PANAGIOTIS YPSILANTIS

The Design, Planning and Execution of Sustainable Intermodal Port-hinterland Transport Networks

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Het ontwerp, de planning en uitvoering van duurzaam intermodaal haven-hinterland vervoersnetwerken

Thesis

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To Magda

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Panagiotis Ypsilantis

Athens, September 2016

Contents

Glossary

AEO	Authorized Economic Operator. The AEO concept is based on the Customs-to-Business partnership introduced by the World Customs Organisation (WCO). Traders who voluntarily meet a wide range of criteria work in close cooperation with customs authorities to assure the common objective of supply chain security and are entitled to enjoy benefits throughout the EU. The EU established its AEO concept based on the internationally recognised standards, creating a legal basis for it in 2008 through the 'security amendments' to the "Community Customs Code" (CCC) (Regulation (EC) 648/2005) and its implementing provisions. The programme, which aims to enhance international supply chain security and to facilitate legitimate trade, is open to all supply chain actors. (ac.europa.eu)
BAPLIE	The BAPLIE message is a widely used EDIFACT message in the shipping industry. It is used by and between various parties to advise the exact stowage positions of the cargo on board of an ocean vessel. It is currently chiefly used for container cargo. Besides the container number and the exact position on board, general information regarding the containers is also specified such as weight and hazardous cargo class. (www.portofantwerp.com)
Carrier haulage	Carrier haulage is when the shipping company itself takes care of pre and end haulage of a container. It is also referred to as liner's haulage. (www.logisticsglossary.com)

Containerization	Containerization is a system of intermodal freight transport using intermodal containers (also called shipping containers and ISO containers) made of weathering steel. The containers have standardized dimensions. They can be loaded and unloaded, stacked, transported efficiently over long distances, and transferred from one mode of transport to another—container ships, rail transport flatcars, and semi-trailer trucks—without being opened. The handling system is completely mechanized so that all handling is done with cranes and special forklift trucks. All containers are numbered and tracked using computerized systems.
COPINO	COPINO is an UN/EDIFACT message that is used by the inland carrier to notify the Terminal he will come to pick up and/or deliver a container. Inland transport is mainly by truck, but the message is also suitable for a pre-notification of inland barges and rail operators. Originally the pre-notification was only meant to pick up the containers: "COntainer PIck-up NOtice", hence the acronym "COPINO". (www.portofantwerp.com)
COPRAR	COPRAR is an UN/EDIFACT message that is used by the shipping company or his ship's agent to instruct the Terminal operators which containers can be loaded ("COPRAR/Load") of discharged ("COPRAR/Discharge"). (www.portofantwerp.com)
Customs	Customs is an authority or agency in a country responsible for collecting customs duties and for controlling the flow of goods, including animals, transports, personal effects, and hazardous items, into and out of a country.
Demurrage Charges	This charge will be levied when the Customer holds containers inside the terminal for longer than the agreed free days and is applicable to all containers that remain at the terminal longer than the agreed free time. (www.cma-cgm.com)

Detention Charges	Detention charges will be levied when the Customer holds containers outside the terminal longer than the agreed free time : it is applicable throughout the duration of Customer's possession of container(s) in his custody, and until its safe return to the shipping line. (www.cma-cgm.com)
Detention & Demurrage Charges	Detention & Demurrage charges will be applicable for shipments wherein customers have exceeded the standard free time applicable both in the import & export cycles. (www.cma-cgm.com)
Dry port	A Dry Port is an inland intermodal terminal directly connected to seaport(s) with high capacity transport mean(s), where customers can leave/pick up their standardised units as if directly to a seaport. (Leveque and Roso, 2002)
Dwell time	The time cargo remains in a terminal's in-transit storage area while awaiting shipment by clearance transportation. (Collins English Dictionary)
Extended gate	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 with a seaport, and where the seaport terminal can choose to control the flow of containers to and from the inland terminal. (Veenstra et al., 2012)

Freight forwarder	A freight forwarder is an individual or company that dispatches shipments via asset based carriers and books or otherwise arranges space for those shipments. Common carrier types could include waterborne vessels, airplanes, trucks or railroads. Freight forwarders typically arrange cargo movement to an international destination. Also referred to as international freight forwarders, they have the expertise that allows them to prepare and process the documentation and perform related activities pertaining to international shipments. Some of the typical information reviewed by a freight forwarder is the commercial invoice, shipper's export declaration, and other documents required by the carrier or country of export, import, or transshipment. Much of this information is now processed in a paperless environment. As an analogy, freight forwarders have been called travel agents for freight. (http://www.wcscargo.com)
Globalization	Globalization (or globalisation) is the process of international integration arising from the interchange of world views, products, ideas and other aspects of culture. Advances in transportation and telecommunications infrastructure, including the rise of the telegraph and its posterity the Internet, are major factors in globalization, generating further interdependence of economic and cultural activities.
Intermodal freight transport	Intermodal freight transportation is defined as a particular type of multimodal transportation where the load is transported from an origin to a destination in one and the same intermodal transportation unit (e.g. a TEU container) without handling of the goods themselves when changing modes. (Crainic and Kim, 2007)
Merchant haulage	Merchant's haulage is when the pre and end haulage is carried out by the shipper and the receiver of a container, respectively. (http://www.logisticsglossary.com/)

Multimodal transport	Multimodal freight transportation is defined as the transportation of goods by a sequence of at least two different modes of transportation (UNECE, 2009). The unit of transportation can be a box, a container, a swap body, a road/rail vehicle, or a vessel. As such, the regular and express delivery system on a regional or national scale, and long-distance pickup and delivery services are also examples of multimodal transportation. (SteadieSeifi et al., 2014)
ISO container	An ISO container is a container with strength suitable to withstand shipment, storage, and handling. ISO containers range from large reusable steel boxes used for intermodal shipments to the ubiquitous corrugated boxes. In the context of international shipping trade, ”container” or ”shipping container” is virtually synonymous with ”(standard) intermodal freight container” (a container designed to be moved from one mode of transport to another without unloading and reloading).
Shipper	The person for whom the owners of a ship agree to carry goods to a specified destination and at a specified price. The merchant who can be consignor, exporter, or seller (who may be the same or different parties) named in the shipping documents as the party responsible for initiating a shipment, and who may also bear the freight cost. (http://www.oocl.com)
TEU	Abbreviation for twenty-foot equivalent unit: a standard measure for a container for transporting goods, used to calculate how many containers a ship can carry, or a port can deal withtwenty-foot equivalent unit: a standard measure for a container for transporting goods, used to calculate how many containers a ship can carry, or a port can deal with. (http://dictionary.cambridge.org)

The first time each term is used in text is shown in *Italics*.

Clarification of Contributions

This dissertation is the result of a collaboration between myself (Panagiotis Ypsilantis), my promotors (Prof. dr. Rob Zuidwijk, Prof. dr. Leo Kroon) and Assoc. Prof. Jan van Dalen. My promotors offered advice and guidance throughout the entire process and made suggestions for additions and improvements. For each chapter, the contributions were as followed:

- Chapters 1, 2 & 6: Written by myself, improved over several rounds based on feedback and advice by my promotors.
- Chapter 3: The initial research ideas resulted from brainstorming sessions between myself and my promotor Prof. Rob Zuidwijk. My role was to perform literature review, perform data collection and data analysis, develop and test the quantitative models, and write the chapter. After producing the first version, the paper was shared with Assoc. Prof. Jan van Dalen who provided constructive feedback and suggestions on the presentation and contents of the paper that were incorporated in later versions.
- Chapter 4 and 5: The initial research ideas resulted from brainstorming sessions between myself and my promotor Prof. Rob Zuidwijk. My role was to perform literature review, develop and test the quantitative models and the solution procedure, and write the chapter. The chapters resulted in its current form after several rounds of feedback and suggestions of my promotors Prof. Rob Zuidwijk (during the full development of the chapter) and Prof. Leo Kroon (later versions of the chapter), that were incorporated in the final version of the chapters.

1 Introduction

Globalization has led to a tremendous growth in international trade over the last century, from $296 billion in 1950 to $18.8 trillion in 2014 (World Trade Organization / www.wto.org). At the same time, companies have transformed into global or multinational corporations that aim to deploy their global supply chains by sourcing materials, producing goods, and satisfying demand around the world in the most efficient way. This has led to a vast increase in international transportation. Several actors are involved in international trade and transportation, such as *shippers*, shipping lines, inland carriers, truckers, seaport and inland terminals, *freight forwarders*, financial institutions, *customs*, distribution centers, and warehouses.

Fig. 1.1 illustrates the international container transportation process. The figure depicts the physical movement of containers from their origin to their destination, through the network of depots, storage yards and inland and seaport terminals. Inland and sea carriers provide the transport between the nodes of the network. Moreover, the figure depicts how all other actors involved in the process that enable the international transport of containers are linked and interconnected in the global container transport process.

Nowadays, approximately 90% of non-bulk cargo is transported via *shipping containers* (Ebeling, 2009). Containers are boxes with standardized dimensions. The capacity is usually measured in Twenty Feet Equivalent units (*TEUs*), which is a steel box 6.06 meters long, 2.44 meters wide, and 2.59 meters high. The *containerization* of cargo, in which cargo is loaded into containers, has supported and enabled the vast increase in international trade volumes by allowing the efficient international transport of cargo over long distances. The use of standardized loading units enables the effective handling, storage and transport of cargo with different modalities like ships, trains, barges, and trucks. Moreover, the use of standardized boxes simplified the transfer between modes, so the notion of *intermodal transportation* emerged. Intermodal transportation refers to shipping cargo successively using multiple transport modes.

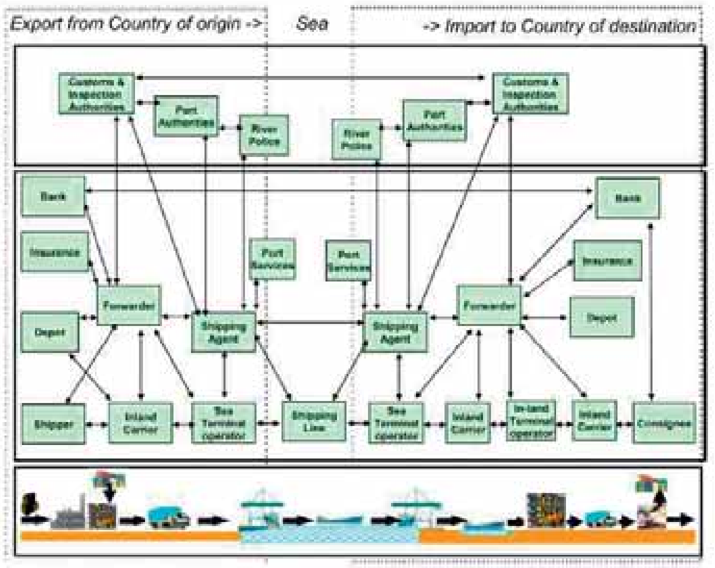


Figure 1.1: Global Freight Transportation (Source: Van Baalen et al. (2009))

International transportation is done via sea, air, or land modes when transportation is done completely over land. The dominant container transport mode measured in TEU-km is maritime. Shipping lines or carriers, responsible for this part of the transport chain, operate big container vessels and connect deep sea terminals around the globe. Economies of scale have driven an increase in the size of container vessels; the biggest vessel built in 2014 has a capacity of 19,000 TEUs. The increasing size of vessels puts pressure on the major seaport terminals that can handle these mega-vessels since handling big vessels requires specific equipment, e.g. sea cranes, and requires specific port infrastructure, e.g. water depth. Moreover, storage capacity in their yard is usually limited and difficult to expand, and the infrastructure connecting the seaport area with its hinterland, via roads, rail and waterways, has limited capacity. So, seaport terminal operators are interested in the effective utilization of transport infrastructure connecting to the hinterland and in the reduction of the time that containers stay in their yard.

The first and the last legs of the international door-to-door transportation chain, usually from the port to the hinterland destination and vice versa, generate a big share of the total transportation costs and total lead time, although the distance to be covered in these legs is just a small portion of total distance. Several processes and actors are involved and several transportation schemes have been proposed to accommodate the needs of this part of the transportation chain. Trucking is still the dominant modality used in the port-hinterland services in Europe, but intermodal, rail-road and barge-road schemes are emerging. The successful execution of port-hinterland multimodal networks lies in the effective design of a high capacity hinterland network and the services associated with it, as much as coordination issues among the different actors involved.

From an economics point of view, the inland dynamics are considered a driver to port development, and hinterland connectivity is a main fundament in the competitive position of a port. This development phase is characterized as “port regionalization” (Notteboom and Rodrigue, 2005). The port-hinterland networks can be represented in three dimensions: the macro-economic, the physical, and the logistical (Notteboom and Rodrigue, 2007). Since the objective is a functionally integrated hinterland, efforts must be put into developing high capacity corridors to the hinterland. Ports are interested in more than their captive service regions, which are close, and compete with neighboring ports on contestable hinterlands in order to attain a larger share of container flows through their networks. This is the case for almost all seaports within the Le Havre - Hamburg range, the hinterland of which is overlapping more.

There are currently several actions taken in Europe to improve the hinterland transportation of cargo. For example, in 2015 the TEN-T policy has been initiated for eleven major inland corridors in Europe (see Fig. 1.2). The policy includes work plans for these 11 corridors until 2030, and include actions to enhance modal integration, cross-border connectivity, sustainability, safety and innovation in freight transportation.

This thesis was part of the research agenda of the ULTIMATE project. The Ultimate project aimed towards efficient multimodal hinterland networks, and had a multidisciplinary research agenda. An overview of the project can be found in Veenstra and Zuidwijk (2015). The project focused on four research streams, that varied from assessing the consequences of integrating transport and cargo handling activities in supply chains, to the legal consequences of mixing transport and storage activities, to investigating the role and position of port authorities vis-a-vis the activities of container terminals, and to integrating new business models in the design of hinterland networks. The latter was the core scope of the research presented in this thesis.

Considering the above, we conclude that the reinforcing cycle of containerization, economies of scale in operations, and the growth of international trade has resulted in an increased pressure on hinterland intermodal systems, which justifies the systematic

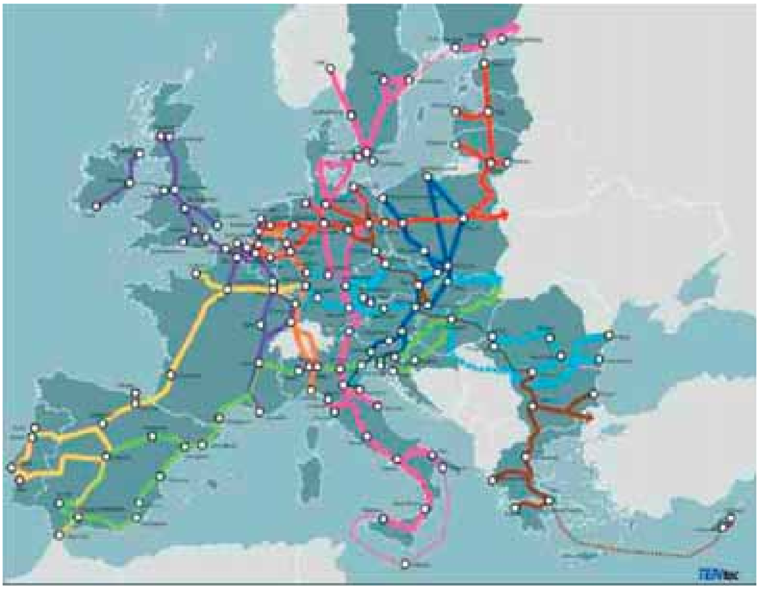


Figure 1.2: Map of TEN-T corridors in Europe (Source: ec.europa.eu/)

study of its design, planning, and execution. Given the motivation for this study, in Section 1.1 we introduce the freight intermodal transportation topic at the port-hinterland level. Section 1.2 provides a brief overview of the research scope and objectives of this thesis. Finally, in the last section we provide a reading guide to this thesis and we formulate the research questions that will be addressed in this thesis.

1.1 Port-Hinterland freight intermodal transportation

Freight intermodal transportation usually refers to the container transport using multiple modes successively to connect the consignor of cargo to its consignee (Crainic and Kim, 2007). Several studies consider the environmental effects of transportation and thrive to propose sustainable intermodal network designs (Bauer et al., 2009). Northern Europe is densely populated by intermodal inland terminals, as shown in Fig. 1.3, and usually inland terminals are connected with seaport areas via waterways and rail networks with high capacity transport means.

Freight transportation with barges or trains always involves a combination of transport modes, and is therefore referred as combined transport. The main haulage be-

Figure 1.3: Map of intermodal inland terminals in Europe (Source: www.inlandlinks.eu) *The data set of inland terminals is incomplete.*

tween the seaport and the inland terminal is performed by the high capacity modes, trains or barges, and the pre- and end-haulage is done by trucks (Frémont and Franc, 2010). Combined transport is enabled by several actors involved; a seaport terminal, an inland terminal, inland multimodal carriers, and a forwarder that usually orchestrates the transport. The international transportation process and the actors involved are depicted in Fig. 1.1. The uni-modal port-hinterland transportation, via trucks, has shifted to intermodal combined transportation that requires one or more transshipments of containers between modes at inland terminals.

Usually some break-even distances exist for which each transport mode becomes economically effective. Current literature suggests that for relatively short distances direct trucking results in lower costs than combined transport if one considers the extra crane moves and the final transportation via trucks to the final destinations (Janic, 2007). On the contrary, business examples suggest that combined transport can be efficient even for relatively short distances, in case high capacity modes are effectively utilized and when container storage and handling is well embedded in the supply chain design. These break-even distances can vary depending on the external costs of intermodal and road transportation. By internalizing external costs, EU policies may reduce the break-even distances of intermodal transportation. External costs that could be internalized include emissions, congestion, noise, etc. Moreover, national governments and port authorities impose regulations on the modal spit for the import and export of containers at major seaport terminals.

Better hinterland connectivity can be achieved by considering several different business models; cooperation between different actors, vertical or horizontal alliances among supply chain players are the most common practices followed in the international shipping industry (Notteboom and Merckz, 2006). Nowadays, the different actors in the supply chain do not have distinctive roles in the transportation chain, and their roles usually overlap. One particular example is the changing role of container terminals from “node operators” to “flow operators” as stated in Veenstra and Zuidwijk (2010) for both the seaport and inland container terminals, and by the many examples of investments of shipping lines in container terminals.

The inland transport of containers is performed under several governance structures. The most common are *carrier haulage* and the *merchant haulage*; in case of the former, containers are transferred to hinterland locations under the responsibility and customs license of shipping lines while in case of the latter, containers are moved under the responsibility of inland carriers with the custom license of the shippers or their representatives. During the last years, more haulage schemes and concepts have been developed; Notteboom (2008) has identified for the port of Antwerp a new haulage concept, the terminal operator haulage in which terminal operators can consolidate and transport flows of different shipping lines to hinterland destinations under their responsibility and customs license; this concept relies on the cooperation between seaport terminals and shipping lines, inland carriers and terminals. There are several business practices followed by both seaport and inland container terminals that resemble the terminal operator haulage concept.

To facilitate a better port-hinterland connectivity, the "*Extended Gate*" (Veenstra et al., 2012) and "*Dryport*" (Roso et al., 2009) concepts emerged and are developed in concrete business models, in several regions around the world. According to these concepts, the seaport and the inland terminals, respectively, extend their role from node operators and claim the roles of inland carriers by providing transport services. Such concepts are used to enhance the competitive position of seaport and inland terminals respectively by providing better hinterland connectivity to selected destinations. Moreover, seaport terminals engage in extended gate concepts to boost their storage capacity by pushing containers immediately after their discharge to inland terminals, while postponing customs clearance and other added value activities to the inland terminals. Moreover, such concepts are in favor of a modal split shift to more sustainable transport modes while leading to several other benefits for the actors involved that are discussed later in this thesis.

1.2 Research scope and objectives of the thesis

The aim of this thesis is to quantitatively and qualitatively address research questions that support the tactical design of port-hinterland multimodal container transport networks. In particular, we analyze the design of port-hinterland multimodal networks, while considering the extended gate and dryport concepts. The design for such networks is evaluated not only according to their economic performance but also according to other performance measures like sustainability, reliability, and service level offered to customers.

To facilitate the reader, we provide in Tab. 1.1 a reading guide of this thesis.

We formulate three main research objectives and briefly elaborate on their motivation. Each research objective is addressed separately in a chapter of this thesis, where relevant literature, methodology used, models developed, and results are presented.

Table 1.1: Reading Guide

	Title	Research Scope	Research Activities	Main Contributions/Findings
Chapter 2	Literature Review on Port- Hinterland Service network design	Literature review on intermodal transportation	1. Literature Review on general intermodal service network design. 2. Literature review on Port-hinterland intermodal network design models	1. Assess how economies of scale, time and transhipments are modelled in intermodal literature. 2. Assess why and how port - hinterland intermodal transport differs from regular intermodal transport.
Chapter 3	Dwell times at container terminals: Shipper effects	Analysis of Multimodal port-hinterland container transport: 1. Analyze factors that affect import Container Dwell times. 2. Analyze performance characteristics of shippers importing containers.	1. Data collection,/ Data analysis. 2. Container import physical and information flow modeling. 3. Econometrics model to analyze the quantitative effect of different factors on container dwell times. 4. Clustering model to perform shipper segmentation according to performance characteristics.	1. First study to quantitatively assess the impact of several factors on the development of container dwell times at seaport terminals. 2. Shipper characteristics and actions significantly affect container dwell times. 3. Shipper clusters with significant different characteristics, needs and performance related to their port - hinterland container transport are identified.
Chapter 4	Joint design and pricing of intermodal port - hinterland services: Considering economies of scale and service time constraints	Analyze the tactical joint design and pricing of intermodal network services: 1. Develop a relevant quantitative modeling approach. 2. Provide managerial insights for the optimal design of such networks.	1. Literature review. 2. Novel Bilevel MIP formulation of the problem. 3. Heuristic procedure to obtain near optimal solutions of the corresponding NP hard problem. 4. Experiment to assess the effectiveness of the model and to provide managerial insights.	1. Pricing and network design are interrelated decisions and thus should be treated simultaneously. 2. Considering time constraints is very crucial modeling feature at the tactical level, and leads to significantly different optimal design. 3. Offering port-to-door hinterland services can lead to better performance compared to port-to-inland-port services, due to higher consolidation in fewer corridors.
Chapter 5	Joint fleet deployment and barge rotation network design: The case of horizontal cooperation of dryports	Analyze the tactical joint fleet deployment and barge rotation for port-hinterland container transport. 1. Develop a relevant quantitative modeling approach. 2. Provide managerial insights for the optimal design of such networks.	1. Literature review. 2. MIP formulation of the problem. 3. Analytical model to assess the main design tradeoffs on joint fleet selection and deployment. 4. Experiment to assess the model effectiveness and to provide managerial insights.	1. Fleet deployment and barge rotation are interrelated decisions and thus should be treated simultaneously. 2. Considering time constraints is very crucial modeling feature at the tactical level, and leads to significantly different optimal design. 3. The analytical models make clear the tradeoffs among the different design parameters. 4. The optimal design is always case specific, and depends on the transport demand, distances and service time requirements set by the shippers.

Research Objective 1

The first objective of this thesis is to assess the implications of different shippers' characteristics on combined port-hinterland transportation. Shippers organize differently their supply chains and may have different priorities over costs, service times, modal choice, and other service characteristics as offered by carriers. To address this objective, we conceptualize the physical import container process next to the information flows among the actors involved. Then we collect and analyze data to study empirically the differences among shippers, modalities, container dwell times, and other performance characteristics.

Research Objective 1. Analyze the combined transport process for port-hinterland container transport based on empirical data. Assess the main performance characteristics of shippers using combined transportation. More specifically, determine which characteristics of shippers influence container dwell times.

The first objective seeks to identify the shipper characteristics that drive modal choice and differentiated service time needs. Our analysis covers the container cycle from discharge of full containers at the seaport terminal to the return of empty containers at the inland terminal. The main determinants of container dwell times in seaport and inland container terminals are qualitatively and quantitatively examined. In Chapter 3, a model is developed that explains and predicts dwell times at container terminals. In particular, 48% of the dwell time variance is explained by factors related to the shippers involved. In contrast to the common assumption that the container terminal performance is the main determinant of dwell times, we show that factors exogenous to the container terminal determine dwell times. To the best of our knowledge, this is the first study that quantitatively assesses the impact of such factors. Our results show connections between dwell times and time criticality, and the value of information in the reduction of dwell times. The assumption that dwell time performance can be treated as a purely endogenous capacity performance criterion of seaport terminals is challenged. Moreover, clusters of shippers are identified with different characteristics and different performances in terms of dwell times and modal choice.

The above results from Chapter 3, which identify the main determinants of container dwell times to be shipper related, motivate the research performed in the next chapters. In particular, we consider three elements to be crucial for the effective design of port-hinterland networks: The different actors involved, the resulting service level offered (measured either by expected service times or by service frequency), and the expected cost of the proposed services which is usually dependent of the achievement of economies of scale.

Research objectives 2 and 3

Current research on intermodal network design mainly considers the objective of one actor which may be the shipper or the carrier. On the one hand, in case of the network design from a shipper perspective, it might be sufficient to use models that select services, modes and routes offered by a collective of carriers that would minimize their expected total logistic cost while satisfying their time constraints. On the other hand, when network design is considered from a carrier perspective, the carrier should design its services at a tactical level while anticipating the demand of a collective of shippers and their service time requirements. So, for the latter case, the resulting service level received by the users of the services should always be incorporated. Moreover, consolidation opportunities exist that can enable the achievement of economies of scale. The achievement of economies of scale and the establishment of frequent connections, with lower costs and expected service times for shippers, mainly drives the market penetration of combined transport services and makes them competitive to uni-modal road transport.

Considering the above, we set up two more research objectives that relate with the development of models suitable for the design of port-hinterland services and that incorporate our findings from Chapter 3.

Our second research objective relates to the design of a multimodal hinterland network according to the Extended Gate concept as it is implemented by a major seaport terminal in the Netherlands, but its scope can be generalized to the joint pricing and design of high capacity shuttle services between seaport and inland terminals.

Research Objective 2. Establish a model to design a multimodal hinterland transport network at the tactical level, by establishing shuttle services of high capacity modes between seaport terminals and inland container terminals. The model should balance costs faced by the carrier, and costs and service levels faced by the shippers that arise from the network design related decisions, such as the optimal mode size, the frequency of connections and pricing of services. The design of such a network and in particular the tariffs and the expected service times establish the market penetration of proposed services, while considering services offered by competitors.

In Chapter 4, a bi-level MIP model to jointly design and price extended gate network services for profit maximization is proposed. The model considers cost, demand data, and other relevant parameters and proposes the optimal design and pricing of such services at a tactical level. The design comes down to the selection of the optimal sizes of transport modes and the optimal frequency of connections at each corridor. At the same time, the optimal tariffs for the services offered to customers are determined. Together with the expected service times at each corridor, that are connected with the frequency of connections, they determine the market penetration of the proposed services in consideration with transportation services offered by competitors.

On the technical side, the model extends previous bi-level formulations and proposes a heuristic that provides near optimal solutions to this NP hard problem. On the managerial side, we study optimal network designs while comparing seaport-to-door and seaport-to-inland port services and situations where transit time requirements do and do not apply. Our results show that there are significant differences in the optimal network designs under the different assumptions, and moreover they show that there is a significant interaction between the design and the pricing on such networks. It follows that the two decisions should be treated simultaneously and one should try to capture the corresponding trade-offs among revenue management, economies of scale and service level offered to customers. The interaction between the design and pricing of network services and service level offered to customers is not limited to the extended gate case studied but may be relevant in a lot of network design cases, like the design of public transport services, where the expected transport time, frequency of connections, and tariffs directly affect the modal choice of customers.

Our third research objective relates to other cases, where point-to-point shuttle services may not be a viable option, and consolidation is best achieved by the rotation of resources, like barges, trains and trucks along terminals, hubs etc.

Research Objective 3. Establish a model to design a multimodal hinterland transport network at the tactical level, by establishing rotation services of high capacity modes along seaport terminals and inland terminals. The model should design the optimal fleet and its deployment on a network, in such a way that costs are minimized while demand is satisfied and expected service levels required by the shippers are met.

In Chapter 5, we consider a case where the optimal fleet is selected and its deployment on a network of inland terminals is explored. In particular we study the design of a multimodal hinterland network according to the Dryport concept as it is implemented by a major alliance of inland terminals in the Netherlands, but its scope can be generalized to the joint fleet selection and routing of high capacity modes in a network consisting of seaport and inland terminals. The model considers cost, demand data, and other relevant parameters, and proposes the joint optimal fleet mix and routing over the network at a tactical level. It minimizes costs by optimizing fleet utilization, both in space and time, and by satisfying expected demand of Origin Destination pairs and service levels set by the shippers.

On the technical side, we develop both an analytical model and an MIP model that capture the connections between network design parameters like the number of vehicles, their size and their routing and performance measures like the total cost, the capacity installed and network coverage. The MIP model aims to support tactical decisions regarding: the fleet size and mix selection, the routing of the fleet over the network for a long time horizon in order to satisfy demand under some service time related constraints and, the assignment of container flows to given services in order to assess the performance of the proposed network design. On the managerial side, the model is applied to a real case of an alliance of closely located dryports that connect with container terminals in a seaport area. We study the impact of cooperation of closely located dryport terminals in terms of sharing transport capacity in both cost and service quality performance. Moreover, we show that although decisions regarding the optimal fleet mix and its deployment are usually treated separately, are actually interrelated and should be treated simultaneously.

2 Literature Review on Intermodal Service Network Design

Summary: In this chapter, we go through the general intermodal service network design literature and we discuss how literature is divided according to the planning levels and problems on hand, while we provide references to extensive literature reviews on the topic. In the following sections, we go into more detail of the modeling techniques used in the literature to incorporate crucial elements to the effective network design. These elements are the consideration of time in modeling, the formulation of economies of scale and the consideration of transshipments. We review them in Sections 2.2., 2.3. and 2.4 respectively. Finally, in Section 2.5 we discuss how and why port - hinterland service network design differs from usual service network design and why the effective consideration of the elements mentioned above is crucial while we review contributions of literature that focus on port-hinterland network design.

2.1 Intermodal Service Network Design

In this section, we go through the most relevant literature to our research and position our work accordingly. First, we go through some general literature on the supply side of freight transportation networks and then we review streams of literature that we consider relevant for the port-hinterland network design and in particular for the modeling approaches we follow in the next chapters. Our literature review is not exhaustive but focuses on specific modeling features that could be applied or adapted to facilitate the port hinterland multimodal network design. The development of the supply side of container transport networks has been studied extensively in the literature and is widely known as the service network design problem. Such problem formulations are increasingly used to designate the tactical issues of carriers (Crainic, 2000).

Some recent overviews of the intermodal freight planning research are conducted by Macharis and Bontekoning (2004), Crainic and Kim (2007), Caris et al. (2008), Wieberneit (2008) and SteadieSeifi et al. (2014). The authors divide the contributions in the field according to the time horizon in strategic, tactical and operational models. Strategic decisions in intermodal transportation usually are long term decisions regarding node and network infrastructure and configurations, infrastructure investments, cooperation among companies, and terminal design. Tactical decisions are medium term, and relate to capacity setting of resources, infrastructure and labor, configuration of consolidation networks, pricing strategies, and allocation of shippers and receivers on a terminal. Operational decisions in this context are in a dynamic and stochastic environment and come down to vehicle routing, assigning containers to specific transport itineraries, resource allocation, scheduling of jobs, redistribution of resources and assets, etc. Decisions at the strategical and tactical levels though can have a significant effect on the operational performance of such networks. The models proposed in literature are most of the time between the tactical and the operational level. Although tactical level problems are treated like the planning of fleet composition and capacity deployment, most models seem to focus on the minimization of operational cost while meeting operational time constraints of deterministic instances.

Moreover, most research in intermodal transportation assumes hub and spoke network topologies while very few consider other network topologies like direct links, corridors, connected hubs, static or dynamic routes that could in several cases depict reality better (SteadieSeifi et al., 2014).

Modeling intermodal transport systems effectively, in an operational, tactical or strategic levels, is a challenging task. The consideration of different modalities with their respective sizes, fixed and operational cost, speeds, handling and service times, and transshipments in intermediate terminals influence the operational performance and complicate the problem formulation since each characteristic has a different effect on the performance of the designed services.

In the context of pre-haulage or end-haulage intermodal transportation, that is from the seaport to the inland destination and vice versa, three elements seem to be the most vital for the effective representation of such systems. These are the consideration of the time dimension in modeling, the formulation of economies of scale through consolidation opportunities, and the consideration of transshipments in modeling. Below we discuss relevant literature on the modeling of each element separately, in

Sections 2.2, and 2.3 respectively. Finally in Section 2.4 we go through the most relevant port-hinterland service network design literature, and position our modeling work (in Chapters 4 and 5) accordingly.

2.2 Consideration of time in intermodal transport

The consideration of time in intermodal transport models constitutes a major research challenge (Crainic and Kim, 2007), mainly because the resulting models become computationally intractable. The use of time in such models is twofold. First, efficient asset management requires the scheduling, coordination and routing of transport modalities, that in its turn affects asset utilization over time. Second, different network configurations (mode speed, frequency of services, number of stops, transshipments) can lead to considerably different results in terms of expected service times, since service times consist of transport, handling, *dwell times* and delays. Especially for the case of port-hinterland transportation, the market penetration of combined transport services compared to trucking may not only depend on cost but also on service times.

