DOCTORAATSPROEFSCHRIFT

2010 | Faculteit Bedrijfseconomische Wetenschappen

Simulation and Optimisation of Intermodal Barge Transport Networks

Proefschrift voorgelegd tot het behalen van de graad van
Doctor in de Toegepaste Economische Wetenschappen, te verdedigen door:

An CARIS

Promotor: prof. dr. Gerrit K. Janssens
Copromotor: prof. dr. Cathy Macharis

universiteit hasselt
INSTITUUT VOOR MOBILITEIT

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Acknowledgements

Writing this Ph.D. thesis has been a journey with many people along the road who have contributed in various ways. After graduating as a Master of Business Economics in 2003, I started working with a private company in the division of inventory management. One year later I received an email of Prof. dr. Gerrit Janssens, who supervised my master thesis, informing me on a vacancy as teaching assistant / Ph.D. student in the field of Operations Research. Gerrit, I would like to thank you for bringing this vacancy to my attention. I never regretted the choice of quitting my previous job and starting a Ph.D. at Hasselt University. Coming to work never felt like coming to work, I enjoyed doing research as well as giving classes.

Motivation is a key success factor in making a Ph.D. thesis. This was first tested during my job interview when, as a future Ph.D. supervisor, Prof. dr. Gerrit Janssens asked me: "Are you prepared to spend the most beautiful years of your life on writing a book nobody will read?" I answered affirmatively but the question stayed in my mind during the past six years. I had the liberty to choose the topic of my research, as long as it was related to the field of Operations Research. In order to stay motivated, I started searching for a topic that was relevant to society. Soon I found two research articles entitled: "Is a new applied transportation research field emerging? - A review of intermodal rail-truck freight transport literature" and "Opportunities for OR in intermodal freight transport research: a review". Both papers were based on the research of prof. dr. Cathy Macharis. We met each other at the yearly conference of the Belgian Operations Research society and she soon became my second Ph.D. supervisor. Cathy, your never-ending enthusiasm works inspiring. After each meeting in your office at the Free University of Brussels, I was full of ideas. I enjoyed doing research projects together and participating in Nectar cluster meetings on freight transport and intermodality. I owe much gratitude to you for your help during the past years and I sincerely hope we continue working together in the future.

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A second key success factor in making a Ph.D. thesis is a good working environment. I have had the fortune of being surrounded by multiple nice colleagues and being supported by our research institute. First of all, I would like to thank prof. dr. Geert Wets for the involvement in the research institute Imob and for introducing management principles in the academic world. Special thanks goes to Nadine and later Kristel for all the administrative support. I got to know several generations of fellow Ph.D. students in Imob as well as in the main building. Many of them became friends instead of colleagues and I thank them all for the lively lunches and the nice activities we did together. I am greatly indebted to two special persons, Katrien and Benoît. Both of them were my soundboard for methodological questions and for all frustrations during my research. Katrien, you were there the first day to welcome me, we went on multiple conferences together and I hope I may say we became true friends. Benoît, we had many boundless discussions on a whole variety of topics, but you also learned me the valuable lesson to program everything and were my helpdesk along the way. Thank you both very much for all the support and for all the nice distractions and laughters we had in our office.

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An Caris
May 7, 2010

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Chapter 1

Introduction and problem statement

1.1 Intermodal freight transport

In recent years intermodal transport has received an increased attention due to problems of road congestion, environmental concerns and traffic safety. A growing recognition of the strategic importance of speed and agility in the supply chain is forcing firms to reconsider traditional logistic services. As a consequence, research interest in intermodal freight transportation problems is growing. Macharis and Bontekoning (2004) define intermodal transport as the combination of at least two modes of transport in a single transport chain, without a change of container for the goods, with most of the route travelled by rail, inland waterway or ocean-going vessel and with the shortest possible initial and final journeys by road. The major part of the transport chain is referred to as main haulage by rail, inland waterway or ocean-going vessel. The initial and final part of the transport chain is denominated pre- and end-haulage by road.

Intermodal transport, by definition, involves several decision makers who need to work in collaboration in order for the transport system to run smoothly. The term intermodal transport implies integration between different operators in the transport chain. The different transport modes should not only be optimized separately, but they should also be attuned to one another. A new transport mode arises when the transport chain is fully integrated. An increased level of coordination is necessary to organize the intermodal transport flow. Decision-making support tools may assist the actors and stakeholders involved in intermodal operations.

Figure 1.1 depicts the cost structure of intermodal freight transport and unimodal road transport in the hinterland of a seaport. The intersection with the vertical axis represents the fixed cost of a transport mode. The pre- or end-haulage in the intermodal transport chain is performed by road. The cost curve of intermodal freight transport runs steeper than unimodal road transport due to the small distance of the initial or final journey by road, which does not allow spreading all the costs over the journey. However the fixed costs of road transport starting at an inland terminal compared to road transport at the sea terminals in the port is lower as less waiting times have to be taken into account. The main haulage is carried by an alternative transport mode, such as rail or barge transport. These transport modes incur higher fixed costs but lower variable costs in function of the distance travelled. Furthermore, terminal operations necessary to tranship the goods from one mode to another imply a vertical leap in the cost curve. The critical distance D_c is defined as the distance from which intermodal freight transport can compete with unimodal road transport in terms of internal costs. Other factors also influence the attractiveness of a transport mode, such as flexibility, speed, reliability, security and environmental impact. For a detailed reading on transport mode choice the reader is referred to the literature review of Meixell and Norbis (2008).

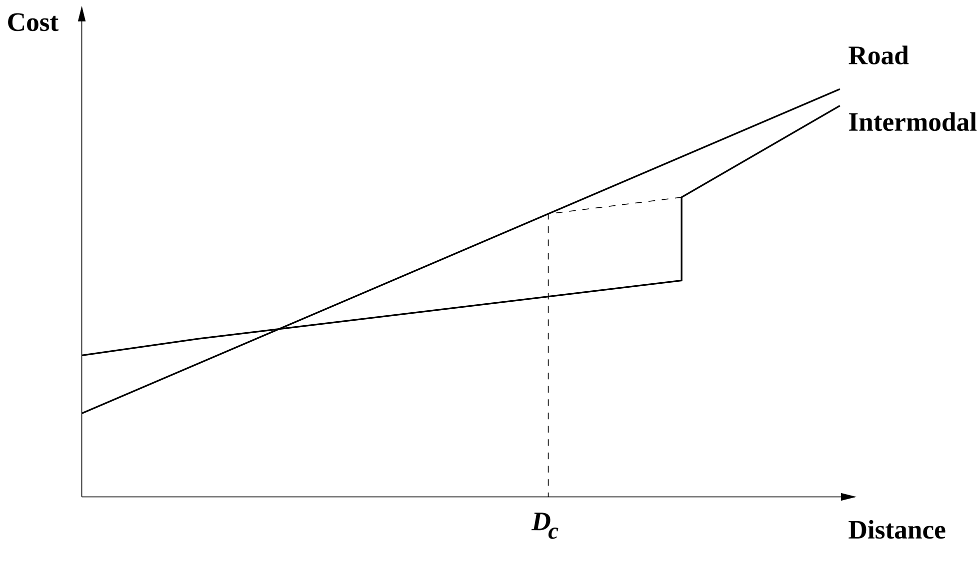

Figure 1.1: Cost of intermodal freight transport and unimodal road transport

Many research efforts focus on intermodal rail transport. An overview of intermodal rail-truck freight transport literature can be found in Bontekoning et al. (2004). In our research we will focus on intermodal container transport including inland navigation. In regions with an extensive waterway network, such as Western Europe, intermodal transport including inland navigation is a good alternative for unimodal road transport. Our focus is on long-haul transportation systems, for which barge transport is a good option. An inland vessel moves freight of multiple customers with possibly different initial origins and final destinations. Barge terminal operators establish regular service routes and adjust their characteristics to satisfy the expectations of the largest number of customers possible. A series of services is proposed, grouped in a schedule that indicates departure and arrival times at the stops of the routes. Internally, barge operators or terminal operators build a series of rules and policies that affect the whole system and are collected in an operational (also referred to as load or transportation) plan.

1.2 Role of ports in transport networks

The role of ports within supply chains has taken several different forms. Traditionally ports have been the interface between land and sea transport. Pettit and Beresford (2009) discuss the increasing integration of ports into the supply chain. During the 1980s some ports diversified into the emerging field of logistics and began to offer value added services. The 1990s are characterized by globalization, leading to mergers and acquisitions in the port industry. During the last decade, hinterland access has become a key element in the competitiveness of seaports. Ports have become a part of intermodal networks and competition takes place between transport chains instead of between ports. Ports are recognized as integral components of distribution systems and have to adapt and develop to allow the supply chains within which they operate to stay competitive. Notteboom and Rodrigue (2005) identify a new phase in port development. Ports are often faced with a lack of available land for expansion, a congested urban road network and environmental constraints. Furthermore, a global dispersion of production and consumption puts pressure on international supply chains. Port regionalization implies an integration of port activities and hinterland activities. Inland distribution systems are targeted for improving their efficiency, enhancing logistics integration and reducing distribution costs. Inland terminals take up an important role in providing a good hinterland access. Corridors are set up to inland terminals, which serve a local collection-distribution network. Inland terminals transfer a part of the collection and distribution function inland away from ports. In the port regionalization phase logistic zones emerge around these inland terminals in the hinterland of seaports. Traditional port functions and logistical services are organized in the neighbourhood of inland terminals.

In the port of Antwerp a modal shift towards inland navigation is observed in recent years. The share of barge transport in the modal split of container transport for the port of Antwerp amounted to 33% in 2008. Inland navigation is often seen as the best solution to ensure an effective hinterland access. Developments in the inland waterway transport market are addressed by Notteboom (2007). The quality of the hinterland access of a port depends on multiple actors in the transport flow, such as truck companies, terminal operators, barge operators, freight forwarders, carriers and port authorities. De Langen and Chouly (2004) think of the improvement of hinterland access as a collective action problem, which requires coordination between actors. Inter-organisational coalitions are necessary to invest in hinterland transport services. Especially container traffic requires joint efforts, due to the numerous actors involved, whereas for some commodities a single or only a few actors manage door-to-door chains. The authors define a Hinterland Access Regime (HAR) as 'the set of collaborative initiatives, taken by the relevant actors in the port cluster with the aim to improve the quality of the hinterland access'. The hinterland access regime is particularly relevant in ports that serve large hinterlands, where the throughput volume is substantial and the number of actors is large. After analysing the HAR of three seaports, they conclude that collective actions do not arise spontaneously. None of the three HARs is very effective, but leader firms and public authorities may play an important role in setting up collective initiatives. In the hinterland of the port of Rotterdam container barge operators already cooperate to provide joint services with large barges and at high frequencies. These alliances lead to better services in the hinterland. Notteboom (2008) elaborates on the relationship between seaports and the intermodal hinterland. The author observes an increasing level of vertical integration in the hinterland transport chain and an increasing pressure on capacity. Terminals, both in the port area as in the hinterland, are expected to increase their role in supply chains.

1.3 Research objective and outline of the thesis

In this thesis intermodal barge transport networks are modelled and analysed with the objective of increasing their attractiveness. Figure 1.1 indicates three cost components that may be improved. Firstly, the cost of the main haulage influences the attractiveness of intermodal barge transport networks. Bundling of freight flows may reduce the cost of main haulage or enable a higher frequency of services. Secondly, terminal operations cause a leap in the cost curve. Konings and Priemus (2008) explore future requirements and opportunities of barge terminals to further improve the competitiveness of container barge transport. Finally, the pre- and end-haulage is an important factor in total intermodal transport costs. Konings (2009) studies major determinants for the performance of intermodal barge transport networks. A conceptual model for network design in intermodal barge transport is developed and empirically tested. The choice of service network depends on the market structure and waterway infrastructure. The author argues that the geographical scale for profitable intermodal services is also strongly determined by the performance of pre- and end-haulage by road. Platz (2009) presents an overview of measures and decisive factors for the efficient integration of inland navigation into continental intermodal transport chains. The author finds that door-to-door transport costs are the most decisive element in the modal choice of logistic decision makers. A crucial requirement to obtain a competitive door-to-door transport cost for continental intermodal barge transport is bundling of freight flows in space and in quantity. Other success factors for continental intermodal barge transport are the provision of backup transportation, guaranteed lead times, easy intermodal load transfer, complete transport-related service packages and loading units providing the capacity of a standard semi-trailer.

This thesis focusses on two key aspects in the competitiveness of intermodal transport making use of inland navigation. The first part of this thesis studies bundling of freight in intermodal barge transport networks. The second part relates to the initial and final journey by road in the intermodal barge transport chain. We aim to study intermodal networks at multiple decision levels. Opportunities for bundling freight flows are identified at the strategic and tactical decision levels. Pre- and end-haulage by road is analysed at the operational decision level. Figure 1.2 presents the outline of the thesis.

In chapter 2 the literature on existing models for intermodal freight transportation is reviewed. Previous research is classified according to the decision level and type of decision maker. This chapter aims to identify gaps in scientific literature and to give directions for research on intermodal freight transport networks.

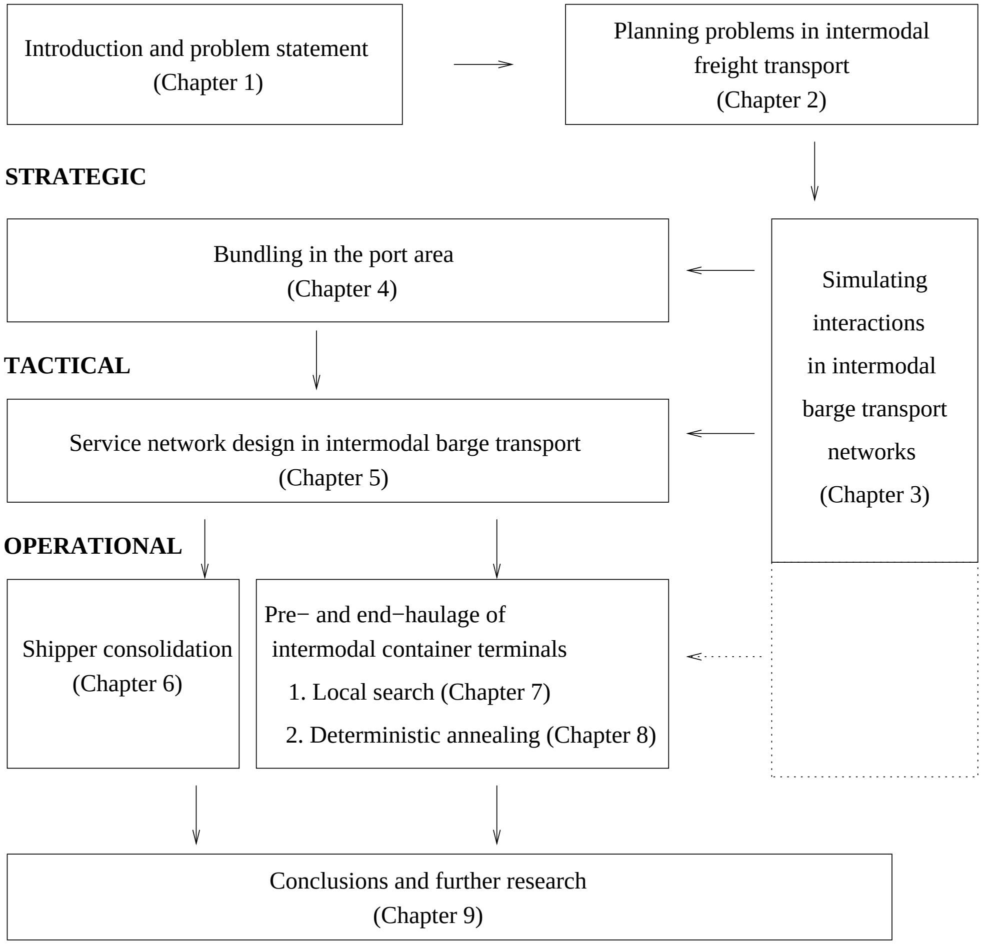

Figure 1.2: Outline of the thesis

Next, in chapter 3 a simulation model is developed to support decisions in intermodal freight transport by barge. This simulation model supports decisions at the strategic and tactical planning level. However, the model could be extended to incorporate scenarios at the operational decision level. The simulation model described in chapter 3 is applied in chapters 4 and 5 to investigate bundling concepts which may contribute to the improvement of intermodal barge operations. Consolidation of freight flows may be realised by providing a hub in the port area, from which cargo is distributed to the different sea terminals (chapter 4). Economies of scale may also be achieved by bundling load of different inland terminals destined to the same sea terminal (chapter 5). A service network design methodology is developed to model cooperation between inland terminals along the same waterway axis. Kreutzberger (2005) argues that the design of a service network depends on the interaction between the following four design variables: network volume, transportation vehicle size, frequency of service and network concentration (i.e. the number of begin- and end-terminals in the network). Network volumes sometimes may be insufficient to run a direct service from a begin- to an end-terminal at the desired frequency level. In this instance scale advantages can only be achieved by reducing frequency of service, increasing concentration of the network or introducing complex bundling. In chapter 5 freight of multiple inland terminals is bundled to obtain economies of scale, while maintaining the same frequency of service.

The following research chapters are concerned with the operational decision level. Chapter 6 discusses bundling of freight inside the same loading unit. Opportunities to increase the fill level and thus reduce the cost of pre- and end-haulage are investigated in a case study. Next, the pre- and end-haulage of intermodal terminals is studied. Cost savings may be attained by combining pickup customers and delivery customers in a single trip. The problem is modelled as a Full Truckload Pickup and Delivery Problem with Time Windows (FTPDPTW). Chapter 7 presents an exact formulation of the problem and a lower bound on the problem solution. A local search algorithm is proposed to find good quality solutions within a reasonable time frame. The local search algorithm is compared with a deterministic annealing approach in chapter 8.

Finally, chapter 9 summarizes conclusions from the various research chapters and offers guidelines for future research.

