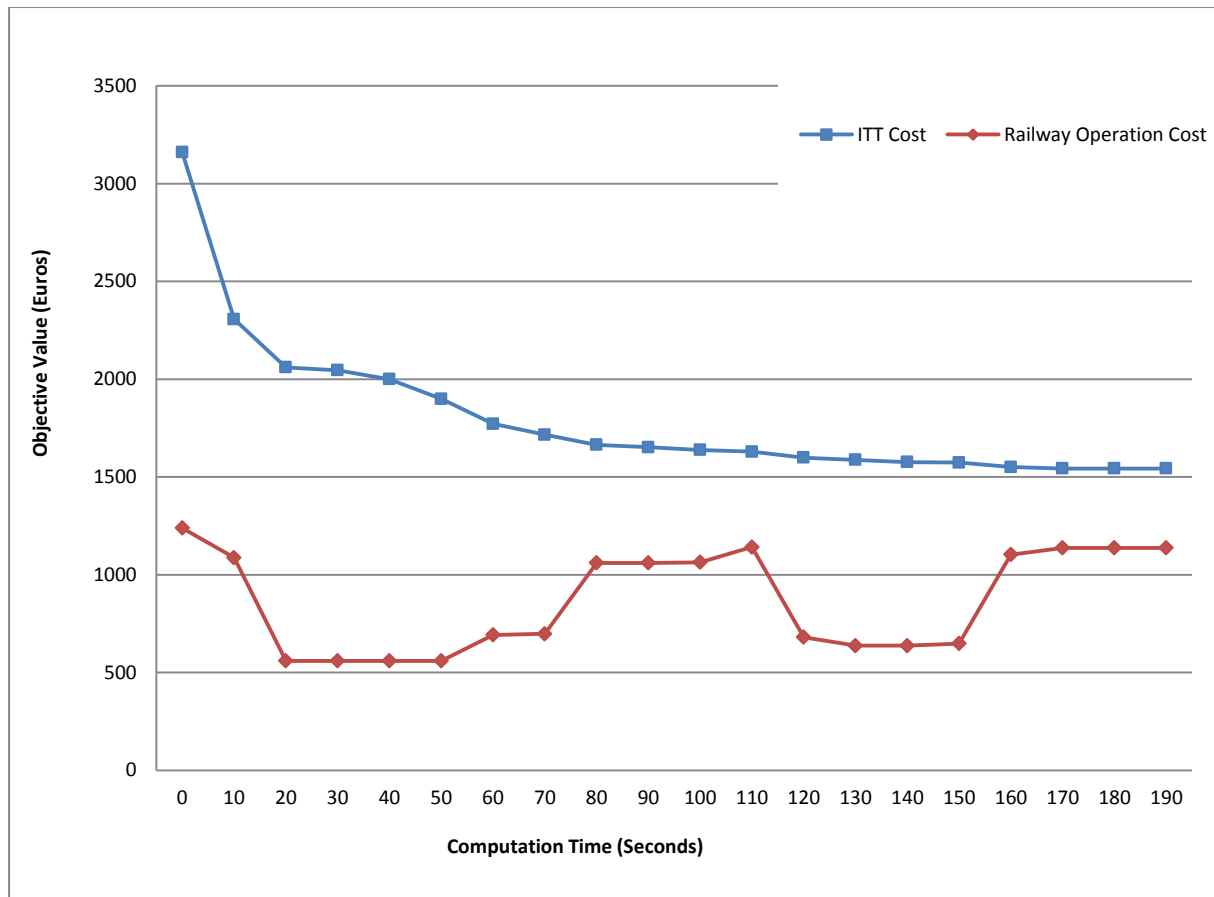


Figure 3.9 Optimization result of ITT model in a medium demand case

In Figure 3.9, which presents the ITT optimization with 500 tasks transported by 20 trucks, we find that when the cost for ITT decreases, the performance of the railway terminal may not be improved or even suffer from worse train delays and train cancellations.

The reason for this is that, as all containers in the ITT system have the same time value, the penalty cost for each container's delay will be the same. However, the rail-oriented container's delay may result in much higher costs as trains may be delayed or cancelled. Thus, an isolated ITT optimization will reduce the delivery delay, but it cannot identify the importance of the containers for the downstream operations, and therefore, it may lead to worse performance in the railway terminals.

Table 3.6. Train delay times (minutes) and missed containers

ITT optimization					
		Train 1	Train 5	Train 7	Train 10
Initial Solution	Delay	Cancelled	0	Cancelled	53
	Missed	42	2	40	0
Final Solution	Delay	Cancelled	44	Cancelled	0
	Missed	42	0	40	0

Integrated optimization					
		Train 1	Train 5	Train 7	Train 10
Initial Solution	Delay	Cancelled	0	Cancelled	53
	Missed	42	2	40	0
Final Solution	Delay	15	0	0	0
	Missed	0	0	0	0

Table 3.6 gives delay time and number of containers which misses the train in initial solution and the final solution after running the algorithm for 190 seconds. Before the ITT optimization, the initial solution is generated according to strategy S1. In that solution, 2 trains are cancelled, 84 containers miss their trains, and the total train delay time is 53 mins. After applying the ITT optimization, there are still 2 trains cancelled, 42 containers that miss their trains, and the total delay time is 44 mins.

When we optimize the integrated ITT model, which uses equation $Z_1 + Z_2 + Z_3 + Z_4 + Z_5$ as the objective function, the railway operation performance can be improved and ITT delay and transport costs can be reduced at the same time, see Figure 3.10.

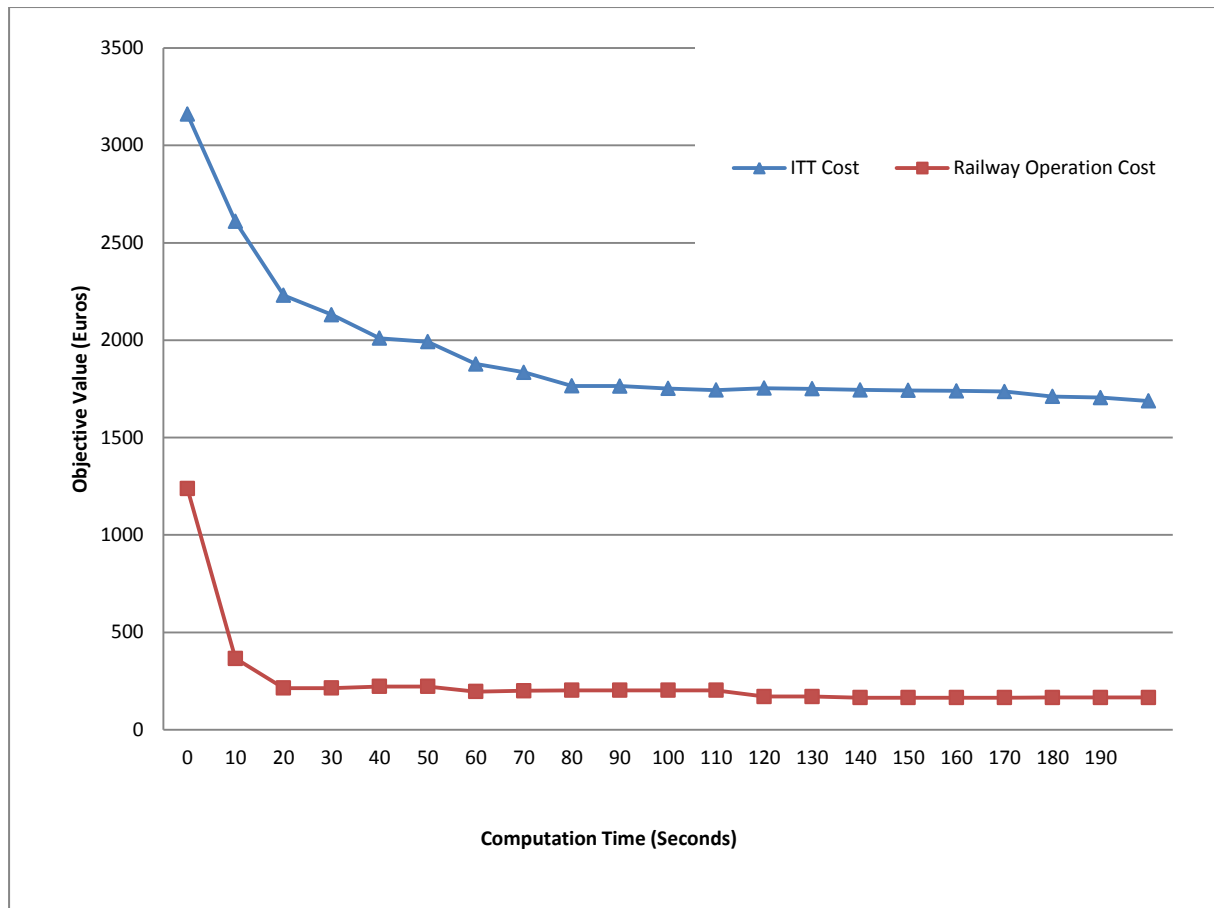


Figure. 3.10 Optimization result of integrated ITT model in a medium demand case

After the optimization, the ITT cost is reduced by 47% and the railway operation cost is reduced by 87%. Table 3.6 shows that after the integrated optimization, only one train is delayed by 15 mins and all containers are loaded onto the trains.

ITT and railway optimization in a large demand case

We also test the model with the large demand case mentioned in section 6.1, where 60 trucks are used to transport the containers in 24 hours. In a first test, only ITT is optimized, see Figure 3.11. The ITT delay and transport costs are reduced by 17%, but the costs in railway operation increase by 93%, which indicates longer train delay times and more containers that miss connecting trains.

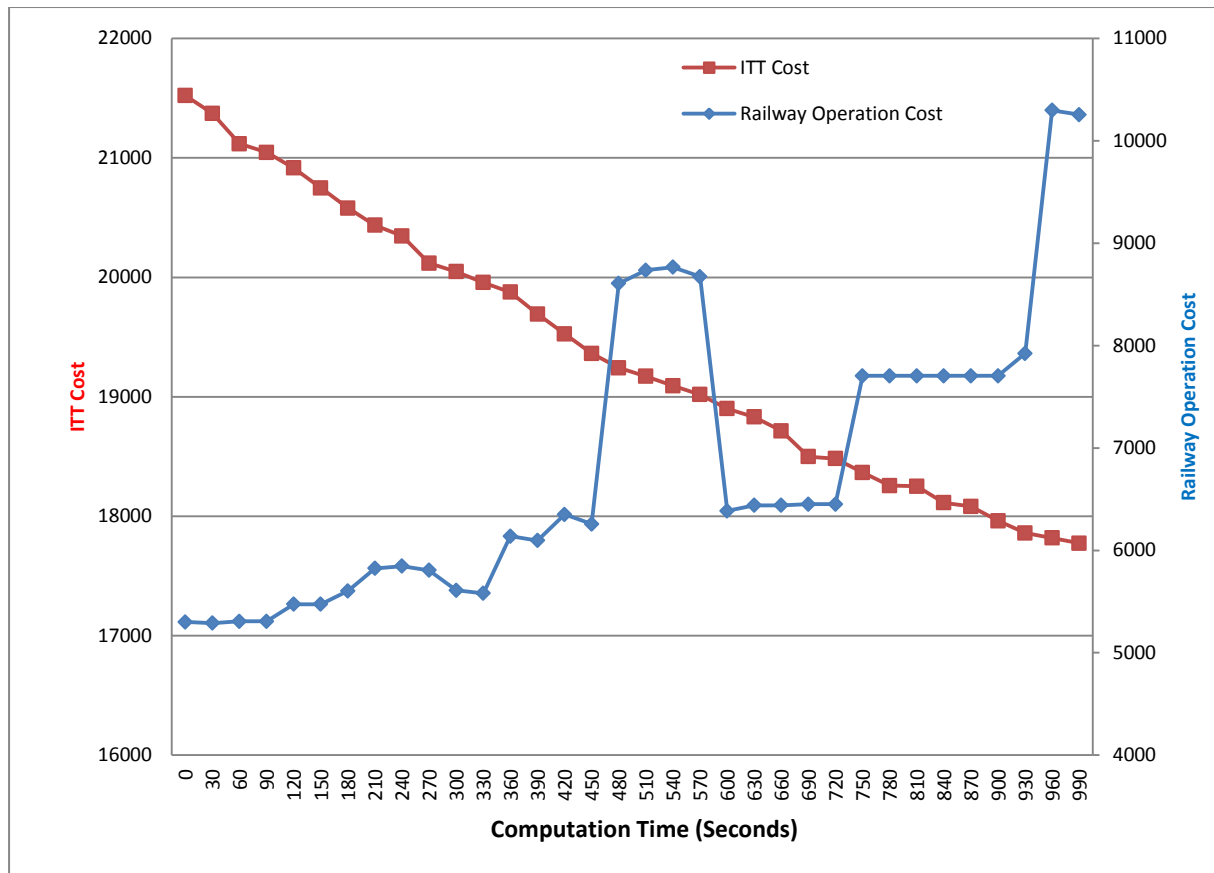


Figure 3.11 Optimization result of the ITT model in a large demand case

We find that before the ITT optimization, the total train delay time is 136 minutes and 212 containers miss their connecting trains. After ITT optimization, 3 more trains are cancelled, the total train delay time increases to 252 minutes, and the number of containers that miss connecting trains increases to 362, see Table 3.7.

Table 3.7 Train delay times (minutes) and missed containers

ITT optimization							
		Train 1	Train 2	Train 3	Train 4	Train 5	Train 6
Initial Solution	Delay	Cancelled	0	0	48	0	46
	Missed	68	6	6	10	5	1
Final Solution	Delay	Cancelled	Cancelled	Cancelled	58	26	58
	Missed	68	56	62	10	2	1
		Train 7	Train 8	Train 9	Train 10	Train 11	Train 12
Initial Solution	Delay	0	Cancelled	0	0	42	0
	Missed	12	69	13	15	5	2
Final Solution	Delay	Cancelled	Cancelled	0	48	60	2
	Missed	66	69	11	12	5	0

Integrated optimization							
		Train 1	Train 2	Train 3	Train 4	Train 5	Train 6
Initial Solution	Delay	Cancelled	0	0	48	0	46
	Missed	68	6	6	10	5	1
Final Solution	Delay	Cancelled	2	1	22	8	4
	Missed	68	7	3	11	3	0
		Train 7	Train 8	Train 9	Train 10	Train 11	Train 12
Initial Solution	Delay	0	Cancelled	0	0	42	0
	Missed	12	69	13	15	5	2
Final Solution	Delay	0	2	Cancelled	0	43	0
	Missed	15	16	55	16	4	1

When an integrated ITT model is used, both ITT and railway operation can be improved. Figure 3.12 shows the optimization of the model with 2399 tasks transported by 60 trucks. The total computation time is 690 seconds. The ITT cost is reduced by 20% and the railway operation cost is reduced by 44% after the optimization.