The time dimension in service network design is usually incorporated at the operational level by considering time windows for the pick up and delivery of cargo, or to satisfy coordination restrictions that apply in some problems, i.e., establishing transfer times between arrivals and departures of modes at a node. This can be done either by applying penalty cost for late deliveries or by imposing hard due date constraints. Contrary to the operational level models, in strategic and tactical level models the time dimension should be used to depict the expected time utilization of assets and the service time performance of services, and capture the effects of competition. Shippers tend to choose their carriers based on the perception of the service quality and price that they will receive (Crevier et al., 2012). In the intermodal network design, the service quality perception can be associated with the service times of intermodal paths which depend among others on the frequency of services (Li and Tayur, 2005). It follows that the market penetration of combined services depends also on the tactical and strategic design of such networks in addition to their operational performance.

Very few modeling contributions at a tactical level seem to take the time dimension explicitly into account, since space-time formulations are mainly at the operational level. In Crainic (2000) the main service network design formulations are reviewed;

the service level is considered by the application of minimum frequency constraints on specific links over the network. Such formulations cannot capture the demand penetration of a carrier based on the service level offered. In order to capture this effect, multi-commodity formulations with differentiated characteristics among the commodities should be developed. In Crainic and Rousseau (1986) this interaction is captured by considering unit delay cost in the objective function differentiated per commodity which depend on both connection frequency delays and transit times in each link over the network. First, unit delay cost can be difficult to approximate for each commodity, compared to setting a desired service time or a minimum frequency constraint per commodity. Second, the routing of containers in the network may rely substantially on the values of the penalty delay cost compared to the cost structure over the network, but still the potential of losing some market to competition is not captured in such models. Li and Tayur (2005) consider the expected total service time constraints set by the clients of the network. They model frequency dependent service times on paths, that consist of link, capacity and frequency delays. The service frequency on the links is then bounded from below to satisfy the time constraints set by the clients. The last formulation of service level constraints seems to be the most considerable if interested in the differentiation of total expected service times of intermodal transport alternative options.

2.3 Network flows and economies of scale

Economies of scale are usually incorporated in Hub and Spoke network formulations. Most of these contributions apply a discount factor a, $0 \leq a \leq 1$, to the unit transportation cost between any two of the selected nodes of the network that will act as hubs. This simplistic approach does not take into account the amount of flow that will pass through the inter-hub link, so post-assessment and post-validation of the solutions are needed. The above explains the shift to flow dependent economies of scale. Several authors consider piece-wise linear functions to depict the economies of scale (O'Kelly and Bryan 1998; Horner and O'Kelly 2001; Klincewicz 2002). Marginal cost is then positive and decreasing in flow volumes.

Applying the former simplistic approach is considered to be wrong since assuming that the discount factors are independent of the flows can lead to false hub allocations and result interpretations (Kimms, 2006). The latter approach with flow dependent discount factors could be valid if the transportation is performed by a third party.

Kimms (2006) proposes an alternative formulation of economies of scale as a non continuous increasing function of the flows, with break points denoting the multiples of the capacity of the mode in reference. In this way, the actual cost faced by a party operating high capacity modes is more effectively approximated. We agree in principle with Kimms (2006), but we argue that in port-hinterland transportation the variable cost per unit transferred is minor compared to the fixed cost associated with operating (leasing) additional units of high capacity modes such as barges and trains; that is why the slope of the piece-wise linear parts of the function should be close to zero.

Of course economies of scale are already embedded in models that allow the fleet selection in the sense that cost for buying or leasing assets like vessels, river vessels of trains are not linear in their respective sizes.

2.4 Consideration of transshipments in intermodal transportation

Transshipment is the process at a terminal to shift flow from one mode to the other (Vis and De Koster, 2003). Port - hinterland intermodal transportation, or combined transport, converts by definition the unimodal transport via trucks to the combined, barge-truck or train-truck format by adding an extra stop at an inland terminal in which the transshipment of containers happens from one mode to the other. Ignoring transshipment in modeling might result in sub-optimal or infeasible solutions (SteadieSeifi et al., 2014). Considering transshipment affects the overall performance of the system, both in terms of total cost but also in terms of total service time.

In literature, there are several cases where transshipments are not explicitly incorporated. When modeled, transshipments usually take the form of a per-unit cost in the objective function (Gelareh and Nickel, 2011; Hamzaoui and Ben-Ayed, 2011; Shintani et al., 2007; Ishfaq and Sox, 2012) or the form of a capacity constraints (Anghinolfi et al., 2011; Meng and Wang, 2011). To the best of our knowledge, there are no service network design models that explicitly consider the transshipment times. This might be the case in liner shipping service network design where transshipment times might be included in the fixed times per stop considered in the models.

In port-hinterland intermodal transportation, it is crucial to consider the transshipment cost and times for two reasons; first, it affects the attractiveness of combined services (total cost and total service time), and second, neglecting transshipments can result in infeasible designs and underestimated capacity requirements.

2.5 Contributions in Port - Hinterland Network Design

In this section we review papers that specifically handle port-hinterland network design problems which we argue to be considerably different from problems handled in general intermodal transportation literature. There are several features that distinguish this class of problems. First, in port-hinterland transportation there is almost always the option of trucking, which is the most dominant mode for hinterland transport due to its flexibility and speed. Considering the above, means that any combined transport service configuration, barge-truck or train-truck, would have to compete in both cost and service times with trucking from a shippers perspective, or that trucking could be considered as a recourse action when planning capacities from an inland carrier perspective. Second, the distance to be covered is usually shorter than the distances covered in international container transport e.g. liner shipping, and this is even more the case regarding transport times, where instead of weeks trucking takes usually less than a day. Considering this, it can be inferred that the other constitutes of total service times, such as dwell times, delays, and transhipment times can account for a big share to total service time. For this reason it is crucial to explicitly consider these time elements in the modeling of such systems. Considering such time and cost elements in the modeling is what differentiates the performance between the different configurations of combined transport and of trucking and what should determine market penetration of each service, modal splits, etc. As we show later in Chapter 3, shippers can have different time needs regarding the inland transport of their containers ranging from a few hours to several days, that gives room to both types of services. Formulations in this regime should focus on effectively capturing these special characteristics of port-hinterland intermodal systems. So, the characteristics of different modalities should be effectively formulated and their utilization should be assessed both in terms of cost and time. Moreover, the demand penetration of intermodal services compared to that of uni-modal truck transport should also be assessed both in terms of cost and of service times from the customer's perspective.

Contributions that could exclusively focus on the port-hinterland tactical intermodal network design area are still limited. Relevant literature includes models focusing on corridor design, line bundling, and the design of hub and spoke networks.

In Tab. 2.1, the main research done for the port-hinterland network design is summarized, and below each paper is briefly discussed. The models considered differ in several dimensions including the planning level, the mathematical formulation, the solution approach, and other modeling considerations.

Crainic et al. (2013) discuss the optimization challenges that arise by the development of the dryport concept and propose a service network design model, in a space-time network, for the operational rotation planning of barges between seaport and inland terminals. The size of the problem becomes restrictive even for small and medium instances due to its space-time format, so commercial solvers fail to find feasible solutions. Further research on the development of efficient solution methodologies for such problems in space-time formulations is needed.

Sharypova et al. (2012) develop a continuous time formulation for the scheduled barge network design problem with synchronization and transshipment constraints. This model can facilitate the operational planing of barge routing. The heterogeneous fleet of barges is routed through the network and the arrival and departure of each barge at each node are specified under a large set of synchronization and coordination constraints. Demand that is organized in commodities is assigned to transport services that satisfy pick up and delivery time windows. The size of the problem allows the treatment of only very small instances with commercial solvers. Therefore, Sharypova (2014) develops some meta-heuristic approaches. Problems at the operational level do not allow for simplifications that reduce the computational complexity, so heuristic procedures are needed for the solution procedure.

Behdani et al. (2014) develop a model for the scheduling of synchromodal services. The authors take as given the fleet composition, the capacity and the frequency of services, and schedule the services such that the overall cost and waiting times (via penalties) are minimized. Constant unit cost per modality are considered so economies of scale are not formulated, while several operational constraints are considered such as opening and closing times of terminals, delivery time constraints, infrastructure usage constraints, etc.

Caris et al. (2012) adapt the generic path-based multi-commodity network design formulation of Crainic (2000) to intermodal barge transport by using a concave cost function to formulate economies of scale for the links operated by barge. The element of time is ignored in this formulation. The impact of cooperation of barge inland terminals is assessed only in terms of consolidating flows on some corridors, but an analysis of overall transport performance and cost or routing are not considered.

Braekers et al. (2012) develop a line bundling MIP model to construct round trips of barges and assign container flows to round-trips in a tactical time horizon. The model gets as input the weekly number of trips - thus maximum round-trip time -, and the number and size of barges. Demand of customers should always be fulfilled by one round trip and trucking is not considered as a recourse action. The authors run a number of scenarios to assess the optimal capacity setting on the corridor. Their results are in favor of bigger barges for the achievement of economies of scale, but as indicated, barge operators may be in favor of providing higher frequencies in order for their services to be more attractive to customers.

Van Riessen et al. (2013) proposes a path-based service network design model that investigates the use of contracted and subcontracted network services for the operation of an extended gate network at a tactical level, while assuming flexible due dates. Their findings show that transshipment cost at terminals should be reduced in order for paths with more than one stop at inland terminals to become cost effective.

Summarizing the literature review, some conclusions can be drawn. Although the supply side of transport networks have been extensively studied in literature, the design of port-hinterland intermodal transport systems has only recently grasped the attention of the academic world. The models proposed are most of the time between the tactical and the operational levels. Although they aim to support tactical decisions like capacity setting or fleet composition, specific demand instances are considered and the models are solved based on minimizing operational cost and meeting operational time constraints. Moreover, most models seem to ignore crucial factors to the multimodal nature of the problem such as the consideration of time, or become too computationally intensive when time is taken into account. Moreover, some do not consider all relevant cost elements.

We suggest that considering total cost and time in such modeling is the most crucial element for the effective modeling of such systems because this is how combined services are differentiated from unimodal road transport which is still the most dominant and flexible mode in the hinterland. In Chapters 4 and 5 of this thesis, we develop two models that aim to take explicitly into consideration these elements along with other elements crucial to the design of port-hinterland network design. The analysis of the results of these two models clearly shows that there are several interactions among the design parameters of such networks which are interrelated. Moreover it is shown that neglecting the time dimension can lead to unrealistic network designs.

In Chapter 4, we develop a model for the joint design and pricing of intermodal shuttle

Table 2.1: Comparison of models in Port-hinterland network design

Paper	Objective	Formulation	Level	Modes	Modeling Considerations	Time	Solution
Crainic et al. (2013)	Minimize operational cost	Service Network design for barge transport	Operational	Barge Truck	Space time network is considered	Space time network is considered Time windows	Heuristic procedures
Sharypova et al. (2012)	Minimize operational cost	Continuous time formulation of the service network design problem	Operational	Barge	Routes are constructed Transshipments are allowed One round trip per vehicle	Synchronization and Coordination of barges Time windows for the pick up and delivery of commodities	Heuristic procedures
Caris et al. (2012)	Concave cost function (Economies scale)	Corridor ND Path-based multicommodity network design	Tactical	Barge	Round trips and cost given Not Elastic demand	Not considered	Commercial Solver
Braekers et al. (2012)	Optimal shipping routes and barge size	ND model adapted for line bundling	Tactical	Barge	Round trips per week given One type of barge No service quality	Time per round trip is considered and bounded from above	Commercial Solver
Van Riessen et al. (2013)	Capacity setting on corridors	Path based network design MIP model	Tactical - Operational	Barge Train Truck	Self Operated and Sub-contracted services	Service time of paths is given Flexible due dates - Penalty cost	Commercial Solver
Behdani et al. (2014)	Minimize Transportation and waiting cost	Synchromodal formulation of one OD pair	Operational	Barge Train Truck	Given Fleet, capacity and Frequency of services	Penalty on waiting times	Commercial Solver
Chapter 4	Maximize Net Profit	Joint capacity setting and pricing of corridors 3 decision actors	Tactical	Barge Train Truck	Shuttle services - No Rotation Economies of Scale - Service level	Frequency dependent expected dwell times Maximum number of round trips given	Heuristic procedures
Chapter 5	Minimize Transport and transhipment cost	Joint Fleet Composition and Routing Cont. time MIP	Tactical	Barge Truck	Several barge round trips per time horizon	Utilization of barges in space and time levels	Commercial Solver

barge services according to the extended gate concept. The bi-level structure of our model allows on the first level the capacity setting on corridors by selecting the size of modalities and frequencies of connections, in parallel with the pricing of the services offered to customers. On the second level, customers select the minimum cost paths that satisfy their service time constraints among the ones operated by the extended gate operator, but also by other transport providers like trucking companies. Both cost and expected service times on corridors are frequency and mode dependent; so penetration of combined transport services is achieved both in terms of cost and time.

In Chapter 5, we develop a model to support the tactical joint fleet deployment and routing of barges in port-hinterland networks. The optimal fleet should be selected based on its expected operational performance and this is why routing plans for barges are considered simultaneously. In this sense, the utilization of the fleet should not only be based on the consolidation of flows but also on the construction of round trips that achieve low circulation times and thus more round trips per barge within the planning horizon. Moreover, by considering the routing of the fleet, we look at the expected service level that shippers of the network will experience by controlling the minimum frequency per OD pair serviced.

3 Dwell Times at Container Terminals: Shipper Effects

Summary: In this chapter, the variation of dwell times of imported containers to the hinterland at seaport container terminals via a multimodal network is analyzed. In contrast to the general belief that container dwell times are mainly a consequence of container terminal performance, we show that other factors, particularly the actions performed by shippers, significantly affect container dwell times as well. Ignoring the effect of such factors can lead to inefficient capacity setting in terminals and to ineffective measures to alleviate the negative effects of large dwell times. We analyze a case where containers are transported from a major seaport container terminal in the Netherlands to its nearby hinterland through a multimodal hinterland network controlled by an intermodal inland carrier. We analyze the physical and information flows of imported containers and collect information and milestone time stamps for all imported containers in the specific region in 2011. A statistical analysis is performed to assess the main factors that affect dwell times at seaport terminals. The results show a large effect of shippers' choices, as reflected by modality, order placement, and due date, on the magnitude of dwell times.

3.1 Introduction

Container dwell time (CDT) at container terminals (CT) is defined as the time a container spends at the container terminal yard. In this study we only consider the dwell times of imported containers. The dwell time of imported containers starts with their discharge from a deep sea vessel and ends with their loading on a truck, barge, train or feeder vessel for further transport. Container dwell times are relevant for assessing the utilization of, congestion in, and efficiency of the terminal. Container dwell times affect lead times for shippers and the utilization of assets (containers) for shipping lines, and are thus considered detrimental to the performance of most stakeholders in the international transport of containers. At the same time, container dwell times incorporate the slack time needed to perform handling, transhipment, and other added value operations before a container is loaded to a mode to exit the terminal, and thus are an integral part of the import and export process.

The capacity of the container terminals in terms of infrastructure and customs facilities affects the average dwell times of containers. According to Little and Graves (2008), the expected number of containers stored in a container terminal yard is determined by the product of the average arrival rate of imported containers and their average dwell time. Thus, shorter dwell times can be associated with the relief of the container terminal stack such that fewer container reshuffles are needed for the retrieval of containers (Castillo and Daganzo, 1993).

Dwell times are frequently quoted in studies that assess the performance of seaport terminals assuming that the container terminals through their operations can have control over the development of dwell times. Chu and Huang (2005) assume that the dwell time performance of a container terminal affects its overall capacity, while Steenken et al. (2004) consider it a performance indicator of the container terminal yard. Cochrane (2008) discusses dwell times as both a determinant of the yard capacity of a container terminal and as a performance indicator of the container terminal. Veeke and Ottjes (2002) and Ottjes et al. (2006) use the distribution of dwell times as input for their simulation model to analyze different layouts for the expansion of the container terminal in Rotterdam at Maasvlakte 2. In their study the dwell times and the arrival pattern of containers in a seaport terminal are identified as the main drivers of the container terminal performance and define the dwell time of containers as the slack time available for customs inspections. In most of these studies, it is assumed that container dwell times depend on container terminal performance, ignoring other exogenous factors. In reality though, container terminals have limited control over the development of dwell times, unless the arrival rates of containers are higher than the capacity installed at the terminal yard. Container terminals can influence container dwell times by incentivizing shippers, through storage fees, or allowing shorter free storage periods. Next to these factors we analyze the import container process and focus on actions and choices made by the shippers that seem to have a great effect on container dwell times.

In this study, we propose that several other factors, exogenous to the seaport terminal, affect container dwell times. Most of these factors are connected with preferences and selections made by shippers, like the selection of shipping lines, inland carriers, the contents and value of goods within the containers, the time criticality for delivering goods, information sharing, and overall the supply chain design of individual shippers. Some shippers opt for the timely and quick transport of their containers in order to reduce in-transit and safety inventories. Others use the CT's yard for the short or even longer term storage of their containers and apply a Just-in-Time (JIT) principle while picking up their containers when needed. The former type of shippers often uses inland terminals for long term storage and quick retrieval of their containers. Moreover, an increasing number of shippers strive to minimize their environmental footprint when fulfilling their transportation needs. Consequently, there is a considerable shift in the modal split to more sustainable modalities such as barge and train. The different modalities used for the transport of containers to the hinterland can affect the dwell times of the containers. Trucking is the most flexible mode compared to rail and barge, for which containers have to wait at the terminal until the next departure.

Long dwell times increase the total lead time for cargo to reach its final consignee and thus increase safety stocks and overall logistics costs faced by the shippers (Daschkovska and Scholz-Reiter, 2008). Moreover, demurrage costs are charged to shippers by the shipping lines when the container cycle times exceed certain thresholds. The expected dwell times at different nodes of container transportation networks affect the route selection through the network, according to most network design contributions formulated from the shipper perspective; see Iannone and Thore (2010).

The policies of shipping lines in terms of demurrage and detention costs may affect container dwell times since they can motivate shippers to accelerate logistic processes in order to avoid paying fees for late returns of the containers to the shipping line's empty container depots. Finally, containers have to be released by customs authorities before they can be transported out of the container terminal. Customs use X-ray equipment or even physical inspections to check only a small portion of the total container flow. The possibility of a container being checked and thus delayed depends on the risk assessment performed by customs, which incorporates several characteristics such as the consignee, consignor, cargo type, shipping line, and AEO status.

The reduction of container dwell times at seaport container terminals is often considered an inexpensive enhancement of terminal capacity, compared to other measures like advanced stacking and handling technologies, optimizing yard space allocation, and expanding the yard (Rodrigue and Notteboom 2009, Moini et al. 2012, Merckx

2005). This research aims to determine the main drivers of container dwell times and propose measures to reduce them.

In this present study, we analyze the import container process and discuss, in parallel to the physical movement of containers, the information streams among actors. The main determinants of container dwell times in seaport and inland container terminals are examined using quality and quantity criteria. In particular, we examine the determinants of dwell times of full imported containers originating from a seaport terminal and destined for an inland region, covered by a network of intermodal inland container terminals. Time stamps for specific milestones are collected from the discharge of full containers at the seaport terminal to the return of empty containers at the inland terminal. Our analysis of dwell times at container terminals shows that 48% of the dwell time variation is explained by factors related to the shippers involved. In contrast to the common belief that container terminal performance is the main determinant of dwell times, we show that various factors, exogenous to the container terminal, influence the development of dwell times. To the best of our knowledge, this is the first study that quantitatively assesses the impact of such factors on dwell times.

The structure of this chapter is as follows. In Section 2, we describe the process regarding the import of containers. We discuss the role of actors involved in the process and present the information flows among them that enable the total process. In Section 3, we discuss possible determinants of container dwell times, and substantiate their possible effect. In Section 4, we present our case study and perfom some descriptive analysis of the data on hand. In Section 5, we propose a model to explain dwell times at seaport container terminals, a model for shipper segmentation, and present our results. Finally, in Section 6, the conclusions are addressed, consisting of managerial insights and of directions for further research.

3.2 The import container process

A stream of information accompanies the physical movement of containers from the seaport to its final hinterland destination, involving transhipment, terminal internal transport, and hinterland transport. The information flows among actors involved in the process are summarized in Fig. 3.1. The shipper of imported containers initiates the process by selecting a shipping line and a preferred import seaport container terminal (1). The shipping line that usually operates under a liner service, loads the container at the first available vessel and notifies the shipper about the estimated time of arrival (ETA) of the specific vessel (2). Due to variation in transport times, the ETA is updated regularly. At least 24 hours before the deep sea vessel calls at the seaport terminal, the shipping line shares the unloading list of containers for the specific call with the seaport terminal and with the customs authorities. Based on this list, the seaport terminal plans the unloading of the vessel, while customs authorities decide whether to put containers under the customs hold status.

The shipper contacts the forwarder responsible for the inland transport of the containers and provides them with information about the imported container. Specifically, the shipper announces the ETA of the container and the due date when the container should be delivered at the shippers premises (3). Depending on the available intermodal services and the time criticality of the container, the shipper indicates whether truck transport, combined barge-truck or train-truck service is preferred. Before the container is transported from the seaport to the hinterland, it is cleared both by the shipping line (4) and customs (5). After that the seaport terminal changes the status of the container such that it can be picked up by inland carriers (6). customs clearance of a container may be postponed when it is transported to an inland terminal with customs facilities.

The intermodal inland carrier plans its barge or train calls at the terminal well in advance of their realization. A call at a seaport terminal is initially communicated to the terminal at least forty eight hours in advance and is updated twenty four hours in advance. At the time the barge or train call is scheduled, the inland carrier partially knows how many and which containers will be picked up. The inland carrier checks regularly with the seaport terminal whether the containers are cleared for further transport and sends the loading list of containers of the barge eight hours before the barge/train call (7). In this way, the seaport terminal can internally transport containers near the crane that will load the barge or train calling. The containers are then transported to the inland terminal, where they dwell until they are transported to the customer's premises by trucks around the due date and time. In some cases, when time is really critical or it is preferred by the customer, containers are transported via trucks from the seaport terminal directly to the customer's location.

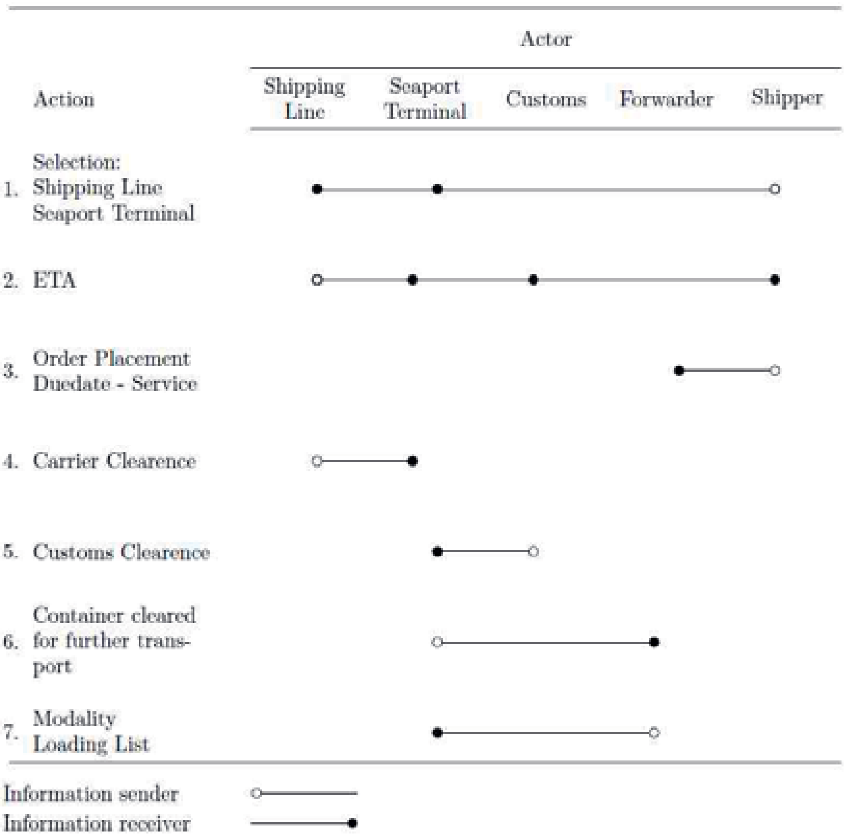


Figure 3.1: Information Flows

3.3 Candidate dwell time determinants

The determinants of container dwell times have not been extensively studied in the literature. A first study investigating this issue is done by Moini et al. (2012), who list the following determinants of container dwell times: terminal function and location; port policy and management; shipping line; truck carrier; modal split; container status; content of a container; cargo flow pattern; container security level; business connection; shipper; consignee, and Third Party Logistics company (3PL). The possible impact of these factors is qualitatively discussed, but only a few are subject to further analysis: the shipping line, truck carrier and container status. They employ data mining algorithms to search through the candidate determinants of the dwell times. Through a case study they demonstrate the importance of container dwell times in assessing the container terminal yard capacity.

In our study, we extend Moini et al. (2012) by analyzing the container dwell times at a seaport terminal destined to its hinterland and transported via a multimodal transport network consisting of waterways, rails and roads. Qualitatively we consider the same factors as suggested by Moini et al. (2012) to be relevant for explaining container dwell times, but we have on hand more data for our analysis. Specifically, in addition to the three factors available at Moini et al. (2012) analysis, we have registered for each container in our data-set the specific shipper of the container, the modality used for its transport from the seaport terminal and the inland region it was destined. Furthermore, we modeled the information flow (Fig. 3.1), among relevant actors, in parallel to the import container process and collected performance measures and timestamps of relevant events, as shown later in Fig. 3.2. Moreover, we provide a quantitative analysis of the impact effect of each factor on the development of dwell times. Our analysis points out the shipper as the main actor having control over the development of dwell times at container terminals and provides empirical evidence of the various causes of variation in container dwell times. This leads to the clustering analysis we performed on shippers.

Below we discuss the main determinants of dwell times that we consider in this study.

3.3.1 Shipper (Client)

The shipper is the owner of the contents of the container and the one to whom the containers are destined. Different shippers have different needs regarding the transport of their containers, which can affect the dwell times of containers. Some prefer the use of barge or train, possibly motivated by an interest in sustainability and cost reduction. Others prefer the timely transport of their containers and consequently prefer trucks. Moreover, each shipper organizes his supply chain differently and may or may not have an interest in the timely transport of his containers. The time criticality for the delivery of containers is inferred by three quantities: import modality, order placement and due date, as explained below.

3.3.1.1 Import modality

The import modality is the first transport mode used for further container transport to the hinterland of the port. Possible modes are truck, barge and train. The intuition of including the import modality as an explanatory factor lies in the fact that containers transported by barge or train are supposed to dwell longer at the seaport terminal, since they have to wait until the next barge or train itinerary or until several containers can be consolidated in a single barge or train itinerary. But the modal choice cannot be assumed exogenous to the process since it is performed by the shipper after considering the time criticality for final delivery and after considering the next available itinerary.

3.3.1.2 Due date

The due date indicates the time criticality for the delivery of a container and can affect container dwell times in several ways. The due date limits the dwell time from above. The time between the container discharge at the seaport terminal and the due date consists of dwell time at the seaport terminal, transportation to the inland terminal, dwell time at the inland terminal and transportation to the shipper location. Setting the due date earlier or later can impact the modal choice when considering the available transport itineraries of high capacity modes that could satisfy the time limitations.

3.3.1.3 Order placement

The time of the order placement for container transport at the forwarder can affect container dwell times in several ways. First, the time of order placement limits the container dwell time from below, since the container will definitely dwell at the seaport terminal until its further transport is booked and organized. Second, the time of the order placement for the transport of a container compared to its time criticality can affect the modal choice. The early information availability allows the forwarder to organize the transport of containers and to seek for consolidation opportunities among the collectively available orders.

3.3.2 Selection of shipping line

The shipping line is the owner of the container, and is responsible for the sea transport of the container. Every shipping line applies different demurrage and detention schemes, and implement contractual agreements with clients regarding specific details that include both the the free-periods for demurrage and detention as much as the charges that apply after the end of the free period. The demurrage and detention periods can be considered jointly or separately. These demurrage and detention schemes can affect the dwell time of containers at both the seaport and inland terminals. For example, in case demurrage and detention periods are considered separately, the shipper may opt to the maximum use of the free demurrage period at the seaport terminal before picking up the container and allowing the detention period to start.

3.3.3 Selection of inland container terminal

Containers destined for different inland terminals can have different dwell times at the seaport terminal. First, each terminal has a different connection availability. Some are tri-modal but most of them are either rail-road or barge-road terminals. So, not all modalities are always available. Second, container flows are not balanced among the terminals. Some have large flows that justify higher frequency on the inland high capacity corridors, while others are smaller and just serviced once or twice a week. Moreover, each terminal satisfies a specific collection of shippers that almost always use the same inland terminal for the handling of their containers.

3.4 Dwell time analysis

Dwell times and other performance measures analyzed and presented in this section are under our confidentiality agreements with Europe Container Terminals (ECT) and Brabant Intermodal. We apply a confidentiality factor to all time measures and change the time units (e.g. 1 day =0.83α*). By such transformation no exact performance data are shown while the validity of results remain.*

3.4.1 Case and sample

Our analysis of dwell times is based on an elaborate data set from two companies: (*i*) Europe Container Terminal (ECT) the biggest container Terminal Operator Company (TOC) in Europe, operating three deep sea terminals within the Port of Rotterdam; and (*ii*) Brabant Intermodal (BIM) a collaboration of six intermodal inland container terminals (ICT) located in the Brabant region of the Netherlands. BIM also acts as an intermodal inland carrier and provides transport services to its customers, next to the usual handling and storage services.

The data contain timestamps of milestones and specific characteristics of 15,100 imported containers that were transported from one of ECT's deep sea terminal to the Brabant region through the BIM's inland multimodal network in 2011. The containers were destined to the 102 clients of BIM through its six inland container terminals. The containers were transported by nine shipping lines.

The information and milestone timestamps gathered for this research are schematically presented in Fig. 3.2. In particular, factors like the shipping line, the inland terminal, the modality used and the shipper of the container have been registered. Moreover, timestamps of milestones, either of physical movements or of information flows between actors, have been registered. From the shipping lines, the arrival time (ATA) and departure time (ATD) of the vessel carrying the containers at the seaport terminal were recorded. Furthermore, the times that the shipping line provided the unloading list and position of containers in the vessel, to the seaport terminal and to the custom authorities were registered (*BAPLI*, *COPRAR*). For the seaport terminal, we recorded the time of discharge, when the dwell time begins, and the gate-out time, when the dwell time period ends. We also recorded the time that customs put the containers under customs hold status and the time they were released.

We recorded milestones about the inland transport of containers through Brabant Intermodal which plays a central role in the total process. BIM acts as an inland carrier, inland terminal operator and a forwarder. The time the shipper contacted BIM regarding a specific container and provided BIM with the information regarding its arrival, due date and import modality to be used, was registered. The times the containers passed through the gate of the inland terminal and their delivery at the customer's location and their empty return were also registered. Moreover, the time BIM provided the seaport container terminal with the loading list (*COPINO*) has been recorded.

3.4.2 Descriptive analysis of container dwell times

The time between the container discharge and its due date consists of dwell times at both the seaport and the inland terminals and transport times, the average distribution is shown in Fig. 3.3. This slack time starts from the container discharge at the seaport terminal and ends at the arranged due date for delivery. On average, 48.93% of the slack time was spent at the inland terminals, 45.86% at the seaport terminal, and only 4.91% for transportation.

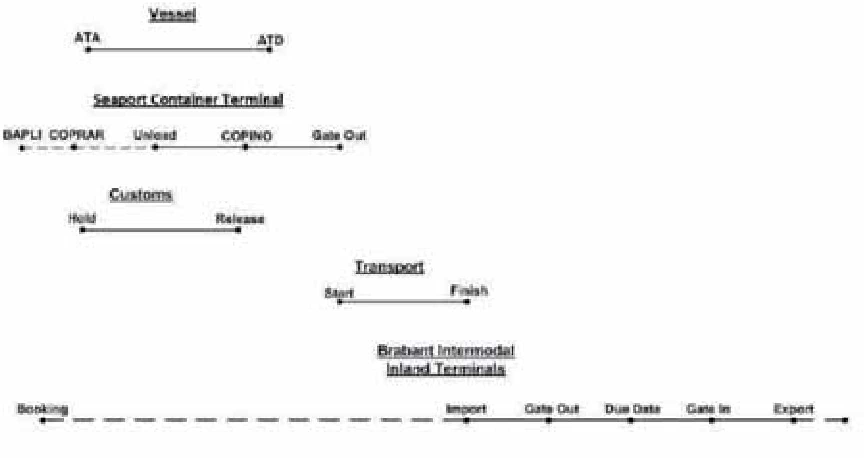


Figure 3.2: Timestamps relevant to the import container process

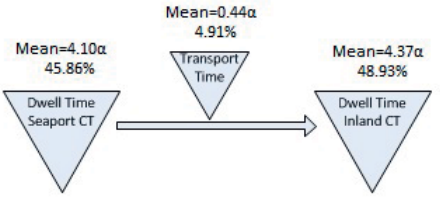


Figure 3.3: Distribution of dwell times among seaport and inland terminals

The dwell times at seaport terminals, have a skewed distribution with fat tails as shown in Fig. 3.4.a. The container dwell time statistics for both the seaport terminal and inland terminals are summarized in Tab. 3.1. There is a large variation in dwell times even though several characteristics of the general flows are controlled for this study. In particular, we only investigate full containers that are imported from a single seaport container terminal and are destined to clients located in a specific region of the Netherlands. Moreover, BIM acts for all these containers as the forwarder as well as the inland carrier.