Chapter 2

Planning problems in intermodal freight transport

2.1 Introduction

Emerging freight transport trends, such as a geographical expansion of distribution networks and the increasing development of hub-and-spoke networks, demonstrate the importance and necessity of intermodal freight transport systems. A general description of current issues and challenges related to the large-scale implementation of intermodal freight transportation systems in the United States and Europe is given by Zografos and Regan (2004) and by Vrenken et al. (2005). The objective of this chapter[1] is to provide an overview of the state-of-the-art research on planning problems in intermodal freight transport (Figure 2.1). Macharis and Bontekoning (2004) discuss the opportunities for operations research in intermodal freight transport. The authors give a review of operational research models that are currently used in this emerging transportation research field and define the modelling problems which need to be addressed. Because this is a very young field in transportation research, a significant number of papers on this topic have appeared in recent years. In this chapter the overview of Macharis and Bontekoning (2004) is updated with a focus on planning issues in intermodal freight transport research. Following Crainic and Laporte (1997), the presentation is organized according to the three classical planning levels: strategic, tactic and operational. Conclusions are drawn on the accomplishments and future perspectives in intermodal freight transport.

[1] This chapter is based on Caris et al. (2008).

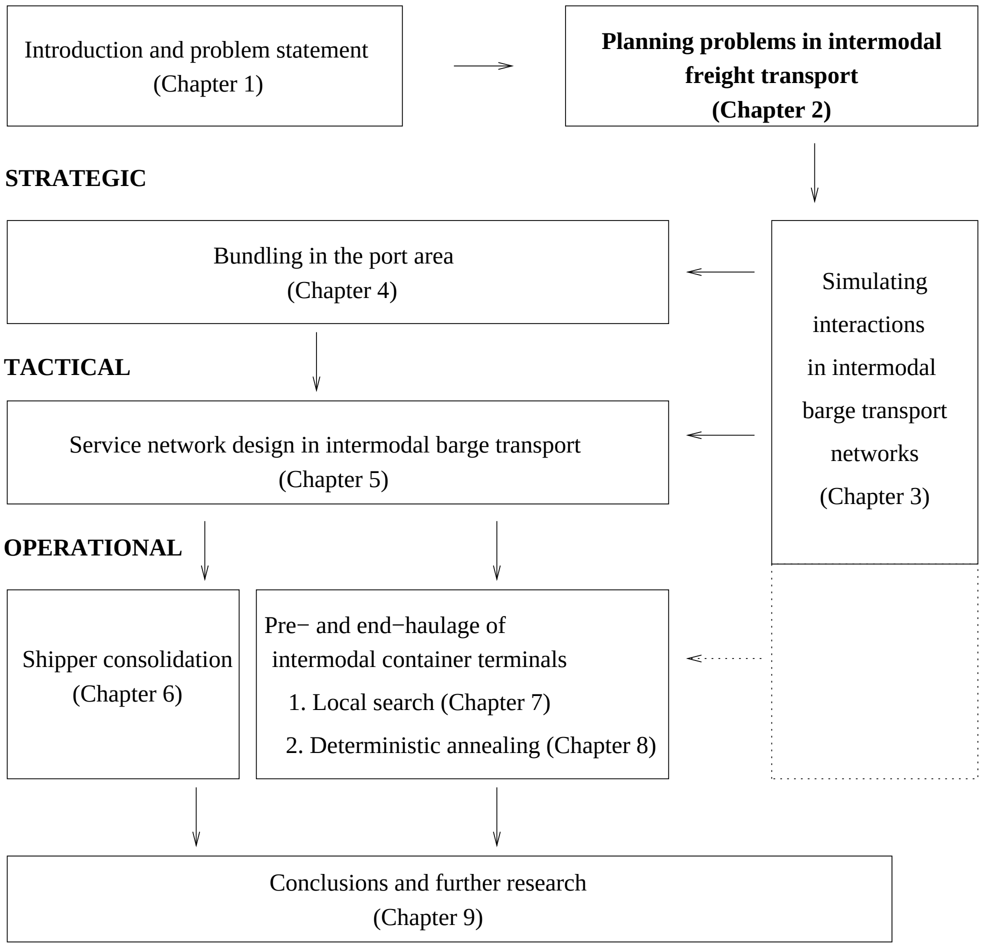

Figure 2.1: Outline of the thesis - Chapter 2

2.2 Methodology

A scientific literature review is performed to update the survey of Macharis and Bontekoning (2004). A computerised search strategy was selected in order to detect recent publications in intermodal freight transport. First, the database of Dissertation Abstracts and the (Social) Sciences Citation Index (SCI) are searched. Next, a separate search is performed of electronic journals concerning transportation which are not covered by those channels. Finally, an ancestry approach is applied.

Planning problems in intermodal freight transport can be related to four types of decision makers, based on the four main activities in intermodal freight transport.

First, drayage operators organize the planning and scheduling of trucks between terminals and shippers and receivers. Second, terminal operators manage transhipment operations from road to rail or barge, or from rail to rail or barge to barge. Third, network operators are responsible for the infrastructure planning and organisation of rail or barge transport. Finally, intermodal operators can be considered as users of the intermodal infrastructure and services and select the most appropriate route for shipments through the whole intermodal network.

Each type of decision maker is faced with planning problems with different time horizons. Long term, strategic planning involves the highest level of management and requires large capital investments over long time horizons. Decisions at this planning level affect the design of the physical infrastructure network. Medium term, tactical planning aims to ensure, over a medium term horizon, an efficient and rational allocation of existing resources in order to improve the performance of the whole system. Short term, operational planning is performed by local management in a highly dynamic environment where the time factor plays an important role. The dynamic aspect of operations is further compounded by the stochasticity inherent in the system. Real-life operational management is characterized by uncertainty.

The combination of both classes provides a classification matrix with twelve categories of intermodal operations problems, as depicted in table 2.1. The classification is not exhaustive and some decision problems can be faced by several decision makers and can be relevant for the same decision maker at different time horizons. However, the decision problems have been placed in the classification matrix of table 2.1 were they are most prominent. Table 2.1 provides a structured overview of planning problems in intermodal transport involving a single decision level and a single decision maker. Section 2.3 discusses studies on strategic planning problems. Papers on a tactical decision level are presented in section 2.4. Section 2.5 deals with scientific research on intermodal transport at the operational decision level. Two separate tables have also been constructed. Table 2.2 compiles scientific research in intermodal transport involving multiple decision makers. Table 2.3 presents studies that explicitly take into account multiple decision levels. These integrating studies are discussed in section 2.6. The number of studies that require decisions from more than one decision maker or that cover various time horizons are limited. This important conclusion has been formulated already by Macharis and Bontekoning (2004). However, intermodal transport, by definition, involves several decision makers who need to work in collaboration in order for the system to run smoothly. An increased level of coordination is necessary to improve the intermodal transport flow. If intermodal transport is to be developed it will require more decision-making support tools to assist the many actors and stakeholders involved in intermodal operations. A very good attempt at outlining these tools can be found in Van Duin and Van Ham (1998) in which a three-level modelling approach is followed in order to take account of the different goals of the different stakeholders.

Decision maker	**Time horizon**		
	Strategic	Tactical	Operational
Drayage operator	*Co-operation between drayage companies* Spasovic (1990) Walker (1992) Morlok and Spasovic (1994) Morlok et al. (1995) *Truck and chassis fleet size* -	*Allocation of shippers and receiver locations to a terminal* Taylor et al. (2002) *Pricing strategies* Spasovic and Morlok (1993)	*Vehicle routing* Wang and Regan (2002) Francis et al. (2007) Imai et al. (2007) *Redistribution of trailer chassis and loading units* Justice (1996)
Terminal operator	*Terminal design* Ferreira and Sigut (1995) Meyer (1998) Rizzoli et al. (2002) Ballis and Golias (2004) Bontekoning (2006) Vis (2006)	*Capacity levels of equipment and labour* Kemper and Fischer (2000) Kozan (2000, 2006) Kulick and Sawyer (2001) Huynh (2005) Alessandri et al. (2007) *Redesign of operational routines and layout structures* Voges et al. (1994) Marin Martinez et al. (2004)	*Resource allocation* Alessandri et al. (2009) *Scheduling of jobs* Gambardella et al. (2001) Alicke (2002) Corry and Kozan (2006, 2008)

Decision	**Time horizon**		
maker	Strategic	Tactical	Operational
Network operator	*Infrastructure network configuration* Crainic et al. (1990) Loureiro (1994) Southworth and Peterson (2000) Klodzinski and Al-Deek (2004) Tan et al. (2004) Groothedde et al. (2005) Parola and Sciomachen (2005) *Location of terminals* Meinert et al. (1998) Rutten (1998) Arnold and Thomas (1999) Groothedde and Tavasszy (1999) Macharis and Verbeke (1999) Arnold et al. (2004) Macharis (2004) Racunica and Wynter (2005) Kapros et al. (2005) Rahimi et al. (2008) Limbourg and Jourquin (2009)	*Configuration consolidation network* Janic et al. (1999) Newman and Yano (2000a) Newman and Yano (2000b) *Production model* Nozick and Morlok (1997) Choong et al. (2002) Lin and Chen (2004) Li and Tayur (2005) Kuo et al. (2008) *Pricing strategy* Tsai et al. (1994) Yan et al. (1995) Li and Tayur (2005) Andersen et al. (2009b)	*Load order of trains* Feo and Gonzalez-Velarde (1995) Powell and Carvalho (1998) *Redistribution of railcars, barges and loading units* Chih and van Dyke (1987) Chih et al. (1990)

Decision maker	**Time horizon**		
	Strategic	Tactical	Operational
Intermodal operator	n.a.	n.a.	*Routing and repositioning* Min (1991) Barnhart and Ratliff (1993) Boardman et al. (1997) Ziliaskopoulos and Wardell (2000) Erera et al. (2005) Grasman (2006) Chang et al. (2007) Chang (2008)

Table 2.1: Papers involving a single decision level and a single decision maker

2.3 Strategic planning

Crainic and Laporte (1997) mention location models, network design models and regional multimodal planning models suitable for strategic planning in intermodal transport. Location models help to determine the optimal location of an additional intermodal terminal. Network design models are concerned with the configuration of the infrastructure network. Regional multimodal planning models consider the entire transportation system in a certain region, the products that use it, as well as the interaction between passenger travel and freight flows. The impact of infrastructure modifications, evolution of demand or government and industry policies is verified. Other planning problems at a strategic decision level, identified by Macharis and Bontekoning (2004), include cooperation between drayage companies, determination of truck and chassis fleet size and terminal design. The strategic planning problems of each decision maker and solution methods proposed in scientific literature are discussed in the following sections.

2.3.1 Drayage operator

At a strategic decision level a drayage operator might decide to cooperate with other drayage companies, with the objective to improve cost efficiency without affecting the timeliness of operations. Spasovic (1990), Morlok and Spasovic (1994) and Morlok et al. (1995) investigate whether a central planning of pickups and deliveries of multiple drayage companies serving one intermodal terminal is able to reduce drayage costs. The problem is formulated as a large-scale integer linear program, taking time windows and service constraints into account. The authors conclude that substantial cost savings can be realised through cooperation between drayage companies. Trips are combined in a more efficient manner, leading to a reduction of empty hauls. The central planning problem of multiple drayage companies is also addressed by Walker (1992). He discusses a cost-minimising vehicle-scheduling algorithm to generate an efficient set of tours consistent with the shippers' pickup and delivery times, travel times and realistic limits on the length of a working day.

2.3.2 Terminal Operator

The design of the terminal is a strategic planning problem of terminal operators. Decisions regarding design include the type and number of equipment used and type and capacity of load unit storage facilities, the way in which operations are carried out at the terminal and how the equipment is used, and the layout of the terminal. Simulation models have been developed by various researchers.

Simulation models for rail/road intermodal terminals have been constructed by Ferreira and Sigut (1995), Ballis and Golias (2004) and Rizzoli et al. (2002). Ferreira and Sigut (1995) compare the performance of conventional rail/road intermodal terminals and RoadRailer terminals. A RoadRailer terminal uses trailers with the capability of being hauled on road as well as on rail. These bi-modal trailers are not carried on railway wagons. They are provided with a detachable bogie or a single rail axle permanently attached to the trailer. Both concepts are evaluated by means of discrete event simulation. Speed of operation is chosen as performance criterion, expressed as mean loading finish time. The authors conclude that for a comparable cycle of manipulations, containers are handled faster than RoadRailer trailers. The comparison does not take into account the full set of costs incurred when operating both types of terminals. Initial capital costs, in terms of track and vehicle equipment, are significantly higher in the case of conventional container terminals. Ballis and Golias (2004) present a modelling approach focusing on the comparative evaluation of conventional and advanced rail/road terminal equipment. The modelling tool set consists of a micro-model to compare alternative terminal designs and a macro-model to analyse the attractiveness of the intermodal transport chain. The micro-model incorporates an expert system, a simulation model and a cost calculation module. The expert system assists users to form technically sound terminal designs. The simulation model is used to determine train and truck service times, which are then compared to predetermined service criteria. For each accepted terminal design a cost-versus-volume curve is calculated. Truck waiting time costs are taken into account. The micro-model reveals that each design is effective for a certain cargo volume range and is restricted by capacity limitations. The effects of an efficient terminal operation in conjunction with advanced rail bundling designs is further investigated in the macro-model. The discrete event simulation model of Rizzoli et al. (2002) can be used to simulate the processes in a single terminal or in a rail network, connecting several rail/road terminals through rail corridors. The objective of the model is to assess the impact of various technologies and management policies to enhance terminal performance and to understand how an increase in intermodal traffic affects terminal performance.

Two studies discuss the simulation of rail/rail intermodal terminals. Meyer (1998) faces the design problem of a rail/rail terminal in a hub-and-spoke system for the exchange of a maximum of six trains at a time. In addition, the terminal should be able to handle a limited volume of rail/road exchanges. A dynamic computer simulation model with Petri net applications has been developed to determine required capacity for cranes and internal transport systems, and the most efficient arrival pattern of trains. Bontekoning (2006) develops a simulation model to perform a systematic comparison between various hub exchange facilities in an intermodal rail network. Her main objective is to identify favourable operational conditions for an innovative intermodal terminal concept (Bontekoning and Kreutzberger 1999), which can replace shunting yards.

Vis (2006) discusses the strategic decision of choosing the type of material handling equipment for storage and retrieval of containers in and from the yard at sea terminals. Simulation is used to compare the use of manned straddle carriers with automated stacking cranes. The total travel time required to handle a fixed number of requests serves as performance measure. A sensitivity analysis of the input parameters is executed in order to formulate an advice on the choice for a specific type of material handling equipment in relation with the layout of the stack.

2.3.3 Network operator

At a strategic decision level a network operator has to plan the infrastructure of the intermodal network. This implies decisions regarding investments in links and nodes. Network models have been proposed by various authors. Crainic et al. (1990) extend uni-modal network models by adding links connecting the various modes in order to derive an intermodal network model. The development of geographic information system (GIS) technology yields new opportunities for modelling large multi-modal freight networks as Southworth and Peterson (2000) show. Loureiro (1994) presents a multi-commodity multi-modal network model to be used as a planning tool for determining investment priorities for intercity freight networks. The main component of the model incorporates a non-linear bi-level multi-modal network design formulation. Its aim is to minimise the transportation costs incurred by shippers and the environmental impacts caused by the use of less efficient modes of transportation for moving freight. Investment options to be considered by the model may involve the addition of new physical links to the network, the improvement of existing links (i.e. an increase of capacity), and the location of intermodal transfer facilities at specified nodes of the network. Groothedde et al. (2005) propose a collaborative hub network for the distribution of fast moving consumer goods. The available transport modes include inland navigation and road transport by trucks. Inland navigation is used for inter-hub transportation in order to achieve economies of scale. Pre- and end-haulage is performed by truck. Parallel to this hub network, direct trucking is used to maintain responsiveness and flexibility. Predictable demand should be sent through the hub network before the order is placed. Peak demand can be accommodated by direct trucking. The hub network design problem is formulated as a cost model and solved with an improvement heuristic. The heuristic starts with a feasible and cost-efficient solution and seeks to improve it by adding barge capacity or hubs to the network. Simulation models may also be applied to plan the infrastructure network configuration. Tan et al. (2004) discuss a modelling methodology for building discrete-event simulation models for a state-wide intermodal freight transportation network. Their model simulates the movements of trucks, trains, barges and ships as well as transhipment of freight between different modes. The objective of their modelling effort is to demonstrate interactions between transport modes under various intermodal policy chances and to support transport planning on a regional and state-wide level.

Two research papers focus on the impact of transport growth on the hinterland network. Parola and Sciomachen (2005) analyse the impact of a possible future growth in maritime traffic on land infrastructure in the north-western Italian port system.

The central question is how to achieve a modal split equilibrium between transport by rail and transport by road. Discrete event simulation is used to model a set of maritime terminals, their interconnections and land infrastructures. The simulation model is validated by means of the present configuration. Three future scenarios of land infrastructure are evaluated, assuming a constant growth in sea traffic in the time period 2002-2012. The authors examine the degree of saturation of railway lines and the level of congestion at truck gates. Klodzinski and Al-Deek (2004) develop a methodology for estimating the impact of an intermodal facility on a local road network. First, an artificial neural network model is used to generate truck trips from vessel freight data. Second, the generated truck volumes serve as an input for a microscopic network simulation model. By doing so critical links in the road network can be identified. This methodology may also be used to evaluate local port networks to manage traffic efficiently during heavy congestion or to investigate the impact of forecasted port growth on a road network.

