Delft University of Technology

FACULTY OF MECHANICAL, MARITIME AND MATERIALS ENGINEERING
Department of Marine and Transport Technology

ERASMUS SCHOOL OF ECONOMICS
Econometric Institute

EUROPE CONTAINER TERMINALS B.V.
European gateway services

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Transport Engineering and Logistics (TU Delft)
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Planning of hinterland transportation in the EGS network

B. van Riessen

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Title (in Dutch): Planning van achterlandtransport in het EGS netwerk

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Description of the assignment

Student:	B. van Riessen	Assignment type:	Master thesis
Supervisor (TUDelft):	dr R.R. Negenborn	Credits (ECTS):	36 (TU Delft) + 20 (EUR)
Supervisor (EUR):	prof dr ir R. Dekker	Specialization:	TEL
Supervisors (ECT)	Mr A. van Rijn	Report number:	2013.TEL.7743
	Mr R.Th. van Barneveld	Confidential:	No

Subject: The requirements for synchromodal planning in European Gateway Services

European Gateway Services (EGS) is a product of Europe Container Terminals (ECT) in Rotterdam, the largest deep-sea terminal operator in Europe. In the port of Rotterdam, three ECT container terminals are operated: the ECT Delta Terminal and the Euromax Terminal Rotterdam at the Maasvlakte and the ECT City Terminal in the Eemhaven area, close to the city. Through European Gateway Services, ECT offers shipping lines, forwarders, transport companies and shippers a variety of services to facilitate the optimal flow of containers between the deep-sea terminals in Rotterdam and the direct European hinterland. Based on TNO's roadmap to synchromodality, a synchromodality pilot study has been carried out between Rotterdam, Moerdijk and Tilburg, which showed promising results. The assignment is to research the requirements for synchromodal planning in the EGS network. The requirements of the network to allow synchromodal planning must be determined. The relevant disturbances that influence a synchromodal planning must be identified. Bart van Riessen will carry out the project to graduate on two master programs:

- A specialization of econometrics: Operations Research and Quantitative Logistics (Erasmus University. Supervision by prof.dr.ir. R. Dekker
- A specialization of mechanical engineering: Transportation Engineering & Logistics (TU Delft), prof.dr.ir. G. Lodewijks. Supervision by dr. R.R. Negenborn

ECT will facilitate the graduation project. Supervision by Mr A van Rijn and Mr R.Th. van Barneveld.

The supervisor, the professors,

Dr R.R. Negenborn (TU Delft) Prof G. Lodewijks (TU Delft) Prof R. Dekker (EUR)

Preface

This thesis has been achieved thanks to the outstanding cooperation of all supervisors involved. I want to express my gratitude to all of them for their involvement and understanding of the project at hand: a combined graduation for two Master specializations at two universities. These two Masters are Transportation Engineering and Logistics at the Delft University of Technology (TU Delft) and Operations Research and Quantitative Logistics at the Erasmus University Rotterdam (EUR). The thesis will be reviewed, defended and judged separately for each of these Master studies.

For the graduation at the TU Delft, the committee consists of prof dr ir G. Lodewijks (the professor), dr R.R. Negenborn (supervisor), ir R. Hekkenberg (co-reader), all with the TU Delft, and prof dr ir R Dekker, with the EUR (co-reader). The external supervisors A. van Rijn and R.Th van Barneveld (ECT) are invited as advisors of the committee. The main point of attention for this committee will be Part II of the research, involving the operational network planning. Note that both parts are strongly interconnected and cannot be reviewed separately.

For the graduation at the EUR, the committee consists of prof dr ir R. Dekker (the professor), dr. R.R. Negenborn (as co-reader). The external supervisors A. van Rijn and R.Th van Barneveld are again invited as advisors of the committee. The main point of attention for this committee will be Part I of the research, involving the tactical service network design. Note that both parts are strongly interconnected and cannot be reviewed separately.

The research for this thesis has been carried out during an internship facilitated by EUROPE CONTAINER TERMINALS (ECT). ECT has provided a workplace at the planning department of the subsidiary EUROPEAN GATEWAY SERVICES (EGS). The colleagues at EGS delivered all transportation data used in the report and they helped with practical advice on all subjects of container transportation. The report will refer to three categories of the colleagues as a source for specific information about the EGS container network and working procedures. First of all, the people at the Business Development department delivered detailed information on the current and future cost structure of the EGS network, as well as data on the historic transportation on the network. At the planning department, the network planners provided information on their planning procedures, also in case of disturbances. The operational planning manager helped with estimates of data that was not available. I want to thank them for their help and support throughout the research and writing of this thesis.

Abstract

Keywords *Intermodal planning, synchromodal planning, network optimization, container transportation*

An intermodal container transportation network is being developed between Rotterdam and several inland terminals in North West Europe: the EUROPEAN GATEWAY SERVICES network. To use this network cost-efficiently, a more integrated planning of the container transportation is required. The most relevant aspects of such a planning are identified with a new model. This model introduces three new features to the intermodal network planning problem. Firstly, a combination of a path-based formulation with a minimum flow network formulation is used. Secondly, overdue deliveries are penalized instead of prohibited. Thirdly, the model combines self-operated and subcontracted services.

Two versions of the model are applied at two different levels. At a tactical level, the optimal service schedule between the network terminals is determined, considering barge or rail modes and both operation types. The most influential costs in this problem are determined. Another version of the model is applied at an operational level. With this model the impact of a disturbed service is determined, by comparing the undisturbed planning with the best possible update after the disturbance. Also the difference between an optimal update and a usual local update is measured, defined as the relevance.

It is shown that each of the models is suitable for solving the problems. Properties that indicate a disturbance with a high impact or relevance are identified. Points of attention for the manual planning are recommended and a focus for automated planning is proposed.

Summary

An intermodal container transportation network is being developed between Rotterdam and several inland terminals in North West Europe. This EUROPEAN GATEWAY SERVICES (EGS) network enables an integrated network transport between 7 inland terminals and 3 Rotterdam seaports. To use this network cost-efficiently, a more integrated planning of the container transportation is required. The most relevant aspects of such a planning are identified with a new model. This model introduces three new features to the intermodal network planning problem. First, the model combines two formulations for a multi-commodity network: a minimum cost network flow problem and a path-based network design formulation. Secondly, the model allows for overdue delivery at a penalty cost. In this way the practical flexibility of negotiating delivery times with customers is more closely represented than the use of strict delivery time restrictions. Thirdly, the model combines two types of operation: both self-operated services, operated by the network company as subcontracted services, operated by partners are used. The model distinguishes between rail and barge services and the use of truck when necessary.

The model is applied at two different levels. At a tactical level, the optimal service frequencies between the network terminals is determined, considering barge or rail modes and both operation types (self-operated and subcontracted). This is called the service network design. The model is used to determine the optimal service frequencies between the terminals in the EGS network. The most influential aspects for the costs of this service network design are determined. The results of the experiments at the tactical level show that the costs for transferring have a strong impact on the amount of containers that are transported with intermediate transfers. An increase in intermediate transfers can lower the costs for transportation significantly.

The results are used as a basis for an adapted model at an operational level. With this model the impact of a disturbed service is determined, by comparing the undisturbed planning with a full planning update after the disturbance. This impact can be seen as a measure for the gravity of a disturbance: a high impact means that a disturbance comes at high costs, even if handled in the best possible way. Hence, a high impact indicates disturbances that must be prevented. A second measure is the difference between an optimal (full) update and a local update, defined as the relevance. The local update represents the current practice of the manual planners. A high relevance indicates a disturbance that can be solved in a much more cost-efficient way by updating the existing planning fully, compared to only updating directly disturbed containers. The model is used for the same EGS case that was used at the tactical level. The impact and relevance of early departure, late departure and cancellation of services in the network are determined. The results show that service cancellations have the largest impact. Apart from that, early departure of a barge has a high impact as well. Indicators of disturbances that have a high relevance and should be solved with a full update are the

following: the disturbed service is a barge, is self-operated and/or operates on a corridor with a high frequency of alternative services.

The study shows that the new model is suitable for solving the problem at both the tactical and operational level. Points of attention for the manual planning are recommended and a focus for automated planning is proposed.

Samenvatting (summary in Dutch)

Tussen Rotterdam en verschillende achterlandterminals in Noordwest Europa wordt een intermodaal containertransportnetwerk ontwikkeld. Dit netwerk van EUROPEAN GATEWAY SERVICES (EGS) maakt geïntegreerd transport tussen drie zeehavens en 7 achterlandterminals mogelijk. Om dit netwerktransport kostenefficiënt uit te voeren is een meer geïntegreerde planning van het containertransport noodzakelijk. De meest relevante aspecten van zo'n planning worden geïdentificeerd met een nieuw model. Dit model introduceert drie nieuwe eigenschappen ten opzichte van bestaande formuleringen voor intermodale netwerkplanning. Ten eerste combineert het model twee type formuleringen voor netwerken met meerdere vrachttypes: het netwerkstroomprobleem met minimale kosten en het netwerkmodel gebaseerd op paden. Ten tweede staat het model te late levering toe ten koste van een boete. Op deze manier wordt de flexibiliteit uit de praktijk, waarbij planners met klanten onderhandelen over precieze aflevering, beter gemodelleerd dan met strikte tijdsrestricties. Ten derde combineert het model twee soorten diensten: er worden zowel netwerkdiensten, uitgevoerd door de netwerkbeheerder, als uitbestede transporten, uitgevoerd door partners, gebruikt. Het model maakt onderscheid tussen trein- en lichterdiensten en het gebruik van vrachtwagens waar nodig.

Het model wordt toegepast op twee niveaus. Op een tactisch niveau worden de optimale dienstenfrequenties bepaald, rekening houdend met de modaliteiten lichter en trein, uitgevoerd door het netwerk of uitbesteed aan partners. Dit wordt het ontwerp van het dienstennetwerk genoemd. Het model wordt gebruikt om de optimale frequentie van diensten tussen de netwerkterminals van EGS te bepalen. De aspecten die de meeste invloed hebben op de kosten van het dienstennetwerk worden bepaald. De resultaten van de experimenten op dit tactische niveau laten zien dat de kosten voor de overslag een grote impact hebben op het aantal containers dat onderweg een of meer keer wordt overgeslagen. Een groter aantal van deze tussentijdse overslagbewegingen kan de kosten van het netwerktransport significant verlagen.

De resulterende frequenties worden gebruikt als basis voor een aangepast model op operationeel niveau. Met dit model wordt de impact van een verstoorde dienst bepaald, door de planning zonder verstoringen te vergelijken met een volledige update van de planning na de verstoring. Deze impact kan worden gezien als een maat voor de ernst van de verstoring: een hoge impact betekent dat de verstoring hoge kosten met zich meebrengt, zelfs als er op de best mogelijke manier mee omgegaan

wordt. Verstoringen met een hoge impact moeten dus worden voorkomen. Een tweede maat is het verschil tussen een volledige update en een lokale update van de planning, gedefinieerd als de relevantie. De lokale update vertegenwoordigt de huidige praktijk van de handmatige planners. Een hoge relevantie geeft een verstoring aan die tegen veel lagere kosten kan worden opgelost door de gehele planning te herzien, vergeleken met het alleen updaten van direct verstoorde containers in de planning. Dit model wordt gebruikt voor dezelfde EGS situatie als in het tactische model. De impact en relevantie van het vroeg vertrekken, laat vertrekken of uitvallen van diensten in het netwerk worden bepaald. De resultaten laten zien dat het uitvallen van een dienst de grootste impact heeft. Los daarvan heeft het te vroeg vertrekken van een lichter een grote impact. De volgende indicatoren geven een verstoring aan met een hoge relevantie die met een volledig herziene planning zouden moeten worden opgelost: de verstoorde dienst is een lichter, de verstoorde dienst wordt uitgevoerd door het netwerk zelf en/of de dienst reist op een corridor met een hoge frequentie aan alternatieve diensten.

Het onderzoek laat zien dat het nieuwe model geschikt is voor het oplossen van het planningsprobleem op zowel tactisch als operationeel niveau. Er worden aanbevelingen voor de handmatige planning gedaan en er wordt een focus voor geautomatiseerde planning voorgesteld.

List of abbreviations

ATA	*Actual Time of Arrival*
ATD	*Actual Time of Departure*
ECT	*Europe Container Terminals*
EGS	*European Gateway Services*
ETA	*Expected Time of Arrival*
ETD	*Expected Time of Departure*
EU	*European Union*
EUA	*EU emission allowance*
EU ETS	*EU Emission Trading System*
HLP	*Hub location problem*
HPH	*Hutchison Port Holdings*
MCNF	*Minimum cost network flow problem*
MIP	*Mixed-integer programming*
MRE	*Mean relative error*
KPI	*key performance indicator*
PBND	*Path-based network design model*
SND	*Service network design*
TEU	*Twenty feet equivalent unit*

CONTENTS

Chapter 1. Introduction

This chapter will introduce this study into planning of intermodal container transportation. First, a general introduction of the environment of the studied network is presented in Section 1.1. Section 1.2 describes the case of container transportation in the EGS network. Section 1.3 sets the problem statement that motivates the research, this is translated into research questions in Section 1.4. The research approach to answer these questions is introduced in Section 1.5 and finally, Section 1.6 will describe the structure of the remainder of the report.

1.1 General introduction

EUROPEAN GATEWAY SERVICES (EGS) is a subsidiary company of EUROPE CONTAINER TERMINALS (ECT) in Rotterdam, the largest deep-sea terminal operator in Europe. In the port of Rotterdam, ECT operates three container terminals: the DELTA TERMINAL and the EUROMAX TERMINAL ROTTERDAM at the Maasvlakte and the CITY TERMINAL in the Eemhaven area, close to the city centre of Rotterdam. Through its subsidiary EUROPEAN GATEWAY SERVICES, ECT offers shipping lines, forwarders, transport companies and shippers a variety of services to facilitate the optimal flow of containers between the deep-sea terminals in Rotterdam and the European hinterland (see Figure 1).

Figure 1 Schematic overview of the EGS network [source: EGS]

The EUROPEAN GATEWAY SERVICES (EGS) provides extended gate services for customers of the ECT terminals. It comprises a *tri-modal container transportation* network between three Rotterdam sea terminals and extended gates in the Netherlands, Belgium and Germany (hinterland terminals in Duisburg, Nuremberg, Neuss, Dortmund, Moerdijk, Venlo and Willebroek). A tri-modal network is a network with three modes, in this case barge, rail and truck connections. The network makes the transportation of containers more efficient and more sustainable, by bundling them in rail and barge transport when possible. Also, with transportation over the EGS network, in some cases custom formalities can be postponed to the extended gates, allowing quicker delivery.

Several projects are investigating the business opportunities and possibilities for cooperation in this network, currently. The ECT aims for a *synchromodal* container transportation network, within DINALOG's ULTIMATE project and the SYNCHRO-pilot Rotterdam-Tilburg (Topsector-logistiek 2011; Lucassen and Dogger 2012).

The phrase *intermodal transportation* refers to transportation of containers in a chain of different modes. *Synchromodal container transportation* is an extension of intermodal transportation. It refers to transportation over an intermodal network, but with dynamic adaptation of the planning when information about changes and disturbances becomes available. In the case of EGS, the transportation will be planned jointly for the network (Topsector-logistiek 2011; Lucassen and Dogger 2012). Although the definition of synchromodality is not yet fully established, in this research it will be used to refer to an *intermodal transportation network with online planning*, able to adapt in real-time to meet delivery requirements. With online planning is meant that the planned transportation can be adapted during the process in the case of changes.

To be able to operate transportation in a synchromodal way, information sharing between stakeholders is essential. Then, using all information available, the container transport planning must be created and updated. This planning method must be able to solve the integral problem of transporting containers in the tri-modal EGS network and use information about disturbances to update the planning. This can be done manually or by using software planning tools. To determine the benefit of planning automation, *the aim of this research is to find the relevant aspects of a synchromodal planning method in the EGS network*. Simultaneously, a pilot is carried out at ECT with the PARIS TMS planning software, already used in other ports of the HUTCHISON PORT HOLDINGS PLC. This goal is more extensively described in Section 1.3. The findings of the research into the planning method will be of use for the actual planning department of the EGS-network.

In the remainder of this chapter the case of EGS will be described in more detail. Definitions about container transportation are introduced and the problem statement, research questions and approach are introduced.

1.2 Case description

This research into the online intermodal planning in container transportation networks takes place in the framework of EGS. The transportation network of EGS connects the ECT seaport terminals in Rotterdam to several hinterland terminals by barge and rail.

First, in Section 1.2.1 some terminology on container transportation is introduced. Then, the current situation and the vision of the future of EGS are described in Section 1.2.2, is shortly introduced. Finally, Section 1.2.3 summarizes the subjects of this study and describes the scope of this study.

1.2.1 Transportation of containers

Container transportation plays a major role in the current global supply chains. In 1950, the standardized ISO container was introduced. Some variation exists, but a reference container measures 8′ (feet) wide, 8′6″ high and 20′ long and is simply called a 20′ container. Other regular standard containers have a length of 40′ or 45′. An alternative height is 9′6″ (ISO-668 1984). Throughput is measured in equivalence of such a 20′ container, a twenty feet equivalent unit (TEU). Global throughput has grown from 40 million TEU in 1980 to more than 500 million TEU in 2008 (Dewry-Shipping-Consultants 2008). In the Rotterdam port, the throughput in the same period grew from 1.9 million TEU to 10.7 million TEU (Port-of-Rotterdam 2011-3). Container transportation will continue to grow in the coming decades. According to the port authority's throughput forecasts for Rotterdam, container transportation is expected to grow from 135 million tons per year in 2010 to 310 million tons per year in 2030 (Port-of-Rotterdam 2011-1). Meanwhile, container transportation formed 8% of the total throughput in the Rotterdam port in 1980, currently 25% (2010), in 2030 this will grow up to 42% (Port-of-Rotterdam 2011-1; Port-of-Rotterdam 2011-3).

Dimensions, loads, mass and corner fittings for lifting containers are standardized, enabling easy worldwide transportation with several modes. A mode denotes the means of transportation, such as barge, train, truck or deep-sea ship. In Figure 2, a schematic overview of a container transport is shown to clarify the terminology used in this report.

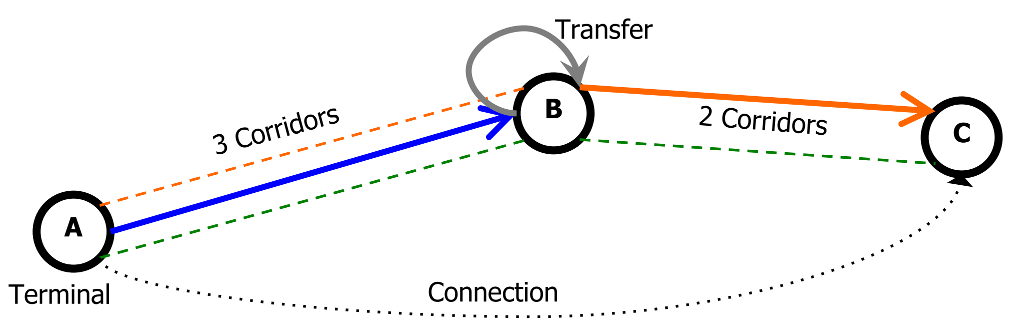

Figure 2 Container transport (schematic)

The figure shows three *terminals*. At terminals, containers can be exchanged from one mode to another. In scientific literature, transhipment is used for all types of exchange. However, to prevent confusion with the common practice in the Rotterdam port, the following definitions are used throughout this report. An exchange at a terminal is called *transhipment* if the container is exchanged from one ship to another and *transfer* if other modes are involved. The figure shows five mode-specific *corridors* by which the terminals are directly connected. As multiple modes connect two terminals, multiple corridors exist. Terminal A and C are indirectly connected via terminal B, and transport is possible using the corridors to B and then to C. The figure shows the blue barge corridor A-B and red train corridor B-C. Each of these transport steps is called a *leg*. This is referred to as a *connection* between A and C. The *service* on a corridor between terminals is the movement of a vehicle from one terminal to another, following a specific *route*. The number of services per time period on a certain route is called the *service frequency*. EGS uses frequency to denote the number of services per week on a corridor. The specific path of a container, including the terminals and services used, is called an *itinerary* (Crainic and Kim 2007) or a *path*.

In this study the term *intermodal transfer* is used for a transfer between barge or rail services. A container that has an itinerary with two services (barge or rail) uses such an intermodal transfer. Throughout this report, a transfer within the network is considered an *intermediate transfer*. In the case of synchromodal planning as introduced in Section 1.1, the planning is updated in real-time. When a container is scheduled on a different service than in the initial planning, this is called *switching*. Lucassen (Lucassen and Dogger 2012) defines *switching* as having the opportunity to change to the best transport modality at any time to optimize network utilization and fulfil transport demand. Switching can be seen as the implementation of online planning in the intermodal network. Switching can occur in three ways:

- A service on the same corridor is selected, e.g. the next one
- A different mode is selected on the same connection
- An alternative connection (using an alternative terminal) is selected

From a network theory perspective, terminals are considered as *nodes*, and the corridors between terminals are considered as *links*. If a link operates only in one direction, the corridor is an *arc*. An arc is a directed link.

This report focuses on the transportation from the seaport terminal to a hinterland terminal (import) or vice versa (export). This is called *hinterland transportation*. Hinterland transportation can take place under various regimes. Under *merchant haulage*, transportation takes place under the responsibility of a merchant, who takes control of the transport of the various legs of the transport. Under *carrier haulage*, the deep-sea carrier organises the hinterland transport (often contracted to third parties) (Veenstra, Zuidwijk et al. 2012).

1.2.2 Description of the EGS network

The EUROPEAN GATEWAY SERVICES (EGS) provides extended gate services for customers that import or export containers via the ECT seaports. It comprises a tri-modal container transportation network between three Rotterdam sea terminals and extended gates in the Netherlands, Belgium and Germany. The network makes the transportation of containers more efficient and more sustainable, by bundling them in rail and barge transport when possible. The EGS network has been operational since 2007, but is continuously being extended (Veenstra, Zuidwijk et al. 2012). In the next years, ECT plans on expanding the network with more inland destinations and connections.

The current network (February 2013) has corridors between three Rotterdam seaport terminals and around 20 hinterland terminals. In this study, the situation of June 2012 is studied, with three seaports and 7 hinterland terminals. The network consists of a set of point-point connections that have no reciprocal operational influence. Truck transport is hardly considered and is only used in case of urgency, currently. Transportation within the EGS network occurs in two different ways: EGS either books containers on existing connections (subcontracted transport) or EGS is (co-)operator of services on a corridor (self-operated transport). In the former case, costs are calculated per container, whereas in the latter case EGS carries (partial) responsibility for the entire set of available slots on a service. The inland terminals function as extended gates for the Rotterdam seaport. For some of the connections, transportation to the hinterland is possible without customs documents. Only at the extended gate, the customs documents are required.

EGS distinguishes carrier and merchant haulage. These are defined as follows:

1. Merchant haulage: EGS performs transport between a hinterland terminal and the seaport.
2. Carrier haulage: EGS carries out transport between the seaport and a hinterland location (such as a distribution centre). This includes the *last leg*, the transport between hinterland location and hinterland terminal (or vice versa).

A customer may or may not impose requirements on the means of transportation. This results in the following type of bookings:

a. Specified transports
b. Mode-free (any route to MOERDIJK CONTAINER TERMINALS (MCT) before Thursday 3PM)

The EGS network cannot yet accomplish synchromodal transportation for two reasons. Currently, most shippers book containers on specified transports: on specified modes (a barge to DELTA before Thursday 3PM) or – even stricter – on specified services (e.g. Tuesday's 10AM barge from DELTA to MCT). Secondly, corridors between inland terminals are not yet used. Hence, a joint planning for the network is not yet possible. From a logistic point of view, EGS does not have the properties of a network yet. However, the future network vision of EGS comprises the following developments:

- Mode-free booking from and to destinations in the network area
- Joint network optimization
- Corridors between hinterland terminals: *land corridors* or *cross-connections*
- Truck transportation for more flexible planning

The possibility of using land corridors is shown in the network map in Figure 3. For instance, if the rail and barge connections to Duisburg are fully booked, an urgent container transport from Rotterdam to Duisburg could be sent by truck. A cheaper possibility would be to use another rail or barge connection to Venlo, and use a much shorter leg of truck transportation from there. In this case, the rail transport to Venlo has almost no additional costs for EGS as the train to Venlo is operated by EGS – provided that capacity on this train is available.

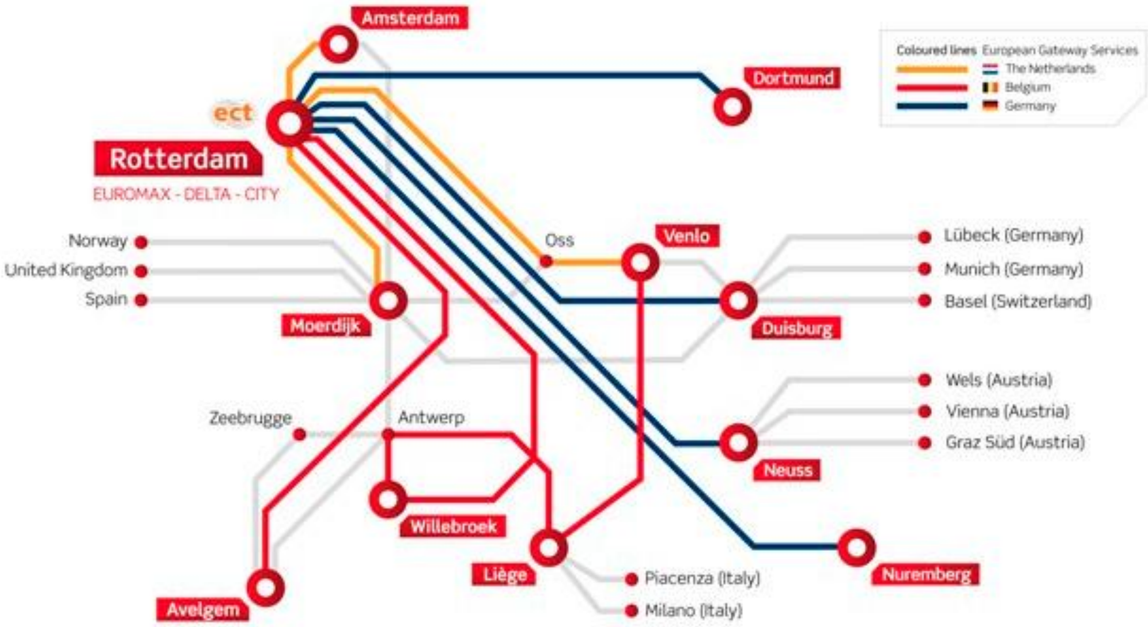

Figure 3 EGS network map including land corridors [source: EGS]

A pilot of the synchromodal network vision has been carried out already. Since December 14th 2011, EGS and several partners carried out synchromodal transportation in a pilot between Rotterdam, Moerdijk and Tilburg (not part of the EGS network). During this pilot, transportation was possible using five different connections (see Figure 4). Shippers that participated in the pilot booked mode-free, such that the network could select the best modes for each container, with respect to network utilization and delivery time. The processes and results are described by Lucassen (TNO) (Lucassen and Dogger 2012). Switching, the changing of the planning in real-time, was not applied in the pilot between Rotterdam, Moerdijk and Tilburg and is not applied in the EGS network, currently, due to operational limitations. The next section describes the research of this study into land corridors and real-time switching.

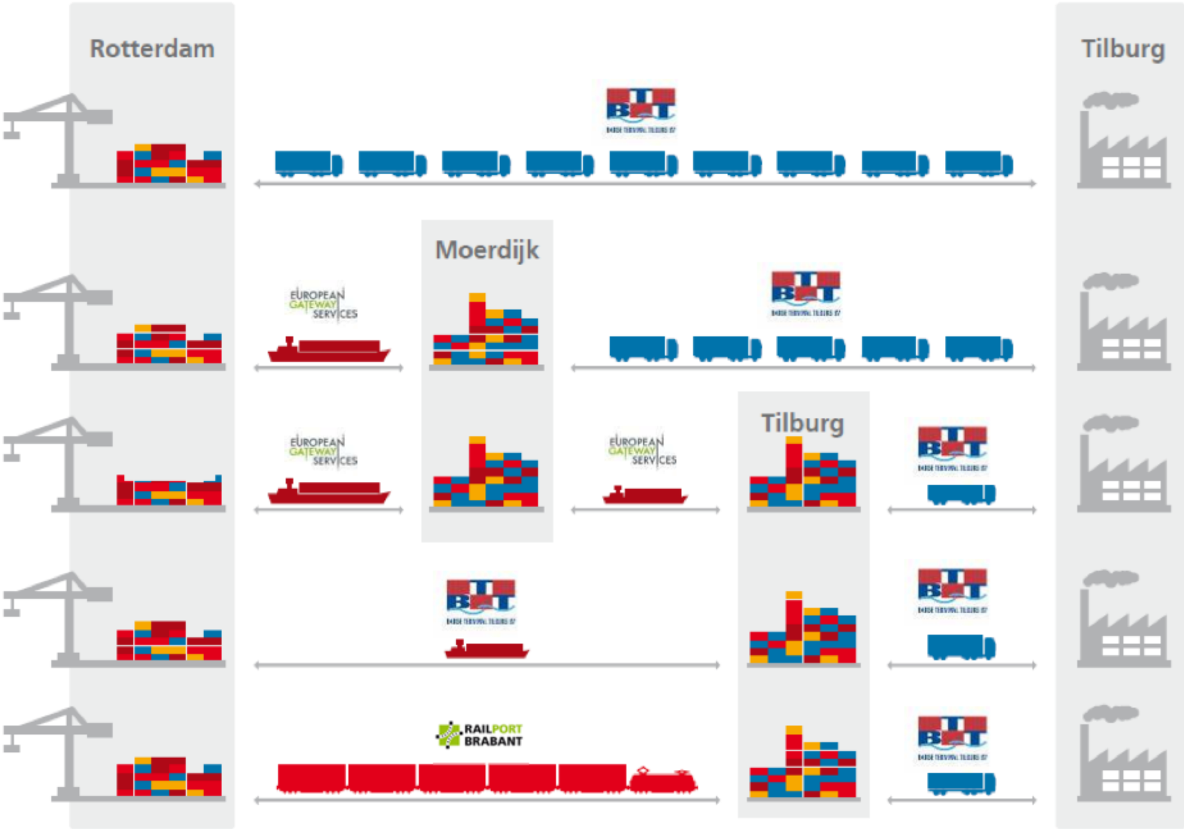

Figure 4 Five connections between Rotterdam and Tilburg [source: EGS]

1.2.3 Scope

EGS

This study will consider the EGS network with mode-free bookings as it is envisioned to be in a couple of years. Transportation to and from specific hinterland locations such as distributions centres will not be considered, because limited data about this last leg is available. The research will focus on transportation to and from hinterland terminals. The hinterland terminals in the network of June 2012 will be considered. It consists of three seaports (DELTA, EUROMAX and CITY) in Rotterdam and 7 hinterland terminals (hinterland terminals in Duisburg, Nuremberg, Neuss, Dortmund, Moerdijk, Venlo and Willebroek). The network depicted in Figure 1 also shows the hinterland terminals in Amsterdam, Liège and Avelgem, but these were not a regular part of the network during the time of this study and were omitted in this study. Adding additional hinterland terminals is not within the scope of this research. The possible set of corridors will be studied, where the possibility of adding land corridors will be considered. The selection of corridors is a part of the research as described in Section 1.3. These land corridors are referred to as *cross-connections*, as these create connections between the hinterland terminals.

Truck transportation will also be included in the research into corridor selection. In practice, trucks always carry out the last leg of transportation. When a container is transported to the hinterland using truck transportation, a transfer at a hinterland terminal is not required. However, as only delivery to terminals is considered, this benefit is not included in the models. So, in order to get the maximum result of an online planning, including delivery to final destinations may be an important extension, that is suggested for further research in Section 7.2.

The following components are used as input:

- The network topology (hinterland terminals and possible connections)
- The travel times on the corridors
- The transfer times and costs per terminal
- The performance is measured as a balance between multiple key performance indicators (KPIs): economic, environmental and quality aspects. The balance of the individual KPIs used to measure the total performance is subject of Section 3.1.

Optimizing this input is not part of this research. The components are based on data delivered by EGS Business Development and EGS planning. The values are quantified in Chapter 3.

Container flows

Historical data of container flows in the network is available. The data is used to determine stochastic distributions of the container flows per origin-destination pair. Several scenarios with different growth rates are considered based on the historic distributions. Demand prediction of future demand patterns is not part of the research.

Historical information about delivery time windows is not available. Currently, customers book most of the transportation mode-specific on a specific service, so no information about the final delivery time is recorded. An estimated distribution of due dates will be based on the EGS planners' experience.

Disturbances

Many sources of random effects influence the daily operation in a transportation network, e.g. delays of services or blockades by customs. It is not in the scope of this research to list all possible influences in container transportation. The influences will be categorised per step in the transportation process in Chapter 3. For disturbances of services, this study will determine the effect on the performance of the existing planning.

Paris TMS

A pilot with the PARIS TRANSPORTATION MANAGEMENT SYSTEM is currently carried out at ECT. With this pilot, ECT wants to find out whether or not this software can assist in the online operational planning of transportation in the EGS network. Several expectations exist at ECT of the implementation of PARIS:

1. A tool for intermodal planning of container transportation
2. Online planning based on real-time monitoring of the network
3. Dashboards providing overview of the actual status of container transports over the network

The third expectation, a dashboard with an overview of information, required by operational planners, is not in the scope of this research. This research will focus on two network properties that are important for an online planning tool:

- The optimized set of network connections and service frequencies for efficient intermodal planning, also considering land corridors.
- Disturbances with a large impact on the efficient intermodal planning and disturbances for which a real time online planning tool is relevant

These two aspects constitute the two parts in which this study will be carried out. The results will indicate the benefit of an online planning tool and show important disturbances. These research steps are elaborated in Section 1.3. The implementation of an operational planning tool is not in the scope of this research. However, the analytical results found in this research will be used to assess the most important aspects of the implementation of the PARIS planning tool. Apart from this, the study has no connection to the pilot with PARIS TMS.

1.3 Problem statement

The development of the EGS network has started in 2007. Since then, the network is being extended with more terminals, corridors and services. A scientific approach to the strategic decisions about the network topology of EGS is currently studied by Ypsilantis (Ypsilantis and Zuidwijk expected May 2013).

Currently, the planning of container transportation is carried out manually. However, as EGS continues to extend the network, planning gets more difficult and more critical (Zografos and Regan 2004; Caris, Macharis et al. 2008). On top of that, the container transportation business demands for reduction of pollution and increasing quality, in terms of faster delivery and higher reliability (Crainic and Kim 2007; Caris, Macharis et al. 2008; Zuidwijk and Veenstra 2010; Veenstra, Zuidwijk et al. 2012). For instance, governmental demands require a reduction of trucking. The port authority requires that the modal split between the modes truck/barge/rail changes from the current 47/40/13 in 2009 to 35/45/20 in 2035 (Port-of-Rotterdam 2011-2). Veenstra et al. (Veenstra, Zuidwijk et al. 2012) mention a modal split with even more trucking in 2010: 55/35/10. Moonen states that the transportation of containers can be improved by using automation in the planning process (Moonen 2009).

Currently, there is no interconnectivity between the corridors to the hinterland destinations in the network. The Business Development department of EGS expects that interconnectivity helps to optimize performance of the network. Hence, a planning method is required to optimize the network performance. This planning must be adaptable at the occurrence of disturbances. The network performance is measured as a balance between multiple key performance indicators (KPIs): economic, environmental and quality aspects. These aspects are quantified in Section 3.1.

To develop such a planning method, two challenges must be met:

- The frequency of the services in the network must be determined, including services on land corridors to allow alternative routes in the planning. The benefit of these *cross-connections* in the network must be determined. This is the focus of Part I of the study.
- Secondly, the influence of disturbances on the networks performance must be identified. Disturbances for which an updated planning improves the network performance are important to incorporate quickly in the planning process. Hence, this part helps identifying what disturbances must be used in an online planning method. Part II of the study focuses on this aspect of the planning.

The current network uses mainly the modes rail and barge, but can use a truck in urgent cases. The last leg of transportation, from the hinterland terminal to a specific location or vice versa, is always operated by truck. This last leg is not part of this research.

1.4 Research questions

This research project will contribute twofold to EGS, at a tactical and an operational level. The goal is to answer the following main question:

What are the most important aspects for the online intermodal planning of the EGS network?

To answer this question, the research is split in the following two parts. These steps are elaborated further in the next sections.

1. Decision support at a tactical level: given the network topology, with what frequency and capacity should services between the inland terminals be operated?
2. Assessment for synchromodal planning at operational level: what disturbances have the largest influence on the network performance?

Together, these two parts will formulate the requirements for a synchromodal-planning tool. These parts are assessed separately. The strategic level decisions of the network topology are not part of the research, but are shortly addressed in Section 2.4. The research questions of Part I and Part II are subject of Section 1.4.1 and 1.4.2, respectively.

1.4.1 Decision support at tactical level

The first step will provide an insight in the network flexibility when using services between inland terminals. The results will indicate the benefits of using *intermodal transfers* in container itineraries. E.g. when available capacity to the terminal in Duisburg is scarce, the network can be used to transport some containers via alternative terminals, such as Venlo or Neuss. A model of the container transport flows is used to determine useful land corridors. The stochastic effects in container flow to the inland terminals are taken into account, to determine the optimal service frequencies subject to varying demand patterns.

The questions in this part are:

1. Can services on corridors between inland terminals improve network performance?
2. If so, how regular will these services be in use?
3. How should these services be executed: by self-operated services or subcontracting?
4. A specific corridor must be operated with what mode and frequency?

In this case, the flow variation on the performance from week to week is relevant: hence, a single schedule must be created that is cost-efficient in different weekly demand patterns.

This part of the research will not result in a full network design for EGS; it will only assess the usefulness of adding services between existing EGS terminals. The results will indicate the network topology of the near future. Services between terminals in the hinterland will increase the level of planning that is required, as Braess's paradox states: adding connections may increase travel times if planning is not at an aggregated level (Braess, Nagurney et al. 2005). The resulting network structure will provide a starting point for the second part of the research. To answer the questions, a model of the network is made to optimize service frequencies for multiple weekly demand patterns simultaneously. The model will be described extensively in Chapter 3.

1.4.2 Assessment of synchromodal planning

The second part will assess how synchromodal planning can improve the network performance. The results of this part will indicate the benefit of *real-time switching*. An assessment of influences on the intermodal planning is made. Besides, the conditions under which a container can be rerouted are identified. For instance, if the study shows that delay of barges has a large influence on the performance, an online planning tool must use the actual barge departure times to reroute some of the cargo for a delayed barge.

The questions are:

1. Which types of disturbances occur in the network transportation?
2. Which disturbances have the largest influence on the network performance?
3. Under what conditions and at what moment can a container be rerouted?

This study will show two things. On the one hand the study will show disturbances that have a large *impact* on the network performance even if the planning is updated as good as possible. Secondly, the study will show for which disturbances the planning can be improved by a full update compared to a local solution for the disturbance.

1.5 Approach

The research approach is specified in more detail later, but it is shortly summarized here. At first the tactical decision support is considered. To determine the relevancy of land corridors, the following approach is used. The historic container flows in the EGS network are used to create container flows per origin-destination pair. A mixed-integer programming (MIP) problem is formulated that includes the capacity constraints per corridor. This problem is solved to determine the size of the flows per corridor. This results in the optimal frequency of services per corridor. If land corridors prove relevant, lower frequencies on some existing corridors between a seaport and the hinterland may suffice.

In the second part, relevant disturbances are identified. To do so, a network model is developed to plan the transports for one week. This model is solved offline to an optimal solution. The model and the evaluation of the model's optimality are discussed in Chapter 5. Using simulation, disturbances are generated. For each disturbance – one at a time – the planning is updated from the point in time were the information of the disturbance comes available. Two separate updates are carried out. With a *full update*, all transports after the time of information are re-planned. This update represents the method of an automated online intermodal planning tool. With a *local update*, only the transports that are directly affected by the disturbances are re-planned. This update represents the result of the manual planners in the current situation.

The *impact* of the disturbance is assessed by comparing the performance of the full update with the original planning. Disturbances with a large impact must be prevented when possible. Secondly, the difference between the two updates shows the *relevance* of re-planning after a disturbance: how much would an automated planning tool improve the re-planning compared to the current situation? A future online planning tool for the EGS network must be able to handle disturbances with a high relevance on the re-planning.

1.6 Structure of the report

The report describes the two parts of the research subsequently. In this report the results of both parts are presented separately. But first, the relevant literature about intermodal transportation networks and (online) planning is discussed in Chapter 2.

The research is split into a Part I and II. Part I describes the tactical flow model (0) and the research with this model into the network topology (Chapter 4) as described in Section 1.4.1. Then, Part II consists of the description of the offline operational planning model (0) and the research into the influences of disturbances on the operational planning (Chapter 6).

Finally, conclusions on both parts are presented in Chapter 7. The results are discussed and further research is proposed in this chapter as well.