In the previous section three possible determinants of container dwell times directly connected with the shipper were motivated: import modality, due date and time of order placement. Below we analyze these determinants using the data at hand.

Table 3.1: Dwell time Statistics

	Mean	St. Dev	Median
Dwell time Seaport Terminal	4.10α	3.93α	3.18α
Log Dwell time Seaport Terminal	1.12	1.01	1.15
Dwell time Inland Terminal	4.38α	1.89α	8.08α

3.4.2.1 Import modality

Three possible modes are available in our case, barge, train and truck; the modal split of the containers considered was 59.84%, 24.48% and 15.68%, respectively. It is obvious that BIM achieves a modal split in favor of high capacity modalities, since intermodal combined transport is its core competence. The histograms of dwell times for different modalities in Fig. 3.5 show that containers with short container dwell times, less than a day, are mainly transported by trucks, while the dwell time distributions of the different modalities are overlapping.

3.4.2.2 Time between container discharge at seaport terminal and due date at the clients location (CDDD)

The time between container discharge and due date indicates the time criticality for the delivery of a container. It can be interpreted as the available time given to BIM by its clients to fulfill their transport orders. The histograms in Fig. 3.6 show how this time is distributed over different modalities. One can infer that not all orders are satisfied by the quickest transport mode. Orders with higher slack time are satisfied through slower but more cost effective transport means. For the latter case, the inland terminal yard could be used for medium term storage instead of keeping them at the congested seaport terminal yard. Since containers are to be delivered at the specific due date set by the shipper, the container discharge to due date measure, $CDDD$, consists of the dwell times at the seaport(CDT_{ST}) and inland (CDT_{IT}) terminals enhanced by the transport times(TT) between the terminals and to the final destination (FD) plus a random time to account for possible delays on delivery.

$$CDDD = CDT_{ST} + TT_{ST-IT} + CDT_{IT} + TT_{IT-FD} \tag{3.1}$$

3.4.2.3 Time between the order placement at BIM and the container discharge at the seaport terminal (OPCD)

The time difference between the order placement at BIM and the container discharge at the seaport terminal is illustrated in Fig. 3.7, per modality. The order placement for most of the containers happens well in advance of their discharge at the seaport terminal, on average, 1.88α in advance. This early information availability allows BIM to organize the transport of containers and seek for consolidation opportunities among the collective of available orders. It is noted that this variable is related with the dwell times at the seaport terminal: when the order is placed at BIM after the discharge of the container, the dwell time cannot be less than the time between the order placement and the container discharge, $OPCD$, which is part of the total dwell time. An indicator $OPAD$ is introduced to denote whether the order placement for a container at BIM was performed prior to its discharge at a terminal or not. A distinction is made between the two cases, leading to $OPCD^{+}$, $OPCD^{-}$.

$$OPCD^{+} = \begin{cases} OPCD & if\, OPAD = 1 \\ 0 & else \end{cases} \tag{3.2}$$

$$OPCD^{-} = \begin{cases} -OPCD & if\, OPAD = 0 \\ 0 & else \end{cases} \tag{3.3}$$

3.5 Evaluation of various effects on container dwell times

In the previous sections various determinants of container dwell times were motivated and an empirical case was presented. In this section, we aim to quantitatively assess the main determinants of container dwell times at seaport terminals. First, aregression model is presented, which is used to explain the variation in container dwell times. Second, a cluster analysis of clients according to their operational performance is performed.

3.5.1 Dwell time analysis

The following model has been applied to assess the influence of various factors on container dwell times at seaport terminals:

$$\ln\left(DT_{ST}\right) = \beta_0 + \beta_1 \text{Shipper} + \beta_2 \text{Modality} + \beta_3 \text{Carrier} + \beta_4 \text{IT} + \beta_5 CDDD + \beta_6 OPCD^+ + \beta_7 OPCD^- + \beta_8 \left(OPCD^+\right)^2 + \beta_9 \left(OPCD^-\right)^2 + \beta_{10} OPAD + \varepsilon \quad (3.4)$$

Where ε is an identically independently distributed term with zero mean and variance σ^2. The natural logarithm of the dwell times is used as a dependent variable for two reasons. First, container dwell times are positively skewed. Second, the dwell times can take only positive values, that would contradict the main assumptions of an OLS model and thus the predictive power of the model.

Tab. 3.2 summarizes the results of the regression model. We tested two models with and without the quadratic terms, $(OPCD^+)^2$and $(OPCD^-)^2$. The partial F-test reveals that the quadratic terms have a significant effect ($F = 391.08$, $p = 0.01$). The model is significant and counts for almost 48% of the variation of the log dwell times at seaport terminals. All proposed variables have significant effects on the development of dwell times. The partial eta square indicators are calculated to indicate the effect sizes.

We also tested whether any second order interactions have significant effect. Based on partial F-tests, some interactions among variables appear to be jointly significant ($p < 0.001$), but since this inclusion has no additive explanatory power to our model

Table 3.2: Results OLS model on ln(Dwell Times)

	Model 1		Model 2		
Variable	F[a]	Partial Eta Square	F[a]	Partial Eta Square	Parameters
Shipping Line	5.0	.003	6.1	.004	[-0.057 , 0.477]
IT	7.3	.002	5.8	.001	[-0.664 , 0.282]
Shipper	9.7	.062	10.4	.066	[-0.581 , 1.027]
Modality	196.6	.026	211.4	.027	Truck=0 Train=0.237 Barge=0.296
OPAD	452.0.3	.029	34.5	.002	0.096
CDDD	761.7	.05	785.9	.05	0.025
$OPCD^+$	1521.2	.09	2854.5	.160	0.194
$(OPCD^+)^2$	-		867.2	.055	-0.004
$OPCD^-$	111.7	.007	92.0	.006	-0.054
$(OPCD^-)^2$	-		58.0	.004	0.002
R^2	0.453		0.484		

[a]All variables are significant at the 1% level

(the R^2 increases only slightly), these interaction terms were not finally included into the model.

As the proposed determinants are under direct control of the shipper, our analysis assesses the effect of shippers' selections on the development of dwell times at the seaport terminal. It should be noted though that some explanatory variables are not independent from each other. For example, shippers often import containers to the inland terminal located closer to their premises, while selecting the shipping line preferred. Furthermore, there seems to be some patterns that connect the modal choice with the time criticality $CDDD$, and the modal choice with the time of order placement, as illustrated in Fig. 3.6 and Fig. 3.7, respectively.

The shippers identity seems to have largest effect on the development of log dwell times, counting for 6.6% of the variability. This supports our hypothesis that shippers can influence the dwell times of their containers at the seaport terminal. Further insights into the shipper effects are given below.

The import modality follows with an effect size around 2.7%. This is consistent with the hypothesis that containers with high time criticality are mainly transported via trucks while others with less time criticality are transported via intermodal transport. A significant number of containers with relatively prompt due dates, $CDDD$, are transported via high capacity, slow modes (barge, train), while others with tardy due dates are transported by trucks. This variation, even among subjects within the same modality, may be due to the availability of itineraries around the time of booking. The latter depends on the schedule of high capacity modalities and on other characteristics like the time of booking which acts as an enabler for BIM to organize the transport of a specific container.

Regarding the shipping line and inland terminal factors, we found that their effect is statistically significant ($p < 0.001$), but that their effect size is considerably smaller than other variables, 0.4% and 0.1%, respectively.

The time of the order placement at BIM, $OPCD$, has a significant effect on the development of dwell times. Two cases are distinguished depending on whether the order placements are performed before or after the container discharge at the seaport terminal. First, an earlier booking $OPCD^-$ by α leads to 5.4% less dwell time at a decreasing rate of 0.2%. Second, a tardier booking, $OPCD^+$ seems to increase the total dwell time by 19.4%, but at a decreasing rate 0.4% per α. Note that the dwell time starts at the time of the discharge preceding the time of the order placement, and there is a high correlation between the two but at a decreasing rate. This paradox can be explained by considering that the tardier the order placement, the larger the time criticality $CDDD$ of a container to be delivered.

The time criticality of the container has a large effect on the development of dwell times. Postponing the due date by α, increases the dwell time of containers by almost 2.5%. It is clear though that when due dates are further away containers dwell more time at the inland terminals.

3.5.2 Shipper clustering analysis

Our analysis showed that the shippers are the key actors accounting for the development of dwell times. In order to illustrate the main differences among the different shippers, we classify them in groups with similar characteristics. A k-means cluster analysis is performed on the shippers based on their quantitative characteristics and performance measures. In particular, four quantitative measures were considered in the clustering of shippers: (i) mean dwell time of containers at the seaport terminal, (ii) mean dwell time of containers at the inland terminal , (iii) mean time difference between the order placement and the container discharge ($OPCD$) and, (iv) mean time difference from container discharge to its due date ($CDDD$).

The number of clusters was derived by applying the Wards method on the principal components scores and then checking the Agglomeration schedule. We performed k-means clustering for six clusters. Clients assigned to each cluster had significantly different characteristics. The results are summarized in Tab. 3.3. The clusters are organized in the table according to the mean time criticality $CDDD$ needed to transport the containers, from the left, the most time critical, to the right, the less time critical. In order to assess the significance of the clustering we performed an reggression of the log dwell times on cluster membership and achieved an R^2 equal to 11%. Moreover, modifying the initial regression model presented in section 3.5.1, by substituting the shipper identity with the cluster membership, yields a slightly smaller R^2 equal to 45%.

Clusters 1, 2 and 3 represent shippers with the highest time criticality in transporting their containers with mean time between container discharge and due date $CDDD$ equal to 5.15α, 5.51α and 7.01α. Clusters 1 and 2 seem to have similar dwell time performance in both seaport and inland terminals but there is a significant difference on how these dwell times are achieved. Cluster 1 clients place their orders at BIM on average 15.29α in advance of the discharge of their containers at the seaport terminal while those of Cluster 2 only 4.11α earlier. Though this difference does not affect significantly the dwell time of containers, it does affect the modal choice since in the latter case 22% of containers are transported by trucks compared to 4% trucking that is realized for shippers assigned to cluster 1. Shippers assigned to Cluster 3 place their order at BIM on average 1,05α after their containers are discharged at the seaport terminal. This leads to an increase in both their average container dwell time at the seaport terminal and also in the trucking percentage.

Clusters 4, 5 and 6 represent shippers with lower average time criticality in transporting their containers with mean CDDD times equal to 10.64α, 12.51α and 17.10α. Shippers assigned to Clusters 4 and 6 place their orders in advance of the discharge of their containers at the seaport terminal on average 1.88α and 0.44α, respectively and both achieve the longer dwell times at the storage yard of the inland terminals. More time availability to perform the transport in case of cluster 6 shippers leads to lower trucking which is only 4% compared to that of 16% that is realized in case of cluster 4 shippers. Shippers assigned to Cluster 5 use the seaport container yard for the storage of their containers and only place their order at BIM some days before the cargo is needed, in average 4.85α after the containers where originally physically available at the seaport terminal. The lack of information availability on BIM in order to organize the transport leads to both larger average dwell times at the seaport area and also higher trucking, averaging in 22%.

Table 3.3: Performance characteristics of clusters of clients

	Cluster					
	1	2	3	4	5	6
Dwell Time ST (α)	3.21	3.15	4.27	4,77	9.18	5.10
Dwell Time IT (α)	1.90	1.86	2.34	5.48	3.19	11.49
Order placement to container discharge (OPCD) (α)	-15.29	-4.11	1.05	-1.88	4.85	-0.44
Container discharge to due date (CDDD) (α)	5.15	5.51	7.01	10.64	12.51	17.10
Trucking Percentage	4%	22%	25%	16%	22%	4%

Moreover, the resulting clustering of shippers was analyzed together with BIM's executives such that other motivations that explain the different performances of shippers emerged. For example, clients assigned to cluster 1 import goods from distant regions, like China, and provide BIM with the information of their incoming containers as soon as their containers are loaded in the deep sea vessel. So that is what drives the early information availability for this cluster compared to the clients of cluster 2 that provide the same information some days later. Other clients like those assigned in clusters 4 and 6 usually have contracts with the shipping lines with separate *demurrage* and *detention* periods so they are motivated to fully use the free demurrage period, usually 5 days, before they allow their containers to be picked up and consecutively start the detention period.

Overall, the presented clustering shows that the time criticality for delivering the containers is the main driver of the container dwell times at both the seaport terminals and inland terminals. Moreover, the information availability at the forwarder, which in our case is BIM, can provide a shift in container dwell times from the seaport to the inland terminals, and a shift in the modal split in favor of sustainable modalities such as barges and trains.

3.5.3 Summary and discussion of results

The analysis provided in this research could lead to some measures regarding the reduction of container dwell times at seaport terminals, and also to a modal shift in favor of sustainable modes which is increasingly considered to be a major concern of seaport terminals. Since in this analysis we considered only one seaport terminal we cannot propose measures that are related with the direct operational performance of the terminals, like stacking methods, cranes capacity, customs capacity etc. On the other hand, we can discuss measures that are not in direct control of the terminals but more in control of shipping lines, inland carriers and shippers and with which terminals cooperate and may have contractual agreements. The problem owner of long dwell times is still the terminal operator for which the capacity of the terminal is determined; so the optimal measure for terminal operators would be to motivate other actors to perform towards the reduction of dwell times.

There seem to be three major observations derived from our analysis, and measures taken against them would have a significant impact on the reduction of container dwell times.

First, when demurrage and detention periods are treated separately, they seem to motivate shippers to fully use the free periods (see shippers assigned to clusters 4 and 6 in the previous section). So shipping lines should be motivated to change their policy. That could be partly enforced by container terminals by alternating their contractual agreements with shipping lines regarding the storage scheme they impose (free storage periods and storage charges after the free period).

Second, the information availability for incoming containers seems to have a great impact to both the reduction of dwell times and to a modal shift towards more sustainable modalities. This early information availability enables the forwarder to better organize the transport of containers and shorter dwell times can be achieved. So shippers should be prompt to provide this information to the inland carriers as soon as they have it available. Still there is not a clear motivation for shippers and inland carriers towards the reduction of dwell times of containers at seaport terminals apart from the charges when containers dwell longer than the free period, so maybe shorter free storage periods could act as a motivation to accelerate the import process.

Third, the observation that the time criticality for the transport of a container has a significant relationship with the dwell times of containers next to the fact that several containers had very short dwell times (less than a day for all import modalities

(Fig. 3.5)) indicates that there is not a real lower bound on the dwell times. Thus there is room for improvement for all clusters of shippers and not only the ones with high average dwell times. This is especially interesting for cases where containers are transported via combined transport through inland terminals, like our case, and there can be an straightforward shift between dwell times at seaports and inland terminals. So enhancing the connectivity of the seaport terminal with more frequent service would lead to the reduction of dwell times.

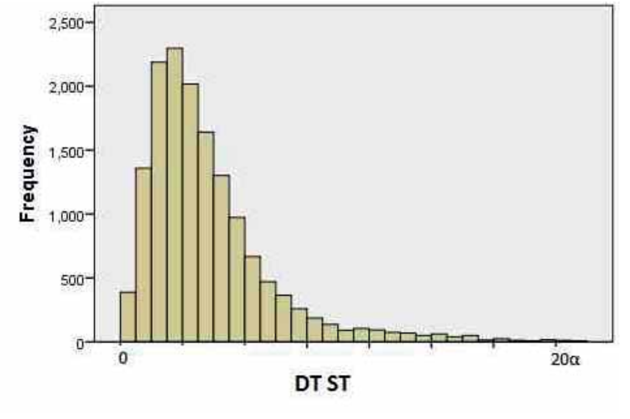
3.6 Conclusion

In the present study, we examined the factors affecting container dwell times at a major seaport container terminal. We found that there is a significant relationship between the shipper and the time their containers dwell at seaport terminals. The models proposed has considerable explanatory power on imported container dwell times, and on the different clusters of shippers. The impact of exogenous factors has been analyzed qualitatively and quantitatively.

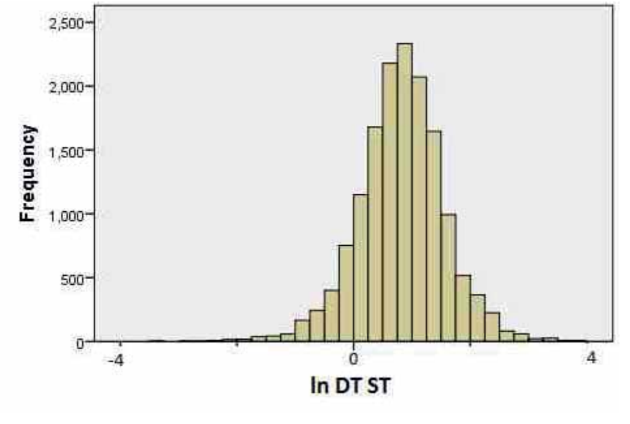
Container dwell times at seaport terminals can be shorted by a combination of improved operational performance of the terminals (e.g. automated terminals), as suggested from previous literature, and from motivating other actors relevant to the process to act towards this enhancement. Shippers, Shipping lines, Inland carriers and Inland terminal operators are relevant actors to the development of dwell times.

The analysis above seems to look at several factors relevant to the process but is not exhaustive. For example, the development of the extended gate concept in which seamless connections to inland terminals are formulated and customs and other added value activities are postponed to the inland terminals could be a relevant solution for the reduction of dwell times. Moreover, the connectivity of the seaport terminal with high capacity frequent connections could also be a step towards both the reduction of dwell times and the shift towards sustainable modalities. Unfortunately, we do not have enough data to support such a quantitative analysis.

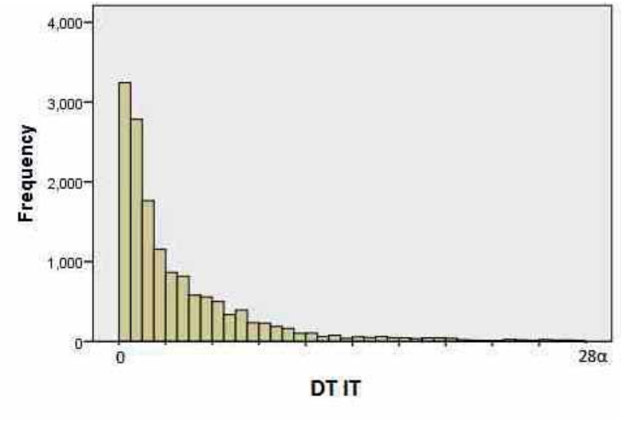
The results of this research are essential for both academics and industry. The assumption that dwell time performance can be treated as a purely endogenous capacity performance criterion of seaport terminals is challenged. Dwell times are influenced by various exogenous factors outside the control of terminals. Moreover, congested seaport terminals should incentivize shippers and other important actors involved in the process in order to achieve a significant reduction of container dwell times at seaport terminals.



(a) Dwell time at Seaport Container Terminal



(b) ln(Dwell Time) at Seaport Container terminal



(c) Dwell Time at Inland Container Terminals

Figure 3.4: Dwell time histograms

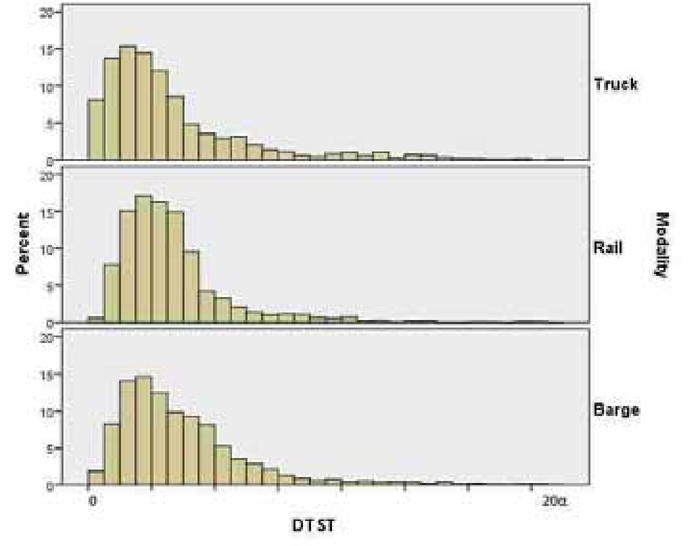


Figure 3.5: Container dwell times distributions per import modality

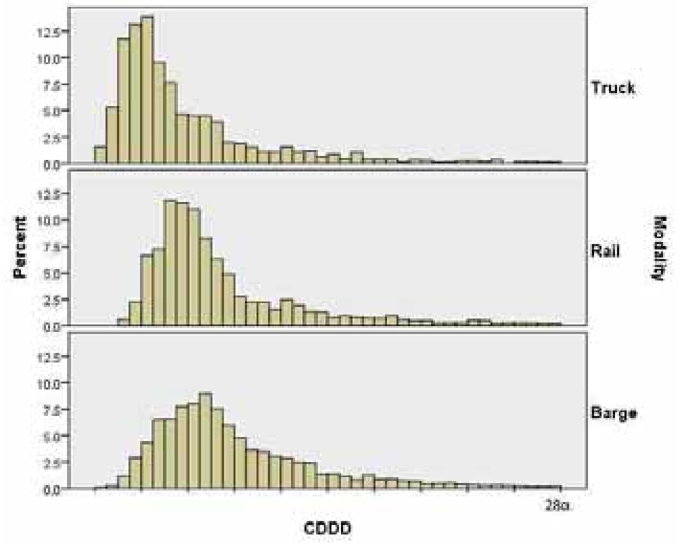


Figure 3.6: Histogram Discharge Seaport terminal to Due-date

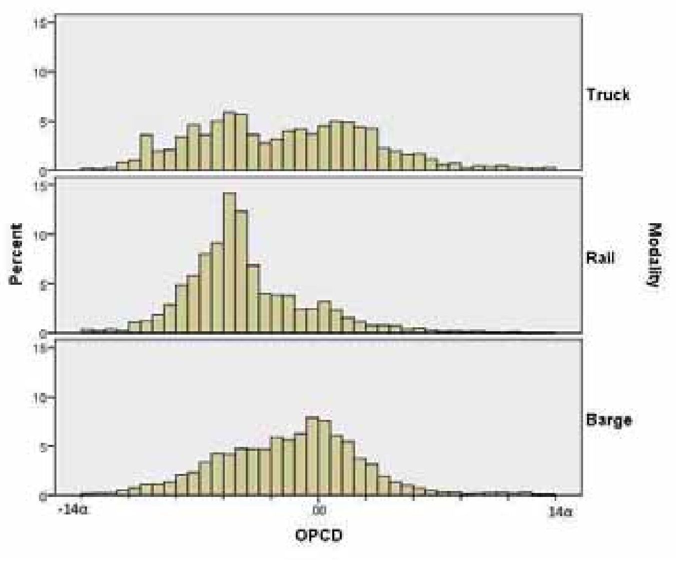


Figure 3.7: Order Placement - Container Discharge

4 Joint Design and Pricing of Intermodal Port - Hinterland Network Services: Considering Economies of Scale and Service Time Constraints

Summary: Maritime container terminal operating companies have extended their role from node operators to that of multimodal transport network operators. They have extended the gates of their seaport terminals to the gates of inland terminals in their network by means of frequent services of high capacity transport modes such as river vessels (barges) and trains. These network operators face the following three interrelated decisions: (1) determine which inland terminals act as extended gates of the seaport terminal, (2) determine capacities of the corridors, i.e. size of the transport modes and frequency of service, and (3) set the prices for the transport services on the network. We propose a bi-level programming model to jointly design and price extended gate network services for profit maximization. The network operator does so while anticipating the decisions of the customers who choose minimum cost paths to their final destinations, and who always have the option to choose direct trucking offered by the competition.

The model in this chapter extends existing bi-level models in a multimodal format by including service time constraints and economies of scale. Considering the special structure of our problem, we propose a heuristic that provides near optimal solutions to our problem in substantially less time than commercial solvers. Through experimental results in some realistic instances, we study optimal network designs while comparing seaport-to-door and seaport to inland port services and situations where transit time requirements do and do not apply. Our results show that when demand

is relatively low, there are significant differences in the optimal network designs for port-to-door versus port-to-port services. In the case of port-to-door services, the prices of services are determined through the competition and not by the design of the network, so the network is designed against minimum costs, and economies of scale are achieved by consolidating flows through a limited number of extended gates. The case of port-to-port services is different, i.e. revenues are enhanced not so much by reducing costs through the exploitation of economies of scale, but by exploiting the possibilities to dedicate extended gates to market segments for which the competition leaves room for higher port-to-port tariffs.

4.1 Introduction

Maritime container terminal operating companies around the globe have recently started to actively participate in land-side transport networks to enhance their connectivity to destinations inland while relieving some of the negative effects of freight transportation. Container terminal operators have done so by extending their role from node operators to that of multimodal transport network operators. They have extended the gates of their seaport terminals to the gates of inland terminals in their network by means of frequent services of high capacity transport modes such as river vessels (barges) and trains. Moreover, customs clearance and other added value activities can be postponed until the containers leave the inland terminal gates instead of the seaport terminal gates (Veenstra et al., 2012). The operator of this network of transport connections between deep sea ports and inland terminals is referred to as extended gate operator, and we will use this term from now on. The extended gate operator at the tactical design of the land-side transport network faces the following three decisions: (1) determine which inland terminals act as extended gates of the seaport terminal, (2) determine capacities of corridors, size of the transport modes and frequency of service, and (3) set the prices for the transport services on the network. The three decisions are interrelated, because inland terminals are located in relatively close distances, usually close to industrial regions, so the hinterland of inland terminals is contestable. Thus, the network operator could connect the seaport terminal either to a limited number of inland terminals while using high frequent and high capacity transport services, or it could connect with more inland terminals while using less frequent services or lower capacity transport means. The price per TEU at each corridor should make the routing of all containers through that corridor cost effective compared to the service provided by the competition. It follows that, when an extended gate is meant to attract demand destined to regions other than its captive hinterland, for flow consolidation purposes, the price setting at its corresponding corridor should be low enough to make the path to the distant regions also cost effective. This reduction in the prices would affect also the revenues the extended gate operators receive from clients located in the captive hinterland of the extended gate.

Port-Hinterland intermodal transportation is usually referred to in the literature as combined transport (Frémont and Franc, 2010), so this term will be used throughout this chapter, and can take either the rail-road or waterway-road scheme indicating that usually the end haulage trip is performed by trucks. The international shipping of containers can be organized either under merchant haulage or under carrier haulage. Port - hinterland transport of containers can also be offered under the so called terminal operator haulage (Notteboom, 2008). In the latter case, transport services are offered either as port-to-port services or port-to-door services. In case of port-to-door services, the terminal operator, that acts as an extended gate operator, orchestrates the transport of containers from the port to their final destination, while under port-to-port services he only offers transport from the seaport terminal to inland terminals. In other words, under port-to-door service the extended gate operator is assumed to control all links and nodes over the inland network while under port-to-port service it controls only flows on the high capacity corridors while the remaining is outsourced to competition. Under port-to-port service the prices should be set low enough such that they make the combined transport path, via the extended gates, at least cost neutral to the best alternative service offered by the competition (Roso and Lumsden, 2010) for all containers routed through it. In this setting, the design of the inland transport network and the pricing scheme are interrelated. On the contrary, under port-to-door service the price of transport from seaport to final destination mainly depends on the best alternative transport service offered by the competition and does not depend on the routing of the containers through the network since it is assumed that also the end haulage legs performed by trucks are offered by the extended gate operator. Thus for port-to-door services pricing and network design decisions do not have to be considered jointly. The term competition is used to denote other intermodal carriers or trucking companies that can offer alternative transport solutions to shippers than the ones offered by the extended gate operator. The last leg of transport is usually performed by trucking companies who also benefit from the use of the extended gate concept since congested roads to seaport terminals are avoided. While the pick up and drop off of containers is performed at the inland terminals, the above can sufficiently increase the number of trips they can perform per day.

The profitability of the extended gate operator, apart from the pricing, also depends on the cost of delivering the network services, where the effective utilization of high capacity transport means provides the opportunity for economies of scale. Moreover, higher frequency of transport services reduces the average throughput times of containers which enlarges the market potential for such services. The trade-off between customer demand characteristics and carrier strategies should be considered, as it is supposed to lead to the development of a variety of possible inland container routing patterns (Notteboom, 2008). Finally, consolidation helps to hedge against demand uncertainty (Lium et al., 2009).

In this chapter, we propose a model to jointly design and price extended gate network services to reap possible benefits. We contribute to the existing body of knowledge by extending joint design and pricing bi-level formulations, as proposed by (Brotcorne et al., 2005, Brotcorne et al., 2008), to fit the port-hinterland multimodal network design by including service time constraints and high capacity modalities. Considering the special structure of our problem we propose a heuristic that provides near optimal solutions to our problem in substantially less time than it takes CPLEX to solve the MIP equivalent formulation of our problem. Finally, through experimental results in some realistic instances we analyze the optimal network configurations under service type, demand and service time scenarios. Our results show that when demand is relatively low, which can be the case for several inland regions, there is a significant difference in the optimal network configuration between considering port-to-port and port-to-door services. Moreover, the consideration of service time constraints in tactical network design shows that demand penetration through frequent services has a larger effect than achieving economies of scale through the use of larger barges.

4.2 Theoretical background in joint design and pricing of networks

In addition to the the literature review presented in Chapter 2 of this thesis, which focused on general and port-hinterland intemodal network design literature, in this section we review contributions on the joint design and pricing of transportation services which is the core modelling technique in this chapter. Our view of the problem on hand is that the extended gate operator aims at optimizing the design of his hinterland network while anticipating the routing decisions by the shippers of containers. Shippers can route their containers via links controlled by the extended gate operator or by its competitors or by a combination. Bi-level formulations of the network design problem capture the decisions of these three different actors involved.

The joint design and pricing of transportation networks is mainly modeled by bi-level mathematical models. Bi-level models are seen as a static version of the non-cooperative Stackelberg game. Most of them have in common that they try to maximize the revenues of an actor that is considered to be the leader and controls a set of arcs and nodes of the network while minimizing the total cost faced by the users of the network. These features are in line with our view of an extended gate operator that endeavors to maximize his profitability by attracting flows through his network. The proposed network design must add value to the shippers by reducing their total cost. The main assumption of such formulations is that the competitors do not react to the final configuration proposed by the leader of the network. Due to the difficulties that arise when solving such formulations, which are proven to be NP-hard even in the simplest linear case, most papers focus on alternative modeling formulations of the problem and on the development of novel solution procedures. Contributions with managerial relevance in the sense of what is the impact of considering joint design and pricing in a network are yet limited.

Brotcorne et al. (2000) introduce the freight tariff setting problem in which the objective is to maximize the revenues of a carrier who controls a set of arcs of the network, by setting the tariffs for using these arcs, while the flows over the network are determined in the second level minimizing the total transport cost faced by the users of the network. This is the simplest formulation since all terms are assumed to be continuous. The authors develop the single level equivalent bi-linear formulation of the problem with disjoint constraints, and solve it with heuristics based on the primal-dual heuristic proposed by Gendreau et al. (1996). Brotcorne et al. (2001) extend their previous work by considering a multicommodity network in which the leader maximizes his revenues by setting the tolls on the set of arcs he controls. In this setting, again a primal-dual based heuristic is used with an extension that forces tolls applied for each commodity to be equal.Moreover an arc sequential heuristic is proposed.

Brotcorne et al. (2005) further extend their previous model by considering the joint pricing and capacity setting problem in a multicommodity transportation network.

This problem is formulated as a mixed integer bi-level program and is again solved by using a primal-dual based heuristic. This model incorporates the tradeoffs between revenue and cost generated for the leader when designing his network. The paper states that until then these issues were treated separately although they are intrinsically linked and should be treated jointly. The economies of scale principle is assumed to be satisfied by assuming the marginal cost of increasing capacity to be decreasing. In Brotcorne et al. (2008) the authors consider the joint design and pricing of a network by assuming that investment fixed cost apply to the leader for operating arcs over the network. This case is formulated as a mixed integer bi-level program with binary decision variables indicating whether or not an arc is used in a multicommodity transportation network. A novel heuristic based on Lagrangian relaxation is applied to incorporate the binary design variables in the solution method. An exact algorithm for solving the pricing problems on a network by partially and efficiently generating candidate solutions is presented in Brotcorne et al. (2011), while a tabu search algorithm is presented in Brotcorne et al. (2012).

To the best of our knowledge, only a few bi-level formulations of the intermodal network design problem exist in the literature. Crevier et al. (2012) propose a path based bi-level formulation of the rail-road integrated operations planning and revenue management problem, at an operational level, while proposing some exact algorithms for its solution. The pricing of services depends on the prices set by the competition for the different service levels while the capacities of the corridors are obtained by solving a service network design model at the tactical level.

The joint design and pricing of an intermodal network has been addressed also in other than bi-level programming formats. Li and Tayur (2005) jointly design and price an intermodal network by using a traditional marketing research approach for the pricing part. In this approach, a customer chooses an intermodal service based on its expected service level and is charged based on the best alternative transport solution cost which provides the same service level. The paradox of this approach is that customers with different service level characteristics pay different prices while experiencing the same service level. So the pricing with the design gets disconnected.