Locations for intermodal terminals may be determined by means of network models. Arnold and Thomas (1999) minimise total transport costs in order to find optimal locations for intermodal rail/road terminals in Belgium by means of an integer programming model. Groothedde and Tavasszy (1999) minimise generalised and external costs in order to find the optimal location of intermodal rail/road terminals. Simulated annealing is used to find near-optimal locations of terminals. Arnold et al. (2004) propose an alternative formulation closely linked to multi-commodity fixed-charge network design problems. The resulting integer linear program is solved heuristically. The model is illustrated for the location of rail/road terminals in the Iberian Peninsula. In this application, the impact of variations in the supply of transport on modal shares of containerised freight transport is explored. Macharis (2004) develops a GIS model to analyse the potential market area of new terminals and to analyse their effect on the market area of the existing ones. Rutten (1998) investigates the interrelationship between terminal locations, number of terminals, shuttle train length and system performance in an intermodal rail network. The author discusses the TERMINET model, which comprises a traffic conversion method and a freight flow consolidation method. First, freight flows are converted from tonnes to numbers of load-units. Second, freight volumes are assigned to routes and consolidated with the objective to find terminal locations that will attract sufficient freight to run daily trains to and from the terminal. The model is applied to the design of an inland road and rail terminal network in the Netherlands. Racunica and Wynter (2005) discuss the optimal location of intermodal hubs in a hub-and-spoke network with (semi-) dedicated freight rail lines. The problem is formulated as a frequency service network design model with frequencies of service as derived output. A concave cost function is applied in order to capture cost reductions obtained by consolidation at hub nodes. The resulting model is a non-linear, mixed-integer program. Next, the concave increasing cost terms are approximated by a piecewise linear function in order to obtain a linear program. This linear program is solved by two variable-reduction heuristics, which solve a sequence of relaxed subproblems. Finally the solution method is tested on a case study of the Alpine freight network. Rahimi et al. (2008) identify inland terminals using a location-allocation methodology. Their objective is to minimize total truck-miles travelled in a regional intermodal goods movement system. Limbourg and Jourquin (2009) point at the international network effects underlying the decision to open a new intermodal rail-road container terminal. The authors propose an iterative procedure based on a p-hub median problem and a multi-modal assignment problem. The p-hub median problem minimizes costs for rail haulage, transshipment and pre- and post-haulage by road. Demand is assigned over all transportation modes, with the possibility of using transshipment facilities. Next, the p-hub median problem is solved with updated transshipment costs based on the estimated flow at each terminal. This procedure is repeated until the relative difference in transshipment costs between two iterations is smaller than a given threshold. A set of potential locations is used as an input and final results are optimal locations for European transfer terminals embedded in a hub-and-spoke network.

Second, simulation may be used to define terminal locations. Meinert et al. (1998) investigate the location of a new rail terminal in a specific region in which three rail terminals are already located. The authors specifically consider the impact of the location of the new terminal on drayage length and time. In order to accomplish this, a discrete event simulation tool is developed which provides the ability to address individual rail terminal design considerations such as handling capacity required, regional design considerations related to terminal location and trucking distances, and demand distribution over time. A significant feature of this simulator is that, rather than modelling only the operation of the terminal, it also models the drayage to and from regional destinations.

Third, multi-criteria analysis can be applied to select the most appropriate location out of a number of potential sites for an intermodal terminal. Macharis and Verbeke (1999) examine four potential sites for new barge terminals in Belgium by means of a multi-actor, multi-criteria analysis. Their criteria represent the aims of the actors who are involved, namely the users of the terminal, the operators/investors and the community as a whole. The evaluation of the terminal projects was carried out with the GDSS-PROMETHEE-method (Preference Ranking Organization METHod for

Enrichment Evaluations, (Macharis et al. 1998)). A multi-criteria analysis is also proposed by Kapros et al. (2005) to evaluate intermodal terminal projects. The central idea in their methodology is the trade-off between public interest and business interest. Criteria are weighted using the Rembrandt method and location alternatives are ranked using a linear additive aggregation function.

2.4 Tactical planning

According to Crainic and Laporte (1997), the service network design problem is a key tactical problem in intermodal transport. The service network design problem concerns the selection of routes on which services are offered and the determination of the characteristics of each service, particularly their frequency. For each origin-destination pair a routing has to be specified. A decision needs to be made about the type of consolidation network, general operating rules for each terminal and work allocation among terminals. Empty balancing looks for an optimal repositioning of empty vehicles to meet forecast needs of the next planning period. Crew and motive power scheduling regards the allocation and repositioning of resources required by the selected transportation plan. Tactical planning problems for each decision maker are described in the following sections.

2.4.1 Drayage operator

One tactical decision of drayage operators concerns the assignment of freight locations to intermodal terminal service areas. Taylor et al. (2002) compare two alternative heuristic methods that seek to reduce total empty and circuitous (out of route) miles incurred during intermodal drayage movements. The first heuristic uses the minimization of circuitous miles as criterion to assign freight to an intermodal terminal. The second heuristic minimizes the sum of total circuity, empty miles associated with the geographical separation of pickups and deliveries and empty miles due to operational fluctuations in inbound and outbound freight demand within a small service area. Both heuristics are tested in a large experimental design. Conclusions are formulated on the appropriateness of each heuristic in particular situations.

Spasovic and Morlok (1993) use their strategic planning model for the highway portion of rail-truck intermodal transport, described in section 3.1, to develop pricing guidelines for drayage service. The model generates marginal costs of moving loads in the drayage operation. The marginal costs are used to evaluate the efficiency of drayage rates charged by truckers in the current operation as well as rates used in a proposed operation with centralized planning of tractor and trailer movements. The need for railroad management to become aware of the characteristics of drayage operations and the system-wide impacts of drayage movements on the profitability of intermodal transport are indicated.

2.4.2 Terminal Operator

A terminal operator has to decide on the required capacity levels of equipment and labour. Kemper and Fischer (2000) model the transfer of containers in an intermodal rail/road terminal with a single crane. Their objective is to determine quality of service in terms of waiting times and utilisation of resources, especially with regard to the dimensions of the waiting areas for incoming trucks. Stochastic Petri nets are used as modelling language and results are obtained numerically by computation of the steady state distribution of an associated Markov chain. In Kozan (2000) a network model is presented to analyse container progress in a multimodal container terminal. As objective the author minimizes total throughput time, which is defined as the sum of handling and travelling times of containers from the time the ship arrives at the port until the time they are leaving the terminal and in reversed order. The mathematical model can be applied as decision support tool for equipment investments. Long-term data collection should be carried out before implementing the model. Simulation models are also frequently designed to support tactical decisions at an intermodal terminal. Kulick and Sawyer (2001) develop a simulation model to support the analysis of labour deployment and other resource capacities at a major intermodal terminal. The model is used to explore areas where container throughput can be improved. Huynh (2005) proposes statistical and simulation models to explain the relationship between the availability of yard cranes and truck turn time. Truck turn time is defined as the time it takes a truck to complete a transaction at an intermodal terminal. An analytically based simulation model is developed by Kozan (2006) to analyse the impact of different service configurations on delays of trains at an intermodal terminal. The simulation model may be used to select efficient handling technology as well as to assess changes in operating policies. Finally, Alessandri et al. (2007) describe the dynamic evolution of queues inside an intermodal terminal by discrete-time equations. State variables represent queue lengths and control variables take into account resource utilization. The model is applied to determine the number of container handling resources, but may also be adopted to determine optimal control strategies.

A second tactical planning problem of terminal operators concerns the redesign of operational routines and layout structures. Voges et al. (1994) analyse operating procedures for an existing terminal. Three questions are studied. How should the dispatcher at the gate and the crane drivers make their decisions on how to plan the process? If a certain crane strategy would result in favourable waiting times for trucks, are the crane drivers able to follow the strategy without computer support? When would it be useful to abandon the strategy and to work intuitively? Average waiting time of trucks serves as performance criterion. A combination of Human Integrated Simulation (HIS) and computer simulation based on a Petri net model has been applied. This combined approach takes both objective influences and human factors into account. In this game approach human beings play the role of operators at the terminal. A study of operational routines for the transhipment process at intermodal terminals is also given by Marín Martínez et al. (2004). The authors investigate a set of operation modes for a gantry crane at a rail-rail terminal. A discrete event simulation model is built of a Spanish border terminal. Four operation modes are evaluated in a number of scenarios, varying crane characteristics, container sizes and degree of coordination of train scheduling. The authors prefer to recommend rules of operation instead of generating the optimal solution for each particular combination of trains because rules may be easier to implement in practice.

2.4.3 Network Operator

First, a network operator has to decide which consolidation network to use. Four basic types of consolidation networks are considered: a point-to-point network, a line network, a hub-and spoke network and a trunk-collection-and-distribution network. Janic et al. (1999) evaluate rail-based innovative bundling networks operated in the European freight transport system. Their objective is to identify promising or preferable network configurations which can increase the competitiveness of intermodal transport. Indicators for network performance have been defined and quantified for selected bundling networks. The evaluation of consolidation networks is performed by means of the Simple Additive Weighting (SAW) multi-criteria method. Newman and Yano (2000a, 2000b) compare a variety of decentralized planning approaches with a centralized approach for scheduling trains in an intermodal network. The authors simultaneously determine an explicit direct and indirect (i.e. via a hub) train schedule and corresponding container routing decisions. The problem is formulated as an integer program and decomposed into a number of subproblems. Their decentralized scheduling approaches lead to near-optimal solutions within significantly less computational time than the centralized approach.

A second tactical decision of a network operator is the type of production model, i.e. how to operate the trains or barges. This involves decisions about frequency of service, train length, allocation of equipment to routes and capacity planning of equipment. Nozick and Morlok (1997) study a medium-term operations planning problem in an intermodal rail-truck system. The authors develop a modelling framework to plan various elements of rail-truck intermodal operations simultaneously. The problem is formulated as an integer program and solved heuristically. The model encompasses all elements of the operation, including road haulage, terminals and rail haulage. However, attention is focused on the portion of service that is usually within the control of a railroad company, i.e. rail haulage and terminal operations. Moreover, train schedules and the configuration of the network are assumed to be fixed. Choong et al. (2002) present a model for empty container management in intermodal transportation networks. The authors analyse the effect of planning horizon length on mode selection. They state that a longer planning horizon leads to higher utilization of slower modes of transportation. Empty containers can be transported by barge at a very low cost. Within barge capacity limits, empty containers can be piggy-backed onto existing barge tows of loaded containers. However, a trade-off has to be made between the low transportation cost and the relatively slow speed of barge transport. The problem is formulated as an integer programming model that minimizes total cost of empty container management. Based on a case study of the Mississippi River basin, the authors conclude that a longer planning horizon, used on a rolling basis, can give better empty container distribution plans for the earlier periods in the planning horizon. However, advantages might be small for a system that has a sufficient number of container pools. The authors do not integrate loaded and empty container flow decisions in a single model. Lin and Chen (2004) study a network design problem of a door-to-door express service. An air-ground intermodal carrier provides a delivery service in a hierarchical hub-and-spoke network. The network consists of multiple clusters. Local cluster centres are connected to their own hub through a secondary route. Each hub is connected to other hubs through a primary route. Large trucks or aircrafts are used on primary routes, smaller trucks or aircrafts on secondary routes. The problem is to determine fleet size, routes and schedules for both primary and secondary trucks or aircrafts simultaneously, with the objective to minimize the sum of fixed and operating costs while meeting the desired service level. The authors formulate the problem as an integer program in a route-space directed network. The binary program is solved through an implicit enumeration algorithm that contains an embedded least time path sub-problem. Kuo et al. (2008) propose collaborative decision-making strategies at the tactical level for rail-based intermodal freight transport. Three collaboration schemes are assessed by means of a simulation-assignment framework. Train slot cooperation involves two or more carriers who jointly operate a train slot. Train slot swapping allows two carriers to exchange capacity rights for two train slots. In the third collaboration strategy a carrier leases a portion of his train capacity to other carriers. Experimental results show significant improvements in terms of shipments attracted to the proposed services. Andersen et al. (2009b) emphasize the need for synchronization in intermodal rail transport. The authors address multi-fleet management and coordination in intermodal rail transport as well as interactions between rail services and services in collaborating transportation systems. The problem is modelled as a service network design problem with asset management and multiple fleet coordination. Computational results demonstrate potential advantages of removing border operations between countries, collaborating railroads or administrative divisions within the same railroad.

Finally, pricing strategy decisions have to be considered at the tactical planning level. Li and Tayur (2005) develop a tactical planning model for intermodal rail transport that jointly considers operations planning and pricing decisions. In the operations-planning subproblem, freight routing, train routing and train assignment are considered simultaneously. Train routes, frequency of service and number of locomotives and flatcars used on each route need to be determined. The combined problem is formulated as a nonlinear programming model. It is solved to optimality through a decomposition that exploits the structure of the subproblems. The model is developed for the intermodal transport of trailers, but may be easily extended to intermodal transport of containers. Two other papers on pricing strategy decisions are given by Yan et al. (1995) and Tsai et al. (1994). Yan et al. (1995) develop a framework for estimating the opportunity costs for all services in trailer-on-flatcar operations. These opportunity costs are to be taken into account when setting the price level of intermodal transport. The framework is based on a network model, formulated as a linear network flow problem with side constraints. A mathematical program is formulated to address this problem incorporating an efficient algorithm for approximating better the reduced costs. The algorithm combines the use of Langrangian relaxation with a minimum cost algorithm and a shortest path algorithm. Tsai et al. (1994) construct two models to determine an optimal price level and service level for intermodal transport in competition with truck transport. The authors consider the whole intermodal chain, contrary to Yan et al. (1995) who only consider rail haul. The models take into account not only carriers' pricing behaviour (supply side) but also shippers' mode choice behaviour (demand side). Solutions to find an equilibrium are pursued by a mathematical programming approach. The objective is to optimise intermodal profit within some constraints, which include shippers' mode choice behaviour, non-negativity of carrier price and cargo amounts and intermodal volume constraints.

2.5 Operational planning

Important operational decisions include the scheduling of services, empty vehicle distribution and repositioning, crew scheduling and allocation of resources. The main issues are similar to those at the tactical decision level. However, while tactical planning is concerned with 'where' and 'how' issues (selecting services of given types and traffic routes between spatial locations), operational planning is interested in 'when' issues (when to start a given service, when a vehicle arrives at a destination or at an intermediary terminal, etc.). (Crainic and Laporte 1997)

2.5.1 Drayage Operator

The distribution of containers by truck may be considered as a pickup and delivery problem (PDP), which is a special case of the vehicle routing problem. Full containers need to be picked up at their origin and brought to the terminal or delivered from an intermodal terminal to their destination. In a recent study Imai et al. (2007) propose a heuristic procedure based upon a Lagrangian relaxation in order to schedule pickups and deliveries of full container load to and from a single intermodal terminal. Wang and Regan (2002) propose a hybrid approach to solve a PDP containing one or more intermodal facilities. The authors apply time window discretization in combination with a branch and bound method. Francis et al. (2007) model intermodal drayage operations as a multi-resource routing problem (MRRP) in which two resources (tractors and trailers) perform tasks to transport loaded and empty equipment. The authors introduce the concept of flexible tasks for which the origin or destination is not a priori defined. A randomized solution method, called the Greedy Randomized Procedure, is proposed to solve the resulting problem.

Justice (1996) addresses the issue of chassis logistics in intermodal freight transport. A drayage company has to provide sufficient chassis at terminals in order to meet demand. A planning model is developed to determine when, where, how many and by what means chassis are redistributed. The problem is mathematically formulated as a bi-directional time based network transportation problem. Own software has been developed to calculate solutions using five sub-problems: find planning horizon, determine train arrivals and departures, obtain chassis supply and demand, obtain unit costs with each supply-demand pair, optimize for minimum cost solution through simplex based iterations. It is assumed that supply and demand of chassis at a terminal in a given time period are known.

2.5.2 Terminal Operator

During daily operations terminals have to assign resources such as yard cranes or reachstackers to jobs. Alessandri et al. (2009) study operational decisions at an intermodal terminal by means of a discrete-time dynamic simulation model. The allocation of available handling resources is modelled as a mixed-integer nonlinear programming problem, with the objective to minimize a performance cost function. Solution techniques are evaluated based on simulation results in a case study.

A second operational planning problem of terminal operators concerns the scheduling of jobs in a terminal. Corry and Kozan (2006) develop a load planning model to dynamically assign containers to slots on a train at an intermodal terminal. The objectives are to minimize excess handling time and optimize the mass distribution of the train. Because truck arrival times are not known in advance, the model needs to be applied over a rolling horizon. The simplifying assumption is made that all containers have equal length. A simulation model is developed to assess the performance of the dynamic assignment model under two different operating environments, a simplified case and a more realistic scenario. Significant reduction of excess handling time could be achieved with a relatively small concession in mass distribution. The study is extended with the introduction of technical constraints and container types of various length (Corry and Kozan 2008). Gambardella et al. (2001) split loading and unloading operations in an intermodal terminal into a resource allocation problem and a scheduling problem. The two problems are formulated and solved hierarchically. First, quay cranes and yard cranes are assigned over a number of work shifts. The resource allocation problem is formulated as a mixed-integer linear program and solved using a branch-and-bound algorithm. Then a scheduling problem is formulated to compute loading and unloading lists of containers for each allocated crane. The scheduling problem is solved using a tabu search algorithm. The authors validate their approach by performing a discrete event simulation of the terminal. A new intermodal terminal concept called 'mega hub' is investigated by Alicke (2002). In a mega hub the connection of containers to wagons is not fixed, therefore no time consuming shunting is necessary. Loading units are transhipped between several block trains during a short stop at the intermodal terminal. Trains operate according to timetables and arrive in bundles of six trains in which transhipment takes place. Rotter

(2004) provides an overview of the operating concept of a mega hub and summarizes potential benefits and necessary requirements. Alicke (2002) models the terminal as a multi-stage transhipment problem, in which the optimal transhipment sequence of containers between trains needs to be determined. An optimization model based on Constraint Satisfaction is formulated and various heuristics are developed. The objective is to minimize the maximum lateness of all trains. Practical constraints like the distinction between direct and indirect transhipment as well as overlapping crane areas are included. The model may be used to calculate an initial schedule or to reschedule in case of delay of a train.

2.5.3 Network Operator

Network operators have to take daily decisions on the load order of trains and barges. Feo and González-Velarde (1995) study the problem of optimally assigning highway trailers to railcar hitches ('piggyback' transport) in intermodal transportation. The problem is defined as a set covering problem and formulated as an integer linear program. Two methods are proposed to minimize a weighted sum of railcars used to ship a given set of outbound trailers. First a general purpose branch-and-bound code is applied, second a Greedy Randomized Adaptive Search Procedure (GRASP) is developed to approach optimal solutions. The heuristic incorporates a selection of the most difficult to use railcars available together with the most difficult to assign trailers. In doing this, the least compatible and most problematic equipment is considered first. Feo and González-Velarde (1995) only consider the local trailer assignment problem at a single yard, at a single point in time. Powell and Carvalho (1998) want to introduce network level information to improve decisions made at a local level. The previous model ignores the importance that the choice of destination has in the aim to fully utilize the equipment. For example, if the container is going to a destination that pools a large number of trailers, flatcars are prefered that can carry trailers. Network information such as this can influence the decisions made by the local terminal. Powell and Carvalho (1998) propose a dynamic model for optimizing the assignment of trailers and containers to a flatcar. The problem is formulated as a logistics queuing network which can handle a wide range of equipment types and complex operating rules. The repositioning of railroad-owned equipment is integrated in this problem formulation.