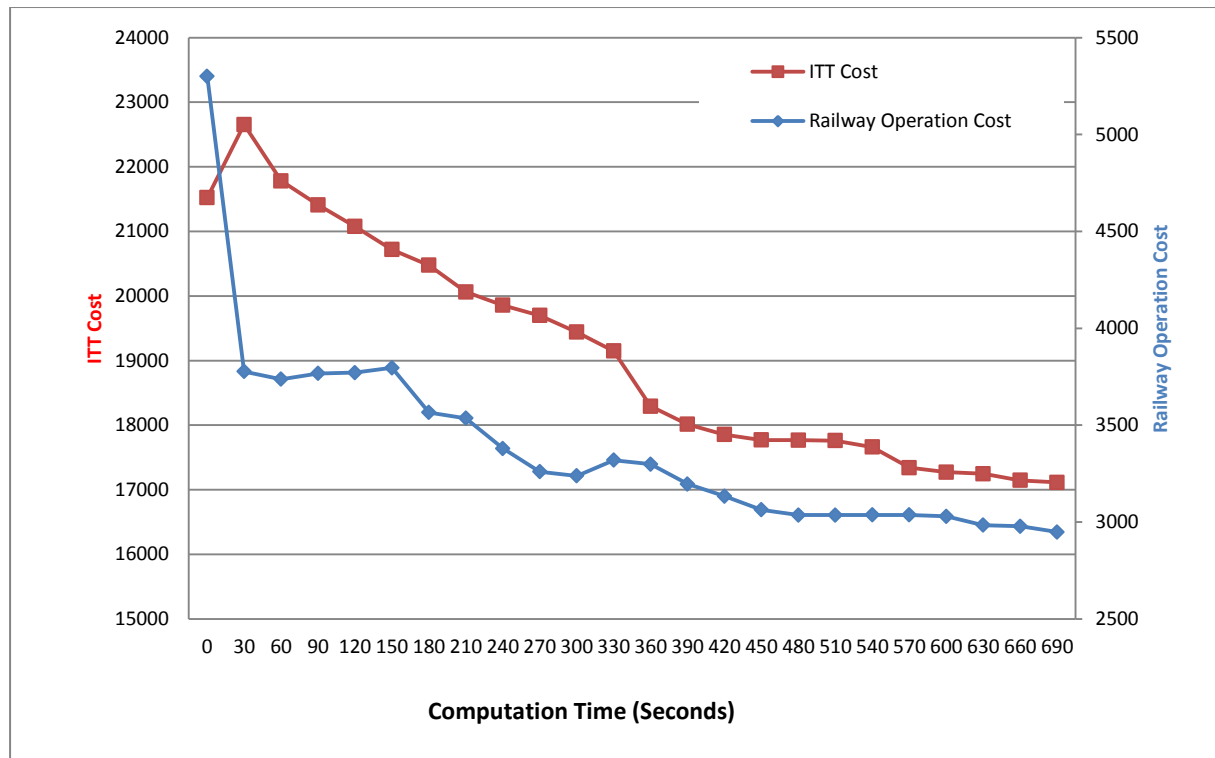


Fig 3.12 Optimization result of the integrated ITT model in a large demand case

In the railway terminal, the total train delay time is reduced to 82 minutes, which is 40% lower than the initial solution. Although two trains are cancelled both in the initial solution and after optimization, 13 more containers can be loaded onto connecting trains, see Table 3.7.

From the analysis above, we can conclude that the integrated ITT system shows significant impact on subsequent transport operations. Overall, the integrated ITT network costs can be reduced and its two components (Railway and ITT) both show cost reductions. Therefore, when optimizing the ITT system, all involved stakeholders should be taken into consideration.

3.6.5 Empty movement and waiting time at intersections in more detail

The traveling time of a vehicle includes the time spent moving full, i.e. with a container; the empty movement time, waiting time inside a terminal and waiting time at intersections. Figure 13 reflects the total traveling time of 20 and 30 vehicles in a medium test case (Figure 3.13.a) and 50 and 60 vehicles in a large test case (Figure 3.13.b). The initial solutions were generated with strategy S1 described in section 5.2 and the final solutions were obtained after running the optimization algorithm with the objective to minimize both ITT and railway operation cost, i.e., function (3.6).

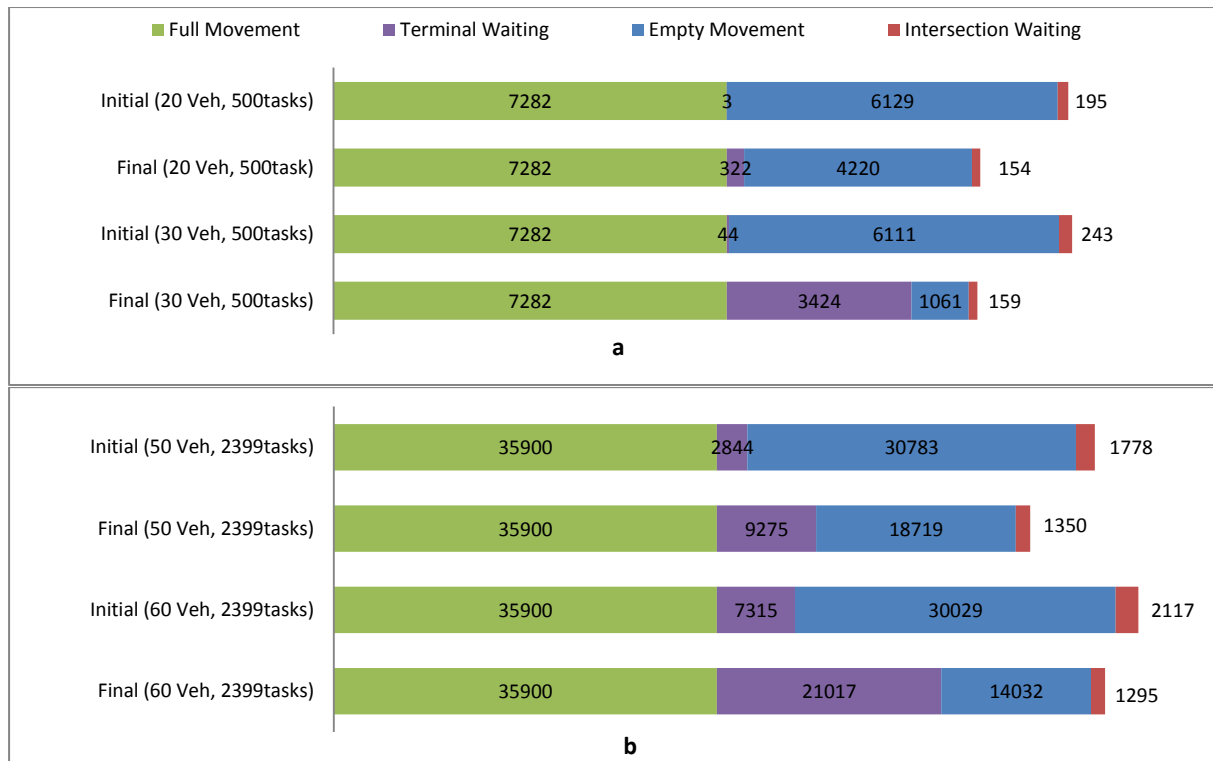


Figure 3.13 Vehicles' travel and waiting time (minutes) in initial and final solution

The length of total empty movement is used to estimate the quality of a solution. When the number of vehicles is fixed, the reduction of empty movement will reduce the total travel time and improve the container delivery. On average, the empty movement in the final solution was reduced by 48% compared with the initial solution, and the total travel time was reduced by 7%.

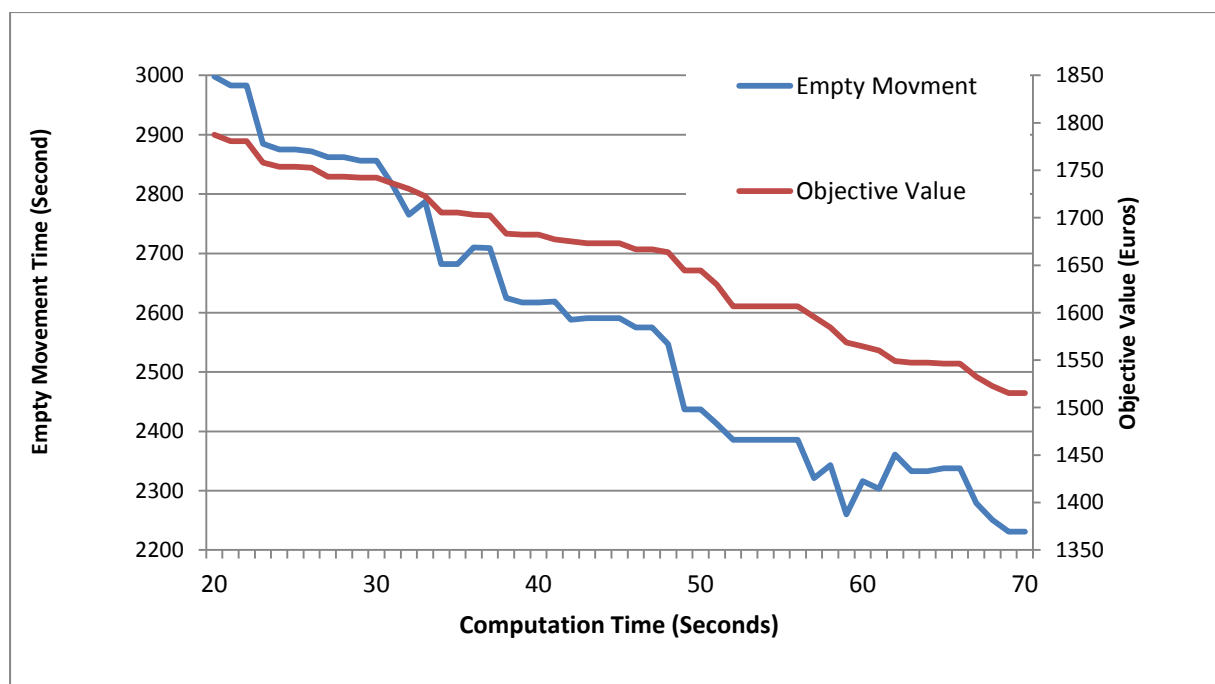


Figure 3.14 Vehicles' travel and waiting time in initial and final solution

It is also notable that if more vehicles are used, the total empty movement could be smaller. Heilig et al. (2017a) also indicate that, if fleet size is an optimization variable, the reduction of empty movement may result in a larger fleet size and larger costs. But in our setup, the number of vehicles is fixed, and thus the number of empty trips performs well as a proxy for the quality of a solution.

Theoretically, the objective value could be improved when the empty movement increases, see discussion in section 3.5.5. Figure 3.14 shows the computation result between 20 to 70 seconds for a medium case. During the computation, the objective of the best solution found by the algorithm kept reducing; the corresponding empty movement also decreased by 26%, but showing some fluctuation at the same time.

The waiting time at intersections also influences the ITT delivery, especially given the relatively short average travel time in ITT network, e.g., the average travel time of the links in the studied network is 2.4 minutes. Trucks could spend 2.8% of their total time for intersection delays in a large demand case with a fleet of 60 trucks. This number can be reduced to 1.7% with our model, which means one truck will spend 21.5 minutes for intersection waiting on average. The intersection waiting time also increases if more vehicles are used, or more tasks are moved. If the fleet size increased from 20 to 30 in a medium test case, the intersection waiting time increased by 15% on average. The waiting time at intersections can also be reduced by the algorithm: the total waiting time at intersections was reduced by 29% in Figure 13.a and 31% in Figure 3.13.b.

3.7 Discussion on the experiment results

In order to optimize the ITT delivery and hinterland railway delivery at the same time, a tabu search algorithm was developed to solve the integrated ITT model with different demand cases. Tabu search components, including initial solution, neighborhood structure, tabu list, search strategy and move evaluation were tested with all demand cases and the best configuration was found. Besides, we also used CPLEX and a local search algorithm to validate the model and to test the performance of the tabu search. In the comparison, CPLEX has to deal with a large number of variables and constraints, thus, it is only able to solve very small test cases. When solving the case with 10 and 20 tasks, tabu search has a longer computation time and gives results similar to those of CPLEX. When there are more than 30 tasks, tabu search can still provide similar results but in a shorter computation time. Local search can solve medium and large test cases, but the performance is not as good as the tabu search. When solving a medium test case, the result of local search is 7% better while the result of tabu search is 38% better than the naïve planning. When solving a large test case, the total cost is reduced by 1% using local search and 24% using tabu search.

Meanwhile, to analyze to what degree the delay ITT will impact the entire transport process, we tested the performance of the integrated ITT system with different demand scenarios. We found that, if we focus on ITT only, ITT performance can be 17% better, but the cost associ-

ated with railway terminals increased largely, by 93%. This is because all containers in the ITT system are considered the same, and have the same time value, thus, they have the same penalty cost for delay. However, the rail-oriented container's late delivery for railway terminal may cause train delays or cancellations, which results in much higher costs to the overall integrated system. When we optimized the integrated ITT with railway operation, the overall system performance improved: ITT cost was 20% better and the railway operational cost was 44% better than the naïve planning. Therefore, it is of great importance to consider the subsequent transport operations when making a transport plan in a port area, along with the general trend of integrating multiple processes in logistics research.

We also found that if the ITT fleet size is fixed, the reduction of the empty movement will reduce the total travel time of the ITT vehicles and thus improve the ITT delivery. For example, when 60 vehicles are used for a large test case, the empty movement can be reduced by 46% and results in a 6% reduction of total vehicle travel time, 20% reduction of ITT cost and 44% reduction of railway operation cost. This means reducing the empty movement is an efficient way to improve the ITT delivery when fleet size is fixed. The intersection waiting time also influences the vehicle travel time; the waiting time will increase with the number of vehicles used and the number of tasks to be moved. In this chapter, only a limited number of ITT vehicles use the road network; in reality, other public vehicles may also use this network, which could lead to more congestion in the intersections. Therefore it is meaningful to manage the vehicles' routes to reduce the congestion at intersections.

3.8 Conclusion

To answer the **Research question 2**, i.e., how to formulate and optimize the connection between railway system and the ITT system, this chapter focuses on a road-based ITT system connected to railway hinterland transport. We proposed a mathematical optimization model to integrate ITT transport with railway terminal operations, and hinterland rail transport aiming at reducing the costs in both transport systems, i.e., lateness of ITT delivery, ITT traveling cost, hinterland railway transport delay cost, alternate hinterland transport cost and train usage cost. The experiments conducted in this chapter show that the operations in the road-based ITT system and the railway hinterland transport system should be coordinated due to their interaction.

This chapter mainly discussed the formulation and optimization of the connection between ITT system and the hinterland railway transport. In next chapter, both of the ITT system and hinterland railway transport will be discussed in a more detailed way by taking into account the terminal operation, different ITT connections and railway timetables.

Chapter 4

Strategy and Performance Analysis of Integrated ITT and Hinterland Railway System

This chapter investigates the problem of inter-terminal movements of containers and vehicles within a port area in order to achieve an integrated and effective transport within the port and towards the hinterland. Containers from different port terminals are first moved to a rail yard and then delivered to the hinterland by rail. To provide insights for stakeholders such as port authority and terminal operators into tactical planning problems, e.g., the coordination between terminals, railway timetable and train sizes, this chapter proposes an optimization model describing the movement of containers and various vehicles between and inside terminals. The model aims at improving the container delivery from container terminals to the hinterland considering both railway hinterland transport and terminal handling operations. A network inspired by a real-life port area and its hinterland is used as a test case to test different components, i.e., inter-terminal transport connections, train formation, railway timetable. A rolling horizon framework is used to improve the computation efficiency in large transport demand cases. The result of the optimization helps in identifying the most promising features, namely, that more connections between terminals and a flexible outbound railway timetable could contribute to improving the integrated container transport performance.