4.3 Modeling

The extended gate operator aims to design the capacities, frequencies, and prices of combined transport services on its network in such a way that profits are maximized.

Table 4.1: Notation of sets

$i \in \mathcal{N}$	Nodes
$(i,j) \in \mathcal{A}$	Arcs on the network, $\mathcal{A} = \mathcal{A}_1 \cup \mathcal{A}_2$
$(i,j) \in \mathcal{A}_1$	Arcs on the network controlled by the network operator
$(i,j) \in \mathcal{A}_2$	Arcs on the network controlled by competition
$c \in C$	Commodities
$b \in B$	Set of Barges
$r \in R = \{1,2,3,..\}$	Barge round trip

He does so while anticipating the decisions of the customers who choose minimum cost paths to their final destinations, possibly under service time related constraints.

We model the extended gate operator as a Stackelberg leader, followed by its customers. We formulate the above situation as a bi-level mathematical program where on the first level, the extended gate operator maximizes its profits which are given by the revenue of the extended gate services minus the fixed and variable costs of operating the extended gates. On the second level, the collective of customers minimizes the total system cost which consist of transportation cost and handling charges at the container terminals. The total network consists of links and nodes controlled either by the extended gate operator or by the competition. In particular, each hinterland destination can also be served by a direct trucking option offered by the competition. Therefore, prices set by the extended gate operator are always constrained by a competitive price from above. The model formulation extends the one proposed by Brotcorne et al. (2008) in a multimodal format by the consideration of economies of scale when assigning high capacity modalities to corridors and by the formulation of connection frequency dependent service times.

4.3.1 Notation

Let us consider an underlying network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ with node set $\mathcal{N}$ and arc set $\mathcal{A}$. We assume that a node can be a supply, demand or a transhipment node in case it represents a deep sea terminal, client, and inland terminal, respectively. The set of arcs $\mathcal{A}$ is partitioned in two subsets; the set $\mathcal{A}_1$ which represents the candidate corridors to extended gates which are controlled by the leader and the set $\mathcal{A}_2$ which represents all remaining arcs which are controlled by the competition.

Table 4.2: Characteristics of commodities

O^c	Origin of commodity c, $O^c \in \mathcal{N}$
D^c	Destination of commodity c $D^c \in \mathcal{N}$
t^c	Maximum expected service time of commodity $c \in C$
f_{ij}^c	Minimum frequency of commodity $c \in C$ on corridor $(i,j) \in \mathcal{A}_1$
d^c	Expected demand in TEUs of commodity $c \in C$

4.3.1.1 Commodities

We consider a multicommodity formulation of the problem in which each commodity, $c \in \mathcal{C}$, represents a share of the weekly container demand for a specific origin and destination (OD) pair, $(O^c, D^c) \in \mathcal{N} \times \mathcal{N}$, under some service time requirement. The demand volume of a commodity c expressed in TEUs is denoted by d^c, and represents the level of demand for both inbound and outbound flows regardless of whether the containers are full or empty. In reality, some empty containers dwell at the inland terminals until some demand for export containers is generated so they are full also on their return trip. Usually, there exist weight and balance constraints for the loading of containers on barges and trains but such issues are addressed at an operational level and are out of the scope of this study. The desired service level is assumed to be expressed either as an upper bound for the expected service time, t^c, or as a minimum weekly frequency constraint, f_{ij}^c for all $(i,j) \in \mathcal{A}_1$, for the combined transport services. Considering the above demand formulation, we aim at analyzing the market penetration of combined services compared to direct transport based on the service frequency of high capacity modalities. The demand data requirements for the model can be derived by analyzing historical data or by having experts in the field approximating them.

To facilitate our modeling, we use:

$$d_j^c = \begin{cases} d^c, & j = D^c \\ -d^c, & j = O^c \\ 0, & otherwise \end{cases} .$$

4.3.1.2 Costs

We assume that cost of transport operated by the competition is linear in volume. The transport cost per unit (TEU) on an arc is denoted by C_{ij} for all $(i,j) \in \mathcal{A}_2$ and

Table 4.3: Cost and Capacity Parameters

C_{ij}	Trucking cost per TEU for traveling link $(i, j) \in \mathcal{A}$
H_{ij}	Handling cost per TEU for traveling link $(i, j) \in \mathcal{A}$
Q^b	Capacity in TEUs of barge $b \in \mathcal{B}$
w^b :	Weekly cost for leasing barge $b \in \mathcal{B}$
v^b_{ij}	Variable cost of barge $b \in \mathcal{B}$ traveling in arc $(i, j) \in \mathcal{A}_1$
n^b_{ij}	Maximum number of round trips of barge $b \in \mathcal{B}$ in arc $(i, j) \in \mathcal{A}_1$per time horizon

the container handling charges at the transhipment nodes are also linear in volume and denoted by H_{ij} for all $(i, j) \in \mathcal{A}_1 \bigcup \mathcal{A}_2$. The handling cost applies to all arcs since every arc starts or ends at a seaport or inland terminal; the main difference between combined and road transport is that in the former handling charges are applied twice both at the seaport and the inland terminal compared to just the seaport handling charges that apply in the latter.

We consider a set of barges, $b \in \mathcal{B}$, with different cost and capacity characteristics. The cost of operating barges, from a barge operator's perspective, consists of several components, such as assets, crew, fuel, and maintenance (Braekers et al., 2012). The cost faced by the extended gate operator, assuming that it does not use its own barges, is the price scheme proposed by barge operating companies which consists of the above costs enhanced by a profit margin for the barge operator. The leasing cost of a barge for a week is denoted by w^b for all $b \in \mathcal{B}$ which includes both asset and staff cost required to navigate and operate the barges. Economies of scale apply in this leasing cost when higher capacity barges are selected; crew cost for barge navigation and operation are concave in the capacity of the barge. A variable cost per round trip, v^b_{ij} for all $(i, j) \in \mathcal{A}_1, b \in \mathcal{B}$, is also considered to represent the fuel cost of barges which is assumed to be linear to distance traveled but variable to the size (capacity), Q^b, of the barge. The number of round trips per time horizon that a barge can perform to an extended gate, n^b_{ij} for all $(i, j) \in \mathcal{A}_1, b \in \mathcal{B}$ is bounded from above by physical and technical characteristics like the distances traveled, sailing speed, handling times on seaport and inland terminals, and delays.

4.3.1.3 Decision variables

At the first level, the extended gate operator designs and prices its services. First, the prices T_{ij} for all $(i, j) \in \mathcal{A}_1$ are modeled as the price per TEU transferred

Table 4.4: Decision variables

T_{ij}	Price per TEU for traveling on arc $(i,j) \in \mathcal{A}_1$
u_{ij}^b	Number of barges, $b \in \mathcal{B}$, assigned to corridor $(i,j) \in \mathcal{A}_1$
y_{ij}^b	Number of shuttle services performed per barge $b \in \mathcal{B}$ on corridor $(i,j) \in \mathcal{A}_1$
y_{ij}	Frequency of services on corridor $(i,j) \in \mathcal{A}_1$
$\tilde{y}_{ij}^c \in 0,1$	Denoting whether commodity $c \in \mathcal{C}$ can be routed through link $(i,j) \in \mathcal{A}_1$ with respect to the time constraints.
Y_{ij}^c	Amount of TEUs of commodity $c \in \mathcal{C}$ assigned in arc $(i,j) \in \mathcal{A}_1$
X_{ij}^c	Amount of TEUs of commodity $c \in \mathcal{C}$ assigned in arc $(i,j) \in \mathcal{A}_2$
t_{ij}^d	Frequency delays, inversely proportional to the connection's frequency on arc $(i,j) \in \mathcal{A}_1$

through a corridor to and from an extended gate. This decision variable determines the revenue for the extended gate operator at the first level and part of the cost faced by the shippers at the second level. Second, the design variables u_{ij}^b for all $(i,j) \in \mathcal{A}_1, b \in \mathcal{B}$ denote the number of barges of type b that are assigned to each extended gate. The integer design variables y_{ij}^b for all $(i,j) \in \mathcal{A}_1, b \in \mathcal{B}$ denote the number of trips a barge of type b will perform at corridor (i,j), and y_{ij} for all $(i,j) \in \mathcal{A}_1$ denote the frequency of service on the candidate extended gate corridors. We also introduce the auxiliary Boolean variable $\tilde{y}_{ij}^c$ for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$ that denotes whether commodity c can be routed through link $(i,j) \in \mathcal{A}_1$ with respect to the time constraints. On the second level, the collective of customers chooses the minimum cost paths to transport their containers by deciding on the flow variables, Y_{ij}^c for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$ and X_{ij}^c for all $(i,j) \in \mathcal{A}_2, c \in \mathcal{C}$ which denote the amount of TEUs assigned to each arc of the network.

4.3.1.4 Time parameters

We assume the transport times, t_{ij}^b for all $(i,j) \in \mathcal{A}_1, b \in \mathcal{B}$ and t_{ij}^t for all $(i,j) \in \mathcal{A}_2$ for barges and trucks respectively. The expected dwell time of containers at seaport terminals is assumed to consist of two components. First, a customs delay t_{ij}^n for all $(i,j) \in \mathcal{A}_1 \bigcup \mathcal{A}_2$ that would be the average time it takes for a container to be released by customs so that containers could leave the seaport terminal. Under the extended gate concept, containers are transported to the inland terminals under the customs license of the extended gate operator so these customs delays are considerably

Table 4.5: Time Parameters

t_{ij}^b	Transportation time of barge $b \in \mathcal{B}$ traveling on arc $(i,j) \in \mathcal{A}_1$
t_{ij}^t	Transportation time of trucks traveling on arc $(i,j) \in \mathcal{A}_2$
t_{ij}^n	Customs delay associated with travelling on arc $(i,j) \in \mathcal{A}_1 \bigcup \mathcal{A}_2$

lower than the ones realized by direct trucking. Second, the frequency delays t_{ij}^d for all $(i,j) \in \mathcal{A}_1$ which are assumed to be inversely proportional to the connection's frequency and can be calculated by $t_{ij}^d = \frac{1}{2y_{ij}}$. The frequency delays represent the expected time a container would have to dwell at the seaport terminal until the next barge itinerary would depart. For arcs served by trucks infinite frequency is assumed and thus zero frequency delays are considered for direct truck transport. The frequency of connections is a design variable in our model and thus the service time of combined transport is also a design variable that determines the market penetration of combined services.

The parameter M represents a relatively large value for which we assume that $M \geq \sum_{c \in \mathcal{C}} d^c$.

4.3.2 The model

In this section the mathematical formulation of our bilevel model is presented.

4.3.2.1 First level (FL)

$$FL: \max_{T,Y,u,y} \sum_{c \in \mathcal{C}} \sum_{(i,j) \in \mathcal{A}_1} T_{ij} Y_{ij}^c - \sum_{b \in \mathcal{B}} \sum_{(i,j) \in \mathcal{A}_1} w^b u_{ij}^b - \sum_{b \in \mathcal{B}} \sum_{(i,j) \in \mathcal{A}_1} v_{ij}^b y_{ij}^b \tag{4.1}$$

$$\sum_{c \in \mathcal{C}} Y_{ij}^c \leq \sum_{b \in \mathcal{B}} Q^b y_{ij}^b \qquad \forall (i,j) \in \mathcal{A}_1 \tag{4.2}$$

$$y_{ij}^b \leq n_{ij}^b u_{ij}^b \qquad \forall (i,j) \in \mathcal{A}_1, b \in \mathcal{B} \tag{4.3}$$

$$y_{ij} = \sum_{b \in \mathcal{B}} y_{ij}^{b} \qquad \forall\, (i,j) \in \mathcal{A}_1 \tag{4.4}$$

$$\tilde{y}_{O^c k}^{c} \leq 2 \cdot \left(t^c - t_{O^c k}^{n} - t_{O^c k}^{b} - t_{kD^c}^{t}\right) \cdot y_{O^c k} \qquad \forall\, (O^c, k) \in \mathcal{A}_1, c \in \mathcal{C} \tag{4.5}$$

$$Y_{ij}^{c} \leq \tilde{y}_{ij}^{c} M \qquad \forall\, (i,j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{4.6}$$

$$\tilde{y}_{ij}^{c} \in \{0,1\} \qquad \forall\, (i,j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{4.7}$$

$$y_{ij} \in \mathbb{N}^0 \qquad \forall\, (i,j) \in \mathcal{A}_1 \tag{4.8}$$

$$u_{ij}^{b} \in \mathbb{N}^0 \qquad \forall\, (i,j) \in \mathcal{A}_1, b \in \mathcal{B} \tag{4.9}$$

The first level objective (4.1) represents the profits of the extended gate operator and consists of the revenue from the extended gate services diminished by the cost of operating the extended gate corridors. The capacity constraints are given in (4.2) which guarantee that the sum of the flows in each corridor is less than its capacity. Constraints (4.3) and (4.4) determine the service frequency in a corridor when several barges are assigned to it. Service time constraints are introduced in (4.5) and (4.6) that guarantee that the expected service time for each commodity should be less or equal than its desired service time, t^c. It should be noted that in order to obtain a feasible solution it should hold that $t^c \geq t_{O^c D^c}^{n} + t_{O^c D^c}^{t}$ for all $c \in \mathcal{C}$; that is that the time restriction set by each commodity can always be satisfied by the quickest path, which is direct trucking.

Constraints (4.5) are the linear equivalent of constraint (4.10) in which the left hand side expresses the expected service time for combined transport while the right hand side is the desired level of service time as expressed by the shippers for each commodity.

$$\tilde{y}^c_{O^c k}\left(\frac{1}{2y_{O^c k}} + t^n_{O^c k} + t^b_{O^c k} + t^t_{kD^c}\right) \leq t^c \qquad \forall\,(O^c,k)\in\mathcal{A}_1,(k,D^c)\in\mathcal{A}_2,c\in C \quad (4.10)$$

The service time constraints could also be expressed as a minimum frequency at each corridor, f^c_{ij}, so in that case constraints (4.5) should be substituted by constraint (4.11). The minimum frequency requirements f^c_{ij} can be derived from the desired service time t^c according to $f^c_{ij} = \left\lceil \frac{1}{2\cdot\left(t^c - t^n_{O^c k} - t^b_{O^c k} - t^t_{kD^c}\right)} \right\rceil \quad \forall\,(O^c,k)\in\mathcal{A}_1,(k,D^c)\in\mathcal{A}_2,c\in C$.

$$f^c_{ik}\tilde{y}^c_{ik} \leq y_{ik} \qquad \forall\,(i,k)\in\mathcal{A}_1,c\in\mathcal{C} \quad (4.11)$$

4.3.2.2 Second level (SL)

$$SL:\ \min_{X,Y} \sum_{ij\in\mathcal{A}_1}(T_{ij}+H_{ij})\sum_{c\in\mathcal{C}}Y^c_{ij} + \sum_{ij\in\mathcal{A}_2}(C_{ij}+H_{ij})\sum_{c\in\mathcal{C}}X^c_{ij} \quad (4.12)$$

$$\sum_{i\in\mathcal{N}}\left(Y^c_{ij}+X^c_{ij}\right) - \sum_{i\in\mathcal{N}}\left(Y^c_{ji}+X^c_{ji}\right) = d^c_j \qquad \forall j\in\mathcal{N},c\in\mathcal{C} \quad (4.13)$$

$$X^c_{ij},Y^c_{ij} \geq 0 \qquad \forall\,(i,j)\in\mathcal{A}_1,\mathcal{A}_2,c\in\mathcal{C} \quad (4.14)$$

The second objective (4.12) minimizes the total system cost. This cost consists of transport cost in arcs controlled both by the extended gate operator (what is seen as revenue for the leader is seen as cost for the follower) and by the competition, and of the container handling charges on both seaport and inland terminals. Constraints (4.13) are the flow conservation constraints.

4.3.2.3 Moving constraints to the upper Level

In general bi-level programs, constraints that contain decision variables of both the first and second level should apply at the second level. Moving such constraints between the levels changes both the feasible region and the optimal solutions of the problem. So both capacity constraints (4.2) and minimum frequency constraints (4.6) should originally apply at the second level.

Brotcorne et al. (2008) showed, for the general case, that a problem P2 where capacity constraints apply on the upper level is a restriction of an equivalent problem P1 where the same constraints apply on the lower level but it is a special feature of joint design and pricing class of problems that the optimal solution is not affected by this operation.

In particular she showed that general capacity constraints with $A \cdot x \leq b$ format, that could result for given design vectors, can be freely moved from one level to the other. Both our capacity constraints $\sum\limits_{c \in \mathcal{C}} Y_{ij}^c \leq \sum\limits_{b \in \mathcal{B}} Q^b y_{ij}^b$, and minimum frequency constraints $Y_{ij}^c \leq \tilde{y}_{ij}^c M$, can take the above format with the appropriate A and b vectors, when the design parameters y_{ij}^b and $\tilde{y}_{ij}^c$ are given. So the corollary 1 given by Brotcorne et al. (2008) will also hold for this case and the sets of constraints (4.2) and (4.6) can be moved to the upper level, without affecting the optimal solution space.

4.3.3 MIP equivalent formulation (MIP_EQ)

In this section, we define the MIP equivalent formulation of our problem in order to be able to solve to optimality instances of our problem using commercial solvers like CPLEX. The difficulty in solving this problem lies in the bi-level structure of our model and in the bi-linear term, $T_{ij} Y_{ij}^c$, in the objectives. The bi-linear term in the objective is usually eliminated by the use of its complementarity slackness constraints while the second level objective is replaced by its primal dual optimality conditions (Brotcorne et al. 2008, 2005). This approach in addition to the constraints that force the equality of the primal and dual lower level objectives restricts every commodity to be routed exclusively through its minimum cost path. The above may be sufficient if one considers the uncapacitated version of the problem, where routing through the minimum cost path always provides the optimal solution for both the upper and lower levels of the problem, but can have significant impact when capacities over the arcs of the network are considered. In the latter case, the flows of a commodity might be routed through several paths either controlled by the extended gate operator or by the competition if the total flows on a corridor exceed its capacity. Flows of containers are attracted to corridors controlled by the extended gate operator when they result in path cost lower or equal to the minimum cost path offered by the competition.

We propose an alternative approach to address the problems arising by the bi-linear term in the objective, in which we obtain a linear equivalent formulation of this term. In our case, every port-to-door path can go through at most one tariff arc controlled by the extended gate operator. This simplifies the pricing scheme, since prices in different corridors do not interact. So we introduce the equilibrium level of the prices, γ_{ij}^c for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$, that would make the routing of a commodity through a corridor economically effective. Setting the price at a corridor above or below that equilibrium level would prohibit or allow the flow of the corresponding commodity through that corridor. These levels of prices should make the combined transport path cost neutral to the tariff free path offered by the competition, and we can obtain them according to $\gamma_{O^cj}^c + H_{O^cj} + C_{jD^c} + H_{jD^c} = C_{O^cD^c} + H_{O^cj}$ for all $(O^c, j) \in A_1, c \in \mathcal{C}$. The γ_{ij}^c takes both positive and negative values but of course the optimal price at a corridor, T_{ij}, will take positive values such that revenues will be generated and will take the value of the equilibrium level of the price for some commodity. The auxiliary Boolean variable, β_{ij}^c for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$, denotes which exactly equivalent level of price of commodities will be the price at each corridor such that $T_{ij}Y_{ij}^c = \gamma_{ij}^e \beta_{ij}^e Y_{ij}^c$ for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}, e \in \mathcal{C}$. The new formulation of the revenues is still bi-linear, since it is the product of Boolean and continuous variables, but such a bi-linearity can be easily linearized by the introduction of a continuous variable, $\delta_{ij}^{c,e} = \beta_{ij}^e Y_{ij}^c$ for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}, e \in \mathcal{C}$ and the set of constraints (4.16) – (4.20).

We substitute the second level (SL) problem with its optimality conditions (4.21) – (4.26). For this purpose some additional notation is used. The auxiliary Boolean variables $\tilde{Y}_{ij}^c$ for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$ and $\tilde{X}_{ij}^c$ for all $(i,j) \in \mathcal{A}_2, c \in \mathcal{C}$ denotes whether flows from commodity c can be routed through the associated links with respect to the total cost of the path they belong to. The price per commodity and arc is denoted by T_{ij}^c for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$ and is restricted to take the same value for containers routed through the same corridor by constraints (4.24) – (4.25). Constraints (4.23) impose that flows can be routed through a corridor controlled by the leader only if they result in path cost lower than the one offered by the competition; that means

Table 4.6: Additional decision variables for MIP formulation

γ_{ij}^{c}	Equilibrium level of prices that make cost effective the routing of commodity $c \in \mathcal{C}$ through arc $(i,j) \in \mathcal{A}_1$
$\beta_{ij}^{c} \in 0,1$	Denotes which price level will be assigned on arc $(i,j) \in \mathcal{A}_1$.
$\delta_{ij}^{c,e}$	Denotes the flow of commodity $c \in \mathcal{C}$ on arc $(i,j) \in \mathcal{A}_1$ under the equilibrium level of price of commodity $e \in \mathcal{C}$ on arc $(i,j) \in \mathcal{A}_1$
$\tilde{Y}_{ij}^{c} \in 0,1$	Denotes whether flows from commodity $c \in \mathcal{C}$ can be routed through arc $(i,j) \in \mathcal{A}_1$ with respect to the total cost
$\tilde{X}_{ij}^{c} \in 0,1$	Denotes whether flows from commodity $c \in \mathcal{C}$ can be routed through arc $(i,j) \in \mathcal{A}_2$ with respect to the total cost
T_{ij}^{c}	Price per TEU of commodity $c \in \mathcal{C}$ traveling on arc $(i,j) \in \mathcal{A}_1$

that the total system cost is decreased when flows go through the corridors and thus the lower level objective is satisfied.

The capacity (4.2), frequency (4.3) and (4.4), service time (4.5) and (4.6), feasibility (4.7) – (4.9) and (4.14), and flow conservation (4.13) constraints that apply in the original model should also apply in this model.

$$MIP\_EQ: \max_{T,X,Y,u,y,\beta,\delta} \sum_{e\in\mathcal{C}} \sum_{c\in\mathcal{C}} \sum_{(i,j)\in\mathcal{A}_1} \gamma_{ij}^{c} \delta_{ij}^{c,e} - \sum_{b\in\mathcal{B}} \sum_{(i,j)\in\mathcal{A}_1} w^{b} u_{ij}^{b} - \sum_{b\in\mathcal{B}} \sum_{(i,j)\in\mathcal{A}_1} v_{ij}^{b} y_{ij}^{b} \quad (4.15)$$

$$\delta_{ij}^{c,e} \leq M\beta_{ij}^{e} \qquad \forall (i,j) \in \mathcal{A}_1, c, e \in \mathcal{C} \quad (4.16)$$

$$\delta_{ij}^{c,e} \leq Y_{ij}^{c} \qquad \forall (i,j) \in \mathcal{A}_1, c, e \in \mathcal{C} \quad (4.17)$$

$$\delta_{ij}^{c,e} \geq Y_{ij}^{c} - M\left(1 - \beta_{ij}^{e}\right) \qquad \forall\, (i,j) \in \mathcal{A}_1, c, e \in \mathcal{C} \tag{4.18}$$

$$T_{ij} = \sum_{c \in \mathcal{C}} \gamma_{ij}^{c} \beta_{ij}^{c} \qquad \forall\, (i,j) \in \mathcal{A}_1 \tag{4.19}$$

$$\sum_{c \in \mathcal{C}} \beta_{ij}^{c} \leq 1 \qquad \forall\, (i,j) \in \mathcal{A}_1 \tag{4.20}$$

$$Y_{ij}^{c} \leq M \cdot \tilde{Y}_{ij}^{c} \qquad \forall\, (i,j) \in \mathcal{A}_1 \tag{4.21}$$

$$X_{ij}^{c} \leq M \cdot \tilde{X}_{ij}^{c} \qquad \forall\, (i,j) \in \mathcal{A}_2 \tag{4.22}$$

$$T_{O^c j}^{c} + H_{O^c j} \tilde{Y}_{O^c j}^{c} + \left(C_{jD^c} + H_{jD^c}\right) \tilde{X}_{ij}^{c} \leq C_{O^c D^c} + H_{O^c D^c} \qquad \forall\, (O^c, j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{4.23}$$

$$-M \cdot \left(1 - \tilde{Y}_{ij}^{c}\right) \leq T_{ij}^{c} - T_{ij} \leq M \cdot \left(1 - \tilde{Y}_{ij}^{c}\right) \qquad \forall\, (i,j) \in \mathcal{A}_1, c \in C \tag{4.24}$$

$$-M \cdot \tilde{Y}_{ij}^{c} \leq T_{ij}^{c} \leq M \cdot \tilde{Y}_{ij}^{c} \qquad \forall\, (i,j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{4.25}$$

$$\beta_{ij}^{c},\, \tilde{Y}_{ij}^{c},\, \tilde{X}_{ij}^{c} \in \{0,1\} \qquad \forall\, (i,j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{4.26}$$

$$\delta_{ij}^{c,e} \geq 0 \qquad \forall\,(i,j) \in \mathcal{A}_1, c, e \in \mathcal{C} \tag{4.27}$$

4.3.4 Experimental design

In this section, we discuss some of the main assumptions that underlie the Joint Design and Pricing models and compare them with the assumptions that underly the usual network design models. Moreover we propose a transformation of our original model in a single level network design model to assess the effect of joint design and pricing.

4.3.4.1 Port-to-port service

Our model in the present format fits the definition of port-to-port transport service. That is the extended gate operator provides transportation services only among the seaport and inland terminals with high capacity modalities while the last leg of the transportation path from the inland terminal to the customer premises is organized by the competition. It follows that the prices over the extended gate services should be such that the total cost of the path through the extended gates should be at least cost neutral to the direct path provided by the competition.

4.3.4.2 Port-to-door service

In other cases, the extended gate operator can offer port-to-door transport services. If so, prices do not depend on the routing of the containers but on the best alternative transport solution to that specific destination. Thus we can derive an alternative port-to-door network design model by fixing the prices per commodity for the entire path, T^c. This will determine the revenues of the carrier which will be diminished by all costs for leasing and operating the barges as much as the transport cost and handling charges in order to obtain its profits, so the objective function will be equal to (4.28). The capacity (4.2), frequency (4.3) and (4.4), service time (4.5) and (4.6), feasibility (4.7) – (4.9) and (4.14), and flow conservation (4.13) constraints that apply in the original model should also apply in this model. Since the prices are considered fixed, for the port to door case, the bi-linear term in the objective is eliminated, so a classical single level MIP is considered.

$$\max_{X,Y,u,y} \sum_{c\in\mathcal{C}} T^c d^c - \sum_{(i,j)\in\mathcal{A}_1} H_{ij} \sum_{c\in\mathcal{C}} Y_{ij}^c - \sum_{(i,j)\in\mathcal{A}_2} (C_{ij} + H_{ij}) \sum_{c\in\mathcal{C}} X_{ij}^c$$
$$- \sum_{b\in\mathcal{B}} \sum_{(i,j)\in\mathcal{A}_1} w^b u_{ij}^b - \sum_{b\in\mathcal{B}} \sum_{(i,j)\in\mathcal{A}_1} v_{ij}^b y_{ij}^b \quad (4.28)$$

4.3.4.3 Extensions

Some extensions of the model could be considered to enhance the applicability of the model in real cases. First, a discount factor, α^c for all $c \in \mathcal{C}$ with $0 \leq \alpha^c \leq 1$, could be considered if one assumes that a client would be willing to shift to services offered by the extended gate operator only when they would lead to a cost reduction of his total cost. In this case the right hand side of constraints (4.23) would become $(1-\alpha^c)(C_{O^cD^c} + H_{O^cD^c})$.

Second, the cost and service time associated with transport services offered by the competition could be further distinguished between trucking services with cost, C_{ij}^t for all $(i,j) \in \mathcal{A}_2$ and service time t_{ij}^t for all $(i,j) \in \mathcal{A}_2$, and combined transport services with cost C_{ij}^b for all $(i,j) \in \mathcal{A}_2$ and service time t_{ij}^b for all $(i,j) \in \mathcal{A}_2$. Here $C_{ij}^t > C_{ij}^b$ and $t_{ij}^t < t_{ij}^b$.

4.4 Solution approach

Our bilevel model is hard to solve, mainly due to two reasons. First, its structure as a bilevel program indicates that the lower level should be replaced by its complicating optimality condition constraints. Even the simplest case of such models has been shown to be NP-hard (Labbé et al., 1998). Second, without considering the pricing, our model could be reduced to a quite complicated network design problem, which has also be shown to be NP-hard. Thus such models combine two NP-hard problems.

Although algorithmic procedures have been proposed to address the bilevel freight tariff setting problem (Brotcorne et al., 2000, 2001, 2011, 2012), for cases where the pricing is considered jointly with the design of the network, the contributions are limited. In terms of the modeling formulation, the main difference is the consideration of the integer variables associated with the design or the capacity setting of different links. Some heuristic procedures have been proposed for the simpler cases of Joint

Pricing and Capacity setting problem (Brotcorne et al., 2005), and of the Joint Design and Pricing problem (Brotcorne et al., 2008), where in both cases only a binary design variable is considered for opening links. The heuristics proposed apply a primal-dual algorithm while penalizing the lower level complementarity constraint. The heuristic alternates between solving the penalized problem for fixed flows to determine the price levels and, and for fixed prices to determine the design variables while in every iteration the penalty increases. In the later paper, the primal-dual heuristic is extended by applying the Lagrangian relaxation framework in bilevel programs, by adding to the objective the design constraint multiplied with a Lagrangian factor, so another outer iterative procedure is considered, in which in every iteration the Lagrangian factor is updated.

In our case, the formulation of economies of scale and service time constraints is more explicit and thus the use of more integer and Boolean variables regarding the design of the network (service frequency, number of barges assigned to each link, etc) is needed. This complicates the resulting problem on hand and makes the application of the existing heuristics challenging since advanced calibration is needed (1. Update of penalty factors, 2. Several constraints should be moved to the objective (Lagrangian), 3. Update of Lagrangian factors). Our effort to adapt the heuristics on our problem did not yield promising results.

Therefore, wee develop a heuristic to provide high quality solutions to our problem in an efficient way. by taking advantage of the special structure of our problem and of some observations. These observations are:

(a) The joint design and pricing of only one link is a much simpler problem, and computation times are significantly smaller (Labbé et al., 1998).

(b) Every port to hinterland path can go through one tariff arc controlled by the extended gate operator, so prices do not interact with each other for the total cost of a path.

(c) Considering the above, it follows that the optimal level of price at each corridor will be one of the equilibrium price levels as introduced in section 4.3.3.

The steps of our heuristic are described in detail in the next section, but there is a simple intuition under our heuristic. That is that we find an initial solution by solving the MIP equivalent model for each corridor seperately, this results in high consolidation of flows at each corridor and thus to lower prices. Then we look which commodities can be satisfied by more than one corridor and we increase prices at the corresponding corridors. Finally, when the prices cannot be further updated we solve the MIP equivalent model for a fixed price vector and define the optimal network design.

4.4.1 Heuristic development

In Step 0, we set the value of the equilibrium level of prices, γ_{ij}^c for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$, as it is discussed in section 4.3.3 of this chapter.

In Step 1 we solve $\mid \mathcal{A}_1 \mid$ times the MIP Equivalent formulation of our problem, each time allowing only one corridor controlled by the extended gate operator to open. This reduces sufficiently the size of the problem and thus CPLEX can solve the problem in substantially less time, as reported by Labbé et al. (1998). Allowing only one corridor to open has the effect of concentrating the flows that would maximize the profitability of the extended gate operator in one corridor; thus the optimal price is set such that the cost of all commodities routed through the corridor is at least cost neutral to their best tariff free path. It follows that there is some revenue increase opportunity from commodities that had higher equilibrium prices than the price set on the corridor. It is clear that, if all corridors were available, the extended gate operator could increase the prices in some corridors to segment the market in favor of his revenue maximization. One might expect that for this reason the level of prices derived from Step 1, T^*, are smaller or equal to the optimal level of prices of the original problem. Although this does not hold true for the general capacitated version of the problem, it holds true for the uncapacitated version of the problem.

In Step 2, we aggregate all the individual solutions generated in Step 1 in one feasible solution by solving for a given price vector, T^*, the FL_A model which is a constrained version of the first level (FL) problem, as explained below.