A second operational planning problem of network operators relates to the redistribution of railcars, barges and loading units. In Chih et al. (1990) a decision support system called RAILS is set up to optimally manage intermodal double-stack trains.

This assignment problem is complex as there are height constraints and choices between different modes. The system is to be used on a daily basis to ensure the correct size of each train and to generate rail car repositioning instructions. The planning horizon is two weeks and takes the local and global system needs into consideration. The problem is formulated as a non-linear multi-commodity integer network flow problem. As the problem is NP hard, a heuristic method is developed in order to be able to solve the network optimisation problem within a reasonable time. The heuristic breaks the solution procedures into several components and uses well developed traffic assignment and capacitated network transhipment optimisation algorithms to solve the problem. In Chih and van Dyke (1987) a similar approach is followed for the distribution of the fleet's empty trailers and/or containers.

2.5.4 Intermodal Operator

At the operational level an intermodal operator has to determine the optimal routing of shipments. Barnhart and Ratliff (1993) discuss methods for determining minimum cost intermodal routings to help shippers minimize total transportation costs. Their models are focused on the rail/road combinations compared to uni-modal road transport. Two types of decision settings are identified depending on who owns the equipment and who is providing the service. When rail costs are expressed per trailer, minimum cost routings are achieved with a shortest path procedure. For rail costs expressed per flatcar, optimal routings are determined with a matching algorithm and a b-matching algorithm. The latter models are also able to incorporate non-monetary constraints such as schedule requirements and flatcar configuration restrictions in case different types of flatcars and trailers exist.

A decision support system is constructed by Boardman et al. (1997) to assist shippers in selecting the least cost combination of transportation modes (truck, rail, air, barge) between a given origin and a corresponding destination. As an indicator of cost, average transportation rates for each transportation mode are used. This is a simplification of reality as most likely a cost difference between long haul truck and short haul drayage costs exists. Least-cost paths in the network are calculated by means of the K-shortest path double-sweep method. The minimization of transportation costs is the single objective stated in this study. In multi-objective shortest path problems distance, time, reliability, accessibility and capacity may also be taken into account. The software is interfaced to a commercial geographic information system software package to assist the user in visualizing the region being analysed.

Ziliaskopoulos and Wardell (2000) discuss a shortest path algorithm for intermodal transportation networks. The authors introduce the concept of time dependency of optimal paths in their routing model. The time horizon is divided into discrete intervals. Also delays at switching points, fixed time schedules of transport modes and movement delays or movement prohibitions are taken into account. The algorithm computes optimal routes from all origins, departure times and modes to a destination node and exit mode, accounting for the time-dependent nature of the arc travel times and switching delays, without explicitly expanding the network. The computational complexity of the algorithm is independent of the number of modes. Computational time increases almost linearly with the number of nodes in the network and the number of time intervals. An extension of this work is presented by Chang et al. (2007), who calculate time-dependent intermodal minimum cost paths. Cost rather than time is optimized, based on time-dependent and fixed travel and transfer costs. The algorithm is adapted to solve the problem of intermodal routing of hazardous materials, taking into account both travel risk and travel cost. Grasman (2006) presents dynamic programming formulations for the optimal routing of freight in an intermodal network. Either the least cost route is identified subject to a lead time constraint, or a least lead time route is searched for while constraining total cost.

Min (1991) focuses on the multi-objective nature of the modal choice decision. A chance-constrained goal programming (GP) model is constructed that best combines different modes of transportation and best maintains a continuous flow of products during intermodal transfer. The GP model is a multiple objective technique for determining solutions. The comparison between transportation modes is based on cost, market coverage, average length of haul, equipment capacity, speed, availability, reliability and damage risk. The most service-cost-effective transportation mode is sought for each segment in the international distribution channel. Chang (2008) formulates the international intermodal routing problem as a multiobjective multimodal multicommodity flow problem with time windows and concave costs. The objective function minimizes the weighted sum of total flow cost and total travel time. The cost associated with each link in the network is assumed to be a continuous non-convex piecewise linear function of the total flow along the link, representing economies of scale in intermodal freight transport. The author proposes a heuristic algorithm in which the original problem is broken into a set of smaller and easier subproblems.

An integrated model for routing loaded tank containers and repositioning empty tank containers in an intermodal network is defined by Erera et al. (2005). The problem is formulated as a deterministic network flow model over a time-expanded network. A computational study verifies that integrated container management can substantially reduce empty repositioning costs. The results also indicate that it is worthwhile to make repositioning decisions daily as opposed to weekly. Imposing a lower bound on the repositioning quantity has relatively little impact on total costs.

2.6 Integrating applications

2.6.1 Multiple Decision Makers

Van Duin and Van Ham (1998) construct a three-stage modelling approach for the location and design of intermodal terminals. The authors incorporate the perspectives and objectives of shippers, terminal operators, agents, consignees and carriers. For each stage, an appropriate model is developed. In a first stage, a linear programming model determines the optimal locations for intermodal terminals. This model takes account of the existing terminals in the Netherlands and can then be used in order to find some new prospective area. In the next stage a definite location in the prospective area is found by means of a financial analysis. Here the location of large potential customers is one of the most decisive factors. In the last stage a discrete event simulation model of the terminal offers the opportunity to simulate the operations of the terminal. This model can be used to make decisions on the amount of cranes, amount of employees, etc.

A strategic analysis involving all four decision makers has been performed by Gambardella et al. (2002). The authors model the complete logistic chain in a complex network of intermodal terminals in order to understand how intermodal transport can be put in competition with road transport. The model consists of two subsystems: an Intermodal Transport Planner and a simulation system, including a road, rail and terminal simulation module. The planning of intermodal transport is performed by means of an agent-based model of the intermodal transport chain. A discrete event simulation system is designed to verify the feasibility of these transport plans and to measure their performance.

Evers and De Feijter (2004) investigate strategic decisions of both terminal operators and network operators. An explorative study is carried out on the choice between centralized versus decentralized service of inland barges and short sea vessels in a seaport area. The authors propose to equip the central service station with an automated quay stack. Both scenarios are simulated for the Maasvlakte harbour area of Rotterdam. In this case study a centralized service appears to be preferable.

Bostel and Dejax (1998) integrate operational planning decisions of terminal operators and network operators. The operational problem of optimizing container loading on trains in rail/rail transhipment is addressed. The authors seek to determine the loading place of containers in initial terminals as well as their reloading place after transhipment at a rail/rail terminal, with the objective to minimize transfer operations and therefore the use of handling equipment. The problem is formulated as a minimum cost multi-commodity network flow problem with binary variables. The following two cases are analysed: first, optimisation of container transfers with imposed initial loading and second, joint optimisation of initial loading and reloading. Both cases are considered in the situation of unlimited storage capacity and in the situation of limited storage capacity. Because of the complexity of the problem, the authors developed a heuristic solution method. Experiments on large-scale real datasets show that joint optimization of initial loading and transfer of containers increases the productivity of bottleneck equipment.

In table 2.2 the papers, described in this section, are positioned in the decision maker/time horizon matrix.

<table>
<tr><th></th><th colspan="4">Decision maker</th></tr>
<tr><th>Time horizon</th><th>Drayage operator</th><th>Terminal operator</th><th>Network operator</th><th>Intermodal operator</th></tr>
<tr><td rowspan="3">Strategic</td><td></td><td colspan="2">Van Duin and Van Ham (1998)</td><td></td></tr>
<tr><td colspan="4">Gambardella, Rizzoli, and Funk (2002)</td></tr>
<tr><td></td><td colspan="2">Evers and De Feijter (2004)</td><td></td></tr>
<tr><td>Tactical</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Operational</td><td></td><td colspan="2">Bostel and Dejax (1998)</td><td></td></tr>
</table>

Table 2.2: Multiple decision makers

2.6.2 Multiple Decision Levels

A general summary of decisions facing a terminal operator can be found in Vis and de Koster (2003). For each process taking place at a container terminal, the authors discuss types of material handling equipment used and related decision problems at all three decision levels. Quantitative models proposed in literature to solve these problems are presented. Most models address a single type of material handling equipment. The authors conclude that joint optimization of several types of material handling equipment is a topic for future research. Furthermore, it is necessary to extend models from simple cases to more realistic situations.

A second study integrates strategic and tactical planning decisions of a network operator. Jourquin et al. (1999) combine a network model with GIS software to support strategic decisions of a network operator. A virtual network is constructed in which all successive operations involved in multi-modal transport are broken down in a systematic way and a detailed analysis of all costs is included. The generalised costs are minimised according to the shortest path algorithm. By simulation with different parameter values, the software can provide performance measures such as tons per km, total distance, total cost, duration and capacity utilisation of nodes and links. At a tactical level the model is used to derive the impact of different types of consolidation networks on the distribution of flows over the available infrastructure and transport modes. Table 2.3 shows the position of both papers.

Caramia and Guerriero (2009) study how to support an intermodal operator at the tactical and operational decision level. At the tactical level the best set of transport services that serves customer requests is identified. In the operational phase the operator decides how to route a specific transportation request. The authors refer to the problem as a vehicle routing problem in a multimodal network. The objective is to minimize travel time and route cost, while maximizing a transportation mean sharing index. The latter presents opportunities to attain economies of scale in the network. Constraints are related to vehicle capacity, time windows, mandatory nodes and forbidden nodes. The authors describe a local search heuristic to find solutions in a reasonable time frame.

<table>
<tr><th></th><th colspan="3">Time horizon</th></tr>
<tr><th>Decision maker</th><th>Strategic</th><th>Tactical</th><th>Operational</th></tr>
<tr><td>Drayage operator</td><td></td><td></td><td></td></tr>
<tr><td>Terminal operator</td><td colspan="3">Vis and de Koster (2003)</td></tr>
<tr><td>Network operator</td><td colspan="2">Jourquin et al. (1999)</td><td></td></tr>
<tr><td>Intermodal operator</td><td></td><td colspan="2">Caramia and Guerriero (2009)</td></tr>
</table>

Table 2.3: Multiple decision levels

2.7 Conclusions and prospects

Intermodal transport has grown into a dynamic transportation research field. Many new intermodal research projects have emerged. An investigation has been made into planning issues in intermodal transport. Intermodal planning problems are more complex due to the inclusion of multiple transport modes, multiple decision makers and multiple types of loading units. Three strategic planning problems, terminal design, infrastructure network configuration and the determination of terminal locations have received an increased attention in recent years. Research efforts have also been directed towards intermodal routing decisions. The number of scientific publications on other intermodal planning problems remains limited. Topics such as the allocation of resources to jobs in an intermodal terminal or the determination of truck and chassis fleet size in intermodal drayage operations still need to be tackled.

The following themes are interesting for future research. Until now the main attention is given to intermodal transport by rail. In regions with an extensive waterway network, such as Western Europe, intermodal transport including inland navigation is also important. Future research is necessary to improve operations in intermodal barge transport. A tactical planning problem that requires more research attention is the design of the intermodal service network and in particular the determination of an optimal consolidation strategy. Additional insight should be gained into which bundling concepts can contribute to the improvement of intermodal transport operations. At the operational level, drayage operations constitute a relatively large portion of total costs of intermodal transport. The development of efficient drayage operations can encourage its attractiveness. However, few research has been conducted on intermodal drayage operations. Research efforts are also needed into the further development of solution methods and the comparison of proposed operations research techniques. Metaheuristics can offer an interesting perspective in view of the increased complexity of intermodal planning problems. A final research field for the future concerns the cooperation between actors in the intermodal transport chain. Few studies take multiple decision makers into account. An increased level of coordination is required to improve the performance of intermodal freight transport. Also more integration can be achieved between planning problems at different decision levels.

This thesis deals with intermodal barge transport. A simulation model is developed in chapter 3 to analyse intermodal freight transport networks which incorporate inland navigation. Bundling concepts are analysed at the strategic and tactical decision level. In chapter 4 bundling is organised in the port area by providing a barge hub for inland freight flows. Cooperation between terminal operators with the objective to bundle freight flows along the same waterway axis is discussed in chapter 5. Next, chapter 6 investigates shipper collaboration in order to bundle freight during daily operations inside a loading unit. Finally, intermodal drayage operations are studied in chapters 7 and 8. A local search heuristic and a deterministic annealing heuristic are proposed to find near-optimal solutions in a reasonable time frame.

Chapter 3

Simulating interactions in intermodal barge transport networks

3.1 Introduction

In this chapter[1] a discrete event simulation methodology is developed to capture and analyse interactions in intermodal freight transport networks at the strategic and tactical decision level (figure 3.1). In regions with an extensive waterway network intermodal transport including inland navigation is a good alternative for unimodal road transport. A discrete event simulation methodology is proposed to analyse policy measures for stimulating intermodal barge transport. The objective of the simulation model is to assess the impact of policy measures on performance measures such as turnaround time of vessels, waiting time of barges in the port area and handling time of inland barges at sea terminals. According to Law (2007), simulation is a technique to imitate the operations of a real-world facility or process. The facility or process of interest is called a *system* and a set of assumptions about how it works is made in order to study it scientifically. An intermodal freight transport network is modelled with the objective to understand the system and analyse various network configurations. Intermodal transport networks exhibit an increased complexity due to the inclusion of multiple transport modes, multiple decision makers and multiple

[1] This chapter is based on Caris, Janssens, and Macharis (2009).

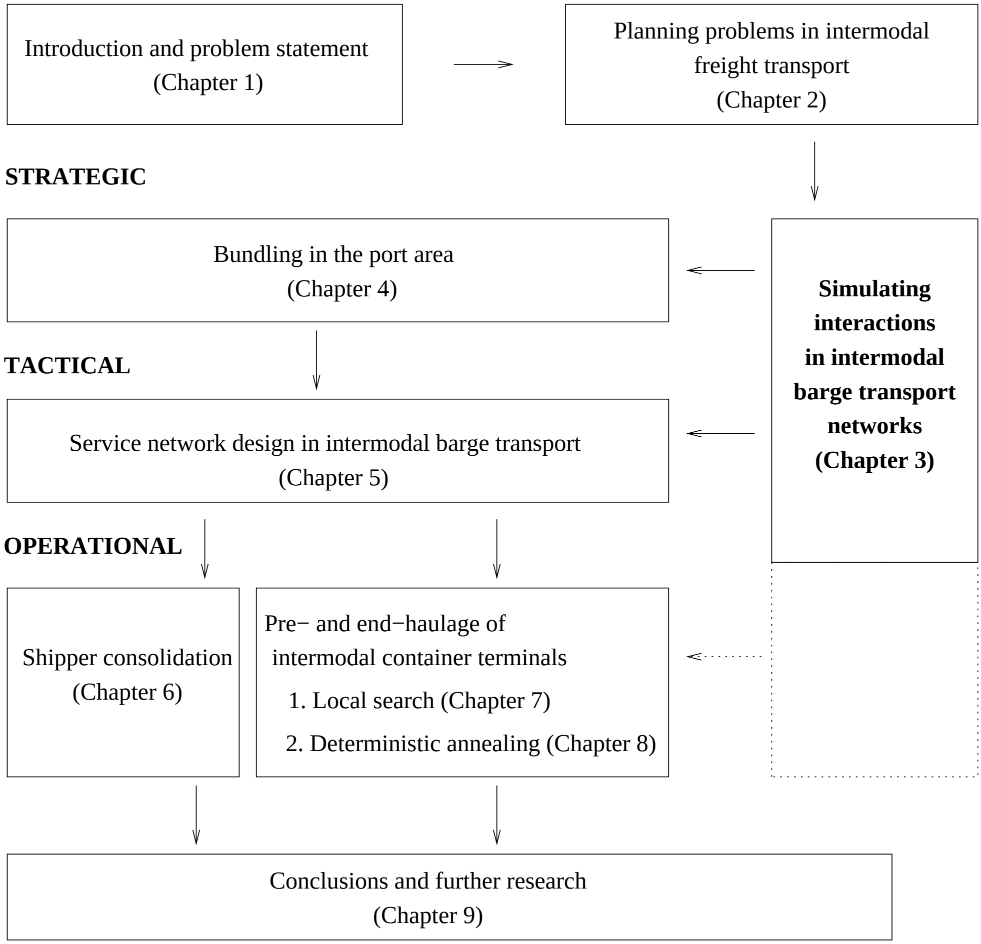

Figure 3.1: Outline of the thesis - Chapter 3

types of loading units. The complexity of the intermodal transport system makes it impossible to describe all interactions by a mathematical model. Because of this increased complexity and the required level of detail, discrete event simulation is the appropriate tool of analysis. Lyons et al. (2003) discuss the role of complex systems models in strategic decision making. The authors indicate that simulation models are appropriate to interpret the structure of a complex system. They allow one to explore the outcomes of alternative strategic choices, rather than providing a forecast of a predetermined future. The simulation model for intermodal barge transport is used in chapter 4 to compare the outcome of alternative bundling scenarios. Chapter 5 applies the simulation model to support the tactical decision level. The simulation model may be extended in future research to model decisions at the operational decision level.

Simulation models have been widely used at the strategic planning level in intermodal transport, as discussed in section 2.3. An example of optimizing the design of intermodal terminals is given by Rizzoli et al. (2002). The authors present a simulation tool for the combined rail/road transport in intermodal terminals. Their simulator may be applied to simulate both a single terminal and a rail network. Statistics concerning the performance of the terminal equipment, the residence time of intermodal transport units and terminal throughput are gathered. Simulation models are also useful at the strategic decision level for network operators. Parola and Sciomachen (2005) describe a strategic discrete event simulation model to analyse the impact of a possible future growth in sea traffic on land infrastructure in the north-western Italian port system. Outputs are concerned with the degree of saturation of railway lines and the level of congestion of truck gates.