4.1 Introduction

Container ports need to handle large container volumes, for example, tens of thousands of containers arrive at Rotterdam port by sea every day. To move these containers, road, inland waterway and railway transport are provided connecting terminals and the hinterland. Traditionally, road transport took the largest share in the freight transport market both inside the port area and in the hinterland. However, waterway and railway transport are stimulated by the port authority as economical and environmental friendly alternatives. For example, the port authority published a strategic plan, i.e., Port Vision 2030, stating that stakeholders within Rotterdam port have agreed to reduce the usage of road transport: a maximum of 35% of containers transported to and from the Maasvlakte by road in 2030 (Port of Rotterdam, 2011). The strategic Plan covers the period up to 2030 and in more recent progress report, it states that rail transport should be developed with priority and that rail transport share is falling short of the target established in Port Vision 2030 (Port of Rotterdam, 2014).

The development of multiple transport modes, on the one hand, increases the transport capability; but on the other hand, leads to higher infrastructure investment and more operations between modes inside the port area. In Rotterdam port, the port authority pursues the improvement of the port efficiency and accessibility by cooperation between transport modes (Port of Rotterdam, 2011). For example, a Barge Service Center has been established to provide better waterway transport and the same is pursued for rail transport. This terminal handles inland waterway barges and sends containers to other terminals and vice versa. Moreover, the port authority subsidizes the PortShuttle services, which connect the rail yards in Maasvlakte and the Railway Service Center in the hinterland by feeder trains ("PortShuttle adds second shuttle," 2017). This chapter seeks to improve the multi-modal transport system in the port area. We put the focus on the rail-road transport system and study how to move containers from different port terminals to rail yards in the port area and then deliver the containers to the hinterland by rail.

The container transport in this chapter involves moving containers inside a terminal, moving containers between port terminals using a variety of modes (railway and road) and moving containers from rail yard in the port area to the hinterland using railway. Generally, there are two types of intermodal terminals with rail connection in a port area, i.e., railway terminal with road connection (RTR), and maritime terminal with both road and on-dock railway connections (MTRR). Inside these terminals, transshipment can be performed and containers from sea transport and/or road transport can be transshipped to rail transport. In another type of terminals, which is called maritime terminal with road connection and rail off-dock (MTR), containers cannot be transshipped to rail transport directly — the containers must be moved to a RTR or MTRR through inter-terminal transport (ITT) first. Actually, ITT also connects MTRRs and RTRs, which makes it possible to exchange containers between different rail yards in the port area in order to fill the trains towards the hinterland with containers.

To achieve an integrated ITT and hinterland rail transport, several planning problems should be solved. On a strategic level, a proper ITT network must be built to connect the terminals. The ITT network involves the connection between terminals and ITT fleet that moves containers between them. On a tactical level, the port authority and terminal operators must first determine if and how it is possible to share the resources, e.g., rail yards and ITT trains. It is notable that not all containers can be exchanged between all terminals as ITT requires coordination between terminal operators and freight shippers, which means information and facilities should be shared and the coordination benefits must be clear. Then, the railway timetable and the size of the trains which could guarantee the efficiency of railway transport must be designed. On an operational level, the terminal operator also has to decide when and how to move the containers to a rail yard according to the ITT network and also to the timetable of outbound trains.

This chapter focuses on the tactical planning problems, i.e., how would the different ITT connections, train formation strategies and railway timetables affect the container delivery performance? Additionally, we also develop a rolling horizon framework to guarantee the model can be used in operational planning, i.e., planning the container handling operations and design the vehicles' routes? We assume that terminals in a port area could coordinate with each other in a certain level, and resources such as ITT trucks and ITT trains are shared among terminals. Therefore, the decision on the ITT organization considering terminal handling capacity and the railway timetable could be made to maximize the number of containers to be delivered by train within a certain time period (e.g. a day). Then, a mathematical model which could formulate the vehicle and container movements considering the terminal handling capacity is proposed. In that model, different ITT connections, hinterland train sizes and railway timetables are tested with a given ITT fleet to provide insights into the possible strategies which could improve the integrated container delivery to the hinterland.

The remaining part of this chapter is organized as follows. Section 4.2 reviews the studies on terminal operations and ITT. Section 4.3 will define the integrated port container transport system studied in this chapter in great detail. In section 4.4, the problem is mathematically modeled with a time-space graph and the performance is tested with different transport strategies. Section 4.5 contains the experiments and section 4.6 presents the conclusion and further research.

4.2 Literature review of ITT and container terminal operations

This section reviews the research related to different aspects of the container transport from the port area to the hinterland: research on ITT mainly focuses on the container and vehicle movement between terminal; and the research on terminal operations covers problems such as crane scheduling, container transshipment, train loading and departing.

ITT itself can be based on different modes, such as railway, road and inland waterway. A detailed review of ITT can be found in Heilig and Voß (2017). The implementation of a multi-

modal ITT system among several terminals usually requires coordination between terminal operators and the port authority. Duinkerken et al. (2006), proposed an ITT system which is shared among the terminals at the Maasvlakte, Rotterdam. Heilig et al (2017) investigated the truck-based ITT system provided by a third party ITT provider. The ITT provider collects demand information, monitors the trucks' positions and schedules the trucks' routes. Schepler et al. (2017) studied an ITT system based on road, waterway and railway transport and provided suggestions for the port authority and terminal operators in terms of vehicle routings. Our research considers a rail-road network for ITT and the rail connections to the hinterland. The studied ITT system provides service for multiple terminals in the port area aiming at improving the ITT transport system efficiency.

Most existing research on ITT only focused on the transport inside the port area. Ottjes et al. (2007) studied an AVG-based ITT system for the Maasvlakte terminals in Rotterdam and tested the traffic flow between the terminals. Hendriks et al. (2012) focused on the berth allocation problem among multiple terminals considering quay crane operation cost and ITT costs. In Li et al. (2017a) and Li et al. (2017b), inland waterway vessels are used to carry ITT containers between certain terminals in the port. Both studies aim at reducing the time that vessels spend in the port while increasing the number of ITT containers that can be transported. Our research considers the railway transport to the hinterland, therefore the railway timetable must be taken into account. Tierney et al. (2014) propose the first fully defined mathematical model of ITT using a time-space graph. Based on the graph, the authors present an integer-programming model to optimize the container and vehicle flow between terminals. In our study, we also use a time-space model, but we extend the model developed by Tierney et al. to study an ITT integrated with detailed terminal operations and hinterland rail connections.

Different terminal operation problems have been intensively studied. Stahlbock and Voß (2008) provide a detailed review of the operational problems in a maritime container terminal. When moving a container inside a terminal, the movement of cranes and trucks is a key process to be optimized to accelerate that process. Kim and Park (2004) study a quayside crane scheduling problem which determined the order of ship loading and unloading operations. The authors considered containers with same destination and size as a group and assumed that a group of containers should be put into adjacent slots in the ship, which was defined as clusters. Then the problem was formulated as moving containers between several clusters and ship-bays using cranes. In our research, we focus on the operations related to railway transport, therefore, quay crane scheduling problem and other operation problems on the sea-side, see Héctor et al (2013), are not considered in detail. But Kim and Park (2004) inspired us with the container group abstraction: in our research, a group of containers with the same release time and origin terminal is defined as a transport task. Inside the terminals in our model, transport tasks should be executed between different terminal locations with cranes and trucks. Froyland et al. (2008) optimize the landside crane operations in a maritime container terminal. To reduce the complexity, the authors de-composed the problem into three stages:

first determine the container flow between quayside and landside on an hourly basis; then determine the stacking positions for the import containers on the quayside; and finally, determine the order of containers and trucks served by Rail Mounted Gantries (RMGs) and the containers temporary stacking position on the yard side. In our research, containers are not only moved inside a terminal but also moved between terminals in the port area. To reduce the computational intractability, we do not consider the precise position of a container in the storage yard nor on the train, and we use a uniform handling time for every container. However, in future research, these items can be taken into account.

When loading a train in a MTRR and RTR, a well-organized deployment of the handling equipment and spatial arrangement of containers on a train could reduce the working time of the equipment and increase the utilization of a train's carrying capacity. Corry and Kozan (2008) present a mixed integer programming (MIP) model to assign containers to rail wagons using RMGs. The objective is to minimize the number of rail wagons required and the working time. Wang and Zhu (2014) optimize the container transshipment between trucks, storage yards and trains. The objective is to minimize the RMGs' idle time. In our research, trains with different capacities are used, and the train loading process is performed considering the railway timetable.

In European countries, the passenger trains have a higher priority: the passenger trains' timetable is prescribed, a freight train's operator can only request to insert the freight train between passenger trains, see Cacchiani et al. (2010). Delayed trains may not be allowed to enter a rail section to avoid potential conflicts. Thus, delayed trains must be rescheduled with a new time slots by the infrastructure manager. In the Netherlands, requests for using the railway capacity should be submitted to the infrastructure manager. The infrastructure manager will allocate the capacity with a timetable. According to ProRail, the rail infrastructure manager in the Netherlands, any party wants to use the rail capacity could submit the request on the preliminary phase (when ProRail makes the annually timetable), or on the ad-hoc phase. The ad-hoc request will be checked by ProRail and the conflicts-free requests will be accepted with a first come first serve principle. A fee will be charged by the infrastructure manager for the accepted request. It is notable that, ProRail introduces a surcharge for capacity in congested period. Moreover, ProRail will also levy reservation charges if a transport operator cancels a train path usage. When arranging rail transport from the port area to the hinterland, it is important to coordinate the terminal operations and the railway timetable. Delayed trains must be rescheduled to a new conflict-free time slot. The rescheduling not only result in extra cost related to waste of rail capacity and new rail time slots, but also lead to uncertainty of the terminal operations and container delivery time.

A possible way to improve the flexibility for the rail operator, e.g., in D'Ariano (2008), is reserving longer departure time slots for the trains, which makes the timetable more robust for delays. In our research, we handle the delayed hinterland trains with new departure time slots. Usually, a train is assigned with a departure time slots from its departure terminal to make

sure this train could enter the inland railway network without blocking other trains. We assume that the departure time slots could be shared among several terminals in the port area; therefore, the terminal operator has some flexibility in organizing the ITT delivery and hinterland train loading. Our model improves the usage of the railway capacity. In the case of fixed timetable, we analyze the best ITT connection and train size which can maximize the usage of allocated time slots. By using the flexible timetable, as the time slots pool is pre-determined, the terminal operator has better knowledge of the possible departure time and therefore, has a better control of the terminal operations. The using of periodic and flexible timetable is explained in detail in Section 4.3.1.

Overall, the existing research has tackled different sub-problems while neglecting the integration of these highly interactive problems in port areas and their hinterlands. This chapter optimizes the container movement inside and between terminals and the port hinterland, by using RMGs, shared ITT trucks and ITT trains. The objective is to maximize the container delivery for all terminals in a certain time period. The container delivery performance is discussed with different ITT network configurations, train formation strategies and types of railway timetable.

4.3 Container Movement inside Port Area and to the Hinterland

4.3.1 ITT and Rail Transport to the Hinterland

ITT connects different terminals in a port area. In this chapter, MTRs are connected with other terminals by road; MTRRs and RTRs are connected with other terminals by both road and rail. Containers are released at MTRs and MTRRs and then moved to a rail yard using shared ITT trains and trucks through ITT. In this system, ITT trucks move containers from MTRs to MTRRs and RTRs; ITT trains and trucks exchange containers among MTRRs and RTRs.

To reveal how different ITT connections can affect the container transport, two types of ITT connections are applied in this chapter: complete ITT and incomplete ITT. In the complete ITT case, containers from MTRs can be moved to all MTRRs and RTRs; MTRRs and RTRs accept containers from any other terminal. In the incomplete ITT case, some connections are excluded. ITT trains and trucks are used in both cases.

Containers leave the port area with hinterland trains from MTRRs and RTRs. The hinterland trains depart according to the railway timetable. If a train is not fully loaded at its departure time, the terminal operator must decide whether the train should depart or not. When a train cannot depart at the scheduled departure time slot, the railway terminal operator and the network operator must find another solution like either rescheduling or canceling the train.

Our research considers both periodic and flexible timetable. In the periodic timetable scenarios, each train has a predetermined departure time slot from a predetermined departure terminal. Therefore, each train could leave the port area and enter the inland railway network at a proper time without blocking other trains. We assume that in flexible timetable scenarios, the

railway operator only cares about the time when a train enters the inland railway network, and the train could move freely inside the port area. Thus, a departure time slots pool could be shared among all rail terminals inside the port area and the train could depart at any departure time slot from any one of the terminals which is not occupied by another train. Additionally, two types of train size are used: small trains with 40 TEU and large trains with 80 TEU capacity. All trains must reach a minimal loading rate (in our case set at 75%) before departure as Boysen et al. (2010) pointed out that trains could only be profitable if full trains are moved.

Based on the ITT connection case and railway timetable to the hinterland, the routes of the vehicles in the port area should be scheduled to make sure every container can arrive at the rail yard on time. Moreover, the transshipment inside terminals must be taken into consideration as well.

4.3.2 Container Terminals and Transshipments inside the Terminals

Three types of container terminals are considered in this chapter, i.e., RTR, MTR and MTRR, see figure 4.1. As we study the container transport from the port to the hinterland, the storage yards in the MTRs and quayside storage yards in MTRRs are the origin of containers and the containers should be moved to the rail side of the RTRs and MTRRs. In these terminals, four types of operations are considered: (1) truck loading, (2) truck unloading, (3) train loading, and (4) train unloading.

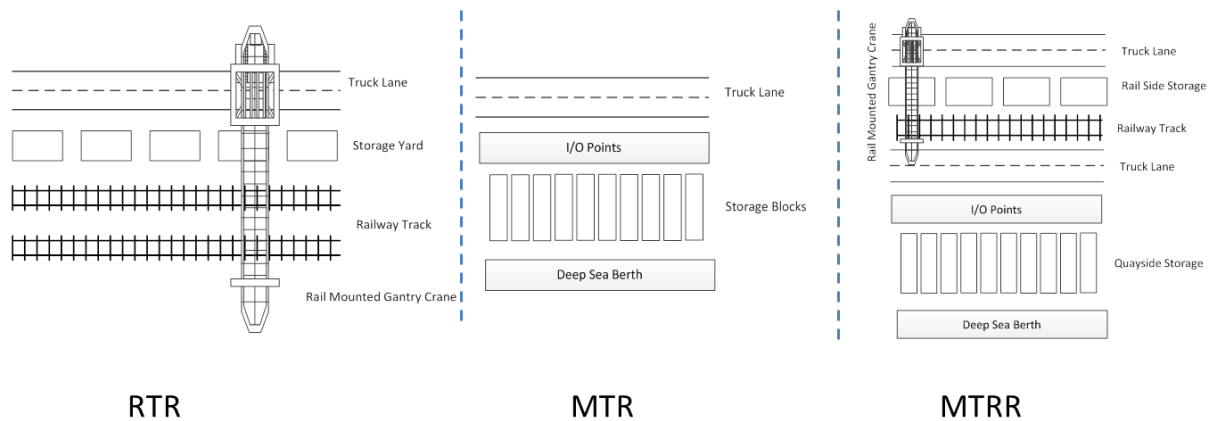


Figure. 4.1 Schematic representation of RTR, MTR and MTRR

In a MTR, several storage blocks are vertically located next to the deep sea berth; automated Guided Vehicles (AGVs) are used to transport containers between the berth and the storage blocks; loading and unloading operations are performed at the I/O points where RMGs move containers between trucks and storage blocks, see Vis et al. (2003) for a detailed description. In our study, ITT trucks pick up containers from the I/O points and move the containers to MTRRs or RTRs.