The FL_A model is a constrained version of the FL model, and it takes the values of the variables T_{ij} and $\tilde{Y}_{ij}^c$ as inputs. The prices are fixed to the values defined by the heuristic, so the bi-linear term in the objective function is eliminated. Second, constraints (4.21) from the MIP equivalent formulation of the problem are included. Constraints (4.21) for the given values $\tilde{Y}_{ij}^c$, defined by the heuristic, substitute the second level objective since they prohibit the assignment of flows to corridors that are part of paths with higher cost than the one offered by competition. Last, constraints (4.29) substitute the demand conservation constraints (4.13) of the second level, in the sense that the summation of flows of one commodity in all corridors should

Step 0
Initialization.
$\gamma^{c}_{O^{c}j} \leftarrow C_{O^{c}D^{c}} - C_{jD^{c}} + H_{jD^{c}} \quad \forall\left(O^{c}, j\right) \in \mathcal{A}_1, c \in \mathcal{C}$.
Step 1
For each $(i, j) \in A_1$, set $\tilde{Y}^{c}_{ij'} = 0 \mid \forall\left(i, j'\right) \neq \left(i, j\right), c \in \mathcal{C}$ and solve MIP_EQ.
$\Longrightarrow T^{*}_{ij},\tilde{Y}^{c*}_{ij}$.
Step 2
Take $T^{*}_{ij}\,\forall\left(i, j\right) \in A_1$, $\tilde{Y}^{c*}_{ij}\,\forall\left(i, j\right) \in \mathcal{A}_1, \forall c \in \mathcal{C}$ as input and solve the FL_A.
$\Longrightarrow z^{*}$.
Step 3 Let $\mathcal{C}_1 = \left\{c \in \mathcal{C} \mid \sum\limits_{(i,j)\in A_1} \tilde{Y}^{c}_{ij} \geq 2\right\}$.
Step 4
Let $\mathcal{C}_2 = \left\{c \in \mathcal{C} \mid \gamma^{c}_{\bar{i}\bar{j}} = T_{\bar{i}\bar{j}}\, \exists(\bar{i,j}) \in \mathcal{A}_1\right\}$.
Step 5
If $\mathcal{C}_1 \cap \mathcal{C}_2 \in \emptyset$
then go to Step 8
else go to Step 6.
Step 6
For each $c \in \mathcal{C}_1 \cap \mathcal{C}_2$,
$\tilde{Y}^{c}_{\bar{i}\bar{j}} \leftarrow 0$ and $T_{\bar{i}\bar{j}} \leftarrow \gamma^{'}_{\bar{i}\bar{j}}$ when $\gamma^{'}_{\bar{i}\bar{j}} = min\left(\gamma^{c}_{\bar{i}\bar{j}} \mid Y^{c*}_{\bar{i}\bar{j}} = 1\right)$ and solve the FL_A problem.
$\Longrightarrow z_c$.
$\Longrightarrow \tilde{z} = max\left(z_c\right)$ and $\tilde{c}$ be the corresponding commodity.
Step 7
If $\tilde{z} > z^{*}$then
$z^{*} \longleftarrow \tilde{z}$
$T^{*}_{\bar{i}\bar{j}} \longleftarrow \gamma^{'}_{\bar{i}\bar{j}}$
$\tilde{Y}^{c*}_{ij} \longleftarrow 0$
go to Step 3
else
go to Step 8
Step 8
For fixed $T^{*}_{ij}\,\forall\left(i, j\right) \in \mathcal{A}_1$ solve the MIP_EQ
$\Longrightarrow z^{*}$,u^{b*}_{ij},y^{*}_{ij} Y^{c*}_{ij} & X^{c*}_{ij}
Notation:$\leftarrow$Assign Value to a parameter, $\Longrightarrow$Output is generated by a program

Figure 4.1: Heuristic

not exceed its demand volume. Some commodities can be routed through several corridors controlled by the extended gate operator since their resulting path cost is lower than the one offered by the competition. Considering the price vector of the extended gate operator, they will be routed through the paths that generate the highest profit for the extended gate operator. The solution of this problem is feasible since both capacity and service level constraints are considered while the feasibility of the second level is guaranteed by constraints (4.21) and (4.29).

$$\sum_{(i,j)\in A_1} Y_{ij}^c \leq d^c \qquad \forall c \in \mathcal{C} \tag{4.29}$$

In Step 3, we identify which commodities are assigned to more than one extended gate corridor. If no commodities are assigned to more than one corridor, the aggregation of the individual solutions is the optimal solution.

In Step 4, we identify the commodities for which their equilibrium level of prices is equal to the prices set on the corridors controlled by the extended gate operator.

In Step 5, we check whether the intersection of the two sets of commodities obtained in Steps 3 and 4 is empty. If it is empty, our heuristic terminates in Step 8. Otherwise it continues to Step 6. In case a commodity, c, satisfies both conditions in Steps 3 and 4, then one may opt to increase the price at the corresponding extended gate corridor and thus prohibit its routing through it. In this manner, the commodity is guided via extended gates where the prices are higher, although it remains competitive. The remaining flows in the former extended gate corridor will also generate higher revenues.

In Step 6, for each commodity that satisfies the conditions in Steps 3 and 4, we try to increase the price on the corresponding corridors and solve the FL_A problem while keeping the optimal solutions.

In Step 7, we check whether the maximum among the solutions obtained in Step 6 is higher than the best solution found until now. If it is better, the corresponding variables are updated and the heuristic makes another iteration from Step 4 else it terminates in Step 8.

In Step 8, we solve the MIP equivalent formulation of our original problem for the tariffs obtained such that the design and flow decision variables are determined.

The heuristic will always terminate after a number of iterations. The number of iterations can vary and in the worst case scenario, were all price levels are tried for all corridors, there will be $|\mathcal{A}_1| \cdot |\mathcal{C}|$ iterations.

4.4.2 Heuristic assessment

In order to assess the performance of the heuristic described in section 4.4.1, we generated instances randomly and we solved them by both the MIP equivalent program using CPLEX 12, and by our heuristic. Both the heuristic and the MIP equivalent program were formulated and solved in MATLAB 2012b, while we set for CPLEX a time limit of 500 sec to solve the problem. For the cases where this limit was exceeded, we consider the optimal upper bound achieved.

The instance generator works as follows: first the skeleton of the network is generated by defining the number of source, sink and transhipment nodes, the coordinates of which are randomly generated in two-dimensional space following the uniform distribution within a radius defined by the user. The source nodes are connected with the sink nodes directly with arcs, and then the source nodes are connected with the transhipment nodes; these will be the arcs controlled by the network operator, finally the transhipment nodes are connected with all the sink nodes. The lengths of all arcs are equal to the Euclidean distances between the nodes, and moreover the associated cost is determined by a fixed cost and a variable cost linear in the distance of each arc. Finally, the commodities are randomly generated by defining the sink and source nodes, the amount of flow and service level requirements in terms of minimum frequency required to assign the flows in a specific arc. We solved ten instances for every setting in order to assess the performance of the algorithm.

The results are summarized in Tab. 4.7 where the average computation times and the average gap from the optimal solutions are presented for 10 randomly generated instances with the specifications stated in the first three columns of the matrix. CPLEX needs significantly more computation time on average even for small or medium sized instances, while we see that in both cases the computation time mainly depends on the number of commodities considered while the number of nodes of the network has significant effect only on the computation time of CPLEX. The gap between the optimal solution and the one obtained by the heuristics seems to be less than 2% in average.

Table 4.7: Heuristic Assessment

Instance	Inland Terminals	Client Nodes	Commodities	CPLEX CPU (Sec) (Limit 500 Sec)	Heuristic CPU (Sec)	Optimal Solution %
1	10	20	30	25.53	4.46	99.38%
2	10	20	60	141.97	10.62	98.56%
3	10	30	30	32.67	4.29	98.22%
4	10	30	60	367.48	13.62	97.99%
5	20	20	30	395.95	6.34	99.77%
6	20	20	60	500.13	18.60	99.58%
7	20	30	30	320.56	8.23	99.30%
8	20	30	60	500.27	26.24	99.28%

4.5 Experimental results

In this section we formulate a stylized but realistic example and run experiments in order to assess the effect of the different considerations on the network design problem. In particular, we study whether there are any differences in the optimal network design when we assume port-to-port versus port-to-door services and also we assess the effect of considering service level constraints in the tactical service network design. The optimal multimodal network design is case specific and may depend on physical characteristics of the network, the demand distributions over the network and other parameters, so our results may not be generalized but they do demonstrate the capabilities of our model to capture the tradeoffs among revenue maximization in offering services, cost minimization in setting up the combined transport network, and demand penetration through frequent services on corridors.

Although we develop a stylized example, all cost structures considered in this chapter are inspired by real cost structures covered by a confidentiality factor, i.e. so we use monetary units, m; full details on the cost structures can be found in Van Riessen et al. (2013). We consider a network consisting of one seaport terminal and 3 inland terminals; see Fig. 4.2. That means that container demand for one inland region can be served via an extended gate located in another region. The costs of road transport are presented in Tab. 4.8 and are calculated based on the formula: $C_{ij} = 76.4 + 1.06 \cdot distance\,(i, j)$. In order to simplify the network we assume that demand is destined to the inland regions of inland terminals, so only the fixed cost applies

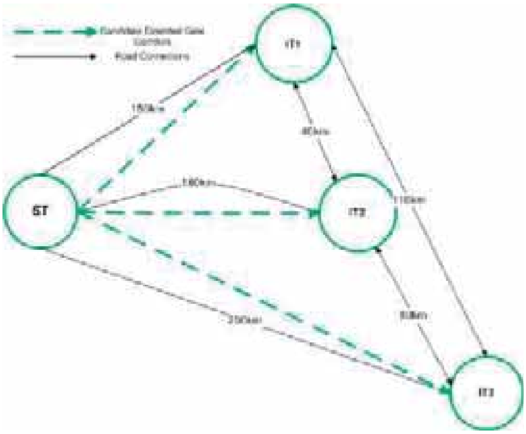


Figure 4.2: Stylized Example Physical Network

Table 4.8: Transportation Cost via Road (m/TEU)

	ST	IT1	IT2	IT3
ST	76.4	232.4	263.6	336.4
IT1	232.4	76.4	118	190.8
IT2	263.6	118	76.4	159.6
IT3	336.4	190.8	159.6	76.4

for the end haulage leg from the inland terminal to the customer's premises located in the same region. The weekly fixed costs for barge leasing and the variable costs per barge trip are presented in Tab. 4.9. The additional handling charges at inland terminals is set equal to 23m/TEU.

In order to assess the performance and the main differences of using the different network design formulations we set up an experiment by differentiating the demand volumes over the stylized network, which ranges from 180 to 2.340 TEUs per week.

Table 4.9: Barge Types and Characteristics

#	Capacity (TEUs)	Weekly Cost	Variable Cost per Trip		
			ST-IT1	ST-IT2	ST-IT3
	Max Number of RoundTrips		3	3	2
1	100	7.500m	225m	270m	375m
2	200	10.000m	285m	342m	475m

Table 4.10: Experimental Setting

OD pair	Commodities	Minimum Service Frequency	Percentile
ST-IT1	1	1	20%
	2	3	50%
	3	6	30%
ST-IT2	4	1	20%
	5	3	50%
	6	6	30%
ST-IT3	7	1	20%
	8	3	50%
	9	6	30%

We assume that the demand is equally distributed among the OD pairs. Finally, the demand is further organized in commodities to capture the different service time requirements which are shown by the minimum service frequency (Tab. 4.10).

The results of the experiment are presented graphically in several figures. Fig. 4.3 and Fig. 4.4 concentrate the results for the cases with and without considering service time constraints, respectively.

The graphs in Fig. 4.3 and Fig. 4.4 should be evaluated with care and be read as follows. There are four main cases tested; 1) port-to-port with service time constraints (Fig. 4.3a,c, and e), 2) port-to-door with service time constraints (Fig. 4.3b,d, and f), 3) port-to-port without service time constraints (Fig. 4.4a,c, and e), 4) port-to-door with service time constraints (Fig. 4.4b,d, and f). For each case, in the horizontal axis of each graph, a weekly demand scenario is considered. The weekly container demand, a variable in our experiment, is considered to be equally distributed over the three inland regions and also further organized in commodities according to Tab. 4.10. The optimal capacity setting (Fig. 4.3.a and Fig. 4.3.b, Fig. 4.4.a and Fig. 4.4.b), connection frequency on the corridors (Fig. 4.3.c and Fig. 4.3.d, Fig. 4.4.c and Fig. 4.4.d), and the flows of containers over the network are shown (Fig. 4.3.e and Fig. 4.3.f, Fig. 4.4.e and Fig. 4.4.f).

The results can be read in two ways. First, for each case one can observe what is the difference in the optimal designs for increasing demand. Second, for the same demand instances one could contrast the differences in the optimal designs among the different cases.

4.5.1 Port-to-port vs port-to-door haulage

In this section we study whether any significant differences appear when assuming port-to-port versus port-to-door services while solving the two models discussed in sections 4.4.1 and 4.4.2. The main modeling difference between the two is that for the port-to-door model the pricing is disconnected from the design of the network, so it is mainly a cost minimization problem, while for the port to port model the joint design and pricing of network services is considered, and thus the pricing affects the routing of flows through the networks discussed previously in this chapter.

We observe that when demand is low flows are concentrated

Fig. 4.5 and Fig. 4.6 present the network configurations for some selected demand instances where the optimal designs significantly differ. In addition to the information provided in the previous figures now also the number and size of barges is presented as much as the path each commodity is assigned to.

When demand is low (180 TEUs per week) only the central one ST-IT2 is opened with one and two small barges, for port to port and port to door cases respectively. In case of port to door services a frequency of 6 trips per week is achieved and all flows are consolidated on that corridor since the service time constraints for all commodities are met when routed through the ST-IT2 corridor. In case of port-to-port service, when pricing is considered, only one barge is assigned to the central corridor and a frequency of 3 trips per week is achieved, thus only medium and slow moving flows are assigned to that corridor. Reducing the price of the central corridor in order to make the routing of flows destined IT3 through the central corridor cost effective would result in lower net revenues for the network operator.

In case of port-to-door service this remains the optimal design until the demand over the network exceeds the capacity of the corridor (Fig. 4.6.a and Fig. 4.6.b). On the other hand, if port-to-port service is assumed, the ST-IT1 corridor is opened earlier for the achievement of revenue maximization through pricing (Fig. 4.5.b). In both cases, there is a range of demand where both ST-IT1 and ST-IT2 corridors are opened by assigning to them one (3 trips per week) and two (6 trips per week) small barges respectively (Fig. 4.5.b and Fig. 4.5.c), where containers destined to the IT1 region with high service level requirements (Commodity 3) are routed through the ST-IT2 corridor. The above design configuration remains in the optimal solutions of even higher demand instances in case of port-to-door services (Fig. 4.6.d) such that economies of scale are achieved by the assignment of larger barges in ST-IT1 corridor with lower frequency. On the other hand, in case of port-to-port services, above a demand threshold each commodity is satisfied by its corresponding corridor such that revenues are maximized through pricing.

It is obvious that considering joint design and pricing has a significant effect on the optimal network configurations compared to the usual cost minimization network design. First, considering the port-to-door services provides more flexibility for the routing of containers through the network with the result of more flow consolidation in fewer corridors, especially when demand is low. Second, when port-to-port services are considered, revenue maximization has a significant effect and high frequencies are set in all corridors to meet service frequency requirements of all commodities such that more dedicated services are offered.

Assuming that demand originates or is destined at the inland regions and that demand is equally distributed among the inland regions may not be realistic. Nevertheless, our results show significant differences in the optimal network designs and assuming unbalanced demand and the actual locations of shippers only has greater effect on the differences among the optimal network designs for port-to-port and port-to door services.

4.5.2 Impact of service level constraints

In this section we consider the same instances without considering the service time constraints and compare them with the results presented in the previous section. The graphs in Fig. 4.4 should be read in comparison with those presented in Fig. 4.3.

First we observe that considering service level constraints had a significant impact on the optimal network design, especially when demand is relatively low. We observe that the effect of economies of scale through the use of bigger barges dominates the optimal network configurations. So high frequent connections are achieved only when demand is high. Second, we observe that all corridors are opened for lower demand realizations; that is because for this case it is assumed that all demand can be satisfied even with low frequency services. That means that beyond a demand threshold in each region, a corridor to that region is opened. Higher demand will also be covered by the same corridor although the capacity on that corridor will increase accordingly. This means that the quality of service provided in each corridor, controlled by its frequency, does not influence the routing of containers based on their service time characteristics. Again one can observe differences between assuming port-to-door and port-to-port services since in the latter the revenue maximization through pricing forces the extended gates to open earlier than they do in the former.

4.6 Conclusions

In this chapter we presented two models for the tactical design of multimodal port-hinterland transport services, namely for the design of port-to-port and port-to-door services. The models capture the trade-offs between revenue maximization, economies of scale and market penetration through the service frequency setting. We contribute to the existing body of modeling literature by extending the joint design and pricing bi-level formulations to the multimodal nature of such services and we add service time constraints to capture the different transport time performances among different modalities. We propose a simple heuristic approach that provides near optimal solutions in substantially less time than CPLEX.

In addition to the modeling contributions of this work, some managerial insights can be drawn from our research. First, it seems that the cost of installing capacity on corridors compared to the possible realization of revenues does not prohibit the setting up of high-frequency services to meet service time constraints and increase their market penetration. High-frequency connections are set up even for instances with low demand, and larger barges are selected only after high-frequency services have been established. In most of the solutions though, it is clear that the installed capacity on the corridors is underutilized; this can be explained by the low break-even utilization points of barges. Installing high-capacity corridors both lowers total cost and provides buffer capacity to carriers to hedge against demand variability (Lium et al., 2009).

Port-to-door services provide more consolidation opportunities because they give more flexibility in the routing of commodities due to the disconnection between routing and pricing. When port-to-port services are assumed, the revenue management (or market segmentation) through pricing that results in more dedicated services is more important than achieving economies of scale through the use of larger barges. It should be noted, though, that different assumptions underlie the two service types and this leads to different optimal combined transport network configurations. So in the case of port-to-port services, where not all links are controlled by the same authority, the optimization models should be adjusted accordingly.

Moreover, our results show that, when an extended gate operator serves several close regions, he has more flexibility in the design of the hinterland network. For example, he can set up frequent services in one central corridor (or with higher flows) to meet the requirements of fast-moving containers for all close regions while also setting up lower-frequency services to transport slow-moving containers at a lower total cost.

The present chapter considers the competitive environment to be exogenous. An extension of the research in this chapter could concern the interaction between two or more extended gate operators that both design and price sub-networks to serve the needs of a contestable hinterland. The above would require a Mathematical Programming with Equilibrium Constraints (MPEC) formulation of the problem which has still not been studied extensively in literature, but could also capture the seaport calling selection of shipping lines based on their hinterland connectivity.

Appendix I

$$FLA: \max_{Y,u,y} \sum_{c\in\mathcal{C}} \sum_{(i,j)\in\mathcal{A}_1} T_{ij} Y_{ij}^c - \sum_{b\in\mathcal{B}} \sum_{(i,j)\in\mathcal{A}_1} w^b u_{ij}^b - \sum_{b\in\mathcal{B}} \sum_{(i,j)\in\mathcal{A}_1} v_{ij}^b y_{ij}^b \quad (4.30)$$

$$\sum_{c\in\mathcal{C}} Y_{ij}^c \leq \sum_{b\in\mathcal{B}} Q^b y_{ij}^b \qquad \forall (i,j) \in \mathcal{A}_1 \quad (4.31)$$

$$y_{ij}^b \leq n_{ij}^b u_{ij}^b \qquad \forall (i,j) \in \mathcal{A}_1, b \in \mathcal{B} \quad (4.32)$$

$$y_{ij} = \sum_{b\in\mathcal{B}} y_{ij}^b \qquad \forall (i,j) \in \mathcal{A}_1 \quad (4.33)$$

$$\tilde{y}_{O^c k}^c \leq 2 \cdot \left(t^c - t_{O^c k}^n - t_{O^c k}^b - t_{kD^c}^t\right) \cdot y_{O^c k} \qquad \forall (O^c, k) \in \mathcal{A}_1, c \in \mathcal{C} \quad (4.34)$$

$$Y_{ij}^c \leq \tilde{y}_{ij}^c M \qquad \forall (i,j) \in \mathcal{A}_1, c \in \mathcal{C} \quad (4.35)$$

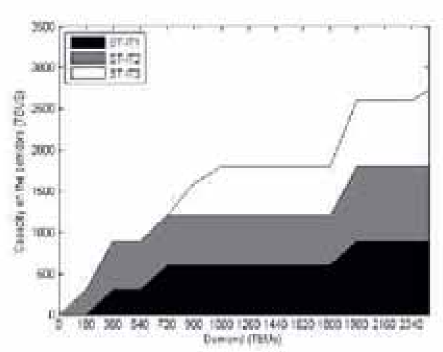
$$\tilde{y}_{ij}^c \in \{0,1\} \qquad \forall\,(i,j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{4.36}$$

$$y_{ij} \in \mathbb{N}^0 \qquad \forall\,(i,j) \in \mathcal{A}_1 \tag{4.37}$$

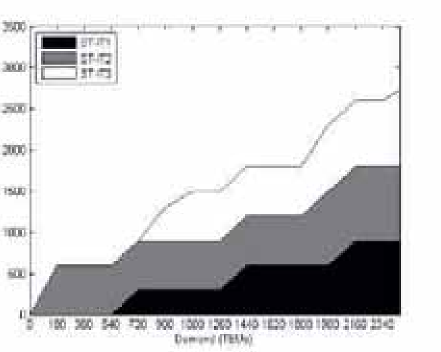
$$u_{ij}^b \in \mathbb{N}^0 \qquad \forall\,(i,j) \in \mathcal{A}_1, b \in \mathcal{B} \tag{4.38}$$

$$Y_{ij}^c \leq M \cdot \tilde{Y}_{ij}^c \qquad \forall\,(i,j) \in \mathcal{A}_1 \tag{4.39}$$

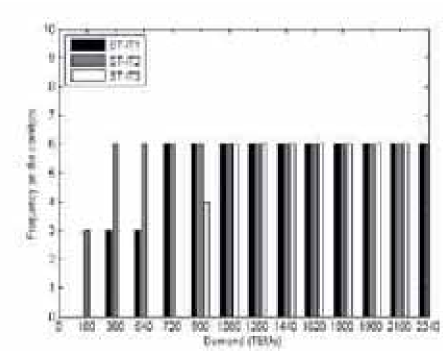
$$\sum_{(i,j)\in A_1} Y_{ij}^c \leq d^c \qquad \forall c \in \mathcal{C} \tag{4.40}$$



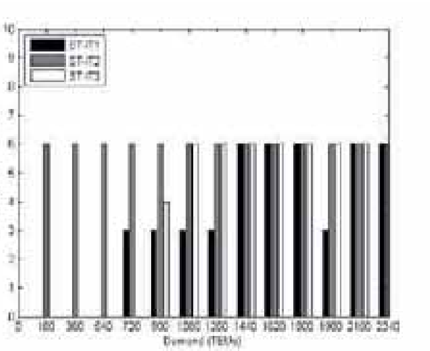
(a) port-to-port



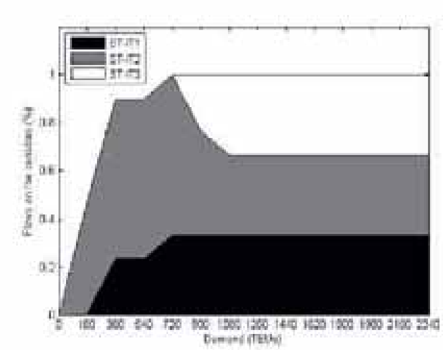
(b) port-to-door



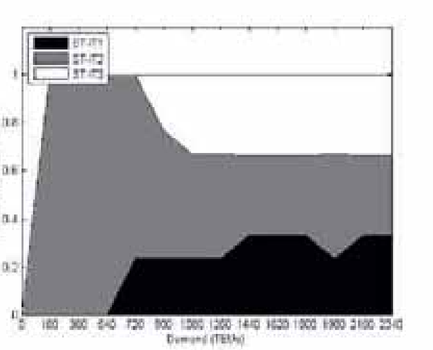
(c) port-to-port



(d) port-to-door

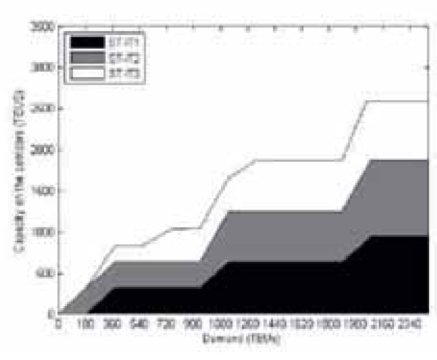


(e) port-to-port

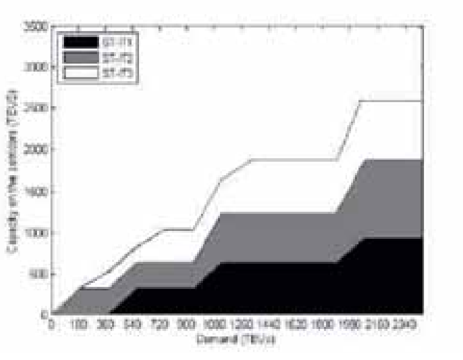


(f) port-to-door

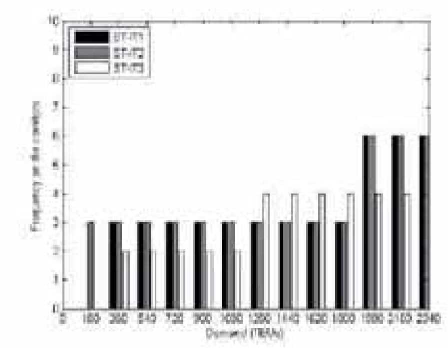
Figure 4.3: Experiment results - With service level constraints



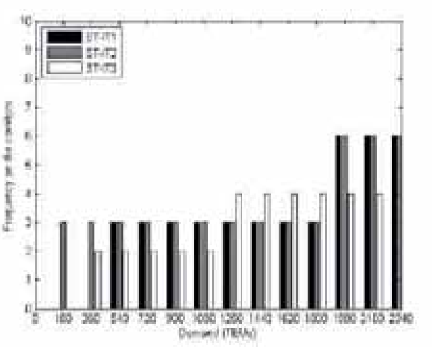
(a) port-to-port



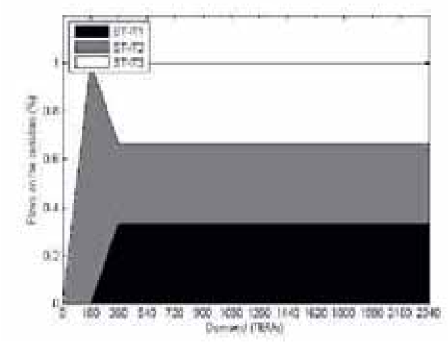
(b) port-to-door



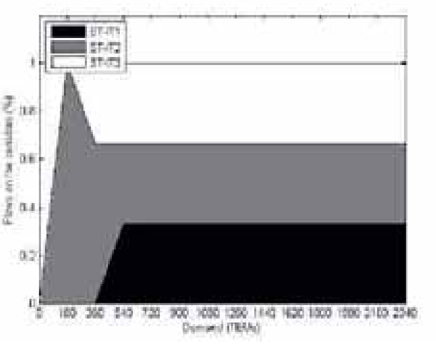
(c) port-to-port



(d) port-to-door

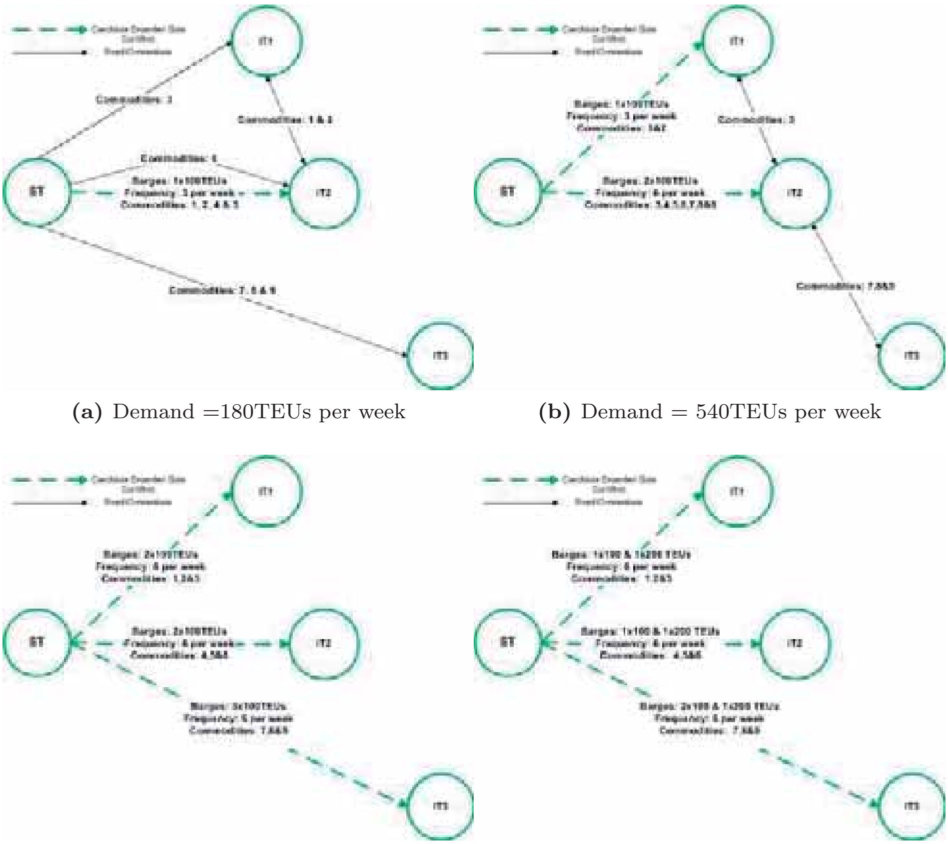


(e) port-to-port



(f) port-to-door

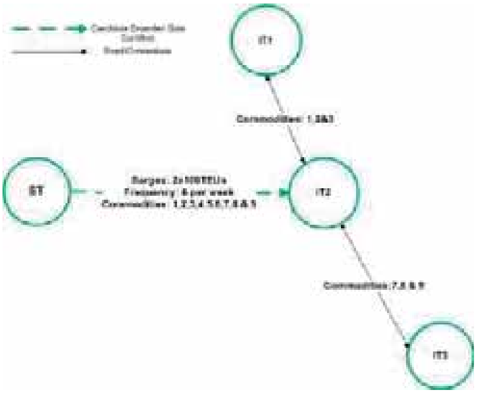
Figure 4.4: Experiment results - Without service level constraints



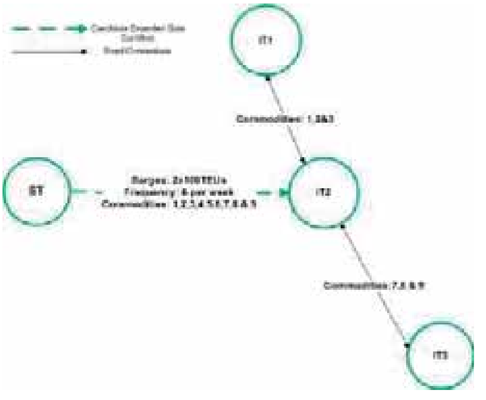
(a) Demand =180TEUs per week **(b)** Demand = 540TEUs per week

(c) Demand=1080 TEUs per week **(d)** Demand=1980 TEUs per week

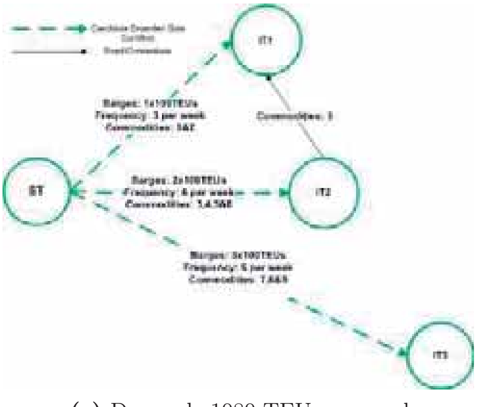
Figure 4.5: Optimal Network Configurations port-to-port haulage



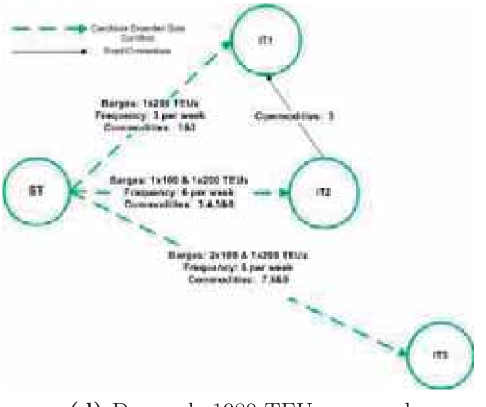
(a) Demand =180TEUs per week



(b) Demand = 540TEUs per week



(c) Demand=1080 TEUs per week



(d) Demand=1980 TEUs per week

Figure 4.6: Optimal Network Configurations port-to-door haulage

5 Joint fleet deployment and barge rotation network design: The case of horizontal cooperation of dryports

Summary: Offering frequent services of high capacity modes can make intermodal transportation of containers between a seaport and inland locations competitive with uni-modal road transport both from time and cost perspectives. The tactical design of scheduled barge transport services involves decisions regarding both the fleet composition and its routing through the inland waterway network. Integrating these decisions would make the resulting network more competitive in satisfying expected demand and service time requirements set by the shippers. We develop some analytical expressions that support the further understanding of how the design variables affect the corresponding cost and service time trade-offs made in the joint deployment and routing of a fleet. Moreover, an MIP formulation for the Fleet Size and Mix Vehicle Routing (FSMVRP) specially adapted to the Port-Hinterland intermodal barge network design is developed. We consider the case of horizontal cooperation of dryport container terminals that aim at efficient capacity sharing. Our results show that in case of cooperation not only cost savings emerge but also the service level offered to customers can be enhanced.

5.1 Introduction

The first and the last leg of international door to door container transport constitutes a big share of the total transportation costs and the total lead time, although the distance covered is usually just a small portion of the total distance (Frémont and Franc, 2010). Several processes and actors are involved, and several transportation schemes have been proposed to accommodate the needs of this part of the transportation chain. The successful execution of port-hinterland networks lies in the effective design of the network and the services associated with it as much as coordination issues among the different actors involved. Intermodal transport for the first transportation leg from the port to hinterland destinations is usually referred to as combined transport and involves barges or trains used for the transport of containers to inland terminals while containers are finally delivered to customers via trucks. In a reverse fashion, the last transportation leg is executed.