In this chapter a simulation model is presented that covers the hinterland waterway network of a major port in Western-Europe in order to analyse effects of future policy measures for intermodal container transport. The simulation model is part of a larger framework, as described in section 3.2. The intermodal hinterland network of the port of Antwerp serves as the real-world application in this study. Section 3.3 gives an overview of the current network configuration. Section 3.4 presents the conceptual model of the hinterland waterway network. In section 3.5 various aspects in the computerized modelling process are discussed. Section 3.6 reports on a first application of the simulation model.

3.2 Decision Support System for Intermodal Transport Policy making

The discrete event Simulation model for InterModal BArge transport (SIMBA) described in this chapter is incorporated in a Decision Support System for Intermodal Transport Policy making (DSSITP), presented in Macharis et al. (2008). Within the DSSITP project [2], the aim was to develop an assessment framework using three different models that are capable of assessing policies intended to enhance the growth of intermodal inland waterway and rail transport. Both combinations have a partic-

[2] **Acknowledgement:** We thank the Belgian Science Policy (BELSPO) for their support on our research project DSSITP (Decision Support System for Intermodal Transport Policy) in the research programme "Science for a Sustainable Development - call 2", under contract number SD/TM/08A.

ular market structure and operations, but it is important to analyse them together in order to take care of potential competition distortions. The assessment of transport policy measures is performed on a European scale by Tsamboulas et al. (2007). The authors focus on the potential of policy measures to produce a modal shift in favor of intermodal transport. Tan et al. (2004) discuss a simulation model for a state-wide intermodal freight transportation network, with the objective to demonstrate interactions between transport modes under various intermodal policy changes. The DSSITP framework intends to take multiple indicators into account when assessing policy measures. The impact of policy measures will be measured on all related transport modes and at multiple aggregation levels.

Three core models, LAMBIT, SIMBA and NODUS make up the decision support system for intermodal transport policy making. For a detailed description of the LAMBIT and NODUS models, the reader is referred to the respective chapters in Macharis et al. (2008). The general assessment framework aims to integrate these models. Figure 3.2 presents the general assessment framework, in which the three models are integrated. Due to the combination of the three models, the analysis of policy measures is performed on multiple levels of aggregation over multiple transport modes.

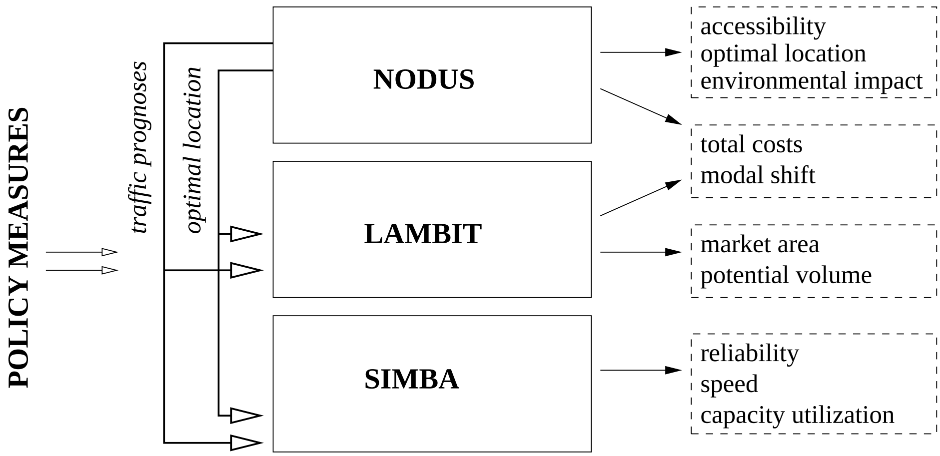

Figure 3.2: Decision Support System for Intermodal Transport Policy (DSSITP)

Each model has its specific purpose and outputs. The multimodal freight model NODUS is situated on the highest level of aggregation and constitutes the first step in the analysis of a potential policy measure. The NODUS model provides traffic prognoses which serve as inputs for the LAMBIT model and SIMBA model. The various outputs of the assessment framework are also stated in figure 3.2. The NODUS model produces aggregated outputs of the various transport modes, such as their accessibility, environmental impact and share in the modal split. Total costs of an intermodal service are measured. In addition, a module is developed for NODUS in order to provide optimal locations of terminals. These optimal locations may be introduced in the LAMBIT and SIMBA models. The LAMBIT model is scaled on the Belgian intermodal network. The model analyses the potential market area of a new terminal and assesses the impacts on existing terminals. It may also be applied to analyse changes in market areas as a consequence of price changes, for example through subsidies. The model further produces cost indicators and potential modal shifts. The SIMBA model is situated on the lowest level of aggregation and produces detailed output related to the reliability, speed and capacity utilization of the waterway network. The simulation model is used to analyse policy measures that impact container flows in the intermodal barge network and the port area of Antwerp. It allows to detect future bottlenecks in the infrastructure of the network. With the SIMBA model, the impact of volume increases in the network or the introduction of new intermodal barge terminals can be simulated. Section 3.6 presents a first application in which a new inland terminal is introduced in the current network. Also alternative consolidation strategies may be compared. A policy measure related to the consolidation network in the port area is presented in chapter 4. Bundling in the hinterland is simulated in chapter 5.

3.3 Intermodal transport network

The port of Antwerp is currently in a regionalization phase. Notteboom and Rodrigue (2005) define regionalization as a new phase in port development. In this phase, inland distribution becomes of great importance in port competition. Land transport forms an important target for reducing logistics costs. A modal shift to rail and barge transport may provide a more efficient access to the hinterland. The port is establishing functional links with regional inland nodes, which may result in a broader and potentially discontinuous hinterland. Since the mid 1990s a wave of investments in new intermodal terminals has taken place in the hinterland of Antwerp (Macharis et al. 2008). Notteboom (2007) warns that a rationalisation in the Benelux terminal network is to be expected. The author suggests that some strategically located terminals will obtain a hub status and will serve large and long distance markets. Others will become subordinated to these hub terminals and will serve only local and regional markets. At this moment however, it is not clear how it will further evolve. The simulation model proposed in this chapter, may help to see which further evolutions are most desirable.

Figure 3.3 represents the port area of Antwerp. Three clusters of sea terminals can be identified. Until recently the main center of activity was situated on the right river bank. Sea terminals on the right river bank are either situated behind the locks (cluster 1) or in front of the locks at the river Scheldt (cluster 2). The two clusters are separated by three lock systems, indicated in figure 3.3 by three white blocks. Barges have to pass one of the three available lock systems to sail between cluster 1 and cluster 2. With the construction of a new dock (Deurganckdok) in the port of Antwerp, a third cluster of sea terminals emerged on the left river bank. Inland barges spend time in the port area, calling at multiple sea terminals and passing through the time-consuming locks. In the analysis of potential hub scenarios in chapter 4, clusters are defined as all sea terminals at the same side of the three lock systems. Cluster 2 and cluster 3 are both situated on the left of the locks, directly accessible from the sea side through the river Scheldt. Therefore, these clusters are jointly referred to as 'left river bank' in the subsequent analysis, as depicted in figure 3.4. Cluster 1 will be referred to as 'right river bank'. Inland vessels have to pass through a lock in the port area to sail from cluster 1 behind the locks on the right river bank to the sea terminals at the river Scheldt or on the left river bank in the Deurganckdok. However, inland barges coming from the Albert canal have direct access to sea terminals on the right river bank in cluster 1 without having to pass through a lock system. Barges may also sail through the Scheldt-Rhine connection to Rotterdam and Amsterdam. A last destination is the port of Zeebrugge, which can be reached via Antwerp and short sea shipping on the river Scheldt. Table 3.1 summarizes all origins and destinations of shuttle services.

Origins	**Destinations**
Albert Canal	Antwerp: right river bank
Brussels-Scheldt Sea Canal	Antwerp: left river bank
Upper Scheldt and Leie	Rotterdam
	Amsterdam
	Zeebrugge

Table 3.1: Origins and destinations

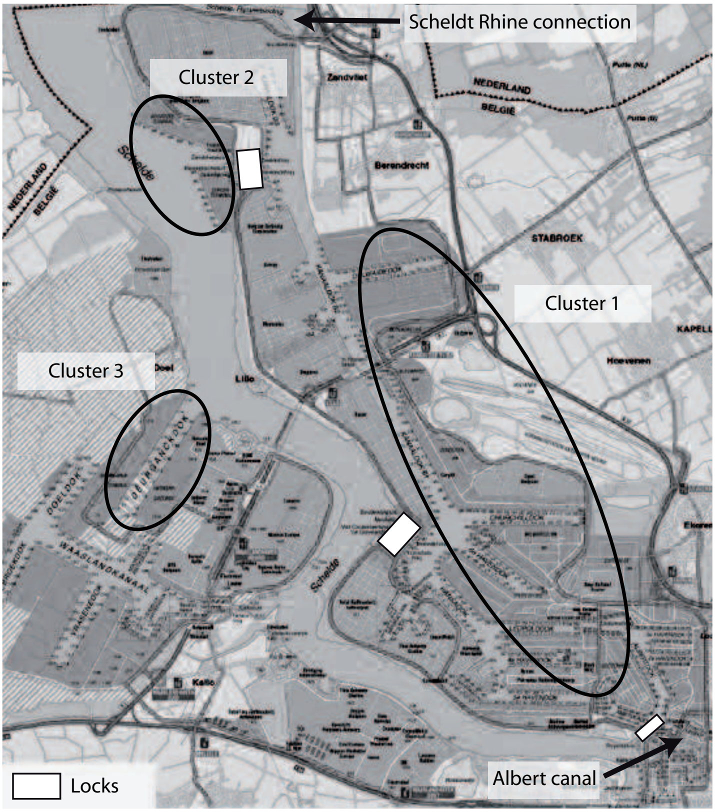

Figure 3.3: Port area of Antwerp (Adapted from Port of Antwerp)

Shuttle services transport containers from inland terminals to sea terminals in the port area and carry containers from sea terminals to inland destinations in a round trip. A structural overview of the current network figuration, as assumed in the further analysis, is presented in figure 3.4. All inland terminals along each waterway axis that are included in the simulation model are mentioned. Three regions of origin can be identified in the Belgian hinterland network of the port of Antwerp (figure 3.5). The first group of intermodal container flows originates in the basin of the Upper Scheldt and the river Leie. A second region of origin is located in the central part of the country, connected to the port of Antwerp by the Brussels - Scheldt Sea Canal. The third group of container terminals is situated along the Albert Canal towards the eastern part of Belgium. All intermodal container terminals organize shuttle services either to the port of Antwerp or to the ports of Rotterdam and Amsterdam.

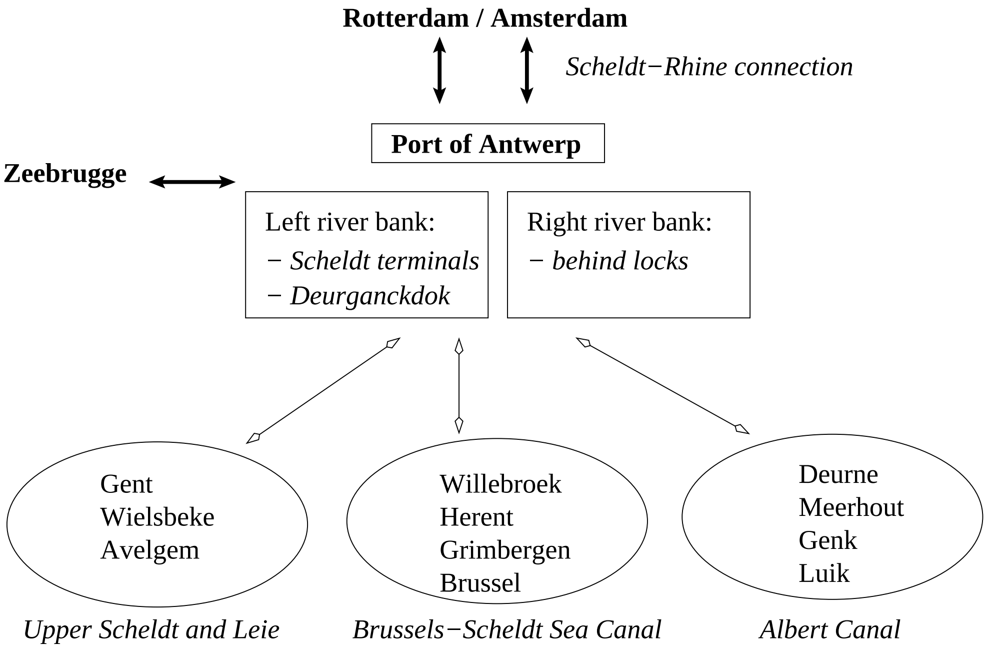

Figure 3.4: Current network configuration

3.4 Conceptual Modelling

Three interrelated components can be identified in the intermodal hinterland network, as depicted in figure 3.6. The first component in the intermodal freight transport network is the inland waterway network. The inland waterway network is made up of terminals, waterway connections and container flows. Barges originate from the different inland terminals and carry containers in round trips to the various ports. Barges are of multiple sizes and carry a variable number of containers, based on real data input from inland container terminals. A second component is the port area of Antwerp. Barges may visit sea terminals at the left river bank and right river bank in the same round trip. When sailing from one cluster of sea terminals to the other, barges have to pass through one of the lock systems in the port area. Other port destinations are the port of Rotterdam or Amsterdam via the Scheldt-Rhine connection or the port of Zeebrugge via the Scheldt estuary. On the right and left

Figure 3.5: Belgian hinterland network of Antwerp (www.containerafvaarten.be)

river bank, barges queue for handling at the sea terminals. Service capacity at sea terminals is limited by the quay length for handling vessels. Maritime as well as inland vessels moor for loading or unloading containers at sea terminals. However, priority is given to seaborne vessels. Inland barges moor as soon as enough quay length is available. The handling time at the sea terminal depends on the number of containers that need to be unloaded from or loaded into the inland vessel. In the inland waterway network as well as in the port area multiple locks are present. Therefore, the lock planning constitutes a third major component.

The objective of the SIMBA model is to simulate possible policy measures for intermodal barge transport, but it can also be applied to analyse planning decisions of private stakeholders. For example in section 3.6 the introduction of a new inland terminal in the network is simulated. Consequences and implications for the network performance measures can be estimated before implementation of a policy measure. Various conceptual models may be necessary to analyse the implications of proposed policies. The conceptual model of the current container flow is depicted in figure 3.7. Inland terminals are connected by shuttle services on a regular basis to one or

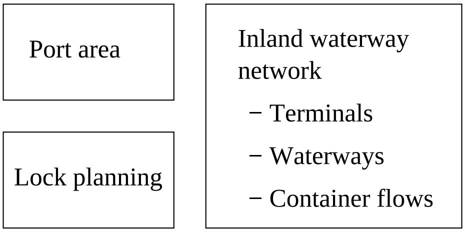

Figure 3.6: Components

multiple port destinations. Barges visit only one or a limited number of terminals in the hinterland. As a consequence, all barges enter the port area and visit one or multiple sea terminals. This may result in a low number of containers loaded or unloaded during a terminal call.

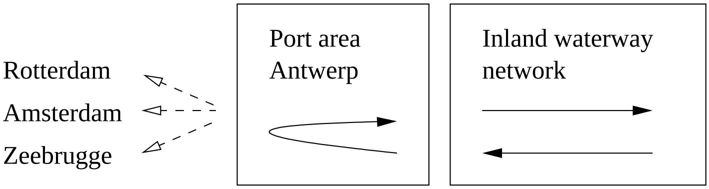

Figure 3.7: Conceptual model current situation

3.5 Computerized modelling in Arena

This section describes how the conceptual model is translated into a computerized model in the simulation software Arena. The first subsection presents the general simulation approach. Next, assumptions underlying the simulation model are summarized. The following two subsections give an overview of inputs and outputs of the SIMBA model. Finally, the modelling of lockage operations and the calibration of the SIMBA model are discussed.

3.5.1 Discrete event simulation

In a discrete event system, one or more phenomena of interest change value or *state* at discrete points in time. These points in time are moments at which an *event* occurs. An event is defined as an instantaneous occurrence that may change the state of the system. (Fishman 2001; Law 2007) The players or *entities* in our discrete event simulation model are barges which sail through the waterway network. The simulation model is constructed in Arena, a simulation software based on queuing theory. Entities are defined as barges which originate from each inland terminal. Barges queue for handling at locks along waterway connections. Locks may be considered as a first group of service facilities in the network. Opening hours of locks are introduced in the simulation software as schedules for the availability of resources. Barges are collected in batches to go through the lockage process. After lock passage, batches are split into the original entities. When arriving in the port area, barges queue for handling at the quays of sea terminals. A second group of service facilities are thus the quays in the port area. The concept of shared queues is applied to model queueing at sea terminals throughout the model logic. Figure 3.8 depicts the flow of entities through the simulation model.

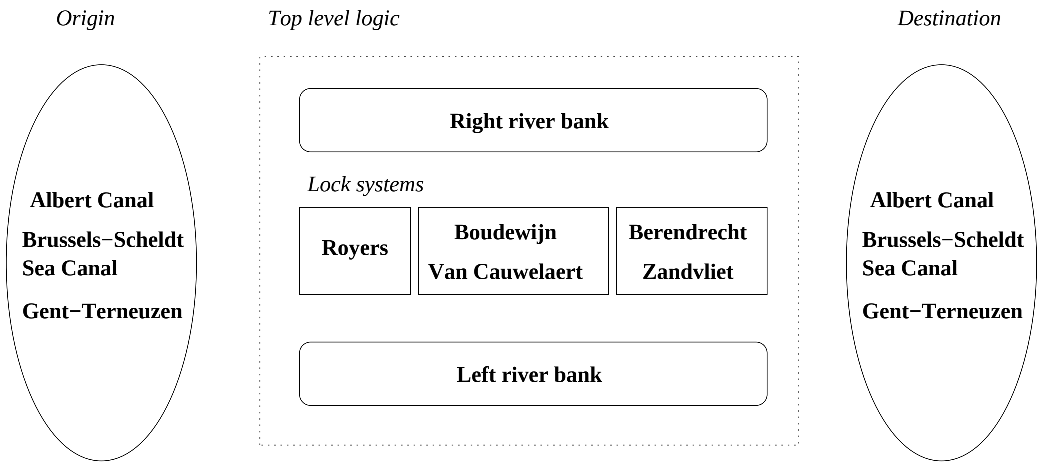

Figure 3.8: Flow of entities through the simulation model

The top level logic represents the port area. The model logic describes the two clusters of sea terminals on the right and left river bank, separated by three lock systems. Locks are constructed in separate submodels. Submodels are also applied for the three regions of origin in the hinterland network, namely the Albert Canal, the Brussels-Scheldt Sea Canal and the canal Gent-Terneuzen. Barges originating in the western part of the hinterland may sail through the canal Gent-Terneuzen and the Scheldt estuary to the port of Antwerp. After visiting all required terminals in the port area, barges return to their inland terminal and leave the simulation system. Stations and Route modules are introduced to keep the simulation model manageable. Examples of state variables in this discrete event system are the status of the servers (idle or busy), the number of barges waiting in a queue for handling at a lock or the time of arrival of a barge waiting in a queue for handling at a sea terminal. Events are for example the completion of service of a barge at a lock or the arrival of a barge at a sea terminal.