In a MTRR, when an outbound container is unloaded from the deep-sea ship, if the railway tracks are constructed along the quayside, then it is possible to load the container onto the train using RMGCs or RTGCs; otherwise, vehicles such as trucks and reach stacker will be

used to transport the container from the quay to the rail yard. In the rail yard of a MTRR, RMGs moves containers between trains, rail side storage blocks and trucks.

In this chapter, the container from quayside will be first moved to the I/O points and then loaded onto an ITT truck by a RTG. Then the truck will send the container to the rail yard inside the terminal or to another terminal in the port area. When a truck arrives at the rail yard in MTRR, without losing generality, the container carried by truck should be firstly unloaded to the storage yard and loaded onto a train later. Rail-rail transshipments also take places in the rail yard in the MTRR, where cranes move containers from one train to another. In our research, the rail-rail transshipment between ITT trains is excluded because it can be avoided by running a train visiting all rail terminals. It is assumed that the rail-rail transshipment is performed in the following way: a RMG unloads the container from an ITT train and moves it to the storage blocks; when the train to the hinterland is ready for loading, that container will be loaded onto that train. This assumption, however, could lead to an increase of RMG operations and transshipment time.

In a RTR, storage yards and truck lanes are constructed along the railway tracks and rail mounted gantry cranes (RMGs) are used to move containers between truck, storage yards and trains, see e.g. Boysen et al. (2010). In some cases, for example, if the storage yards and truck lanes are not built next to the railway tracks, extra vehicles such as reach stackers and forklifts are used to move containers, see e.g. Kozan (2006).

This chapter focuses on the terminals using RMGs, therefore, truck unloading, train loading and unloading are performed in a way similar to the operations in rail yards in MTRRs. The rail–road transshipment is not considered because due to the typical size of ITT (up to 20 kilometers in this chapter), it is not logical to make a transfer from a train to a truck, therefore, no trucks are loaded in RTRs or rail yards in MTRRs for ITT transport. The road-road transshipment is not considered in this chapter because it will not improve the transport performance while requiring extra transshipment cost. In the next section, the integrated ITT, terminal operations and hinterland rail transport will be modelled.

4.4 Problem modelling

4.4.1 Time-space network representation

Links and arcs

The container and vehicle movement is formulated by a directed graph denoted as $G(N, A)$, where N is the set of nodes (i.e., locations of terminals and locations to pick up or drop off containers in the network) and A is the set of arcs. The subsets N^{ter} , N^{pickup} , $N^{dropoff}$ and N^{hin} refer to the terminal, container pick-up, drop-off points and destination node in the hinterland respectively.

Let two adjacent nodes $i, j \in N$ identify an arc (i, j) , which refers to the possibility of moving from one node (location) to another one at a given time. Each arc, $(i, j) \in A$, is associated with a traverse time $f_{i,j}$. To model the moving and staying status of vehicles and containers, two types of arcs are considered, i.e., stationary arcs and moving arcs (subsets A^{sta} and respectively). Vehicles and containers on a stationary arc do not move in space but simply stay at the same node (location) during the given time step. In other words, the only thing changing between the start- and end-node of the arc is time. Vehicles and containers on a moving arc are moving from one terminal to another; the arcs connect two different locations at different times.

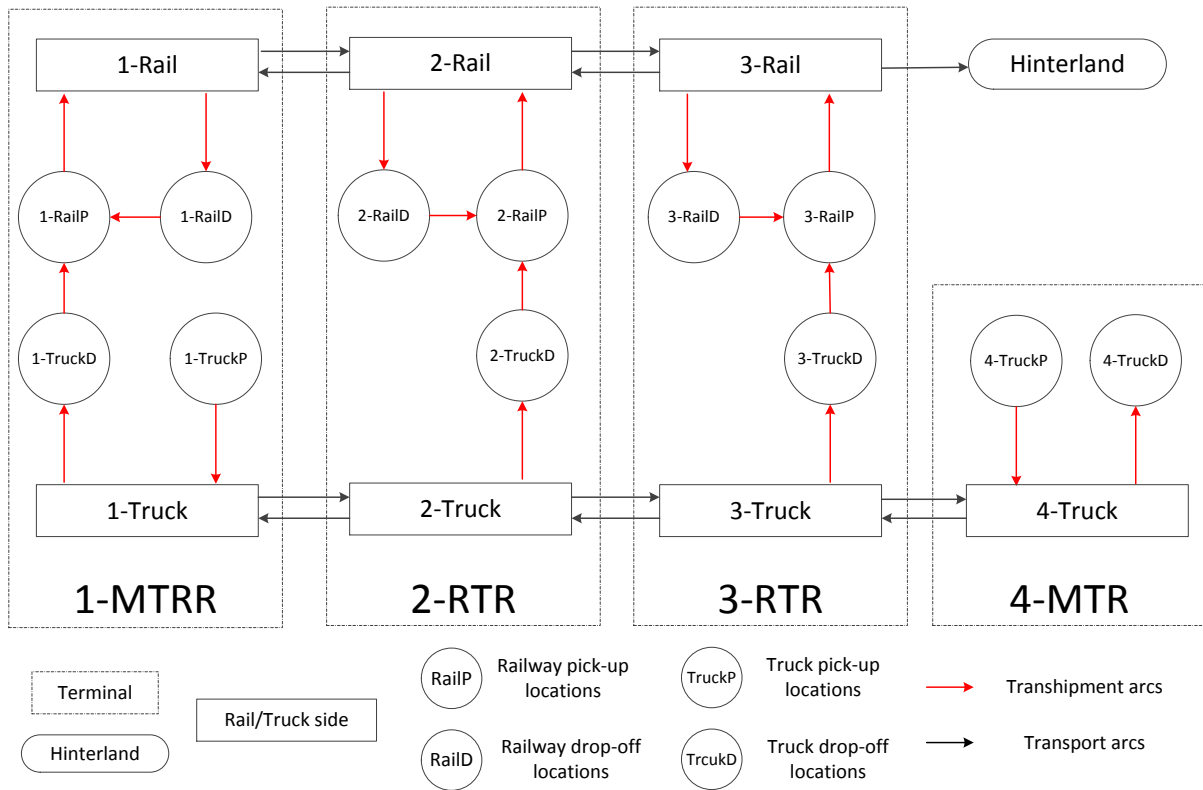


Figure 4.2. Schematic representation of a 4-terminal network with dummy nodes

Figure 4.2 shows a simple ITT network with four terminals: one MTRR, two RTRs and one MTR. This simple network illustrates how the time-space network represents the real ITT network. In order to distinguish the railway and road connection, 2 dummy nodes are used to represent the transport segments. Node and denote the rail side and truck side in terminal 1 respectively. Railway tracks in terminal 1, 2 and 3 are connected while road in terminal 1, 2, 3 and 4 is connected.

Transport operations

Table 4.1. Parameters used in the model

Θ	The set of tasks.
Dem_{θ}	Number of containers in task θ .
A	The set of arcs.
A^{mov}	The set of moving arcs.
A^{sta}	The set of stationary arcs.
o_{θ}	Origin node of task θ .
d_{θ}	Destination node of task θ .
u_{θ}	Planned delivery time of task θ .
r_{θ}	Release time of task θ .
T	The set of time steps.
N	The set of nodes.
N^{hin}	The set of hinterland nodes.
$N^{dropoff}$	The set of drop off nodes.
N^{pickup}	The set of pick up nodes.
N^{ter}	The set of terminal nodes.
$V^{TruckITT}$	The set of ITT trucks.
$V^{TrainITT}$	The set of ITT trains.
$V^{TrainHin}$	The set of hinterland trains.
V	The set of all vehicles.
o_v	The origin node of vehicle v .
$f_{i,j}$	The traveling time on arc (i, j) .
Win_v	The time slot for train v .
$VehCap_v$	The carrying capacity of vehicle v .
$ArcCap_{i,j}$	The handling capacity on arc (i, j) .
η	The minimal loading rate.

The railway segments nodes are further connected to the destination in the hinterland, i.e., , by directed arcs. These arcs are only accessible at certain time slots according to the railway timetable. Therefore, containers will stay in the drop-off nodes before moving to their destinations. Let θ denotes the demands to be served and Θ denotes the set of demands. More precisely, each demand $\theta \in \Theta$ is named as a task. Each task is associated with a certain number of containers Dem_θ in TEU, an origin node $o_\theta \in N$, a destination node $d_\theta \in N$, an earliest release time r_θ and an intended delivery time u_θ . This chapter only discusses the outbound transport flow from port area to the hinterland and not the return flows to the port area. Therefore, pick-up nodes $N^{pickup} \in N$, e.g., 1–*RailP* in figure 4.2, will be the origin of the task and the hinterland node $N^{hin} \in N$ will be the destination of the task.

Let $V^{TrainITT}$, $V^{TruckITT}$ and $V^{TrainHin}$ be the set of vehicles used in this chapter, i.e., ITT trains, ITT trucks and hinterland trains. Each vehicle v has a carrying capacity $VehCap_v$. Vehicles can move containers between terminals using the transport arcs, i.e., black arcs in figure 4.2. Win_v is the set of possible time slots for hinterland train $v \in V^{TrainHin}$. Let η , which is 75% in this case, represent the minimal loading rate which trains must reach before departure.

Transshipment operations

The transshipments between transport modes can also be represented by the nodes and arcs. These arcs are named transshipment arcs, i.e., colored arcs in figure 4.2. As mentioned in section 2.2, transshipments are performed via storage yards: when a container is transferred from road to rail inside a terminal, e.g. terminal 1, the drop-off location in storage yard 1–*TruckD* is connected to the pick-up location 1–*RailP*. Thus it is possible to move from a truck to a train with an operation time $f_{1-TruckD,1-RailP}$. Similarly, when a container is transshipped from one train to another, it will be moved from the railway drop-off node 1–*RailD* to railway pick-up node 1–*RailP* with an operation time $f_{1-RailD,1-RailP}$. To represent the RMGs capacity, $ArcCap_{i,j}$ is used to limit the number of containers that can be moved via transshipment arcs at each time step.

4.4.2 Mathematical Model

The parameters used in the model are shown in Table 4.1. We use an integer programming model to formulate the movement of containers and vehicles and maximize the number of containers which can be delivered to the hinterland. Two integer variables are used to formalize the temporal and spatial movements of vehicles and containers respectively. Let variables $x_{i,j,t,v}$ indicate the number of v type of vehicle travelling on arc (i, j) at time t . Variables $y_{i,j,t,\theta}$ represent the number of containers for task θ is delivered on arc (i, j) at time t . We assume that containers that cannot be delivered before their due time will remain at the origin

terminals. The objective function can then be expressed as minimizing the number of containers cannot reach their destination on time. The final optimization model would then read:

$$\min Z = \sum_{\theta \in \Theta} \sum_{(d_\theta, d_\theta) \in A^{sta}} (Dem_\theta - y_{d_\theta, d_\theta, u_\theta, \theta}) \quad (4.1)$$

S.T.

$$\sum_{(o_\theta, j) \in A} y_{o_\theta, j, r_\theta, \theta} = Dem_\theta, \forall \theta \in \Theta \quad (4.2)$$

$$\sum_{(i, j) \in A} y_{i, j, t - f_{i, j}, \theta} = \sum_{(j, k) \in A} y_{j, k, t, \theta}, \forall \theta, t \in T, t - f_{i, j} \geq 0, \forall (i, j) \in A, (j, k) \in A \quad (4.3)$$

$$\sum_{(o_v, j) \in A} x_{o_v, j, t, v} = |V^{TruckITT}|, t = Min(r_\theta), \forall v \in V^{TruckITT} \quad (4.4)$$

$$\sum_{(o_v, j) \in A} x_{o_v, j, t, v} = |V^{TrainITT}|, t = Min(r_\theta), \forall v \in V^{TrainITT} \quad (4.5)$$

$$\sum_{(o_v, j) \in A} x_{o_v, j, t, v} = |V^{TrainHin}|, t = Min(r_\theta), \forall v \in V^{TrainHin} \quad (4.6)$$

$$\sum_{(i, j) \in A} x_{i, j, t - f_{i, j}} = \sum_{(j, k) \in A} x_{j, k, t}, \forall t \in T, t - f_{i, j} \geq 0, v \in V \quad (4.7)$$

$$\sum_{i \in N} \sum_{j \in N^{hin}} \sum_{v \in V^{TrainHin}} x_{i, j, t, v} \leq 1, \forall t \in Win_v \quad (4.8)$$

$$\sum_{v \in V} x_{v, i, j, t} = 0, \forall t \notin Win_v, i \in N^{dropoff}, j \in N^{hin}, v \in V^{TrainHin} \quad (4.9)$$

$$\sum_{\theta \in \Theta} y_{i, j, t, \theta} \leq \sum_{v \in V} VehCap_v \cdot x_{i, j, t, v}, \forall t, i \in N^{ter}, j \in N^{ter}, (i, j) \in A^{mov} \quad (4.10)$$

$$\sum_{(i, j) \in A^{mov}} x_{i, j, t, v} = 0, \forall t, v, \forall i \in N^{pickup} \quad (4.11)$$

$$\sum_{(i, j) \in A^{mov}} x_{i, j, t, v} = 0, \forall t, v, \forall j \in N^{dropoff} \quad (4.12)$$

$$\sum_{i \in N^{ter}} \sum_{t \in T} y_{i, j, t, \theta} = \sum_{k \in N^{ter}} \sum_{t \in T} y_{j, k, t, \theta} + \sum_{p \in N^{dropoff}} \sum_{t \in T} y_{j, p, t, \theta}, \forall j \in N^{ter}, \theta \in \Theta \quad (4.13)$$

$$\sum_{\theta \in \Theta} y_{i, j, t, \theta} \geq \sum_{v \in V^{TrainHin}} \eta \cdot VehCap_v \cdot x_{i, j, t, v}, \forall t, i \in N^{ter}, j \in N^{hin}, (i, j) \in A^{mov} \quad (4.14)$$

$$\sum_{\theta \in \Theta} y_{i, j, t, \theta} \leq \sum_{v \in V} ArcCap_{i, j}, \forall t \in T, i \in N^{ter}, j \in N^{dropoff}, (i, j) \in A^{mov} \quad (4.15)$$

$$\sum_{\theta \in \Theta} y_{i,j,t,\theta} \leq \sum_{v \in V} ArcCap_{i,j}, \forall t, i \in N^{pickup}, j \in N^{ter}, (i, j) \in A^{mov} \quad (4.16)$$

$$y_{i,j,t,\theta} = 0, \forall \theta, t < r_\theta, (i, j) \in A \quad (4.17)$$

$$x_{v,i,j,t} = 0, \forall t < \min(r_\theta), (i, j) \in A \quad (4.18)$$

$$y_{o_\theta, o_\theta, r_\theta, \theta} + y_{d_\theta, d_\theta, u_\theta, \theta} = Dem_\theta, \forall \theta \in \Theta \quad (4.19)$$

$$x_{v,i,j,t} \in \{0,1\}, \forall t, v, (i, j) \quad (4.20)$$

$$y_{i,j,t,\theta} \in \{0,1\}, \forall (i, j), t, \theta \quad (4.21)$$

Function (4.1) minimizes the number of containers that cannot reach their destination before the due time. Constraints (4.2) and (4.3) ensure the consistency of containers' movement for each demand at origin, intermediate, and destination node. Constraints (4.4) to (4.6) guarantee that vehicles depart from pre-determined terminals at the earliest release time. For each node, constraint (4.7) forces the number of incoming vehicles to equal the number of outgoing vehicles at any time. Constraint (4.8) ensures that at any departure time slot, only one train could depart from any of the terminals, which prevents one time slot being occupied by more than one train. Constraint (4.9) is used to force trains to depart based on the given timetable. In constraint (4.10), the number of containers delivered by a truck or train cannot exceed its carrying capacity. Constraint (4.11) and (4.12) prevent vehicles traveling to the dummy nodes. Constraint (4.13) ensures that containers on ITT trains cannot be moved to hinterland trains directly. When containers moved to a terminal by ITT trains, these containers must be either moved to another terminal by ITT train or dropped off first. Constraint (4.14) ensures that a train will not leave before it reaches the minimum required loading rate. In constraint (4.15) and (4.16), the number of containers being handled cannot exceed the handling capacity of the terminal. Constraint (4.17) ensures that containers cannot be moved out of their origin nodes before the corresponding release times. Constraint (4.18) ensures that vehicles will not move before the earliest container release time. Constraint (4.19) ensures that at the due time of task θ , all containers in that task should be at their origin or destination node. In our model, the ITT will send as many containers as possible to rail terminal before the departure of the train. In that case, delayed delivery to a rail terminal is meaningless as the connecting train could have departed or cancelled. Thus, we assume that the containers cannot be sent to destinations before their due time will stay at their origin terminals. With this assumption, we could: 1) avoid the non-performance in ITT; 2) rule out some similar solutions for the solver (as the delayed containers can be at any locations at its due time, while the location of these containers has no influence to our objective function). In other terms, this fix helps as the final loca-

tion of the delayed containers, i.e. the index (i, j) , for which $y_{i,j,t,\theta}$ is non-zero, for the time $t = u_\theta$, for each θ , has no direct influence on to our objective function. Constraints (4.20) and (4.21) state the restriction of the variables $x_{i,j,t,v}$ and $y_{i,j,t,\theta}$.