Chapter 2. Literature review

In order to develop the methods to answer the research question of Section 1.4, a literature review is carried out. In Section 2.1 an overview is provided of relevant literature on intermodal transportation and derived topics. In the Section 2.2 the literature on the concept of seaports with extended gates will be studied, to clarify the transportation on the EGS network. Subsequently, Section 2.3 presents existing models on transportation planning. Since several decades, research into intermodal transportation is performed and OR models to evaluate all aspects of the supply chains are continuously developed. The intention is not to provide an overview of all existing OR models, but to present several models that contain relevant aspects for the current case. Finally, Section 2.4 gives an overview of the current work on the strategic development of the extended gate network of EGS. Apart from this section, the strategic analysis is out of scope of this research. The tactical and operational planning levels of EGS are subject of the next chapters.

2.1 Container transportation developments

The global throughput in container transportation continues to grow and constitutes a growing portion of the global transportation (Dewry-Shipping-Consultants 2008). Meanwhile, supply chains get increasingly interconnected and shippers demand higher levels of service, such as short delivery times and reliability (Crainic and Laporte 1997; Crainic 2000; Veenstra, Zuidwijk et al. 2012). The logistic expression for integrated transportation is intermodality. The International Transport Forum (former European Conference of Ministers of Transportation) defined intermodal transportation as:

Multimodal transport of goods, in one and the same intermodal transport unit by successive modes of transport without handling of the goods themselves when changing modes (International-Transport-Forum (Mario Barreto), Eurostat (Ould Khou Sid'Ahmed) et al.).

So, intermodal transport is a special case of multimodal transport, defined as *Transport of goods by at least two different modes of transport*. Crainic and Kim (Crainic and Kim 2007) discuss some definitions of intermodal transportation: intermodal transportation is used to indicate the transportation of a person or a good by a sequence of at least 2 modes. According to them, the term refers to a multimodal chain of container transportation services. Ishfaq and Sox (Ishfaq and Sox 2011) distinguish multimodal and intermodal networks as follows: transportation in multimodal networks occurs using one preselected mode per transport, whereas intermodal transportation uses at least two modes for a transport. The definition by the European Conference of Ministers of Transportation is too strict according to Crainic and Kim, as it excludes goods that are handled themselves during transhipment, such as mail. Macharis and Bontekoning (Macharis and Bontekoning 2004) add that intermodal transportation aims for the shortest possible initial and final journeys by road (*last leg*).

In this report *intermodal transportation* is used to refer to the *transportation of containers in a chain of different modes*. The use of barge and rail transportation in an intermodal network differs from the classical use of these modes: barges and rail are often operated according to a fixed schedule in an intermodal network (Macharis and Bontekoning 2004). Crainic and Kim distinguish between two types of intermodal transportation: consolidated or customized. It the former, freight from different origins and destinations is bundled, such as mail and container transportation on barges or trains. Container transportation by truck is typically customized transportation. In general, consolidation transportation results in longer transfer times and allows longer decision times than customized transportation. Consolidation of flows between hubs in intermodal networks is cost efficient as it benefits of the economies of scale (Ishfaq and Sox 2012; Ypsilantis and Zuidwijk expected May 2013). The planning of intermodal transportation requires a network-wide approach (Crainic 2000; Jansen, Swinkels et al. 2004; Crainic and Kim 2007).

Heck and Vervest (Heck and Vervest 2007) stated 6 critical elements of smart business networks:

- Membership selection
- Linking
- Continual improvement
- Fault tolerance mechanisms
- Goal setting
- Risk and reward management

Veenstra et al. (Veenstra, Zuidwijk et al. 2012) analyse the EGS network along these six elements. The development of the network is continuously going on, by adding partners, links and terminals. This covers the first three elements. The fault tolerance mechanism consists of the alternative routing that is possible in the network. ECT has set the goal for EGS: to gain more influence on the hinterland transportation of containers. Less well developed is the risk and reward management in the cooperation between shippers, service operators and customers, according to Veenstra et al.

2.2 Extended gate concept

Important aspects in container transportation are the quality of service, such as the reliability, frequency and speed of delivery, the costs and the sustainability of the transportation (Crainic 2000; Veenstra, Zuidwijk et al. 2012). Since several years the concept of a *dry port* is used to describe the shift to inland nodes with good infrastructure, which are directly connected to a maritime port. Roso et al. (Roso, Woxenius et al. 2009) narrowed the concept further down by stating that customers should be able to leave and pick up containers as if they were directly at the seaport.

Veenstra et al. (Veenstra, Zuidwijk et al. 2012) introduced the *extended gates concept*, which is an extension to the dry port concept:

An extended gate is an inland intermodal terminal directly connected to seaport terminal(s) with high capacity transport mean(s), where customers can leave or pick up their standardised units as if directly at a seaport, and where the seaport terminal can choose to control the flow of containers to and from the inland terminal.

The idea was introduced by the need to free capacity in the Rotterdam ports in 2004/05. By allowing the seaport to influence the container flow into the hinterland, the extended gate concept will contribute to the required modal shift to barge and rail transportation, logistic performance can be increased by consolidation of containers and by stimulating regional development around the extended gates. The additional service can improve business (Ypsilantis and Zuidwijk expected May 2013).

The main idea of the extended gates concept consists of the following aspects (Veenstra, Zuidwijk et al. 2012; Ypsilantis and Zuidwijk expected May 2013):

- The delivery point is extended to the inland terminal, and possibly even to the final destination such as a distribution centre
- The gate is placed at the inland terminal. In this sense, *gate* refers to the entrance for truck delivery or pick-up of containers.
- Transportation occurs on a multimodal platform. The inland terminals can develop further when incorporating the modalities.
- Custom facilities are postponed to the extended gate where possible

2.2.1 Developments in transportation planning: quality added as target

Transportation used to be optimized based purely on costs. However, Crainic and Laporte (Crainic and Laporte 1997) signal that carriers and transporters cannot only optimize the transportation on cost efficiency anymore. Apart from low tariffs, customers demand for a higher quality of service. According to Crainic and Laporte, quality of service consists of three parts: on-time delivery (time window), delivery speed (service time) and consistency of these aspects. Veenstra et al. (Veenstra, Zuidwijk et al. 2012) mention reliability as an important quality of service, comparable to the consistency mentioned by Crainic and Laporte. Ishfaq and Sox (Ishfaq and Sox 2010) mention six performance targets for intermodal logistic networks: cost, service frequency, service time, delivery reliability, flexibility and safety. They propose methods to optimize the costs of intermodal logistic networks, while meeting service time requirements. The other performance targets are neglected in their work.

2.2.2 European Gateway Services

Veenstra et al. (Veenstra, Zuidwijk et al. 2012) signal that chain innovations often are introduced with a focal point in the Netherlands, due to the high number of global supply chains that use the port of

Rotterdam and the Dutch logistic industry. Since 2007, ECT developed the extended gate concept with the subsidiary EUROPEAN GATEWAY SERVICES. The first step was the introduction of regular services on the corridor between Rotterdam and the inland terminal TCT Venlo. Currently, the concept is extended to around 20 hinterland terminals. A more extensive description of the concept and the implementation was provided in Section 1.2. The concept of EGS was introduced by Veenstra et al. (Veenstra, Zuidwijk et al. 2012) as described in the beginning of Section 2.2. Several challenges were recognized and are repeated here. The current work on these challenges is mentioned and the links with this report are made clear.

- Network design of the physical structure of the network and the information structure. The network design has aspects at different levels of planning. Currently, research is in progress into the strategic network design (Ypsilantis and Zuidwijk expected May 2013). A more detailed description follows in Section 2.4. A tactical part of the network design, the selection of corridors and service frequencies are analysed in this report (0).
- Network transportation: integration, competition and collaboration of stakeholders are unexplored. With EGS, ECT is learning on the actual implementation of the network transportation and the cooperation with multiple companies.
- Legal consequences: responsibilities shift from shippers and carriers to seaports.
- Tri-modality: research into multimodal transportation focuses mainly on co-modal transportation, that is, without considering truck. Veenstra et al. signal that no research or applications of tri-modal transport are available. The model formulations in this report will explicitly consider tri-modal transportation with truck, barge and rail.
- Operational and analytical problems: several operational aspects need to be addressed with respect to the extended gate transportation, such as efficient network transport planning. At the end of this section, all aspects recognized by Veenstra et al. are mentioned. The results of this report will add to the implementation of efficient operational network planning.
- Business model: the development of the business model is in progress, i.e. in the Ultimate project (DINALOG 2010). The role of the port authority in the process of network integration and cooperation is not entirely clear yet. This requires attention in the development of the business model.

Several challenges are present during the daily operation of EGS. The cooperation with all partners (both transporters as inland terminals) requires a lot of communication. Another challenge is the merging of the stevedoring activities of ECT in the seaport and the transportation activities of the EGS network. Tight scheduling of transfers on the seaport side is possible, but requires effort of all planning levels. The customer care in the logistics business requires another level than in the regular seaport business. The challenges on legal responsibilities and operational problems are elaborated further below.

Legal responsibilities

A *Bill of Lading* accompanies each container transport. This *B/L* specifies to what destination the sea transportation is carried under responsibility of the carrier. In the case of *carrier haulage*, the B/L specifies the inland terminal or final destination. In the case of *merchant haulage*, the B/L is the seaport, and inland transportation occurs under responsibility of a merchant. In both cases the legal position of a seaport that does a part of the transportation is difficult. Two possibilities are explored within EGS:

- EGS organises the transportation, i.e. *self-operated* services
- The seaport contracts a third party to do the transportation, such as TEU slot reservations on existing services, i.e. *subcontracted* transports

Operational and analytical problems

In the case of *merchant haulage,* the Bill of Lading may only specify the seaport, and not the inland terminal. In this case, the terminal has no knowledge of the final destination until informed by the merchant. EGS has a booking office that collects information and books the inland transportation.

When the modal split shifts towards more rail and barge transport and these corridors will be operated at more regular intervals, the efficiency of container stacking must be improved (van Asperen, Borgman et al. 2010; Veenstra, Zuidwijk et al. 2012). Also, the turnaround times of barges and trains must be improved to increase performance of hinterland connections. Especially the turnaround time of barges is a problem at the ECT Rotterdam terminals (Veenstra, Zuidwijk et al. 2012).

Furthermore, to allow for investments in the hinterland network: the benefits in the operational process must be exploited, planning must allow pushing of containers to free capacity, reliability must be increased and trucking must be reduced.

2.3 Transportation planning models

In this section, the literature on transportation planning models is reviewed. The review is divided in the three levels of planning in transportation networks: strategic, tactical and operational. Although this study does not investigate the strategic planning level, available literature at this level is reviewed for the sake of completeness. The models and methods used at a strategic, tactical or operational level are often similar and the planning level is denominated depending on the author's perspective. The three planning levels are described in the subsequent Sections 2.3.1-2.3.3. For the tactical and operational levels, not only the mathematical models in literature are introduced, but also some solution methods to find the (optimal) solutions of these models.

The research into intermodal transportation planning is an emerging application field of transportation research since the 1990s (Macharis and Bontekoning 2004). Most types of intermodal problems are covered, although the number of studies was considered limited in 2004 (Macharis and Bontekoning 2004) and in 2007 (Crainic and Kim 2007). Many studies recognize three levels of planning (Crainic and Laporte 1997; Macharis and Bontekoning 2004): strategic, tactical and operational. The different levels are shortly introduced here; examples of planning problems in all levels follow in the next sections.

The strategic planning level involves the highest level of planning in the firm. Problems with a long time horizon are addressed, typically 10 to 20 years. To this category belong problems such as the physical network structure, the main facilities in the network and the acquisition of resources. At the tactical planning level (months or weeks ahead), the use of the network is addressed. Typically, this comprises the allocation of resources (static), the choice of routes, the types of service and repositioning of empty containers and resources. The first three together comprise a service schedule. Finally, the operational planning level handles the daily operation: scheduling of all assets on individual basis and allocation of resources. The environment of planning on this level is highly dynamic with many changes. Depending on the specific activities at a firm and the typical time horizon, problems are considered tactical/operational or strategic/tactical (Crainic 2000). In the following sections, typical problems in the available literature are introduced.

Macharis and Bontekoning (Macharis and Bontekoning 2004) carried out a computerized literature search in 2004. They made a distinction between four types of operators: drayage, terminal, network and intermodal operators. Network operators are the companies operating the services in a transportation network, whereas intermodal operators carry out the booking of containers in the network. EGS combines both of these functions, so the relevant studies for these types of operators are included in the following sections.

2.3.1 Strategic

Macharis and Bontekoning (Macharis and Bontekoning 2004) signal that many strategic models for intermodal networks are built as an aggregation of multiple unimodal networks with transfers at certain nodes.

Crainic and Laporte (Crainic and Laporte 1997) recognize three types of strategic models: location models, network design models and regional multimodal planning models. Location models are used to determine where to place the facilities in a region, often the vertices of a network. Also the hub-location problem belongs to this category. Network design models represent both these vertices and the connections between the vertices. A direct connection (corridor) is represented by an edge. At a strategic level, network design models can be used to select the network edges. The regional multimodal planning valuates high-level aspects, such as infrastructure and demand predictions.

Crainic and Kim (Crainic and Kim 2007) describe three types of strategic network design:

- Locating with balancing requirements: determining the location of depots, considering the repositioning of empty containers
- Multicommodity production-distribution: a simplification of the former, without transportation between hubs. An itinerary passes no more than one consolidation terminal.
- Hub-location models: a more general case than both former problems. It is assumed that an itinerary passes two hubs. The consolidated transportation between the hubs benefits from the economies of scale.

Kagan (Kagan 2012) distinguishes two different types of intermodal network models: those based on the hub-location problem (HLP) and those based on the minimum cost network flow problem (MCNF). The hub-location problem is typically used for selecting the places for transhipment or transfer of cargo. The minimum cost network flow problem finds the minimum cost solution for transporting a flow from the sources to the sinks. The min-cost network flow problem is often used for strategic level problems.

Ishfaq and Sox proposed several models and solution methods to select hubs in intermodal transportation networks. The models are used to select hubs for the most cost efficient intermodal transportation. At first, they added service time requirements and the costs of transfers at hubs to existing hub-location models (Ishfaq and Sox 2010). The addition of service times is considered essential in networks with short service times. This study was extended and the influence of several parameters are investigated (Ishfaq and Sox 2011): the fixed cost to start a certain hub, the costs for transfers at a hub, the cost ratio between road and rail transport, service time requirements and the economies-of-scale for consolidated flows between hubs. The cost of transfers (*modal connectivity costs*) is an essential part of the cost structure when choosing between direct transport or transport via hubs. Service time requirements are considered as an input parameter, for each transport flow.

For small problems (with a maximum of approximately 30 hubs) a method is described to calculate lower bounds using lagrangian relaxation. A *sub gradient optimization* technique is used to update the Lagrange multipliers iteratively. A lagrangian relaxation must result in sub problems that can be solved more easily and still provide tight bounds. Their strategy is to split the formulation in two sub problems by relaxing the constraints that contain two types of decision variables. As a result, the sub problems contain only one type of decision variable and are easier to solve. For larger problems they use a tabu search method to improve the lagrangian relaxation solutions.

Finally, the influence of hub delays was investigated by introducing a queuing model of the hub operations into the hub-location model (Ishfaq and Sox 2012). The dwell times of ships during hub operations are modelled stochastically using a GI/G/1 queuing model. In this model, a maximum dwell time is introduced to make sure that service time requirements are met. A partial linear relaxation method is described that linearizes the flow variables to find lower bounds. Again, tabu search was used as a metaheuristic. Some of the aspects of Ishfaq and Sox's models are used in this study's models. That will be explained in Section 3.2.

2.3.2 Tactical

At a tactical level – among other things – decisions are made about what services are operated on what corridors. This includes the selection of the mode, capacity and frequency of such a connection. Crainic and Laporte (Crainic and Laporte 1997) recognize five types of tactical planning problems in transportation:

- Service network design (hubs, route frequencies)
- Traffic distribution (routing of requests)
- Terminal policies (handling at terminal)
- Empty balancing (repositioning of resources)
- Crew and motive power scheduling (positioning of crews and resources)

In general, these types of problems can be handled by using simulation models or network optimization models. Simulation models are often used in rail applications (Crainic and Laporte 1997). These do not result in new strategies, but can be used for informative analyses.

Network optimization techniques do result in new strategies; they can be solved fast, but are in general less detailed. Containers are mostly bundled as a cargo class: planning is not performed for containers at an individual basis, but containers are grouped into cargo classes. Containers that have the same origin-destination and have specific container characteristics in common are grouped (Crainic and Kim 2007; Ishfaq and Sox 2011). Such a group can be considered as a flow of the size of the number of containers.

Service network designs are used for the system's transportation plan: the routing and scheduling of services, consolidation of freight and the routing of each cargo class on itineraries through the physical network (Crainic and Laporte 1997; Crainic and Kim 2007). A scheduling of services includes the decision of frequency of each service. Service network design problems are difficult, as an interaction between the provided service level and the costs exists. With high frequency connections, the delivery time is short and the service level is high. This is at the expense of additional costs, though. A balance between service level and costs must be found using a trade-off cost function (Crainic and Kim 2007). In Europe, environmental considerations become increasingly important. Hence, a third component of the cost function of service network designs is the environmental impact of the solution (Veenstra, Zuidwijk et al. 2012).

Crainic and Kim (Crainic and Kim 2007) describe two types of service network design (SND):

- Static service network design
- Time-dependent service network design

Both consider the service network design for multiple cargo classes and capacitated services, assuming deterministic transportation demands and fixed costs. Two types of models are used to describe the static service network design: *path-based network design models* (PBND) and *min cost network flow* (MCNF) models

An example of a static service network model by Crainic and Rousseau (Crainic and Rousseau 1986; Crainic and Laporte 1997; Crainic 2000) is introduced (Model 4). The formulation can be found in Appendix B. This is a PBND formulation. All containers are bundled according to their origin, destination and service characteristics. This is called a cargo class. All possible itineraries for transportation are called *paths*. Such a path includes the used services and intermediate terminals. Now, container flows are assigned to paths to solve the network transportation problem.

Another representation of a service network is an MCNF formulation (Model 3) (Crainic 2000). This formulation can also be found in Appendix B. This type of formulation is used to select the services that satisfy the transportation demand at the lowest possible costs. Each service has a fixed cost if it is selected. On top of that, a variable cost per container on a corridor applies. These costs are minimized while planning the transportation of the deterministic demand. The model can be extended with additional constraints to model relationships between services. Both formulations can be simplified to the *uncapacitated* problem by removing the capacity constraints.

Boardman et al. (Boardman, Malstrom et al. 1997) indicate that multimodal networks can be modelled using a multiple link or multiple node method. In the former case, each terminal is represented by one node. When a connection to another terminal is possible with multiple modes, than the nodes are connected with multiple links, one for each mode. In a multiple node model, each terminal is represented by multiple nodes, one for each mode. This allows for more specific modelling of the various transfers between the modes, but also makes the network model significantly larger.

Several representations can be used to model the time constraints in the static SND. It can be used in the formulation by including the available delivery time in the cargo class. Containers are then grouped according to origin, destination, service characteristics and the delivery time. E.g. in the path-based formulation, the set of possible itineraries for containers with a certain time window can be selected such that timely delivery is ascertained (Crainic 2000). Ishfaq and Sox also used time constraints for the delivery of specific cargo classes (Ishfaq and Sox 2010; Ishfaq and Sox 2011). However, they did not use a path-based formulation, but a formulation using maximally 3 corridors. The delivery time is determined by the transit times on the transportation legs. However, to incorporate the transfer times between the transportation legs, the middle transportation leg is multiplied by a delay factor. They mention that the effect of increasing this delay factor corresponds to reducing the available service time for the transportation.

Alternatively, explicit time-dependent formulations can be used: for instance, a space-time network can be used. Arcs represent the temporal links of services between terminals. Apart from the temporal links and terminal representation this model is similar to the static version, but is much harder to solve, due to the large size of the space-time network (Crainic 2000).

Out of the five types of tactical planning problems by Crainic and Laporte, Jansen et al. (Jansen, Swinkels et al. 2004) take traffic distributions, empty balancing and motive power scheduling simultaneously into account. The model that they developed can be used at a tactical level for what-if analyses, but is mainly used for the operational planning at Deutsche Post AG. See Section 2.3.3 for more details on this model. Other researches also indicated the use of tactical models for what-if analyses (Crainic and Kim 2007).

Macharis and Bontekoning (Macharis and Bontekoning 2004) describe the research by Newman and Yano. They created a model for rail transportation considering the punctuality and capacity requirements that was able to solve the problem to optimality for three or four nodes.

Methods

The mixed integer problem (MIP) formulations for the tactical models are often NP-hard and get more complex as the modelled networks get larger and more complex. Adding tighter constraints often decreases the solution time. Solution techniques often use Lagrangian relaxation of the integer constraints to find lower bounds for the optimal solution. Alternatively, bounds can be found by solving the linear relaxation of the dual of the MIP (*dual ascent*). These bounds are used by Crainic in a branch-and-bound algorithm, to find optimal solutions (Crainic 2000). Crainic further mentions several heuristics that are often used to solve capacitated network design problems:

- greedily adding and dropping arcs
- heuristic use of dual ascent and linear relaxations
- metaheuristics such as tabu search, simulated annealing or genetic algorithms

The capacitated problems that were presented in this section are often poorly approximated by the linear relaxations (Crainic 2000). Crainic and Rousseau (Crainic and Rousseau 1986) describe a technique that uses decomposition and column generation to solve a path-based formulation such as in Model 4. To solve the models, research into better bounds and exact methods are required, as well as improved metaheuristics (Crainic and Kim 2007).

A solution for the uncapacitated problem is easier to find. Several heuristic methods have been reported using dual ascent procedures. Holmberg and Hellstrand (Holmberg and Hellstrand 1998) proposed an exact solution method for the uncapacitated problem using a Lagrangian branch-and-bound method.

2.3.3 Operational

The planning at operational level is the most dynamic level. This level of planning determines the actual performance of the process. The variability of the operation can be incorporated in the model in several ways. If distributions of variables are known, a stochastic network model can be created. This type of problem is often modelled as a chance-constrained program or as a stochastic program with recourse. The former results in a solution with a probability of failure below a certain threshold. In the latter, the expected costs of the changes in the original planning are minimized. Solution is often difficult, though (Crainic and Laporte 1997). Crainic and Laporte also mention the use of queuing networks.

Crainic and Kim (Crainic and Kim 2007) describe several operational problems for container terminals, such as berth scheduling, quay-crane scheduling and storage planning. For the case of network transportation they describe a model for a specific part of container fleet management: *empty repositioning*. The model describes the container fleet management on land: the system is composed of inland terminals, seaports and customers. Customers obtain containers from inland or seaport terminals. If a container is not available in time for the customer, substitute containers can be leased. Repositioning of the empties occurs via two mechanisms: tactical balancing movements and decisions on what empty container to use for a specific request. The model does not take into account the transportation of loaded containers. The container fleet management and, specifically, empty repositioning, is highly time-dependent and stochastic.

Guélat et al. (Guélat, Florian et al. 1990) describe a multimodal, multiproduct network assignment problem. Their research is aimed at making strategic decisions, but their work also contributes to the operational container planning, as recognized by Crainic and Kim (Crainic and Kim 2007). The model represents terminals and connections with multiple modes. Also, the transfer of containers from one mode to another is included in the model.

Ziliaskopoulos (Ziliaskopoulos and Wardell 2000) also proposed a multimodal network. In this formulation, explicit switching time delays from one mode to another were used. Also, the travel time per arc is variable, depending on the point in time.

Jansen et al. (Jansen, Swinkels et al. 2004) describe a model for daily planning of container transportation throughout Germany, for delivery within 24h hours. Around 1500 trucks and a number of trains are used to transport an average of 4000 containers between 100 nodes. An order for a container contains the information on the container type, pick-up and drop-off windows and locations. Also, possible modes are defined. The order is flexible in routing and timing. Constraints can be categorized in capacity constraints, route constraints and order constraints (such as pick up windows). Capacity constraints are the number of available slots on specific services, maximum mass and capacities at terminals. Route constraints ensure the feasibility of the transportation route of each container: the services of consecutive legs should connect geographically and in time. Also, several constraints are required for each truck tour, such as home locations and resting times for truck drivers. Order constraints focus on time windows for the pick-up and delivery.

The model proposed by Jansen et al. minimizes the transportation costs within the constraints. The solution also incorporates the balancing of trucks and empties up to the planning horizon.

Methods

The model by Jansen et al. is handled by solving a series of sub problems iteratively. First, by customer preference, containers are placed on available train slots in a greedy way. Then, the following problems are solved repeatedly: repositioning (min cost flow problem), consolidation (weighted matching problem), planning of consolidated orders (solving truck planning with a sliding window), heuristic plan improvement, entire routes test on feasibility and costs. Jansen et al. do not provide extensive details on the specific solution approaches.

For intermodal operators, the literature study of Macharis and Bontekoning (Macharis and Bontekoning 2004) mentions only the work of Boardman et al. (Boardman, Malstrom et al. 1997). In this study, a decision support system was developed to assist the user in selecting the least cost combination of transfer nodes for a specific transportation request. In this study, the *k*-shortest paths per origin-destination combination are determined in advance. Then, during daily operation, for each new booking the path with the lowest costs that meets all delivery requirements is selected. The method does not take the integral optimization of the network, nor service capacity into account.

2.4 Strategic network model

Although the strategic aspects of transportation network design are not a part of this study, a short overview is provided in this section. The strategic design of the EGS network focuses on the question where to make hinterland terminals? This question can be answered by strategic network optimization. Current research on this subject is carried out by Ypsilantis in corporation with the EUR and ECT (Ypsilantis and Zuidwijk expected May 2013). Ypsilantis uses a bi-level programming approach. The first level optimizes the revenue of the network operator, with respect to the maximum price that customers want to pay. This price is determined at the second level, while optimizing the minimum cost for customers of the network or competition. The cost of investment of new arcs in the network is also incorporated. The model takes into account the economies of scale of transportation on each arc. Two approaches for this aspect are introduced:

- Piecewise linear formulations of the costs
- Discount factors per corridor, the value of these discounts is calculated iteratively

Preliminary results on the subject show that a trade-off exists between a centralized or decentralized inland system: multiple hinterland terminals result in short last legs, but can be served less frequent from the seaport, due to the smaller volumes. A single hinterland terminal requires longer last legs, but can be served frequently. This trade-off can be analysed using a balance between cost efficiency (occupation), emissions and service. An important question that remains is the incorporation of time constraints versus price.

Some of the aspects of the research at the strategic level are important to consider for the tactical level. The economies of scale must also be applied at the tactical level. However, the investment for new services and the influence of competition on demand levels are typically strategic aspects. The models in this report do not use these aspects.

Ypsilantis will apply his model to the EGS case to assess current performance and determine future network extensions.

Overview Chapter 2

This chapter presented relevant literature for this research. In Section 2.1 and 2.2 the developments in new transportation concepts, such as extended gates, were introduced. Section 2.3 described models at three planning levels: strategic, tactical and operational. The research for EGS at a strategic level was presented in Section 2.4. The following chapters, Chapter 3 and Chapter 4, constitute Part I of this study and describe the research into the optimal selection of corridors and service frequencies.

<u>**PART I – TACTICAL LEVEL**</u>

This part of the research looks into the benefits of using intermodal transfers in container itineraries. For that purpose, the optimal service frequency in the network is determined, including the possibilities of connections between hinterland terminals. Such connections will allow intermodal itineraries with one more transfers in between. The research questions for Part I are repeated below from Section 1.4.1:

1. *Can services on corridors between inland terminals improve network performance?*
2. *If so, how regular will these services be in use?*
3. *How should these services be executed: by dedicated services, or subcontracting? What capacity?*
4. *A specific corridor must be operated with what mode and frequency?*

0 will introduce a new tactical network model to determine the optimal service frequencies. This tactical network model can be used to evaluate the usage of land corridors in different scenarios. Subsequently, Chapter 4 will address the experiments with that model and results.

Chapter 3. Tactical network model

In this chapter the model and research approach to determine the optimal service frequencies on the network corridors are described. Two types of network models, the PBND and MCNF models that were found in the literature review of Chapter 2, will be combined to create a model for the case of the EGS network that was introduced in Chapter 1. Furthermore, the model will be designed specifically to allow overdue delivery at a penalty cost and to combine subcontracted transport with self-operated transport.

In the first section, the relevant targets for the model are identified: the key performance indicators (KPIs). The model formulation is introduced in Section 3.2. In Section 3.3 the methodology is described to find the optimal tactical planning within the model. Finally, the chapter is concluded with Section 3.4, where the data for the model is described and analysed. The research experiments and results are presented in Chapter 4.

3.1 Quantification of KPIs

In the review of literature it was found that the model must consider a triple target objective, based on economic, environmental and quality measures. While competition is fierce, society demands for more sustainable transportation, while customers expect reliable services (Crainic and Laporte 1997; Crainic and Kim 2007; Port-of-Rotterdam 2011-2; Veenstra, Zuidwijk et al. 2012). The three objectives are all translated to a cost in euro (€). Please note that all costs in this report are scaled by a confidentiality factor to protect the sensitive information that was provided by ECT. This will be further explained in the section Data (3.4). The way that the three objectives are translated to euros in this study is explained in the following sections.

Economic target

The economic target is to minimize the total cost of network transportation between the terminals. As was explained in Section 1.2.2, two cost structures exist for the container transportation in the EGS network. Containers are either booked on existing services, incurring a cost per TEU, or containers are booked on an EGS service. In the latter case, costs are incurred per service and no additional costs per TEU arise. This means that – as long as capacity suffices – the transport of a container on an EGS-service does not result in additional costs. Transfer costs per TEU apply independently of the cost structure. Transfer costs apply each time for the loading and unloading of containers at a terminal. In Section 3.4, all these costs are estimated based on the actual costs of transportation in the EGS network.

Environmental target

To incorporate the minimization of the environmental footprint, the CO_2-emission per service (EGS-services) or per TEU (subcontracted slots) is used. These emissions are based on the STREAM-report by CE Delft (den Boer, Brouwer et al. 2008). The report proposes estimation methods for all types of transportation and all modalities, also average values for the emissions are provided. The estimation methods distinguish between tank-to-wheel and well-to-wheel methods. In the former, only the emission of the vehicle during transport is used, as is common practice in current CO_2-emission calculations. In the latter, also the emissions during the process of producing fuel or power are calculated and included in the emissions. Electric vehicles do not directly emit CO_2, but the power generation causes emissions (depending on the used mix of power sources). In the EGS network, electric trains are used as well. For an accurate implementation of the balance of CO_2 emissions, well-to-wheel emissions are used as the STREAM-report suggests. To assess the well-to-tank part of emissions for electricity, the average Dutch power mix is used as provided in the report.

To estimate the costs of emitting CO_2, the European Union Emission Trading System (EU ETS) is used. This system was launched in 2005 to limit the emission of greenhouse gasses. Factories, power plants and others may trade their emissions among each other, effectively creating a market with a price for emitting greenhouse gasses (European_Comission 2010). In this study, the price for emitting one metric tonne of CO_2 is assumed to be €8[1]. This is the current price of an EU emission allowance (EUA) for 1 tonne of CO_2 as reported by Bloomberg on August 24th, 2012 (Bloomberg 2012).

Quality target

The literature review revealed several quality aspects for transportation: on-time delivery, reliability, and flexibility. In EGS customer agreements, the first is the most important, currently. Moreover, the on-time delivery is most easily integrated in the network formulations. Hence, in this study the quality target is measured as the total tardiness of all transported containers. Tardiness is defined as the number of days a delivery is overdue and it equals zero in case of early delivery. The price of overdue delivery is estimated at $c_\tau =$ €50[2] per day. In practice, late delivery for export is far worse than late delivery for import. A late arrival at the seaport may result in missing the departure of the deep-sea vessel. Import containers may cause problems at the inland address, but do not directly influence the transportation chain. In this report, no distinction between tardiness of import or export containers is made yet, though.

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[1] Not masked by a factor in the report, as this number is based on public resources. Naturally, the confidentiality factor is applied to the CO_2 the computations of the study.
[2] Masked by confidentiality factor

3.2 Model formulation

In order to find the optimal tactical network planning, a mathematical model of the network is developed. Section 3.3 describes the methodology to find the optimal planning within this model. In this section the mathematical formulation of the tactical model is introduced and the considerations that resulted in the development of this model are described. At first, the model is introduced in Section 3.2.1. Then, in Section 3.2.2 the mathematical formulation of the model is presented step-by-step. Section 3.2.3 shows some alternative formulations that are not yet used in the model but may be used as an extension in further research.

3.2.1 Introduction of the tactical network model

The tactical network model is developed to find the optimal weekly schedule of barge and rail services in a hinterland transportation network. A schedule of one week is chosen in consultation with the EGS planning manager, because this is the common time period in this type of networks. Such a schedule must operate well under several demand patterns. Hence, the model must result in one optimal schedule based on several demand patterns.

The objective is to select a service schedule that minimizes simultaneously the three targets that were introduced in Section 3.1:

- Fixed costs per self-operated service and variable cost for transport on TEU slot basis
- Cost of total number of overdue days (total tardiness)
- Cost of CO_2-emission due to the network transportation

The quantification of these targets is subject of Section 3.4. Next, the modelling of the network topology is explained, followed by the modelling of the transportation demand. After that, in the subsequent section the mathematical formulations are introduced.

Modelling network topology

The model must be able to represent the typical North-Western Europe hinterland transport networks. As a test case, the EGS network will be used. In general, the model comprises terminals and corridors between the terminals. The model does not differentiate between seaport and hinterland terminals. Services of a specific mode operate on a corridor and provide transportation between two terminals. At terminals, a container can be transferred from one service to another, possibly of a different mode.

The EGS case in this study consists of 10 terminals, of which three are Rotterdam seaports. Most of the hinterland terminals are connected to the seaports with barge, rail and truck, i.e. via three corridors. The available corridors and the implementation of other data of this model are further described in Section 3.4. In this section the theoretical model is introduced.

As was introduced in the literature review in Chapter 2, Boardman et al. distinguished two ways to incorporate mode transfers into a network model (Boardman, Malstrom et al. 1997). One method – a multiple node model – uses three nodes to represent a trimodal terminal: one for each mode. This way of modelling can also incorporate the terminal's transfer costs and transfer times as the properties of the links between these three nodes. Ziliaskopoulos (Ziliaskopoulos and Wardell 2000) used this to model the transfer times specifically for each mode to another mode. The second option – a multiple link model – uses one node per terminal, but models multiple links between terminals to represent different modes. In this case, the transfer costs cannot be integrated in the properties of the links in the network. The transfer costs and times must be modelled separately in this case.

In this study, a multiple node model was used at first. However, due to the fact that some of the terminals are geographically close to each other, containers could be transported along a huge amount of suitable paths between all nodes. Using a multiple link model and modelling the transfers separately proved simpler and effective.

Let N be the set of nodes. Each node represents a terminal in the network. The links between the nodes represent corridors. In Figure 5 an overview of the model is shown with one path of all possible paths of transporting a container from terminal 1 to 3, i.e. connection $(1 \rightarrow 3)$. As defined before, a *connection* represents an origin-destination pair for a container transport.

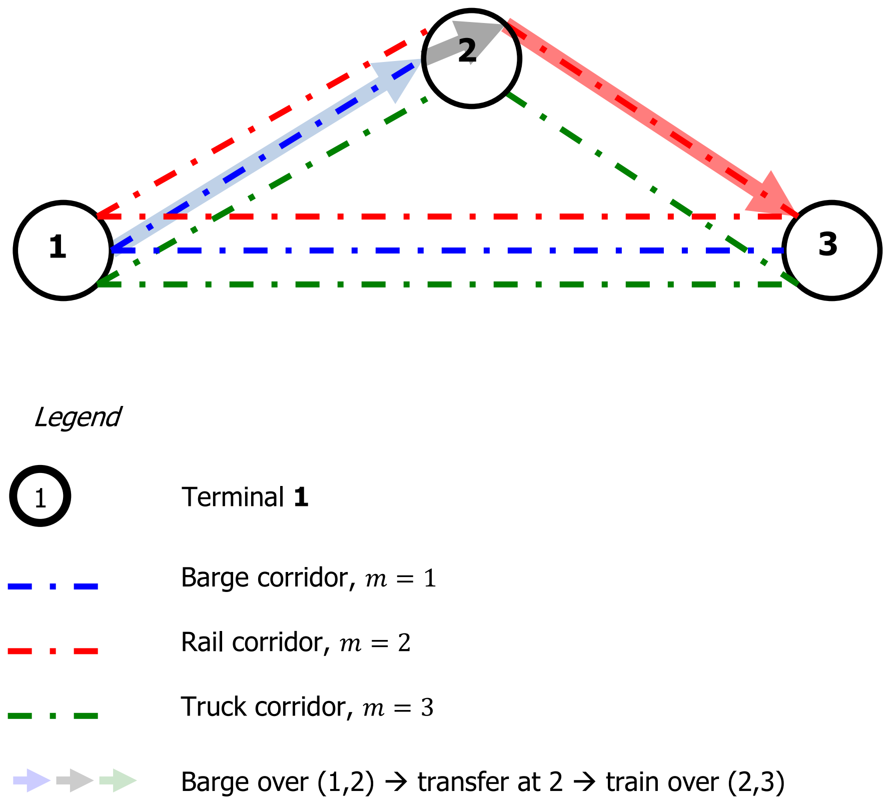


Figure 5 Network model

The figure shows a network model with three terminals and 8 corridors. From terminal 1, transportation to terminal 2 and 3 is possible with all three modes: barge, rail and truck. Between terminal 2 and 3 transportation is possible with either rail or truck. In this case, a path is shown for connection $(1 \rightarrow 3)$. This path uses two corridors with a transfer at terminal 2 from barge to rail.

The set of all corridors is denoted A. The corridor from terminal $i \in N$ to terminal $j \in N$ with mode m is referred to as $(i, j, m) \in A$. The mode is denoted by $m \in \{1, 2, 3\}$, for barge, rail or truck respectively. The set of all connections is denoted C. Note that a connection represents the origin-destination pair for a container, whereas a corridor represents the physical connection between two terminals with a specific mode. The set of all suitable paths is denoted P, where $P_c \subset P$ denotes the subset of paths that connect the origin-destination pair c. Each path has an associated *delivery time* T_p, which denotes the amount of time for the transport from the initial terminal to the final destination. This delivery time includes the transfer time of all transfers. In the next section Methodology (3.3), the approach to find all suitable paths for a connection will be elaborated.

Modelling transportation demand

As this model looks into the network at a tactical level, it is unnecessary to model all individual containers. Instead, all containers that must be transported over the network are categorized in cargo classes. Such a cargo class groups containers based on four properties of the container: the connection, the mass category, the due category and the demand pattern. The cargo class is denoted by (c, w, t, q). The *connection* c represents the origin and destination of the container. For most transports a seaport is either the origin (for import containers) or the destination (for export containers). The terminal closest to the hinterland destination is the other end of the connection. *Mass categories* w are used, as some rail corridors have a limited mass capacity per train. *Due categories* t are introduced to be able to measure overdue deliveries. The quantification of mass and due categories is further specified in section Data (3.4). As was introduced in the beginning of this section, the model represents a single service schedule that must operate well under several demand patterns. Hence, the model can represent several *demand patterns* q for which the schedule is solved simultaneously. In this study, demand patterns are based on the normal distribution of the weekly transportation flow (see Section 3.4 for the quantification of all data). Hence, a demand pattern can be seen as a week's transportation. The model's solution is a service schedule that is optimized for the joint set of demand patterns.

3.2.2 Tactical network model formulation

The mathematical formulation for the model that was described in the previous section is introduced here. The formulation combines aspects of the linear cost and path-based network design (PBND) models (Model 3 and Model 4) that were introduced in Section 2.3.2. The goal of the model is to find the optimal number of services on the available corridors. For this reason, capacity restrictions per corridor are required as in Model 3. On the other hand, the containers that are transported over the network have a due time; hence, the transportation time must be restricted as well. Ishfaq and Sox (Ishfaq and Sox 2011) used a maximum transportation time as a restriction for each route a container could use. In this model, the routes will be formulated explicitly as *paths*, using the formulations of the PBND model (Model 4). In this model three new elements are added. First, a specific mapping between the paths and corridors is introduced, in order to use the aspects of both models in one formulation. Secondly, the time constraint per container is *not* considered a restriction, in contrary to the models formulated by Ishfaq and Sox. Instead, each day of overdue delivery incurs a penalty in the objective value. The daily practice at EGS shows that the delivery date is continuously negotiated with customers, so strict restrictions would not represent the actual case. Thirdly, the model combines self-operated and subcontracted transportation. The model in this study does not explicitly use formulations to represent the economies of scale. However, economies of scale are implicitly included in the selection of the two transport types for the container transportation.

A linear model is created to be able to solve it as a Mixed Integer Program (MIP), equal to the models by Crainic and Ishfaq and Sox on which this model is based. All constraints can be expressed linearly. The only elements that may not behave linearly are the cost structures. Ishfaq and Sox also propose a linear cost structure (Ishfaq and Sox 2012). The accuracy of the linear model of the cost structure will be assessed in the section Data (3.4). The service capacity constraints are based on Model 3. Besides, the model uses the path-based network design formulations of Model 4. The full model and all notations are presented at the end of this section (Model 1), but it is first introduced here step-by-step.