3.5.2 Assumptions

A number of assumptions are made to translate the conceptual model of the intermodal network into a discrete event simulation model. The emphasis lays on inland waterway transport. Rail connections in the hinterland network are not taken into account. All main waterway connections between inland terminals and the port area are incorporated in the simulation model. Small waterways without inland terminals are not included in the simulation model of the current situation. Pre- and end-haulage by road is also not incorporated. A modelling methodology and solution methods for pre- and end-haulage of intermodal container terminals are presented in chapters 7 and 8.

In the first group of service facilities, the stochastic lockage times are represented by a triangular distribution. Sailing times on the network connections are assumed to be stochastic and also follow a triangular distribution. The arrival process of barges is based on real data input collected from the inland terminals, the waterway operators and the port authority.

The second group of service facilities consists of the quays at sea terminals. A fixed quay length is assumed for handling inland barges at each sea terminal. In reality the layout of sea terminals is aimed at handling seagoing vessels. In the port of Antwerp no dedicated quay sides are provided for inland navigation. Inland barges are handled with the same infrastructure and equipment and priority is given to handling seagoing vessels. However, no data is available on the arrival pattern and length of maritime vessels at the sea terminals. Therefore maritime vessels are not introduced into the simulation when modelling the handling at sea terminals. Instead, a given percentage of total available quay length is assigned to serving inland barges. In order to take the variability in available quay length into account, the handling of barges is modelled as a stochastic process. The handling of inland barges consists of mooring and loading or unloading containers. Both elements are modelled stochastically. The model further assumes a homogeneous container type. The same probability distribution is used for modelling the handling time of each container.

The variance-reduction technique of common random numbers is applied to synchronize various scenarios in the following chapters. A separate random number stream is assigned to each source of randomness. The basic idea is to compare alternative scenarios under similar experimental conditions so that observed differences are due to differences in the system configuration rather than to fluctuations of the experimental conditions (Law 2007). A stream of random numbers is dedicated to the lockage times, sailing times, handling times at terminals and choice of lock in the port area.

3.5.3 Data Requirements

All intermodal terminals in the inland waterway network are asked for information to identify current container flows in the network. Real data on shuttle services is used as an input for the simulation model. For each shuttle service the following information is required: which type of barge is used, which destinations are visited and what is the average number of import and export containers for each destination. Table 3.2 lists the attributes of each barge entering the network. In the second column an example is given. The simulation is run over 28 days or 672 hours. In this example a barge arrives in the simulation system at 16.43 hours, meaning it departs from the inland terminal Genk and sails to the port area of Antwerp. The barge has a width of 11.5 metres and a length of a hundred metres, leading to a surface area of 1150 m^2. In the port area first the cluster of sea terminals on the right river bank is visited. 57 containers need handling (loading or unloading) at two sea terminals. Next, the barge moors at four sea terminals on the left river bank and requires handling of 85 containers.

Container transport interacts with other freight flows. Therefore, the flow of non-containerized goods on the inland waterway network is introduced as an input in the simulation model. These flows affect the waiting times at locks. Information is also necessary on the network connections. The waterway administrators (Waterwegen en Zeekanaal nv, nv De Scheepvaart en Gemeentelijk Havenbedrijf Antwerpen) provided information on the number of locks on each waterway, distances between locks, average lockage times, number of lock chambers and size of the chambers. Table 3.3 presents the main characteristics of the locks incorporated in the simulation model. The columns mention the waterway along which the lock is situated, exact location, number of lock chambers, length and width expressed in meters and probability distribution chosen to model the lockage time. The lock systems along the Albert canal, each consist of two identical lock chambers and a single larger lock chamber. The lockage process is further discussed in subsection 3.5.5.

In the port area of Antwerp three clusters of locks connect the inner port area with

Attribute	Example
Departure time	16.43
Origin	Genk
Destination1	Antwerp: right river bank
Destination2	Antwerp: left river bank
Surface area	1150 m^2
Width	11.5 m
Length	100 m
Nb terminals right river bank	2
Nb handlings right river bank	57
Nb terminals left river bank	4
Nb handlings left river bank	85

Table 3.2: Entity attributes

the sea side. Data is required on the choice of locks when sailing in the port area. The average quay length available for handling inland navigation at sea terminals gives an indication of the service capacity in the port area of Antwerp. The port authority provided the average mooring time and time for loading and unloading in order to model service times of inland container barges in the port area. Service times in the port area include the time for mooring at each sea terminal plus the handling time of all import and export containers.

3.5.4 Performance measures

The simulation model allows to quantify a number of network properties resulting from the interaction of freight flows. Table 3.4 gives an overview of performance measures which are generated by the SIMBA model. The turnaround time of shuttles is defined as the total time necessary for a barge to sail from an inland container terminal to the port area, visit all sea terminals and return to the inland terminal. The turnaround time depends on the waiting times at locks and in the port area. The outputs measured at locks are the percentage of barges that have to wait, the number of barges that have to queue and the waiting time of barges in the queue. In the port area the waiting time before handling is measured, as well as the number

Waterway	**Location**	**nb**	**length**	**width**	**lockage time**
Upper Scheldt	Asper	1	124	13.7	TRIA(6,12,16)
Upper Scheldt	Oudenaarde	1	124	13.7	TRIA(6,11,16)
Upper Scheldt	Berchem Kerkhove	1	122	13.2	TRIA(8,10,12)
Brussels-Scheldt Sea Canal	Wintam	1	215	24	TRIA(10,20,24)
Brussels-Scheldt Sea Canal	Zemst	1	204	23.8	TRIA(35,40,45)
Ringvaart	Merelbeke	2	178	17.7	TRIA(6,12,16)
Ringvaart	Evergem	1	134	15.7	TRIA(15,20,25)
Ringvaart	Evergem	1	230	25	TRIA(15,20,25)
Leie	St. Baafs-Vijve	1	43.2	6	TRIA(6,12,16)
Leie	St. Baafs-Vijve	1	140	15.7	TRIA(16,20,24)
Albert Canal	Wijnegem	2	134	12.5	TRIA(12,16,20)
Albert Canal	Wijnegem	1	200	23	TRIA(16,18,20)
Albert Canal	Olen	2	134	12.5	TRIA(12,16,20)
Albert Canal	Olen	1	196	23	TRIA(16,18,20)
Albert Canal	Kwaadmechelen	2	134	12.5	TRIA(12,16,20)
Albert Canal	Kwaadmechelen	1	196	23	TRIA(16,18,20)
Albert Canal	Hasselt	2	134	12.5	TRIA(12,16,20)
Albert Canal	Hasselt	1	196	23	TRIA(16,18,20)
Albert Canal	Diepenbeek	2	134	12.5	TRIA(12,16,20)
Albert Canal	Diepenbeek	1	196	23	TRIA(16,18,20)
Albert Canal	Genk	2	134	12.5	TRIA(12,16,20)
Albert Canal	Genk	1	196	23	TRIA(16,18,20)
Port of Antwerp	Royerssluis	1	182.5	22	TRIA(35,40,45)
Port of Antwerp	Berendrecht	1	500	68	TRIA(50,60,70)
Port of Antwerp	Zandvliet	1	500	57	TRIA(50,60,70)
Port of Antwerp	Boudewijn	1	360	45	TRIA(35,40,45)
Port of Antwerp	Van Cauwelaert	1	270	35	TRIA(35,40,45)

Table 3.3: Characteristics of locks

of vessels queueing for service. A final group of performance measures concerns the capacity utilization. In the port area this is expressed as the average percentage of quay length occupied. In the hinterland network the average and maximum number of barges on each network connection is recorded. Other performance measures can be added to the simulation model when necessary for future analyses.

Shuttles	turnaround time
Locks	total number waiting (%)
	number waiting in queue
	waiting time in queue
Port area	waiting time in queue
	number waiting in queue
Capacity utilization	quay length
	network connections

Table 3.4: Performance measures

3.5.5 Lockage process

The operations of locks strongly affect waiting times of barges for lockage. A number of decision rules are defined to make the operations of the locks in the simulation model reasonably realistic. A first group of decision rules relates to the assignment of barges to lock chambers, as depicted in figure 3.9. Barges are assigned to a lock chamber only if its size is within the allowed dimensions. The second decision rule assigns barges to the lock chamber with the smallest number of barges in queue. Thirdly, when no barges are waiting or an equal number of barges are queueing in front of each lock chamber, barges are assigned to the smallest lock chamber that is open. This decision rule focuses on a rapid lockage process of barges. Smaller lock chambers have a shorter lockage time. On the other hand, a more intensive use of larger lock chambers may reduce waiting times because more barges can be served simultaneously. A final decision rule is applied when in the latter case no lock chamber is open in the sailing direction of the barge. In this situation the barge is assigned to the lock chamber which is the first available. A second group of decision rules concerns the closing of lock chambers. A lock chamber is closed when there is not enough remaining space for the next barge in queue or when no additional barges arrive within a predefined number of time units. From interviews with waterway administrators it appears that the operations of locks are entrusted to a lockkeeper, without fixed rules. Future research could introduce more complex decision rules in the simulation model. For example, Ting and Schonfeld (1996) propose heuristic methods for the sequencing of vessels through locks, including locks with two dissimilar chambers. Theunissen and Janssens (2005) formulate a heuristic algorithm for the placement of inland vessels in a lock, with the aim to place as many vessels as possible from the arrival queue.

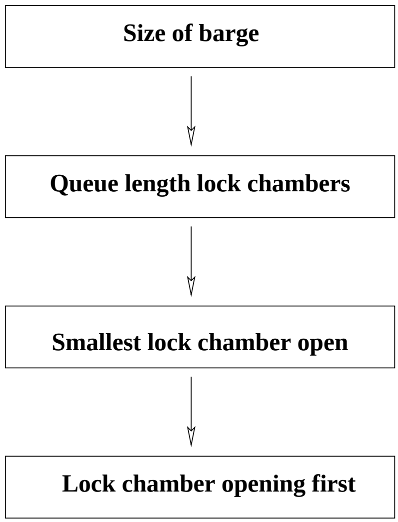

Figure 3.9: Decision rules for the assignment of barges to lock chambers

3.5.6 Calibration

Parameter settings for the description of locks are based on data input from the waterway operators. As an example, the parameter settings of the locks along the Albert Canal are described. Six lock systems are constructed on the Albert Canal, each consisting of two lock chambers for vessels up to 2000 tonnes and a third, larger lock chamber for push-towing. The standard service time for the first two lock chambers equals 45 minutes and for the third lock chamber 50 minutes. The standard service time is defined by the waterway operator as the maximum time in normal circumstances between arrival at 500 metres distance from the lock system and opening of the lock chamber to leave the lock system. This includes waiting until the lock chamber opens, sailing into the lock chamber and lockage time, but excludes sailing out of the lock chamber. From the data on lock passages provided by the waterway operator, an estimation could be made of the lockage times. For the two smaller lock chambers a triangular distribution is chosen with a mode of 16 minutes and a minimum and maximum of 12 to 20 minutes. The lockage time of the larger lock chamber is modelled with a triangular distribution with a mode of 18 minutes and a minimum and maximum of 16 to 20 minutes. The distance between locks is used together with an average speed of 10 km per hour to determine the average sailing time between locks. Table 3.5 summarizes the distances between the locks along the Albert Canal.

Locks	**Distance**
Wijnegem - Olen	23.92
Olen - Kwaadmechelen	18.62
Kwaadmechelen - Hasselt	27.09
Hasselt - Diepenbeek	4.46
Diepenbeek - Genk	4.25

Table 3.5: Distance between locks (km) - Albert Canal

The parameter setting in the port area is based on data provided by the port authority. The mooring and unmooring of barges takes 10 to 14 minutes, with a mode of 12 minutes. The loading or unloading of a single container when the inland barge has moored, is assumed to take 2.5 minutes and varies between 2 to 3 minutes. Table 3.6 summarizes the choice of locks in the port area. For example 15 % of all vessels sailing from the Upper Sea Scheldt to the right river bank pass through the lock system Berendrecht - Zandvliet. The same parameter settings for sailing times, lockage times and service times in the port area are made in all simulation scenarios in the following chapters.

During the DSSITP project, progress was regularly reported to a follow-up committee. This committee consisted of various stakeholders from the freight transport field, including waterway operators, railway operators, the Belgian railway infrastructure manager, terminal operators, the road haulage federation and the port authority. These follow-up committee meetings enabled a first verification of the model. Next, an enquiry is made into the turnaround times of vessels in order to verify the model. Table 3.7 summarizes transit times expressed in hours for sailing one way to the ports of Antwerp, Rotterdam and Amsterdam, as reported by the inland terminals. Some terminals mention a time interval, for example sailing from the terminal in Meerhout to the port of Antwerp may take six to eight hours. The data is based on the ex-

Origin	Destination	Lock	Percentage
Upper Sea Scheldt	Right river bank	Berendrecht - Zandvliet	15
Upper Sea Scheldt	Right river bank	Royers	60
Upper Sea Scheldt	Right river bank	Boudewijn - Van Cauwelaert	25
Right river bank	Upper Sea Scheldt	Berendrecht - Zandvliet	20
Right river bank	Upper Sea Scheldt	Royers	45
Right river bank	Upper Sea Scheldt	Boudewijn - Van Cauwelaert	35
Left river bank	Albert Canal	Berendrecht - Zandvliet	30
Left river bank	Albert Canal	Royers	20
Left river bank	Albert Canal	Boudewijn - Van Cauwelaert	50
Albert Canal	Left river bank	Berendrecht - Zandvliet	15
Albert Canal	Left river bank	Royers	40
Albert Canal	Left river bank	Boudewijn - Van Cauwelaert	45
Left river bank	Right river bank	Berendrecht - Zandvliet	55
Left river bank	Right river bank	Boudewijn - Van Cauwelaert	45
Right river bank	Left river bank	Berendrecht - Zandvliet	50
Right river bank	Left river bank	Boudewijn - Van Cauwelaert	50

Table 3.6: Choice of locks in port area

perience and general knowledge of inland terminal operators. Table 3.8 reports on the average transit times expressed in hours in the simulation model from the inland terminals to the entry point in the port area without lock passage. The transit times to the ports of Rotterdam and Amsterdam represent an inland barge sailing directly from the inland terminal to this port. As sailing times and lockage times are stochastic processes, individual transit times of vessels may deviate from the reported averages. Differences between the reported transit times of terminal operators and transit times in the simulation model may depend on the final point assumed in the port area. Furthemore, terminal operators may assume a combination of port visits. When looking at table 3.7, differences are also observed between estimates of various terminals. However, table 3.8 shows that transit times in the simulation model represent the estimates of the terminal operators. Finally, results of various simulation

Terminal	Antwerp	Rotterdam	Amsterdam
Deurne	3	12	
Meerhout	6-8	14-16	16-20
Genk	10-12	19-22	
Luik	14		
Gent	5-6	13	
Wielsbeke	12	18	
Avelgem	15	18	
Willebroek	4	14	
Grimbergen	5	15	
Brussel	5-6	19-20	
Herent	6		

Table 3.7: One way transit times (hours) - terminal operators

scenarios, reported in the following chapters, were presented and discussed with the port authority of Antwerp.

3.6 Analysis of policy measures

In this section the SIMBA model is applied to analyse the impact of a new intermodal barge terminal on the waterway network. The impact on network characteristics such as average and maximum waiting times at locks and in the port area is measured. Potential bottlenecks and necessary capacity investments may also be deducted. As depicted in figure 3.2, the location and volume of a new intermodal barge terminal is received from the NODUS model. The market area may also be analysed with LAMBIT. A new location is identified in the southern part of the country, at Roucourt on the Nimy-Blaton-Pronnes canal. A potential volume of 7,000 containers per year with the port of Antwerp as origin or destination is assumed. Vessels will sail via the Upper Scheldt to the port area in Antwerp. The Nimy-Blaton-Pronnes canal is navigable for vessels up to 1350 tons. As the terminal currently does not exist, assumptions have to be made regarding the service schedule offered to customers. Vessels of size 32 TEU and 66 TEU sail in a roundtrip to the port area. Three

Terminal	Antwerp	Rotterdam	Amsterdam
Deurne	1.7	10.3	
Meerhout	6.6	15.2	19.2
Genk	11.9	20.5	
Luik	15.9		
Gent	6.0	14.4	
Wielsbeke	11.8	20.2	
Avelgem	15.9	21.5	
Willebroek	3.2	11.9	
Grimbergen	6.5	15.2	
Brussel	7.5	16.2	
Herent	7.3		

Table 3.8: One way transit times (hours) - SIMBA

departures are equally distributed in a weekly schedule. Vessels may visit both clusters of sea terminals on the right and left river bank in a single roundtrip. As the new terminal is situated in the southern part of Belgium, it takes almost a day to sail from the hinterland to the port of Antwerp. Barges depart in the morning of day 1 in Roucourt and arrive at sea terminals in the morning of day 2. No changes are made to the schedules of the existing inland terminals. A separate random-number stream is dedicated to each source of randomness in the model in order to synchronize the current and new situation as much as possible.