4.5 Computational experiments

Computational experiments are conducted under different conditions, several scenarios were created by varying the transport demand, ITT terminal connections, train formation and railway timetables. The tested cases need to be complex enough to reflect realistic conditions but at the same time be solvable in an acceptable time period. Thus, the test cases were designed as container transport from 11 container terminals to a single destination in the hinterland with 2 ITT trains, 8 ITT trucks and maximum 20 trains to the hinterland (an extended version of Figure 4.2). The scenarios represent a randomized transport demand day with different distributions. A planning horizon of 24 hours with a 5-minute discretization was used.

4.5.1 Container Terminals and Transport Network: Instances and Assumptions

We use a simplified network based on the terminals in Maasvlakte 1&2. 11 real-life container terminals are considered:: four MTRRs, five MTRs and two RTRs. The MTRRs and RTRs are connected to the Port Railway Line and then further connected to the Betuweroute, which heads to Germany. The terminals' names and types are shown in Figure 4.3.

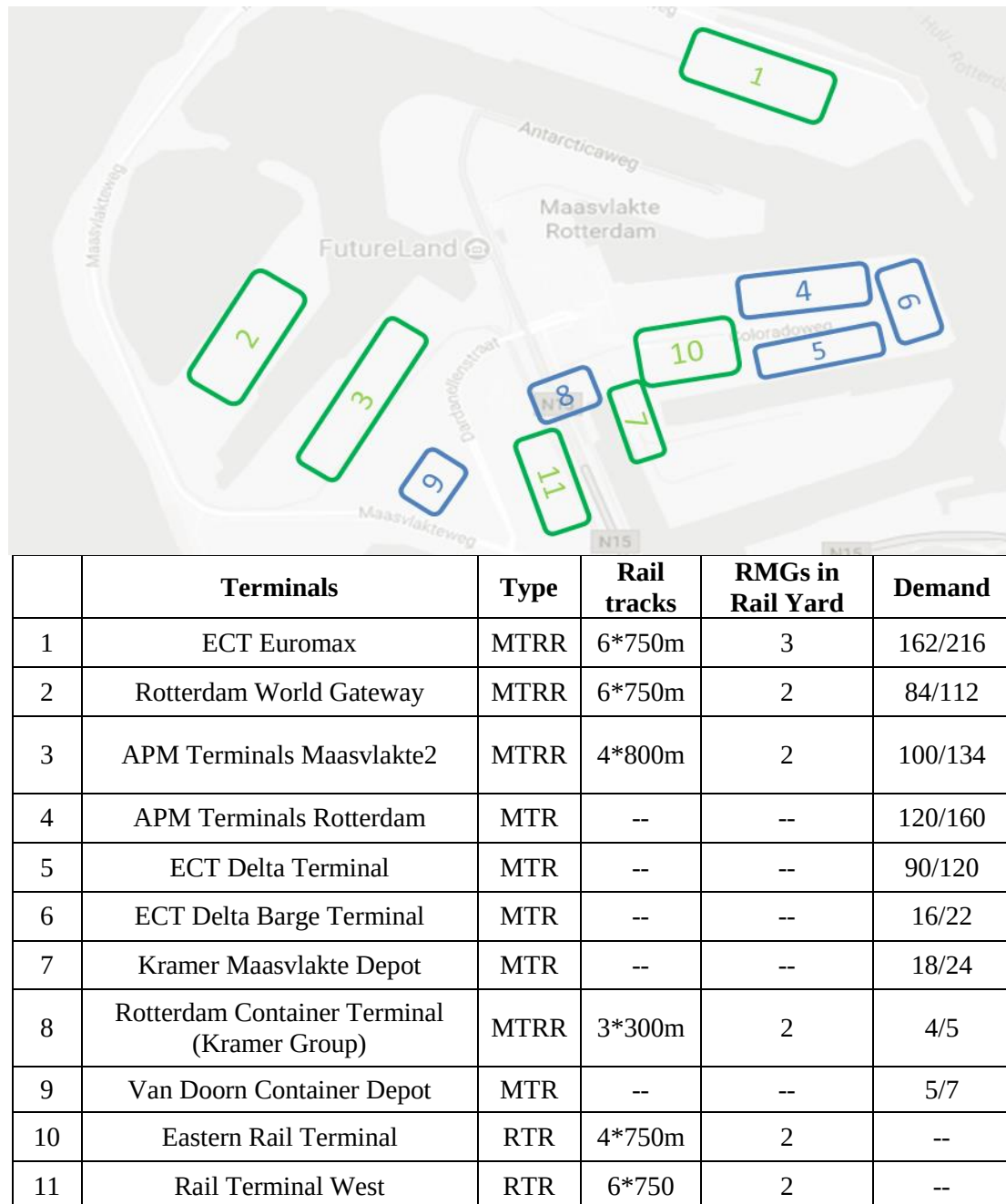


Figure. 4.3. Container terminals in Maasvlakte 1&2

In order to plan the vehicle and container movement among these terminals, the following key information about the containers, ITT vehicles, hinterland railway, and terminals over a certain time period (e.g. daily basis) should be collected and available in advance, see Table 4.2.

For the containers, information about transport volume, origin terminal or yard in the port, release time in the origin terminal, the destination of the container, and the destination is needed. The transport volume, the origin terminal or yard and the release time can be obtained from terminal operators based on their operational plan. The terminal operators also have the destination information of each container from the deep-sea container carriers.

For the ITT vehicles, including ITT trucks and ITT trains, we need the information about their location and capacity as the input for our model. The ITT vehicles can be provided by a third party ITT provider, a logistic provider or several terminal operators. Then, information should be collected from different actors involved and identify available vehicles and their capacities.

For the hinterland railway transport, the information about railway timetable and train capacity is needed. The railway timetable, which indicates which time slots are possible for train departure, can be obtained from the track owner; and the capacity of the hinterland train can be collected from the train operator.

For the terminals, the handling capacities and handling speed are needed to calculate the time spent in (un)loading. This information can be collected from terminal operators based on the type of equipment and the operation plan.

We believe that most of the information about the containers and ITT vehicles should be collected at least on a daily basis because the accuracy of the information will become lower over a longer time period. The infrastructure manager (in most cases), e.g., ProRail in the Netherlands, or the track owners (for some industrial private railways) usually use a fixed timetable for a year. Similarly, the terminal handling capacity may remain the same if the same amount and type of equipment and working procedure (number of crew, business hours, etc.) are used. Therefore, the information about the hinterland railway timetable and terminals can be updated only if there are major changes in the terminal.

Table 4.2. Required information for the optimization model

Data		How to collect	How often
Container	Volume	-Get an operation plan from terminal operator	At least daily
	Release time		
	Origin location		
	Destination		
ITT vehicle	Vehicle location	-Get the location and capacity of trucks and trains from ITT operators and/or logistic providers and/or terminal operators.	
	Transport capacity		
Hinterland railway	Timetable	-Get the timetable from the infrastructure manager and/or track owner	Update when there are changes
	Train capacity	-Get the train formation plan from train operator	
Terminal	Handling capacity	-Get the operation plan, equipment information, etc. from terminal operators	
	Handling speed		

Although collecting the information requires considerable effort from the decision maker(s) who wants to schedule the integrated ITT and hinterland rail system, we believe obtaining

these data is possible. For experimental purpose, however, estimation should be made as the input for our model. The estimation could for example be made with on-site observing, however, the complication is that we cannot get these data for all terminals at the same time. Therefore, we made the following assumptions given the conditions of terminals in Port of Rotterdam.

In terms of operational capacity, the capacity is assumed to be always enough for loading and unloading trucks as well as for the transshipment from trucks to trains. The capacity of train loading, unloading and transshipment, however, can be estimated by the number of rail tracks and rail cranes in each yard. The number of cranes in each rail terminal can be found in Figure 4.3. Every railway crane can handle one TEU per time step.

Among the studied terminals, six terminals possess rail access, as shown in Figure 4.3. All these terminals except terminal 8 can handle ITT trains and hinterland trains. As the rail track length in terminal 8, Rotterdam Container Terminal is much shorter than 750m, it is assumed that no hinterland trains depart from that terminal. As for the capacity of trains, ITT trains can carry 20 TEU containers and hinterland trains can carry either 40 TEU or 80 TEU containers. The minimum assumed loading rate of the hinterland train is 75%. In terminal 1, 2, 3, 10 and 11, maximal four small trains or two large trains could depart every day.

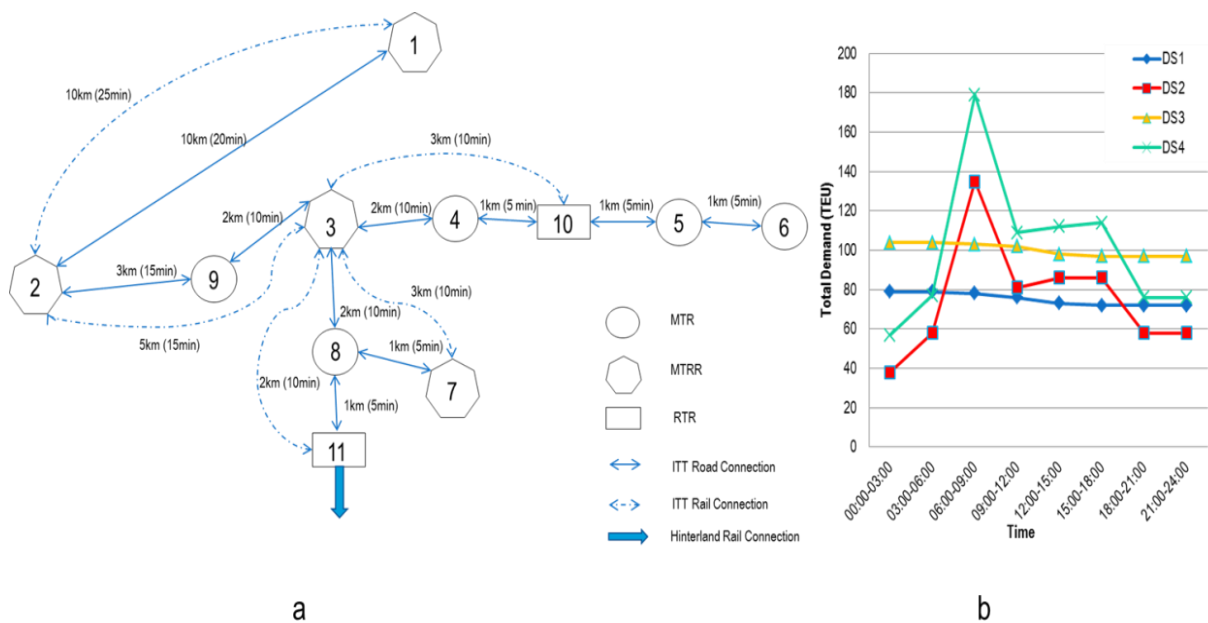


Figure. 4.4. Connections between terminals and peak demand factors

The possible connections between the terminals, their distance, and the minimum travel time (if there is no queue for loading/unloading) are shown in Figure 4.4.a.

The transport demand is generated considering the throughput of the Rotterdam port and the modal split. In 2017, approximately 1.2 million TEU containers are sent to the hinterland from Rotterdam port (Port of Rotterdam, 2017). According to the port authority, rail transport

covered around 15% of the total transport demand in 2011 and will cover at least 20% of these containers before 2030 (Port of Rotterdam, 2011). In order to reflect the daily transport demand, we considered two small transport demand cases (DS1 and DS2) and two large transport demand cases (DS3 and DS4). In small transport demand cases, 18% of the total transport demand is covered by rail (600 TEU per day) and in the large transport demand cases, 24% of the containers are covered by rail (800 TEU per day).

To reflect the transport demand from the four MTRRs and five MTRs to the hinterland, four demand scenarios (**DS**) are considered: two small transport demand scenarios with 600 TEU containers and two large transport demand scenarios with 800 TEU containers. In this chapter, all containers have the same destination in the hinterland, thus we only need to generate the release time and origin terminal of each task. Among the four DSs, two of them (DS1 and DS3) are released evenly within the day and two of them (DS2 and DS4) are released with peak factors. The peak factors, i.e., the ratio of peak demand to the average demand, used in the experiment were reported in Nieuwkoop (2013), which studied the variation in ITT transport demand between terminals of Maasvlakte 1&2. The variation of the transport demand can be found in Figure 4.4.b. To avoid infeasible transport demand, it is assumed that the last transport demand is released 3 hours before the end of the planning horizon. The transport demand of each terminal is shown in Figure 4.3, e.g., the total transport demand of terminal 1 in DS1 and DS3 is 162 TEU; the total transport demand of terminal 1 in DS2 and DS4 is 216 TEU. The transport demand scenarios are as follows:

DS1 65 tasks: 600 TEU containers distributed evenly;

DS2 61 tasks: 600 TEU containers distributed with peak factors;

DS3 65 tasks: 800 TEU containers distributed evenly;

DS4 67tasks: 800 TEU containers distributed with peak factors.

4.5.2 ITT Connections: Complete and Incomplete Connections

To test container delivery with different ITT connections, a complete and an incomplete ITT system were created. In the complete ITT, we assumed that containers can be moved to any MTRR or RTR (terminal 1, 2, 3, 10 and 11) before being loaded onto the train to the hinterland. Then, we constructed the incomplete ITT network considering the existing current terminal connections. As a result, connections between ECT terminals (terminal 1, 5, 6, 10, 11), Rotterdam World Gateway (terminal 2) and APM terminals (terminal 3 and 4) were excluded. Therefore, containers from the ECT terminals, i.e., terminal 1, 5 and 6, can only be moved to terminal 10 and 11; containers from terminal 4 can only be moved to terminal 3; containers from terminal 2 and 3 cannot be moved to other terminals; containers from other terminals can be moved to any MTRR or MTR. In the incomplete ITT network, only four terminals (terminal 2, 3, 10 and 11) can be used for the hinterland trains.