Inland terminals usually adapt to the “Dryport” concept (Roso et al. 2009; Roso and Lumsden 2010) in order to facilitate better port-hinterland connectivity. The implementation of such concept presupposes the extensive use of inland terminals, which are connected to seaport terminals via high capacity transport modes such as barges and trains. Thus, such concepts are in favor of a modal split shift to more sustainable modalities while suggesting several other benefits for the actors involved. The core activity of inland terminals is the handling and storage of containers while providing added value activities. In addition, inland terminals that adapt to the dryport concept provide transport services by organizing self - operated high capacity itineraries to enhance their connectivity with main ports. In such cases, the dryport operator extends its role to a network operator, and designs his hinterland network by composing a fleet and deploying it over the given physical network of rails and waterways in order to accommodate the expected demand for container transport between seaport and inland terminals.

The successful implementation of combined transports relies, among others, on the efficient utilization of high capacity modes. This in its turn mainly depends on consolidation of container flows such that economies of scale are achieved while providing frequent services to customers. Business examples show that when implemented successfully, combined transport can compete with uni-modal truck transport both in cost and time even for relatively short distances. Consolidation of flows is usually achieved in two ways. First, hub and spoke networks concentrate flows in corridors that connect main hubs, resulting in economies of scale. Routing barges along several terminals helps to consolidate flows originating or destined to the various locations.

The main question to be addressed in barge network design is: *How to balance the various design possibilities such that barges are deployed at minimum costs and such that service requirements are met?* A framework to address this issue is developed by Konings (2003). The design tradeoffs and perfomance indicators in barge net-

Table 5.1: Barge design tradeoffs and performance indicators

Design Tradeoffs	**Performance Indicators**
Number of Barges Size of Barges Number of calls Distribution of calls between inland and seaport terminals	Costs Capacity Installed Service Frequency

work design are summarized in Tab. 5.1. The economies of scale emerge from the deployment of bigger barges that are effectively utilized. The utilization on its turn depends on fill rates but also on the number of round trips per time horizon that can be achieved when the circulation times of barges are considered. When high demand flows are concentrated on an OD pair, point-to-point services can be established that keep circulation times low. When point-to-point flow volumes are small, rotation of barges along multiple terminals can be used to consolidate these flows. Although this improves the space utilization of the barges, time utilization decreases as the circulation time increases, caused by delays at each stop. Delays occur especially when calling at the congested seaport terminals, since deep sea vessels tend to get priority in berthing over barges. Konings (2007) proposes the reorganization of services of barge operators by splitting services in trunk line operation in the hinterland and collection/distribution services in the seaport area In this way, fewer calls are performed at the seaport area so the utilization of barges increases. A barge visiting the port of Rotterdam, for instance, calls on average eight terminals (Douma et al., 2009). Shippers opt for cost and time effective services that relate both to transport time but also to dwell times connected to the frequency of services. Considering the above, the design of a multimodal hinterland network should not only aim at achieving economies of scale but also at providing shippers with frequent services.

To achieve this, we formulate a MIP model for the Fleet Size and Mix Vehicle Routing problem (FSMVRP) with multiple depots especially adapted for the tactical design of port hinterland intermodal services. The model aims to support tactical decisions regarding: 1) the fleet size and mix selection, 2) Routing of the fleet over the network for a long time horizon in order to satisfy demand under some service time related constraints, and 3) the assignment of container flows to given services in order to assess the performance of the proposed network design. FSMVRP models are NP-hard since they can be reduced to the VRP. We take advantage of the special structure of the problem in our case by the use of some artificial variables.We provide a compact MIP formulation that enables the easy construction of round trips that can be solved with commercial solvers. Moreover, the model is applied to a real case of an alliance of clustered dryports located in the Brabant region of The Netherlands that connect with container terminals located within the port of Rotterdam. We investigate the impact of cooperation, i.e. sharing transport capacity, between these dryport terminals on costs but also on service frequency. Moreover, we consider the construction of round trips in depth by also investigating their relationship with other variables like the size of barges used and the expected service times. Our results show that cooperation between clustered dryports enhances their performance in terms of both costs and service level, especially when higher minimum frequencies are imposed. Moreover, we observe that especially for scenarios with high delays at the seaport terminals there is a shift of the location of calls from seaport terminals to inland terminals; so a lower number of calls at the seaport terminals are realized resulting in more barge trips.

For particular instances, the FSMVRP can be used to find the optimal design, and this is done in Section 5.4. However, we aim to analyze the structure of these optimal solutions in terms of trade-offs made. We introduce these trade-offs in Section 5.2 by means of a simple example. In Section 5.5, we develop an analytical model that will help us to analyze the trade-offs more explicitly. The optimization model does not provide us with these insights. The analytical model can be considered a stylized version of the optimization model introduced in Section 5.4 and we demonstrate how it can be used to interpret solutions provided by the FSMVRP as the result of basic trade-offs. It will also become clear that the analytical model does not provide us with optimal solutions, and that the optimization model is of value in that respect. Section 5.3 discussesthe theoritical background in which we buildup our model, while finally section 5.6 provides the conclusions of this chapter.

5.2 Basic Trade-offs in Port-Hinterland Barge Network design

The problem of an intermodal barge operator that aims to connect a set of inland container terminals with a set of seaport container terminals by frequent barge services to satisfy expected demand is analyzed. Port hinterland container transport demand

Figure 5.1: Map of inland terminals

can be satisfied by either combined barge-truck services or by direct trucking, since shippers are usually indifferent to the mode used as long as service requirements are met and cost benefits emerge. We use the term elastic demand to denote the above. The term elastic demand also assumes infinite capacity for trucking as a recourse action to barge-truck services. Combined barge-truck transport can satisfy part of the demand. The barge operator has to jointly decide on the fleet composition and on the routing of barges through the network such that expected demand and preferred service levels are met.

Northern Europe is densely populated with intermodal inland terminals. Usually clusters of inland terminals are connected with seaport areas with the same inland waterway and rail networks. For this reason, cooperation among the inland terminals can be performed in terms of transport capacity sharing and in particular by rotation of barges along inland terminals. An example of an inland waterway network, which connects a set of seaport terminals in Rotterdam and a set of inland terminals in the Brabant region of the Netherlands, is shown in Fig. 5.1 and corresponds with the case study presented later in this chapter.

There are several design tradeoffs that can be associated with the resulting performance of of such a transport network. Fleet selection and routing decisions are interrelated, and as shown analytically in section 4.6, these design variables are the main determinants on all cost, capacity and service time performance indicators.

The basic design tradeoffs are:

- Fleet composition: the use of big barges to reap economies of scale versus the use of small barges to operate at a higher frequency

- Fleet routing: routes with many stops to consolidate demand and to provide high frequency of services versus routes with few stops to have short circulation times.

Both trade-offs need not be made similarly for all barges and all routes, so that the fleet composition and its routing are a mixture of these trade-offs.

To illustrate let us assume a very simplistic case where the circulation time of a round trip consists of a fixed time, 12 hours (for sailing the common part of the inland waterway connecting the seaport and the inland terminal) and for a variable handling time depending on the number of calls at seaport and inland terminals, let them be 6 and 4 hours respectively. Moreover, we look at two cases: First, 2 barges of 90 TEUs capacity constantly sail according to the structure of the round trips, and second, only one barge of the double capacity, 180 TEUs, is used. The scenarios that correspond to the use of one bigger barge lead to reduced cost since economies of scale can be achieved. We summarize the results of this simple example in Tab. 5.2.

Even for this small stylized example there are clear tradeoffs between capacity setting, service level provided to customers, and cost efficiency that are related to fleet selection and its routing structures. First, we observe that the structure of the round trips can significantly affect both the capacity installed over the network and the number of services offered to customers. Given the same number and type of barges, the capacity installed can be enhanced by reducing the number of calls per round trip since the circulation times are reduced and more round trips are achieved per planning horizon. But reducing the number of calls also reduces the OD pairs that can be served per round trip and thus such round trip structures would result in lower service frequency levels. The service frequency increases linearly in the number of vehicles used for the same round trip structures but using fewer and bigger barges can lead to economies of scale. The optimal design is case specific and would depend on the demand, travel distances, cost data and other relevant parameters that we will discuss later in this chapter. Solving the optimal fleet selection and routing problem for real sized instances requires can be a very complex challenge. In order to support such decisions we develop a MIP model for the mixed fleet and routing problem that is presented in section 5.4 while we further assess the main tradeoffs with the analytical model presented in section 5.6.

Table 5.2: Simplistic Numerical Example

#	Inland Terminal Calls	Seaport Terminal Calls	Number and Type of Barges	Expected Circulation time	Expected Number of Round trips (144 hours)	Number of Weekly Services	Installed Capacity
1	1	1	2x90 TEUs	22 hours	6.54	13.08	1177.2
2	1	2	2x90 TEUs	28 hours	5.14	10.28	925.7
3	2	1	2x90 TEUs	26 hours	5.54	11.08	996.9
4	2	2	2x90 TEUs	32 hours	4.50	9	810.0
5	2	3	2x90 TEUs	38 hours	3.79	7.58	682.1
6	3	2	2x90 TEUs	36 hours	4.00	8	720.0
7	3	3	2x90 TEUs	42 hours	3.43	6.86	617.1
8	1	1	1x180 TEUs	22 hours	6.54	6.54	1177.2
9	1	2	1x180 TEUs	28 hours	5.14	5.14	925.7
10	2	1	1x180 TEUs	26 hours	5.54	5.54	996.9
11	2	2	1x180 TEUs	32 hours	4.50	4.50	810.0
12	2	3	1x180 TEUs	38 hours	3.79	3.79	682.1
13	3	2	1x180 TEUs	36 hours	4.00	4.00	720.0
14	3	3	1x180 TEUs	42 hours	3.43	3.43	617.1

5.3 Theoretical background

The tactical decisions related to barge network design mainly relate to the selection of the optimal fleet and its effective routing through the network such that service levels offered to customers are met. The general case of such problems is addressed in the literature by the solution of the Fleet Size and Mix Vehicle Routing problem (FS-MVRP). The FSMVRP was introduced by Golden et al. (1984) as an extension of the vehicle routing problem by considering a heterogeneous fleet of vehicles. Salhi and Rand (1993) review models on vehicle fleet composition problems and highlight the importance of incorporating vehicle routing in such decisions. Since its introduction, several extensions of the problem have been proposed in literature like considering multiple depots by Salhi and Sari (1997) or the consideration of time windows by Liu and Shen (1999). Given the difficulty of solving such problems, literature contributions in this field are mainly focusing on the development of efficient heuristic procedures for the solution of the problem.

The aim of this chapter is to support the tactical joint fleet deployment and routing of barges in port hinterland networks. The optimal fleet should be selected based on its expected operational performance and that is why routing plans for barges should be considered simultaneously. In this sense, the utilization of the fleet should not only be based on the consolidation of flows but also on the construction of round trips that achieve low circulation times and thus more round trips per barge whithin the planning horizon. Moreover, by considering the routing of the fleet, we look at the expected service level that shippers of the network will experience by controlling the minimum frequency per OD pair serviced. In the case of port hinterland services, demand can always be satisfied via trucking so the multimodal nature of the problem should be considered. Thus the modal split between barge and truck transport should be connected via cost and service time performance of each mode. The optimal barge network design seems to depend, on the demand consolidation opportunities, on the characteristics of the waterway network (distances, depth, bridges, locks, etc), and on demand characteristics like service time requirements, cost elasticity, service time elasticity on different modalities. Our research contributes to existing literature by proposing models that take all the above factors into consideration.

5.4 Model formulation

We develop a model for the tactical joint fleet selection and barge routing in order to provide intermodal port-hinterland transport services. The model aims to provide an optimal scheduled network design in which the Fleet Size and Mix Vehicle Routing Problem is addressed. The utilization of the fleet is not only optimized by achieving a high fill rate of their capacity but also by achieving more trips through an efficient routing. The above can be achieved by the explicit consideration of time in our formulation.

As discussed already in the literature review section the FSMVRP is NP-hard and usually difficult to solve even for small and medium size instances. In order to solve our problem we formulate a compact and tight MIP formulation of the problem that significantly reduces its size, without deviating its scope, while it can be solved to near optimality with commercial MIP solvers. We achieve the above by three main modeling tricks. First, we provide a special structure on our network to facilitate the construction of round trips for barges. By the introduction of some artificial nodes the number of available arcs in the network significantly reduces since their number increases linearly in an increasing number of nodes. Second, we reduce the number of commodities by organizing them as the collectively expected weekly demand of customers in Origin - Destination (OD) pairs that can be satisfied by a number of services spread over the week. We control that by imposing minimum frequency constraints for each OD pair that is served. Third, we provide an upper bound for our objective by considering elastic demand by allowing the trucking option for all OD pairs.

5.4.1 Notation

The main idea of the structure and the construction of the routes that we implement is presented schematically in Fig. 5.2. A round trip of a barge in our regime is as follows. The barge loads containers at the inland region and discharges them at the seaport terminals, where it loads others that in their turn are discharged at the inland terminals. That completes a barge's round trip and the barge is then ready to start its next round trip. It should be noted that during a round trip some inland terminals can be visited twice while each seaport terminal can be visited at most one time.

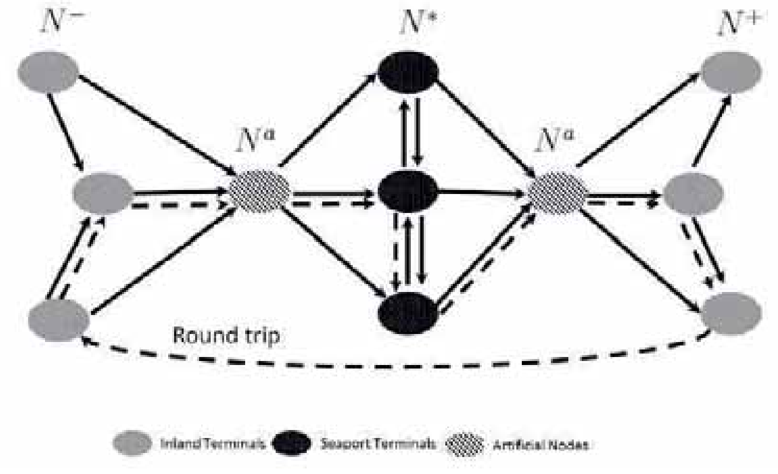


Figure 5.2: Construction of barge routes

5.4.1.1 Sets

Let us consider an underlying directed network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ with node set $\mathcal{N}$ and arc set $\mathcal{A}$.

5.4.1.2 Commodities

We consider the multicommodity formulation of the problem in which each commodity, $c \in \mathcal{C}$, is associated with the expected weekly container demand for a specific Origin and Destination (OD) pair, $(O^c, D^c) \in \mathcal{N} \times \mathcal{N}$, under some service time constraints. The demand volume of a commodity c expressed in TEUs is denoted by d^c, and represents the level of demand for both inbound and outbound flows regardless of whether the containers are full or empty. The inbound and outbound flows of containers are assumed to be balanced, since any inbound flow of full containers would lead to the return of an empty and vice versa. In reality, some empty containers dwell at the inland terminals until some demand for export containers is generated. So they are full also on their return trip. Usually there exist weight and balance constraints for the loading of containers on barges and trains but such issues are addressed at an operational level and are out of the scope of this chapter. The desired service level is assumed to be expressed as a minimum weekly frequency constraint, f^c for all $c \in C$, for the combined transport services. Considering the above demand formulation, we

Table 5.3: Notation of sets

$i \in N$	Nodes
$i \in N^- \subseteq N$	Nodes representing inland terminals at the start of the round trip
$i \in N^+ \subseteq N$	Duplicate nodes representing inland terminals at the end of the round trip
$i \in N^* \subseteq N$	Nodes representing seaport terminals
$i \in N^a \subseteq N$	Nodes representing artificial nodes that are used to connect the inland terminal region to the seaport terminal region
$(i, j) \in A$:	Arcs on the network
$c \in C$	Commodities
$b \in B$	Set of Barges
$r \in R = \{1, 2, 3, ..\}$	Barge round trip

Table 5.4: Characteristics of commodities

O^c	Origin of commodity c, $O^c \in N$
D^c	Destination of commodity c $D^c \in N$
f^c	Minimum frequency of commodity $c \in C$
d^c	Expected demand in TEUs of commodity $c \in C$

aim at analyzing the market penetration of combined services compared to direct transport based on the service frequency of high capacity modalities.

To facilitate our modeling, we use:

$$d_j^c = \begin{cases} d^c, & j = D^c \\ -d^c, & j = O^c \\ 0, & otherwise \end{cases} .$$

5.4.1.3 Costs-Capacity

We assume that cost of road transport operated by the competition is linear in volume and distance denoted by c_{ij} for all $(i, j) \in \mathcal{A}$. The container handling charges at transhipment nodes are also linear in volume and denoted by e_i for all $i \in \mathcal{N}$. The main difference between combined and road transport is that in the former handling charges are applied twice both at the seaport and the inland terminal compared to just the seaport handling charges that apply in the latter.

Table 5.5: Cost and Capacity Parameters

Q^b	Capacity in TEUs of barge $b \in \mathcal{B}$
W^b :	Weekly cost for leasing barge $b \in \mathcal{B}$
v_{ij}^b	Variable cost of barge $b \in \mathcal{B}$ traveling in arc $(i, j) \in \mathcal{A}$
e_i	Transhipment cost at node $i \in \mathcal{N}$
c_{ij}	Trucking cost per TEU for traveling link $(i, j) \in \mathcal{A}$

We consider a set of barges, $b \in \mathcal{B}$, with different cost and capacity characteristics. The cost of operating barges, from a barge operator's perspective, consists of several components, such as assets, crew, fuel, and maintenance (Braekers et al., 2012). On the other hand, the cost faced by a dryport operator, assuming that it does not use its own barges, is the price scheme proposed by barge operating companies which consists of the above costs enhanced by a profit margin for the barge operator. The leasing cost of a barge for a week is denoted by W^b for all $b \in \mathcal{B}$ which includes both asset and staff cost required to navigate and operate the barges. Economies of scale apply in this leasing cost when higher capacity barges are selected; crew cost for barge navigation and operation are concave in the capacity of the barge. A variable cost v_{ij}^b for all $(i, j) \in \mathcal{A}, b \in \mathcal{B}$, is also considered to represent the fuel cost of barges which is assumed to be linear to distance traveled and variable to the size (capacity), Q^b, of the barge.

5.4.1.4 Time parameters

For the consideration of time, we assume the travel times t_{ij}^b of barges to be linear in the distance of the traveled arcs but variable in the different barge types. We also consider a handling time h_i per container loaded or unloaded on a barge in order to assess the minimum time spent on a call at a terminal which is variable in the terminal called. Finally, we consider delays l_i faced at seaport and inland terminals. The delays consist of mooring and unmooring times but also from the actual delays faced at calls until there is sufficient space and time to berth. At seaport terminals delays can account for several hours per call since deep sea vessels get priority over barges while delays on inland terminals are usually quite low.

Table 5.6: Cost and Capacity Parameters

t_{ij}^{b}	Transportation time of barge $b \in \mathcal{B}$ traveling on arc $(i,j) \in \mathcal{A}$
l_i :	Expected delay at terminal $i \in \mathcal{N}$
h_i	Handling time for loading/ unloading a TEU at terminal $i \in \mathcal{N}$

5.4.1.5 Decision variables

We can separate the decision variables into four different sets according to their use. First, the Boolean variables Y_b denotes whether barge b is selected and the Boolean variables $y^{b,r}$ denotes whether barge b will perform route r. Second, we have variables associated with the construction of the routes. The Boolean variables $s_i^{b,r}$ denotes whether node i is part of the route r of barge b and $m_{ij}^{b,r}$ denotes whether arc $(i,j) \in \mathcal{A}$ will be part of the route r of barge b; these two variables are connected via the vehicle routing constraints. Third, we have variables associated with the assignment of flows to specific transport services. The Boolean variables $g_c^{b,r}$ denote whether demand associated with commodity c will be satisfied by barge b in route r, while $z_{ij,c}^{b,r}$ represents the amount of TEUs of commodity c on barge b on route r traveling in arc ij. The amount of TEUs of commodity c transported by trucks is denoted by w_c. Finally, we have continuous time variables $t_i^{b,r}$ which denote the arrival time of barge b on route r on node i and $u^{b,r}$ that denotes the end time of route r of barge b or else the time the barge becomes available for its next route.

5.4.2 MIP formulation

In this section the mixed integer formulation of the problem is presented.

$$\min \sum_{b} Y^b W^b + \sum_{b,r,ij} m_{ij}^{b,r} v_{ij}^{b} + \sum_{b,r,n,c} \left| x_{i,c}^{b,r} \right| e_i + \sum_{c} c_{O^c D^c} w_c \tag{5.1}$$

$$\sum_{b,r,j} z_{ij,c}^{b,r} - \sum_{b,r,j} z_{ji,c}^{b,r} = \begin{cases} d^c - w_c & i = O^c \\ 0 & else \\ w_c - d^c & i = D^c \end{cases} \qquad \forall i \in \mathcal{I}, \forall c \in \mathcal{C} \tag{5.2}$$

Table 5.7: Decision variables

$Y_b \in 0, 1$	Denoting whether barge $b \in \mathcal{B}$ is used
$y^{b,r} \in 0, 1$	Denoting whether route $r \in \mathcal{R}$ will be performed by barge$b \in \mathcal{B}$
$s_i^{b,r} \in 0, 1$	Denoting whether node $i \in \mathcal{N}$ will be called by barge $b \in \mathcal{B}$ in route $r \in \mathcal{R}$
$m_{ij}^{b,r} \in 0, 1$	Denoting whether arc $(i, j) \in \mathcal{A}$ will be used by barge $b \in \mathcal{B}$ in route $r \in \mathcal{R}$
$g_c^{b,r}$	Denoting whether demand of commodity $c \in \mathcal{C}$ will be partly satisfied by barge $b \in \mathcal{B}$ in route $r \in \mathcal{R}$.
$z_{ij,c}^{b,r}$	Amount of TEUs of commodity $c \in \mathcal{C}$ is transported in arc $(i, j) \in \mathcal{A}$ by barge $b \in \mathcal{B}$ in route $r \in \mathcal{R}$
w_c	Amount of TEUs from commodity $c \in \mathcal{C}$ satisfied by trucks
$x_{i,c}^{b,r}$	Amount of TEUs transshipped in node $i \in \mathcal{N}$ for commodity $c \in \mathcal{C}$ barge $b \in \mathcal{B}$ in route $r \in \mathcal{R}$
$t_i^{b,r}$	Arrival of barge $b \in \mathcal{B}$ in route $r \in \mathcal{R}$ at node $i \in \mathcal{N}$
$u^{b,r}$	End of route $r \in \mathcal{R}$ of barge $b \in \mathcal{B}$

$$x_{i,c}^{b,r} = \sum_j z_{ij,c}^{b,r} - \sum_j z_{ji,c}^{b,r} \qquad \forall i \in \mathcal{I}, \forall c \in \mathcal{C}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.3}$$

$$\sum_j m_{ij}^{b,r} = s_i^{b,r} \qquad \forall i \in \mathcal{I}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.4}$$

$$\sum_j m_{ji}^{b,r} = s_i^{b,r} \qquad \forall i \in \mathcal{I}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.5}$$

$$\sum_c z_{ij,c}^{b,r} \leq Q^b m_{ij}^{b,r} \qquad \forall ij \in \mathcal{A}, b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.6}$$

$$\sum_r y^{b,r} \leq Y^b M \qquad \forall b \in \mathcal{B} \tag{5.7}$$

$$\sum_{ij} m_{ij}^{b,r} \leq y^{b,r} M \qquad \forall i \in \mathcal{I}, \forall j \in \mathcal{J}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.8}$$

$$t_j^{b,r} - t_i^{b,r} \geq m_{ij}^{b,r} t_{ij}^{b} + \sum_{i,c} h_i \cdot x_{i,c}^{b,r} + l_i - M\left(1 - m_{ij}^{b,r}\right) \qquad \forall i,j \in \mathcal{I}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.9}$$

$$u^{b,r} \geq t_i^{b,r} \qquad \forall i \in \mathcal{I}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.10}$$

$$t_i^{b,r+1} \geq u^{b,r} \qquad \forall i \in \mathcal{I}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.11}$$

$$2 \cdot g_c^{b,r} \leq s_{O^c}^{b,r} + s_{D^c}^{b,r} \qquad \forall c \in \mathcal{C}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.12}$$

$$f^c \cdot z_{ij,c}^{b,r} \leq d^c \cdot g_c^{b,r} \qquad \forall ij \in \mathcal{A}, c \in \mathcal{C}, \forall b \in \mathcal{B}, \forall r \in \mathcal{R} \tag{5.13}$$

The objective function (5.1) minimizes all incurred costs. The costs consist of the weekly costs of leasing barges, the variable costs associated with the routing of barges, the handling costs for loading and unloading barges and finally the trucking costs for containers that are going to be transported by trucks. The objective function is bounded from above since all containers can be moved by trucks to their final destination. Constraints (5.2) stand for the flow conservation constraints while with constraints (5.3), the loading and unloading of containers to barges are calculated. Constraints (5.4) – (5.5) are the vehicle routing constraints that guarantee that an arc starts and ends at each node that is called in every round trip. Constraints (5.6) are the capacity constraints. Constraints (5.7) allow a round trip to be constructed for a barge only if the barge is selected while constraints (5.8) allow arcs to open only when a round trip is opened.

The arrival times of barges at specific nodes are formulated in constraint (4.9) as follows; if barge b on route r travels on link ij the arrival time on node j, $t_j^{b,r}$, is equal to its arrival time on node i, $t_i^{b,r}$, enhanced by the travel time between nodes i and j, the handling time of loading and unloading containers at node i and the delay occurred at node i. Constraints (5.10) – (5.11) ensure time continuation between successive trips of barge b.

Constraints (5.12) ensure that a commodity can be assigned to a route of a specific barge only if both its origin and destination nodes are called at the specific route. Constraints (5.13) represent the demand balancing or minimum frequency constraints. These constraints ensure that not all weekly demand can be consolidated in a single barge trip, which makes sense since demand arrivals are spread over the week as much as their due dates so usually several services per OD pair are performed per week and consolidation is performed mainly with other commodities. So the minimum frequency is used here also as a consolidation factor: the higher it is the less consolidation can be achieved in a single OD commodity.

5.5 Case study and results

We develop an experiment to assess how the optimal fleet selection and routing decisions change under different parameters and characteristics assumptions. We develop a realistic case based on a network design problem of Brabant Intermodal (BIM), which is an alliance of five dryports located in the Brabant region of The Netherlands in the proximity of the port of Rotterdam and the port of Antwerp. In particular, we analyze a part of the network in which BIM provides transport services, as depicted in Fig. 5.1. The case of cooperation for capacity sharing for three dryports is considered. These dryports are OCT in Oosterhout, BTT in Tilburg and ITV in Veghel that are connected to the port of Rotterdam through the same waterway. Barges can start from either BTT or ITV, and pass by the OCT terminal with a very small detour. Cost and demand data are realistic but not the actual numbers since the actual data were confidential to BIM.

The experiment presented in this section is not meant to solve the actual problem of BIM, but to depict the capabilities of the model presented in the previous section, and moreover to identify design characteristics and assess how these characteristics

Table 5.8: Expected weekly demand in OD pairs for Low/High scenarios

	DDE	DDW	EMX	APM
BTT	90/180	40/80	80/160	35/70
OCT	70/140	60/120	40/80	40/80
ITV	70/140	30/60	55/110	35/70

affect the optimal design. We focus on four dimensions: (1) cooperation of inland terminals, (2) the consideration of service frequency constraints in such a regime, (3) the demand volume, and (4) the expected delays before the barges berth at the seaport terminals. By analyzing the results we show for each of the four dimensions how the optimal solutions change in terms of cost performance, fleet selection and routing structure.

5.5.1 Experiment

The demand considered for our case is presented in Tab. 5.8 while cost data derived from BIM are not presented due to confidentiality. In order to assess the impact of cooperation we first apply our model to each dryport individually and we aggregate the solutions, and then we apply our model for the case where all dryports cooperate. We run 8 scenarios that correspond to different demand volumes (High - Low), delays at seaport terminals (High-Low) and Minimum frequency (0 - 4 times per week).

The different scenarios are coded with four characters codes, in the *abcd* format:

(a) $\{I, C\}$: C denotes the case of cooperation of inland terminals and I denotes the aggregated solution of each inland terminal considered independently.

(b) $\{H, L\}$: H denotes scenarios with high delays and L with low delays.

(c) $\{1, 4\}$: 1 denotes scenarios with no minimum frequency constraints 4 with minimum frequency constraints.

(d) $\{H, L\}$: H denotes scenarios with high demand and L with low demand.

5.5.2 Results

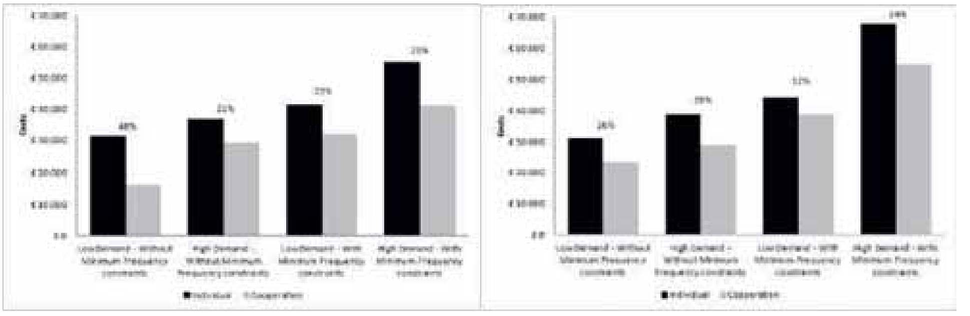
We summarize the results of our experiment in Tab. 5.9. Moreover, some of the results are also graphically illustrated in Fig. 5.3-Fig. 5.9.

Table 5.9: Results MIP model

Scenario	Capacity Installed	Total Cost	Network Coverage	Containers on Barge	Number of Barges	Average Barge Size	Average Calls/ Trip
IL1L	810	31.207	1,00	100,0%	3	90	2,33
IL1H	1500	36.968	1,50	100,0%	3	110	2,29
IL4L	480	41.544	1,67	51,1%	2	60	3,50
IL4H	1320	55.114	2,92	82,3%	3	110	3,92
CL1L	750	16.235	1,00	96,1%	1	150	3,20
CL1H	1500	29.245	1,25	99,2%	2	150	2,50
CL4L	630	31.925	3,33	84,3%	2	90	5,00
CL4H	1410	41.217	4,25	100,0%	3	130	4,55
IH1L	810	31.207	1,00	100,0%	3	90	2,33
IH1H	1500	38.760	1,25	100,0%	3	150	2,50
IH4L	0	44.000	0,00	0,0%	0	0	0,00
IH4H	1440	67.911	4,00	98,4%	6	90	4,00
CH1L	660	23.189	1,25	100,0%	2	120	3,17
CH1H	1350	28.964	1,33	98,4%	2	150	2,78
CH4L	450	38.745	2,50	63,5%	2	90	5,00
CH4H	1230	54.897	3,50	88,7%	4	90	3,27

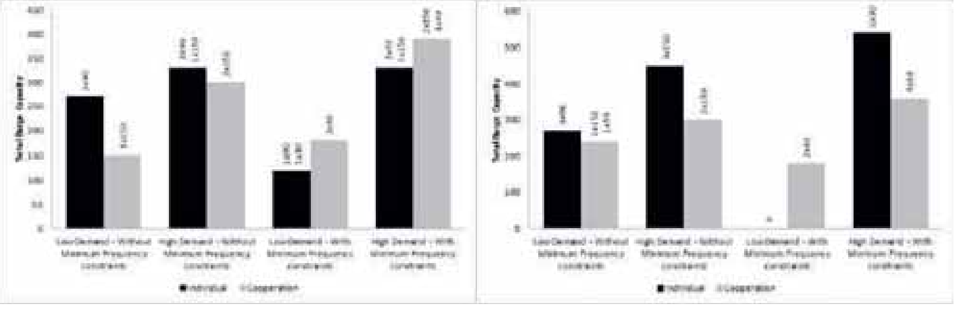
In Fig. 5.3 the costs resulting from each scenario are presented. There is a clear cost benefit resulting from cooperation among the dryports; the cost savings range form 12% to 48%. Moreover, as expected imposing minimum frequency constraints, or considering higher delays increase overall costs. The drivers of the cost increase are still not clear so we have to further analyze the solutions.