Decision variables

The most important result of the model, the weekly service frequency, is denoted by y_{ijm}. This integer specifies the number of services between terminal i and j with mode m. The allocation of containers to paths is denoted by $x_p^{c,w,t,q}$, indicating the number of TEU from cargo class (c, w, t, q) allocated to path p. Two other variables assist in the mapping from the path allocation to the service schedule: $z_{ijm}^{w,q}$ and $\zeta_{ijm}^{w,q}$. For each corridor (i, j, m), and per mass category w and demand pattern q, $z_{ijm}^{w,q}$ denotes the number of TEU allocated *on self-operated services*; and $\zeta_{ijm}^{w,q}$ denotes the number of TEU that is allocated *on a slot basis*. These variables are determined per mass category, due category and demand pattern.

The final variable τ_p^c denotes the total days of tardiness of containers for connection c on path p. All variables apart from y_{ijm} are relaxed to nonnegative real valued numbers.

Objective

The objective (1) minimizes the threefold objective on economic, environmental and quality targets:

$$\min \sum\nolimits_{(i,j,m)\in \mathrm{A}} f_{ijm}\, y_{ijm} + \sum\nolimits_{(i,j,m)\in A,(w,q)\in W\times Q} c_{ijm}\, \zeta_{ijm}^{w,q} + c_F \sum_p F_p \sum\nolimits_{\mathrm{c,w,t,q}} x_p^{c,w,t,q} + c_\tau \sum_{p\in P} \sum\nolimits_{\mathrm{c}\in C} \tau_p^c + c_e \sum\nolimits_{(i,j,m)\in \mathrm{A}} \left\{ h_{ijm}\, y_{ijm} + \sum\nolimits_{(w,q)\in W\times Q} w e_{ijm}\, \zeta_{ijm}^{w,q} \right\}, \tag{1}$$

where the first two terms represent the fixed cost f_{ijm} per service and variable cost c_{ijm} per TEU. The third term accounts for the transfers, with transfer cost c_F. The fourth measures the number of overdue days with cost c_τ. The fifth term represents the cost for emitting CO_2, with cost c_e per tonne CO_2. The self-operated services emit a quantity of h_{ijm} per service. Secondly, e_{ijm} denotes the emission in tonne CO_2 per tonne cargo on subcontracted services on corridor (i,j,m). This is multiplied by the mass category w and summed over all categories. The values of the cost parameters are subject of the section Data (3.4).

Constraints on path allocation

All containers are grouped in cargo classes (c,w,t,q). A cargo class is transported over one or more paths, but the total transportation must equal the demand for that cargo class $d_{c,w,t,q}$. This is enforced by the demand constraint (2):

$$\sum\nolimits_{p\in P} x_p^{c,w,t,q} = d_{c,w,t,q} \qquad \text{for all } c,w,q. \tag{2}$$

By constraint (3) the path transport is mapped onto corridor variables $z_{ijm}^{w,q}$ and $\zeta_{ijm}^{w,q}$:

$$z_{ijm}^{w,q} + \zeta_{ijm}^{w,q} = \sum\nolimits_{(c,t)\in C\times T} \sum\nolimits_{p\in P_c} \delta_{ijm}^p x_p^{c,w,t,q} \qquad \text{for all } i,j,m,w,q, \tag{3}$$

where the mapping δ_{ijm}^p denotes whether or not corridor (i,j,m) belongs to path p. Note that the transport on self-operated services $z_{ijm}^{w,q}$ is not part of the objective. Hence, transporting TEU on self-operated services is essentially free, as long as capacity remains. The capacity constraints follow next.

Capacity constraints

Constraint (4) and (5) limit the TEU and mass capacity per service, respectively:

$$\sum_{w \in W} z_{ijm}^{w,q} \leq u_{ijm} y_{ijm} \qquad \text{for all } i, j, m, q, \qquad (4)$$

$$\sum_{w \in W} w z_{ijm}^{w,q} \leq m_{ijm} y_{ijm} \qquad \text{for all } i, j, m, q, \qquad (5)$$

where the maximum capacity in TEU of a service (i, j, m) is denoted by u_{ijm} and the maximum mass capacity of service (i, j, m) is denoted by m_{ijm}. The constraints limit the weekly capacity transported on the self-operated services. This must be the case for all demand patterns q. Note that the capacity limits for containers booked on a slot basis are not part of the capacity restrictions. It is assumed than sufficient capacity on external services is always available.

Delivery time constraint

Although late delivery is highly unfavourable in the network transportation, the model allows for some slack in the delivery times. Without the slack, the model may result in very costly solutions to allow 100% on-time delivery in all cases. Constraint (6) calculates τ_p^c as the *total number of overdue days*, i.e. the total *tardiness*, for a specific cargo class c over a specific path p. The time T_p for path p consists of the travel time and the transfer time at the intermediate terminals. The index t denotes the due time for flows $x_p^{c,w,t,q}$. Hence, $(T_p - t)$ denotes the *lateness* of 1 container (a negative value denotes early arrival). This is multiplied by the number of containers $x_p^{c,w,t,q}$. By the nonnegativity constraint on τ_p^c, only tardiness is measured, not *earliness*.

$$\sum_{(w,t,q) \in W \times T \times Q} x_p^{c,w,t,q} (T_p - t) \leq \tau_p^c \qquad \text{for all } c, p \qquad (6)$$

Return trip constraint

In order to get a balanced service schedule, the number of self-operated services moving back and forth to a destination must be equal:

$$y_{ijm} = y_{jim} \qquad \text{for all } i, j, m \qquad (7)$$

Full model formulation

The full model is presented here (Model 1). It consists of the objective and constraints that were introduced here and contains some additional constraint to ensure feasible values of the decision variables. Constraints (8) and (10) are the non-negativity constraints for the container flows. Constraint (9) is the nonnegativity constraint for the number of tardiness days. Constraint (11) is the integer constraint for the number of services.

$$\min \sum\nolimits_{(i,j,m)\in \mathrm{A}} f_{ijm}\, y_{ijm} + \sum\nolimits_{(i,j,m)\in A,(w,q)\in W\times Q} c_{ijm}\, \zeta_{ijm}^{w,q} + c_F \sum_{p} F_p \sum\nolimits_{\mathrm{c,w,t,q}} x_p^{c,w,t,q} + c_\tau \sum_{p\in P} \sum\nolimits_{\mathrm{c}\in C} \tau_p^c + c_e \sum\nolimits_{(i,j,m)\in \mathrm{A}} \left\{ h_{ijm}\, y_{ijm} + \sum\nolimits_{(w,q)\in W\times Q} we_{ijm}\, \zeta_{ijm}^{w,q} \right\} \quad (1)$$

s.t.

$$\sum\nolimits_{p\in P} x_p^{c,w,t,q} = d_{c,w,t,q} \qquad \text{for all } c,w,t,q \quad (2)$$

$$z_{ijm}^{w,q} + \zeta_{ijm}^{w,q} = \sum\nolimits_{(c,t)\in C\times T} \sum\nolimits_{p\in P_c} \delta_{ijm}^{p} x_p^{c,w,t,q} \qquad \text{for all } i,j,m,w,q \quad (3)$$

$$\sum_{w\in W} z_{ijm}^{w,q} \le u_{ijm} y_{ijm} \qquad \text{for all } i,j,m,q \quad (4)$$

$$\sum_{w\in W} w z_{ijm}^{w,q} \le m_{ijm} y_{ijm} \qquad \text{for all } i,j,m,q \quad (5)$$

$$\sum\nolimits_{(w,t,q)\in W\times T\times Q} x_p^{c,w,t,q} \left(T_p - t\right) \le \tau_p^c \qquad \text{for all } c,p \quad (6)$$

$$y_{ijm} = y_{jim} \qquad \text{for all } i,j,m \quad (7)$$

$$x_p^{c,w,t,q} \ge 0 \qquad \text{for all } p,c,w,t,q \quad (8)$$

$$\tau_p^c \ge 0 \qquad \text{for all } c,p \quad (9)$$

$$z_{ijm}^{w,q}, \zeta_{ijm}^{w,q} \ge 0 \qquad \text{for all } \mathrm{i},j,m,w,q \quad (10)$$

$$y_{ijm} \in \mathbb{N} \qquad \text{for all } \mathrm{i},j,m \quad (11)$$

Data sets

A	The set of corridors (i,j,m) on which services can operate
C	The set of connections between origins and destinations
P_c	The set of possible paths for connections c
Q	The set of independent periods where the same schedule of services must apply

T	The set of due categories, with due times $t \in T$ in [days]
W	The set of mass categories, with masses $w \in W$ in [tonne/TEU]
(c,w,t,q)	A cargo class is specified by connection $c \in C$ with mass category $w \in W$, due category $t \in T$ in period $q \in Q$
Data variables	
δ_{ijm}^{p}	Indicator whether corridor (i,j,m) is part of path $p \in P$
c_e	Cost of emitting CO_2 [€/tonne CO_2]
c_F	Cost of a transfer [€/transfer]
c_{ijm}	Cost per TEU for moving a container on corridor (i,j,m) [€/TEU]
c_τ	Cost of an overdue container per day [€/day]
$d_{c,w,t,q}$	Total demand of cargo class (c,w,t,q) [TEU/week]
e_{ijm}	Emission in tonne CO_2 per tonne cargo for corridor (i,j,m) [tonne CO_2/tonne]
f_{ijm}	Fixed cost for operating a service on corridor (i,j,m) [€]
F_p	The number of transfers in path p
h_{ijm}	Emission in tonne CO_2 *per service* for corridor (i,j,m) [tonne CO_2]
m_{ijm}	The mass capacity per service on corridor (i,j,m) [tonnes]
T_p	Travel time on path p in [days]
u_{ijm}	The volume capacity per service on corridor (i,j,m) [TEU]
Decision variables	
τ_p^c	Total tardiness of all containers on connection c over path p [TEU × days]
$x_p^{c,w,t,q}$	The transported TEU of cargo class (c,w,t,q) on path $p \in P$ [TEU]
y_{ijm}	The nr. of services per week between terminal i and j with mode m [-]
$z_{ijm}^{w,q}$	The transportation of TEU of mass category w on self-operated service (i,j,m) in the case of demand pattern q [TEU/week]
$\zeta_{ijm}^{w,q}$	The transportation of TEU of mass category w on external services (i,j,m) in the case of demand pattern q [TEU/week]

Model 1 Linear cost path-based network design model

3.2.3 Alternative formulations

In this research Model 1 is used such as formulated in Section 3.2.2. For further research, some alternative formulations are introduced here. These are not considered in this study, though.

Container sizes

In the formulation of Model 1, all containers are considered according to the number of TEUs. However, transfer costs differ for two 20’ containers and one 40’ container, although both are equal to two TEUs. The following constraints could replace constraints (3,4) in Model 1 to incorporate container sizes. In this constraint, s represents the number of TEU of a container in cargo class (c, w, t, q, s).

$$z_{ijm}^{w,q,s} + \zeta_{ijm}^{w,q,s} = \sum\nolimits_{(c,t,p)\in C\times T\times P_c} \delta_{ijm}^{p} x_p^{c,w,t,q,s} \qquad \text{for all } i, j, m, w, q, s$$

$$\sum_{(s,w)\in S\times W} s z_{ijm}^{w,q,s} \leq u_{ijm} y_{ijm} \qquad \text{for all } i, j, m, q$$

If this constraint is applied, the other formulations with $x_p^{c,w,t,q,s}$ need to be summed over t as well.

Delivery times

Ziliaskopoulos (Ziliaskopoulos and Wardell 2000) used specific values for transfer times from one mode to another. In this study a fixed transfer time is included in the path time for reach transfer. In the proposed model, the waiting times at intermediate terminals are not taken into account. Ishfaq and Sox used a delay factor for intermediate transport legs (Ishfaq and Sox 2011). However, they also state that reducing the due time has a similar effect as increasing the delay factor. In this study, this alternative approach is used: due times are reduced compared to the actual case to incorporate the waiting times at intermediate terminals. Alternatively, an explicit formulation using the inverse of the service frequency may be used as an estimate of the waiting time between two services. This would make the problem nonlinear, though. If such a formulation for the waiting time would be included, the reduced due times t should be corrected too.

Service paths

Services may or may not call at several terminals in a cycle. In Table 1 the possible locations in the network are listed that may be connected as a multi-stop. The influence of these service-specific routing can be added by using a similar path-based formulation for the trains or barges as is used for the containers. However, this would make the mathematical formulation far more difficult to solve. For the problem under consideration, the selection of services on corridors, this is now not considered. In a future research, the influence on the planning may be of interest.

Terminal combinations for multi-stops
Moerdijk-Venlo
Moerdijk-Willebroek
Moerdijk-Duisburg
Duisburg-Venlo
Duisburg-Neuss-Stuttgart-Basel-Strasburg
Delta-Euromax-Home

Table 1 Possible locations for multiple stops of a single service

3.3 Methodology

In this section the research methodology is introduced, to find the optimal solution for the model that was introduced in the previous section. The optimal solution consists of the values for the decision variables that result in the minimum of the global objective. I.e., this is the schedule for a week that is able to fulfil the demand of all demand patterns with a minimum amount of cost. Note that in this sense, the minimum costs refer to the minimum of the threefold objective, including the transportation cost, CO_2 and tardiness components. To find this minimum, a series of steps is carried out:

1. Determining general transportation parameters
2. Determining paths P_c
3. Solving the MIP model optimally with CPLEX 12.4

The first two steps are considered as pre-processing, the third step is the actual solving of the model. The next sections address these. In Section 3.3.2 the used MIP solution strategy is described, but also some alternative heuristics are introduced.

3.3.1 Pre-processing

In the first step, parameters are determined as function of transport distance, based on the data for existing EGS connections. The parameters are generalized to be able to use the model for new corridors as well. Then, in the second step, for all connections, the set of suitable paths is determined. The first two steps are pre-processing steps for the actual experiments. In the third step, experiments are carried out, i.e. the model is solved. To answer the research questions, several experiments are carried out using different variations of the input parameters. The values of the input parameters are described in Section 3.4. The results of the other two steps including the experiment plan are subject of Chapter 4.

Step 1: Determining general transportation parameters

The model is introduced to find optimal service schedules for intermodal transportation networks. As a basis for this type of networks, a model of the EGS network is used. In order to determine the general cost parameters that describe this type of networks, for each mode a generalized set of parameters is determined. These parameters are all estimated as a linear function of the transportation distance:

$$c_{ijm} = \alpha d_{ijm} + \beta$$

Here, α and β are the parameters to be estimated in order to approximate the cost c_{ijm} based on the distance d_{ij} between the terminals i and j using mode m.

The transportation demand is modelled with normal distributions based on the historic transportation on the EGS network. The results of these generalizations are subject of the section Data (3.4).

Step 2: determine paths P_c

This step is meant to identify all paths that can be used in the network. All paths that could reasonably be used for a transport of connection c should be included in P_c. Note that connection c refers to all containers that have the same origin and the same destination and thus share the same set of suitable paths. The smaller the set of paths in P_c, the easier the model can be solved. One could choose to let a user specify the set of possible paths for each connection. However, with a too small set, the final solution may not be optimal. Because of the small distance between the three seaports of EGS, a lot of paths may be suitable for all connections between Rotterdam and the hinterland. In order to find all these paths an automatic procedure is developed. The following procedure is repeated for each connection in the network.

For the transport of hazardous material, research is done on finding dissimilar paths to spread risk, such as by Akgün et al. (Akgün, Erkut et al. 2000). The main goal is to find paths of acceptable length with as few common links as possible. Several methods are discussed to select dissimilar paths from a generated set of *k-shortest paths.* However, for our application the dissimilarity of the paths is not relevant; only the set of short paths is required. To find a reasonably small set of suitable paths, we try to find all paths that take less time than n times the shortest path. Boardman et al. (Boardman, Malstrom et al. 1997) used a k-shortest path method to assist transport bookers to select feasible routes. In this study Yen's method (Yen 1971) is used to find k shortest paths without loops. The exclusion of paths with loops is evident in the case of container transportation.

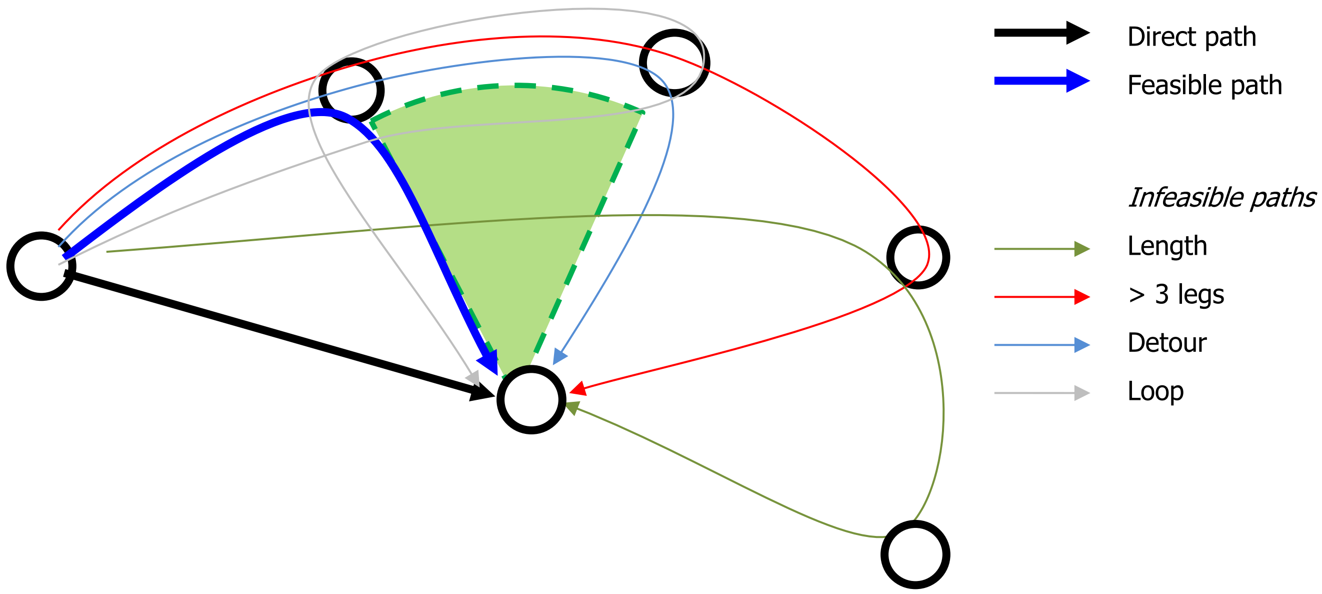


Figure 6 Path selection

The shortest paths are determined based on the travel time between the terminals *by truck,* see Figure 6. As long as the k^{th} path is shorter than n times the shortest path, more paths are generated, with n a given threshold. Hence, all paths are determined that have a delivery time

$T_k < n \min_k T_k$, $(n \geq 1)$. This means that we exclude all paths with a delivery time longer than n times the shortest path. In this study, a threshold of $n = 3$ is used, because a larger detour than this is considered undesirable in the EGS organisation, as indicated by the operational planning manager.

To further decrease the size of P_c, all paths with excessive detours are omitted as well. Let T_{iD} denote the time required for the direct transport from terminal i to the final destination D. Now, if for any leg (i, j) the direct transport time becomes m times larger, the path is omitted. Thus, if for any i in path p the following is true, the path is omitted: $T_{iD} \leq mT_{jD}$, $i < j$. In this study, a value of $m = 1.1$ is used. This allows paths in which some legs may bring a container slightly further away from the destination, but no more than 10%. Again, this is considered the limit for detours by the EGS organisation, as indicated by the operational planning manager.

Finally, only paths consisting of maximally l legs are used. In this study, a maximum number of $l = 3$ is used, i.e. a maximum of 2 intermediate transfers. The effect of allowing 3 intermediate transfers was studied as well, but proved insignificant as will be shown in Chapter 4.

To summarize the path generation procedure: all paths are selected that take by road maximally three times the time of the shortest path, none of the legs increase the distance to the destination more than 10% and each path uses maximally four terminals (three legs).

In the example of Figure 6, two paths remain after this selection; a direct path and an indirect path with an intermediate transfer. Each path is now translated into intermodal paths (see Figure 7): all combinations of barge and rail corridors on the path's legs are formed. Truck corridors are only used as start or final leg, or if no other mode between two terminals is possible. Truck transport on intermediate legs is not a solution that occurs in practice, as indicated by the EGS operational planners. In Figure 7 this results in 6 paths with an intermediate transfer and 3 direct paths.

For each of the paths, also the number of transfers F_p in the path p is pre-processed. A transfer consists of an unloading and a loading handling, i.e. two handlings. A path that has only 1 leg still is accounted for 1 transfer, as the container requires two handlings. A 3-leg path, counts for 3 transfers, following the same reasoning. As a result, a set P_c is found per connection c. To use this in the model, the set is translated into the parameters δ_{ijm}^p that denote which corridors belong to path p:

$\delta_{ijm}^p = 1$ if corridor (i, j, m) belongs to path p

$\delta_{ijm}^p = 0$ in all other cases

Also the total transportation time T_p on each path is pre-processed in this step, including the time required for transfers in the path.

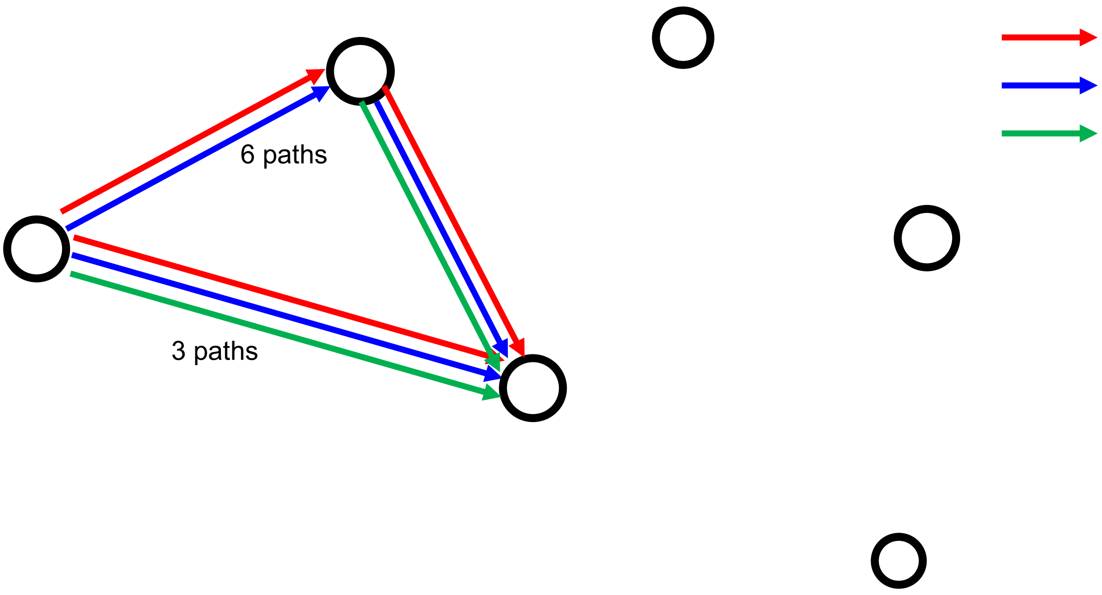


Figure 7 Intermodal path generation

3.3.2 Solving the model

Step 3: Solving the MIP model optimally with CPLEX 12.4

The path-based network design (PBND) formulation was introduced in Section 3.2. The results of the first two steps provide the input for all parameters of the model. The model is solved using the software package AIMMS 3.12. This package uses the CPLEX 12.4 algorithm to find the mathematical optimum of the objective function in the Mixed Integer Programming (MIP) model. As was found in the literature review of tactical network problems, solving MIP formulations to optimality may take a long time (Crainic 2000). AIMMS allows the user to stop the iterations if a solution that is guaranteed to be within a certain factor ε above the minimum. The formulations in this study were simplified by pre-processing the path data (Step 2) and the problem instance is relatively small. Hence, results within 10% of the optimum are found in seconds, and optimal solutions can be found within approximately 1-5 minutes. The precise computation times are reported with the results in Chapter 4. If future experiments with this model prove more difficult due to larger problem instances, an alternative solution strategy is shortly introduced below. This solution strategy is not implemented for this study, though.

Heuristic approach

In this study, all problem instances could be solved to optimality with the MIP solution method described above. To solve larger problem instances some alternative solution strategies are introduced here. These strategies were not investigated, though. A similar approach may be used as the method described by Ishfaq and Sox (Ishfaq and Sox 2011). In their strategy they used a lagrangian relaxation method to find tight lower bounds for their model. The approach is to add those constraints to the objective that contain different sets of variables. The remaining constraints make up simpler sub problems with only one variable set each. By solving the lagrangian multipliers, the solution can be found. Model 1 also consists of two sets of decision variables: path-based variables ($x_p^{c,w,t,q}, \tau_p^c$) and corridor based variables ($y_{ijm}, z_{ijm}^{w,q}$). By using Lagrangian relaxation of the constraint that contains both sets, constraints (3), the model will be split in two simpler sub problems.

For large problem instances, Ishfaq and Sox used a tabu search method, which was already shortly described in Section 2.3.1. In their hub allocation model, the 2-exchange neighbourhood was searched for the best possible improvement. The 2-exchange neighbourhood in their case are all solutions in which a hub and a non-hub node are interchanged, compared to the current solution.

In the case of this study a tabu search could be performed by searching the neighbourhood of adding or removing a specific service. As the total number of services is not fixed, an interchange between a selected and a non-selected service is not required.

3.4 Data

This section concludes the research approach chapter. Here the actual data that is used during this study is described. To protect the confidentiality of some of the EGS data, two confidentiality factors are introduced in 3.4.1. Subsection 3.4.2 introduces the generalized network data, based on the EGS network. The network data consists of transport times, costs and volumes per corridor. In Subsection 3.4.3 the demand data is introduced. Here is explained how the historic network data is used to generate the demand patterns for all cargo classes.

3.4.1 Confidentiality factors

To protect the confidential nature of some of the data that is used in this study, two confidentiality factors are introduced, one for the TEU volumes and one for the costs. All TEU volumes are multiplied by factor α. This includes all demand volumes and capacity volumes. Secondly, all costs are multiplied by factor β. This includes all costs for subcontracted and self-operated transportation, transfers, CO_2 emissions and tardiness. The cost of operating a service is multiplied by both factors, in order to keep the correct balance between the cost structures. All results with volumes and costs are reported with these same factors in this study. However, the costs per tonne CO_2 is reported without the factors, because it comes from a public source. The same holds for the volumes and mass capacities of 3.4.2. In contrary to the publication in this report, these parameters are factored in the implementation of the model, of course.

Naturally, the value of the factors is not published.

3.4.2 Generalized network data

This research considers hinterland transportation in extended gate networks, such as EGS. The model is evaluated using a generalized network description of EGS. In this part, the generalized network will be introduced as used in this study. It is based on information of EGS Business Development and EGS transportation planners.

Terminals

The set of terminals that are part of the network can be found in Table 2. For the sake of clarity, a distinction between seaports and inland terminals is made. In the model all terminals are modelled in the same way, though. The geographic location of terminals can be seen in Figure 1 (Chapter 1).

Seaports Rotterdam (RTM)	Inland terminal
Delta (including APM)	CCT Moerdijk
Euromax	Dortmund (CTD)
Home (including Rotterdam city depots)	Duisburg (DeCeTe)
	Neuss (NSS)
	Nuremberg (NUE)
	TCT Belgium
	TCT Venlo

Table 2 Network terminals

Corridors

Corridors represent the routes between these terminals that can be operated by barge, rail or truck. Truck transportation is possible from and to all terminals. Barge and rail transportation is limited, as not all terminals can serve barge or rail. A barge or rail corridor exists only between terminals that can accommodate these. Table 3 shows which modes can be accommodated at the hinterland terminals. The seaport terminals in Rotterdam (Delta, Euromax and Home) accommodate all modes. The distances in the table are those as measured from the Delta terminal. An overview of the possible corridors is presented in Figure 8.

	Road distance [km]	Water distance [km]	Barge	Rail
CCT Moerdijk	74	58,4	✓	-
CTD	297	-	-	✓
DeCeTe	244	242	✓	✓
NSS	257	280	✓	✓
NUE	708	-	-	✓
TCT Belgium	153	165,8	✓	-
TCT Venlo	201	215,1	✓	-

Table 3 Data per hinterland terminal

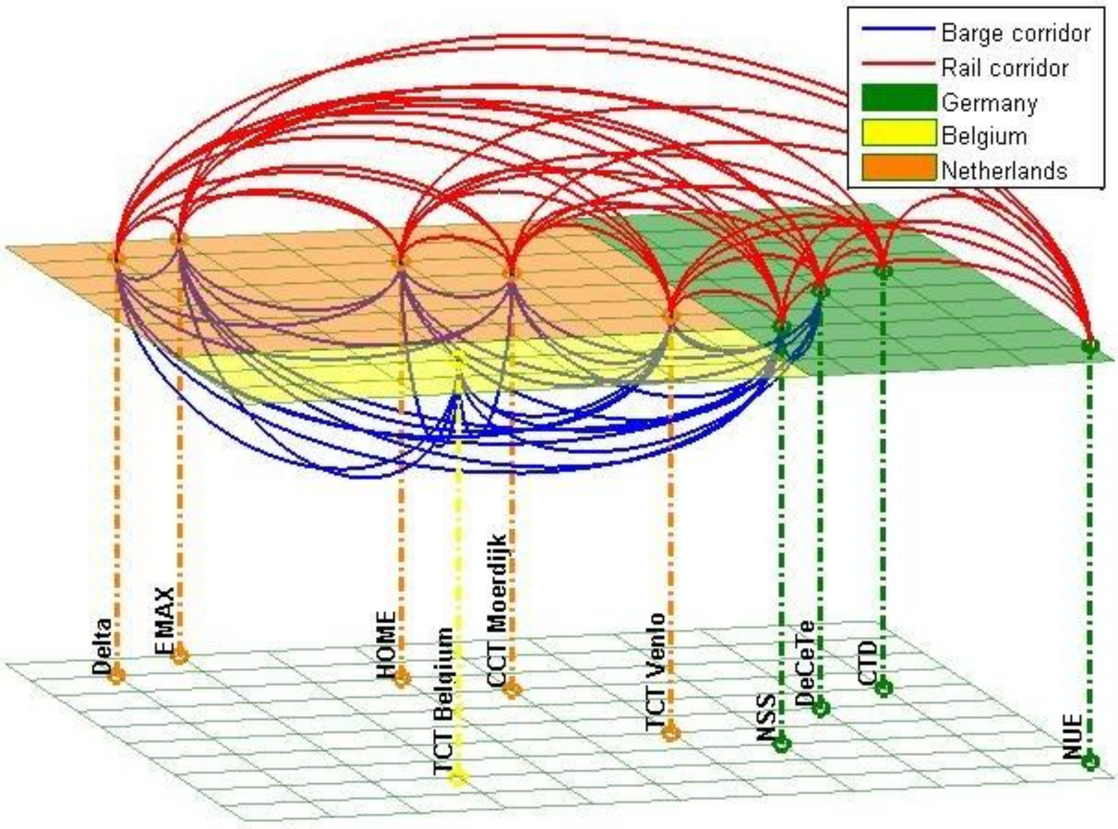


Figure 8 Generalized network overview

Costs

In Figure 8 a large set of corridors is visualised. In the generalized network, all these corridors are considered when creating a service schedule. Note that the positions of the terminals in Figure 8 are not to scale. On each barge or rail corridor, the transport can be carried out in two different ways:

1. By other operators. Hence, only the transportation cost per container is calculated. This is called *subcontracted transportation* in this study
2. By the network. In this case, only costs for the service are calculated. In this study, this is called *self-operated transportation*.

The costs for both types are estimated with a linear approximation, based on known tariffs within the EGS network. An approximation is used in order to represent a general version of the network. Also, in this way, the costs for new corridors can be incorporated as well. The resulting cost structures are reported in Table 4. Where applicable, the *mean relative error (MRE)* is reported. A description of the approach to find these estimations is added as Appendix C.

		Barge	Rail	Truck
Sub-contracted	Cost[1] [€/TEU]	$18.78 + 0.14d_{ijm}$	$25.42 + 0.16d_{ijm}$	$76.4 + 1.03d_{ijm}$
	MRE	15%	14%	4%
Self-operated	Cost[1] [€/service]	Benelux: $7083 + 1.79d_{ijm}$ Rijn: $8784 + 4.73d_{ijm}$	Diesel: $7.60d_{ijm}$ Electric: $11.43d_{ijm}$	-[2]
	MRE[3]	-	-	-
Capacity	[TEU]	Benelux: 192 Rijn: 380	Diesel: 84 Electric: 100	-
	Mass [tonne]	-	Diesel: - Electric: 1000	-
Transfer	Cost[1] [€/TEU]	23.89	23.89	23.89

Table 4 Network cost structure

[1] Note that costs are multiplied by the confidentiality factor β.

[2] Trucks are not operated along service schedules but always on a subcontracted basis.

[3] Based on single case. No MRE available. See Appendix C for details.

For all modes, subcontracted transport is possible. A linear approximation is used to represent these costs, based on the distance between two terminals for this mode. Self-operated services are only possible for barge or rail transportation. The costs for such a service are also approximated linearly based on distance. Two types of barges are considered: 192-TEU vessels on Benelux corridors, 380-TEU vessels on corridors between Rotterdam and Germany, based on the information by EGS Business Development. Rail services are split up in electric and diesel trains. Electric trains are used where possible; diesel trains are used from and to TCT VENLO and CCT MOERDIJK. Only on electric trains a mass restriction is considered. All other mass restrictions are neglected in this study as they are seldom limiting, as indicated by EGS transportation planners.

For all transports, the same (un)loading costs are used. These terminal handling costs include two handlings; both unloading and loading are included. Based on an EGS expert's opinion, the cost of two handlings, a transfer, is set to €23.89. Also, the time for such a transfer is set to 4 hours, which is currently seen as the minimum time required for a transfer.

CO_2 emissions

In relation to the reduction of CO_2 emissions, the emission of CO_2 per corridor must be determined. All CO_2 emissions are based on the STREAM report (den Boer, Brouwer et al. 2008) that was introduced in 3.1. All emissions are based on the well-to-wheel principle. In the STREAM report, an average mass of 10 tonnes per container is used. In this study, the average mass of EGS containers in the period of January 2011 to June 2012 is used: 9 tonnes. Likewise as with the cost structure of the previous section, the CO_2 emissions are determined for entire services and for single TEU transports. The truck emissions are based on the data for trucks with a capacity of 10-20 tonnes and an average occupancy of 33%. The barge emissions are estimated from the STREAM data of barges with 100, 270 and 470 TEU capacity, with occupancy 65%. The rail emissions are scaled from the data for 90 TEU trains, with occupancy of 87%. As the well-to-tank emission for electricity production, the STREAM data for an average energy mix is used: 180g/MJ.

The resulting emissions are presented in Table 5. A more detailed cost summary is added as Appendix E.

		Barge	Rail	Truck
Sub-contracted	CO_2 [g/tonne-km]	34	Diesel: 31.8 Electric: 25.4	98.2
Self-operated	CO_2 [g/tonne-km]	Rhine: 77,030 Benelux: 31,650	Diesel: 13,130 Electric: 16,420	-

Table 5 Network CO_2 - emissions

3.4.3 Transportation demand

The second category of model input is the demand for transportation over the network. The demand is based on the historical data of the actual container transportation over the EGS network in January 2011 – June 2012. In Figure 9, the historic weekly demand since 2009 is shown, including a two-period moving average (2-MA). Although some periodic behaviour and a growth trend may be recognized from the figure, these are neglected in this study.

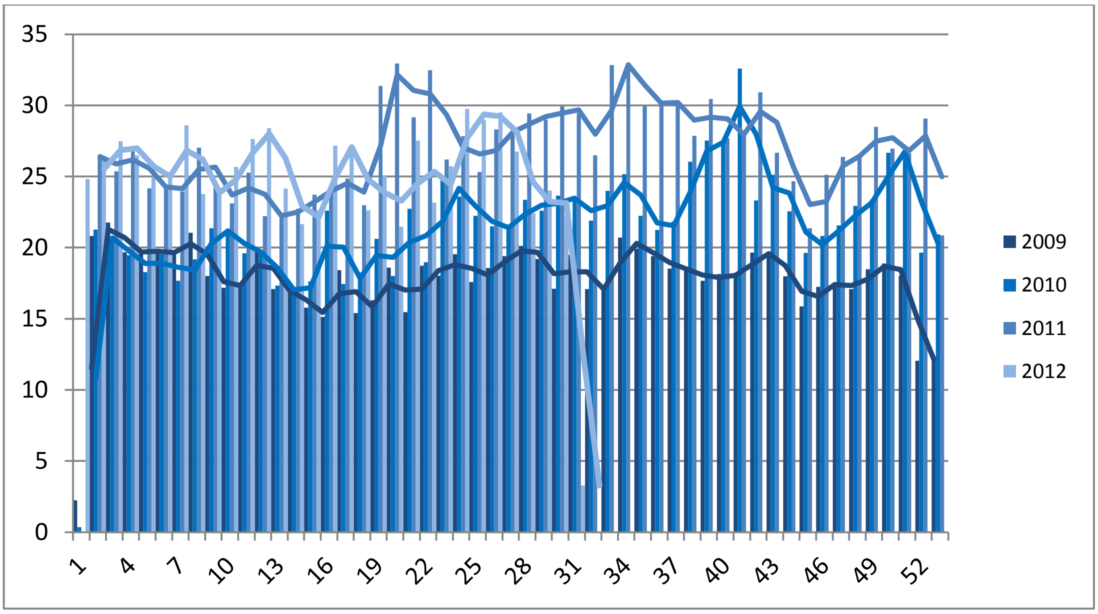


Figure 9 Historic transportation demand on the EGS network

In this study the data since 2011 is used. Before 2011, the network existed of a smaller set of terminals, which makes the data less diverse. The data is used to create cargo classes for each origin-destination connection. The demand on a single connection is split into several mass and due time categories. These demands are denoted in the model by $d_{c,w,t,q}$, for cargo class (c, w, t, q): the demand on connection c, with mass category class w, due time t and demand period q. The weekly transportation demand for each cargo class is modelled as a normal distribution, measured in TEU per week. Note that all demand volumes are multiplied with factor α. The model of Section 3.2 is set up to create a schedule for multiple periods, denoted by q. The normal distributions are translated into ten periods, by using 10-percentile fractions of the demand distribution. So, a single service schedule is created, evaluated in all ten of these 10-percentile demand situations. Per period, the same percentile of the demand on all connections is considered. The influence of local demand fluctuations is not considered. Mass categories are determined by the average mass in 4 categories of 10 tonnes. These categories are listed in Table 6. The due times of demand cannot be based on EGS network data, as this information is not recorded. Instead, an estimate by an EGS operational planning manager is used. These due times are estimated, considering that the waiting time at terminals is not included in the tactical model. Hence the due times are shorter than in the real-world situation, as suggested by Ishfaq and Sox (Ishfaq and Sox 2011). The due time categories are presented in Table 7.

Category [tonnes]	Average mass [tonnes/TEU]
Empty	2070
0-10000	5,500
10000-20000	13,900
20000-30000	24,600
>30000	30,400

Table 6 Average mass per category (based on all EGS network transport)

Due time [days]	Fraction [%]
0.5	20
1	40
2	30
7	10

Table 7 Due time categories (estimate)

In Appendix D the approach to find the demand patterns is elaborated in more detail. Using the historic transport flows is not necessarily a good approximation of the historic demand: the lost sales due to fully booked services are not measured in this way. However, as EGS is still in development, most transport requests are accepted and transported. It is assumed that lost sales are not a large factor.

Overview Chapter 3

> *Chapter 3 introduced the linear cost path-based network design model (Section 3.2). Also the model objective was determined, using economic, environmental and quality aspects of the container network transportation (Section 3.1). The 3-step methodology to solve the model was described in Section 3.3. The first step, determining the network parameters was described in Section 3.4. The experiments with the model are subject of Chapter 4.*

Chapter 4. Determining a weekly service schedule

In Chapter 3 the tactical network model was introduced. The model formulation, the methodology to find the solution to the model and the data are described in that chapter. The solution of the model results in the optimal weekly service frequencies to satisfy the demand patterns for transportation over the network. In this chapter, the experiment plan is described in Section 4.1. The validation of the model is described in Section 4.2. Subsequently, Section 4.3 covers the results for the various experiments. The results of Part I are summarized in Section 4.4.

4.1 Experiment plan

In order to find the weekly service schedule, the model is validated first. Subsequently, experiments are carried out for the generalized case of the EGS network. To validate the results, the model is solved with settings similar to the current EGS network case, i.e. without intermediate transfers. Only direct connections are allowed. If the resulting service schedule is similar to the actual service schedule, this shows that the model with the generalized costs is an accurate approximation. If not, the model is not correct, or the current operation is very inefficient. The latter is unlikely. The validation is presented in Section 4.2.