4.5.3 Railway timetable: periodic timetable and flexible timetable

Two timetable scenarios are proposed: the periodic timetable and the flexible timetable. In the periodic timetable, each planned train is assigned with a departure time slot. If a train is delayed, then the train will be canceled. In a flexible timetable case, instead of assigning the departure time slots to each train, we assume that there is a departure time slots pool and these slots can be shared among the trains and terminals. So the terminal operator could choose a suitable departure time slot from the pool as long as that time slot is not occupied by another train. Moreover, in the periodic timetable case, each train has a fixed terminal to depart and a maximum of four trains can depart from each terminal during the planning horizon; in the flexible timetable case, there is no limitation for the number of trains departing from each terminal.

4.5.4 Test Scenarios and container delivery

The experiments include 24 scenarios are created, see Table 4.3. The small transport demand scenarios (DS1 and DS2) are tested with complete and incomplete ITT connections; small and large hinterland trains; and flexible and periodic timetables. In the complete ITT connections, maximal 20 small trains or 10 large trains can depart from each of the five terminals (i.e., terminal 1, 2, 3, 10 and 11); in incomplete ITT connections, maximal 16 small trains and 8 large trains could depart from the four terminals (i.e., terminal 2, 3, 10 and 11). Therefore, the configuration of large transport demand scenarios (DS3 and DS4) and incomplete ITT connection are infeasible and not included in the experiments. The 24 scenarios are solved using IBM ILOG OPL CPLEX OPTIMISER version 12.7.1 on a machine with Microsoft Windows 7 operating system, Intel i5 core 3.2 GHz CPU, 16 GB RAM. The small transport demand scenarios (e.g., S1-S4) can be solved within 10 minutes, the computational time solving the largest case, i.e., S24 was 61 minutes.

Table 4.3 Overview of tested scenarios

	Demand scenario	ITT Connection	Number of Trains	Train capacity	Railway timetable
S1	DS1: 600 TEU container without peak hours	Complete	20	40TEU	Periodic
S2					Flexible
S3			10	80TEU	Periodic
S4					Flexible
S5		Incomplete	16	40TEU	Periodic
S6					Flexible
S7			8	80TEU	Periodic
S8					Flexible
S9	DS2: 600 TEU container with peak hours	Complete	20	40TEU	Periodic
S10					Flexible
S11			10	80TEU	Periodic
S12					Flexible
S13		Incomplete	16	40TEU	Periodic
S14					Flexible
S15			8	80TEU	Periodic
S16					Flexible
S17	DS3: 800 TEU container without peak hours	Complete	20	40TEU	Periodic
S18					Flexible
S19			10	80TEU	Periodic
S20					Flexible
S21	DS4: 800 TEU container with peak hours	Complete	20	40TEU	Periodic
S22					Flexible
S23			10	80TEU	Periodic
S24					Flexible

Figure 4.5 shows the movement of one task in the optimization results. In this case, demand scenario DS2 with incomplete ITT connection was executed. The arcs in Figure 4.5 represent 12 TEU containers released from terminal 1 at 0:00 and finally loaded onto a hinterland train

departed from terminal 11 at 11:30. Because the incomplete connection was used, these containers had to be sent to terminal 10 or 11. The transshipment operations started from 6:25, and all 12 TEU containers were ready for the ITT trains at 8:35. At 8:45 an ITT train took these containers from terminal 1 to terminal 11. This train arrived at terminal 11 at 9:35 and then containers were dropped off from the ITT train. After that, containers were loaded onto the hinterland train. The loading process ended at 11:20.

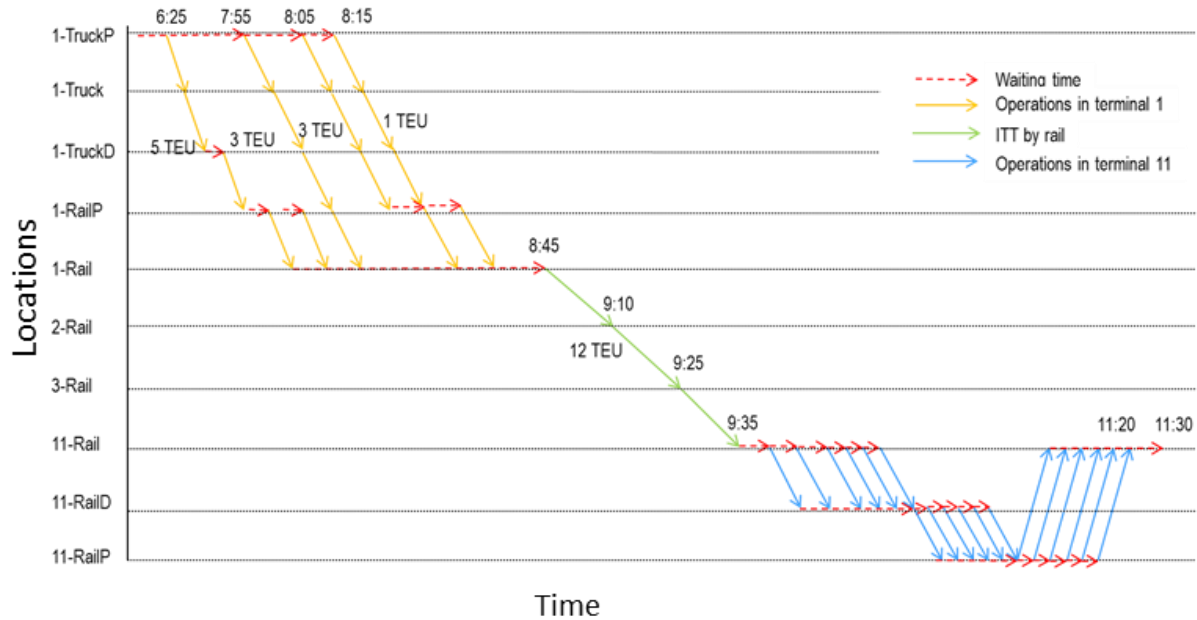


Figure. 4.5 Illustration of the optimization results

Figure 4.6 demonstrates the hinterland train loading process in Terminal 1 with test scenario S3 and S4. In S3, two trains depart at 16:30 and 24:00; in S4, three trains depart at 14:00, 16:00 and 24:00.

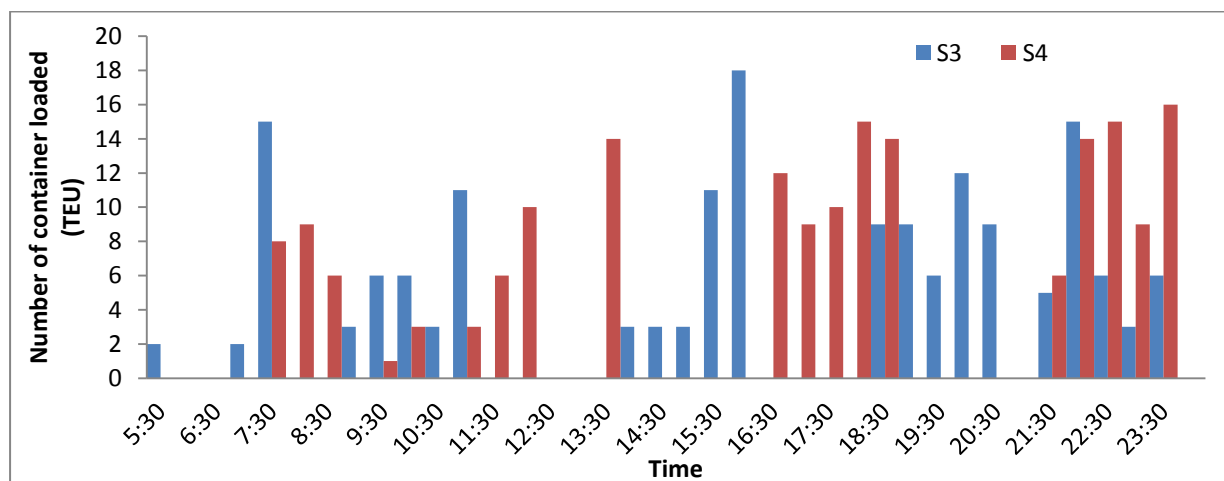


Figure. 4.6. Hinterland train loading in Terminal 1

Table 4.4 gives an overview of the experiment results. The first column is the index of the test scenarios. The last four columns show the number of containers delivered on time to the hin-

terland, the number of hinterland trains that departed, the average loading rate of the hinterland trains, and the CUP time used for each scenario.

Table 4.4. Overview of Container Delivery

	ITT Connection	Railway timetable	Container Delivery (TEU)	Trains Departed	Average Train Loading Rate	CPU Time (minutes)
S1	Complete	Periodic	598	17	87,94%	6,2
S2		Flexible	600	18	83,06%	8,7
S3		Periodic	536	7	95,71%	6,7
S4		Flexible	600	10	75,00%	12,0
S5	Incomplete	Periodic	540	14	96,43%	7,0
S6		Flexible	600	16	93,75%	8,1
S7		Periodic	520	7	92,86%	7,1
S8		Flexible	596	8	93,13%	9,3
S9	Complete	Periodic	598	17	87,94%	6,8
S10		Flexible	600	18	83,06%	10,7
S11		Periodic	552	8	86,25%	7,2
S12		Flexible	600	9	83,33%	9,9
S13	Incomplete	Periodic	540	15	90,00%	3,5
S14		Flexible	600	16	93,75%	6,4
S15		Periodic	524	7	93,57%	5,9
S16		Flexible	596	8	93,13%	8,6
S17	Complete	Periodic	742	20	92,75%	38,5
S18		Flexible	800	20	100,00%	42,1
S19		Periodic	658	9	91,39%	36,5
S20		Flexible	800	10	100,00%	43,6
S21	Complete	Periodic	743	20	92,88%	56,4
S22		Flexible	800	20	100,00%	76,2
S23		Periodic	677	9	94,03%	59,5
S24		Flexible	800	10	100,00%	61,2

The complete ITT connection performed better than the incomplete ITT connection. Test scenarios with complete ITT connection (S1-S4, S9-S12) delivered more containers to the hinterland regardless of transport demands and train capacity: on average, 98% of the containers were delivered on time with complete ITT while 94% of the containers were delivered on time with incomplete ITT. Moreover, the incomplete ITT network puts more pressure on the rail yards. Table 4.5 shows the number of containers handling operations, i.e., pick-up, drop-off and transfer in two RTRs, for a relevant subset of scenarios. For example, when small trains with periodic timetable are used to transport 600 TEU containers with evenly distributed release time, the rail yards in MTRR and RTR need to perform 606 handling operations in a complete ITT connection (scenario 1), while the figure is 1034 for incomplete connection, i.e., 71% increase. On average, the total number of handling operations increased by 67% and 78% if the incomplete ITT connection was used for DS1 and DS2 respectively. It is also notable that in some complete ITT cases (S4, S11 and S12), no train departed from rail terminal 11, but the system could still deliver more containers than the incomplete ITT.

Table 4.5. Number of Containers Handling Operations in Rail Yard of MTRR and RTR

	ITT Connection	Terminal 10	Terminal 11	Total Moves
S1	Complete	133	65	606
S2		148	37	616
S3		155	87	707
S4		120	0	608
S5	Incomplete	324	276	1034
S6		373	237	1094
S7		317	296	1014
S8		439	175	1090
S9	Complete	137	62	604
S10		108	32	606
S11		127	0	558
S12		152	0	606
S13	Incomplete	254	342	1030
S14		319	291	1092
S15		280	332	1016
S16		456	158	1088

Two types of hinterland trains were tested. According to Table 4.4, the terminal operator should consider smaller trains when using fixed timetables: trains with 40 TEU transported more containers in all scenarios. This increases the flexibility of the system against higher operational costs (more locomotives, more drivers). When using flexible timetable, the loading rate of smaller trains is higher.

The flexible railway timetable has a promising role in improving the container delivery performance. Table 4.4 shows that when the transport demand was 800 TEU, trains with a flexible timetable could deliver all containers; when the total transport demand was 600 TEU and the complete ITT was used, trains with flexible timetable could deliver all containers. Trains with fixed timetable could not deliver all containers in any case. It is notable that in the flexible timetable cases, the average train loading rate is lower because fewer trains were cancelled.

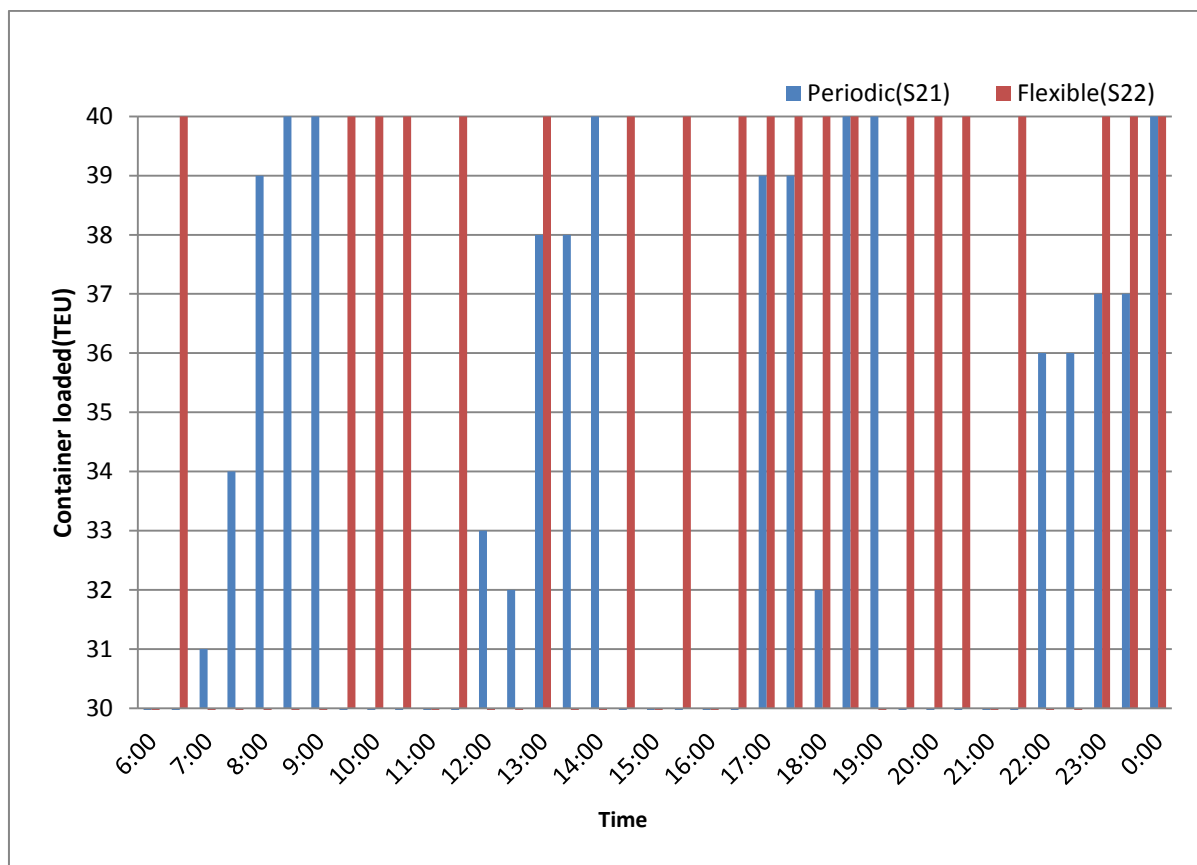


Figure. 4.7. Periodic and flexible timetable

Figure 4.7 shows that in a flexible timetable case, 20 trains were fully loaded while in the periodic timetable, the average loading rate of the 20 trains departed was 92.88%. DS4 was used in these two cases. As shown in Figure 4.4.b, the peak hours were between 6:00 to 9:00, and the periodic trains departed during the peak hours without fully loading, which could result in lost capacity.