First, we look at the optimal fleet selection for each scenario in Fig. 5.4. In case of cooperation, less and bigger barges are selected in the optimal solutions compared to the case where each dryport is considered individually, such that economies of scale are achieved. Moreover, imposing minimum frequency constraints has also an impact on the optimal fleet selection: smaller barges have to be deployed so that more round trips can be achieved; this is particularly clear when high delays at the seaport terminals are considered. There are some cases where this is not realized though. This is due to the elastic demand formulation; so for the scenarios with low demand and minimum frequency constraints we observe that in the optimal solutions, only a small part of the demand is satisfied via barges while the rest is satisfied via trucks, as shown in Fig. 5.5. The relationship between network coverage and the percentage of demand satisfied by barges is shown in Fig. 5.6, in which the consideration of



(a) Low Delays **(b)** High Delays

Figure 5.3: Cost benefit from dryport cooperation

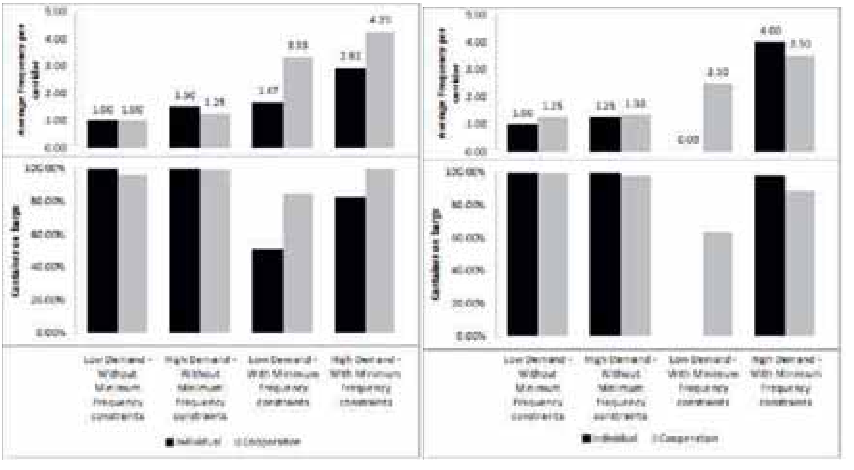


(a) Low Delays **(b)** High Delays

Figure 5.4: Fleet Selection

minimum frequency constraints separates the optimal solutions in two distinctive groups. For scenario IH4L all demand is satisfied by trucking since meeting the minimum frequency requirements when delays are high and demand is low would result in costs higher than trucking all containers. Overall, one can observe that when the minimum frequency constraints are not considered, the network coverage and modal split are disconnected, while when they are considered it is easier to achieve higher network coverage and thus modal split in favor of barges when cooperation is considered.

Second, we look at the number of round trips constructed at each solution as much as the average number of calls at both seaport and inland terminals visited in each trip. This is shown in Fig. 5.7. The total number of round trips decreases when cooperation is considered while usually bigger barges are selected except for the cases



(a) Low Delays **(b)** High Delays

Figure 5.5: Frequency on corridors and flow assignment

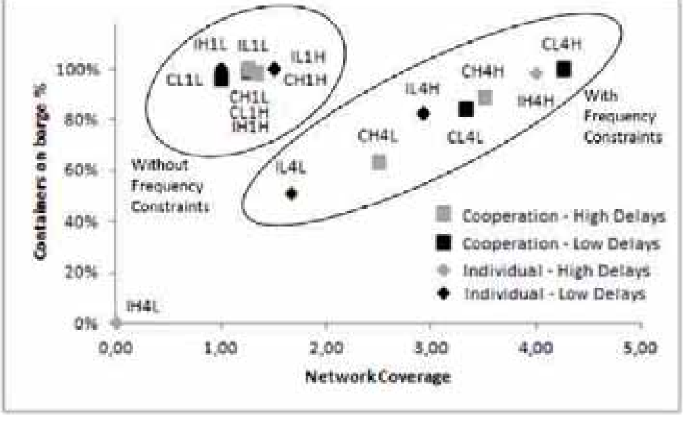
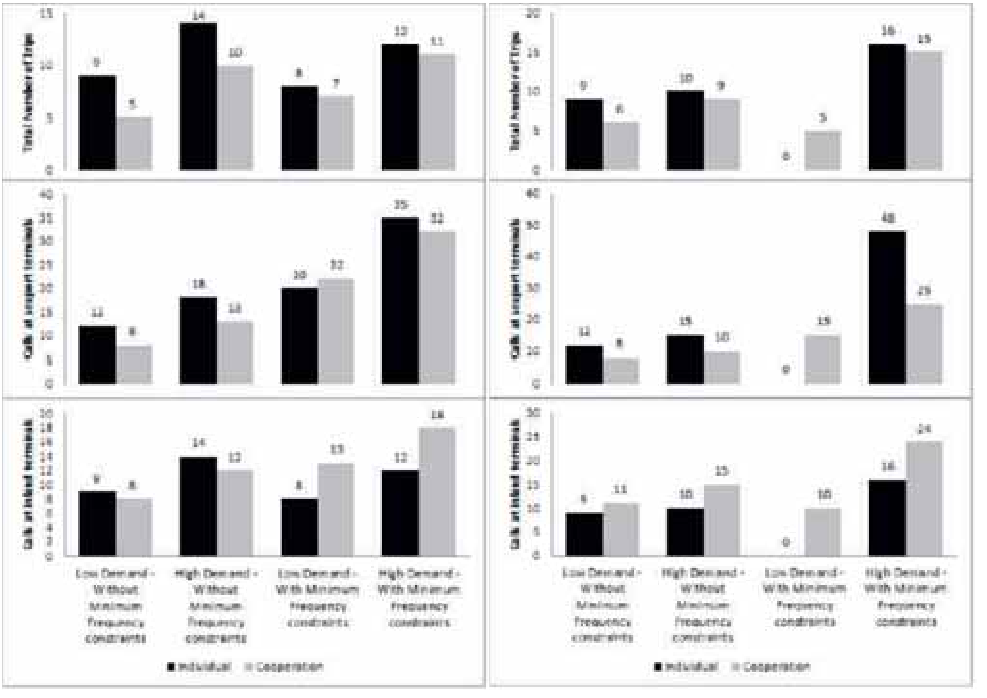


Figure 5.6: Network Coverage vs Containers on barge



(a) Low Delays

(b) High Delays

Figure 5.7: Round trips and calls at seaport and inland terminals

also mentioned before that a big share of demand is satisfied with trucking. The effect of minimum frequency constraints also seem to have a great effect on the construction of round trips. More round trips are constructed with more calls at seaport terminals so that each round trip satisfies smaller batches of demand of a greater number of OD pairs. This is more apparent in Fig. 5.8, that contrasts the average number of terminals visited with the average network coverage, in which again the consideration of minimum frequency constraints separates the solution in two different distinctive groups. Moreover, in Fig. 5.7, it is shown that when cooperation is considered there seems to be a clear advantage for barges adding calls at the inland terminals where delays are considerably shorter than adding calls at the congested seaport area such that demand of more OD pairs can be served per round trip.

Last, we look at the quality of the service provided by each network configuration by looking at the average frequency of services provided for the OD pairs and the percentages of demand satisfied by barges and by trucks in Fig. 5.5 and Fig. 5.6 while

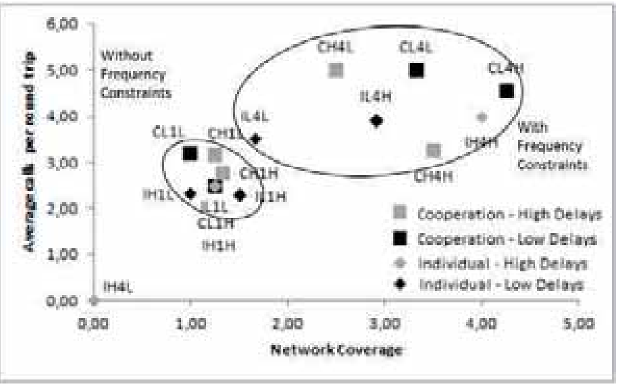


Figure 5.8: Network Coverage vs Number of calls

we contrast the network coverage with the capacity installed in Fig. 5.9, in which again the solutions are separated in two distinctive groups by the implication of the minimum frequency constraints. On the one hand, when no minimum frequency constraints are considered, almost all demand is satisfied by barge trips while the frequency of services for each OD pair increases only when it is dictated by higher demand. In that way, barges call at fewer terminals and that lowers the circulation times of their round trips such that more round trips can be achieved. On the other hand, when minimum frequency constraints are imposed, smaller batches of demand for each OD pair have to be consolidated in round trips such that efficient round trips can be formed. Of course considering minimum frequency constraints makes solutions more realistic since it is hardly ever the case that weekly demand of an OD pair can be satisfied by one or two itineraries. In our model not meeting the minimum frequency constraints leads to higher truck usage.

5.5.3 Experimental results summary

The effects of the main experimental dimensions on the optimal barge network design are summarized in Tab. 5.10.

Our results show that all dimensions considered have a significant effect on the optimal design of such networks. On the one hand, the optimal network design can be considered to be case specific, and thus only some directions can be drawn on how the different characteristics affect the optimal solutions.We develop an analytical model in the next section to study how these design trade-offs interact. On the other hand, our observation regarding the significance of considering the service time constraints

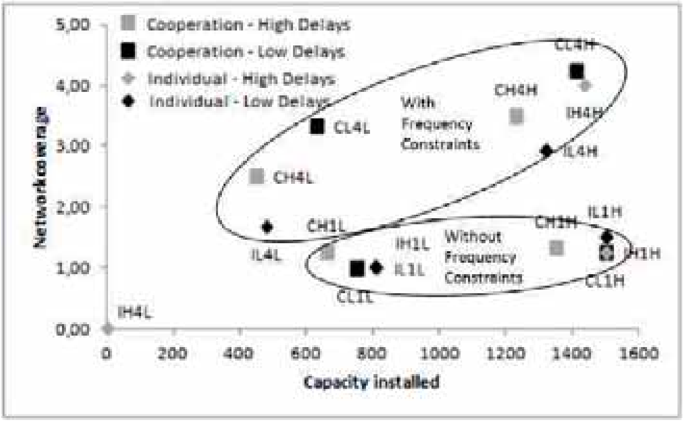


Figure 5.9: Network Coverage vs Capacity Installed

Table 5.10: Effect of variables on optimal network designs

	Cost (per TEU)	Network Coverage	Size of Barges	Number of Barges	Round trips per barge	Calls per round trip	Trucking
Cooperation	⇓	⇑	⇑	⇓	⇑	⇓	⇓
Service time constraints	⇑	⇑	⇓	⇑	⇓	⇑	⇑
Higher Delays	⇑	⇓	⇓	⇑	⇓	⇓	⇑
Higher Demand	⇓	⇑	⇑	⇑	⇑	⇓	⇓

(as show in Fig. 5.6, Fig. 5.8, and Fig. 5.9) has a more general effect. In case service time constraints are considered, the network coverage is not only driven by demand volume but also by demand characteristics. This is quite crucial when planning high capacity mode services at the tactical or strategic levels and such demand characteristics should be considered. Considering them leads to more realistic solutions, since demand is distributed over several services on the planning horizon. Moreover, high capacity services compete with road transportation not only in terms of costs but also in terms of service times. The above is crucial to the effective modeling of such systems at the tactical and strategic levels.

5.6 Stylized analytical model to illustrate design trade-offs

The optimal fleet selection and routing is always case specific and will depend on several characteristics like expected demand, delays, distances, available resources and others. This is supported by the results of the optimization model that has been presented in section 5.4. To better understand and appreciate the outcomes of the optimization model, we discuss in this section a simplified analytical model that provides a better understanding of how the different design parameters can affect the different performance characteristics of such networks. At the end of this section, we compare the outcomes of the analytical model with the outcomes of the optimization model. This will allow us to intuitively understand how the optimal solutions are driven by basic trade-offs already captured by the analytical model and where the optimal solutions are tuned to more complex features of the decision problem at hand.

The analytical model presented in this section is not completely equivalent to the MIP model presented in the previous section, since several assumptions and simplifications have been considered for its formulation. The assumptions that underlie the analytical model are the following: (a) demand is equally distributed among OD pairs, (b) the design variables (number of barges, barge size, number of calls, frequency) are assumed to be continuous, (c) the actual cost data are replaced by approximating continuous cost functions, (d) the circulation time of a round trip is assumed to only depend on the number of calls and not the routing itself, (e) trucking is not considered since the design parameters are continuous and elastic demand need not to be considered.

Table 5.11: Notation

Sets	**Decision Variables**
N^I: Set of inland terminals (3 used)	Q: Size of barges
N^S : Set of Seaport Terminals (4 used)	x: Number of barges
Costs	n_r: Average number of terminals visited per round trip
W: Cost of leasing barge. $W = f_w(Q) \approx u_1 + u_2 Q$ (Economies of scale) $W = 5000 + 50Q$ (used)	N_I^r and N_S^r: Average number of inland and seaport terminals visited per round trip
v: Variable cost per round trip of a barge. $v = f_v(Q) \approx u_3 + u_4 Q$ (Economies of scale) $v = 300 + Q$	p_I: Percentage of calls at inland terminals such that $N_I^r = n_r p_I$ and $N_S^r = n_r(1 - p_I)$
Time	**Performance Indicators**
T: Planning horizon (168 hours)	SOD: Average number of OD pairs served per round trip
τ : Fixed time per round trip (16 hours)	CT: Average circulation time of a round trip
d_I, d_S: Variable time per call in a round trip (d_I: 2hours, d_s: 4 or 8 hours)	RT: Average number of round trips per barge
	$TotalCost$: Estimated cost of plan
	$Capacity$: Port hinterland capacity installed over the network
	$NetworkCoverage$: Average service frequency per OD pair

5.6.1 Analytical expressions

The model presented in this section provides some analytical expressions that connect performance indicators like the cost, capacity and network coverage with different design parameters like size of barges, number of calls per round trip, distribution of calls between seaport and inland terminals.

The notation used in this section and the values of some parameters fixed in this study are summarized in Tab. 5.11. A network is considered consisting of the node sets N^I and N^S denoting inland and seaport terminals respectively. It follows that $|N^I| \cdot |N^S|$ undirected (O, D) pairs are considered, each associated with some demand that will be satisfied by a number of transport services. Vehicles of different types are considered, that would result in an average barge size of TEUs. The fixed (leasing) and variable (routing) costs of using barges are assumed to depend on their size, which allows us to model economies of scale. The barges are assumed to perform round trips continuously over the planning horizon. The round trips are characterized by their expected average circulation time, CT, which is inversely proportional to the expected number of round trips that a barge can perform during the time horizon. The expected circulation time (CT), equation (5.2) , is calculated as a fixed sailing time, τ, connecting the seaport with the hinterland areas enhanced by the variable delay times, d_I, d_S, associated with the additional time needed for calling at inland and seaport terminals (sailing, mooring, unmooring, handling, delays). In our case we consider a hinterland and a seaport area where terminals in each area are located relatively close to each other so the main difference in the variable times is in the delays faced which are much higher at the seaport terminals. Considering the above it is clear that the expected circulation time of round trips is connected with the average number of inland terminals n_I, and seaport terminals, n_S. The number of calls and the distribution among inland and seaport terminals also affects the expected number of OD pairs that are served per round trip, SOD, as calculated in equation (5.16).

The three performance indicators, namely the expected total cost, installed capacity, and network coverage can be calculated by means of formulas (5.17) – (5.19). It is clear that all measures are linearly proportional to the number of barges used.

The expected total cost (5.17) is calculated as the product of the average fixed and variable cost of a barge per time horizon and the number of barges. The fixed and variable costs are calculated with functions that depict economies of scale and are connected with the average size of the barges used.The capacity installed (5.18) is calculated as the product of the average barge size, the number of barges, and the expected number of round trips. The network coverage measure (5.19) depicts the expected frequency of services per OD pair and is calculated as the product of the average number of OD pairs served per round trip (5.16), the expected number of round trips per barge (5.15), and the number of barges divided by the number of OD pairs considered.

$$CT = \tau + 2d_I n_I + d_S n_S \tag{5.14}$$

$$RT = \frac{T}{CT} \tag{5.15}$$

$$SOD = n_I \cdot n_S \tag{5.16}$$

$$\begin{aligned} TotalCost &= (W + vRT)\, x \\ &= \left(f_w\,(Q) + f_v\,(Q)\, \frac{T}{\tau + 2d_I n_I + d_S n_S} \right) x \end{aligned} \tag{5.17}$$

$$\begin{aligned} Capacity &= Q \cdot RT \cdot x \\ &= Q \cdot \frac{T}{\tau + 2d_I n_I + d_S n_S} \cdot x \end{aligned} \tag{5.18}$$

$$\begin{aligned} NetworkCoverage &= \frac{SOD}{|N^I|\,|N^S|} \cdot RT \cdot x \\ &= \frac{n_I n_S}{|N^I|\,|N^S|} \cdot \frac{T}{\tau + 2d_I n_I + d_S n_S} \cdot x \end{aligned} \tag{5.19}$$

We evaluate formulas (5.17) – (5.19) for a range of their input parameters in order to identify how the different network design characteristics interact and affect the performance indicators of such a network. There are several input parameters, so for a better illustration of the results we construct grids, each is associated with a specific number of barges, while each line is associated with either a barge size or a number of terminals included in a round trip.

The tradeoffs between capacity installed and network coverage are shown in Fig. 5.10. The capacity can be increased by employing more and bigger barges while reducing the average number of terminals per round trip, while the network coverage can be increased by either employing more barges or by increasing the average number of

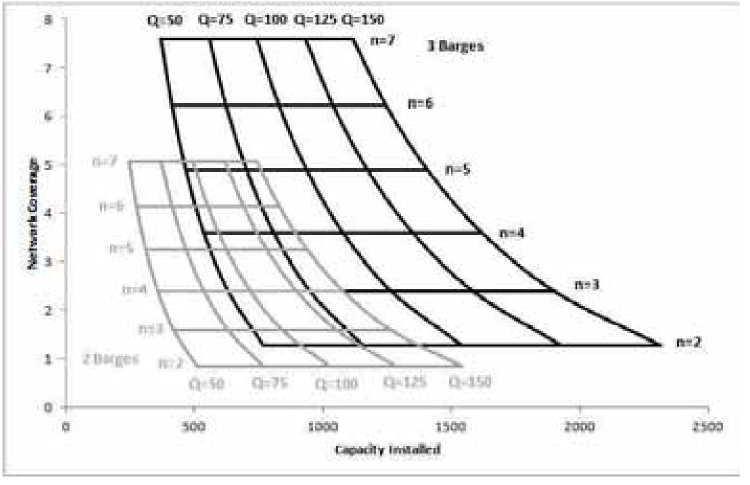


Figure 5.10: Capacity installed vs Network coverage

terminals visited per trip. It is clear that the same capacity and network coverage levels can be achieved with several combinations of the design parameters, but these different combinations can result in considerably different costs.

The relationship between network coverage and capacity installed with costs for several characteristics are shown in Fig. 5.11 and Fig. 5.12, respectively. The total costs mainly depend on the number of barges employed. Reducing the average number of calls increases the total costs, while increasing capacity and decreasing network coverage as discussed previously.

5.6.2 Analytical optimization model

Considering the above analytical expressions we could formulate a nonlinear constrained optimization problem with the same format as the MIP model presented in Section 5.4. In that sense, we would have the following nonlinear problem.

$$\min_{Q,x,n_s,n_I} \; TotalCost\,(Q, x, n_s, n_I) \tag{5.20}$$

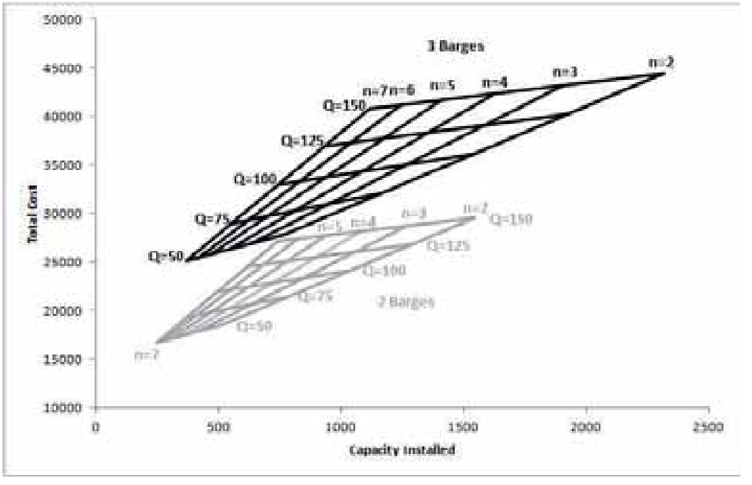


Figure 5.11: Capacity installed vs Total cost

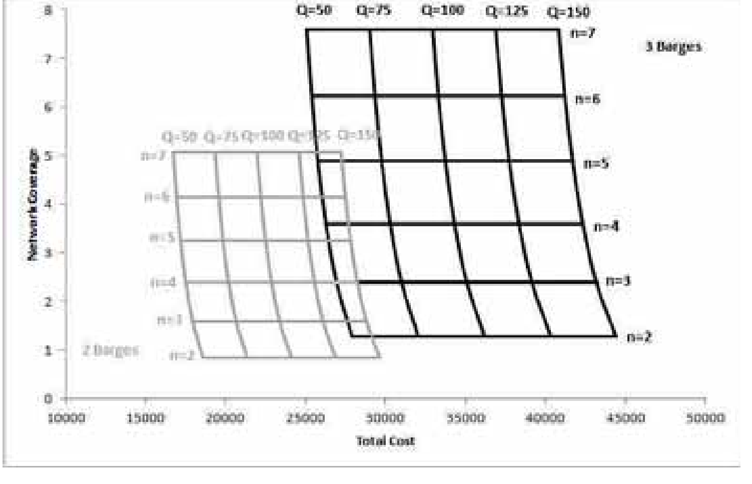


Figure 5.12: Network coverage vs Total costs

subject to:

$$Capacity\,(Q, x, n_s, n_I) \geq d \tag{5.21}$$

where d denotes the demand volume or the minimum capacity to be installed over the network, and

$$NetworkCoverage\,(x, n_s, n_I) \geq f \tag{5.22}$$

where f denotes the minimum sailing frequency per time period T.

The objective function was given by (5.17) , while the constraint functions where given by (5.18) and (5.19) respectively.

The above problem has an analytical unique optimal solution. Since the objective function is increasing in x and Q, their optimal values x^* and Q^* can be found as a function of n_I and n_S by solving the constraints with respect to them. The above yields the optimal number of barges

$$x^*\,(n_I, n_S) = f\frac{\tau + 2d_I n_I + d_S n_S}{T}\frac{N_I N_S}{n_I n_S} \tag{5.23}$$

and optimal average barge size

$$Q^*\,(n_I, n_S) = \frac{d\,(\tau + 2d_I n_I + d_S n_S)}{Tx^*} \tag{5.24}$$

respectively. By substituting (5.23) in (5.24), we obtain:

$$Q^*\,(n_I, n_S) = \frac{d}{f}\frac{n_I n_S}{N_I N_S} \tag{5.25}$$

The constraints indicate that the minimum attainable cost is given by (5.25) which

Table 5.12: Results analytical model

Scenario	Capacity Installed	Total Cost	Network Coverage	Containers on Barge	Number of Barges	Average Barge Size	Average Calls/ Trip
IL1L	650	25.420	2,42	100,0%	3,00	41.17	2,84
IL1H	1300	31.576	1,50	100,0%	3,00	72.22	2,00
IL4L	650	27.375	4.00	100,0%	3,00	54,2	5,00
IL4H	1300	36.150	4.00	100,0%	3,00	108,3	5,00
CL1L	650	13.560	1.00	100,0%	1,00	127,7	3,08
CL1H	1300	20.593	1.00	100,0%	1,00	255,3	3,08
CL4L	650	19.811	4.00	100,0%	1,67	108,3	6,00
CL4H	1300	29.482	4.00	100,0%	1,70	210,2	5,88
IH1L	650	26.598	1.29	100,0%	3,00	42.13	2,00
IH1H	1300	33.567	1.29	100,0%	3,00	84.26	2,00
IH4L	650	37.652	4.00	100,0%	4,33	54,2	5,00
IH4H	1300	49.919	4.00	100,0%	4,50	98,5	4,64
CH1L	650	14.975	1.00	100,0%	1,00	162,5	3,50
CH1H	1300	23.710	1.00	100,0%	1,06	297,32	3,37
CH4L	650	26.749	4.00	100,0%	2,36	105,1	5,88
CH4H	1300	38.621	4.00	100,0%	2,79	148,7	4,74

is a function of n_I and n_S .

$$TotalCost^* (n_I, n_S) = \left(f_w (Q^* (n_I, n_S)) + f_v (Q^* (n_I, n_S)) \frac{T}{\tau + 2 d_I n_I + d_S n_S} \right) x^* (n_I, n_S) \tag{5.26}$$

The optimal n_I and n_S can be derived by solving the system of equations that results from the partial derivatives of the cost function with respect to n_I and n_S. Although the above can lead to some complex analytical expressions depending on the assumed cost functions f_w and f_v, it can be easily approximated by using mathematical programming languages.

So we solved the same experiment as the one discussed in section 5.5 with the analytical model and we present the results in Tab. **??**.

By analyzing the results of the analytical model the barge design tradeoffs become clear. The number of barges and successively the number of calls per round trip is determined such that the minimum service frequency is achieved. The resulting service frequency exceeds the minimum required level only when its “free”; e.g. due to the minimum number of barges (scenarios IL1L and IL1H) where cooperation is not considered and at least one barge should be assigned for each inland terminal. The minimum service frequency is achieved first by increasing the number of calls, and thus the average number of demand OD pairs served per round trip, which has a small impact on cost, and then by increasing the number of barges which has a higher impact on cost. After a routing plan has been determined the optimal barge size is determined such that the resulting capacity meets the assumed demand. Of course this simplistic sequential optimization would not hold in the real case where design variables can only take discrete values. Overall, the results of the simplified model make clear and verify our observations based on the results of the MIP model.

5.7 Conclusions

In this paper, the heterogeneous fleet selection and barge routing problem in a port-hinterland network, connecting a set of closely located seaport container terminals with a set of closely located dryport terminals has been introduced. The analysis of the problem has been done based on a MIP and an analytical model, that have been proposed.

We formulated the MIP model at a tactical level such that the demand over a time horizon is served by a number of services distributed over that time horizon. The utilization of the barges is considered not only in terms of space utilization of their capacity but also in terms of time, by considering a continuous time formulation of the model. We take advantage of the special structure of the problem and provide a tight formulation that keeps down the number of variables and enables the efficient construction of round trips such that commercial solvers can be used to find near optimal solutions in relatively low computation times.

We developed a case and solved it with both the MIP and the analytical model aiming first to assess the impact of cooperation of closely located dryport terminals for capacity sharing, when visiting a main port area that consists of several container terminals, and second, to assess the main design tradeoffs in the optimal barge network design of such a case. In our experiment, we vary several parameters like the demand volume, the expected delays, and minimum frequency requirements, as described previously.

For the former case, the analysis of the results indicates that for our case cooperation will always lead to cost reductions varying from 12% to 48%. For the latter case, the optimal solutions were qualitatively analyzed. Bigger barges were deployed when cooperation was considered, while each barge in a round trip served more OD pairs but with smaller batch sizes; this is how a high frequency for every OD pair is achieved. Moreover, in case of cooperation, barges in most round trips seem to call more at the inland terminals instead at the congested seaport terminals.

The main driver of cost is the number and size of barges used. Network coverage is mainly affected by the number of barges and their rotation over the network. With bigger barges economies of scale can be achieved but their effective utilization usually leads to longer round trips with more calls at terminals such that demand for more OD pairs can be aggregated. This usually leads to increased circulation times and higher in-transit times for cargo. On the other hand, smaller barges usually can be used effectively for the formation of frequent shuttle services that satisfy demand for a single or few OD pairs. Shuttle services or routes with few calls usually achieve lower circulation times and more round trips can be realized within a given time horizon. Moreover, the number of calls during a round trip can affect the scheduling complexity as much as the reliability of transport times.

Although the case developed is rather small and results cannot be generalized easily, the main tradeoffs in such a design emerge. Moreover, our results demonstrate some features that seem to be critical for the tactical port hinterland network design and that models in this regime should incorporate. Our paper extends existing literature on port hinterland network design in this direction by proposing models on the tactical fleet selection and barge routing design incorporating these critical features.

6 Conclusion

This thesis contributes to the literature in two ways. From the technical side, new mathematical models aimed at port hinterland network design are formulated and heuristic procedures for their solutions are developed. The main technical contributions of this thesis are summarized in Tab. 6.1. From the managerial side, the data analysis and the experimental cases solved with the models provide insights for the main drivers that should be considered in the optimal design of freight combined transport services. The main managerial contributions are summarized in Tab. 6.2. Below we discuss the contribution of this thesis by going through the contents of the three chapters, and then in the following section we propose directions for future research in this regime.

Table 6.1: Technical contributions of this thesis

Chapter 1	1. Information flow framework for combined transport
	2. Regression model to explain container dwell times at seaport terminals
	3. Clustering analysis of shippers.
Chapter 2	1. Bi-level MIP formulation for the multimodal port-hinterland network design with frequency dependent economies of scale and frequency-dependent service times
	2. Development of MIP -equivalent formulation of the bi-level problem
	3. Development of heuristic procedure for solving the bi-level model
Chapter 3	1. Analytical expressions for calculating the expected cost, capacity and average frequency
	2. MIP formulation of Joint Mix Fleet deployment and Routing problem for the port hinterland network design
	3. Efficient formulation solved by commercial solvers

Table 6.2: Managerial contributions of this thesis

<table>
<tr><td rowspan="4">Chapter 1</td><td>1. Container dwell times determinants and their effect size</td></tr>
<tr><td>2. Shippers effect on container dwell times</td></tr>
<tr><td>3. Shippers characteristics and service-time needs</td></tr>
<tr><td>4. Insights into modal choice determinants</td></tr>
<tr><td rowspan="3">Chapter 2</td><td>1. Combined services market penetration through tradeoffs among economies of scale, service frequency and pricing</td></tr>
<tr><td>2. The effect of considering expected service time constraints in network design</td></tr>
<tr><td>3. Port-to-Door vs Port-to-Inland Port network design</td></tr>
<tr><td rowspan="3">Chapter 3</td><td>1. Relationships and tradeoffs among cost, capacity installed and network coverage</td></tr>
<tr><td>2. Effect of cooperation of dryports in cost and network coverage and fleet mix</td></tr>
<tr><td>3. The effect of considering expected service time constraints in network design</td></tr>
</table>

6.1 Summary of results

The conclusions of this thesis present our main findings towards the research objectives as they were formulated in the introduction of this thesis.

Research Objective 1. Analyze the combined transport process for port-hinterland container transport based on empirical data. Assess the main performance characteristics of shippers using combined transportation. More specifically, determine which characteristics of shippers influence container dwell times.

The first research objective was addressed in chapter 2. We analyzed the import container process and discussed the physical movement of containers in parallel to the information streams among actors. Our analysis covered the container cycle from discharge of full containers at the seaport terminal to the return of empty containers at the inland terminal. The main determinants of container dwell times in seaport and inland container terminals were qualitatively and quantitatively examined. In particular, we examined the determinants of dwell times of full imported containers originating from one seaport terminal and destined to an inland region covered by a network of intermodal inland container terminals. We presented a model that explains and predicts dwell times at container terminals. In particular, 48% of the dwell time variance is explained by factors related to the shippers involved. In contrast to the common assumption that the container terminal performance is the main determinant of dwell times, the shipper has emerged as the most important actor in control of the import process and we showed that other factors exogenous to the container terminal significantly influence dwell times. To the best of our knowledge, this is the first study that quantitatively assesses the impact of such factors. Our results show connections between dwell times and time criticality, and the value of information in the reduction of dwell times. The assumption that dwell time performance can be treated as a purely endogenous capacity performance criterion of seaport terminals is challenged. The identification of the main determinants of container dwell times is useful to policy makers at container terminals and port authorities when identifying measures for the reduction of container dwell times; an effective measure would be be to incentivize or penalize shippers to accelerate the process.

Moreover, clusters of shippers are identified with different characteristics and different performances in terms of dwell times and modal choice. It was shown that shippers have different service time needs regarding the inland transport of their containers. The above observation motivated the research performed in the next chapters, in which we considered that including the resulting service level offered to clients is crucial to the effective design of port-hinterland services. This was a main modeling concern relevant to addressing Research Objectives 2 and 3.

In particular, we consider three elements to be crucial for the effective design of port hinterland networks: The different actors involved, the resulting service level offered (measured either by expected service times or by service frequency), and the expected cost of the proposed services.

The modeling of port-hinterland combined services is challenging and differs from usual service network design. The main difference lies in the fact that demand for combined port-hinterland transport services is elastic. That means that demand can always be satisfied via trucking, the quickest and most flexible modality. Given the above, effective models in this regime at the strategic and tactical levels should consider the penetration of combined transport compared to road trucking and other services provided by the competition. The penetration of combined services is based on three pillars: cost, service times, and sustainability.

Research Objective 2. Establish a model to design a multimodal hinterland transport network at the tactical level, by establishing shuttle services of high capacity modes *between seaport terminals and inland container terminals. The model should balance costs faced by the carrier, and costs and service levels faced by the shippers that arise from the network design related decisions, such as the optimal mode size, the frequency of connections and pricing of services. The design of such a network and in particular the tariffs and the expected service times establish the market penetration of proposed services, while considering services offered by competitors.*

The second research objective is addressed in chapter 3. We discussed the case of extended gate operators in which maritime container terminal operating companies have extended their role from node operators to that of multimodal transport network operators. They have extended the gates of their seaport terminals to the gates of the inland terminals in their network by means of frequent shuttle services of high capacity transport modes such as river barges and trains. These network operators face the following three interrelated decisions: (1) determine which inland terminals act as extended gates of the seaport terminal, (2) determine capacities of the corridors, i.e. capacity of the transport means and frequency of service, and (3) set the prices for the transport services on the corridors. The network operator does so while anticipating the decisions of the customers, with different time requirements, who choose minimum cost paths to their final destinations, and who always have the option to choose alternative services offered by competitors. A bi-level MIP model to jointly design and price extended gate network services for profit maximization was proposed. The model extends existing bi-level models in a multimodal format by including service time constraints and economies of scale that are crucial for the efficient formulation of the multimodal nature of the problem. The resulting model was NP hard and its bi-level structure with the existence of bi-linear terms prohibited the use of commercial solvers. We proposed an alternative way to obtain a linear equivalent MIP formulation of the problem and to find optimal solutions for small instances. Considering the special structure of our problem, we proposed a heuristic that achieves near optimal solutions to larger instances of our problem in substantially less time.