Subsequently, several experiments with the generalized model are carried out. In the basic case, the experiment is carried out as described in the Section Methodology (3.3). For this case, only paths with a maximum of 3 legs (2 transfers) are allowed. A transfer costs €23.89[1]; each day that a container is overdue costs €50,-[1]; the emission of 1 tonne of CO_2 is assigned a cost of €8,-[2]. Each corridor can be operated by self-operated services and/or subcontracted services. The demands of the current network are used, where the service schedule is determined for all 10-percentile demands simultaneously as described in Section 3.4.3. Then, several other experiments are carried out to find the influence of these parameters.

At the end of this section, an overview of the experiments is provided in Table 8. The validation and basic case are denoted by experiment A and B, respectively. To validate the assumption that paths with maximally 2 transfers suffice, the basic case is also tested with all paths that consist of maximally 3 transfers (experiment C). The other experiments are introduced next by denoting what settings are changed with respect to the basic case. The results are described in Section 4.3. All results are summarized in Section 4.4.

[1] Masked by a confidentiality factor.

[2] Not masked by a factor in the report, as this number is based on public resources. Naturally, the confidentiality factor is applied to the CO_2 the computations of the study.

Impact of transfer costs

Experiments D-G assess the impact of the cost of transfers. Experiment D considers the hypothetical case where no transfer costs apply at all. This case is considered because the strong intertwinement of transportation and terminal activities in the business of ECT and EGS. Although transfers will never be free of charge, this is considered as an extreme case. Experiment E and F consider the case where the transfer costs are half those of the basic case, for maximally 2 and 3 intermediate transfers per path, respectively. Experiment F is done again to check the assumption of maximal two intermediate transfers.

Influence of due times

To evaluate the time pressure in the network, two cases are considered where the overdue costs are neglected. Hence, the due times of the transported containers don't matter in the experiments G and H. In experiment G, the transfer costs are also neglected. The latter reduces the model to a simpler flow model, without impact of due times and transfer costs and is mainly interesting for analytical reasons, not so much for practical reasons.

Impact of costs for CO_2-emissions

The CO_2-emissions per TEU are in the order of 30g/tonne-km for subcontracted transports. This corresponds to a CO_2-emission in the order of 0.06 tonnes for a regular transport, or roughly €0,50[1]. Hence, CO_2-emissions are not expected to have a large influence on the solution. To evaluate the possible impact of CO_2, the basic case is solved with a tenfold CO_2-emission price of €80[1] per tonne in experiment I.

Necessity of subcontracted transportation

To assess the importance of subcontracted transportation, the basic case is also solved without the possibility to use subcontracted transportation (Experiment J). This will show the benefit of allowing both subcontracted and self-operated transport in the model.

Demand: growth and fluctuation

Part I of this study aims to find an optimal service schedule for the EGS in the near future. Hence, the demand growth for the next couple of years should be assessed. The Port Authority of Rotterdam has presented the Port Vision 2030 (Port-of-Rotterdam 2011-2). This vision includes four growth scenarios until 2030:

- Global economy
- High oil price
- Low growth
- European trend

---

[1] Not masked by a factor

To apply the tactical network model for next year's situation of EGS, for two scenarios the yearly growth rate is determined, assuming it is constant during the period from 2010 to 2030. In the low growth scenario, this still amounts to 2.5% for container transportation. In the European trend scenario, the yearly growth rate is 4.2%. The global economy scenario has a yearly growth rate of 5%, but is not used in this study. To show the impacts of growths over multiple years, the basic case is also assessed with growths of 10% and 25%. Experiments K-N consider the demand growths 2.5%, 4.2%, 10% and 25%.

Apart from these growth scenarios, another aspect of the demand is assessed. In all experiments before, the optimal service schedule was determined simultaneously by ten cases of 10-percentiles of the normalized demand. Now, also four solutions are found where the 10 demand cases were selected randomly from the normal distribution. These four solutions are denoted as experiment O.

The most important results of the experiments are described in Section 4.3. The results of all experiments are summarized in Section 4.4. First the validation experiment is described in Section 4.1.

Experiments	
A. Validation (no transfers)	I. Tenfold costs for CO_2-emissions
B. Basic case	J. Only self-operated services
C. Basic case (max 3 transfers)	K. Basic case with 2.5% growth
D. Free transfers	L. Basic case with 4.2% growth
E. Half transfer costs (€11.95)	M. Basic case with 10% growth
F. Half transfer costs (€11.95), max 3 transfers	N. Basic case with 25% growth
G. Free transfers, no overdue costs,	O. Basic case with 10 periods of random demand (4x)
H. No overdue costs	

Table 8 List of experiments

4.2 Model validation with current case

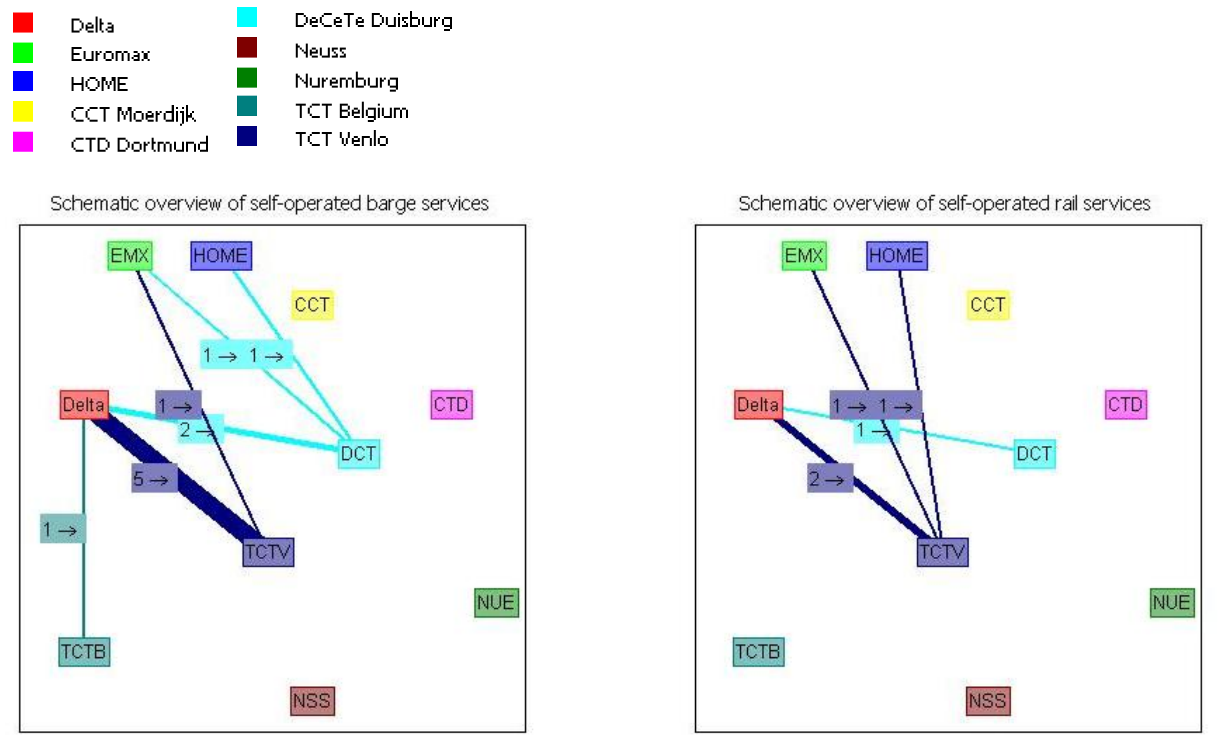
Transfers of containers are not used in the EGS transportation planning, currently. To approximate the current EGS network case, the model is solved using only paths of 1 leg, i.e. direct connections. To check whether the generalized transportation costs can be used throughout this study, the resulting service schedule is compared to the actual service schedule. The resulting service schedule is presented in Figure 10 for both the current EGS case as for the results if the validation experiment A. Note that the number of subcontracted services does not follow from the model results. Instead, the total transported volume is depicted in the bottom Figure 11. The size of the minimum and maximum flow are indicated. The actual sizes of the real-world EGS transportation flows are unfortunately not available. Alternatively, the number of available subcontracted services is shown in Figure 11.

Several differences between the current case and the validation exist. These are assessed here:

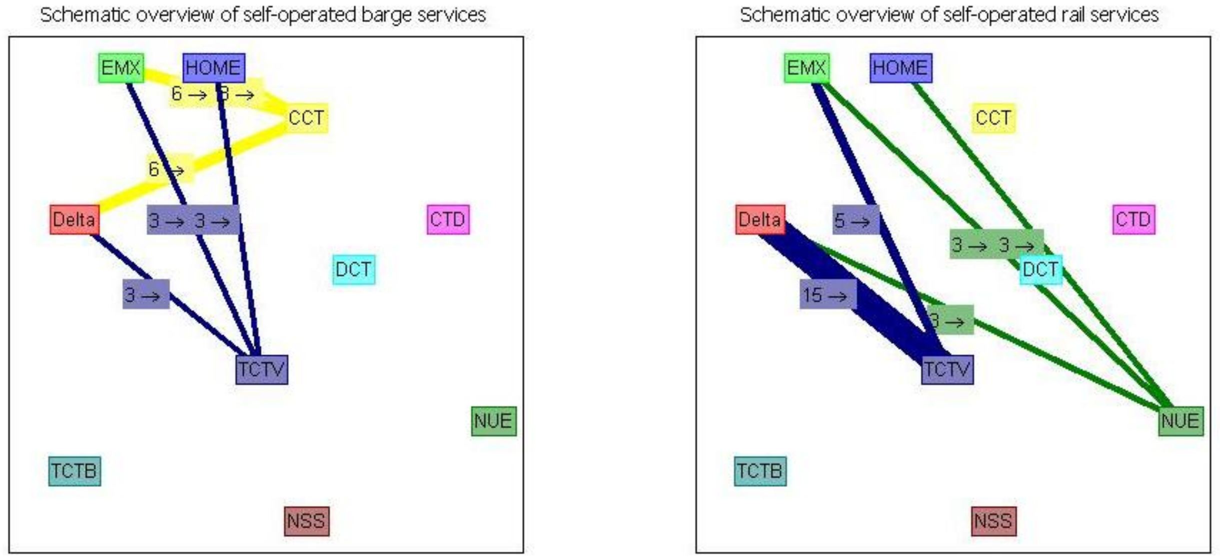
- To compare the number of weekly services in the model solution and the current practice, note the following: in practice, several multi-stop services exist that call at all three seaports and travel then to the hinterland. In Figure 11, these are shown as separate services between the seaports and the hinterland. As the model is for a large part capacity driven, a comparison should be made on the number of inland barges and trains, not the number of connections. When the multi-stop services are counted as 1 voyage, the current EGS network uses 64 self-operated services (9 barges and 23 trains in both directions). The model solution selects 32 services (11 barges and 5 trains in both directions). The differences are mainly caused by the large number of trains between Rotterdam and Venlo (40 a week) of which not all data was available for this study. Hence, the model selected only two trains on this corridor. Secondly, the tactical model does not take the effects of the daily departure schedule into account, but only selects the number of required services based on capacity.
- The model selects subcontracted transport towards Nuremberg. In the current EGS operation, these trains are self-operated for commercial reasons, as no existing connection existed yet.
- The transportation between TCT Belgium and TCT Venlo is carried out per truck in the model solution (not shown in the figure). In practice, a barge connection is used. The model selects truck to meet delivery demands. In practice, these delivery demands are not so tight on this specific connection. The model did not select truck corridors elsewhere in the network.
- The corridors to CCT Moerdijk are carried out with a self-operated barge in the current EGS network. However, the model solution selects subcontracted transports for cost efficiency on this short connection. Within the EGS department, this was recognized as well. However, a self-operated barge is used to ensure a reliable and fast connection.
- Finally, the model solution shows both self-operated and subcontracted transport from Rotterdam to the hinterland. E.g. a self-operated train from DELTA to Duisburg is selected,

while a subcontracted rail connection from EUROMAX to Duisburg is also used. In real-world practice, this is a multi-stop connection that is self-operated for both terminals. This use of multi-stop connections is not possible in the network model.

The validation result show differences with the current case of the EGS network. All of these differences could be explained, though. If the differences between the model results and the current EGS case are kept in mind, the model is fit to assess the future typology of the EGS service schedule.

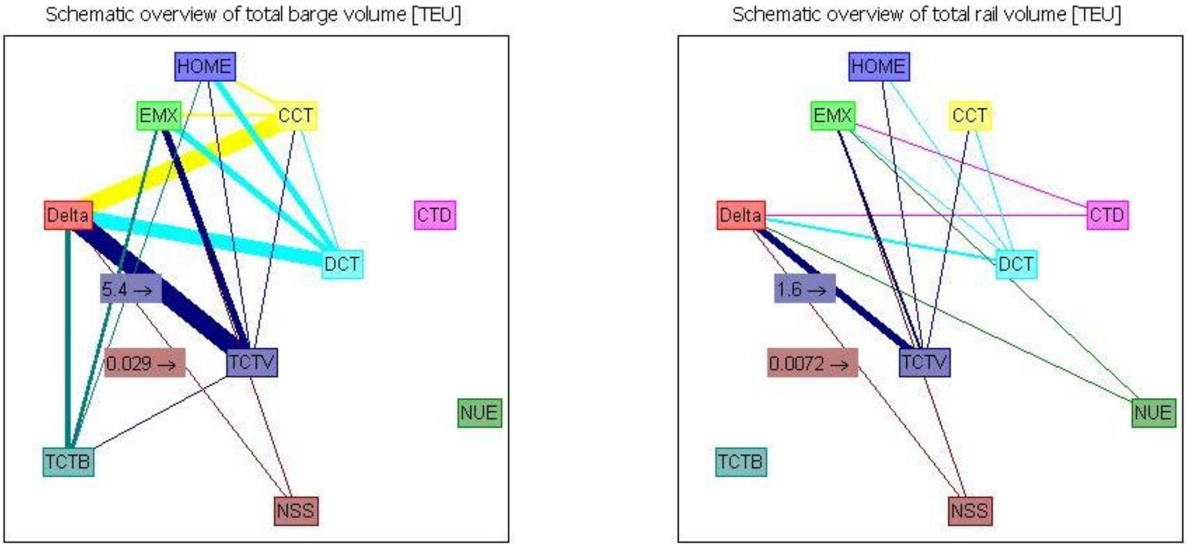


a) Validation results (Experiment A)

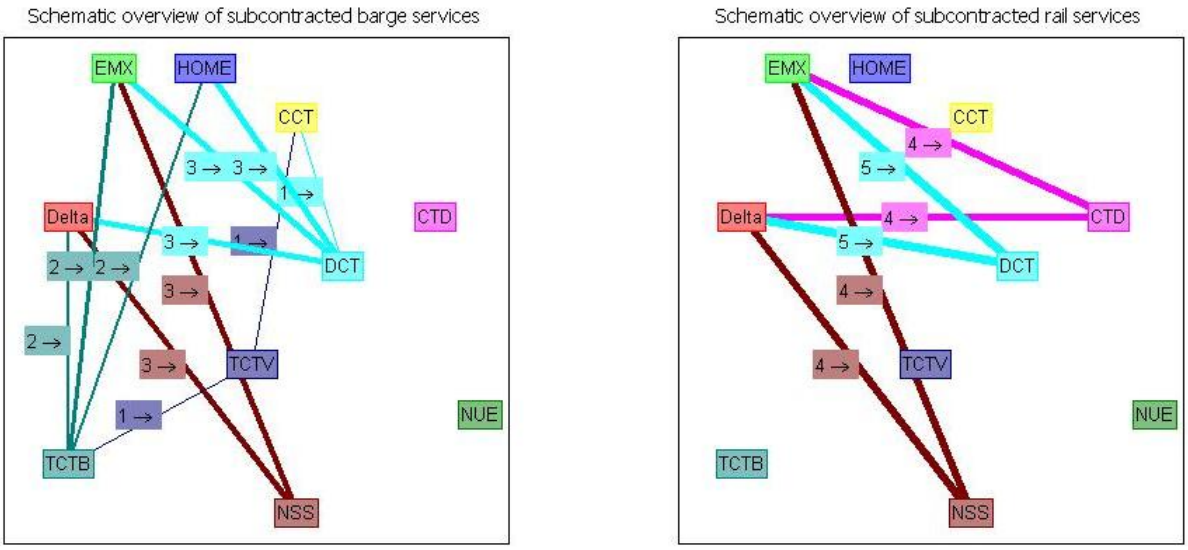


b) Current EGS case

Figure 10 Self-operated services



a) Total transportation volume in validation (Experiment A)



b) Number of subcontracted services in current EGS case

Figure 11 Total volume (experiment A) and subcontracted services (current EGS case)

4.3 Experiments

The experimental plan was introduced in Section 4.1. In this section, the results of some of the experiments are visualized in the same way as the validation results. To make a good comparison between the several experiments, all results are summarized in Section 4.4.

Basic case

The selected self-operated services of the basic case are shown in Figure 12. The basic case is the case where a maximum of two intermediate transfers are allowed. The service frequency results are identical to the results of the validation experiment. The bottom half of Figure 12 shows the entire volume of container transports in the network. Note that the width of each line denotes the relative size of the transportation on that corridor. The maximum and minimum flow sizes are indicated. In the figure, no distinction is made between self-operated or subcontracted transports. The color of the lines denote to what inland terminal the line is connected. It can be seen that some transports use cross connections in the hinterland now: both from TCT Venlo and from DeCeTe (Duisburg), connections towards the inland terminals are made, such as NSS (Neuss), CTD (Dortmund) and NUE (Nuremburg). Again, one truck connection was selected from TCT Belgium to TCT Venlo (not shown in the figure). Two types of transfer can be recognized from the figure:

- Barge transport from or to the seaport, with a rail leg in the hinterland, e.g. between DeCeTe and Nuremburg or CTD Dortmund.
- Consolidation of cargo in the seaport, with a combined leg to or from the hinterland. E.g. the shipment between EMX (EUROMAX) to DELTA: inspection of the data showed that this flow consists of cargo from Venlo via DELTA to EUROMAX.

In the remainder of this section, the differences of the other experiments compared to this basic case will be described.

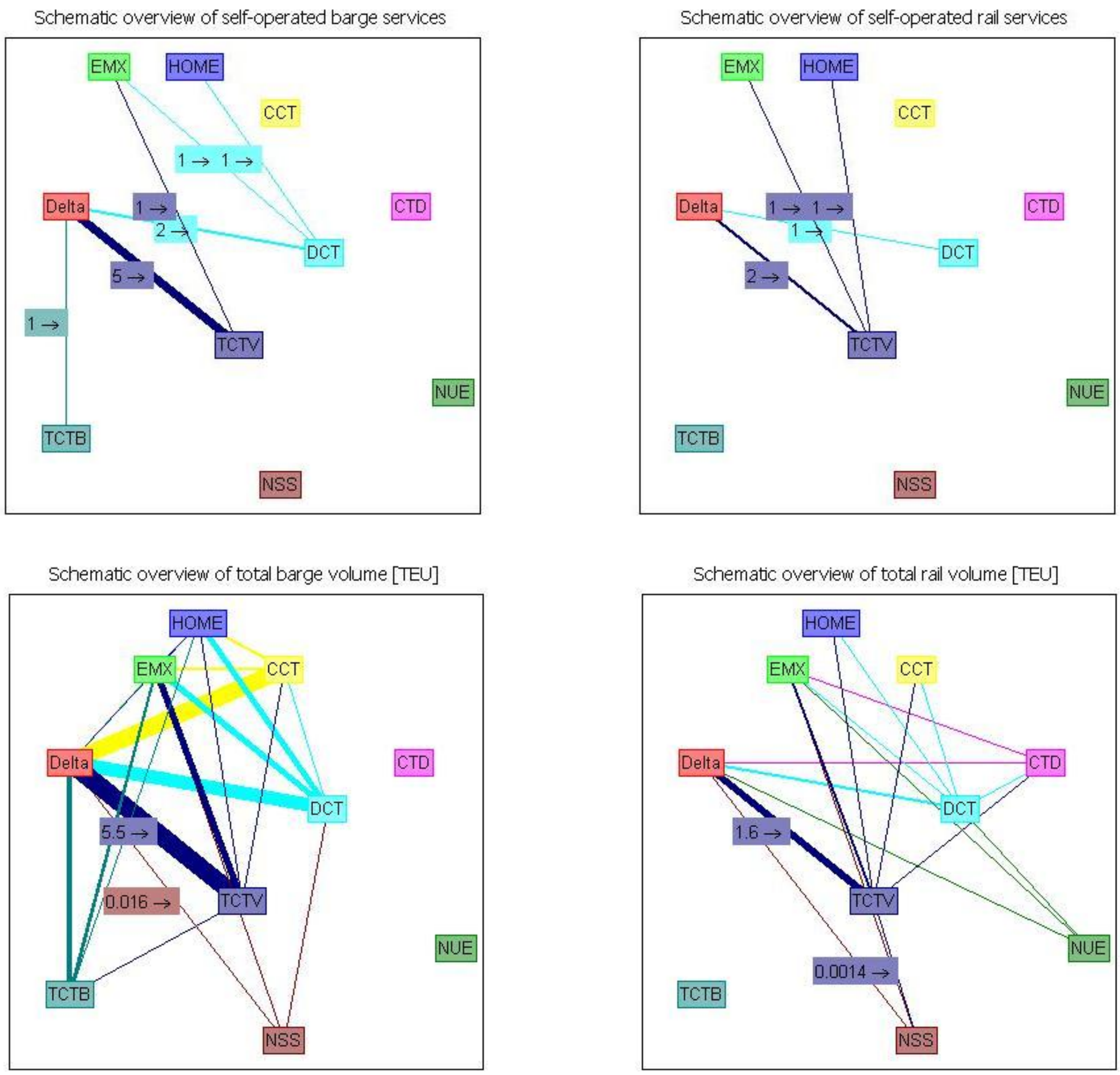


Figure 12 Service schedule in basic case (Experiment B)

Impact of transfer costs

Several experiments were carried out to study the influence of the transfer costs. All results are listed in Section 4.4, but here the results of Experiment E, the basic case with half the transfer costs will be described. Figure 13 depicts again the schematic service schedule. Only a few connections are added compared to the base case: with the cheaper transfers new land connections from TCT Venlo to DeCeTe and Nuremburg are selected. In the figures with the total volume, more differences become apparent: far more different paths with transfers are selected than in the basic case and even some paths are selected that contain two intermediate transfers. For this reason, this case was also tested while also allowing paths with three intermediate transfers. This experiment (F) did however provide equal results, proving that three intermediate transfers are not beneficial.

Influence of due times

Two experiments were carried out to see the influence of due times. Experiment H tested the basic case while no costs for overdue delivery were applied. In experiment G, the transfer costs are also neglected. The resulting service schedule is shown in Figure 14. The figure shows clearly that only a few barge services are selected. The figure with the flows is not shown, as very large subcontracted barge transport is used between the seaports. Subcontracted rail transport is only selected to those locations where only rail connections are available (NUE, CTD). A rail corridor between TCT Venlo and DeCeTe is selected, because of the long detour a barge between both places would be required to take (from Meuse to Rhine). Remarkable is that mostly subcontracted services are selected. Because of the cost structures, the subcontracted services have an advantage over the self-operated services on short distances.

Necessity of subcontracted transportation

This study differentiates between self-operated and subcontracted transportation. To review the importance of sub-contracted transports, an experiment was carried out where subcontracted transport was excluded. The resulting service schedule can be seen in Figure 15. It is apparent that only self-operated services are shown, but it can also be seen that more land corridors are used between TCT Venlo and Germany and between DeCeTe, CTD and NUE. Also, the transports from Delta and Euromax are consolidated in one corridor. This is because of the required cargo consolidation on the self-operated services. In order to achieve higher utilization of the capacity of the self-operated services, more transfer costs are incurred.

Other experiments

The figures of the other experiments are not shown, as they are very similar to the basis case. The resulting solutions do differ in the total network costs for transportation, overdue delivery and CO_2-emission. These results are all presented next, in Section 4.4.

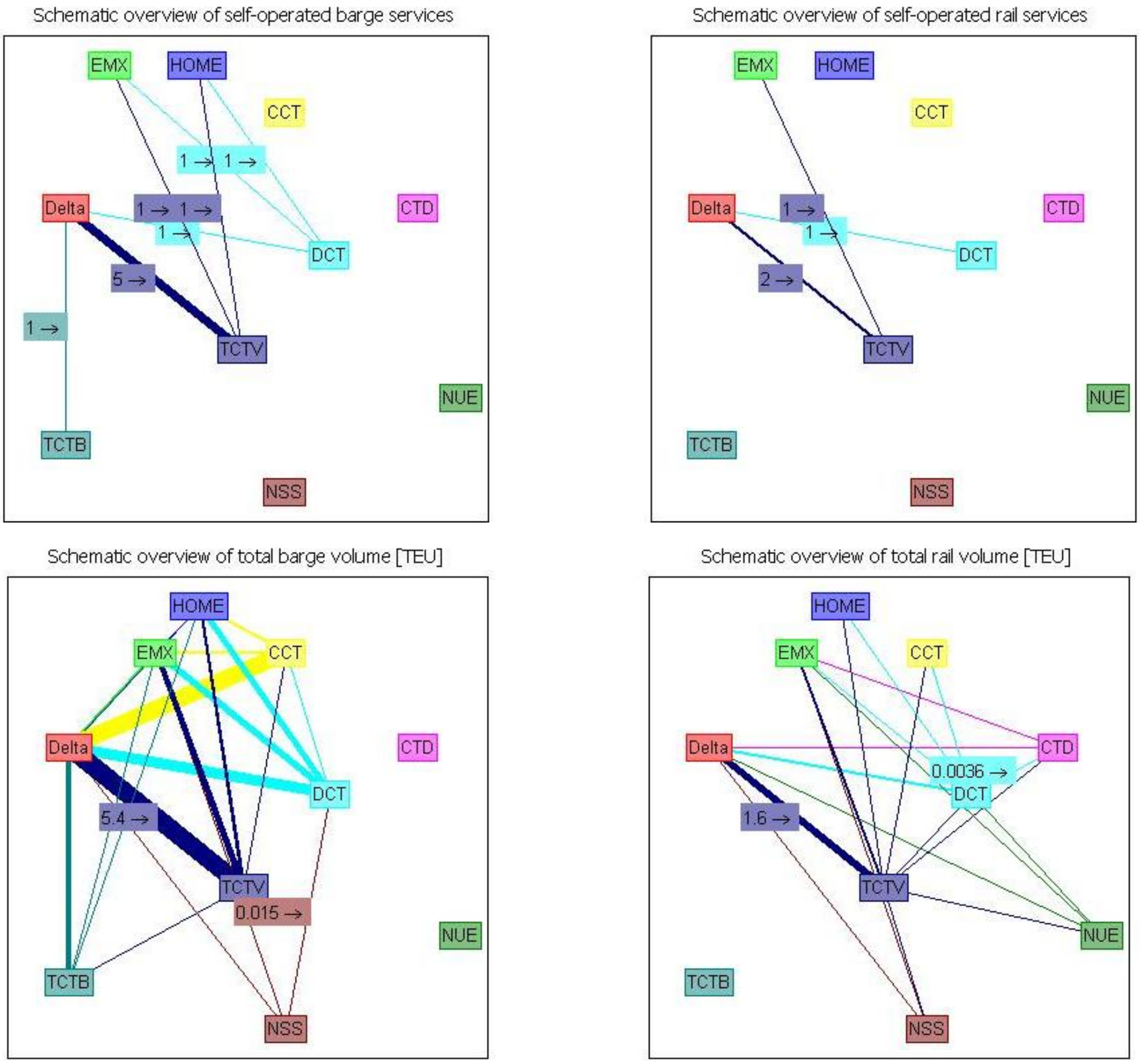


Figure 13 Service schedule based on half transfer costs (Experiment E)

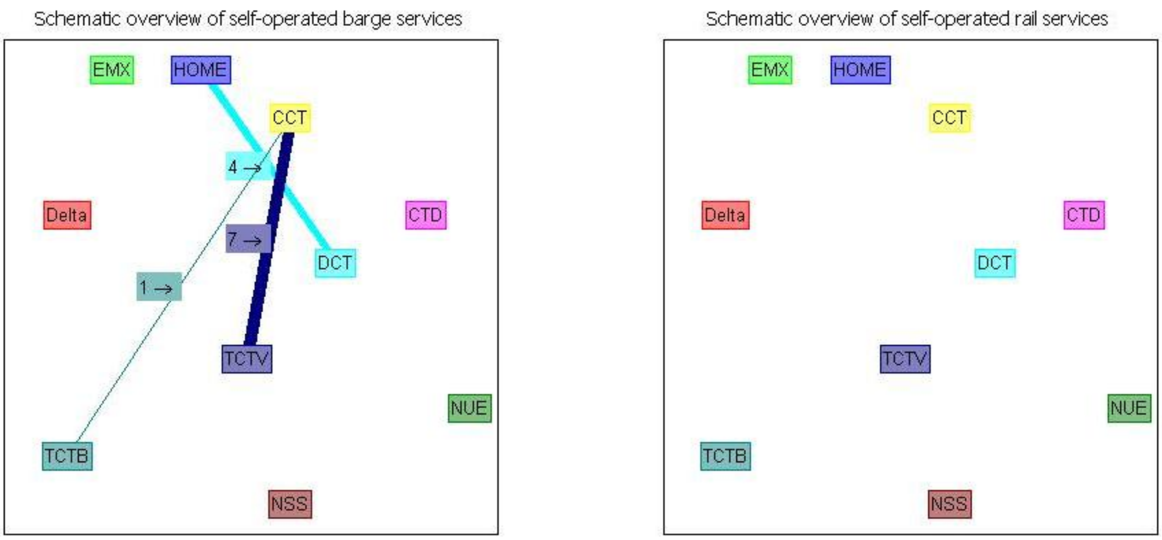


Figure 14 Service schedule when no overdue or transfer costs apply (Experiment G)

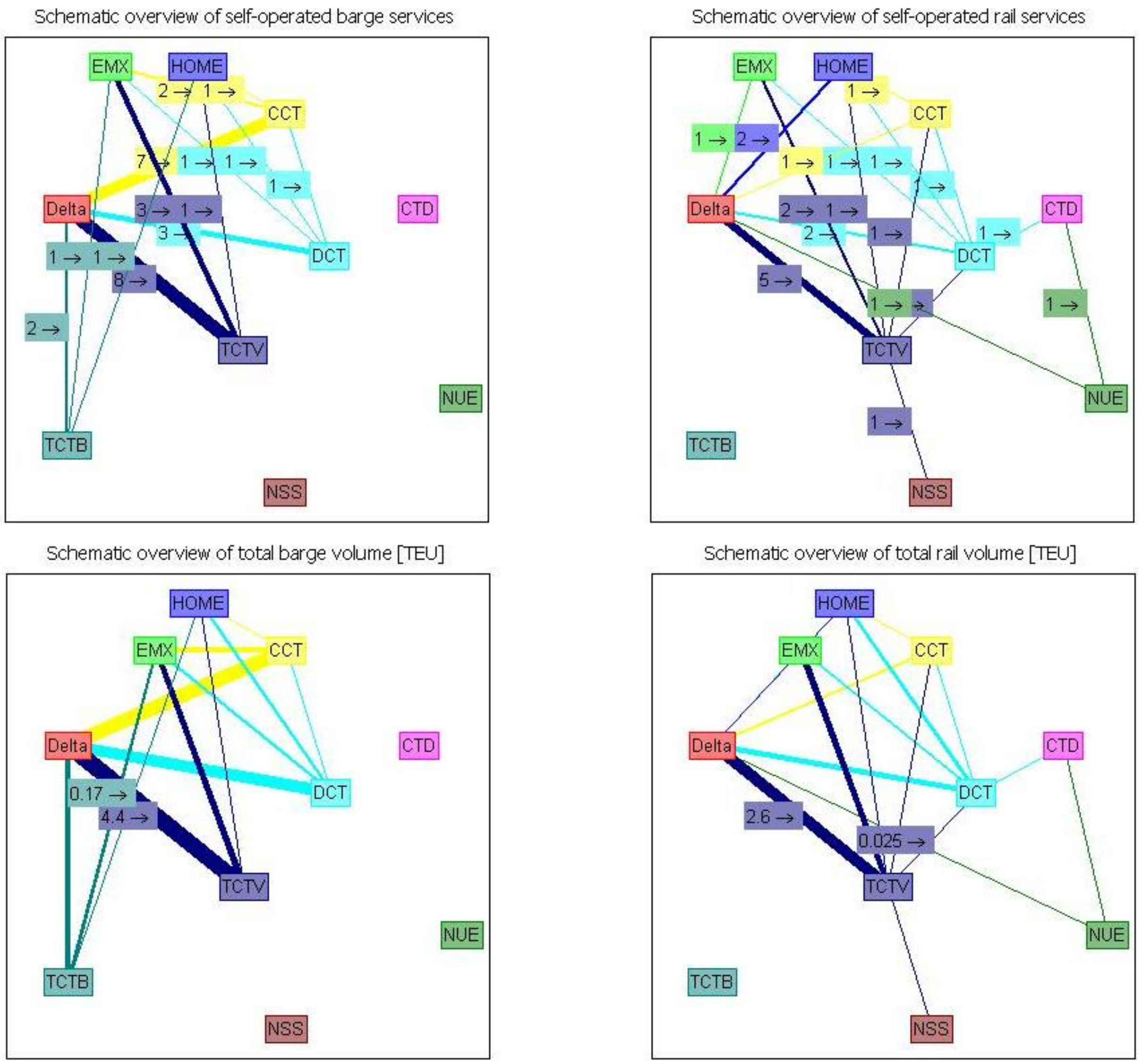


Figure 15 Service schedule without subcontracted transports (experiment J)

4.4 Results of Part I

This section presents the results of all experiments. For the experiments, three sets of paths were pre-processed: the validation used a set of paths without intermediate transfers. Two experiments (C and F) used an extended set of paths with maximally 3 intermediate transfers. All other experiments, including the basic case used a set of paths with maximally 2 intermediate transfers. The computation time and sizes of these sets are listed in Table 9.

Set	Nr. of paths [-]	Computation time [s]
No transfers	218	6
Paths with max 2 transfers	13977	177
Paths with max 3 transfers	39575	576

Table 9 Generated sets of paths

The results of the experiments that were described in the previous sections are summarized in Table 10. All resulting costs are printed here with the confidentiality factor. All experiments, except G and H, use an overdue cost of €50[1] per day. Transfer costs, amount €23.89[1] per transfer, except in the experiments D-G. Note that a transfer includes two handlings: also in the validation experiment, without transfers, two handlings (one transfer) are required.

All experiments are based on the basic case, the specific changes in variables or settings were described in Section 4.1. From the results, the following observations can be made. With *transportation cost* the combined costs for self-operated and subcontracted transport is meant.

(1) The proportion of self-operated transport increases with growing demand. The costs for the self-operated services amount about 57% in the basic case and increase up to 60% in the 10% growth case. The number of self-operated services grows from 32 to 38. However, with 25% growth, the volume that is planned on self-operated services grows further to 40 services, but the subcontracted transportation grows relatively fast compared to the 10% case. This suggests that a point exist where adding additional services is less beneficial than using subcontracted transport.

(2) A considerable amount of overdue containers results. This does not correspond to the daily practice, according to EGS transportation planners. The daily practice is that all containers are planned initially on rail and barge service in close cooperation with customers. Only after disturbances truck is used. This motivates the used of overdue delivery flexibility in the model as well.

[1] Masked by a factor.

(3) The model can be solved very quickly, about two minutes for the basic case. However, the solutions with cheaper transfers prove harder to solve (3-4 minutes). Also, the experiments with more paths take a longer solution time (7-9 minutes). One case was exceptionally hard: the situation where only self-operated transports are allowed. In this case the integer variables to select services are a lot more important in the solution, as no 'slack' is provided by the flows using subcontracted transportation.

(4) The relatively large cost of subcontracting shows that a considerable amount of containers is transported with subcontracts. This may be unwanted for other reasons. However, experiment J with only self-operated services shows that the transportation costs increase by 65% without subcontracted transportation. This shows the necessity of combining subcontracted transportation with self-operated transportation in the model.

(5) Allowing transfers in the container paths results in a reduction of the total costs of only 0.3% (the validation compared to the basic case). The transport costs are reduced by 2.5%, almost entirely equal to the additional transfer costs

(6) However, if transfer costs would be halved, the transportation costs would be reduced by 7.3% compared to the current situation (validation). The number of transfers would go up by 3.8%. Although this is a hypothetical case, an accurate assessment of transfer costs within the network is important, especially for terminals that are owned by ECT.

(7) For the cases where paths with up to 3 transfers were used, the results were identical to the cases with up to 2 transfers, but calculation time was a lot higher.

(8) The experiment with tenfold CO_2-costs did result in some CO_2 reduction: a reduction of 23% was achieved, with 8 additional self-operated barges.

(9) The four experiments with random runs resulted in very similar results compared to the basic case. The modelling of the demand with ten periods of 10-percentile parts of the demand distribution proves effective. So, time-consuming random sampling of experiments is not required to get accurate results.

(10) Apart from the case with higher CO_2-costs, the CO_2-emissions changed not much. On top of that, the influence of the CO_2-emissions on the total costs is only 0.8% or 2.3% of the transport costs. Hence, the influence of CO_2-emissions on the results is just marginal.

The results of this model are consistent with the managerial insights as described by Ishfaq and Sox. When the required due time decreases, more consolidation on intermodal connections will be beneficial, i.e. more transfers. Also the reduction in costs of transfers (*modal connectivity costs*) results in more intermodal connections. Their work did not allow overdue deliveries, that were used in this model.

Experiments	Total [€]	Services [€]	Subcon-tract [€]	Late [€]	Handling [€]	CO_2 [€]	B/R services	Comp. Time [s]
A. Validation (no transfers)	1151	223	173	122	624	9	22/10	2
B. Basic case	1149	223	163	122	632	9	22/10	119
C. Basic case (max 3 transfers)	*identical to basic case*							369
D. Free transfers	466	179	157	122	0	9	18/8	205
E. Half transfer costs	827	201	166	122	329	9	22/8	111
F. Half transfer costs max 3 transfers	*identical to cheap transfer case*							518
G. Free transfers, no overdue costs,	246	147	89	0	0	10	24/0	207
H. No overdue costs	955	206	103	0	638	9	30/0	106
I. Tenfold costs for CO_2-emissions	1217	248	145	122	634	69	30/10	170
J. Only self-operated services	1433	636	0	153	634	9	64/48	4067[1]
K. Basic case (+ 2.5%)	1177	223	171	125	648	9	22/10	94
L. Basic case (+ 4.2%)	1195	233	167	127	659	9	24/10	140
M. Basic case (+ 10%)	1258	255	166	134	693	9	28/10	94
N. Basic case (+ 25%)	1420	267	198	153	792	10	32/8	83
O. Basic case (random demand)	1130	201	150	125	646	8	22/8	130
	1153	233	141	130	642	8	24/10	129
	1122	200	148	116	650	8	20/10	126
	1113	223	142	129	612	8	22/10	134

Table 10 Summary of tactical network model results

[1] a solution within 2% was found within 600 seconds.

Overview Chapter 4

Part I showed that container transfers are almost never beneficial in the current situation. However, if the cost of a transfer would be considered lower, they become beneficial. Experiments were carried out for a situation where the transfer costs are reduced with 50%. In that case, the number of transfers increases by 3.8% and the costs for transportation are reduced with 7.3%. Note that this reduction is without the obvious decrease in transfer costs by reducing these with 50%. As the terminals of the EGS network are more and more cooperating, transfers at terminals become part of the same business. Hence, the results of this study indicate possibilities for a combined business model for both terminals and network transportation.

PART II – OPERATIONAL LEVEL

In this part of the research, the benefits of real-time switching of container itineraries in case of disturbances are assessed. The service frequency results of Part I will be used as a basis for the analysis of the operational planning. The following list repeats the research questions of Section 1.4.2 and summarizes the ideas of the research of Part II.

1. *Which types of disturbances occur in the network transportation?*
2. *Which disturbances have the largest influence on the network performance?*
3. *Under what conditions and at what moment can a container be rerouted?*
4. *Under what circumstances can a container be rerouted?*

0 describes the model that is used in this part, to study the planning at an operational level. Chapter 6 describes the research and results to assess the disturbances and influences on the planning.

Chapter 5. Operational network model

In this chapter the operational network model is introduced. This model is used to analyse the impact of specific disturbances on the operational planning. In Section 5.1 the container transportation process is described in more detail. The process is analysed to identify the time constraints for the container transportation that were ignored in Part I so far. Section 5.2 introduces the general operational planning model. In Section 5.3 the methodology is described to solve the model and find the influences on the operational planning. Finally, Section 5.4 introduces the specific data for the operational model. Note that the large part of the used data is identical to the data used in the tactical research part, introduced in Section 3.4.

5.1 EGS Container transportation process

In this section, the process of transporting a container in the EGS network is clarified. A comprehensive process description is not the aim; only the steps of the process that influence the transportation planning are assessed.