4.5.5 A rolling horizon approach to solving large cases

When solving the problem with smaller transport demand and a periodic timetable, the computation is efficient enough to provide solutions to dispatch the transport and handling operations. The last column of Table 4.4 shows the CPU time for solving each scenario. Most of the test cases with small transport demand can be solved within 10 minutes. However, the computation time increases significantly when dealing with larger transport demand and flexible timetable. In this section, a rolling horizon procedure is proposed to improve the computation so that the optimization could also be implemented in practice.

Rolling horizon framework is usually used when solving dynamic problems or when commercial software fails in finding an optimal solution within a reasonable computation time. Wang and Kopfer (2015) solve a dynamic vehicle routing problem with two types of rolling horizon framework. The first one is the rolling horizon with fixed interval and the second type is called request triggered rolling horizon. In the first type of rolling horizon, the length of the planning horizon is fixed and pre-determined. In the second type of rolling horizon, the release of a new transport request will terminate the previous planning horizon and start a new one. Liang et al. (2018) focus on an automated taxi routing problem. With the proposed rolling horizon procedure, real-time transport requests are considered when a new planning horizon starts. Our research uses a rolling horizon with fixed interval because we only consider static transport demand.

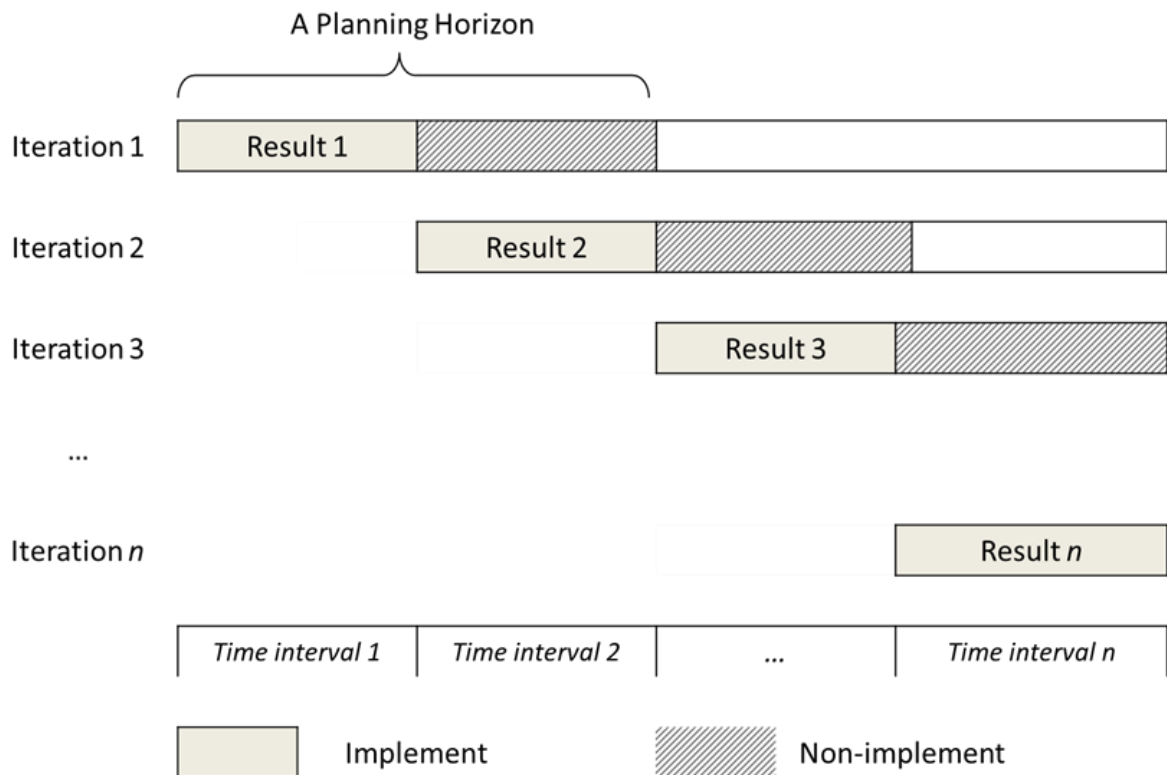


Figure. 4.8. Rolling horizon framework

In the proposed rolling horizon framework (see Figure 4.8), the planning for one day is performed with several iterations. In the first iteration, a planning horizon with fixed length (from Time interval 1 to Time interval 2) is considered. The optimal solution for vehicle routing and container handling is found based on the transport demand and available vehicles in that planning horizon. Then, the solution for Time interval 1, i.e., Result 1, is implemented for dispatching the transport and handling operation and the status of vehicle and containers is recorded as the input of next planning horizon which starts from Time interval 2.

In practice, the rolling horizon framework can be used to consider real-time demand information: in this case, the demand information will be updated at the beginning of each planning horizon. In this chapter, we use static transport demand data and there is no transport demand released after 21:00. Therefore, we divide the one-day planning into five planning horizon: each horizon covers 8 hours. In the first four planning horizon, the solution of the first 4 hours is implemented; and in the last horizon, the solution for the entire planning horizon is implemented.

Table 4.6. Computation time in minutes and number of containers delivered

	Rolling Horizon							Optimal Solution	
	H1	H2	H3	H4	H5	Total Time	TEU*	Time	TEU
S21	0.2	0.5	0.8	10+	5.1	16.6	680	56,4	743
S22	1.9	10+	0.6	6.2	1.1	19.8	734	76,2	800
S23	0.2	10+	0.5	1.5	0.9	13.1	610	59,5	677
S24	9.2	10+	10+	10+	0.5	39.7	785	61,2	800

TEU is the number of containers delivered on time. 10+ means the optimal solution is not found within 10 minutes and the algorithm stops at 10 minutes.*

When solving the problem with the rolling horizon, a maximum computation time, i.e., 10 minutes, is set for each planning horizon. If the optimal solution cannot be found within 10 minutes, the best solution found will be accepted and the next planning horizon will start. Table 4.6 shows the computation results with the rolling horizon and optimal solution. For most of the planning horizons, it is possible to finish the computation within the time limit. The rolling horizon algorithm can give good solution compared with the optimal solution: the difference between the rolling horizon and the optimal solution are large in terms of the computation time (the rolling horizon is much faster). However, the performance of the rolling horizon in terms of delivered containers is lower as compared to the optimal solution.

Table 4.7. Number of trains departure and container delivered

Time Period	S21				S22			
	Rolling Horizon		Optimal Solution		Rolling Horizon		Optimal Solution	
	Trains	TEU	Trains	TEU	Trains	TEU	Trains	TEU
00:00-04:00	0	0	0	0		0	0	0
04:01-08:00	3	120	3	104	5	174	1	40
08:01-12:00	4	160	3	113	3	118	4	160
12:01-16:00	3	120	4	148	3	120	3	120
16:01-24:00	7	280	10	378	8	322	12	480
Total	17	680	20	743	19	734	20	800

Table 4.7 gives an example of the system performance when using rolling horizon approach. S21(scenario with 800 TEU, 20 planned trains, periodic timetable) and S22(scenario with 800 TEU, 20 planned trains, flexible timetable) are used to test the system performance. Experiment results obtained by rolling horizon and the optimal solution obtained in section 4.5.4 are shown in the table. The columns Trains show the number of trains departure in each time period, and the columns TEU show how many containers are delivered in each time period. From the table we can find that the rolling horizon approach generated better solutions at the earlier time periods, e.g., between 04:01 and 08:00. At these time periods, the number of trains departure and delivered containers are higher than the figure in optimal solution. This is because in each planning horizon, no information about next planning horizon is known, thus, the algorithm maximizes the container delivery without considering transport demand and capacity in later stage. As a result, less containers are delivered in the later time periods of a day when using rolling horizon approach.

4.6 Discussion on the experiment

In this section, we conducted computational experiments to evaluate the container deliver performance with different transport demands, variations in available ITT connections, hinterland train capacities and railway timetables. The results show that a better ITT connection can improve the container delivery to the hinterland. If the Port authority and terminal operators can reach an agreement to provide more ITT access to each other then they can increase the number of containers delivered on time and reduce the number of handling operations. In the experiments, 98% and 94% of the total containers from the terminals can be delivered to their destination with complete ITT and incomplete ITT respectively. This indicates that the port authority may encourage the coordination between terminals as this increases the performance of the ITT network and its connections to the hinterland. Next, if a more flexible railway timetable is possible, i.e., terminals could have more choices on when the train departs, more containers can be delivered on time. In the experiment, all containers can be delivered to their destination with the flexible timetable and complete ITT connection. When using a periodic

timetable, 91% of the container can be delivered with complete ITT connections and 89% of the containers can be delivered with incomplete ITT connections. Also, this means that a better performance of the ITT network and its hinterland connections is possible if more flexibility is introduced by the infrastructure provider.

When using a periodic timetable, smaller trains with higher frequency perform better than large trains with low frequency. Although smaller trains are more expensive, they also offer more flexibility and higher frequencies leading to a better performance in the model (although possibly at higher costs).

Moreover, a rolling horizon framework is proposed to provide solutions with shorter computation time. Each of the 5 planning horizons considers the transport demand for 8 hours. By solving the problem based on a shorter planning horizon, the computation time is reduced, however, the number of delivered containers is considerably lower (although the difference in general remains under 10%).

4.7 Conclusions

This chapter focused on the integration of inter-terminal transport (ITT) within the port area and answered **Research question 3**, i.e., how to quantify and optimize the performance of different ITT system and railway hinterland transport strategies. With the proposed model, which could formulate the transshipment operations between different vehicles and the storage yard considering the handling capacity, we compared the ITT performance with different ITT network connections, hinterland train capacities and railway timetables. The results of the experiment indicate that more ITT connections and more flexibilities in the railway timetable will improve the performance of the container delivery. Moreover, smaller trains with higher frequency will increase the number of delivered containers if periodic railway timetable is used.

Chapter 5

Conclusion

This thesis has investigated the integrated modelling and optimization of the container transport inside the port area and to the hinterland. Multiple terminal types and two transport modes (rail and truck) were considered in the inter-terminal transport (ITT) system and railway transport is used to move the containers to the hinterland sentence is unclear. This chapter first presents the main scientific contributions and conclusions of this thesis and then points out directions for future research.

5.1 Main contributions and conclusions

In this thesis, we discussed the following problem: 'How to formulate and optimize the most critical operations at the interface between a railway network and a container port?' In order to identify the key elements that affect the container transport at that interface, we first reviewed the existing scientific research on ITT. Then we formulated and optimized the ITT system integrated with railway transport to the hinterland.

The three main contributions of this thesis are as follows:

- We reviewed the existing research of ITT planning problems aiming at identify the planning objectives, actor responsibility and methodology used in the ITT system planning. The results show that considerable effort has been put in ITT planning, including terminal layout design, ITT fleet configuration, vehicle dispatching, etc. It is also noteworthy that the responsibility and benefit division must be further clarified for the stakeholders involved and the integration between ITT and terminal operations requires further study to improve both the ITT, terminal operations and hinterland transport.
- We presented a mathematical model integrating container and vehicle movement in ITT and rail yard operation for hinterland rail transport. The ITT costs, such as vehicle traveling costs are considered integrated with railway hinterland transport cost. The hinterland train loading and departure operations were scheduled based on the ITT delivery. We also discussed the relationship between delays in ITT system and hinterland railway transport. A tabu search algorithm was developed to solve the problem based on realistic transport demand.
- We further developed the mathematical model to integrate ITT with both hinterland railway transport and terminal operations considering various vehicles types and terminal types. ITT connection, train capacity, railway timetable and other factors that could affect the hinterland delivery were discussed.

More specifically, the three main research questions posed in Chapter 1 are answered as follows:

1. What kind of ITT system is needed to improve the transport efficiency and how to reduce the ITT related costs in both constructions and operations?

Chapter 2 reviewed the scientific research of ITT planning. In the existing research, the configuration of ITT fleet and terminal layout which reduce the volume of ITT operations could be planned for the terminal operator and port authority. Meanwhile, coordinated operation plan can be scheduled for terminal cranes and ITT vehicle to reduce the equipment idle time and operation costs.

The literature review also indicates that several problems should be solved to improve the efficiency of the ITT system. Firstly, the multi-mode ITT system should be further studied in much greater detail. Apart from road transport, rail and also barge can also be used in the ITT

and the interaction between different transport modes should be further studied. Secondly, the division of the responsibilities, costs and benefits among the actors should be further clarified. Usually, it is assumed that a single ITT provider will plan and deliver containers for all terminals, however, the potential competitive relationship between the actors makes the fully cooperative planning often impossible or unreasonable. Therefore, different ITT networks and ITT providers should be taken into account, and the costs of coordination between actors should also be considered when planning the ITT system in strategic and tactical level.

2. How to formulate and optimize the connection between railway system and the ITT system?

In Chapter 3, we investigated how to formulate the ITT operations considering the hinterland railway system. A mathematical optimization model was built to integrate ITT transport with railway terminal operations (train loading and departure) and hinterland rail transport. In the model, hinterland trains could only depart on time when ITT system could deliver enough containers. Otherwise, the train will be delayed or canceled. With the model, we could improve the container delivery not only at terminals inside a port area, but also to the hinterland by trains.

The optimization results indicate that ITT should be planned integrated with hinterland operations as the ITT could affect the railway schedule and performance significantly: if we focus on ITT only, ITT delivery punctuality can be 17% better, but the cost associated with railway terminals increased enormously, by 93%. This is because some rail-oriented container's late delivery for railway terminal may cause train delays or cancellations, which results in much higher delay costs to the overall integrated system. Generally, the ITT system may connect multiple types of operations downstream. When the railway transport is considered, the late delivery in the ITT system could disturb the train loading plan or delay the departure of the train. Because the freight train usually follows a rigid timetable, the delay could be extended to the inland railway network and lead to extra rescheduling or capacity waste. Therefore, it is of great importance to integrate railway terminal operation with the connected ITT operations.

Moreover, given the complexity of the integrated system, approaches that could provide good solution in a reasonable computation time are needed to solve the planning problem. In the computational experiment, CPLEX can hardly handle the vehicle and container flow optimization for a simplified network (18 terminals) with a small transport demand (50 task, 69 TEU containers). Therefore, a tabu search algorithm capable of solving large-scale instances of the problem was proposed in Chapter 3. This algorithm could give results similar to those of CPLEX when solving small demand cases (e.g., around 50 TEUs per day) and handle large demand cases (e.g., more than 5000 TEUs per day).

3. How to quantify and optimize the performance of different ITT system and railway hinterland transport strategies?

In order to integrate the ITT, terminal operations and railway transport to the hinterland, Chapter 4 proposed an integer programming model. The model optimizes the movements of container and vehicles inside terminals, between terminals in the ITT network and from railway terminals to the hinterland. The model could formulate operations in different terminals, including maritime terminals with rail on-dock, maritime terminals with rail off-dock and railway terminals, and the movement of different vehicles, including ITT truck, ITT train and hinterland train.