Through experimental results for some realistic instances, we studied optimal network designs while comparing seaport-to-door and seaport-to-inland port services and situations where transit time requirements do and do not apply. Technically, our analysis revealed that network design and pricing of services decisions are interrelated, and that including service time constraints significantly affects the optimal network configurations. Managerially, our results show that when demand is relatively low, there are significant differences in the optimal network designs for port-to-door versus port-to-port services. In the case of port-to-door services, the prices of services are determined by the competition and not by the design of the network, so the network is designed against minimum costs, and economies of scale are achieved by consolidating flows through a limited number of extended gates. The case of port-to-port services is different, i.e. revenues are enhanced not so much by reducing costs through the exploitation of economies of scale, but by exploiting the possibilities to dedicate extended gates to market segments for which the competition leaves room for higher port-to-port tariffs. Thus container terminals participating in an extended gate concept should provide port-to-door services instead of port-to-port services.

The research in chapter 3 is calibrated to fit the case of extended gate operators but the model developed can be actually used in more general settings. The connections among the design and pricing of network services and service level offered to customers may be relevant in a lot of freight network design cases. Moreover, it may be applied to the design of public transport services, where the expected transport time, frequency of connections, and tariffs directly affect the modal choice of customers.

The model in chapter 3 is limited to the design of point-to-point connections and consolidation mainly happens on some corridors. There are other cases, where point-to-point connections may not be a viable option, and consolidation is best achieved by the rotation of resources, like barges, trains and trucks along terminals, hubs etc. In chapter 4, we consider such a case where the optimal fleet is selected and its deployment on a network of inland terminals is explored.

Research Objective 3. Establish a model to design a multimodal hinterland transport network at the tactical level, by establishing rotation services of high capacity modes along seaport terminals and inland terminals. The model should design the optimal fleet and its deployment on a network, in such a way that costs are minimized while demand is satisfied and expected service levels required by the shippers are met.

The third research objective is addressed in chapter 4. We studied the case of inland intermodal carriers that schedule barge rotations to satisfy demand between seaport and inland terminals. At the tactical level, the optimal fleet composition has to be determined and rotation plans have to be proposed such that capacity is installed over the network, while anticipating demand realization. We developed a MIP model for Fleet Size and Mixed Vehicle Routing problem (FSMVRP) with multiple depots especially adapted for the tactical design of port hinterland intermodal services. The model aims to support tactical decisions regarding: (1). the fleet size and mix selection, (2). the routing of the fleet over the network for a long time horizon in order to satisfy demand under some service time related constraints, and (3). the assignment of container flows to given services in order to assess the performance of the proposed network design. FSMVRP models are NP-hard since they can be reduced to the VRP but we took advantage of the special structure of the problem in our case, and we provided a compact MIP formulation that enables the easy construction of round trips that can be solved with commercial solvers. The utilization over time is assessed by allowing multiple round trips per vessel during the time horizon while considering the circulation times of round trips, that consist of sailing times, handling times and expected delays. The model was applied to a real case of an alliance of closely located dryports that connect with container terminals in a seaport area, and we studied the impact of cooperation by capacity sharing, demand variations and delay scenarios. Our results show that the fleet size and mix should be jointly considered with its routing, since together they determine the capacity installed, the resulting cost and the network coverage of the proposed collective of services. Our case study shows that the collaboration of closely located dryports, for capacity sharing, not only results in lower costs by the achievement of economies of scale through the selection of bigger vessels but also to a higher market penetration of barge services through the achievement of higher network coverage. Moreover, there is a capacity boost associated with more calls at the inland side where delays are usually lower, which results in lower circulation times and more round trips are achieved.

Our analysis showed some trends on how the different design parameters can affect the performance in terms of both costs and service levels, but also revealed that the optimal design is case specific. So, we developed some analytical expressions that depict the connection between design parameters like the number of vehicles, their size and their routing characteristics, and performance measures like the total cost, the capacity installed and network coverage.

6.2 Discussion and future research

The supply side of transport networks has been studied extensively in literature. Most contributions are focused on vehicle routing and network design models and their extensions. Most models concern decisions that are somewhere in between the operational and tactical levels. Much effort is given to the development of efficient heuristic procedures to solve these computationally intensive models for real sized instances.

In practice though, these generic models have to be adapted to fit effectively the specific needs and structures of every industry, especially at the tactical level. This is usually done by modifying the objective functions and constraints used in the model or by considering nonlinear relationships between decision variables and parameters. The above, on the one hand, makes solutions more realistic and with higher practical impact, but on the other hand, does not allow the use of already defined algorithms for their efficient solution, since usually these are built to solve generic problems.

Since computational power increases continuously and commercial solvers become more and more efficient, efforts should be given in literature to define models that fit reality better. This can be achieved by addressing two main issues. First, in most transport systems several actors are involved, at least the service operator and the service receiver, usually with different objectives and constraints; the perspectives of which should be considered for the realization of effective optimal solutions. Second, several decisions that are interrelated are treated separately in literature, in order to reduce the computational intensiveness.

So, our main proposition for future research in the field would the development of optimization models with higher practical impact. Several optimization modeling structures exist that would allow the consideration of the above issues but very few are applied in a real context. This especially holds true for port-hinterland network design. Bilevel, multilevel, non Linear, stochastic programming, mathematical programming with equilibrium constraints (MPEC) formulations allow for a more realistic representation of systems, but still there are very few contributions on these types with high practical impact.

The models in this thesis can be considered first steps toward these goals, since integrated decisions and multiple stakeholders are model elements in chapters 3 and 4. Our research could be extended in several ways. In particular, we discuss bellow some possible extensions of the research performed in this thesis.

Regarding the analysis of container dwell times, the container export process could also be considered since at the same time both import and export containers are stored in container terminal yard. Moreover, the analysis could be extended for several container terminals and inland carriers. In that way, the impact of all the different possible determinants on container dwell times could be assessed simultaneously and findings could be generalized.

The analysis we did in the second chapter also revealed that the shippers have different characteristics, and needs, and that they can affect the port-hinterland transport process with their actions and selections. We considered this and incorporated the expected service times offered to shippers in the models developed in chapters 3 and 4. But the demand side of port-hinterland container transport should be analyzed in more depth, such that factors that determine mode and service selection should become clear. Then, the demand side should be incorporated more explicitly when designing the supply side of such networks. For example, hinterland multimodal networks offer to shippers many transport alternatives: different modalities, combined transport services, transport services combined with other added value activities, door-to-door services or port-to-port services, just in time services etc. All these different options result in different costs, internal and external, and different service times and services levels. So the demand side should be studied extensively in order to better understand which shipper characteristics and needs are the main drivers of transport service selection.

Finally, all the different transport services are offered to shipper by several parties, competitors, and thus the competition should also be considered in the tactical design of transport services. This is especially the case for multimodal inland carriers, that design multimodal hinterland networks in which they offer transport services. These hinterland networks are usually overlapping and the competitive position of the network operators depend on services offered compared to those offered by competition. In chapter 3, we explicitly considered the competition in terms of pricing while in chapter 4 we considered the competition in terms of recourse actions (trucking). But the competition should be considered more explicitly when one is interested on penetration of the designed services. For example, an MPEC formulation could be used to extend the bilevel formulation we proposed on chapter 3 to consider several inland network operators offering transport services in overlapping networks.

Bibliography

Anghinolfi, D., Paolucci, M., Sacone, S., Siri, S., 2011. Freight transportation in railway networks with automated terminals: A mathematical model and mip heuristic approaches. European Journal of Operational Research 214 (3), 588–594.

Bauer, J., Bectas, T., Crainic, T., 2009. Minimizing greenhouse gas emissions in intermodal freight transport: an application to rail service design. Operational Research Society 61 (2), 530–542.

Behdani, B., Fan, Y., Wiegmans, B., Zuidwijk, R., 2014. Multimodal schedule design for synchromodal freight transport systems. Available at SSRN 2438851.

Braekers, K., Caris, A., Janssens, G., 2012. Optimal shipping routes and vessel size for intermodal barge transport with empty container repositioning. Computers in Industry 64 (2), 155–164.

Brotcorne, L., Cirinei, F., Marcotte, P., Savard, G., 2011. An exact algorithm for the network pricing problem. Discrete Optimization 8 (2), 246–258.

Brotcorne, L., Cirinei, F., Marcotte, P., Savard, G., 2012. A tabu search algorithm for the network pricing problem. Computers & Operations Research 39 (11), 2603–2611.

Brotcorne, L., Labbé, M., Marcotte, P., Savard, G., 2000. A bilevel model and solution algorithm for a freight tariff-setting problem. Transportation Science 34 (3), 289–302.

Brotcorne, L., Labbé, M., Marcotte, P., Savard, G., 2001. A bilevel model for toll optimization on a multicommodity transportation network. Transportation Science 35 (4), 345–358.

Brotcorne, L., Labbé, M., Marcotte, P., Savard, G., 2008. Joint design and pricing on a network. Operations Research 56 (5), 1104–1115.

Brotcorne, L., Marcotte, P., Savard, G., Wiart, M., 2005. Joint pricing and network capacity setting problem. Advanced OR and AL Methods in Transportation

(Jaszkiewicz, Kaczmarek, Zak and Kubiak, eds.). Publishing House of Poznan University of Technology.

Caris, A., Macharis, C., Janssens, G., 2008. Planning problems in intermodal freight transport: accomplishments and prospects. Transportation Planning and Technology 31 (3), 277–302.

Caris, A., Macharis, C., Janssens, G. K., 2012. Corridor network design in hinterland transportation systems. Flexible Services and Manufacturing Journal 24 (3), 294–319.

Castillo, B. D., Daganzo, C. F., 1993. Handling strategies for import containers at marine terminals. Transportation Research Part B: Methodological 27 (2), 151–166.

Chu, C., Huang, W., 2005. Determining container terminal capacity on the basis of an adopted yard handling system. Transport Reviews 25 (2), 181–199.

Cochrane, R., 2008. The effects of market differences on the throughput of large container terminals with similar levels of efficiency. Maritime Economics & Logistics 10 (1), 35–52.

Crainic, T., 2000. Service network design in freight transportation. European Journal of Operational Research 122 (2), 272 – 288.

Crainic, T., DellÓlmo, P., Ricciardi, N., Sgalambro, A., 2013. Optimizing dry-port-based freight distribution planning. CIRRELT-2013-10.

Crainic, T., Kim, K., 2007. Chapter 8 intermodal transportation. In: Barnhart, C., Laporte, G. (Eds.), Transportation. Vol. 14 of Handbooks in Operations Research and Management Science. Elsevier, pp. 467–537.

Crainic, T. G., Rousseau, J., 1986. Multicommodity, multimode freight transportation: A general modeling and algorithmic framework for the service network design. Transportation Research Part B: Methodological 20 (3), 225–242.

Crevier, B., Cordeau, J.-F., Savard, G., 2012. Integrated operations planning and revenue management for rail freight transportation. Transportation Research Part B: Methodological 46 (1), 100–119.

Daschkovska, K., Scholz-Reiter, B., 2008. Electronic seals for efficient container logistics. In: Haasis, H., Kreowski, H., Scholz-Reiter, B. (Eds.), Dynamics in Logistics. pp. 305–312, 1st International Conference on Dynamics in Logistics, Bremen, 2007.

Douma, A., Schutten, M., Schuur, P., 2009. Waiting profiles: An efficient protocol for enabling distributed planning of container barge rotations along terminals in the port of rotterdam. Transportation Research Part C: Emerging Technologies 17 (2), 133–148.

Ebeling, C., 2009. Evolution of a box. Invention and Technology 23 (4), 8–9.

Frémont, A., Franc, P., 2010. Hinterland transportation in europe: Combined transport versus road transport. Journal of Transport Geography 18 (4), 548–556.

Gelareh, S., Nickel, S., 2011. Hub location problems in transportation networks. Transportation Research Part E: Logistics and Transportation Review 47 (6), 1092–1111.

Gendreau, M., Marcotte, P., Savard, G., 1996. A hybrid tabu-ascent algorithm for the linear bilevel programming problem. Journal of Global Optimization 8 (3), 217–233.

Golden, B., Assad, A., Levy, L., Gheysens, F., 1984. The fleet size and mix vehicle routing problem. Computers & Operations Research 11 (1), 49–66.

Hamzaoui, S., Ben-Ayed, O., 2011. Parcel distribution timetabling problem. Operations Management Research 4 (3-4), 138–149.

Horner, M., O'Kelly, M., 2001. Embedding economies of scale concepts for hub network design. Journal of Transport Geography 9 (4), 255–265.

Iannone, F., Thore, S., 2010. An economics logistics model for the multimodal inland distribution of maritime containers. International Journal of Transport Economics 37 (3), 281–326.

Ishfaq, R., Sox, C. R., 2012. Design of intermodal logistics networks with hub delays. European Journal of Operational Research 220 (3), 629–641.

Janic, M., 2007. Modelling the full costs of an intermodal and road freight transport network. Transportation Research Part D: Transport and Environment 12 (1), 33–44.

Kimms, A., 2006. Economies of scale in hub & spoke network design models: We have it all wrong. In: Perspectives on Operations Research. Springer, pp. 293–317.

Klincewicz, J., 2002. Enumeration and search procedures for a hub location problem with economies of scale. Annals of Operations Research 110 (1-4), 107–122.

Konings, R., 2003. Network design for intermodal barge transport. Transportation Research Record: Journal of the Transportation Research Board 1820 (1), 17–25.

Konings, R., 2007. Opportunities to improve container barge handling in the port of rotterdam from a transport network perspective. Journal of Transport Geography 15 (6), 443–454.

Labbé, M., Marcotte, P., Savard, G., 1998. A bilevel model of taxation and its application to optimal highway pricing. Management Science 44 (12(1)), 1608–1622.

Leveque, P., Roso, V., 2002. Dryport concept for seaport inland access with intermodal solutions. Master Thesis. Department of Logistics and Transportation. Chalmers University of Technology.

Li, L., Tayur, S., 2005. Medium-term pricing and operations planning in intermodal transportation. Transportation Science 39 (1), 73–86.

Little, J. D., Graves, S. C., 2008. Little's law. In: Building Intuition. Springer, pp. 81–100.

Liu, F.-H., Shen, S.-Y., 1999. The fleet size and mix vehicle routing problem with time windows. Journal of the Operational Research Society, 721–732.

Lium, A.-G., Crainic, T., Wallace, S., 2009. A study of demand stochasticity in service network design. Transportation Science 43 (2), 144–157.

Macharis, C., Bontekoning, Y., 2004. Opportunities for or in intermodal freight transport research: A review. European Journal of Operational Research 153 (2), 400–416.

Meng, Q., Wang, S., 2011. Liner shipping service network design with empty container repositioning. Transportation Research Part E: Logistics and Transportation Review 47 (5), 695–708.

Merckx, F., 2005. The issue of dwell time charges to optimize container terminal capacity. In: Proceedings of the IAME 2005 Annual Conference, Limassol, Cyprus.

Moini, N., Boile, M., Theofanis, S., Laventhal, W., 2012. Estimating the determinant factors of container dwell times at seaports. Maritime Economics & Logistics 14 (2), 162–177.

Notteboom, T., 2008. The relationship between seaports and the inter-modal hinterland in light of global supply chains (2008/10).

Notteboom, T., Merckz, F., 2006. Freight integration in liner shipping: A strategy serving global production networks. Growth and Change 37 (4), 550–569.

Notteboom, T., Rodrigue, J., 2005. Port regionalization: towards a new phase in port development. Maritime Policy Management 32 (3), 297–313.

Notteboom, T., Rodrigue, J., 2007. Re-assessing port-hinterland relationships in the context of global commodity chains. In: Wang, J., Olivier, D., Notteboom, T., Slack, B. (Eds.), Ports, Cities, and Global Supply Chains. Ashgate Publishing,Ltd, pp. 51–69.

O'Kelly, M. E., Bryan, D., 1998. Hub location with flow economies of scale. Transportation Research Part B: Methodological 32 (8), 605–616.

Ottjes, J. A., Veeke, H., Duinkerken, M., Rijsenbrij, J. C., Lodewijks, G., 2006. Simulation of a multiterminal system for container handling. OR Spectrum 28 (4), 447–468.

Rodrigue, J.-P., Notteboom, T., 2009. The terminalization of supply chains: reassessing the role of terminals in port/hinterland logistical relationships. Maritime Policy & Management 36 (2), 165–183.

Roso, V., Lumsden, K., 2010. A review of dry ports. Maritime Economics & Logistics 12 (2), 196–213.

Roso, V., Woxenius, J., Lumsden, K., 2009. The dry port concept: connecting container seaports with the hinterland. Journal of Transport Geography 17 (5), 338–345.

Salhi, S., Rand, G. K., 1993. Incorporating vehicle routing into the vehicle fleet composition problem. European Journal of Operational Research 66 (3), 313–330.

Salhi, S., Sari, M., 1997. A multi-level composite heuristic for the multi-depot vehicle fleet mix problem. European Journal of Operational Research 103 (1), 95–112.

Sharypova, K., 2014. Optimization of hinterland intermodal container transportation. Ph.D. Thesis, Technische Universiteit Eindhoven.

Sharypova, K., Crainic, T. G., van Woensel, T., Fransoo, J., 2012. Scheduled Service Network Design with Synchronization and Transshipment Constraints for Intermodal Container Transportation Networks. Publication CIRRELT-2012-77, Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport, Université de Montréal.

Shintani, K., Imai, A., Nishimura, E., Papadimitriou, S., 2007. The container shipping network design problem with empty container repositioning. Transportation Research Part E: Logistics and Transportation Review 43 (1), 39–59.

SteadieSeifi, M., Dellaert, N. P., Nuijten, W., Van Woensel, T., Raoufi, R., 2014. Multimodal freight transportation planning: A literature review. European Journal of Operational Research 233 (1), 1–15.

Steenken, D., Voss, S., Stahlbock, R., 2004. Container terminal operation and operations research - a classification and literature review. OR Spectrum 26 (1), 3–49.

Van Baalen, P., Zuidwijk, R., Van Nunen, J., 2009. Port inter-organizational information systems: Capabilities to service global supply chains. Foundations and Trends (R) in Technology, Information and Operations Management 2 (2-3), 81–241.

Van Riessen, B., Negenborn, R., Dekker, R., Lodewijks, G., 2013. Service network design for an intermodal container network with flexible due dates/times and the possibility of using subcontracted transport. Tech. rep., Erasmus School of Economics (ESE).

Veeke, H., Ottjes, J., 2002. A generic simulation model for systems of container terminals. In: Amborski, K., Meuth, H. (Eds.), Modelling and Simulation 2002. pp. 581–587, 16th European Simulation Multiconference, Germany, 2002.

Veenstra, A., Zuidwijk, R., 2010. 17.the future of seaport hinterland networks. In: Liber Amicorum, In memoriam Jo van Nunen. Dinalog, pp. 205–215.

Veenstra, A., Zuidwijk, R., van Asperen, E., 2012. The extended gate concept for container terminals: Expanding the notion of dry ports. Maritime Economics & Logistics 14 (1), 14–32.

Veenstra, A. W., Zuidwijk, R. A., 2015. Towards efficient multimodal hinterland networks. Logistics and Supply Chain Innovation: Bridging the Gap between Theory and Practice, 55.

Vis, I. F., De Koster, R., 2003. Transshipment of containers at a container terminal: An overview. European journal of operational research 147 (1), 1–16.

Wieberneit, N., 2008. Service network design for freight transportation: a review. OR Spectrum 30, 77–112.

Summary

Globalization has led to a tremendous growth of international trade over the last century amounting to $18.8 trillion in 2014. Approximately 90% of non-bulk cargo is transported in shipping containers. The dominant mode in container transportation is maritime, in which containers are transported from a seaport to another seaport around the globe. Import containers are discharged in seaport container terminals and are destined to inland locations, a reverse process happens for export containers. The inland terminals can be close or far away from the seaport terminals where the containers were discharged. The container transport between the seaport and the inland locations is called port-hinterland transportation. Given the specific physical characteristics and infrastructure of each area this part of the transportation chain can be performed via trucks, trains or river vessels. The sequential use of multiple transport modes in port-hinterland transport is called combined transport. The main aim of this study is to analyze the port-hinterland transportation process and to develop models that support the design, planning and execution of port-hinterland transportation networks with high capacity modes such as barges and trains.

In the third chapter of this thesis we studied the port-hinterland intermodal transport process. We analyze container transport data that demonstrate that shippers have different needs regarding the port-hinterland container transport. Some opt to transport their containers in the quickest possible way using trucks, while others opt to use the seaport and inland terminal yards for shorter or longer storage until the cargo of the container is actually needed. In the latter case containers can be moved from the seaport to the inland terminal via trains or barges. The modality and type of port-hinterland transport services may vary from time to time depending on the urgency of the container delivery and available means.

In combined port-hinterland transport, the use of different modalities, the fleet selection, the capacity and frequency setting of services, the routing of assets in a network can significantly affect the overall performance of the transportation network in terms of costs, service times, modal split, sustainability, etc.

In this dissertation we studied two cases of port-hinterland intermodal network design and developed models for their optimal design. The first study, focuses on container terminal operating companies that have extended their role from node operators to that of multimodal transport network operators. They have extended the gates of their seaport terminals to the gates of inland terminals in their network by means of frequent services of high capacity transport modes such as river vessels (barges) and trains. These network operators face the following three interrelated decisions: (1) determine which inland terminals act as extended gates of the seaport terminal, (2) determine capacities of the corridors, i.e. size of the transport modes and frequency of service, and (3) set the prices for the transport services on the network. We proposed a bi-level programming model to jointly design and price extended gate network services for profit maximization. Our results showed that the above decisions are interrelated, and lead to different optimal designs compared to those that would emerge if treated separately.

The second study, focuses on a case of a possible alliance of dryports closely located in the hinterland that share capacity to efficiently transport containers from and to a seaport area that consists of several container terminals. The tactical design of scheduled barge transport services involves decisions regarding both the fleet composition and its routing through the inland waterway network. Integrating these decisions would make the resulting network more competitive in satisfying expected demand and service time requirements set by the shippers. We develop some analytical expressions and a MIP formulation for the Fleet Size and Mix Vehicle Routing (FSMVRP) specially adapted to the Port-Hinterland intermodal barge network design. Our results not only show that in the case of cooperation of the dryports there could be significant costs and service quality benefits but also that the fleet selection and routing are interrelated decisions that should be treated simultaneously.

In this dissertation we develop models that support the design of combined services in networks consisting of seaport and inland terminals such that consolidation opportunities emerge and high frequency services are achieved. We achieve that by explicitly considering the time dimension, economies of scale in our modeling next to other factors crucial to the effective modeling in this regime.

Samenvatting (Summary in Dutch)

Globalisering is gepaard gegaan met een enorme groei aan internationale handel en deze had een waarde van maar liefst $18.8 triljoen in 2014. De grote hoeveelheid lading die over grote afstanden moet worden vervoerd, buiten bulk lading, gaat voor 90% in gestandaardiseerde lading eenheden, zogeheten containers. Containers worden het meest getransporteerd per zee, en dit gebeurt tussen havens wereldwijd. Import containers worden gelost in de zeehaven via container terminals, en zijn bestemd voor locaties landinwaarts, en omgekeerd geschiedt het proces voor export containers. De terminals landinwaarts kunnen dicht bij de zeehaven liggen, maar ook wat verder weg. Het containervervoer tussen de zeehaven en de landinwaartse locaties heet haven-achterland transport.

Afhankelijk van de specifieke fysieke kenmerken en de infrastructuur van dit deel van de transportketen, kan het transport plaatsvinden met gebruik van vrachtwagens, treinen, of binnenvaartschepen. Het opeenvolgend inzetten van meerdere vervoerswijzen in haven-achterlandtransport van containers wordt intermodaal transport genoemd.

Het belangrijkste doel van dit proefschrift is het analyseren en verbeteren van het haven-achterlandtransportproces. Daartoe worden modellen ontwikkeld die het ontwerp, de planning, en de uitvoering van haven-achterlandtransportnetwerken ondersteunen. We richten ons hierbij vooral op vervoersmiddelen als binnenvaartschepen en treinen, die een hoge capaciteit hebben. In het derde hoofdstuk van dit proefschrift onderzoeken we het intermodaal transport proces van het haven-achterland. Uit de data analyse omtrent container transport komt naar voren dat verladers, de verzenders of ontvangers van de lading, verschillende behoeften hebben met betrekking tot het haven-achterland containervervoer.

Sommige veladers kiezen ervoor om hun containers op de snelst mogelijke manier met behulp van vrachtwagens te vervoeren, terwijl anderen ervoor kiezen om de zeehaven en de landinwaartse terminals te gebruiken voor kortere of langere opslag, tot de lading van de container daadwerkelijk nodig is. In het laatste geval kunnen containers worden verplaatst van de zeehaven naar de landinwaartse terminals met gebruik van treinen of binnenvaartschepen. Het gebruikte vervoersmiddel (schip of trein, maar ook: omvang) kan variëren afhankelijk van de urgentie van de container levering en de beschikbare vervoerswijzen. Bij gecombineerde haven-achterlandtransport kunnen het gebruik van verschillende vervoersmiddelen, de beschikbare vloot, de capaciteit en de frequentie van diensten, en de routering van vervoersmiddelen in een netwerk, een aanzienlijke invloed hebben op de algehele prestaties van het vervoersnetwerk qua kosten, service tijden, verdeling van transport over vervoersmiddelen, duurzaamheid et cetera.

In dit proefschrift bestuderen we twee casussen omtrent het ontwerp van haven-achterland intermodale netwerken en ontwikkelen we modellen voor optimalisatie van het ontwerp. De eerste studie richt zich op container terminalbedrijven die hun rol van beheerder van knooppunt hebben uitgebreid naar die van netbeheerder van multimodaal vervoer. Zij hebben de poorten van hun zeehaven terminals in hun netwerk uitgebreid naar de poorten van landinwaartse terminals via regelmatige diensten van transportmiddelen met een hoge capaciteit zoals binnenvaartschepen en treinen. Deze landinwaartse terminals worden dan ook wel dry ports genoemd. Deze netbeheerders worden geconfronteerd met de volgende drie met elkaar samenhangende beslissingen: (1) het bepalen welke landinwaartse terminals fungeren als verlengstuk van de zeehaven terminals, (2) het bepalen welke capaciteiten deze paden hebben, dat wil zeggen de grootte van de transportmiddelen en de frequentie van de diensten, en (3) het bepalen van de prijs voor vervoersdiensten op het netwerk.

We presenteren een lineair programmeringsmodel met twee niveaus om gelijktijdig netwerk diensten van voortgezet transport te ontwerpen en daarvan de prijs te bepalen met als oogmerk winstmaximalisatie. Onze resultaten tonen aan dat de bovengenoemde beslissingen met elkaar verbonden zijn en leiden tot verschillende optimale ontwerpen, vergeleken met een analyse waarbij deze factoren afzonderlijk zouden worden behandeld.

Het tweede onderzoek richt zich op een casus van een mogelijke alliantie van dry ports nabij het achterland die gezamenlijk capaciteit hebben om containers efficiënt te vervoeren van en naar een zeehavengebied dat verschillende containerterminals bevat. Het tactische ontwerp van geplande binnenvaarttransportdiensten betreft beslissingen over zowel de samenstelling van de vloot als de routering ervan door het netwerk van landinwaartse waterwegen.

Door het integreren van deze beslissingen zou het resulterende netwerk meer competitief kunnen worden door beter te voldoen aan de verwachte vraag en gewenste levertijden van de verladers. We ontwikkelen een aantal analytische uitdrukkingen en een meer gedetailleerd optimaliseringsmodel voor de omvang en routering van de vloot, speciaal aangepast aan het Haven-Achterland intermodale binnenvaart netwerk ontwerp. Onze resultaten wijzen uit dat er niet alleen bij samenwerking van de dry ports aanzienlijke verbeteringen in kosten en servicekwaliteit zijn, maar ook dat vloot selectie en routering samenhangende beslissingen zijn die tegelijkertijd dienen te worden beschouwd. In dit proefschrift ontwikkelen we modellen die het ontwerp van de gecombineerde transportdiensten ondersteunen in netwerken van zeehavens en landinwaartse terminals zodanig dat er consolidatie mogelijkheden ontstaan en een hoge frequente van diensten wordt bereikt. Dat bewerkstelligen we door nadrukkelijk rekening te houden met de tijdsdimensie en schaalvoordelen in onze modellen. Ook houden we rekening met een aantal andere factoren die van groot belang en specifiek zijn voor het achterlandtransport.

Curriculum Vitae

Panagiotis Ypsilantis was born on April 30, 1984 in Athens, Greece. In 2008 he received his Mechanical and Industrial Engineering diploma from Aristotle's University of Thessaloniki in Greece. In 2010 he received his M.Sc. degree in Econometrics and Management science, with a specialization in Operations Research and Quantitative Logistics, from Erasmus University in Rotterdam.

In 2011, Panagiotis started his Ph.D. program at the Erasmus Research Institute of Management (ERIM) to work on network design modeling on intermodal freight transportation systems. His research was part of the ULTIMATE project which was funded by DINALOG. During this period he worked for the Technology and Operations Management department of Rotterdam School of Management (RSM). He lecture courses both in bachelor and master levels. His main research interests are in Operations Research applications in freight transportation, maritime industry, revenue management and customer segmentation.

Panagiotis has presented his research at various international conferences, such as TRISTAN, TSL Workshop, IFORS, INFORMS, POMS, OR, and LOGMS. Currently, Panagiotis is a Senior Data Analytics Consultant at Ernst and Young (EY).

Portfolio

PhD training		
Courses		
	Statistical Methods (ERIM)	2011
	Stochastic Programming (LNMB)	2011
	Applied Econometrics (ERIM)	2012
	Cooperative Game Theory (LNMB)	2011
	Logistics and Freight Transport Systems Analysis (TRAIL)	2011
	Research Methodologies for Transport Systems (TransportNet)	2012
	Models for Logistics and Supply Chain Management (DINALOG-BETA-TRAIL)	2012
	Discrete Choice Modelling (TRAIL)	2011
	Reading Group Stochastic Programming	2011
Seminars and workshops		
	The sixteenth ELA Doctorate Workshop	2012
	Joint Technion – Erasmus Workshop: Optimization Methods Applied to Operations Research and Engineering	2011
	TSL Workshop on Maritime Transportation & Port Logistics	2013

(Inter)national conferences		
	5th International ILS conference 2014, Breda, The Netherlands.	2014
	TRISTAN VIII, San Pedro de Atacama, Chile	2013
	Operations Research conference , OR2013, Rotterdam, The Netherlands	2013
	IFORS 2014 Barcelona	
	Informs Annual meetings in San Francisco, Minneapolis & Phoenix	2012, 2013, 2014
	POMS in Denver & Chicago	2011, 2012
Teaching		
	Lecturer in Global Logistics and Information Technology (GLIT), MSc in Supply Chain Management, RSM.	2012,2013,2014
	Lecturer in Ports in Global Networks (PIGN), MSc in Supply Chain Management, RSM.	2012,2013
	Lecturer in Mathematics, Bachelor in International Business Administration, RSM.	2012, 2013
	Assistant in Business Support, Bachelor in International Business Administration, RSM.	2011

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The purpose of this thesis is the analysis and design of intermodal port-hinterland container transport networks. In this line, we go through and discuss relevant academic literature and position our work while identifying gaps that we try to address. We explore the port - hinterland intermodal transport process, by analyzing container transport data given by a major container terminal (ECT) and two major intermodal carriers (EGS of ECT and Brabant Intermodal) in the Netherlands. Our analysis demonstrates the different transport needs of shippers in both time and modality choices. Additionally we investigate the optimal network design configurations of two major intermodal carriers in the Netherlands, by considering the underlying tradeoffs and propose optimization models in this direction. In combined port-hinterland transport, the use of different modalities, the fleet selection, the capacity and frequency setting of services, the routing of assets in a network can significantly affect the overall performance of the transportation network in terms of costs, service times, modal split, sustainability, etc. In the first study, we focus on container terminal operating companies that have extended their role from node operators to that of multimodal transport network operators. These network operators face the following three interrelated decisions: (1) determine which inland terminals act as extended gates of the seaport terminal, (2) determine capacities of the corridors, i.e. size of the transport modes and frequency of service, and (3) set the prices for the transport services on the network. We proposed a bi-level programming model to jointly design and price extended gate network services for profit maximization. The second study, focuses on a case of a possible alliance of dryports closely located in the hinterland that share capacity to efficiently transport containers from and to a seaport area that consists of several container terminals. The tactical design of scheduled barge transport services involves decisions regarding both the fleet composition and its routing through the inland waterway network. Integrating these decisions would make the resulting network more competitive in satisfying expected demand and service time requirements set by the shippers.

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