First, the process of transportation is described in 5.1.1, starting with the moment of booking, up to delivery at the final network destination of the container. Import and export transportation are assessed separately. A schematic timeline of this process is presented to clarify the process. Subsequently, the possible disturbances in this timeline are identified. In paragraph 5.1.2, the important decisions made by the daily planners in the network are described.

Paragraph 5.1.3 the description of the first two paragraphs will be translated into the effects that are studied in Part II. Finally, in 5.1.4 the KPIs of the tactical model are reassessed for the operational planning model.

5.1.1 Container timeline

In this section, the process of the container transportation process is described in detail. This description is made by the author after monitoring the EGS booking and planning department at ECT's DELTA terminal and the terminal process at ECT's hinterland terminal in Venlo (TCT VENLO). The description was checked by EGS's operational supervisor.

The EGS container transportation process comprises three stakeholders: the deep-sea terminal, the service operator and the inland terminal. Apart from the physical transportation process, a booking process and a planning process are associated to the transportation of a container. Two main types of transportation take place: import and export of a container. The former refers to containers that move from a deep-sea carrier to the hinterland, whereas the latter refers to containers from the hinterland towards the deep-sea terminal. These two types are assessed separately. Apart from these, transportation with other restrictions takes place: round trips and empty repositioning. These are shortly described after the import and export procedures. The processes are described for a single container. Often, a booking comprises multiple containers for which the booking and planning process is combined.

Import

Here, the planning steps of a container import transport over the EGS network are described. A schematic overview is shown in Figure 16.

1. As soon as a client books a container, the container planning process is started. At first, the container is inserted in a preplanning for the inland services. Regularly, this takes place within a week before the actual arrival of the container at the deep-sea terminal.
2. During the time until the arrival, the booking information is assembled, including the required pin code for the carrier release and the documentation for customs release. Both releases have a specific validity time, but this is often far longer than required for the transportation, so this validity time is ignored.
3. Meanwhile, until the arrival of the container, the preplanning is continuously updated. The estimated time of departure (ETD) of the deep-sea is used as the time of arrival for the container. This is a conservative estimate of the moment that a container has arrived. The inland service for a container is planned 0-8h after the ETD
4. The container is scheduled on an inland service. The *closing* of a service is the moment that no changes to the loading list can be made anymore. This moment is 9-24h before the estimated time of arrival (ETA) of the inland service at the deep-sea terminal. The loading list for that service must then be ready at the service operator. The interval of 9-24h depends on the specific service[1]. The minimum interval is 9h.
5. The service operator will schedule the terminal calls in communication with the deep-sea terminal. The call is planned 36h before ETA and updated continuously until 6h before ETA of the inland service.
6. After the actual arrival of the container at the terminal, the customs and carrier releases are carried out. These have to be finished at least 6h before ETA of the inland service.
7. If the container is planned on a path with an intermediate transfer, a transfer time of 4h is used in the planning. In the case of truck pick-up for the final delivery, a 1.5h period is used in the planning from the ETA to a planned pick-up.

This process is shown schematically in Figure 16. The booking process, container transportation process and planning process are shown parallel. The planning process stops earlier than the other two, as the planning has no influence during the actual transport anymore. Note that all operational planning about the physical loading and unloading is omitted in this scheme.

[1] The moment of closing of an inland service depends on the service operator.

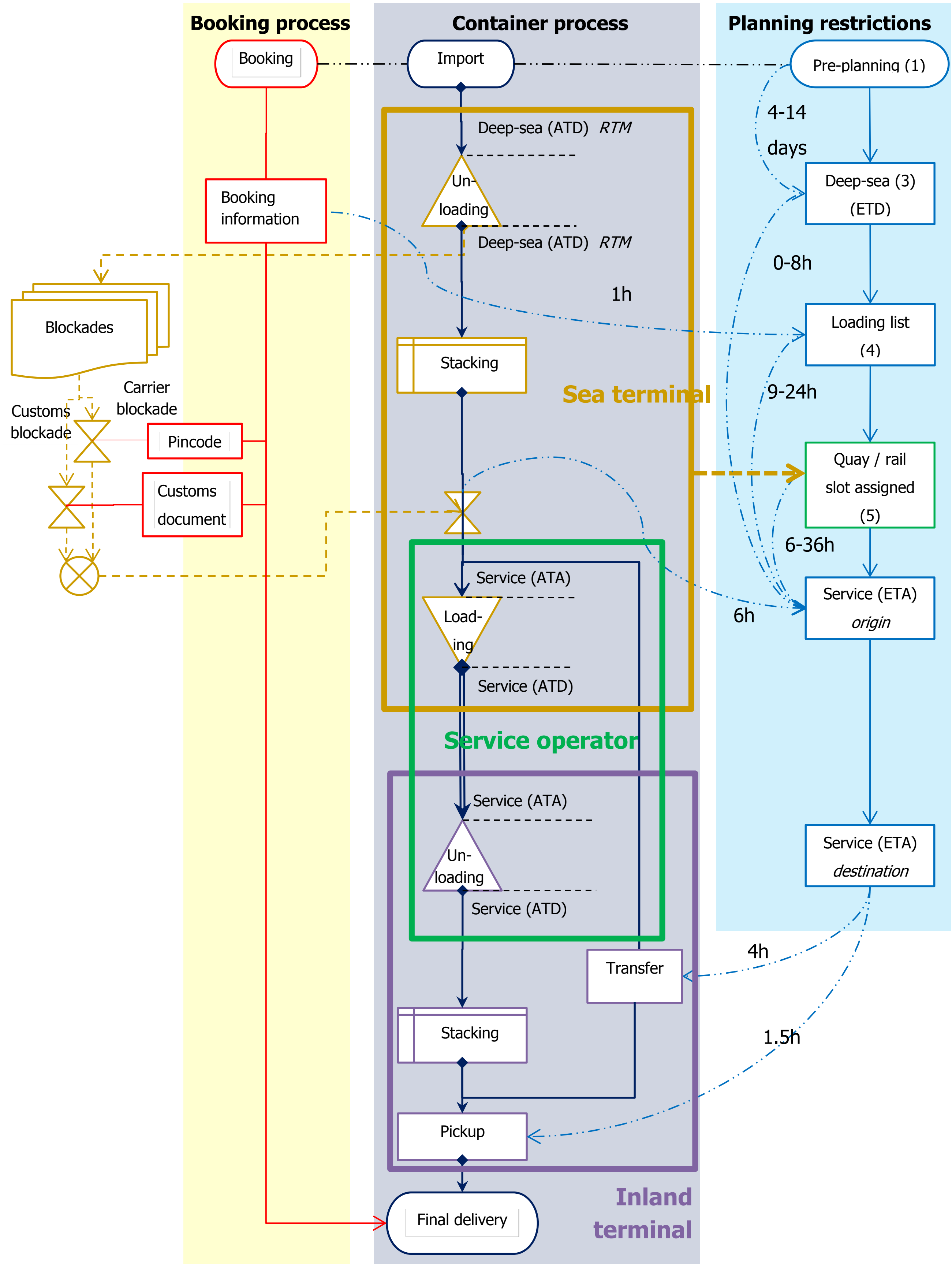


Figure 16 Schematic import process

Export

Here, the planning steps of a container export transport over the EGS network are described. The first steps, booking and pre-planning, are very similar to the import process; in the planning several differences exist though. A schematic overview is shown in Figure 17.

1. As soon as a client books a container, the container planning process is started. At first, the container is inserted in a preplanning for the inland services. Regularly, this takes place within a week before the actual arrival of the container at the deep-sea terminal.
2. During the time until the arrival, the booking information is assembled, including the required carrier reference for acceptance at the seaport terminal. Custom release is not required until after the network transport and is no requirement during the planning process. The carrier reference is required for acceptance at the sea terminal and thus is often a requirement before departure of the hinterland terminal: the requirement is 1h before ETA of the service at the hinterland.
3. Meanwhile, until the arrival of the container, the preplanning is continuously updated. Mostly, the only planning requirement is that the container must be available at the deep-sea terminal before the closing of the deep-sea vessel for the export. This closing is 24h before the ETA of the deep-sea vessel. In case of a late arrival procedure, arrival up to 6h is possible. As the aim is to assess the entire operational planning of the network, this possibility for exceptions is ignored.
4. The container must be available 1-2h before the service departs, but this is less strict at the inland terminal.
5. Again 9-24h *before* the estimated time of arrival (ETA) at the sea terminal, the loading list for that service must be ready at the service operator. The list of containers to unload at the seaport must be communicated to the seaport together with the import loading list. The actual arrival of the container at the terminal occurs sometimes before, but often in this 24h period. The loading list must also be ready about 1h before the inland service departs, but this is often less strict at the inland terminal.
6. The service operator will schedule the terminal calls in communication with the deep-sea terminal. The call is planned 36h before ETA and updated continuously until 6h before ETA of the inland service.
7. Again, a 4h transfer time applies for a transfer to a second service. This transfer time is required between the ETA of the first leg and the ETA of the second leg.

Figure 17 shows this process schematic. The blockades that were shown in the import process do not apply to the export process. The figure also shows that more time constraints apply to the start of the transport process. The reason for this is that a lot of requirements by the seaport (loading list, container info) must be met before the departure of the service. Note that all operational planning about the physical loading and unloading is omitted in this scheme.

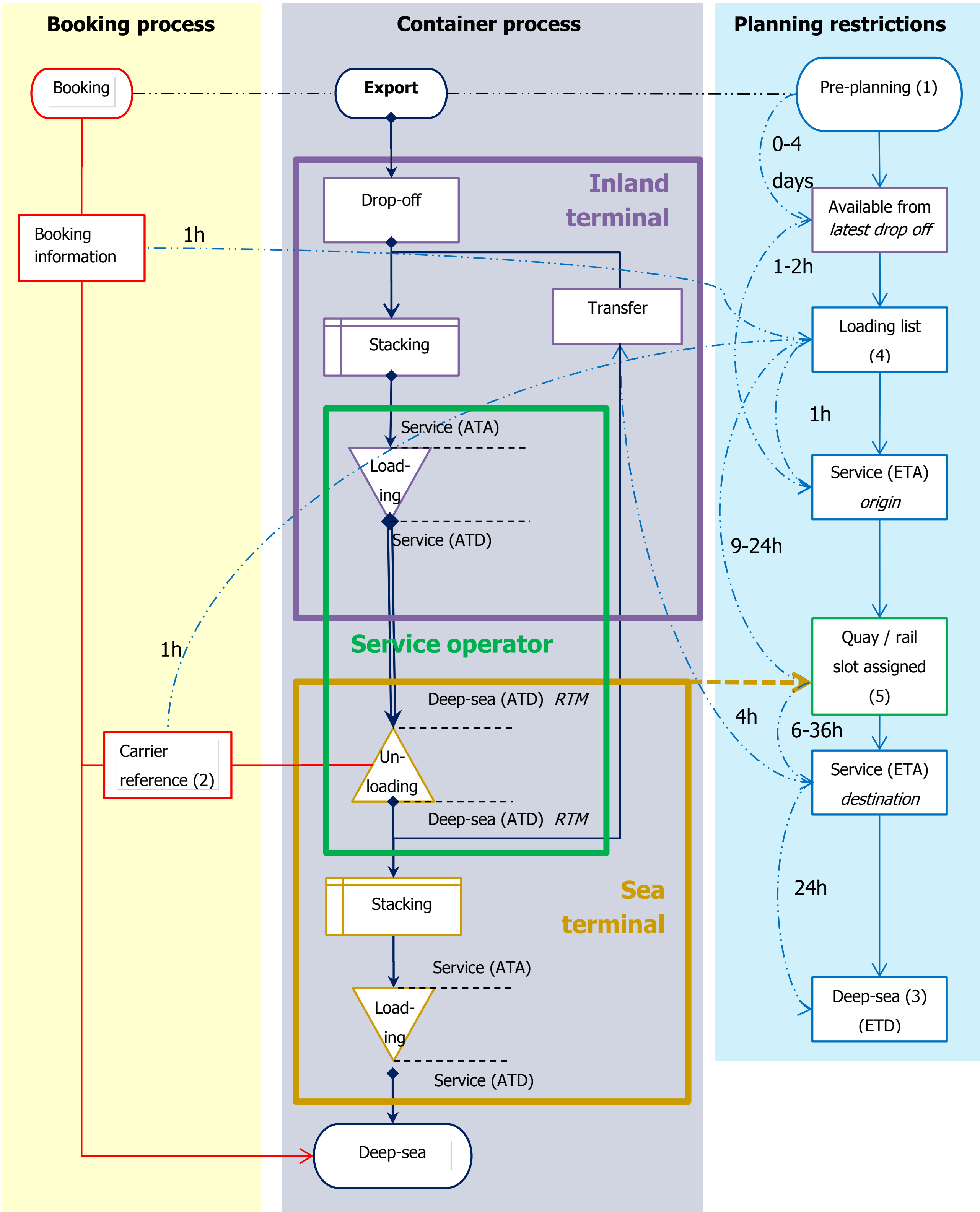


Figure 17 Schematic export process

Empty repositioning and round trips

Apart from the described import and export transports, three types of empty transports occur in the EGS networks:

- Empty return trip of an import transport
- Empty inland trip for an export transport
- Empty repositioning

For both import and export, round trips occur. In the case of an *import round* the container is returned back to the sea terminal depot directly after delivery in the hinterland. This can be modelled as an import trip with an empty transport from the hinterland to the sea terminal. The empty legs of the round trip are simpler than the loaded import leg, as no customs formalities are required and less strict time windows apply. The due time for this transportation is specified by the *detention* time, i.e. the time a customer may use the container. All planning restrictions hold for this type of transportation as well.

With an export round, an empty container is transported from a sea terminal to be loaded in the hinterland and returned back as export container to the sea terminal. This can be modelled as an empty inland trip, directly followed by an export trip. The due time for empty inland trip is the loading date of the client. All planning restrictions hold for this type of transportation as well.

All these types of transports are modelled in the same way as the regular import and export windows, by adjusting the time windows for the transportation to the required arrival and departures.

Finally, large scale empty repositioning takes place over the network sometimes, mostly commissioned by a carrier. Such a batch of empty containers from one terminal to another is often transported as *fill-up*, i.e. only loaded on the service when space is available. This type of transportation is handled in the same way as the regular transports described before. Alternatively, a dedicated one-time service is used sometimes. These are not included in this study.

Summary of timeline container transportation

In this section the import and export container transportation processes were described. Table 11 shows an overview of all time restrictions in the container transportation process. Some additional events are added at the end of the table: demurrage refers to the number of days a container is allowed to be stored at the terminal for free. After that number of days, detention costs are charged. Detention refers to the number of days that a customer may use the container before he is charged additional costs. The validity of the customs clearance is longer than 40 days. Finally, the regular planning horizon is currently about a week. Sometimes transports are booked up to two weeks ahead.

Import event	**Time interval**
Booking	14-4 days before ETA deep-sea vessel
ETD deep-sea	0-8h before ETA inland service at seaport
Quay slot assigned	36-6h before ETA inland service at seaport
Booking stop	24h before ETA inland service at seaport
Service closed for planning	24-9h before ETA inland service at seaport
Releases	6h before ETA inland service at seaport
Container available for transfer	4h after arrival previous inland service
Available for truck pickup	1.5h after arrival at inland terminal
Export event	**Time interval**
Booking	2-4 days before ETA deep-sea vessel
Booking stop	24h before ETA inland service
All info available	1h before ETA at inland terminal
Loading list	1h before ETA at inland terminal 24-9h before quay slot assignment at the seaport
Truck drop-off at inland terminal	2h before ETA at inland terminal
Quay slot assigned	36-6h before ETA at seaport
Available for transfer	4h after ETA at seaport
Closing at sea terminal	24h before ETD deep-sea
Late arrival procedure	6h before ETD deep-sea (ignored in this study)
Additional events	**Time interval**
Detention	Several days (neglected in this study)
Demurrage	~14 days (neglected in this study)
Validity of custom clearance	>40 days (neglected in this study)
Planning horizon	1-2 weeks

Table 11 Summary of time line restrictions

5.1.2 Daily practice of EGS container planning

In Section 5.1.1 the container transportation process was described. The people that operate the transportation planning are continuously busy with the process steps of booking and planning containers on services. The updating of planning occurs continuously using the information of new bookings and disturbances. The anticipation of disturbances proves difficult, hence the assessment of importance of disturbances in this study. Below a list of activities that the daily planners are doing:

1. Use synchromodal allocation (containers on barge or train) to carry out the transportation as cost effective as possible.
2. Diminish the number of calls in a (barge) schedule. If the container transports allow reducing the number of calls, a barge can gain time and save money.
3. Skip a (train) service if demand is low. This occurs less frequently than reducing the number of calls in barge schedules, but can save a lot of money for operating low occupied services.
4. Manipulate clients to deal with capacity shortage (train, barge): move bookings in time (earlier drop-off, later pickup). The communication with clients is mostly done by phone or email on specific bookings. The automatic planning in this study will not consider this possibility, but does allow for overdue delivery. Other models, such as those by Ishfaq and Sox (Ishfaq and Sox 2011), do not use this possibility.
5. When capacity is short, truck transportation is a last resort. The planners may try to cooperate with truck companies that have to reposition empty chassis, e.g. after a truck delivery. The communication for these deals is also not incorporated in this study.
6. Efficient train/barge loading plan (load containers sorted per client or sorted per destination). This specific terminal process is left out of this research.

The operational model will be set up to study the first activity, the efficient allocation of containers to the service schedule.

5.1.3 Studied effects in Part II

In Section 5.1.1 and 5.1.2 the current process of container transport in the EGS network was described. In this part of the study (Part II), first of all, an automated planning method for the container transportation will be developed. This method will plan the container transportation demand on the available services, based on the service schedule of departures and arrivals. Secondly, the effect of disturbances on this planning will be assessed. A disturbance is the change of one of the planning's parameters after the initial planning had been made. The following disturbances on planning process are considered in this study:

1. Early arrival of a service
2. Late arrival of a service
3. Cancellation of the service

Some of these disturbances can have a variety of causes. Service delays can be caused by delays during the journey, but also by shunting or quay planning, terminal delays or (un)loading delays. However, the different causes are not relevant for the assessment of the disturbances. If the results of this study are used to prevent some of the disturbances, then the causes of the disturbances will become important.

The following aspects are not considered in this study.

- With deep sea delays, export containers can arrive later at the deep sea terminal.
- Changing of the hinterland terminal for a container
- The opening times of terminals.
- Rescheduling of the barge or train schedule.
- Detention/demurrage restrictions.
- Stacking planning.
- Work force planning and shift scheduling.
- Vessel, barge or, train loading plan.
- Custom restrictions per connections (extended gate or not).
- Communication between multiple stakeholders (terminals, booking desks, operators).
- Possibility to move bookings in time (earlier drop-off, later pickup). This happens on a daily basis by manual planners in consultation with costumers. Instead, the model allows for overdue delivery while incurring a penalty cost.

In Section 5.2 the model formulation is introduced. The implementation and extent of the disturbances is subject of Section 5.3 (Methodology) and 5.4 (Data), respectively.

5.1.4 KPIs for disturbances in the operational model

The tactical research in Part I aimed to minimize a threefold cost objective, consisting of transportation costs, costs for late delivery and costs for CO_2-emission. On a daily basis, also the operational planning aims to fulfil the transportation in the most cost-effective way. The actual planning is updated continuously, using new information. However, as pick-up and delivery appointments have been made with customers, the daily practice of the operational planners is to keep the scheduled pick-up or delivery times as close to the initial planning as possible. So, instead of costs, the changes to the original planning are used as the criterion for planning updates.

In this part of the study the *total costs* of a week of transportation will be considered again, not keeping the pick-up and delivery times close to the initial planning as is the current practice. The reason for this is twofold. Firstly, using costs as the objective provides continuity with Part I (the tactical results of Part I were based on costs). Secondly, costs are more suitable as an objective for determining the impact and relevance of disturbances, the main goal of Part II.

Although Part II focuses on planning at an operational level, it is not aimed to build a dynamic operational planning tool. The goal is to identify the impact and relevance of disturbances on the operational level planning. To determine the impact of a disturbance, a procedure is used where the entire planning is updated, i.e.: all containers can be reconsidered from the moment that the disturbance became known. This updated planning is called the *full planning update*. The impact of a disturbance is defined as:

$$I_{i,t} = C_{full}^{i,t} - C_{basic},$$

where $I_{i,t}$ denotes the impact of the disturbance i that became known at time t. The initial planning, without knowledge of the disturbance is C_{basic}. The total transportation costs of the fully updated planning are denote by $C_{full}^{i,t}$. Hence, $I_{i,t}$ measures the cost increase as a consequence of a single disturbance when the entire planning is reconsidered in the best possible way to deal with the disturbance.

This part of the study will also assess the relevance of a full update after a disturbance. Currently, the manual planners of the EGS network handle occurring disturbances by re-planning only the affected containers. Other containers that are not directly affected are not reconsidered. This updated transportation planning is called the *local planning update* in this study, where only directly affected containers are re-planned. The relevance of a disturbance is now defined as:

$$R_{i,t} = C_{local}^{i,t} - C_{full}^{i,t},$$

where $R_{i,t}$ denotes the relevance of disturbance i that became known at time t. The total transportation costs of the locally updated planning and the fully updated planning are denote by

$C_{local}^{i,t}$ and $C_{full}^{i,t}$, respectively. Hence, $R_{i,t}$ measures for a single disturbance the cost reduction that can be attained with a full planning update compared to a local updated planning.

The model formulation of Section 5.2 uses the total costs of a week of transportation as objective function. The cost objective is similar to that of the tactical model in Part I, but two aspects are left out. The cost of self-operated services is omitted, as it is a fixed cost at the operational level: the schedule and number of services are predetermined. Secondly, the costs for omitting CO_2 are omitted as they had a negligible influence at the tactical level.

5.2 Model formulation

In this section, the operational model formulation is introduced. First, the operational model is described (5.2.1), emphasizing on the differences with the tactical model of Chapter 3. Subsequently, the mathematical formulations are introduced (5.2.2). In the last part, Section 5.2.3 describes the procedure for planning updates. Section 5.2.4 proposes some possible adaptations to the mathematical formulations in order to assess specific operational planning situations. These are not used in this study, though.

5.2.1 Introduction of the operational model

In order to study the effects of a disturbance on the operational planning, three situations must compared, see Figure 18. The basic case is the solution of the transportation planning without considering disturbances. Let i denote a disturbance, occurring at t_i and let t_{info} denote the amount of time that this information became available before t_i. The update of the planning can commence after information is available, that is at time $t_i - t_{info}$. Now, two updated transportation plans are generated: one local update, where only the directly affected containers are reconsidered, and one full update, where all container transportation after $t - t_{info}$ is reconsidered.

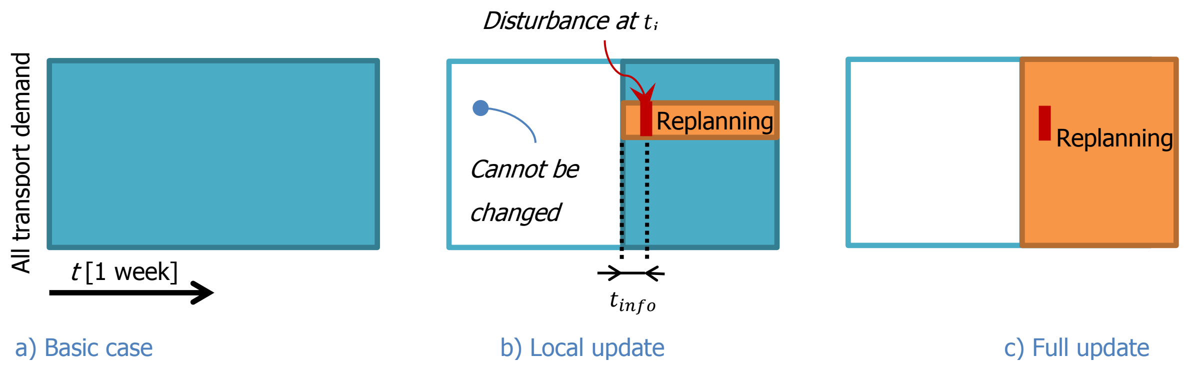


Figure 18 Three solutions with the operational model

The model for these three types of solutions is based on the tactical model. However, at the operational level, the allocation of services for the service schedule is no longer under consideration; the model uses a predefined service schedule. Secondly, the experience of using the tactical model in Part I suggested a slightly different formulation of the transportation demand: all container transportation is categorized in cargo classes c. All containers in a cargo class share the same origin and destination, but also have the same container mass, the time that the cargo class c is available (t_A^c) and the time that the cargo class c is due (t_{due}^c). Note that t_{due}^c denotes the actual *moment in time* the container must be delivered at the latest, instead of the *available time for transportation* that was used in the tactical model. A third difference with the tactical network model is that direct truck connections are modelled specifically.

For each cargo class c, the available paths P_c are determined based on the *service schedule*, considering the time constraints that were described in Section 5.1. The paths can be predetermined considering the time window for the cargo class. Hence, to solve the planning problem the cargo class must be distributed over the available paths, while meeting service capacity constraints. The path generation is further elaborated in Section 5.3. The mathematical formulation of the operational planning model is introduced in Section 5.2.2.

Planning updates

The solution of the basic operational model results in an optimal transportation planning. To be able to do a re-planning, the paths that are influenced by the disturbance must be updated. Also, some new paths may become feasible. In order to do a re-planning the set of available paths is updated. Then, for a local update, all decision variables are set fixed to the value in the basic solution except for the variables associated with the directly affected containers. In the case of a full update only the variables associated with transports before t_{info} are set fixed. Then the model is resolved, starting with the basic solution as the initial solution. This procedure is described in more detail in Section 5.3.

Planning horizon

The model that is used in this part of the study considers one week of container transportation, as was the case in the tactical research path. However, the transportation of containers available on the last day of the week will continue in the next week. A correct planning must also incorporate the influence of next week's transportation in the planning to determine current week's performance. This can be solved in two ways:

a) The planning must take into account the effect of one or more following weeks
b) A cyclic planning is made: the 8th planning day is set equal to the first, etc.

The first option is more computationally heavy, but can accurately model differences in successive weeks. The second option assumes identical bookings in successive weeks, but is computationally less complex. In Appendix D the historical weekly demand is considered, used in Part I. Fluctuations from week to week exist, but no distinct periodic pattern can be used to model successive weeks. And the results of the tactical model also indicated the limited influence of the week-to-week variation in demand. The second option is chosen in this study; hence a weekly cyclic planning is created, assuming identical demands and identical planning in successive weeks. The determining of demands throughout a week is subject of Section 5.4.

5.2.2 Operational model formulation

The model formulation is based on the tactical network model. The formulation is introduced here step-by-step, elaborating on the differences with the tactical model formulation. The container transportation demand is grouped into cargo classes c. The containers in such a class have the same mass, time that they are available and due time. Also, their origin and destination is equal. Hence, the containers in one cargo class share the same set of possible paths. The set of possible paths p for a class c is predetermined and denoted as set $\mathrm{P_c}$. Likewise as in the tactical network model, the model is solved for 10 different demand patterns, the pattern is denoted by q. It will become clear that the solutions for the different demand patterns are independent, as opposed to the tactical model solutions. In the tactical model solutions, the number of selected services y_{ijm} was identical for all 10 demand patterns, by which the different patterns were dependent. Although the 10 demand patterns are independent in this case, the formulation is set up to solve for 10 patterns simultaneously, for convenience. More details on the demand patterns are provided in Section 5.3. First the mathematical formulations are introduced.

Decision variables

The path-variables $x_p^{c,q}$ denote the number of containers of cargo class c that are planned on path p when demand pattern q is considered. This is similar to the use of the x-variables in the tactical model. A new variable $v^{c,q}$ is introduced, denoting the amount of containers of class c that travel by *direct truck* for demand pattern q. The reason for using this variable instead of including the direct truck connection in the set of paths is that no time constraints apply to trucks. It is assumed that a truck can depart at all points in time.

The variables $z_s^{c,q}$ denote the mapping of the path-variables to the services s. Each service is either self-operated or a subcontracted service as determined in advance. The final variable τ_p^c denotes the total days of tardiness of containers for connection c on path p. All variables are relaxed to nonnegative real valued numbers.

The objective of the operational model is formulated as:

$$\min \sum_{p,c,q} c_p \, x_p^{c,q} + c_F \sum_p F_p \sum_{c,q} x_p^{c,q} + c_\tau \sum_p \sum_c \tau_p^c + \sum_{c,q} c_{dt}^c v^{c,q}, \tag{1}$$

where the four terms denote four cost terms. The first term represents the transport costs, where c_p denotes the cost of transporting one TEU on path p. Note that the transfers are not included in this cost. The second term represent these transfer costs, where c_F is the cost of a transfer, set to the same values as in the tactical model (€23,89[1]). The number of transfers in path p is denoted by F_p.

[1] Masked by confidentiality factor

For each path, at least one transfer is used. If the path uses multiple corridors, multiple transfers are used. The third part is identical to the one in the tactical model; it calculates the costs for the overdue delivery, with costs c_τ per day per TEU. Finally, the fourth part represents the cost for direct trucking, where c_{dt}^{c} denotes the costs of direct trucking of cargo class c. As the tactical model shows very limited influence of the emission of CO_2, this cost term is omitted in this model.

Constraints on path allocation

In each demand pattern q, a certain demand of each cargo class c is specified, denoted by $d_{c,q}$. The demand must be satisfied by either intermodal paths or direct trucking, this is ensured by constraint (2):

$$v^{c,q} + \sum_{p} x_p^{c,q} = d_{c,q}. \qquad \text{for all } c, q \qquad (2)$$

All demand that is assigned to an intermodal path is mapped to the services by constraint (3):

$$z_s^{c,q} = \sum_{p \in P_c} \delta_s^p x_p^{c,q} \qquad \text{for all } s, c, q \qquad (3)$$

where this mapping is performed with the mapping variable δ_s^p. This is predetermined when the sets of possible paths are determined. The way in which the paths are generated is different than in the tactical case, but this fact not change the model's mathematical formulation. More on path generation follows in Section 5.3.

Capacity constraints

The capacity constraints are very similar to those of the tactical model. In this case however, the constraints apply to all individual services s. The capacity constraints are:

$$\sum_{c} z_s^{c,q} \leq u_s \qquad \text{for all } s, q \qquad (4)$$

and

$$\sum_{c} W_c z_s^{c,q} \leq m_s, \qquad \text{for all } s, q \qquad (5)$$

where the maximum number of TEU on a service s is denoted u_s, the maximum mass allowed on the train is denoted by m_s. To determine the total mass of the containers planned on a train, the parameter W_c is used. The mass of a TEU in cargo class c is denoted by W_c.

Time constraints

In the operational model, the time constraints differ from the tactical model. For each cargo class, one time constraint applies: a container can only depart after it is available, denoted by $t_{available}^{c}$. Constraint (6) ensures that each container is available for the path it is planned on:

$$x_p^{c,q} \cdot T_D^p \geq x_p^{c,q} \cdot t_{available}^c, \qquad \text{for all } p, c, q \tag{6}$$

where T_D^p denotes the departure time of paths p. Due to this constraint, $x_p^{c,q}$ can only be larger than zero if it holds that $T_D^p \geq t_{available}^c$.

Secondly, a penalty applies for late delivery. The time a container is due is denoted by t_{due}^c. Constraint (7) is similar to the due time constraint in the tactical model:

$$\sum_q x_p^{c,q} \left(T_A^p - t_{due}^c\right) \leq \tau_p^c, \qquad \text{for all } c, p \tag{7}$$

where T_A^p denotes the arrival time of path p. Hence, τ_p^c is equal to zero if the traffic class c arrives on time using path p. If it arrives late, τ_p^c denotes the total number days of late arrival of all containers of traffic class c on path p. Note that a container on a direct truck connection is assumed to arrive on time in all cases.

The full model is presented below as Model 2. In the next Section (5.2.3) the additional constraints for the computation of planning updates are introduced.

$$\min \sum_{p,c,q} c_p\, x_p^{c,q} + c_F \sum_p F_p \sum_{c,q} x_p^{c,q} + c_\tau \sum_p \sum_c \tau_p^c + \sum_{c,q} c_{dt}^c v^{c,q} \tag{1}$$

s.t.

$$v^{c,q} + \sum_p x_p^{c,q} = d_{c,q} \qquad \text{for all } c, q \tag{2}$$

$$z_s^{c,q} = \sum_{p \in P_c} \delta_s^p x_p^{c,q} \qquad \text{for all } s, c, q \tag{3}$$

$$\sum_c z_s^{c,q} \leq u_s \qquad \text{for all } s, q \tag{4}$$

$$\sum_c W_c z_s^{c,q} \leq m_s \qquad \text{for all } s, q \tag{5}$$

$$x_p^{c,q} T_D^p \geq x_p^{c,q} t_{available}^c \qquad \text{for all } p, c, q \tag{6}$$

$$\sum_q x_p^{c,q} \left(T_A^p - t_{due}^c\right) \leq \tau_p^c \qquad \text{for all } c, p \tag{7}$$

$$x_p^{c,q} \geq 0 \qquad \text{for all } p, c, q \tag{8}$$

$$\tau_p^c \geq 0 \qquad \text{for all } c, p \tag{9}$$

$$v^{c,q} \geq 0 \qquad \text{for all } c, q \tag{10}$$

$$z_s^{c,q} \geq 0 \qquad \text{for all } s, c, q \tag{11}$$

Model 2 operational linear cost path-based network design model

Data sets

C	The set of cargo classes c: containers with identical origin, destination, mass, arrival time and due time
P_c	The set of possible paths for cargo class c
Q	The set of independent periods q where the same schedule of services must apply
S	The set of services s in the service schedule

Data variables

δ_s^p	Indicator whether service s is part of path $p \in P$
c_{dt}^c	Cost of using a direct truck connection for one TEU of cargo class c [€/TEU]
c_F	Cost of a transfer [€/transfer]
c_p	Cost per TEU for moving a container on path p [€/TEU]
c_τ	Cost of an overdue container per day [€/day]
$d_{c,q}$	Total demand of cargo class c and q [TEU/week]
F_p	The number of transfers in path p [-]
m_s	The mass capacity per service on corridor s [tonnes]
T_A^p	Arrival time of a container on path p
T_D^p	Departure time of a container on path p
$t_{available}^c$	Time a container of cargo class c is available on the origin of cargo class c
t_{due}^c	Latest time of delivery of a container of cargo class c
u_s	The volume capacity per service on corridor s [TEU]
W_c	The mass of a container in cargo class c [tonne/TEU]

Decision variables

τ_p^c	Total tardiness of all containers on connection c over path p [TEU × days]
$v^{c,q}$	The transportation of TEU of cargo class c with a *direct truck* connection in the case of demand pattern q [TEU]
$x_p^{c,q}$	The transported TEU of cargo class c on path p in demand pattern q [TEU]
$z_s^{c,q}$	The transportation of TEU of cargo class c on service s in the case of demand pattern q [TEU]

5.2.3 Update formulations

In Section 5.1.3 the disturbances that are studied were described. In Section 5.1.4 was introduced that the *impact* and *relevance* of disturbances are measured. For the impact of a disturbance, a *full planning update* is required and compared with the solution for the basic case. For the *relevance* of a disturbance, both a full and a *local planning update* are compared. Here is explained how Model 2 is adapted to do these planning updates. Let t_{info} denote the time interval that the information of a disturbance becomes available in advance.

For both the full update and the local update, all planned transports that start before t_{info} are set fixed. Let $\acute{z}_s^{c,q}$ denote the solution of the basic case. Now, for all services s with a cargo closing before $t - t_{info}$ the values of $z_s^{c,q}$ are set to equal $\acute{z}_s^{c,q}$. When the model is now solved for all other variables $z_s^{c,q}$, this is considered the **full update**.

In the case of the **local update**, an additional restriction is added. This restriction ensures that all traffic classes remain planned on the same services, except the directly affected traffic classes. The directly affected traffic classes may be re-planned using the remaining capacity of the network services. The range of this restriction in case of a disturbed service $\check{s}$ is:

$$z_s^{c,q} \geq \acute{z}_s^{c,q} \qquad \text{for all } (c,q) \text{ where } \acute{z}_{\check{s}}^{c,q} = 0. \qquad (11)\text{ a}$$

This restriction restricts all container assignments, except for those cargo classes that were planned on the disturbed service $\check{s}$. Hence, only the affected cargo classes are re-planned on the remaining capacity in the service schedule. This explains the inequality: planning more of a certain cargo class on a service is allowed, planning less is not.

The update is feasible because the possibility of using a direct truck transport for containers that cannot fit onto suitable intermodal services.

5.2.4 Additional formulations

The model as introduced in the previous sections is used in this study. Some additional formulations are introduced here to show possible extensions of the model. These are not used in the study, though.

Updating after a disturbed deep sea vessel

In this study is only looked into disturbances of network services. However, the model can also be used for the case of a disturbed deep sea vessel, by applying the following update restriction:

$$z_s^{c,q} \geq \acute{z}_s^{c,q} \qquad \text{for all } q, s \text{ and } c \in C \backslash \check{C} \qquad (11)\text{ b}$$

where $\check{C}$ denotes the set of disturbed cargo classes due to the deep sea vessel disturbance. All container assignments are restricted, except for the cargo classes that are disturbed. These cargo classes are re-planned on the remaining capacity in the service schedule. This explains the inequality.

Skipping a service

The disturbances (5.1.3) are studied by changing the set of available paths for the transport classes. However, to address the situations of skipping a service or reducing the number of calls in the seaport, additional formulations for the model are required. Those are introduced here.

The operational model is assessed for multiple periods q. For each service can be decided to skip it in a certain periods. Skipping such a service would not save the entire costs f_s of the service, but only a fraction ε hereof. In order to assess the possibility of skipping a service, the following adaptations to Model 2 are introduced.

To allow the model to skip specific services, the following alternative objective can be used:

$$\min \sum_{s \in S,(w,q) \in W \times Q} c_s\ \zeta_s^{w,q} + c_F \sum_p F_p \sum_{c,w,t,q} x_p^{c,w,t,q} + c_\tau \sum_{p \in P} \sum_{c \in C} \tau_p^c + c_e \sum_{s \in S,(w,q) \in W \times Q} we_s\ \zeta_s^{w,q} - \varepsilon \sum_{s \in S, q \in Q} f_s\ y_{s,q},$$

where a decision variable $y_{s,q} \in \{0,1\}$ for all s, q is introduced, denoting whether or not the service s in period q should be skipped. Note that $y_{s,q} = 1$ means that the service is skipped. If this is the case, the service is not available. Hence, the capacity for this service set to zero.

To set the capacity of the skipped service to zero, constraint (4) changes as follows:

$$\sum_c z_s^{c,q} \leq u_s\left(1 - y_{s,q}\right) \qquad \text{for all } s, q.$$

Minimizing the number of calls in the seaport

As was explained in Section 5.1.3, an important part of the planning is to reduce the number of calls in the seaport. Figure 19 shows the situation of choosing between one or two stops. The barge from Venlo to Rotterdam Maasvlakte can either go directly to the Maasvlakte (service 1) or make an additional call at the City depot (services 2 and 3). Only in the latter case, container transport with service 2 is possible. But, if transport 2 would be used, container transport to the Maasvlakte is routed via services (2,3), not directly via service 1. So, this transport takes longer, influencing the feasibility of the set of paths. I.e. if path 2 is used, then path 1 cannot be used. To incorporate this in the model, all of the barge routing possibilities must be explicitly formulated. Below, a possible implementation is proposed. The service mapping constraint (3) is adapted to be able to switch services 'on' and 'off' with parameter θ_s:

$$\theta_s z_s^{c,q} = \sum_{p \in P_c} \delta_s^p x_p^{c,q} \qquad \text{for all } s, c, q. \qquad (3)$$

where $\theta_s \in \{0,1\}$ for all s. Then, for each of the routing possibilities additional constraints are required. The following constraints (12,13) are shown for the example in Figure 19:

$$\theta_1 + \theta_2 \leq 1 \qquad (12)$$

and

$$\theta_2 = \theta_3. \qquad (13)$$

Hence, the model has to select either service 1 or 2, and if 2 is selected, also service 3 will be available.

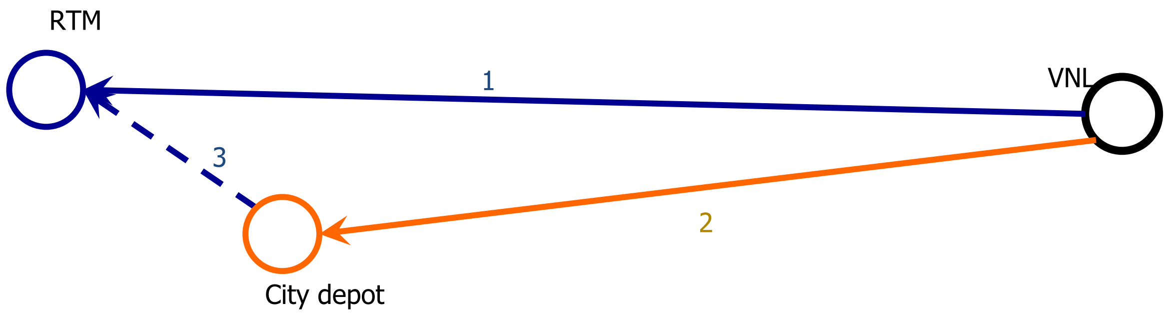


Figure 19 Multi-stop service stops (schematic)

5.3 Methodology

The model that was introduced in Section 5.2 is used to find the impact and relevance of the described disturbances (Section 5.1.3). To find the impact and relevance, three model solutions are compared: the basic case and two updates after receiving information of a disturbance, a full update and a local update. Each disturbance is considered separately, one at a time. In Figure 20, the schematic overview of the three solutions is repeated from Section 5.2.