Different strategies related to ITT and hinterland railway were evaluated. The results show that the complete ITT connection can improve the container delivery to the hinterland. In the complete ITT connection scenarios, all terminals are connected by the ITT network and containers can be moved between any terminals before leaving the port area. The improvements indicate that if the port authority can coordinate the operations among different terminals and provide more ITT access to each terminal, then the overall container delivery punctuality can be increased.

The experiment results also show that if railway terminals could have more choices on when the train departs to the hinterland, more containers can be delivered on time. Moreover, when using a periodic timetable, smaller trains with higher frequencies perform better than large trains with lower frequencies. Although smaller trains are more expensive, they also offer more flexibility and higher frequencies leading to a better performance in the model (although possibly at higher costs).

5.2 Recommendations for future research

This thesis discussed the planning problems related to the container transport inside the port area and from the port area to the hinterland by railway. However, this transport process is complex as multiple actors and operations are involved. Directions for further investigations are given as follows.

- **Coordination between actors**

Multiple actors such as terminal operators, freight forwarders and logistics providers are involved in the transport process. Certain agreements should be reached between them so containers, vehicles and information can be shared among them. Future research may further investigate how to share the cost for the cooperation and how to efficiently use the facilities from different actors.

For example, in order to reach a cooperation agreement in the ITT system, the actors involved must be aware of the costs for joining such a system and if they can be better off. Therefore, it is useful to develop a framework to estimate the benefit and cost for each actor in the shared ITT system.

- **Multi-mode transport system**

This thesis focuses on road and railway transport: trucks and trains are used in ITT and hinterland transport. For the future research, different types of vehicles, such as AGV and MTS, and other transport modes, such as inland waterway transport, could be considered in the system for both ITT and hinterland transport.

For the ITT system, road transport is still important because of its flexibility. Different types of road vehicles, such as AGV could be used to reduce the labor costs. However, reliable AVG and dispatching system is needed as the AGV may have conflicts with public traffic in the ITT network. Rail transport and waterway transport may also be used in ITT. Both trains and barges could provide considerable transport capacity. But the makespan of train and barge (un)loading is much higher than road vehicles. Therefore, a planning system is needed to schedule the handling operations in terminals and the routes of trains/barges.

For the hinterland transport system, railway and waterway transport are stimulated to take a larger share in the transport market. Research on loading planning of railway and waterway considering ITT could be interesting because most of the existing research focuses on the (un)loading operations in the single terminal. Moreover, an integrated scheduling system for road, railway and waterway transport could be significant for intermodal transport carrier.

- **Integration of the operations**

This thesis focuses on the transport from the port area to the hinterland and covers operations including (un)loading trucks and trains with crane, vehicle movement between terminals and trains departure to the hinterland. In a practical situation, both inbound and outbound containers should be considered, and operations such as stacking and inner-terminal transport should also be taken into account. Moreover, if the transport process involves more than one terminal, then, operations in multiple terminals can the transport between them should be also taken into account. That means a larger number of containers and operations must be handled. Besides, containers may have different priorities and restriction in the transport and handling process, which also should be considered in the future research.

- **Advanced decision support system**

When faced with a multi-mode transport system, or a system involves multiple operations and a large transport demand, an advanced system which could handle massive information exchange and computation is needed to provide decision support in the scheduling. In such a decision support system, real-time information about the transport demand and available vehicle must be collected, and then the system must be able to find good solution in a short computation time and give dispatching orders to relevant actors. It is notable that in such a system, having precise information might be hard because some situation is unpredictable, such as the breakdown of equipment. Therefore, robust schedule and powerful algorithm should be developed to help in decision making.

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Glossary

List of symbols and notations

Bellow follows a list of the most frequently used symbols and notations in this thesis.

A	Set of arcs in the time-space graph
A^{mov}	The set of moving arcs
A^{sta}	Set of stationary arcs
$ArcCap_{i,j}$	The handling capacity on arc (i, j)
c^{Rail}	The cost for railway transport from terminal to hinterland
c^{Road}	The cost for road transport from terminal to hinterland
$c^{traverse}$	Travelling cost of vehicles in ITT network
d_{θ}	Destination node of task θ
D_{φ}	The transport distance between railway terminals and destination in the hinterland of train φ
Dem_{θ}	Number of containers in task θ
$f_{i,j}$	Traverse time of arc (i, j)
H_{φ}	Capacity of a hinterland train φ
$l_{t,\varphi}$	The number of containers loaded on the train $\varphi \in V^{TrainHin}$
$N^{dropoff}$	The set of drop off nodes
N^{pickup}	The set of pick up nodes
N^{ter}	The set of terminal nodes
o_v	The origin node of vehicle v

o_θ	Origin node of task θ
P_φ	Planned departure time of train φ when delay is allowed
r_θ	Release time of task θ
S	Capacity of intersection
T	The set of time steps
U	Carrying capacity of ITT vehicles
u_θ	Due time of task θ
$V^{TrainITT}$	The set of ITT trains
$V^{TrainHin}$	The set of hinterland trains
$V^{TruckITT}$	The set of ITT trucks
$VehCap_v$	Capacity of vehicle v
$w_{i,\varphi,t}$	Binary variable, $w_{i,\varphi,t} = 1$ if the train φ departs from terminal i at time t ; otherwise $w_{i,\varphi,t} = 0$
Win_v	The time slot for train v when no delay is allowed
$x_{i,j,t}$	The number of ITT vehicles travelling on arc (i, j) at time t
$x_{i,j,t,v}$	The number of v type of vehicle travelling on arc (i, j) at time t
$y_{i,j,t,\theta}$	The number of containers for task θ delivered on ITT arc (i, j) at time t
$y_{i,j,t,\varphi}$	The number of containers delivered by train φ on ITT arc (i, j) at time t
β	Penalty coefficient for the trains not fully loaded
Θ	Set of container transport tasks

η	The minimal loading rate
δ	Value of time for one container
Δ	Longest delay time of trains

List of abbreviations

The following abbreviations are used in this thesis:

AGV	Automated Guided Vehicle
ALV	Automated Lift Vehicle
ITT	Inter-terminal Transport
MIP	Mix Integer Programming
MTR	Martime Termianl with Road Connection and Rail off-dock
MTRR	Maritime Terminal with both Road and on-dock Railway Connections
MTS	Multi-trailer System
RMGC	Rail Mounted Gantry Crane
RTGC	Rubber Tyred Gantry Crane
RTR	Railway Terminal with Road Connection
TEU	Twenty-foot Equivanlent Unit
VRP	Vehicle Routing Problem
VRPPD	Vehicle Routing Proble with Pickup and Delivery

Samenvatting

De groei van het containervervoer en de steeds groter wordende containerhavens verhogen niet alleen de complexiteit van de terminal operators, maar leiden ook tot een hogere transportvraag van de haven naar het achterland. Meerdere modaliteiten, zoals weg, spoor en binnenvaart worden gebruikt om de operationele efficiëntie te verbeteren en de kosten te verlagen. Dientengevolge moeten containers geregeld het interterminal transport (ITT) systeem gebruiken. Dit systeem transporteert de containers tussen de terminals, de servicecentra (bijv. depots en magazijnen) en de achterland modaliteiten, alvorens de containers het havengebied kunnen verlaten. De organisatie van het ITT-systeem heeft een aanzienlijke invloed op de connectie tussen de haventerminals en het achterlandtransport. Dit proefschrift onderzoekt een ITT-systeem dat is geïntegreerd met het achterlandvervoer per spoor met als doel het container afleveringsproces zowel binnen het havengebied als naar het achterland te verbeteren.

In het bestudeerde systeem moeten de twee onderling verbonden subsystemen, d.w.z. het ITT-systeem en het achterlandspoorwegsysteem, op een geïntegreerde manier worden geformuleerd en geanalyseerd. Daarom zijn er mathematische modellen ontwikkeld, die het ITT-systeem, het achterlandspoorwegsysteem en de connectie daartussen formuleren. Met de voorgestelde modellen kunnen sleuteloperaties in zowel het ITT-systeem als het achterlandspoorwegsysteem (zoals container (in) laden, voertuigbeweging, laden en vertrek van de achterlandtrein) worden geformuleerd en geoptimaliseerd. Verschillende factoren, zoals bijvoorbeeld ITT-netwerk, ITT-voertuigen en verschillende operationele strategieën (de verdragings-tijd en beladingsgraad van het spoorwegsysteem) worden geanalyseerd.

Er worden experimenten uitgevoerd om inzicht te verkrijgen in de prestaties van de verschillende subsystemen en de interactie daartussen. De resultaten van de experimenten kunnen de beslisser(s) helpen bij het verbeteren van de aflevering van de containers. Allereerst worden manieren onderzocht om de ITT-systeemprestaties te verbeteren. De experimenten geven aan dat, als de grootte van de ITT-vloot is bepaald en gefixeerd, de reductie van de lege transporten, de totale reistijd van de ITT-voertuigen zal verminderen en dus de ITT-systeem prestatie zal verbeteren. Dit betekent dat het verminderen van de lege verplaatsingen een efficiënte manier is om de ITT-systeem prestatie te verbeteren wanneer de grootte van de vloot is gefixeerd. De ITT-systeem prestatie wordt ook beïnvloed door de wachttijd bij de ITT-systeemkruisingen en door het aantal gebruikte voertuigen en het aantal te verplaatsen containers. Ten tweede testen we ook de mogelijkheden om de spoorprestaties te verbeteren: als een flexibeler planning van de dienstregeling mogelijk zou zijn, d.w.z. terminals hebben meer

keuzes wanneer de treinen vertrekken en kunnen daardoor meer containers op tijd afleveren. Bij gebruik van een gefixeerde dienstregeling presteren kleinere treinen met hogere frequentie beter dan grote treinen met lage frequentie. Hoewel kleinere treinen duurder zijn, bieden ze ook meer flexibiliteit en hogere frequenties, wat leidt tot betere prestaties in het model (hoewel mogelijk tegen hogere kosten). Ten derde wordt de relatie tussen het ITT-systeem en het achterlandsspoorwegvervoer besproken. De resultaten van de experimenten tonen aan dat de optimalisatie van het ITT-systeem zonder rekening te houden met de dienstregeling van het spoor naar het achterland ernstige vertragingen en annuleringen in het goederenspoorsysteem kan veroorzaken.

Om een goede oplossing voor de voorgestelde modellen te bieden, worden heuristische algoritmen en de rolling horizon-benadering ontwikkeld. Er is een Tabu-zoekalgoritme ontwikkeld en getest met verschillende Tabu-zoekcomponenten (initiële oplossing, structuur van de zoekgebieden, Tabu-lijst, zoekstrategie, verplaatsingsevaluatie) en met verschillende vraag scenario's en daarmee werd de beste configuratie gevonden.

Daarnaast gebruiken we ook CPLEX en een lokaal zoekalgoritme om het model te valideren en de prestaties van de Tabu-zoekfunctie te testen. Bovendien wordt een rollende horizonaanpak gehanteerd om het planningsprobleem te verdelen in verschillende iteraties met kortere planninghorizons. Met de voorgestelde voortschrijdende horizonprocedure wordt de berekeningstijd verkort en kan het model worden gebruikt in de dynamische planning van het totale geïntegreerde systeem.

Concluderend: dit proefschrift gaat in op de connectie tussen containerterminals en het achterland-spoorwegsysteem. Er worden wiskundige modellen voorgesteld om de verschillende relevante operaties te formuleren en methoden worden ontwikkeld om oplossingen te bieden voor de verbetering van de systeem performance. Dit proefschrift kan suggesties geven aan de beslisser(s) met betrekking tot de verbetering in zowel het ITT-systeem als het achterland-spoorwegsysteem en de integratie van beiden (d.w.z. het aantal containers dat op tijd wordt geleverd met lagere kosten kan worden verhoogd).

Summary

The growth of containerized transport and the ever-larger container ports not only increase the complexity in terminal operations, but also lead to a higher transport demand from the port to the hinterland. To handle the demand with high efficiency and low cost, multiple modalities, such as road, rail and waterway, have been used. As a result, containers usually need to enter the inter-terminal transport (ITT) system, which moves containers between terminal, modalities and service centers (e.g., depots and warehouses), before leaving the port area. The organization of ITT system considerably affects the connection between port terminals and the hinterland transport. This thesis investigates an ITT system integrated with railway hinterland transport aiming at improving the container delivery process both inside the port area and to the hinterland.

In the studied system, the two inter-connected sub-systems, i.e., ITT system and hinterland railway system, should be formulated and analyzed in an integrated way. Therefore, mathematical models, which could formulate the ITT system, hinterland railway system and the connection between them, are proposed in this thesis. With the proposed models, key operations in both ITT system and hinterland railway system, such as container (un)loading, vehicle movement, hinterland train loading and departure, could be formulated and optimized. Different factors, e.g., ITT network, ITT vehicles, and different operational strategies (delay time allowed and loading rate for trains), are analyzed.

Experiments are conducted to provide insights into the performance of different sub-systems and the interaction between them. The results of the experiments could help the decision maker(s) improve the container delivery. Firstly, ways to improve the ITT system performance are investigated. The experiments indicate that if the ITT fleet size is fixed, the reduction of the empty movement will reduce the total travel time of the ITT vehicles and thus improve the ITT system performance. This means reducing the empty movement is an efficient way to improve the ITT performance when fleet size is fixed. The ITT system is also influenced by the intersection waiting time; the waiting time will increase with the number of vehicles used and the number of containers to be moved. Secondly, we also test the possibilities to improve the railway performance: if a more flexible railway timetable is possible, i.e., terminals could have more choices on when the train departs, more containers can be delivered on time. When using a periodic timetable, smaller trains with higher frequency perform better than large trains with low frequency. Although smaller trains are more expensive, they offer more flexibility and higher frequencies leading to a better performance in the model. Thirdly, the relation between ITT system and hinterland railway transport is discussed. The experiment results

show that the ITT system optimization without considering the railway timetable to the hinterland may cause serious delays and cancellations in the railway system.

In order to provide good solution to the proposed models, heuristic algorithms and a rolling horizon approach are developed. A tabu search algorithm is developed and the tabu search components, including initial solution, neighborhood structure, tabu list, search strategy and move evaluation were tested with all demand cases and the best configuration was found. Besides, we also use CPLEX and a local search algorithm to validate the model and to test the performance of the tabu search. Moreover, a rolling horizon approach is proposed to decompose the planning problem into several iterations with shorter planning horizons. With the proposed rolling horizon procedure, the computation time is reduced and the model can be further in dynamic planning for the system.

To conclude, this thesis discusses the connection between container terminals and the hinterland railway system. Mathematical models are proposed to formulate the various relevant operations and methods are developed to provide solutions to improve the system performance. This thesis could provide suggestions to decision maker(s) regarding to the improvement in both ITT system and the hinterland railway system, i.e., increasing the number of containers delivered on time with lower costs.

Curriculum vitae

Qu Hu was born on July 18, 1989 in Laohekou, China. He obtained his B.S. degree on Transportation in 2011 and the M.Sc degree on Transportation Planning and Management in 2014, both from Southwest Jiaotong University in Chengdu, China.

In September 2014, he started his Ph.D. research, which is sponsored by China Scholarship Council, in Delft University of Technology. He has been working at the Department of Maritime and Transport Technology and Department of Transport and Planning. His Ph.D. project focuses on the optimization of the interface between container ports and the railway network. His research interests include operations research and its applications in the optimization of the transport system.

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