Performance measures relevant for the comparison of the current and new situation are discussed next. Ten simulation runs of 672 hours are performed. Table 3.9 gives the average turnaround times of all inland terminals, expressed in hours in the current and future situation. Inland vessels may only sail to Antwerp (Antw) or they can make a combined trip to Antwerp and Rotterdam (Rdam) or Amsterdam (Adam). The standard deviation is mentioned between brackets next to the average turnaround time. From table 3.9 may be concluded that the introduction of a new terminal has no influence on the turnaround times of existing terminals. Shuttle services offered by the terminal in Roucourt incur a turnaround time of 63.31 hours.

Turnaround time	**Current**		**New terminal**	
	Avg	*Stdev*	*Avg*	*Stdev*
Deurne - Antw	15.10	(0.32)	15.20	(0.41)
Deurne - Rdam	21.21	(0.09)	21.26	(0.07)
Deurne - Antw/Rdam	22.44	(0.46)	21.64	(0.88)
Meerhout - Antw	29.09	(0.46)	28.84	(0.41)
Meerhout - Rdam/Adam	38.20	(1.07)	38.30	(0.46)
Meerhout - Antw/Rdam/Adam	41.59	(0.42)	41.75	(0.56)
Genk - Antw	38.70	(0.53)	38.84	(0.66)
Genk - Rdam	45.07	(0.46)	45.03	(0.54)
Genk - Antw/Rdam	50.30	(0.95)	49.87	(1.05)
Luik - Antw	46.47	(0.31)	46.28	(0.38)
Gent - Antw	20.24	(0.53)	20.55	(0.69)
Gent - Rdam	35.43	(0.49)	35.28	(0.32)
Wielsbeke - Antw	38.63	(0.51)	38.77	(0.36)
Wielsbeke - Rdam	49.29	(0.91)	49.04	(1.10)
Avelgem - Antw	41.98	(2.13)	42.09	(1.99)
Avelgem - Rdam	57.53	(0.90)	58.21	(1.16)
Avelgem - Antw/Rdam	62.82	(0.48)	62.57	(0.41)
Willebroek - Antw	14.74	(0.19)	14.79	(0.13)
Willebroek - Antw/Rdam	35.47	(0.36)	35.36	(0.36)
Grimbergen - Antw	20.91	(0.17)	21.07	(0.38)
Grimbergen - Rdam	38.17	(0.38)	38.24	(0.11)
Brussel - Antw	21.74	(0.29)	21.76	(0.29)
Brussel - Rdam	40.61	(0.83)	40.84	(0.99)
Brussel - Antw/Rdam	40.63	(0.36)	40.78	(0.45)
Herent - Antw	21.98	(0.27)	21.80	(0.14)
Roucourt - Antw	/	/	63.31	(0.70)

Table 3.9: Average turnaround times current situation and after introduction new terminal

Table 3.10 summarizes performance measures in the port area. The average and maximum waiting time before handling, expressed in hours, are given for the sea terminals on the right and left river bank. The average and maximum utilization of the quays on the right and left river bank are also measured.

Port area	**Current**		**New terminal**	
Waiting time	*Avg*	*Stdev*	*Avg*	*Stdev*
Right river bank	0.0620	(0.0224)	0.0762	(0.0238)
Left river bank	0.0548	(0.0178)	0.0528	(0.0193)
Capacity utilization	*Avg*	*Stdev*	*Avg*	*Stdev*
Quay right river bank	0.1666	(0.0017)	0.1715	(0.0015)
Quay left river bank	0.1742	(0.0017)	0.1786	(0.0019)
Max waiting time				
Right river bank	4.4848		7.7218	
Left river bank	3.9787		3.9748	
Max capacity utilization				
Quay right river bank	0.9834		0.9834	
Quay left river bank	0.9850		0.9850	

Table 3.10: Performance measures in the port area: current situation and after introduction new terminal

Following Law (2007), paired-t confidence intervals are constructed to compare the results. Table 3.11 presents the 95% confidence intervals for which the difference between the introduction of a new terminal in Roucourt and the current situation is significant. The average handling time in both clusters of sea terminals on the left and right river bank increases slightly due to the introduction of a new terminal in the waterway network. An increase of 0.5% is only a minor effect. No large impact was to be expected in light of the small market area of the new inland terminal. However, the analysis clearly demonstrates the possibilities of the SIMBA model and the DSSITP framework. The framework is able to quantify ex-ante the impact of future policy measures.

	Confidence interval new terminal - current
Avg Capacity utilisation	
Quay right river bank	0.0005; 0.0094
Quay left river bank	0.0002; 0.0084

Table 3.11: Confidence intervals comparing the current situation with the introduction of a new terminal

3.7 Conclusions

The modelling process is presented as a discrete event simulation model for an intermodal barge transport network. The model is constructed to make a quantitative ex-ante analysis of policy measures to stimulate intermodal barge transport and is part of a larger decision support system for intermodal barge transport. In the next chapter the simulation model is applied to analyse opportunities of bundling freight flows in the port area. The strategic decision whether to provide infrastructure for an intermodal hub in the port area will be investigated by means of the SIMBA model. In chapter 5 the SIMBA model is applied to simulate bundling of freight along the same river axis in the hinterland. In this study the main focus is on the inland waterway network. Potential extensions to the simulation model include the introduction of rail connections and the addition of a submodel to integrate intermodal terminal planning. The SIMBA model is also suited for other analyses, such as assessing the network wide impact of more complex decision rules for the operations of locks, the introduction of new intermodal barge terminals in the network or analyzing the consequences of growth scenarios on the network capacity.

Chapter 4

Bundling in the port area

4.1 Introduction

Inland navigation is of great importance in the intermodal context in Western Europe and plays a central role in the hinterland access of the port of Antwerp (Notteboom 2007). Hinterland access of ports constitutes a key element in the competitiveness of seaports (Notteboom and Rodrigue 2005). Ports have become a part of intermodal networks and competition takes place amongst transport chains instead of between ports. However, waiting times of inland barges for container handling in the port of Antwerp have been increasing. The hinterland of the port of Antwerp in Belgium is characterized by many small container terminals, each organizing their own shuttle services to the port area. Inland barges visit multiple sea terminals with relatively small call sizes in the port of Antwerp. Calling at several terminals may be a time-consuming process. The queue of barges waiting to be handled may be substantial at peak periods. This is partly due to a limited capacity of labour forces, quaysides or cranes at sea terminals. Capacity of quaysides and cranes has significantly expanded through the construction of the Deurganckdok. Secondly, the layout of sea terminals is aimed at handling seagoing vessels. Inland barges are handled with the same infrastructure and equipment. Sea terminals give priority to handling seagoing vessels, since the cost of a delay for sea-going vessels is much higher than for inland vessels. However, this may further increase waiting time of inland vessels. Moreover, a delay at one terminal may result in missing the agreed time window for handling at a next terminal. Thirdly, sea terminals only have a contractual commitment with sea shipping companies. There is no legal tie between barge operators and sea terminal operators. This places barge operators in a very weak negotiating position concerning service levels, modes of operation and handling charges. In light of the expected ongoing increase in container throughput in the port of Antwerp, the problem of congestion and waiting times for barges may become worse. Container barge services need to be reorganized in order to stay competitive as a transport mode. Bundling of load offers opportunities to realize a more efficient handling of inland barges in the port area. An increased level of synchronization is also possible in the port area. Douma et al. (2009) propose a multi-agent based approach for the alignment of barge rotations and sea terminal quay capacity. This approach enables coordination between multiple parties without exposing too much information about their operations. Integration between the port area and the hinterland is an issue that certainly not only the port of Antwerp is facing. Notteboom (2008) elaborates on the seaport-hinterland interaction in a European context. The author argues that terminals, in the port area as well as inland, are taking up a more active role in hinterland supply chains. Pettit and Beresford (2009) confirm the increasing integration of ports into the supply chain and compare ports in the United Kingdom with continental approaches.

In this chapter[1] alternative bundling strategies for container barge transport in the port of Antwerp are analysed. Bundling in the port area through the provision of an intermodal barge hub requires a decision at the strategic level, as depicted in figure 4.1. Four alternative hub scenarios are simulated and compared with the current situation with respect to operational characteristics of the network. The discrete event simulation model described in the previous chapter is used to analyse the impact on waiting times and capacity utilization at potential hubs and at sea terminals and on turnaround times of inland vessels. The hub scenarios under investigation are the organization of an intermodal barge hub on the right river bank, an intermodal hub on the left river bank, a first multihub scenario with a local collection/distribution network and a potentially improved multihub scenario taking into account the specific structure of the port of Antwerp. The outline of this chapter is as follows. First, scientific research on bundling in intermodal freight transport is discussed in section 4.2. Next, section 4.3 presents the results of analyzing the four alternative bundling scenarios by means of the SIMBA model. Further comments on these results are given in section 4.4. Finally, conclusions are formulated in section 4.5.

[1]This chapter is based on Caris et al. (2010).

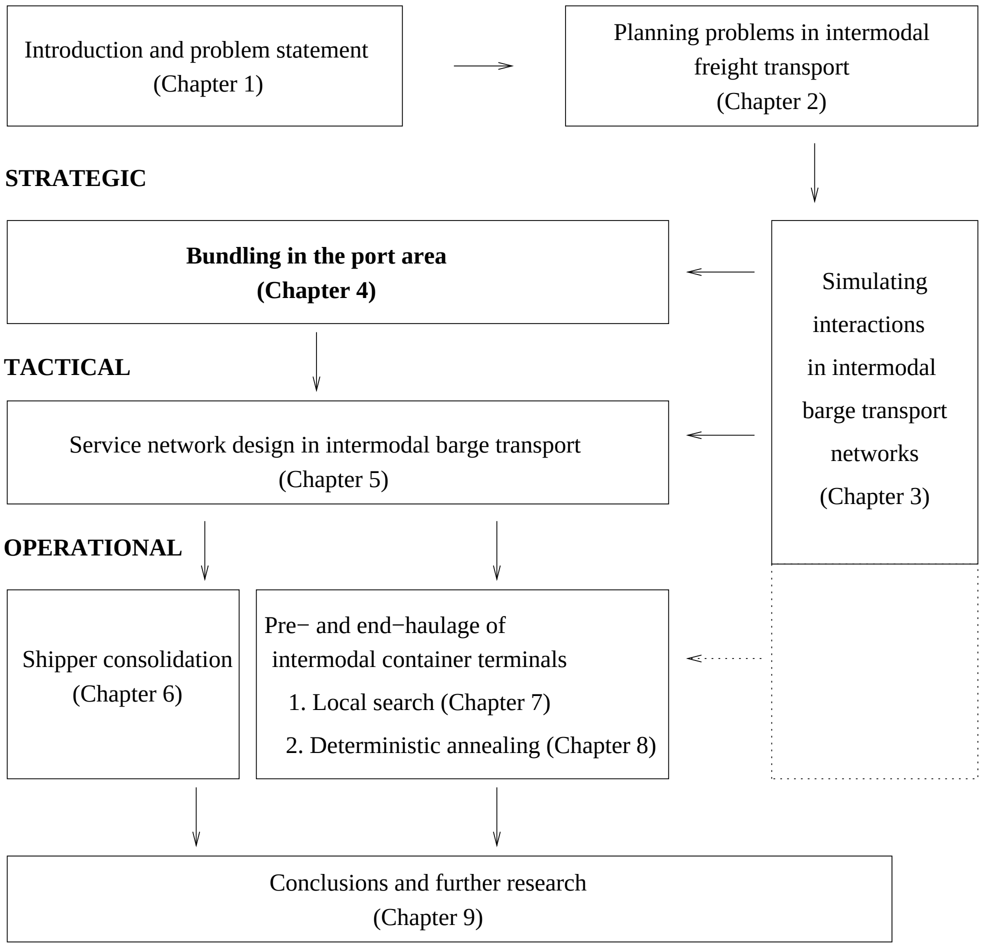

Figure 4.1: Outline of the thesis - Chapter 4

4.2 Bundling in intermodal barge transport

This section first explores scientific literature on consolidation of freight in intermodal transport. Next, a specific consolidation strategy for intermodal barge transport is elaborated.

4.2.1 Bundling in intermodal freight transport

According to Crainic and Kim (2007), the relationships and trade-offs between volume and frequency of shipping on the one hand, and the cost and delivery time of transportation on the other hand, often dictates the use of consolidation in intermodal transportation services. Consolidation has implications on the strategic and tactical level in freight transport planning. Crainic and Laporte (1997) summarize planning models for freight transportation. Strategic decisions affect the design of the physical infrastructure network. The decision where to locate a consolidation point in the intermodal network is a strategic planning problem in intermodal transport. At the tactical level decisions are made concerning the design of the service network. Service network design involves the selection and scheduling of services to operate, the specification of terminal operations and the routing of freight (Crainic 2000). A decision needs to be made whether to offer a direct service for a particular origin and destination or to move freight indirectly through a hub terminal and bundle load from nearby origins or to nearby destinations.

A generic framework for transport network design is presented by Woxenius (2007). The author proposes a generic terminology to describe six alternative designs of transport systems. Operational characteristics of each design are discussed and applications in intermodal road-rail freight transport are covered. Intermodal transport operates on a large scale, relying on the consolidation of loading units into trains or barges. The author finds that direct links dominate in intermodal rail transport and their use increases at the expense of consolidation networks. However, consolidation is a prerequisite for competing with all-road transport on short distances. Focused policy efforts fostering consolidation networks might be more powerful than general subsidies for intermodal transport. Kreutzberger (2003) presents major bundling concepts in intermodal freight transport and analyses their differences in operational costs in intermodal rail operations. Rail-based innovative bundling networks are also evaluated by Janic et al. (1999).

When looking at opportunities for consolidation in intermodal barge transport, two options can be discriminated. Bundling may take place in the hinterland network or freight may be bundled in the port area. Groothedde et al. (2005) describe the design and implementation of a collaborative hub network for the distribution of fast moving consumer goods using a combination of trucking and inland barges. Bundling in the hinterland network is also investigated by Trip and Bontekoning (2002). The authors explore the possibility of implementing innovative bundling models and new-generation terminals as a means to integrate small flows, mainly from outside economic areas, in the intermodal transport system. Bundling in the hinterland may imply cooperation between terminals or shippers. Ergun et al. (2007) investigate shipper collaboration in the trucking industry. This could be extended to intermodal barge transport. Freight may also be bundled in the port area. Konings (2003) presents a framework to identify possible improvements in the performance of intermodal barge transport by redesigning barge networks, as depicted in figure 4.2. Vessel size and circulation time directly influence the cost and quality performance of barge transport. These factors are determined by the network design, transport market and waterway infrastructure. The transport market depends on the transport volume and transport distance. The waterway infrastructure is characterized by the dimensions and quality of waterways, such as width, depth and the presence of locks and bridges. A potential network concept for bundling in the port area is the introduction of an intermodal barge hub dedicated to handling inland vessels (Konings 2007). This consolidation strategy for intermodal barge transport is discussed in the next section.

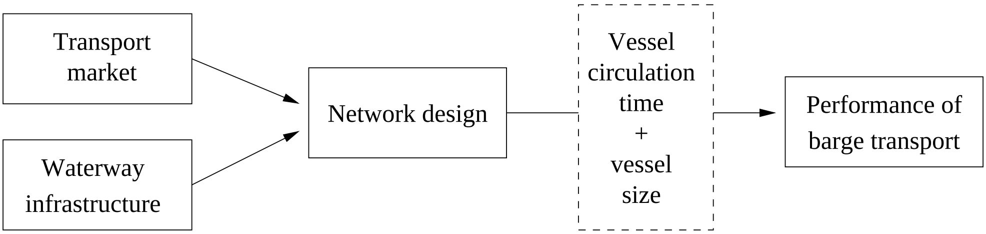

Figure 4.2: Generalized framework for barge network design (Konings 2003)

4.2.2 Intermodal barge hub in port area

The introduction of an intermodal barge hub in the port area results in an uncoupling of collection and distribution services in the port area from trunk haul services to the hinterland (Konings 2007). Such a network concept may be categorized as a connected hubs design in the generic terminology of Woxenius (2007). By doing so inland barges do not have to call at multiple sea terminals. They only visit the intermodal barge hub and the inland terminal. This leads to a reduction in turnaround time of vessels serving the hinterland. In the collection/distribution network containers with the same origin or destination can be bundled. This enables a more efficient and prompt handling of barges at sea terminals. When applying the terminology of the generalized framework in figure 4.2, this change in barge network design leads to a reduction in vessel circulation time, which may reduce the cost and increase the quality performance of intermodal barge transport. Konings (2007) presents and evaluates this consolidation strategy for intermodal transport by barge based on a marginal cost model. The author concludes that the splitting of services can improve the competitiveness of barge hinterland transport, but the effectiveness depends on several conditions. These conditions are related to the design and organization of the collection and distribution network and to the characteristics of the trunk line operation in the hinterland. Distances in hinterland services, market tariffs of these hinterland services and cost of the collection and distribution service in the port area determine whether or not the proposed consolidation strategy is interesting from a cost perspective. A reduction in transhipment costs of containers at the intermodal barge hub can contribute considerably to the attractiveness of the network concept. Konings (2007) further states that the best location for an intermodal barge hub needs to be explored. The introduction of an intermodal barge hub also offers benefits for other operators. Trucks may use the hub location instead of visiting the different sea terminals and may avoid road congestion in the port area. The use of an exchange terminal for inland containers could improve the performance of sea terminals. Larger call sizes may increase the crane or quay productivity and a better utilization of space at sea terminals could be attained. Finally, the intermodal barge hub can take up the role of depot for empty containers and contribute to the reduction of dwelling time of containers at sea terminals.

In this chapter the bundling concept for intermodal barge transport proposed by Konings (2007), is analysed with the SIMBA model. The application of the simulation model allows to demonstrate to what extent waiting times in the port area and turnaround times of inland barges can be reduced. Secondly, efficiency gains at sea terminals can be quantified. The operations of the inland navigation network are modelled in detail. This enables us to examine ex-ante what the effects of a consolidation strategy will be and to take into account interaction effects in container flows. The introduction of an intermodal barge hub in the port of Antwerp, from which load is distributed to the different sea terminals leads to the conceptual model depicted in figure 4.3. A comparison of figure 4.3 with 3.7 shows that existing barge services are split into a trunk-line operation in the inland waterway network and a collection/distribution system in the port area. Alternative hub scenarios for implementing this consolidation strategy in the port of Antwerp are modeled and analysed in the next section.