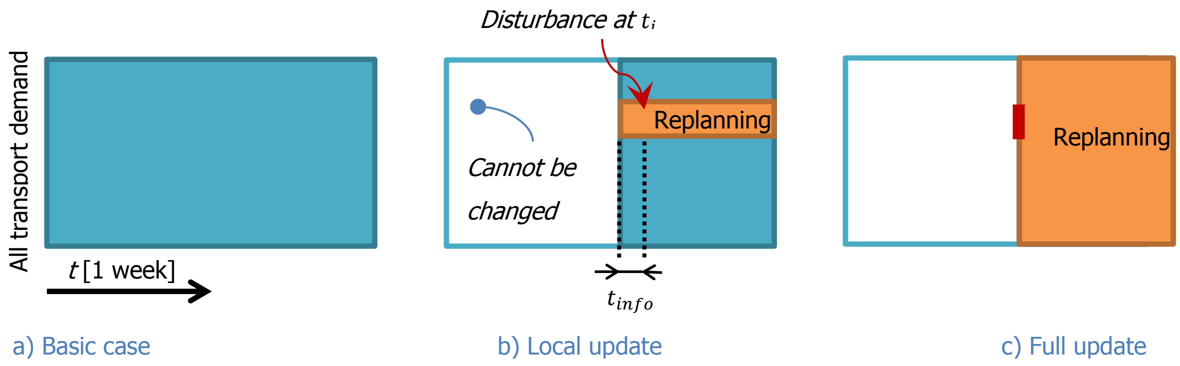


Figure 20 Three solutions with the operational model (repeated from Figure 18)

First, the planning model is solved for the basic case. Six steps are carried out:

1. General transportation parameters
2. Paths generation
3. Solve the operational planning model without disturbances
4. Introduction of a disturbance
5. Solving two updates
    a. The local update
    b. The full update
6. Determination of disturbance impact and relevance

Steps 1-3 are similar to the method used in Part I (Section 3.3). The steps are carried out once as pre-processing steps. Then, for each studied disturbance, steps 4-6 are performed. Note that this section only introduces the methodology, not the actual data and experiments. That is the subject of Section 5.4 and Section 6.1, respectively.

Figure 21 shows a schematic overview of the three operational model solutions and their position in the six steps method. The procedures corresponding to step 1-6 are further elaborated next.

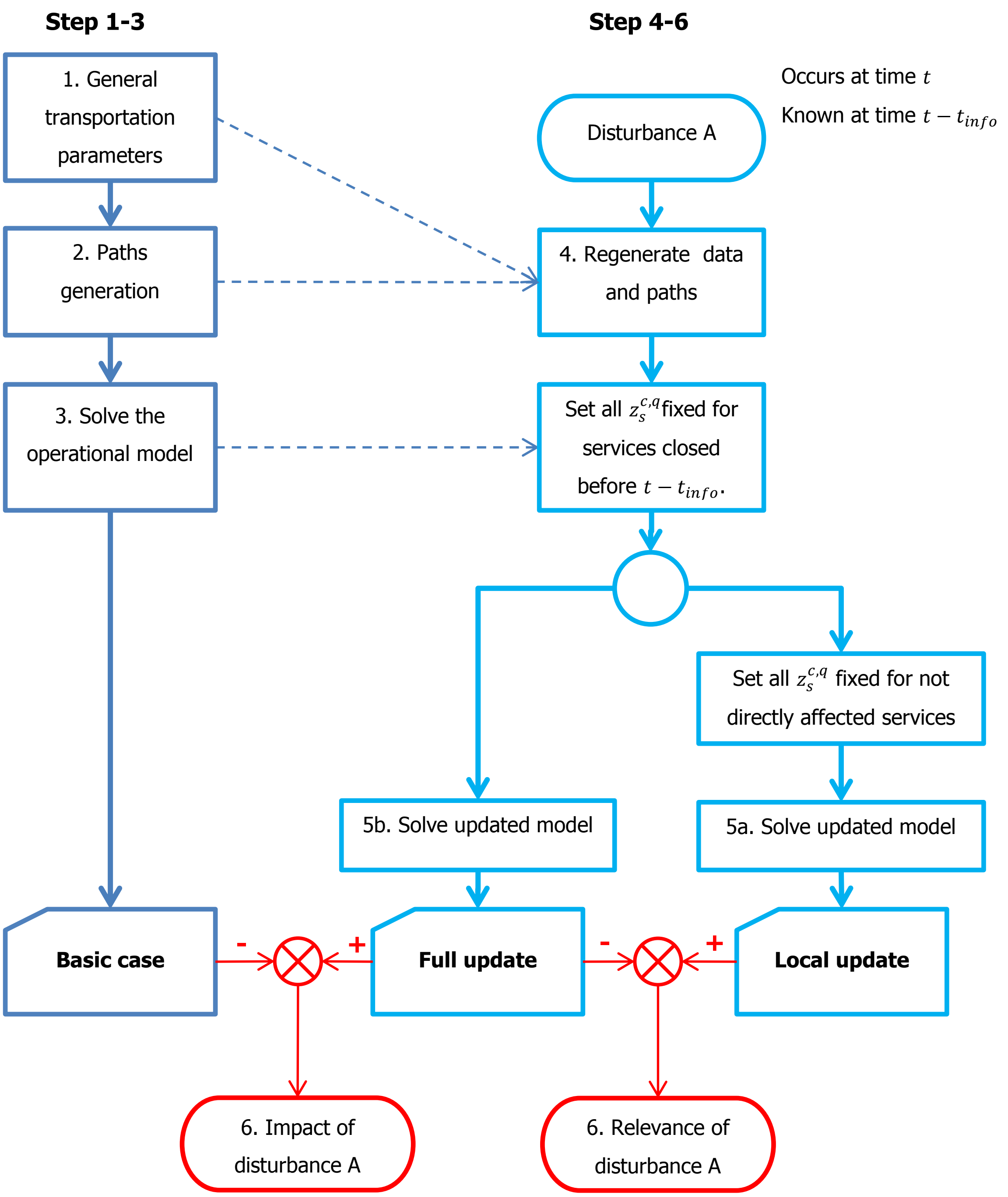


Figure 21 Overview of research method Part II

5.3.1 Basic case solution

Step 1: General transportation parameters

Most of the network parameters are almost equal to those in the tactical network. However, the demand flows are now specified in more detail and a fixed service schedule is used. These two aspects are described here.

Demand

The data is based on the same demand sets as in the tactical case. The details of the demand distributions are found in Appendix D. For this study at the operational level, the demands patterns over the week are generated in the following way.

First, an arrival pattern for the deep sea vessels is assumed. This is based on a regular week's situation. It is assumed that all vessels depart again 24h after arrival. This deep sea arrival pattern is identical in all demand patterns. Then, all the cargo classes are assigned to the deep sea vessels at random for the ten demand patterns. These ten demand sets are identical in all experiments of this Part II. The used data sets, including the demand data, are subject of Section 5.4.

Service schedule

The service schedule that is used in Part II of the research is based on the 10% growth case of Part I. This case is assumed to represent the near future EGS situation. In order to get a service schedule, the solution of the tactical network model must be translated into departure and arrival times of the services.

The tactical network model resulted in a number of self-operated rail and barge connections and subcontracted volumes of container transport. The subcontracted volume on each corridor is translated to the number of available subcontracted services based on a maximum 30% loading degree with EGS containers.

The creation of the service schedule is an optimization problem on its own (Crainic 2000). I.e., the transfer time between subsequent connections may very well influence the usefulness of a specific path. The main result of this research is not the actual implementation of the planning method, but to develop a suitable method to find relevant disturbances. Hence, the service schedule is chosen such that the time between two services that are often connected in the tactical solution are as short as possible (minimum of 4h). All services on a single corridor are distributed evenly over the week. The schedule is set up in such a way that the connection time for switching containers is minimized: based on the selected paths of the tactical case, all consecutive services are planned with a short connection time (4h). The service schedule used in the study is shown in Section 5.4.

Step 2: Paths generation

The service schedule can be represented as a space-time diagram (Figure 22). In the figure, the $t^c_{available}$ and t^c_{due} of an arbitrary cargo class with origin *A* and destination *B* are shown. All services that depart too early or arrive late are greyed out. Note that an overdue delivery with period x is still considered, such a late delivery would incur a cost for overdue delivery. In this study paths of a maximum length of 8 days are selected, so the value for x depends on the time restrictions of the cargo class. For the specific cargo class for which the arrival and delivery windows are indicated, four paths can be selected:

1. Barge 2 → Train 5
2. Train 3 → Train 4
3. Train 3 → Train 5
4. Barge 1 *This results in overdue delivery, but is considered, as the overdue time is less than period x*

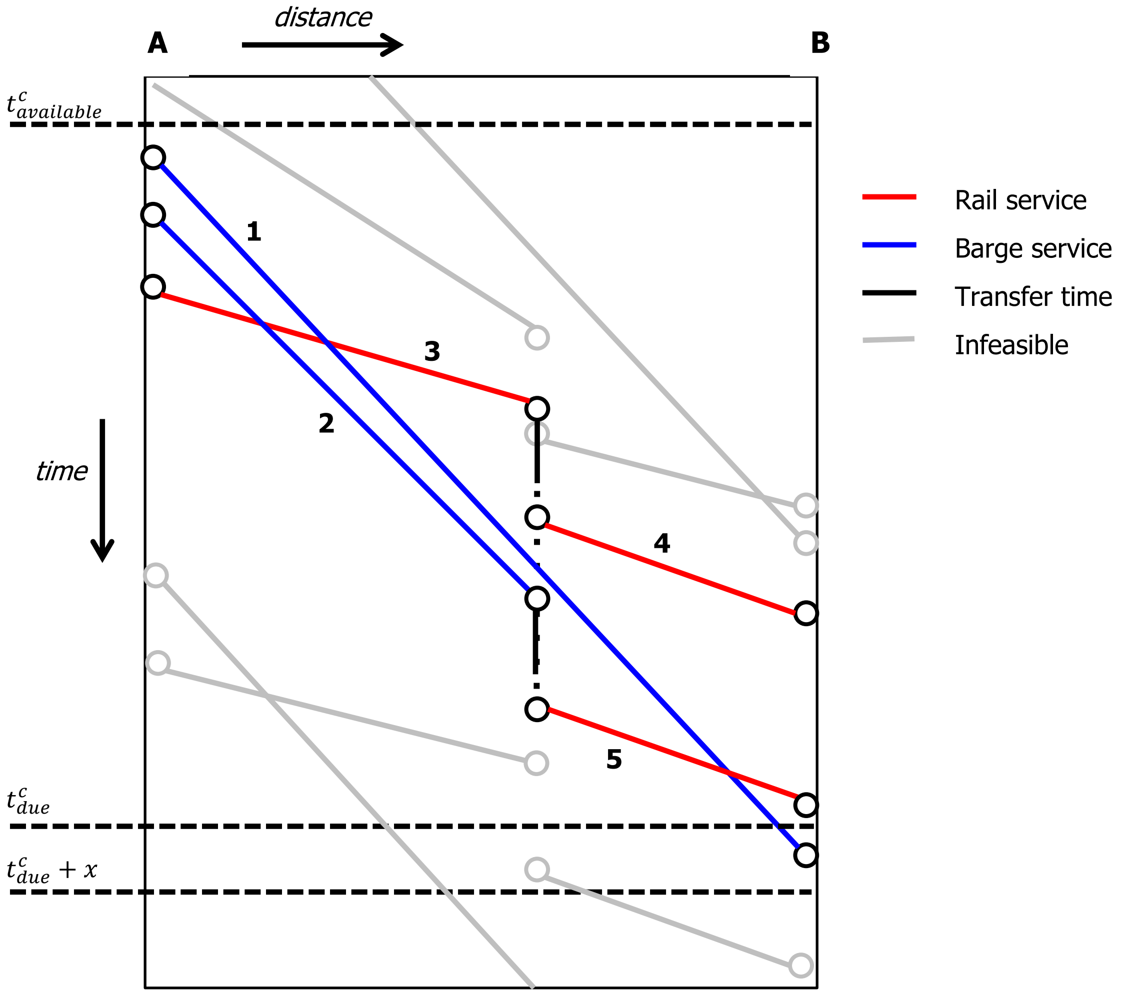


Figure 22 Example of a Space-Time diagram for a container class: 3 terminals, 5 services

The set of paths for each origin-destination pair is generated based on the space-time representation of the service schedule (Crainic 2000). With the generation of the set of paths, the time constraints are omitted. These time constraints are secured by the mathematical model formulation of the operational level (Model 2). Hence, the set of paths is equal for all cargo classes with the same origin-destination pair.

Similar as with the tactical path generation, paths are considered suitable if no loops occur, a maximum of 3 legs and that each leg complies with the following triangular distance constraint:

$T_{iD} \leq mT_{jD}$ (triangular distance)

Where T_{iD} and T_{jD} denote the trucking time to the destination from the terminals before and after the service. Hence, each leg must bring the container closer or at maximum m times further away from the destination. In this study a value of $m = 1.1$ is used. The maximum duration of a suitable path is set to 8 days. As a week's planning is solved, 15 days of planning must be considered. A cargo class arriving at the end of the week, can then still take paths of 8 days.

The paths are generated using the following procedure. A graph is created, where each node represents a service. The graph is created for a period of 15 days, starting on Monday.

Nodes are connected with a directed arc if a transfer from the first service to the next service is feasible in space and time and satisfies the triangular distance constraint. The required transfer time of 4h is a constraint as well. Each path in this graph represents a feasible connection of barge and rail services.

Note that each arc represents the switching of a container. To find all paths that take maximally three services, a very high length (say 10^5) is assigned to each arc. All paths with a length shorter than $4 \cdot 10^5$ consist of 3 legs or less.

The length of each arc is incremented with the cost of transporting a container on that next node. In the case of a subcontracted service, these costs are the cost of transporting a subcontracted TEU. In the case of a self-operated service, these costs are zero.

Then, Yen's method (Yen 1971) is used again to find all paths without loops between an origin-destination pair. The method selects shortest paths in ascending length, starting with the shortest. If a path of length larger than $4 \cdot 10^5$ is found, all suitable paths are found. When the fictional ten-thousands are removed from the length, the path's transportation cost result. Transfer costs are not included; transfer costs are modelled separately in the objective of Model 2. All paths that take longer than 8 days or cost more than a direct truck connection are removed.

Now, a set of paths using barge and rail services is generated. The possibility of a truck leg in the hinterland must still be included. Based on each path with one or two legs, suitable paths with an additional truck leg in the hinterland are added. A path is considered suitable if the addition of the truck leg satisfies the triangular distance constraint introduced before. Truck legs are only considered as the end leg in the hinterland. In the case of import transport, this is the last leg, in the case of export transport it is the first. The cost of a path with an added truck leg is incremented by the trucking costs, *not* with an additional transfer. The reason for this is that this truck leg will in practice be combined with the local truck delivery that is not included in this study. Direct trucking from the seaport is considered separately in Model 2 and not included in the generation of paths. The graph that corresponds to the service schedule of Figure 22 is shown in Figure 23. The figure shows the 5 services represented as nodes. Service 1 is the only direct connection to the destination B. Five other paths are possible. After service 3 two transfers are possible, to service 4 or 5. The latter can also be used after service 2. Alternatively, the last leg can be a truck leg after service 2 or 3.

Finally, for each path, information is stored on the used services, the number of transfers, the costs and the departure and arrival times.

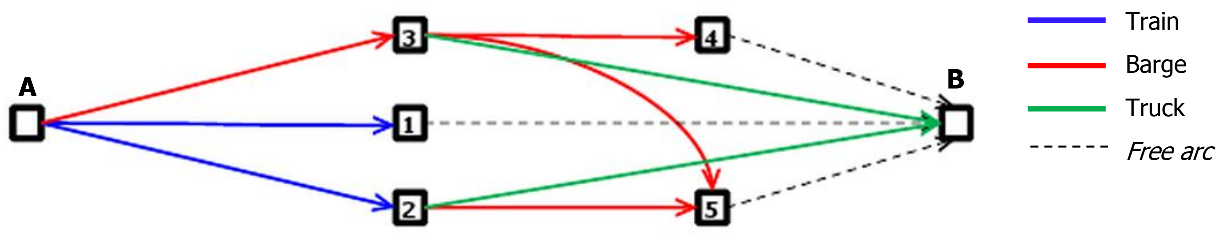


Figure 23 Graph that represents the service schedule of Figure 22

Step 3: solving the basic case of the operational planning model

This step is carried out similar to the solution of the tactical planning model. The operational planning model is solved using the software package AIMMS 3.12 on a MacBook Pro with a dual core 2.66GHz processor and 8GB of RAM memory.

The model is a regular Linear Programming (LP) model. The formulations in this study were simplified by pre-processing the path data (Step 2). The optimal solution for the basic case (without any disturbances) can be found within minutes. The precise computation times are reported with the results in Chapter 6.

Note that the planning is solved for one week. The time is modelled cyclic: demand on services on day 8 is mapped to day 1). This is already taken care of in step 2.

5.3.2 Updating planning solutions

Step 4: Introduction of a disturbance

The disturbances were introduced in Section 5.1.3. Each disturbance may occur at all possible services. Hence, a series of experiments is conducted. A disturbance is applied one at a time, in order to study the effect of these single disturbances. The time that the disturbance occurs is called t. The amount of time that the information of the disturbance becomes available earlier than t is called t_{info}. For instance, it may be known 1 day in advance that a specific service will be cancelled. In Section 5.2.3 was introduced how the mathematical formulation was adapted to incorporate the disturbance. In order to solve an updated planning, all decisions that took effect before $t - t_{info}$ are set fixed. In the case of the local update, all decisions that take effect after $t - t_{info}$ are set fixed as well; only the directly affected cargo classes can be changed. Cases with incomplete information are not considered, i.e. were the information of a disturbance is only known after it took effect already.

In the case of a disturbed service, a service departs earlier, later or is cancelled. All paths using this service may become infeasible. So, these paths are removed from the model. If the service is not cancelled but only changed in time, a new set of paths using this service is generated. These paths are added to the model.

Step 5: Solving the local update and full update

First the basic case was solved (step 1-3). Subsequently, the model is updated with a disturbance, possibly including new paths. Some of the decision variables are fixed.

Starting with the solution of the basic case (step 3) as an initial solution, the model is solved again in the same way with the software package AIMMS 3.12. The model is still a regular Linear Programming (LP) model. The updates take less than a minute in general. The actual calculation times are reported with the results in Section 6.3.

Step 6 Determination of disturbance impact and relevance

The experiments carried out to find the impact and relevance of several disturbances are described in Chapter 6. In Figure 24 the schematic overview of the definitions of the impact and relevance is repeated from the methodology overview in Figure 21.

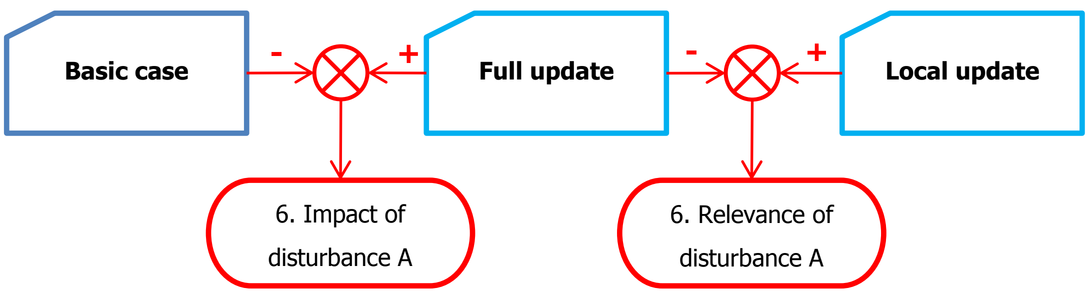


Figure 24 Schematic overview of impact and relevance measures

5.4 Data

The cost data used in this part is equal to the data as specified in Section 3.4. The service schedule and demand data differs from the case of Part I. The methodology to determine the demand patterns and service schedule was already described in Section 5.3.1. Here, the demand patterns and service schedule are described.

Service schedule

In this research, the planning in the near future EGS network is considered. To create a service schedule, the results from Part I are used. The scenario with 10% growth is assessed, as it is expected to represent the near-future EGS transport volume, based on estimates of the EGS Business Development department. This scenario resulted in a number of self-operated services per week and a volume of subcontracted volume. Subcontracted volume is translated in a number of services using a maximum loading degree of 30% of EGS volume. It is ensured that the same number of services travel in both directions. The number of services on each corridor is represented in Figure 25. In total the schedule consist of 166 services per week.

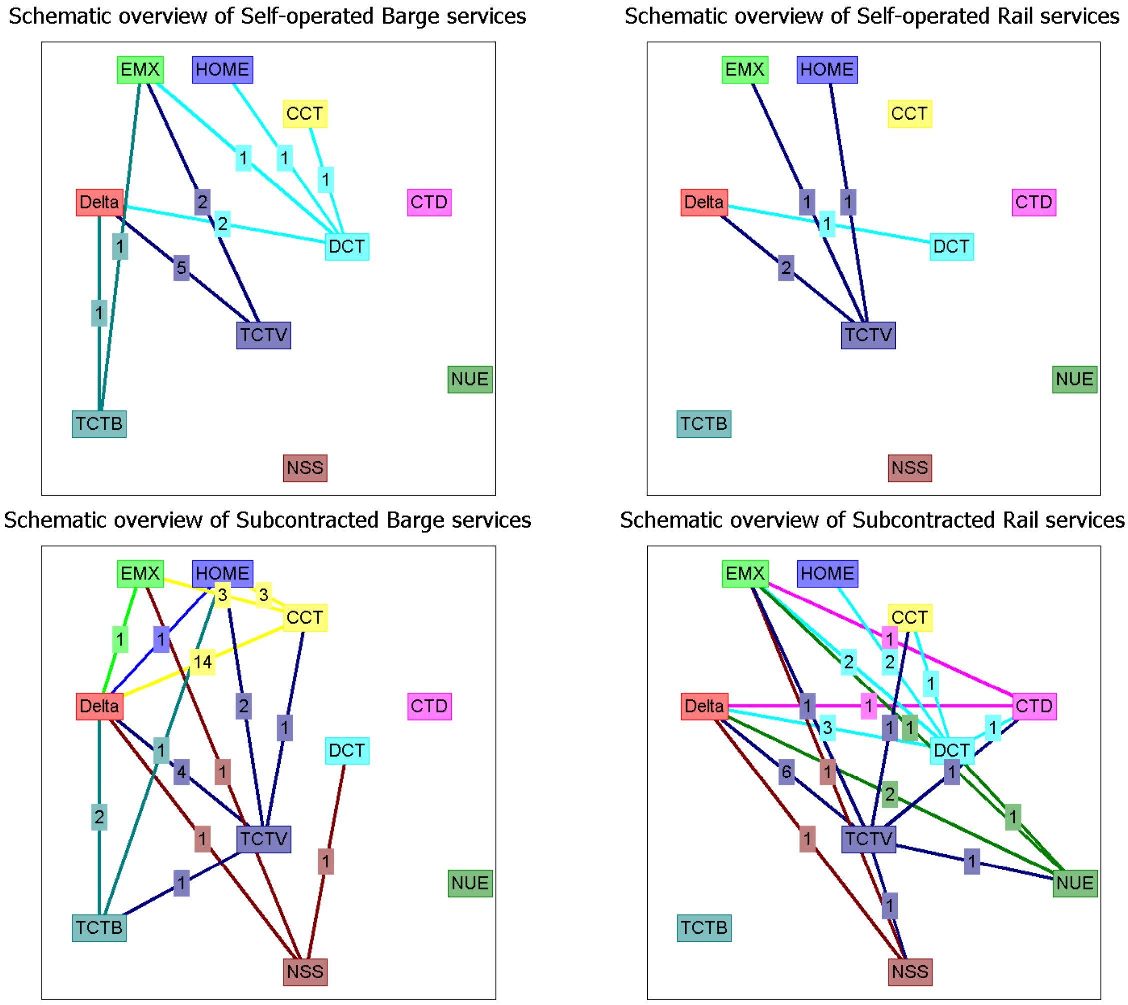


Figure 25 Service schedule Part II (# of one way connections)

The departure times are distributed evenly over the week, making sure that the connection times are short on paths that are selected in the tactical scenario. Table 12 shows the point in the network where intermodal transfers are possible and the average occurring connection time. The minimum transfer time of 4h is excluded from the reported connection times in the table. Although waiting time occurs for almost all intermediate transfers, most waiting times are short: 6h or less. This service schedule is used as a basis for the set of available paths as described in Section 5.3.1.

Transfer point	Origin	Destination	Average transfer time [h]
Euromax	Delta	Venlo	2
	Delta	Euromax	6
Duisburg	Dortmund	Delta	4
	Dortmund	Euromax	6
	Euromax	Dortmund	1
	Euromax	Neuss	4
	Euromax	Nuremburg	5
	Neuss	Delta	3
	Nuremburg	Delta	3
	Neuss	Euromax	0
	Nuremburg	Euromax	2
	Delta	Dortmund	4
	Delta	Neuss	3
	Delta	Nuremburg	4
Venlo	Neuss	Delta	4
	Dortmund	Delta	4
	Dortmund	Euromax	2
	Nuremburg	Delta	4
	Euromax	Dortmund	1
Home	Delta	Venlo	3
	Delta	Duisburg	4
Moerdijk	Delta	Duisburg	3

Table 12 Connection times in service schedule (minimum transfer time of 4h excluded)

Demands

For the experiments in Part II, ten demand patterns are used. The demand patterns are determined based on the same data that was used in the tactical research (Appendix D). This data of weekly demand is translated into specific cargo classes with arrival and departure dates throughout the week.

Each pattern is based on the arrival of 41 deep sea vessels at the seaports, of which 86% bring containers into the EGS network (import containers) and 45% pick up containers of the EGS network (export containers). The values are based on the average of the EGS transports in the period of January 2011 to June 2012. Note that in this case, 'deep sea vessels' refers to all incoming vessels including short sea connections.

The same cargo classes are used as in the tactical research: for each origin-destination pair, the historic data of the period January 2011 - June 2012 is categorized in four mass categories (refer to Table 6 in Section 3.4.3 for the mass categories). All categories are split into four parts, with a different time period available between the availability and due time. These delivery periods are represented in Table 13. In the tactical research, no waiting time due to the schedule was incorporated in the model, so an estimate of the available transport time was used. In this operational model, these waiting times are included; hence a new estimate is made by EGS experts. The first three categories have double as long time available as the times used in the tactical research (Table 7), the fourth category represents containers with hardly any time pressure and is kept equal at 7 days.

Delivery period [days]	Fraction [%]
1	20
2	40
4	30
7	10

Table 13 Delivery period categories

The historic data showed that during a week containers of the same cargo class come from only one ship, with few exceptions. In other words, each cargo class can now be assigned at random to a single deep sea vessel.

For each of the ten demand patterns, two steps are carried out:

- The volume of each cargo class is based on its normal distribution.
- The cargo classes are assigned at random to deep sea vessels

From the arrival time of the deep sea vessel can be calculated what the availability and due time of the cargo class during the week are.

Overview of Chapter 5

In this chapter, the research of Part II was described. The process of container planning was studied, based on the EGS case. The operational network model was introduced; an adapted version of the tactical model of Chapter 3. Subsequently, the methodology to use the model and the used data were described. The experiments with this model are the topic of the next chapter.

Chapter 6. Disturbances in the operational planning

The main goal of Part II is to identify the impact and relevance of several disturbances on the operational planning in the EGS network. In Chapter 5 the operational network model was introduced for this purpose. The experiments with disturbances on the model are subject of this chapter. In Section 6.1 the experiment plan will be described. In the other sections, the results will be presented. Section 6.2 will start with the validation of the operational model result. Subsequently, Section 6.3 will describe the experiments and their results. This chapter will finish Part II of the study.

6.1 Experiment plan

Basic case and validation

a) *Find basic case solution*
   The results of the basic case are the starting point for all updates. The basic case is determined by the solution of the operational planning model (Model 2 in Section 5.2.2). The results are validated by comparison to the tactical model results.

Impact and relevance of disturbances on services

The next part of the research is to find disturbances that have a large impact or relevance for the network planning. For this purpose, simulations will be carried out with disturbances to all services in the network schedule. A disturbance will be applied *one at a time*. After determining the impact and relevance of each disturbance, the correlation with the following service properties will be computed. This provides indicators that show which type of services are more likely to have a large impact or relevance in the network planning than others.

- Service loading degree
- Service frequency
- Rail or barge services
- Self-operated or subcontracted

Apart from finding the indicators for impact and relevance, the following quantitative results are computed:

- *The value of early information*
  How important is it to know information in advance?
- *The effect of early arrival or delays*
  How big is the effect of early arrival or a delay? Is the impact always negative?
- *The effect of cancellations*
  What is the impact of service cancellations

The impact and relevance of the disturbances on different services prove to differ a lot for one service compared to another. Hence, the experiments are carried out in two steps. First, the services on which disturbances have large effect are identified. For these, additional experiments are carried out.

An experiment about a service disturbance can be defined by 3 parameters: the length of the disturbance t_{delay}, the length of time between the information and the estimated departure (t_{info}) and the service on which the disturbance is applied.

b) *Identify services with large effect*

   Let S denote the full set of all services. For all services, 3 situations are tested; each situation both with a local and a full update (see Table 14). Each update is carried out based on the basic case solution, with the additional update constraints as introduced in Section 5.2.3. This results in 6 updates per service and 996 updates for all 166 services in total. For these series of disturbances, the impact and relevance is determined.

c) *Determine the extent of effects on relevant services.*

   The effect of the length of the delay and the earliness of information, a subset B of the services is studied in further detail. Subset B is determined as follows:

$$B : I_{1\%} \cap R_{0,5\%}$$

   Here $I_{1\%}$ denotes the set of all services for which the impact in experiments *b* is larger than 1% of the total objective costs of the basic case. Likewise, $R_{0,5\%}$ denotes the set of all services for which the relevance in the experiments *b* is larger than 0.5% of the basic case objective. Hence, subset B consists of all services that have a large impact or relevance. For these services, a wider range of t_{delay} and t_{info} is tested. Subset B comprises 18 services and for each service 7 additional situations are carried out (Table 14). Again, both a local and a full update are carried out, so 14 updates per service and 252 updates in total are computed.

	t_{info} [h before ETD]	
t_{delay}	**24h**	**12h**
Early		
-24 h	**B**	
-12 h	**B**	**B**
-6 h	**S**	
Delayed		
6h	**S**	
12h	**B**	**B**
24h	**B**	**B**
Cancelled	**S**	

	Experiments
S	For all services
B	For subset B

Table 14 Experiments in Part II for service disturbances

6.2 Model validation

The solution of the basic case was determined, the computation time was 7 minutes. The results are shown in Figure 26. The figure shows the planned transports in 6 categories. For all three sea terminals (Delta, Euromax and Home) the import and export demand is presented separately. The width of each line corresponds to the volume in TEU on that corridor. Note that these volumes are also denoted with each line, masked with the volume confidentiality factor. The colour of the line denotes the hinterland terminal the service travels to (import) or from (export) The few cargo classes with continental transport (e.g. Moerdijk to Venlo) are not shown.

For the export of containers to Euromax and Home, an odd route can be observed. The model plans containers from TCTB via DELTA and CCT towards the final network destination EUROMAX or HOME. In practice, this connection would not occur as local barge transports between the Rotterdam seaport terminals would be a better alternative. The model extension to incorporate this smart barge scheduling was discussed briefly in Section 5.2.4, but not implemented in this study. Apart from this, the basic case solution shows expectable results. Two differences with the current daily practice are the following. The model uses direct truck in the basic case solution, but only for 0.2% of the transported containers. Secondly, some intermediate transfers are planned, as is expected for the optimal solution of this model, based on the results of the tactical model in Part I. This is a difference compared to the current daily practice with only direct Rotterdam-hinterland connections. Two types of transfer occur, likewise as in the tactical research:

- Intermodal routes with intermediate transfers, such as the planned transports between CCT and DCT for some of the EUROMAX import.
- A final truck leg in the hinterland: this is used from Venlo to Duisburg for containers imported from the HOME terminal.

Sample size: 10 demand patterns

The costs of the objective terms are shown in Table 15. The table reports the mean of the ten demand patterns and the standard error of this mean. The relative standard error of the total objective is 3%. A lower relative standard error is not necessary; solving the experiments for 10 demand patterns provides sufficiently accurate results.

Relaxation to linear program

The average total costs of the solution with all planned transports rounded to integers amounts €1060.8, a relative error of 0.2%. This substantiates the relaxation of the integer planning problem into the linear program of Model 2.

€	Subcontracted	Transfers	Late	Direct truck	Total
μ_q	226.7	639.3	186	11	1063.0
s_{μ_q}	17.4	19.2	14.2	4.2	28.4

Table 15 Results Basic Case

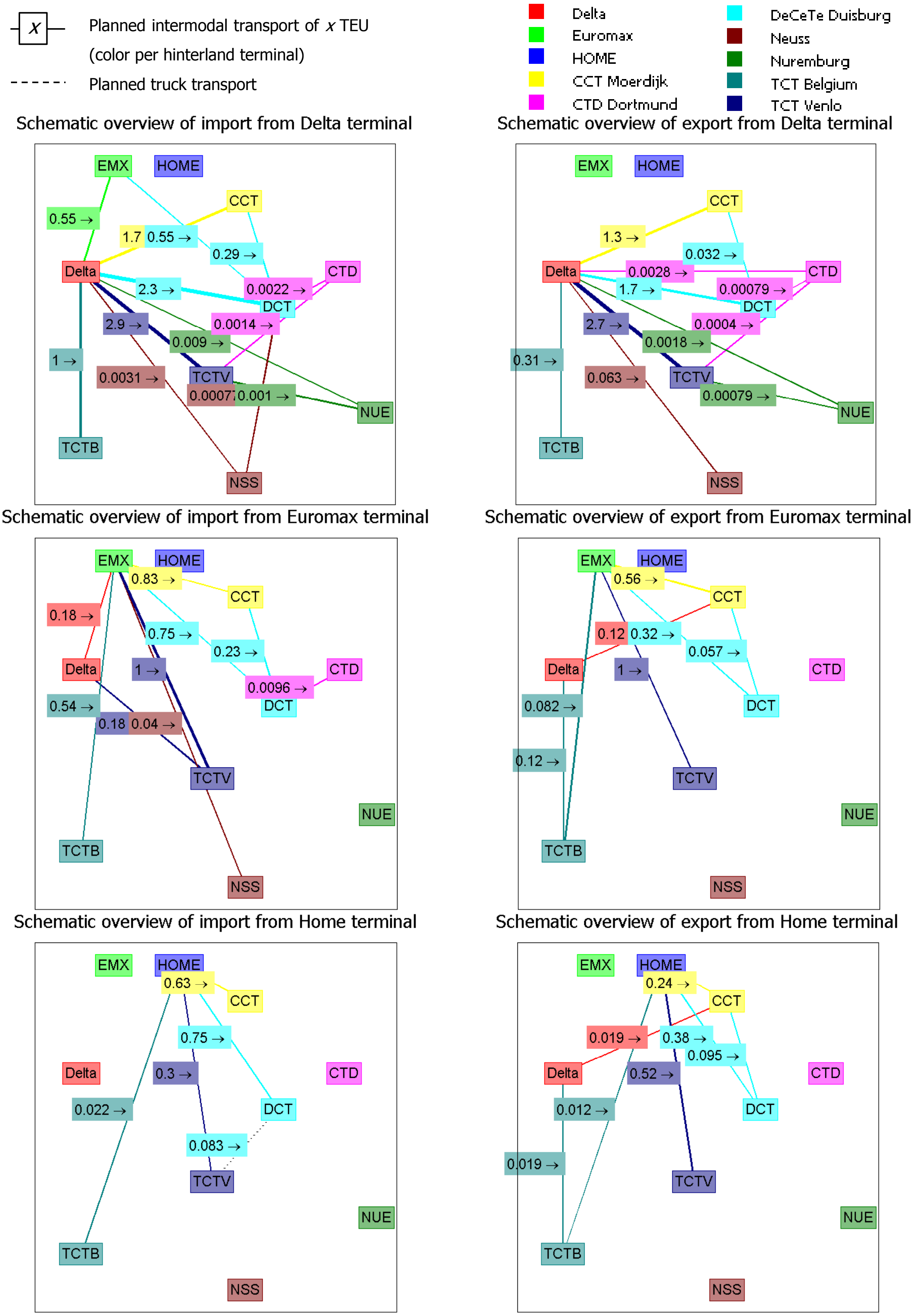


Figure 26 Overview of results Basic Case

Comparison to tactical model results

For reference, the cost structure of the objective value in the 10% growth scenario of Part I is repeated in Table 16. This is the case that the service schedule and demand pattern of Part II are based on. Note that the cost "Services" for self-operated barges and trains is not included in the objective of the operational model. Also, CO_2-costs are not included in the operational model. On the other hand, trucking was considered as subcontracted transport in Part I, but is considered as a separate term in the operational model objective. The costs for subcontracted transport, late delivery and handling are 7% higher in the objective of the operational model than in Part I. This is caused by a higher amount of subcontracted transport (+37%) and late delivery (+39%). A slightly lower amount of transfers takes place (-8%). The tactical model lacks an accurate modelling of the time delays because of the service schedule. That is the most likely cause for the differences. A more detailed assessment of the differences in both models is proposed for further research in Section 7.2.

Experiments	Total [€]	Services [€]	Subcon-tract [€]	Late [€]	Handling [€]	CO_2 [€]
N. Basic case (+ 10%)	1258	255	166	134	693	9

Table 16 Results of experiment N of Part I

Utilization of services

Naturally, the maximum utilization is 100%. This was verified for all 10 demand patterns of the Basic Case. Figure 27 shows a histogram of the average utilization of both self-operated and subcontracted services. On average, the 38 self-operated services are utilized for 50%. Twenty of these are fully utilized in any of the 10 demand patterns. Four of the self-operated services have a utilization that is below 60% in all 10 patterns.

In Section 5.3.1 the service schedule for the experiments was created. The number of subcontracted services was based on the transported volume on subcontracted services, using a utilization of 30% EGS volume on these services. The average loading degree with EGS containers of all subcontracted services in all demand patterns is 19.4%. Out of the 128 available subcontracted services, 33 are utilized for 100% in any of the 10 demand patterns. This may be a problem in practice and should be carefully checked when applying the results of the model for operational planning purposes.

The model without overdue delivery

The used model allows specifically for overdue delivery. To determine the difference with a model that does not allow this, the basic case is solved now without the possibility for overdue delivery. The differences in the results are described here shortly. In the basic case, direct trucking was used for only 0.2% of the transportation. This increases to 8.6% if overdue delivery is not allowed. The costs of this solution are €774 higher than the basic case, an increase of 73%. Hence, the flexibility of the model for overdue delivery is essential to get solutions without excessive truck transportation.

Impact and relevance

A final verification of the used model uses the impact and relevance of the tested disturbances. A disturbance may result in a situation where a cheaper solution becomes feasible, but this is not likely, though. A cheaper solution in case of a service cancellation is never possible. Hence, the majority of the changes in scheduled times should increase the optimal cost, i.e. a positive valued impact. In case of cancellations, the impact must always be positive. The second check uses the relevance. A feasible solution of the local update is by definition also a feasible solution for the full update. Hence, the optimum objective value for the full update is smaller or equal to the optimal value for the local update. Consequently, the relevance must be nonnegative in all cases.

Both of these verifications of the update methods proved useful during the development of the model: in an early development stage of the model a few mismatches in the used database were discovered after the model had resulted in a negative relevance for one disturbance. After solving these problems, all experiments show nonnegative relevance. All experiments with cancelled services show nonnegative impact. Experiments with early or delayed services have a negative impact in 20% of the cases, and most of these impacts are not significantly negative: only 7% of these experiments have an impact below -0.1% (or equivalently €-1.06).

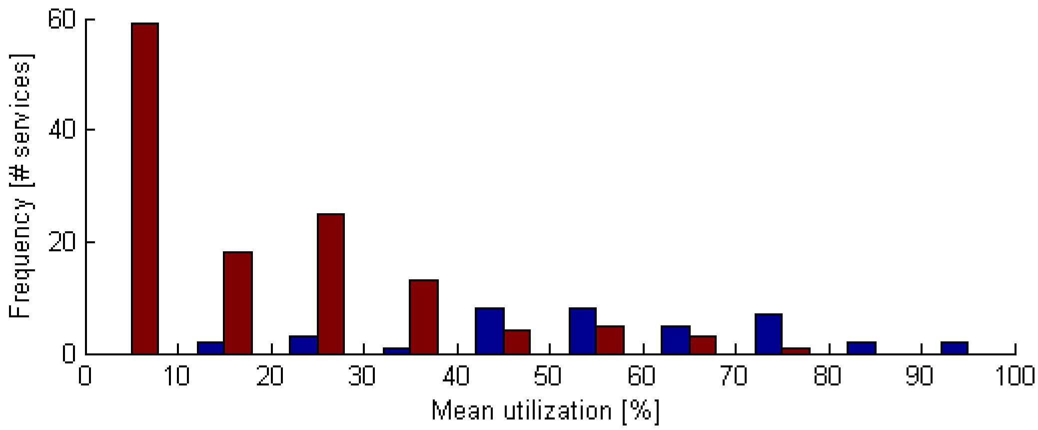


Figure 27 Utilization of services (basic case)

6.3 Experiments

Experiment *a*, the solution of the basic case, was described in the previous section to show the basic case results and validate the model. In this section, the experiments for the various disturbances will be described. First, for all 166 services three disturbances will be studied (experiments *b*). Then, 7 additional disturbances are studied for a subset of the services (experiments *c*). For both experiment sets, the results will be presented and the important observations will be described. The significance and implication of the results are subject of Section 7.1.

Experiments b: Identify services with large effect

The set of experiments *b* consists of 996 updates of the basic case: three disturbances are applied to all services and for each of these disturbances a local and a full update is carried out. This was introduced in the Experiment plan (Section 6.1). The results of the updates are used to determine the impact and relevance of each disturbance. Remember that the impact is defined as the difference in total costs between the undisturbed basic case and the fully updated disturbed case. The relevance is the difference in total costs between a local and a full update for the same disturbance. A positive impact means a cost increase due to the disturbance; a positive relevance means a cost decrease for a full update compared to a local update.

The average computation time for the full updates was 56 seconds, for the local update (with less degrees of freedom) only 36 seconds. A histogram of the impact and relevance of all tested disturbances is shown in Figure 28. Please note that the graph is cut off at the top, to focus on the nonzero impact and relevance values.

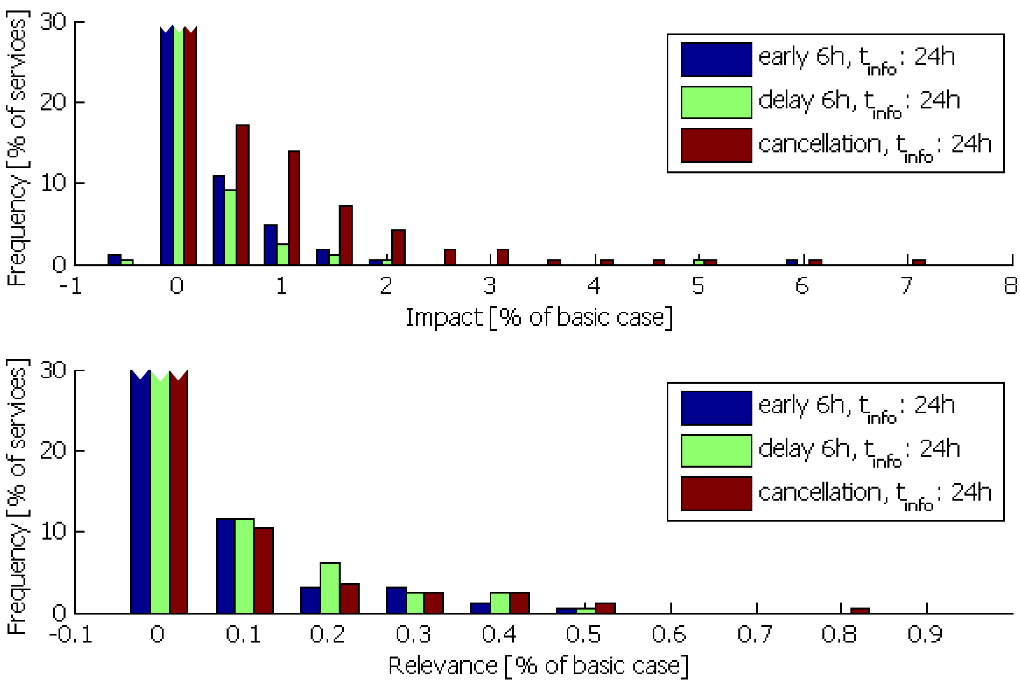


Figure 28 Histogram of impact and relevance of experiments b

From Figure 28 we can see that the majority of the disturbances has a very small impact and very small relevance. Also, we see a similar distribution for both the 6h delayed and 6h early services together referred to as *time shifts*. The impact of cancelled services is significantly larger than a time shift, as may be expected, but the relevance is similar. In Table 17 the average impact and relevance of the three disturbance types are shown. This is shown for the full set of disturbances, but also for a specific mode or transport type (self-operated or subcontracted). Also, the standard error of the sample's mean is reported.

$t_{info} = 24$		Early [6h]	Delay [6h]	Cancellation
All	*Impact:* $\mu(\sigma)$	0.18 (±0.04)	0.13 (±0.04)	0.91 (±0.14)
	Relevance: $\mu(\sigma)$	0.04 (±0.01)	0.05 (±0.01)	0.05 (±0.01)
Disturbances on barges		0.20 (±0.07)	0.16 (±0.06)	1.15 (±0.22)
		0.05 (±0.01)	0.06 (±0.01)	0.06 (±0.01)
Disturbances on trains		0.15 (±0.05)	0.09 (±0.04)	0.56 (±0.09)
		0.02 (±0.01)	0.03 (±0.01)	0.03 (±0.01)
Disturbances on self-operated services		0.29 (±0.07)	0.27 (±0.06)	2.24 (±0.50)
		0.07 (±0.02)	0.11 (±0.02)	0.13 (±0.03)
Disturbances on sub-contracted services		0.14 (±0.05)	0.09 (±0.05)	0.52 (±0.08)
		0.03 (±0.01)	0.03 (±0.01)	0.03 (±0.01)

Table 17 Summary of impact and relevance [% of basic case cost] (experiments b)

For example, the impact of a service that is 6h early has an impact of 0.18% of €1063, or €1.91. The relevance of the same disturbance is €0.43. Unfortunately, these values are masked and the actual values cannot be reported here. However, note the following to place these costs into perspective: the solutions use a service schedule of 166 services. So, the average cost per service is 1063 / 166 = €6.40. So, a service that departs 6h early represents additional costs of €1.91, a cost increase of 30%. The average impact of a service cancellation is 0.91% of €1063, or €9.67. So, a cancelled service causes 151% additional costs, compared to its original costs. This makes sense as operating the average service is beneficial: cancelling it has an impact larger than the average cost part of the transportation of that service.

In general, the impact of a disturbance is larger than the relevance. The cancellation of a service has a larger impact than the time shifts, but not necessarily a larger relevance. Disturbances on barge services show a slightly larger impact than disturbances on rail services. The relevance of these disturbances is twice as large for barges as for trains. The final observation from the table is that disturbances on self-operated services have a larger impact and relevance than disturbances on subcontracted services. Hence, full updates of the planning are especially useful after disturbances of barge services and self-operated services.

The relevance of disturbances of self-operated services may also be related to the loading degree with EGS-containers. So subsequently, the correlation between the impact and the service's loading degree and service frequency is computed. The service frequency denotes the number of services on that corridor during the week, regardless the modality of the services. The service's loading degree is determined based on the solution of the basic case: the average loading degree over all 10 demand sets is computed and used as the service's loading degree. This loading degree was visualized in Figure 27 in Section 6.2.

The correlations between the service loading degree and service frequency and the impact and relevance are determined 10-fold by leaving out 10 disjoint subsets of the services. The mean and standard error of these 10-fold correlations are shown in Table 18.

$t_{info} = 24$		Early [6h]	Delay [6h]	Cancellation
Corr. frequency and impact:	$\mu(\sigma)$	-0.12 (0.01)	-0.14 (0.01)	-0.15 (0.01)
Corr. frequency and relevance:	$\mu(\sigma)$	0.15 (0.03)	0.05 (0.02)	0.14 (0.02)
Corr. loading degree and impact:	$\mu(\sigma)$	0.25 (0.02)	0.30 (0.02)	0.24 (0.04)
Corr. loading degree and relevance:	$\mu(\sigma)$	0.22 (0.02)	0.32 (0.03)	0.30 (0.03)

Table 18 Correlation of impact and relevance with service parameters (experiments b)

The correlations in Table 18 show the relative effects of service frequency and loading degree on the impact and relevance. The following observations can be made: the impact of a disturbance has a weak (inverse) correlation with the frequency of services on that corridor. This indicates that a disturbance on a high-frequency corridor is less costly than on a low frequency, probably because many alternatives for the disturbed service exist. The correlation with the relevance is positive, though. This indicates that a full update is more beneficial on high frequency corridors than on low frequency corridors. See Figure 29 for an intuitive explanation of this effect in the case of three barges a week on Monday, Wednesday and Friday. If a service is cancelled on Monday, the full update is able to re-plan the Wednesday barge partially, and 6 containers get a delay of 2 days compared to the original planning. The local update cannot re-plan the full Wednesday barge and 3 containers get a delay of 4 days compared to the original planning. If the due time of all these containers is two days, only the local update will incur overdue penalty costs. If the frequency is higher than in this example, the full update will also avoid overdue times for situations with shorter due times. One can see that the full update will significantly perform better in the case of high frequency corridors. With a full update, containers on the alternative services can also be re-planned, resulting in a better solution to handle the disturbance.

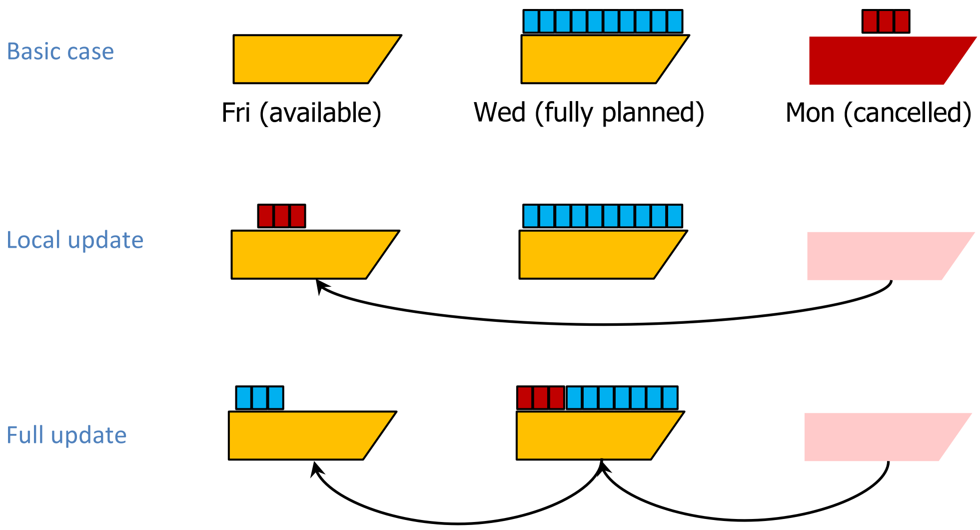


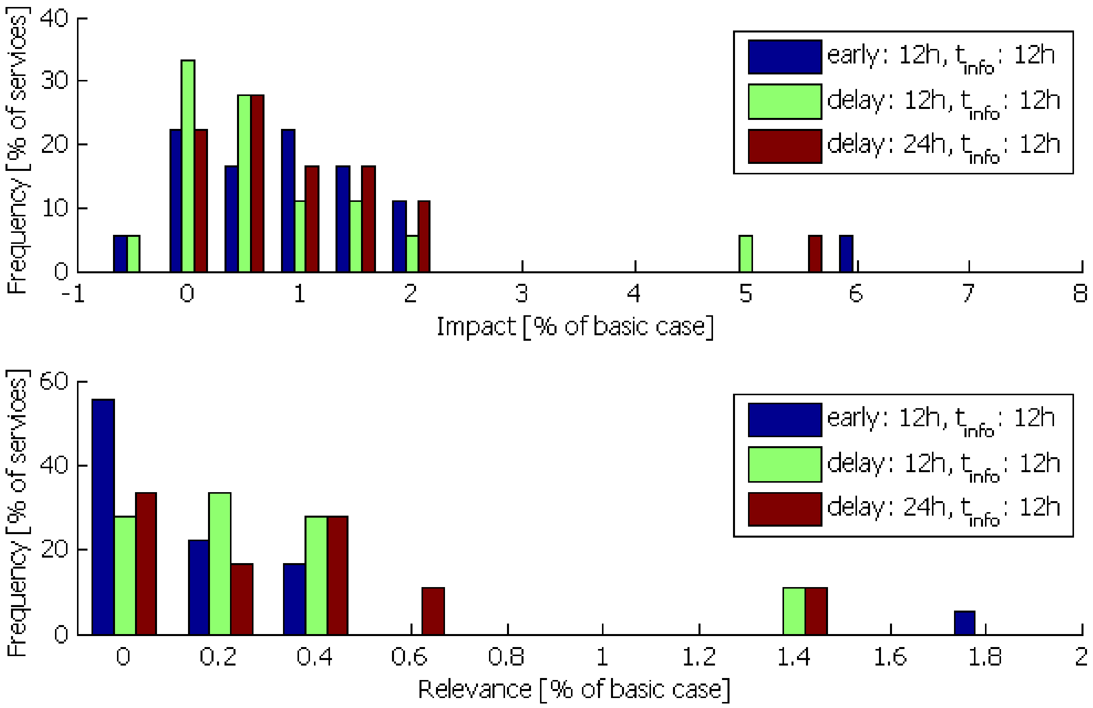
Figure 29 Full and local update on high frequency corridors

As can be expected, the service loading degree has a positive correlation with both the impact and the relevance of a disturbance. Services with a higher loading degree of EGS containers have a larger impact in case of a disturbance; also a full update results in a larger cost reduction for services with a high loading degree. Intuitively, large amount of EGS containers on a disturbed service can be re-planned more efficiently if space can be freed by re-planning non-directly affected containers, i.e. in a full update.

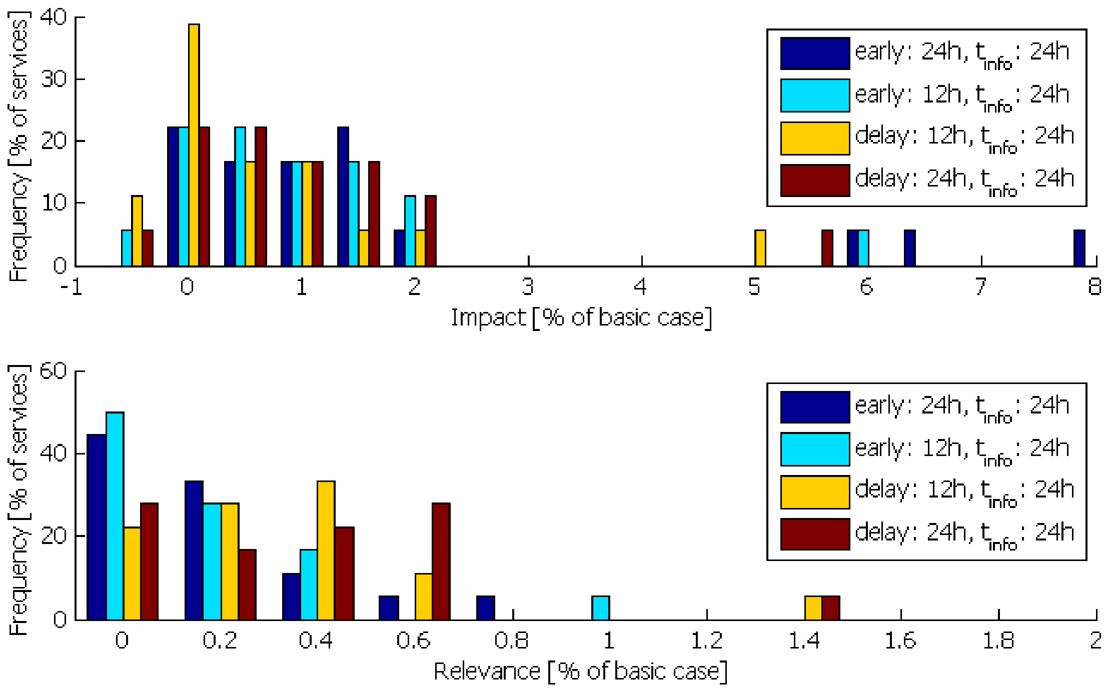
From the results of this experiment a subset B of the services is selected, with all services that show an impact larger than 1% or a relevance larger than 0.5% of the basic case objective, i.e. $B : I_{1\%} \cap R_{0,5\%}$. Subset B contains 18 services: 13 are barge services, 5 are rail services.

Experiments c: Determine the extent of effects on relevant services.

For the services selected as subset B, additional experiments are carried out. These experiments were specified in Section 6.1. See Figure 30 for the results. Note that all results are presented separate for the experiments where information about the disturbance is available 12h or 24h available upfront.



a) Mean impact and relevance for $t_{info} = 12$



b) Mean impact and relevance for $t_{info} = 24$

Figure 30 Histogram of impact and relevance of experiments c

The 18 services of subset B are selected based on a high impact or relevance for any of the disturbances of experiment set *b*. The histograms in Figure 30 show the impact and relevance for the additional disturbances tested in experiment set *c*. A larger part of these experiments show positive impact and relevance than in experiment set *b*. However, the disturbances shows zero impact or relevance for a significant part of the services still. By inspection of the experiment data the extremes are evaluated: the disturbances with an impact ≥ 4% occur at the end of the week. Hence, far less possibilities to update the planning are present. These results may not be representative for the real-world situation, but inspection of the data did not show other large outliers because of this effect. Hence, improving the model to cope with the end of the week is proposed for further research in Chapter 7. The disturbances that show an extreme relevance (≥0.6%) are not due to this end-of-the week effect. In Figure 29 a) for $t_{info} = 12h$, the four cases with highest relevance are all for disturbances on fully loaded Delta → Venlo connections. In Figure 29 b) for $t_{info} = 24h$, these four cases show a slightly smaller relevance between 0.6% and 1%. The two disturbances with a relevance around 1.4% occur for a barge from Euromax to Duisburg.

The mean impact and relevance for the experiments are presented in Table 19, again with the standard errors. From Table 19 we can see that the impact decreases if information is known further upfront (12h or 24h) and this holds for any of the modalities or transport types. The difference is not large though. The relevance is equal or almost equal in general. In some cases, such as the delay of subcontracted services, the relevance is smaller when information is known 24h instead of 12h upfront. Hence, in these cases, the difference between a local and a full update is less relevant when information is known upfront. The results show that an early departure of a service has a larger impact than an equal amount of delay. This was also the case for experiment set *b* with disturbances of 6h early and delay. For the relevance, this effect is opposite, suggesting that full updates are more useful for delays than for early departures.

$t_{info} = 12$		Early [12h]	Delay [12h]	Delay [24h]
All	*Impact:* $\mu(\sigma)$	1.14 (±0.34)	0.81 (±0.30)	1.05 (±0.30)
	Relevance: $\mu(\sigma)$	0.23 (±0.10)	0.33 (±0.09)	0.39 (±0.10)
Disturbances on barges		1.22 (±0.45)	0.81 (±0.38)	1.13 (±0.39)
		0.28 (±0.13)	0.39 (±0.12)	0.46 (±0.13)
Disturbances on trains		0.94 (±0.42)	0.80 (±0.48)	0.84 (±0.46)
		0.09 (±0.07)	0.15 (±0.07)	0.19 (±0.08)
Disturbances on self-operated services		0.94 (±0.21)	0.50 (±0.15)	0.85 (±0.22)
		0.27 (±0.17)	0.46 (±0.15)	0.58 (±0.14)
Disturbances on sub-contracted services		1.40 (±0.74)	1.18 (±0.65)	1.30 (±0.63)
		0.17 (±0.07)	0.15 (±0.06)	0.14 (±0.06)

a) Mean impact and relevance and standard errors for $t_{info} = 12$

$t_{info} = 24$		Early [24h]	Early [12h]	Delay [12h]	Delay [24h]
All	*Impact:* $\mu(\sigma)$	1.82 (±0.56)	1.09 (±0.34)	0.74 (±0.31)	1.00 (±0.31)
	Relevance: $\mu(\sigma)$	0.20 (±0.05)	0.20 (±0.06)	0.34 (±0.07)	0.39 (±0.08)
Disturbances on barges		2.12 (±0.75)	1.16 (±0.45)	0.77 (±0.38)	1.10 (±0.39)
		0.22 (±0.06)	0.24 (±0.07)	0.37 (±0.10)	0.43 (±0.10)
Disturbances on trains		1.00 (±0.39)	0.88 (±0.44)	0.69 (±0.53)	0.74 (±0.50)
		0.16 (±0.13)	0.09 (±0.07)	0.25 (±0.09)	0.28 (±0.09)
Disturbances on self-operated services		2.16 (±0.83)	0.86 (±0.20)	0.44 (±0.15)	0.79 (±0.21)
		0.24 (±0.24)	0.21 (±0.09)	0.43 (±0.11)	0.55 (±0.11)
Disturbances on sub-contracted services		1.39 (±0.75)	1.37 (±0.75)	1.12 (±0.66)	1.25 (±0.65)
		0.16 (±0.06)	0.18 (±0.07)	0.21 (±0.06)	0.19 (±0.07)

b) Mean impact and relevance and standard errors for $t_{info} = 24$

Table 19 Summary of impact and relevance of experiments c

Likewise as with experiment set *b*, in Table 20 correlations are computed for the service loading degree and service frequency with the impact and relevance. Again, the correlations are determined 10-fold by leaving out 10 disjoint sets. However, note that a subset of only 18 services is used to determine these correlations.

$t_{info} = 12$		Early [12h]	Delay [12h]	Delay [24h]
Corr. frequency and impact:	$\mu(\sigma)$	-0.24 (0.03)	-0.22 (0.03)	-0.26 (0.02)
Corr. frequency and relevance:	$\mu(\sigma)$	0.47 (0.10)	0.27 (0.13)	0.41 (0.12)
Corr. loading degree and impact:	$\mu(\sigma)$	0.27 (0.05)	0.27 (0.05)	0.17 (0.05)
Corr. loading degree and relevance:	$\mu(\sigma)$	-0.07 (0.18)	0.10 (0.06)	0.17 (0.07)

a) Correlations of impact and relevance with service parameters and standard errors for $t_{info} = 12$

$t_{info} = 24$		Early [24h]	Early [12h]	Delay [12h]	Delay [24h]
Corr. f and I:	$\mu(\sigma)$	-0.10 (0.05)	-0.22 (0.05)	-0.21 (0.05)	-0.24 (0.05)
Corr. f and R:	$\mu(\sigma)$	0.53 (0.06)	0.41 (0.11)	0.08 (0.09)	0.24 (0.09)
Corr. ld and I:	$\mu(\sigma)$	-0.01 (0.08)	0.24 (0.05)	0.24 (0.04)	0.14 (0.05)
Corr. ld and R:	$\mu(\sigma)$	-0.12 (0.10)	-0.19 (0.12)	0.11 (0.04)	0.19 (0.07)

b) Correlations of impact and relevance with service parameters and standard errors for $t_{info} = 24$

Table 20 Correlation of impact and relevance with service parameters (experiments c)

Table 20 shows again an inverse correlation of service frequency with the impact of a disturbance on a service. Also, the correlation of a disturbance's impact with the service loading degree decreases for larger disturbances (compare also Table 18 for 6h early or late services). The correlation of the relevance with the loading degree is not significant for these disturbances.

Overview of Chapter 6

In this chapter, the experiments with the operational model were described. With the model, a couple of hundred disturbances were solved with local and full updates. The results provided the impact and relevance of several types of disturbances. The general conclusions of these results and the results of Part I are subject of Chapter 7.

End of Part II

Chapter 7. Conclusion

With Chapter 6, Part II of this study is finished. This chapter will conclude the report. In Section 7.1 the results of the study will be discussed. The research questions of the study are reassessed and answered in the most general way possible based on the EGS case study. Also, this section will shortly describe some aspects of the container network that came up during the research, but were not incorporated in the study. Section 7.2 proposes several interesting subjects for further research.

7.1 Discussion

The results of the report are discussed in this section in three parts: first, the academic benefit of the models is discussed. Subsequently, some of the practical improvements suggested by the manual planners are described. In Section 7.1.3 the research questions of this study are evaluated.

7.1.1 The academic benefit of the models

In this study, two new models were introduced. Both models were used for the assessment of the EGS-case. The models used several new features suitable for container network planning, compared to existing network models. A central container planning for the entire network is one of the major requirements for the extended gate concept (Veenstra, Zuidwijk et al. 2012, (DINALOG 2010)).

First of all, the models combined two different families of models: path-based network design models (Crainic and Rousseau 1986; Crainic and Laporte 1997; Crainic 2000) and min cost network flow models (Crainic 2000). In the former type of models, cargo classes are assigned to the paths. This part of the formulation was used in both models of this study, because it allows for easy incorporation of time constraints and limits the problem size. However, the capacity of the used barges and trains cannot be checked directly in this model. The second type of models uses the assignment of cargo classes to specific services, making the capacity checks straightforward, but it cannot use time constraints directly. Hence, a mapping was used to translate the path assignments to the used services, to let the model use the best of both types.

Secondly, the models used a formulation that allows overdue delivery. Although models exists that use time constraints on the transported containers (Crainic 2000) (Ishfaq and Sox 2010; Ishfaq and Sox 2011), those constraints are often too strict for the practical situation of container transportation. In practice, the planners of transporting companies negotiate in close consultation with their customers for suitable pick-up and delivery dates. This flexibility in the requirements for the transported cargo classes cannot be modelled by strict time constraints. Hence, the solution in the models of this study is to allow overdue delivery (at a cost). This flexibility functions as a surrogate for the possibility to negotiate with customers. A solution of the operational model without the possibility to deliver late would increase the week's transportation costs under the current assumptions with €774, i.e. +73%. In that solution the part of the total transportation by direct truck would increase from 0.2% to 8.6% (a factor 43).

Thirdly, the model combines subcontracted and self-operated services together. This combination was required to model the case of the EGS network. Simultaneously, it implicitly models the economies of scale at a tactical level: on corridors with a high demand, self-operated services are selected with high fixed costs, but low costs per TEU. On the other hand, the use of subcontracted transport on corridors with low demand has no fixed costs. Other models (Ishfaq and Sox 2011) (Ypsilantis and Zuidwijk expected May 2013) model the economies of scale explicitly. However, this does not take into account the actual cost structure of the used barge and trains and requires several additional constraints in the formulation. Hence, for the assessment of service schedules in container transportation networks, the use of explicit services as in this study is an accurate and simple alternative for economies of scale formulations.

On the other hand, the models used in this study are restricted because of some assumptions. The tactical model used a simple representation of the available time for transportation. The influence of the service frequency on a specific corridor was not used to model the waiting time between two services on a container route, as the expected waiting time is proportional to the inverse of the service frequency. As the service frequency is a decision variable in this model, the waiting time cannot easily be modelled linearly in the model. The waiting time is explicitly included in the operational model, though. The results of the operational model in Part II showed an increase of 7% in transportation costs compared to the results of the tactical model in Part I (for the case with a 10% growth of the current actual demand pattern). This cost increase is mainly because of the simplified formulation of the transport time in the tactical model.

A second restriction in the models of this study is the implementation of the cargo classes. The cargo classes are represented by continuous variables measured in TEU, instead of variables representing the actual containers. In the second part it was shown that the impact of this restriction is only 0.2% of the total objective value. The feasibility of the rounded solution could not be checked: the model and its restrictions used values masked with a confidentiality factor and could therefore not be rounded.

Altogether, within the assumptions the models were able to find optimal solutions for both the service schedule and the operational planning in minutes. The experiments were carried out on a MacBook Pro with a dual core 2.66GHz processor and 8GB of RAM memory. Solving the tactical model to determine the optimal service schedule took 2 minutes. Solving the operational planning takes 7 minutes for a first solution. Based on this initial solution, full updates to handle disturbances take on average 56 seconds, the local update takes on average 36 seconds.

Both models are suitable to be used in assessments of network planning. Various other disturbances or situations can be assessed with these models or models with minor adaptations. In Section 5.2.4 some alternative formulations of the operational model were proposed to incorporate the skipping of a service or using multiple stops with a single barge. When taking into account the mentioned restrictions, the operational model may also be a base for an automated daily planning method.

7.1.2 Improving the daily planning process

During the author's research into the container transportation process, the booking and planning departments of ECT at the DELTA terminal and at TCT VENLO were monitored. During this period the planners mentioned several quick fixes that could aid the manual process. The main problem for their daily work is the lack of information about the current situation in the network. The daily practice of the planning process was not part of the research. However, for the sake of completeness, these straightforward improvements are proposed as mentioned by the planners.

- Use GPS systems to monitor train and barge movements. This would help the planners by determining the current state of the network and anticipate on delays.
- Synchronize information between terminal systems and the network transport bookings, e.g.: the scheduled arrival times of deep-sea vessels specify the possible network services for import containers.
- Use digital connections (EDI) to synchronize booking information from clients.
- Use automatic triggers to request customs releases or missing client information.

7.1.3 Answers to the research questions

The main research question of this study was *What are the most important aspects for the online intermodal planning of the EGS network?* The answer to this question poses important requirements for an automated planning tool for the EGS network. The question was assessed in two separate parts. These two parts were studied separately, although they were based on the same data and used similar methodology. The data was based on the actual transports of the EGS network in the period January 2011 to June 2012. The parts used two variants of a newly developed MIP formulation for intermodal network transportation. The benefit of these models was described in 7.1.1. The first part focused on the use of land corridors and the benefit of intermodal transfers. The second part focused on disturbances and the benefit of *real-time switching* of container itineraries. The research questions for these two parts are assessed first. In Section 1.4 seven research questions were introduced, divided over the two parts. Here, the research questions are evaluated.

Part I: Decision support at tactical level

1. *Can services on corridors between inland terminals improve network performance?*

Considering the current situation of the EGS network, the use of intermediate transfers is not significantly beneficial. The tactical solution without any intermediate transfers resulted in a total weekly transport costs of €1151, of which €396 were the costs for self-operated and subcontracted container transportation. In total 22 barges and 10 trains where selected for the service schedule (experiment A of Part I). In the basic case (experiment B), intermediate transfers were allowed, but the solution resulted in a weekly cost of €1149, almost equal to the case without intermediate transfers. The reduction of €10 (-2.5%) in direct transportation costs (€386) is voided by an additional €8 in handling costs. In 1.2% of the transports, an intermediate transfer is used. The number of selected barges and trains is equal. Hence, in the current case it is not beneficial to take intermediate transfers into account.

Also, a case with half the transfer costs was computed. Note that this is hypothetical, as transferring containers at half the price is not a realistic case. This case was studied to see the influence of the transfer price on the results. In this case, a transportation cost reduction of 7.3% was achieved and intermediate transfers are used for 5.4% of the transported containers. The results suggest the following: by using transfers in a cost-effective way, the costs for transportation in the network can be decreased significantly. A combined business model for both the network terminals and the transportation over the network would allow EGS to exploit the opportunities of these intermediate transfers. For instance: if a lot of capacity is temporarily available at a certain terminal, this capacity can be used for intermediate transfers at low costs. With the intermediate transfers, the network transportation costs could be reduced. Alternatively, if a terminal is running into high costs due to capacity limits, other terminals in the network could be used to relieve the busy terminal. Such a combined business model is proposed for further research.

2. *If so, how regular will these services be in use?*

The experiments showed that in all solutions, containers are routed on paths with at maximum 1 intermediate transfer. In the basic case, with regular transfer prices, an intermediate transfer was only used in 1.2% of the container transports. For the case with half transfer prices, intermediate transfers were used for 5.4% of the transports. Hence, even in the most extreme case, not much of intermediate transferring is used and the land corridors are not used often or in high capacities.

3. *How should these services be executed: by self-operated services or subcontracting?*

The tactical model results in a solution for the current EGS case with 22 self-operated barges, 10 self-operated trains and additional subcontracted transports. The case with 10% growth was used as a basis for Part II: 6 additional barges were selected and 128 subcontracted services, based on a loading rate with EGS containers of maximum 30%. Note the following: in a case with only self-operated services, the tactical model showed that per week 64 barge services and 48 train services are required. In this case, the direct costs for transportation would be 60% higher than in the current EGS case. Hence, the use of subcontracted transports is essential for an efficient network planning.

4. *A specific corridor must be operated with what mode and frequency?*

The tactical model was suitable for determining the optimal number of services in the EGS network under several circumstances. In general, more barge connections than rail are selected. Note the following: if on-time delivery was irrelevant, only some barge services are self-operated. This would reduce the direct transportation costs by 28% compared to the basic case. The specific results for the service frequencies can be determined using the model of Part I. Some cases were reported in Section 4.3.

Summary of Part I conclusions

The following general conclusions are drawn for intermodal container networks:

- With the current cost structure for transportation in North-West Europe, intermediate transfers will not result in a cost reduction
- A combined business model for network terminals and transportation provides opportunities for reducing transportation costs, by additional use of intermediate transfers
- More than one intermediate transfer is not beneficial, even at very low transfer prices
- The linear cost path-based network design model (Model 1) is suitable for determining service frequencies in an intermodal transport network

Part II: Assessment of synchromodal planning

1. *Which types of disturbances occur in the network transportation?*

In Section 5.1 the container process was assessed. The timeline of containers was described and sources of disturbances were identified. These can be categorized in the following three categories of disturbances:

- Single container affected: Blockades, late or missing information, late drop-off (export), changed container mass, container earlier available, cancellations
- Deep-sea vessel out of schedule
- Transit effects: terminal delays, service delays, late/early finished loading, service documentation, cancelled service

The methodology developed in this study is suitable for studying any of these disturbances by adjusting the model parameters, nut only research into transit effects were carried out in this study.

2. *Which disturbances have the largest influence on the network performance?*

Not all disturbances mentioned above where studied in detail for this report. The study in Part II is focussed on disturbances on the service schedule for two reasons: in the current development of the EGS network, the disturbances on services are a main point of attention. Secondly, a disturbed service is the most complex disturbance for the used model: a disturbed service influences both the available routes in the network and the possible assignment of cargo classes to the routes. So, this type of disturbances was the most interesting to study.

Several disturbances to services were studied and two parameters are used to measure the influence of the disturbance: the impact measures the minimum cost increase due to a disturbance, even when the re-planning is done in the best possible way. The relevance measures the cost difference between a full update or a local update where only directly affected transports are re-planned. The meaning of these measures is the following: a large impact indicates disturbances that must be prevented; a large relevance indicates a disturbance for which a full update is required, i.e. on which an automated planning should focus. Based on these measures the following general conclusions with respect to the disturbance impact can be drawn:

- Generally, the cancellation of a service shows a large impact but not a larger relevance. This effect is strongest for self-operated services. For the EGS network, the following results were shown: on average, the cost of a cancelled self-operated service amount €23.81. This impact of a cancellation is about 8 times as large as an early or late departure of 6h. To place this masked number in perspective, the average portion of the weekly transport costs per service are €6.40. Hence, cancellations should be prevented!
- Disturbances on a barge service have a larger impact than an equal disturbance on a train service. The magnitude of the impact of a barge disturbance ranges on average from €1.70 for a 6h delay to €22.54 for a 24h early departure. This is almost equal to the cost of a service cancellation.
- Considering the time delays, the following was shown: early departure always have a larger impact than late departures of the same magnitude. Intuitively, this can be explained as follows: some containers will miss the early departed service. The (more expensive) alternative for these containers may very well deliver these containers late anyway. A delayed service may result in late delivery for a small subset of the loaded cargo, but for the other part of the cargo the delay has no effect.

  Together with the previous point, this result is important when considering the daily practice of barges in the Rotterdam port: as barges often determine their route in Rotterdam last-minute, they often arrive and depart at a terminal before the time expected by the EGS planners. This may be considered 'early' departure. An early arriving barge shows a large impact in general and should thus be prevented for an efficient network planning.

- Knowing information early reduces the impact slightly. For the EGS-network the effect of knowing information 24h instead of 12h before departure was on average €0.64.

The following general conclusions can be drawn with respect to the disturbance's relevance for planning automation.

- A disturbances on barge services has a higher relevance than the same disturbance on a train service. Also, a disturbance on a self-operated service has a higher relevance than the same disturbance on a subcontracted service. Both of these observations hold for all of the tested cancellations and time shifts. These two observations can be used to assess the influence of an occurring disturbance on a daily basis. Hence, a disturbance on a self-operated barge should get the first priority for a full update. Either an automated solution must focus on this category, or a smart solution for the manual planners must be developed.
- Considering the previous conclusion, a finer assessment of the influence of the disturbance can be made using the frequency on the service's corridor. For those services that have a large impact or relevance, this relevance is strongly correlated with the service frequency. The correlation coefficient of the service frequency with the relevance is almost 50% for early departures. This effect is smaller for delays (8-40%) and is smaller if the information is known earlier.
- The previous two points show that a full update is most beneficial after barge disturbances, disturbances on self-operated services and on corridors with higher frequencies. These three properties give a strong incentive to focus the use of full updates on corridors with many self-operated barge services. Hence, a planning automation should focus at first on the connections to Moerdijk, Venlo and Duisburg.
- For the disturbances of 6h early or late departure, also the loading degree has a strong correlation with the disturbance. Larger disturbances (12h or 24h) didn't show this correlation, but the study did not show whether this was because of the disturbance magnitude or because the used subset consisted mostly of services with high loading degrees.
- Knowing information earlier has no significant influence on the relevance. In some cases the relevance increases by knowing information earlier (the full update becomes more beneficial), but in other cases the opposite is seen. In the latter case, the local update became closer to the optimal update because of the early information.

3. *Under what conditions and at what moment can a container be rerouted?*

In this study intermediate transfers and switching are distinguished. Intermediate transfers are used to transport containers intermodally using multiple consecutive corridors. Two types of transfer occur:

- intermodal routes with intermediate transfers
- a final truck leg in the hinterland

Switching refers to a change of service and/or corridor after re-planning a (sub)set of containers. Switching the container is currently only possible before the closing of a service. The closing of a service is very different for different terminals. In this research, the minimum closing time of EGS-services at the seaports was used: 6h. In the hinterland, this closing may be much shorter. This was not used in the study, because an accurate assessment of the different closing times under various circumstances proved difficult. Four types of switching are distinguished:

- Use a service of the same mode on the same corridor but at a different time of departure (take the next train)
- Use an alternative mode on the same corridor (e.g. switch from barge to rail)
- An alternative route is selected via a different terminal
- The container is transported directly by truck

The conclusions about the impact and relevance of the disturbances are provided to EGS as recommendations for improving the planning process for EGS. Note that, these conclusions are based on a model for an efficient planning. Other relevant aspects, such as customer relationships, the workload for manual planners and available IT-systems for information exchange are not considered in this study. However, based on the results of this report, EGS has decided to postpone the introduction of a network-wide planning system and to focus first on improving the planning on the services with the most relevant disturbances. Meanwhile, the IT architecture and partnerships with all network stakeholders (operators, terminals) can be brought to the level where a network-wide planning system can be implemented

Summary of Part II conclusions

The following general conclusions are drawn for intermodal container networks:

- Apart from cancellations, the early departure of barges can have a large impact on the network transportation costs.
- When assessing a disturbed service, the following aspects indicate that a full update or automated update is relevant: the disturbed service is a barge, the service is self-operated or the service travels on a corridor with a relatively high frequency of alternative services (barge or train).
- A focus on getting information earlier than 12 hours before departure is not necessary.
- The operational linear cost path-based network design model (as Model 2) is suitable for determining an offline planning for a week in an intermodal transport network.
- The model is suitable to determine the impact and relevance of disturbances in an intermodal transport network.

7.2 Further research

The results of this study leave many opportunities for further research. A few of them are proposed here. A first line of new research based on this study could focus on a combined business model of network terminals and transportation, as the results of Part I suggest. Secondly, more research into smart update rules for manual planners can be useful, as Part II showed that the full update outperforms the local update only in a few instances. In the third place further research is proposed into several extension or improvements of the intermodal container network model.

Combined business model

In this study, the cost structure of the EGS network was modelled. A linear cost model was used for the transport costs of self-operated or subcontracted transportation. For all handlings in the network a fixed prices was taken. Part I of the research showed that this fixed handling price has a large impact on the optimal use of intermediate transfers and on the optimal service frequencies. If these handling costs would be reduced with 50%, the transportation costs (without handling costs) are reduced by 7.3%. This cost reduction was attained by increasing the amount of intermediate transfers from 1.2% to 5.4%. Hence, it is interesting to make a more accurate estimation of the handling costs at the terminals where these intermediate transfers occur. With a higher accuracy, the interaction between network transportation and network transfers can be studied in more detail to decrease total network costs. The accuracy can be improved by including the following aspects:

- *Dynamic costs based on terminal capacity utilization*. Then, intermediate transfers can be focussed at terminals that are (temporarily) low-utilized. The operational solution of a problem with dynamic transfer costs can be easily solved with the intermodal container network of this study, by using the dynamic costs in the costs for paths. The service network design at a tactical network is more difficult for a situation with dynamic transfer costs and requires an extended or alternative model.
- *Differentiation between self-operated and subcontracted terminals*. In the current study all terminals are modelled with a transfer cost per TEU. In practice, the costs per TEU may be very low for self-operated network terminals. These self-operated terminals are very suitable for intermediate transfers – if capacity is available. An extension to the intermodal container network models at both the tactical and operational level is required.
- *Integrated business development*. Apart from the more complex planning problem when including the terminal capacity, also a further analysis of the business integration is required. This analysis should include the following aspects of integrating the terminal business with the network transportation business: the information exchange, dynamic pricing and legal aspects between terminals and the network operator. A more detailed analysis of the required business development of the intermodal container transportation network is provided by Veenstra (Veenstra, Zuidwijk et al. 2012).

Smart local updates

The research of Part II focused on the benefit and necessity of automated planning when assessing disturbances. The benefit of using an automated planning was measured in comparison with the performance of a simple local update. This local update stood model for the current practice of manual planning. In this local update, only the containers directly affected by a disturbance are re-planned. The study showed that the difference in operational costs between the local and full update are often small. Only in specific situations the full update showed a larger reduction: the disturbed service is a barge, the service is self-operated or the service travels on a corridor with a relatively high frequency of alternative services. An automated planning system will gain the cost difference in these cases. An automated system would also require a seamless integration of digital information streams of all network stakeholders. Alternatively, the quality and efficiency of the manual planning process can be improved, reducing the need for an automated planning. This was not part of the current research. An analysis of the improvement of the manual planning must focus on the mentioned types of disturbances for which the full update outperforms the local update.

Extensions of the models

The intermodal container network model of this study can be extended in various ways, either to get more accurate planning results, or to gain insight in specific situation. Both the service network model as the operational planning model can be extended with the following additions:

- Transportation of containers to delivery addresses. The model can select the most suitable inland terminal depending on available capacity and transportation costs
- The current practice of container transportation is that clients have specific modal requirements. Based on emissions or expected reliability, a client demands that its containers are not transported on a barge, or never with a direct truck connection. If such restrictions apply for large amounts of cargo, this impact could be influential.
- The case described in this report consists of transportation demand that has short delivery times. For that reason, the costs for containers that stay long on a terminal (demurrage) or that are long on transport (detention) are neglected. In alternative cases with containers that have much longer delivery times, these costs cannot be neglected. Note that detention costs apply for long-lasting possession of a container by a costumer, hence they can apply to the combination of an inland and return trip.
- The use of fill-up cargo with a lower time pressure. The transportation of empty containers was not assessed separately. Common practice is to use these empty containers as fill-up cargo. For this type of cargo the time restrictions are less strict.

The most important drawback of the service network model of Part I is the omission of waiting times at the terminals. Hence, this model can be improved:

- Change the formulation of the service network model to include waiting times. A direct use of the service frequency as an estimate for the terminal waiting time makes the model non-linear. Alternatively, a piecewise linear formulation can be used to model the inverse of the service frequency and link it to an estimated waiting time.

The results of the operational model showed some inaccurate results for the impact and relevance of disturbed services at the end of the week. As inspection of the results only showed this for a few services, this was not investigated further. However, the operational model could be improved to handle the end of the week more accurately.

Finally, the two improvements to the operational planning model that were introduced in Section 5.2.4 are repeated:

- Introduce the possibility of services that make multiple stops in Rotterdam and add the possibility to diminish the number of stops in a such a multistep schedule
- Introduce the possibility to skip a self-operated service if demand is low. A part of the fixed costs for that service are retained.

Overview of Chapter 7

In this chapter, the academic benefit of three aspects of the new intermodal container network model of this study were described. Also, the results of Part I and II were used to draw conclusions on the main research question "What are the most important aspects for the online intermodal planning of the EGS network?". The transfer price is the most relevant parameter for the service network design. For the use of automated operational planning, the properties of the disturbance are the most important. Especially, barge services, self-operated services and disturbances on high-frequency corridors require a smart update.

Further research was proposed to extent the knowledge about intermodal container networks and to extent the use of the new intermodal container network model. As an alternative for the drastic implementation of automated planning, further research into smart manual updating of planning is proposed.

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An intermodal container network model with flexible due times and the possibility of using subcontracted transport

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***Abstract*—An intermodal container transportation network is being developed between Rotterdam and several inland terminals in North West Europe: the EUROPEAN GATEWAY SERVICES network. To use this network cost-efficiently, a more integrated planning of the container transportation is required. The most relevant aspects of such a planning are identified with a new model. This model introduces three new features to the intermodal network planning problem. Firstly, a combination of a path-based formulation with a minimum flow network formulation is used. Secondly, overdue deliveries are penalized instead of prohibited. Thirdly, the model combines self-operated and subcontracted services. Two versions of the model are applied at two different levels. At a tactical level, the optimal service schedule between the network terminals is determined, considering barge or rail modes and both operation types. The most influential costs in this problem are determined. Another version of the model is applied at an operational level. With this model the impact of a disturbed service is determined, by comparing the undisturbed planning with the best possible update after the disturbance. Also the difference between an optimal update and a usual local update is measured, defined as the relevance. It is shown that each of the models is suitable for solving the problems. This paper focuses on the model and methodology at a tactical level to determine the optimal service schedule.**

***Index Terms*—Intermodal planning, synchromodal planning, network optimization, container transportation**

I. INTRODUCTION

THIS paper proposes a new model to study planning in intermodal networks. A tendency of more integrated supply chains has sparked initiative in North-West Europe to create transportation networks for containers [6], [11], [13], [14].

A. Development of intermodal container networks

These intermodal container transportation network are generally a cooperation between multiple barge service operators, rail service operators and terminals. Veenstra [18] introduced the concept of an extended gate: a hinterland terminal in close connection to the sea port, where customers can leave or pick up their standardized units as if directly at a seaport. The seaport can choose to control the flow of containers to and from the inland terminal. This control by the seaport distinguishes the extended gate from a dry port as defined by Roso [15] and introduces a central management for the intermodal container network. This concept has been implemented in the EUROPEAN GATEWAY SERVICES (EGS) since 2007, a subsidiary of EUROPE CONTAINER TERMINALS (ECT) with three seaports in Rotterdam. The network consists of these three seaports and an increasing number of terminals in North-West Europe (see Figure 1).

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Fig. 1. Overview of EGS network [source: EUROPEAN GATEWAY SERVICES]

B. Definitions: intermodal and synchromodal

The central management of the network allows for central intermodal network planning. Intermodal planning is defined as *Multimodal transport of goods, in one and the same intermodal transport unit by successive modes of transport without handling of the goods themselves when changing modes* [17]. With intermodal planning, the routing of containers with multiple consecutive services is possible, using *intermediate transfers* of the containers at network terminals. On top of that, a network with centrally planned transportation can use *real-time switching*, the possibility of changing the container routing over the network in real-time to cope with transportation disturbances. The combination of intermodal planning with real-time switching is often referred to as synchromodal planning, a new term at the agenda of the Dutch Topsector Logistiek [16]. However, no unambiguous definition for synchromodality exists yet. In this study, the following definition for synchromodality is used: *intermodal planning with the possibility of real-time switching*, or online intermodal planning.

C. New aspects of the proposed model

The study focuses on the cost-impact of using intermediate transfers and real-time switching. Existing intermodal planning models do not suffice for this purpose, because they do not allow flexible time restrictions for delivery nor the combination of self-operated and subcontracted services in the network. The daily practice in the container transportation is that planners and customers agree in mutual consultation on delivery times, both are flexible in case of disturbances.

Secondly, container transportation networks use a combination of self-operated services and subcontracted services. In the latter case, transportation is paid for per TEU (twenty feet equivalent unit, a standardized container size measure). In the case of self-operated services, the network operator pays for the entire barge or train and incurs no additional costs per TEU, except for the loading and unloading of containers (handling costs).

A new model is proposed that copes with both these aspects of container networks. The model was used in two forms: first, the model was used for a service network design, where the optimal frequency of services between all terminals in the network is determined. Secondly, an adapted model was used to assess the impact of disturbances on the network transportation costs. Also, the difference to a simple local update and a full update to cope with the disturbance was determined.

D. Structure of the paper

This paper focuses on the model at a tactical level, the service network design model. Section II describes literature on existing service network design models, Section III introduces the new intermodal container network model. The case of EGS is used as an example for the intermodal container network model of this study in Section IV and the results of the experiments are discussed in Section V. Section VI concludes the paper and proposes further research.

II. Literature review

In academic literature, three levels of network planning are distinguished [3], [12]: strategic, tactical and operational planning. The exact boundary between these levels often depends on the point of view of the planning. In general, strategic planning focuses on long-term network design, such as locations of terminals or transport hubs (e.g. Ishfaq and Sox [7]). An overview of hub-location problems (HLPs) is provided by Kagan [10]. Operational planning focuses on the day-to-day planning of network transportation (e.g. Jansen, Swinkels et al. [9], Ziliaskopoulos and Wardell [20]). An overview is provided by Crainic and Kim [5]. The intermodal container network model was also applied at an operational level to identify important categories of disturbances. This paper will focus on a tactical level planning, the service network design. Service network design consists of the following aspects as described by Crainic [4]: the selection and scheduling of the services to operate, the specification of the terminal operations and the routing of freight. Network design models are often MIP-based formulation of a network structure where nodes represent terminals and arcs represent services [4]. Multiple modes can travel between the same network terminals, these are represented by multiple arcs. Both the assignment of cargo to routes and the number of services on each corridor are considered simultaneously. In the existing literature about intermodal container transportation networks, several service network design models occur, which can be categorized in two types:

- Minimum costs network flow models (MNCF)
- Path-based network design models (PBND)

Both types of models are able to consider capacitated flow and multiple commodities, see Table I. In this sense a commodity, or equivalently cargo class, is used to denote a set of containers that have equal properties, such as mass, origin, destination and delivery time.

TABLE I
EXAMPLES OF EXISTING SERVICE NETWORK DESIGN MODELS

	MNCF	PBND
Single-commodity	Ziliaskopoulos 2000 [20]	
Multi-commodity	Crainic & Rousseau [2] Crainic [4] Ishfaq & Sox [7], [8]	Crainic & Rousseau [2] Crainic & Laporte [3] Crainic [4]

MNCF type of models have the possibility of flexible routing of cargo over various links in the network. Also, explicit constraints on the link capacity can be set. However, the main disadvantage is the number of decision variables for multi-commodity, multi-mode formulations. A variable is required for each cargo class on each arc. For applications with many origin-destination pairs, mass categories and delivery times, the number of decision variables becomes too high for practical computation times. For PBND type of models, the possible paths for each cargo class can be predetermined. A path is the exact route of a container using subsequent services and terminals. This reduces the number of decision variables significantly, provided that the number of possible paths is kept at a low enough number. However, with the traditional PBND formulations, the capacity of services travelling on each arc cannot be restricted explicitly, as multiple paths for the same or different cargo classes coincide on single services. For this reason, the model introduced in the next section uses a new formulation that combines the arc capacity restrictions with the routing of containers over predetermined paths. Some of the existing tactical service network formulations use strict constraints on delivery time (e.g. Ziliaskopoulos [20]). These strict constraints do not model the flexibility that transportation planners have in consultation with customers. Other models use formulations that model the economies of scale that occur when cargo is consolidated on an arc (e.g. Ishfaq [8]). The practice in current intermodal container networks is that multiple service and terminal operators cooperate and in this perspective the largest economies of scale occur by selecting services operated by the network operator (self-operated services) or subcontracted services. The difference in cost structure between these two cannot be modeled in the existing formulations for the economies of scale. Hence, the proposed model uses an alternative formulation that better suit the flexible delivery time restrictions and the combined use of self-operated and subcontracted services.

III. Proposed model

The intermodal container network model proposed in this study differs on three main aspects from existing models for intermodal freight transportation:

1) The model combines a path-based formulation with a minimum cost network flow formulation to restrict the problem size and while the explicit capacity restrictions on the network arcs are still included.
2) Overdue delivery is not strictly restricted, but penalized by a penalty per TEU per day overdue.
3) The service network design allows for combined use of self-operated and subcontracted services.

The model uses four sets of decision variables: the service frequencies y_{ijm} denote the amount of self-operated services between terminal i and j with mode m, defined as *corridor* (i, j, m). The service frequencies are determined while considering multiple demand periods q. The amount of TEU of mass w on self-operated or subcontracted services on corridor (i, j, m) in period q is denoted by the flow variables $z^{w,q}_{ijm}$ and $\zeta^{w,q}_{ijm}$, respectively. Finally, the path selection variable $x^{c,q}_p$ denotes the number of TEU of cargo class c transported on path p in period q. A cargo class is a group of containers with equal origin and destination, the same weight class and with the same period for delivery. The objective of the model consists of four cost terms:

$$\min \sum_{(i,j,m)} f_{ijm} y_{ijm} + \sum_{(i,j,m)} \sum_{(c,q)} c_{ijm} \zeta^{c,q}_{ijm} + c_F \sum_p F_p \sum_{(c,q)} x^{c,q}_p + c_\tau \sum_{(p,c)} \tau^c_p, \tag{1}$$

where f_{ijm} and c_{ijm} denote the costs of operating a service or subcontracting one TEU on corridor (i, j, m), respectively, c_F are the costs per transfer, F_p the number of transfers on path p and c_τ are the costs per TEU for each day late delivery.

The constraints of the model are the following:

$$s.t. \sum_p x^{c,q}_p = d_{c,q} \qquad \forall c, q \tag{2}$$

$$\sum_p \delta^p_{ijm} x^{c,q}_p = z^{c,q}_{ijm} + \zeta^{c,q}_{ijm} \qquad \forall i, j, m, c, q \tag{3}$$

$$\sum_c z^{c,q}_{ijm} \leq u_{ijm} y_{ijm} \qquad \forall i, j, m, q \tag{4}$$

$$\sum_c w_c z^{c,q}_{ijm} \leq m_{ijm} y_{ijm} \qquad \forall i, j, m, q \tag{5}$$

$$\sum_q x^{c,q}_p \left(T_p - t_c\right) \leq \tau^c_p \qquad \forall c, p \tag{6}$$

$$y_{ijm} = y_{jim} \qquad \forall i, j, m \tag{7}$$

$$x^{c,q}_p \geq 0 \qquad \forall c, p, q \tag{8}$$

$$\tau^c_p \geq 0 \qquad \forall c, p \tag{9}$$

$$z^{c,q}_{ijm}, \zeta^{c,q}_{ijm} \geq 0 \qquad \forall i, j, m, c, q \tag{10}$$

$$y_{ijm} \in \mathbb{N} \qquad \forall i, j, m \tag{11}$$

Here, $d_{c,q}$ denotes the demand of cargo class c in period q; associated with each cargo class is the weight class w_c and due period t_c, that is the time available for transportation of a container in cargo class c. The mapping of selected paths to the flow variables is done with δ^p_{ijm}. The TEU-capacity and maximum weight of a service on corridor (i, j, m) is denoted by u_{ijm} and m_{ijm}, respectively.

Hence, the first term of the objective represents the cost for the selected services to operate self; the second term sums all costs for subcontracted transports in all periods q; the third term denotes the costs for transfers and the fourth term is the penalty cost for overdue delivery. Constraint 2 ensures that all transportation demand is met in all periods. The allocation of the demand to the paths is mapped to the flow variables by Constraint 3. This mapping depends on the used services (self-operated or contracted) in the predefined paths. Constraints 4 and 5 are the capacity constraints on each corridor, dependent on the selected number of services. Note that the capacity on subcontracted services is considered unlimited in this formulation. Constraint 6 ensures that the auxilary variable τ^c_p equals the total number of overdue days for all TEU of cargo class c on path p, by measuring the difference in the available delivery period t_c and the predetermined path duration T_p. If cargo class c is on time using path p, Constraint 9 ensures that τ^c_p is equal to 0. Constraint 7 ensures the same number of self-operated services back and forth on a corridor, to keep the equipment balances over the network. Finally, Constraints 8 and 10 ensure the nonnegativity of the other variables and Constraint 11 restricts y_{ijm} to the integer set of natural numbers.

The model is applied to the real-world case of the the network transportation in the European Gateway Services network.

IV. Case study disturbances at EGS

A. Network and paths

The EGS network has been continuously growing with terminals and connections. This study's focus is on the network as shown in Figure 1: it consists of three ECT seaports in Rotterdam (Delta, Euromax and Home) and several inland terminals in the Netherlands, Belgium and Germany.

In this network, suitable paths between all locations are predetermined. To do this, Yen's *k-shortest path* method is used [19]. This method is able to select shortest paths without loops in a network, based on Dijkstra's algorithm. In this study, paths are selected based on the geographical length of the network arcs, up to a length of three times the length of the shortest path. Subsequently, the number of paths is reduced by omitting all paths that consist of more than three transportation legs and by omitting paths that have a detour of more than 10% in any of the transportation legs. This detour is measured as the difference in distance to the destination from both ends of leg (i, j), i.e. a path is considered to make a detour if $T_{iD} \leq 1.1 T_{jD}$ in any of its legs. All of the remaining paths describe a geographic route with one to three transportation legs in the network. The final step is to generate all intermodal possibilities of such a route, based on the possibility of barge and train corridors between the network locations. Truck is only considered for the last (first) leg before the hinterland destination (origin). E.g. a route Rotterdam Delta $\rightarrow$ Moerdijk $\rightarrow$ Willebroek results in the following paths:

$$\begin{aligned}
&\text{Delta} \xrightarrow{barge} \quad \text{Moerdijk} \xrightarrow{barge} \quad \text{Willebroek}\\
&\text{Delta} \xrightarrow{rail} \quad \text{Moerdijk} \xrightarrow{barge} \quad \text{Willebroek}\\
&\text{Delta} \xrightarrow{rail} \quad \text{Moerdijk} \xrightarrow{truck} \quad \text{Willebroek}\\
&\text{Delta} \xrightarrow{barge} \quad \text{Moerdijk} \xrightarrow{truck} \quad \text{Willebroek}
\end{aligned}$$

where both Delta and Moerdijk have a rail and barge terminal, but Willebroek doesn't have a rail terminal. Note that truck mode is only considered for the last leg. With each path p is associated a travel time T_p and a number of transfers F_p.

B. Costs and transportation demand

The cost parameters in the study are based on the actual costs in the current operation of the EGS network. For that reason, the costs in this paper are masked by a confidentiality factor. The corridor costs per service (f_{ijm}) and per TEU (c_{ijm}) are modeled with a linear approximation of the actual network costs and the corridor length d_{ijm}, e.g. $c_{ijm} = \alpha d_{ijm} + \beta$. For each transfer a cost of $c_F = 23.89$[1] is used. The cost of overdue delivery per TEU per day is $c_\tau = 50$[1].

An analysis of the transportation on the EGS network in the period of January 2009 - June 2012 did not show significant periodic behaviour. As the transported volume grew fast in 2010, the weekly demands were further analysed based on the period January 2011 - June 2012. Using Pearson's χ^2 Goodness-of-fit test [1], the hypothesis of normality of the distribution of the weekly volume was accepted with a p-value of 0.93. Hence, for all cargo classes the parameters of the normal distribution of the weekly volume is determined. With this, ten 10-percentile subsets of the normal distribution are generated for each cargo class. These sets are used as ten periods q in the proposed model. The model will solve the optimal service frequencies simultaneously, optimized for all ten 10-percentile sets.

[1]Masked by confidentiality factor

TABLE II
RESULTS EGS NETWORK DESIGN

Cost terms [€][2]	Total	Self-operated	Sub-contracted	Late	Transfer
Basic case	1142	223	163	122	632
50% transfer costs	818	201	166	122	329
No due times	946	206	103	0	638
No subcontracts	1424	636	0	153	634

V. RESULTS

A. Experiments

The model is solved for the EGS-case with AIMMS 3.12, using CPLEX 12.4. Four different experiments are carried out. The basic case is the experiment with the parameters as described above. The other three cases are hypothetical situations to assess the influence of some effects:

- a case where the tranfer costs are lowered by 50%, to find the effect of transfer costs on the service schedule,
- a case where due times are ignored, or equivalently, the overdue costs are set to zero. This shows the impact of due times on the results,
- a case without the possibility of selecting subcontracts. This shows the impact of using subcontracts along with the network services.

The results of the basic case and the three hypothetical experiments are shown in Table II. The table shows the resulting costs in total and separately for the four objective terms.

B. Discussion

The proposed intermodal container network model was able to solve the various experiments fast in most cases. Computation times varied between 2-4 minutes, except for the case where no subcontracts were allowed. Solving that hypothetical case took 1.5 hours. The regular solution time of minutes makes the model suitable for the service network design of the current problem instance. With increasing problem sizes, the number of arc-related variables $(y_{ijm}, z_{ijm}, \zeta_{ijm})$ increases quadraticly with the number of terminals. The number of paths (and path-related variables $x_p^{c,q}$ and τ_p^c) could increase exponentially, but smart path generation based on experience or other insights can be applied to restrict the number of paths. Hence, it is expected that the model will perform well for larger problem instances as well.

The case with 50% transfer costs obviously has lower costs for transfers. However, also the transportation costs (i.e. the costs for self-operated services and subcontracted transports) are reduced by 7.3%. The number of containers for which an intermediate transfer takes place increases from 1.2% to 5.4%. These results suggest that the network operator

[2]Costs masked by a confidentiality factor.

must look into the combined business model of services and terminals. Terminals with low utilization of the available capacity can easily handle intermediate transfers, and in that way possibly reduce transportation costs.

The case where due times are omitted also shows a reduction of transportation costs, with 22%. Hence, in the studied case, 22% of the transportation costs (€77) are made in order to deliver on time. On top of that, in the basic case the model accepts a fictional penalty of €122 for late delivery. This shows the importance of the overdue delivery flexibility introduced in the model.

The case where subcontracted transports are not considered shows the importance of the combination of self-operated and subcontracted transports. Without subcontracted transports, the total transportation takes place with self-operated services. Operating all these services increases the transportation costs with 61% compared to the basic case solution. Even then, the number of late containers increases with 25%.

VI. Conclusions

The following general conclusions are drawn for intermodal container networks, based on the results of this study:

- With the current cost structure for transportation in North-West Europe, intermediate transfers will not result in a cost reduction.
- A combined business model for network terminals and transportation provides opportunities for reducing transportation costs, by additional use of intermediate transfers.
- The linear cost path-based network model is suitable for determining service frequencies in an intermodal transport network.

However, the model has some limitations as well. The model does not take waiting times at terminals into account. In practice, a container has some waiting time at each terminal, depending on the service schedule. The expected waiting time depends on the resulting service frequencies that the model provides. Hence, an useful extension of the model would include the expected waiting times in the optimal service network design.

A second limitation is the inland destination of containers. In the EGS example, network terminals are used as final container destination or container origin. In practice, several inland terminals can be used, depending on the inland warehouse address. The model could be extended to include inland addresses or include multiple inland terminals for a specific cargo class.

Other possible extension are the inclusion of demurrage and detention costs for containers that are long on a terminal or in transit or the inclusion of fill-up cargo of empty containers with low time-pressure.

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Appendix B: Mathematical formulations

$$\min \sum_{(i,j)\in A} f_{ij} y_{ij} + \sum_{(i,j)\in A} \sum_{p\in P} c_{ij}^p x_{ij}^p$$

s.t.

$$\sum_{j\in N} x_{ij}^p - \sum_{j\in N} x_{ji}^p = d_i^p \qquad i \in N, p \in P$$

$$\sum_{p\in P} x_{ij}^p \leq u_{ij} y_{ij} \qquad (i,j) \in A$$

$$(y, x) \in \ell \qquad (i,j) \in A\,, p \in P$$

$$y \in Y\,, \qquad (i,j) \in A$$

$$x_{ij}^p \geq 0 \qquad (i,j) \in A\,, p \in P$$

Where,

N	The set of nodes in the network, or *terminals*
A	The set of links in the network, or *corridors*
P	The set of cargo classes that is transported over the network
y_{ij}	The number of services that run on link (i,j)
Y	The set of possible number of services for all links
f_{ij}	The cost of running a service on link (i,j)
u_{ij}	The capacity of a service on link (i,j)
x_{ij}^p	The amount of commodity p that is routed on link (i,j)
c_{ij}^p	The cost of transporting a unit of commodity p on link (i,j)
d_i^p	The demand of commodity p at node i

Model 3 Linear cost, capacitated multi-commodity network design

$$\min \Psi\left(X_k^m, F_s\right)$$

s.t. $\sum_s X_k^m = d^m$ for all m

$X_k^m \geq 0$ for all k, m

$F_s \geq 0$ for all s

$\Psi(X_k^m, F_s)$	The objective function, depending on variable and fixed costs
X_k^m	The amount of cargo class m that is routed on itinerary k.
F_s	The frequency of runs on service s
d^m	The demand of cargo class m

Model 4 Path-based multi-commodity network design

The objective function can have several formulations, for instance:

$$\min \Psi\left(X_k^m, F_s\right) = \sum_s C_s^t F_s + \sum_{m,k} C_{mk}^t X_k^m + \sum_{m,k} C_{mk}^S \left(\min\{0, S_m - E(T_k^m) - n\sigma(T_k^m)\}\right) X_k^m + \sum_s C_s^p \left(\min\{0, \alpha_s F_s - X_s\}\right)^2$$

This formulation includes the operating costs C_s^t per service and the variable cost per unit freight per itinerary (C_{mk}^t). The other terms are penalty terms, with the following parameters:

C_{mk}^S	The cost of a time unit delay for a cargo class per itinerary
S_m	The required delivery time of cargo class m
T_k^m	Stochastic variable of the travel time of cargo class m on itinerary k. The expected value and standard deviation of this variable are used to determine the amount of freight that doesn't meet delivery time objective
d^m	The demand of cargo class m
C_S^p	The costs of over assignment of 1 unit of freight
α_s	The capacity per single trip for service s
X_s	The amount of freight on service s

The first penalty term assigns costs C_{mk}^S to the expected amount of freight that is delivered overdue. The second penalty term assigns costs C_S^p to the amount of freight overbooked on service s. This allows for overbooking, at the cost of a penalty.

Appendix C: Network transport cost estimation

To be able to analyse the transportation in an EGS-type of network, general cost formulas are estimated. The general cost structures are based on the available costs in the EGS network. Assumptions are made in consultation with EGS operational experts. The cost structures are introduced per mode in the following sections. Note that both costs *per service*, as costs *per TEU* are determined.

Barge costs

Barge cost per service

To identify the costs to operate a service, two types of barges are recognized. Two examples in the current EGS network are used. Estimation is based on the weekly cost structures shown in Table 21.

	Rhine-barge ***based on Moonlight***	**Benelux-barge** ***based on Orca***
Case	Moonlight: 4x retour RTM-DeCeTe 4 x 242 = 968 km/wk	Orca: 6x retour RTM-CCT Moerdijk 12 x 58.4 = 700 km/wk
Capacity	380 TEU	196 TEU
Rent	8104€/wk	7083€/wk
Harbour dues	2889€/month = 680€/wk	*(including harbour dues)*
Total fixed cost	**8784€/wk**	**7083€/wk**
Fuel per km	19444€/month = 4575€/wk **4575/968 = 4.73€/km**	1252€/wk **1252/700 = 1.79€/km**

Table 21 Barge cost structures

To estimate a cost per service, the monthly costs must be split over the number of trips per month. For the sake of simplicity, we'll use the following estimated number of services of a piece of equipment per connection to determine the cost per trip. This assumption is considered acceptable from a planning point of view, as the actual acquisition and planning of equipment is not part of the research. The number of trips is based on a 12km/h barge travel speed and 9 hour stop per terminal. Although this is a rough estimate, the numbers of services correspond to the actual number of trips on the corridors that are already in use. The resulting costs per trip of the services from and to the Delta terminal are shown in Table 22.

Terminal	Distance from Delta [km]	# round trips	Barge type	Fixed costs [€/trip]	Fuel [€/trip]	Total [€/trip]
EMAX	5	8	Benelux	549	24	573
HOME	31	7	Benelux	627	148	776
CCT Moerdijk	58	6	Benelux	590	104	694
CTD						
DeCeTe	242	2	Rhine	2196	1144	3340
NSS	280	2	Rhine	2196	1324	3520
NUE						
TCT Belgium	166	3	Benelux	1181	296	1476
TCT Venlo	215	3	Benelux	1181	384	1564

Table 22 Transport from Delta to hinterland (v.v.) *All other corridors are calculated similarly.*

Barge costs per TEU

To determine a generic cost per TEU for transportation per barge, a least-squares estimate is used to fit the available data of costs per container in the EGS network. The costs are fitted on the linear model:

$$\mathrm{c} = \alpha + \beta \mathrm{d},$$

where α, β are the parameters to estimate. d Denotes the distance in km for the container transportation. Note that these costs are without €23,89 transfer costs per container. The least squares estimate results in a mean relative error (MRE) of 15%, with the following formula:

$$\mathrm{c} = -5.11 + 0.14d$$

A negative fixed start-up cost α is unrealistic. Therefore, a minimum transport cost of €0 is used (without handlings). With handlings, this results in a minimum transportation cost of €*23,89*.

Rail costs

Rail cost per service

Two types of trains are recognized: diesel trains and electric trains. In Table 23 three examples of the EGS network are shown, on which the service cost estimation is based.

Train type	Electric train: *Nuremberg*	Electric train: *Duisburg*	Diesel train: *Venlo*
Case	RTM-NUE: 708 km	RTM-DeCeTe: 244 km	RTM-TCT Venlo: 201km
Capacity	100 TEU	100 TEU	78 TEU
Costs	€15778 per round trip	€2008 per single trip *(for 70 TEU)*	€3056 per round trip
Price /TEU/km	€11.10	€11.75 *(Adjusted to 100 TEU)*	€7.60
Average price/TEU/km	€11.43		€7.60

Table 23 Rail cost structures

On certain connections no overhead lines are available. Here diesel trains are used; the price of these services will be estimated using the €7.60 per km. On other connections where electric trains can be used, a price of €11.43 will be used.

Terminal	Distance	Train type	Cost per single trip
EMAX	6	Electric	46
HOME	35	Electric	266
CCT Moerdijk	74	Diesel	562
CTD	297	Electric	3396
DeCeTe	244	Electric	2790
NSS	257	Electric	2938
NUE	708	Electric	8094
TCT Belgium			
TCT Venlo	201	Diesel	1528

Table 24 Transport from Delta to hinterland (and vice versa). *All other corridors are calculated similarly.*

Rail costs per TEU

To determine a generic cost per TEU for transportation per rail, a least-squares estimate is used to fit the available data of costs per container in the EGS network. The costs are fitted on the following formula:

$$c = \alpha + \beta d,$$

where α, β are the parameters to estimate. d Denotes the distance for the container transportation. Note that these costs are without €23,89 transfer costs per container. The least squares estimate results in a mean relative error (MRE) of 14%, with the following formula:

$$c = 1.53 + 0.16d$$

Truck costs

Trucks do not drive according to a fixed service schedule; hence only subcontracted transportation costs are estimated.

Truck costs per TEU

Also for truck costs, a least-squares estimate is done based on the known truck tariffs in the EGS network. The costs are estimated on the linear model: $c = \alpha + \beta d$

The least squares estimate results in a mean relative error (MRE) of 4% with the following formula:

$$c = 76.4 + 1.04d$$

Appendix D: Network demand patterns

The existing demands in the EGS networks are used. To simplify the RTM-side of the problem, the following simplifications are applied.

- The three parts of the Delta terminal are considered as a single terminal
- Transportation to and from the APM-terminal (a seaport terminal next to ECT's Delta terminal) is also included as transportation to and from the Delta terminal
- Transportation to empty containers depots neighbouring a terminal in the network are identified as the network terminal itself. For instance, a container could return empty from Venlo to an empty depot in the city centre of Rotterdam. In this case, the second transport would be considered as a transport from Venlo to the ECT Home terminal.

The historic weekly transportation in the EGS network is shown in Figure 31. The demand distribution does show some periodic behaviour, based on the total weekly transportation on the EGS-network since 2009. This is ignored.

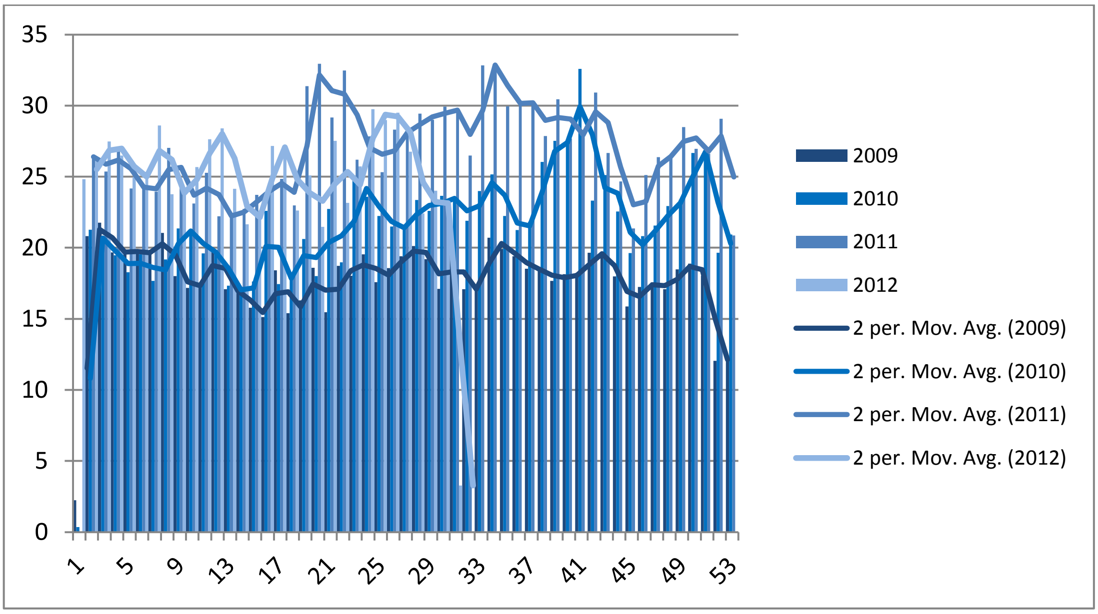

Figure 31 Historic demand of transportation over the EGS-network

Now, the demand pattern since January 2011 is analysed. Earlier years are excluded, as demand went up with a large step in 2010.

The distribution of the weekly demands is analysed here. For two cases, the weekly demand per connection is tested for normality using Pearson's χ^2 Goodness-of-fit test as mentioned by Cochran. The null hypothesis is as follows:

$$H_0\text{: samples are consistent with the theoretical normal distribution}$$

This hypothesis is tested at a significance level of $\alpha = 0{,}05$, while the samples frequency distribution is compared with a normal distribution. In this test, the frequency results are based on the historic weekly demands from January 2011 until June 2012.

Figure 32 and Figure 33 show frequency plots of the results for the transportation from the Delta terminal to CCT Moerdijk and from TCT Venlo to the Euromax terminal. The former shows a normal distribution at a first glance. This results in a p-value of 0.93. So, for this case, the demand can be approximated by a normal distribution very well. The second case shows a less clear distribution. The p-value for this case is 0.10. This is still larger than α, so also for this case, it cannot be rejected that the weekly demands are normally distributed.

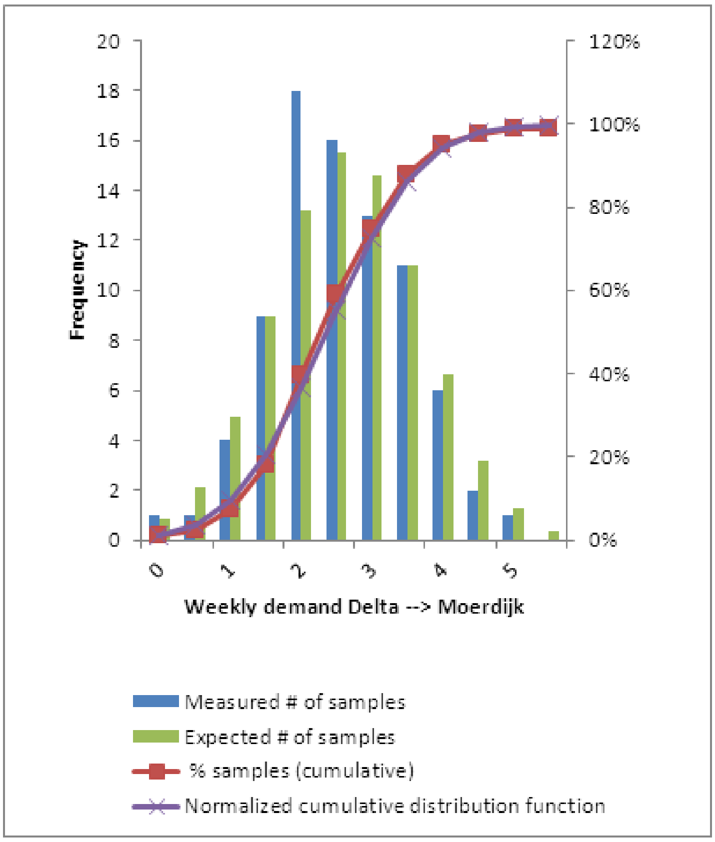

Figure 32 Analysis of historic transportation Delta → Moerdijk

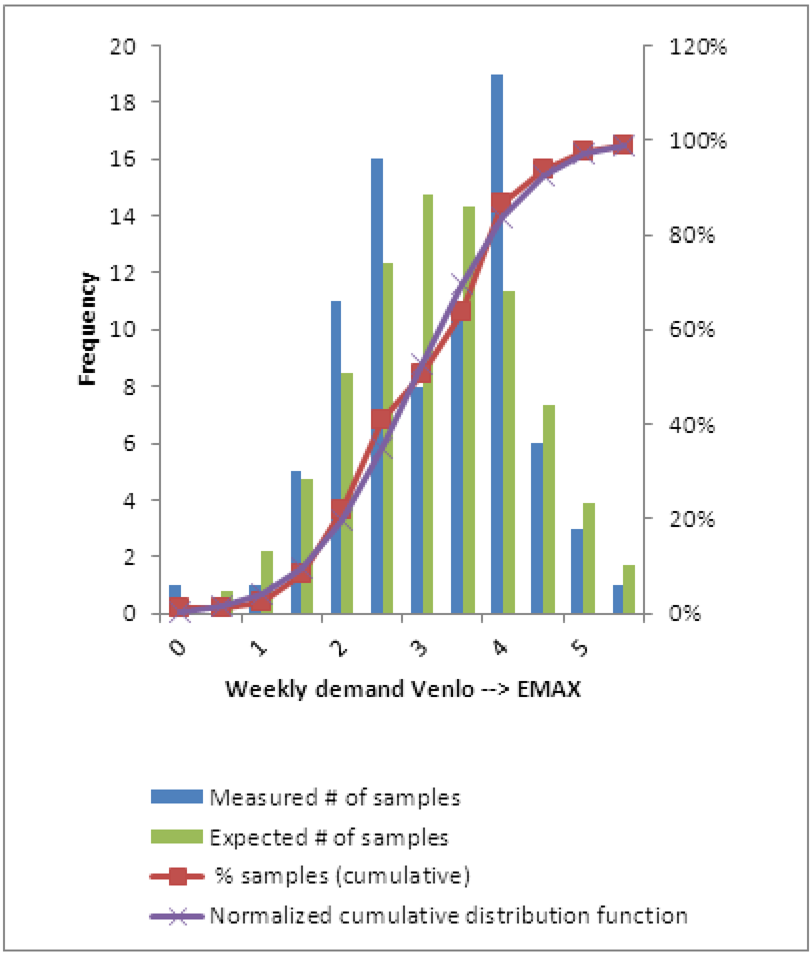

Figure 33 Analysis of historic transportation Venlo → EMAX

Hence, in this study, all demands are approximated by normal distributions, based on the mean and standard deviation of the historic weekly transportation in 2011 and 2012 (until June). Note that Figure 32 and Figure 33 show the entire weekly demand for the mentioned connections. However, in the study, demands were also split into categories based on mass and due time classes. Any negative demands that may result from the normal distributions are considered to be equal to zero. The model is set up to create a schedule for multiple periods, denoted by q. The normal distributions are translated into ten periods, by using 10-percentile fractions of the demand distribution. So, a single service schedule is created, evaluated in all ten of these 10-percentile demand situations. Per period, the same percentile of the demand on all connections is considered. The influence of local demand fluctuations is not considered.

Appendix E: CO_2-emissions

	Well-to-Wheel [g CO2/tonkm]	**Energy usage** [MJ/km]	**CO_2 in energy W2T/T2W** [g CO_2/MJ]	**Mean utilization** [-]	**CO_2-emission** [tonne CO_2 / km / service]
Truck (2 TEU)	98	10	14.2 / 73	0.33	0.88
Electric train (90TEU)	25	77	170 / 0	0.87	13
Diesel train (90 TEU)	32	188	14.2 / 73	0.87	16
Rhine barge (380 TEU)	34	363	14.2 / 73	0.65	32
Benelux barge (push convoy) [160TEU]	34	883	14.2 / 73	0.65	77

Table 25 Based on STREAM-report (den Boer, Brouwer et al. 2008): CO_2-emissions