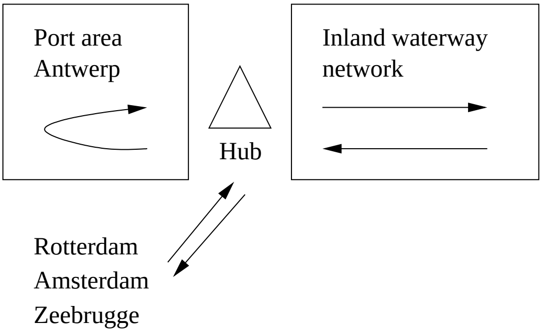

Figure 4.3: Conceptual model intermodal barge hub

4.3 Simulation of alternative hub scenarios

The objective of our research is to analyse and compare alternative consolidation strategies in the port area of Antwerp. Each scenario has its advantages and disadvantages. A discrete event simulation model is developed in Arena simulation software. Four alternative hub scenarios are simulated and compared with the current situation. Section 4.3.1 describes the organization of an intermodal barge hub on the right river bank. In section 4.3.2 an intermodal hub on the left river bank is studied. A first multihub scenario is presented in section 4.3.3. A potentially improved multihub scenario for the port of Antwerp is analysed in section 4.3.4. The variance reduction technique of common random numbers is applied to compare the alternative network configurations under similar experimental conditions. A separate random-number stream is dedicated to each source of randomness in the model in order to synchronize the alternative hub scenarios as much as possible. By doing so one can be more confident that any observed differences in performance are due to differences in the system configurations rather than to fluctuations of the experimental conditions (Law 2007). Service schedules offered in the collection/distribution network in the port area are as uniformly defined as possible to make a fair comparison between the alternative hub scenarios. For each hub scenario ten simulation runs of 672 hours are performed.

The analysis is restricted to the hinterland of the port of Antwerp in Belgium. Inland vessels originating from Rotterdam, the river Rhine and Northern France also call at sea terminals in Antwerp. The aim of this chapter is to analyse the impact of hub scenarios on turnaround times of inland vessels and waiting times in the port area. A simulation methodology is proposed to provide an insight in the network operations. All intermodal terminals in the Belgian inland waterway network are asked for information to identify current container flows in the network. Real data on shuttle services is then used as an input for the simulation model. The analysis could be extended to include real data input from terminals outside the Belgian hinterland network when available. However, the objective of our research is not to determine the optimal capacity of a potential hub, but rather to demonstrate the impact of various bundling scenarios on the network operations. This methodology may add information to bundling issues at the strategic decision level. Capacity of potential intermodal barge hubs is determined so that waiting times at a hub are less than half an hour. This same assumption is made in all four hub scenarios. The analysis demonstrates which bundling strategy in the port area is interesting from the perspective of inland terminal operators on the one hand and sea terminal operators on the other. When the decision is made to implement a certain hub scenario, further analyses will be necessary to determine the required capacity in quay length and handling equipment, operating rules and opening hours at an intermodal barge hub.

4.3.1 Hub on right river bank

In the first new consolidation strategy an intermodal barge hub is located in the cluster of sea terminals on the right river bank. Shuttle services from inland terminals only visit this intermodal barge hub in the port area to deliver and pickup their load. The intermodal hub organizes shuttle services in the port area to collect containers from and distribute containers to all sea terminals. When modelling the new situation, it is assumed that all containers are collected and distributed by barge in the port area. In reality some containers might be transferred by road when the distance between the hub and the sea terminal is small or in urgent cases. A quay length of 500 metres is assumed at the hub. The available capacity, expressed in quay length, is determined so that the average waiting time queuing at the hub is less than twenty minutes. To set a service level for the hub, it is required that all inland containers are delivered within 24 hours to the sea terminals. It is further assumed that on average four shuttle services are organized per day in the collection/distribution network, two in the morning and two in the afternoon, each visiting terminals on the right and/or left river bank. The shuttle services in the port area are carried out with vessels of a size of 96 TEU and 196 TEU. The organization of the collection/distribution network might be optimized. However, this setting already gives an indication of potential improvements in the relevant performance measures. When comparing the current situation with the new consolidation strategy, no changes are made to the schedules of the inland terminals. It is possible that inland terminals change their departures in the new situation. Other measures to enhance the efficiency can be further simulated.

Performance measures relevant for the comparison of the scenarios are discussed next. Table 4.1 gives the average turnaround times of all inland terminals, expressed in hours. Inland vessels may only sail to Antwerp (Antw) or they can make a combined trip to Antwerp and Rotterdam (Rdam) or Amsterdam (Adam). Standard deviations are mentioned in brackets next to the average turnaround times.

Turnaround time	**Current**		**Hub right**	
	Avg	*Stdev*	*Avg*	*Stdev*
Deurne - Antw	15.20	(0.47)	9.93	(0.35)
Deurne - Antw/Rdam	22.08	(0.89)	22.98	(0.29)
Meerhout - Antw	29.24	(0.47)	25.59	(0.18)
Meerhout - Antw/Rdam/Adam	41.70	(0.38)	39.68	(0.89)
Genk - Antw	38.97	(0.62)	35.94	(0.72)
Genk - Antw/Rdam	49.89	(0.87)	47.24	(0.48)
Luik - Antw	46.46	(0.34)	42.10	(0.12)
Gent - Antw	20.62	(0.49)	19.43	(0.42)
Wielsbeke - Antw	38.62	(0.42)	39.60	(0.41)
Avelgem - Antw	41.19	(0.88)	40.78	(2.10)
Avelgem - Antw/Rdam	62.69	(0.48)	61.89	(0.51)
Willebroek - Antw	14.79	(0.17)	14.37	(0.19)
Willebroek - Antw/Rdam	35.59	(0.39)	34.91	(0.14)
Grimbergen - Antw	20.93	(0.21)	19.42	(0.28)
Brussel - Antw	21.91	(0.34)	22.42	(0.17)
Brussel - Antw/Rdam	40.94	(0.29)	40.07	(0.42)
Herent - Antw	21.91	(0.19)	21.68	(0.40)

Table 4.1: Average turnaround times current situation and intermodal barge hub right river bank

Table 4.2 summarizes performance measures in the port area. The average and maximum waiting time before handling, expressed in hours, are given for the sea terminals on the right and left river bank and at the intermodal barge hub. Secondly, the average and maximum utilization of the quays on the right and left river bank and at the hub are measured. In table 4.2 the maximum waiting time over the ten simulation runs is mentioned. More details on the maximum waiting time before handling in the port area may be found in appendix A. Table A.1 reports the maximum waiting time at sea terminals and at the intermodal barge hub in each of the ten simulation runs.

Port area	**Current**		**Hub right**	
Waiting time	*Avg*	*Stdev*	*Avg*	*Stdev*
Right river bank	0.0629	(0.0306)	0.0000	(0.0000)
Left river bank	0.0557	(0.0115)	0.0000	(0.0000)
Hub right	/	/	0.2970	(0.0334)
Capacity utilization	*Avg*	*Stdev*	*Avg*	*Stdev*
Quay right river bank	0.1666	(0.0017)	0.1398	(0.0014)
Quay left river bank	0.1741	(0.0017)	0.1808	(0.0016)
Quay hub right	/	/	0.2682	(0.0022)
Max waiting time				
Right river bank	7.6128		0.0000	
Left river bank	4.3095		0.0000	
Hub right	/		8.4450	
Max capacity utilization				
Quay right river bank	0.9834		0.7867	
Quay left river bank	0.9850		0.6983	
Quay hub right	/		1.0000	

Table 4.2: Performance measures in the port area: current situation and intermodal barge hub right river bank

Following Law (2007), paired-t confidence intervals are constructed to compare the results. Table 4.3 presents the 95% confidence intervals for which the difference between the current situation and the intermodal barge hub is significant. The average turnaround times of shuttles between inland terminals along the Albert Canal and the port of Antwerp are all significantly reduced. The maximum turnaround times of these shuttles also decrease significantly due to the introduction of the hub. A reduction in

	Confidence interval hub right - current
Avg turnaround time	
Deurne - Antw	-6.9143 ; -3.6159
Meerhout - Antw	-4.7188 ; -2.5713
Genk - Antw	-4.8083 ; -1.2481
Genk - Antw/Rdam	-5.1158 ; -0.1897
Luik - Antw	-5.2091 ; -3.5234
Grimbergen - Antw	-2.4003 ; -0.6144
Avg waiting time	
Left river bank	-0.0818 ; -0.0297
Avg capacity utilization	
Quay right river bank	-0.0304 ; -0.0233

Table 4.3: Confidence intervals comparing the current situation with a hub on the right river bank

turnaround time may be the consequence of a reduced waiting time at sea terminals or less time lost by avoiding lock passages. Shuttles originating from the Albert Canal can go directly to the intermodal barge hub without having to pass through a lock in the port area. Shuttles from other inland terminals first have to pass through one of the locks to reach the hub. A reduction in turnaround time is also recorded for the terminal in Grimbergen. Table 4.2 shows that with an equal available quay length, shuttle services in the collection/distribution network of the new consolidation strategy in the port area do not have to wait for handling at sea terminals on the right and left river bank. The sea terminals can handle inland containers more efficiently because only shuttle services with consolidated load moor for service. The waiting time at the intermodal hub depends on the available quay length. A quay length of 500 metres is assumed and leads to an average waiting time of 0.2970 hours or 17.82 minutes. By providing more quay length or negotiating time windows between the hub and inland vessels, the waiting time at the hub at peak hours could be reduced and thus turnaround times could be further decreased. Average capacity utilization on the right river bank decreases significantly, as pointed out in table 4.3. Finally, table 4.2 reveals that at peak moments the maximum capacity utilization decreases by 28.67% on the left river bank and by 19.67% on the right river bank. Less quay length is necessary to handle inland containers at peak hours. These figures demonstrate the efficiency improvements at the sea terminals in the port area. The new consolidation strategy has no significant influence on waiting times at locks in the port area. Inland barges constitute only a small part of total lock passages in the seaport.

4.3.2 Hub on left river bank

In the following scenario the same consolidation strategy is chosen as in the previous scenario, but now the intermodal barge hub is located in the cluster of sea terminals on the left river bank. A fixed quay length of 500 metres is provided at the intermodal barge hub. The same service schedule is assumed as in the previous single hub scenario. On average four departures are organized per day in the collection/distribution network. Two shuttle services depart in the morning and two in the afternoon, each handling containers at sea terminals on the right and/or left river bank. The size of barges in the collection/distribution is 96 TEU or 196 TEU. The average turnaround times of vessels to all inland terminals are reported in Table 4.4.

Table 4.5 compares performance measures in the port area for the current situation and a hub on the left river bank. The average and maximum waiting time before handling and the average and maximum utilization at the sea terminals on the right and left river bank and at the intermodal barge hub are given. Further information on the maximum waiting time in the port area in an individual simulation run is presented in table A.2.

The 95% confidence intervals showing a significant difference between the current situation and the hub scenario on the left river bank are reported in table 4.6. The introduction of an intermodal barge hub on the left river bank has a significantly positive influence on the turnaround times of vessels to all inland terminals situated in the central part of the hinterland along the Brussels - Scheldt Sea Canal and in the basin of the Upper Scheldt and the river Leie. Shuttle services coming from these two regions of origin do not have to pass through locks in the port area to reach the hub on the left river bank. However, a significantly negative influence is observed on the turnaround times of the terminals in Deurne and Genk along the Albert canal. All shuttle services coming from the Albert canal have to pass one of the lock systems in the port area of Antwerp in order to reach the barge hub on the left river bank. This makes the combined trip from Deurne to Antwerp and Rotterdam also less interesting. The barge terminal in Genk already bundles load in the hinterland in the

Turnaround time	Current		Hub left	
	Avg	*Stdev*	*Avg*	*Stdev*
Deurne - Antw	15.20	(0.47)	14.24	(0.53)
Deurne - Antw/Rdam	22.08	(0.89)	26.63	(0.71)
Meerhout - Antw	29.24	(0.47)	29.67	(0.45)
Meerhout - Antw/Rdam/Adam	41.70	(0.38)	45.57	(1.54)
Genk - Antw	38.97	(0.62)	40.67	(0.39)
Genk - Antw/Rdam	49.89	(0.87)	51.44	(0.95)
Luik - Antw	46.46	(0.34)	46.91	(0.23)
Gent - Antw	20.62	(0.49)	14.80	(0.14)
Wielsbeke - Antw	38.62	(0.42)	28.67	(0.24)
Avelgem - Antw	41.19	(0.88)	35.29	(0.46)
Avelgem - Antw/Rdam	62.69	(0.48)	63.64	(0.75)
Willebroek - Antw	14.79	(0.17)	11.43	(0.08)
Willebroek - Antw/Rdam	35.59	(0.39)	36.14	(0.32)
Grimbergen - Antw	20.93	(0.21)	16.49	(0.05)
Brussel - Antw	21.91	(0.34)	19.15	(0.23)
Brussel - Antw/Rdam	40.94	(0.29)	41.39	(0.27)
Herent - Antw	21.91	(0.19)	18.73	(0.10)

Table 4.4: Average turnaround times current situation and intermodal barge hub left river bank

current situation. Consolidating load on the left river bank in the port area is not a good alternative for this inland terminal. Table 4.5 shows that waiting times at sea terminals on the left and right river bank are eliminated in the collection/distribution network, assuming an equal quay length as in the current situation. A quay length of 500 metres at the hub results in an average waiting time of 0.2103 hours or 12.6 minutes for inland vessels. The maximum waiting time of 8.4 hours can be reduced by introducing agreed time windows for inland barges. The same reduction in maximum capacity utilization is obtained as in the previous hub scenario, described in section 4.3.1. A capacity gain of 28.67% is realized on the left river bank and of 19.67% on

Port area	**Current**		**Hub left**	
Waiting time	*Avg*	*Stdev*	*Avg*	*Stdev*
Right river bank	0.0629	(0.0306)	0.0000	(0.0000)
Left river bank	0.0557	(0.0115)	0.0000	(0.0000)
Hub left	/	/	0.2103	(0.0388)
Capacity utilization	*Avg*	*Stdev*	*Avg*	*Stdev*
Quay right river bank	0.1666	(0.0017)	0.1518	(0.0015)
Quay left river bank	0.1741	(0.0017)	0.1786	(0.0013)
Quay hub left	/	/	0.2689	(0.0027)
Max waiting time				
Right river bank	7.6128		0.0000	
Left river bank	4.3095		0.0000	
Hub left	/		8.3733	
Max capacity utilization				
Quay right river bank	0.9834		0.7867	
Quay left river bank	0.9850		0.6983	
Quay hub left	/		0.9900	

Table 4.5: Performance measures in the port area: current situation and intermodal barge hub left river bank

the right river bank. Due to the bundling in the port area, sea terminals operate more efficiently. The consolidation strategy on the left river bank has no significant influence on the waiting times at locks in the port area.

4.3.3 Multihub scenario 1

Both single hub scenarios are mainly advantageous for inland terminals which do not have to pass through a lock system in the port anymore. A multihub scenario with a hub in both clusters of sea terminals on the left and right river bank is investigated next. The first multihub scenario is similar to the multihub service model described by Konings (2007). The collection/distribution of containers in the port area is car-

	Confidence interval hub left - current
Avg turnaround time	
Deurne - Antw/Rdam	2.5314 ; 6.5558
Genk - Antw	0.4468 ; 2.9426
Gent - Antw	-6.9714 ; -4.6517
Wielsbeke - Antw	-11.0999 ; -8.8104
Avelgem - Antw	-8.4234 ; -3.3782
Willebroek - Antw	-3.7680 ; -2.9509
Grimbergen - Antw	-4.9007 ; -3.9916
Brussel - Antw	-3.4585 ; -2.0508
Herent - Antw	-3.5387 ; -2.8121
Avg waiting time	
Left river bank	-0.0818 ; -0.0297
Avg capacity utilization	
Quay right river bank	-0.0188; -0.0109

Table 4.6: Confidence intervals comparing the current situation with a hub on the left river bank

ried out locally. Inland barges only visit the hubs on the left and right river bank. This scenario offers fewer economies of scale in the collection/distribution network because redistribution in the port area is organized separately in the two clusters of sea terminals. In order to provide the same level of service at the hubs as in the previous two scenarios, a quay length of 300 metres is assumed at the hub on the left river bank and 400 metres at the hub on the right river bank. Each hub offers two sailings per day, one in the morning and one in the afternoon. Shuttle services in the collection/distribution network are carried out with barges of 96 TEU and 196 TEU. Table 4.7 presents the average turnaround times of all inland terminals in the current situation and the first multihub scenario. Performance measures in the port area are compared in table 4.8. Table A.3 compares detailed results on the maximum waiting times of inland vessels in the port area. Significant differences between the current situation and the first multihub scenario are given in table 4.9.

Turnaround time	Current		Multihub 1	
	Avg	*Stdev*	*Avg*	*Stdev*
Deurne - Antw	15.20	(0.47)	14.84	(0.32)
Deurne - Antw/Rdam	22.08	(0.89)	21.59	(0.92)
Meerhout - Antw	29.24	(0.47)	28.80	(0.59)
Meerhout - Antw/Rdam/Adam	41.70	(0.38)	41.03	(0.60)
Genk - Antw	38.97	(0.62)	38.13	(0.66)
Genk - Antw/Rdam	49.89	(0.87)	50.62	(1.35)
Luik - Antw	46.46	(0.34)	46.25	(0.39)
Gent - Antw	20.62	(0.49)	20.21	(0.62)
Wielsbeke - Antw	38.62	(0.42)	38.69	(0.27)
Avelgem - Antw	41.19	(0.88)	41.39	(1.38)
Avelgem - Antw/Rdam	62.69	(0.48)	62.54	(0.43)
Willebroek - Antw	14.79	(0.17)	14.35	(0.17)
Willebroek - Antw/Rdam	35.59	(0.39)	35.47	(0.31)
Grimbergen - Antw	20.93	(0.21)	20.61	(0.24)
Brussel - Antw	21.91	(0.34)	21.85	(0.25)
Brussel - Antw/Rdam	40.94	(0.29)	40.67	(0.41)
Herent - Antw	21.91	(0.19)	21.90	(0.25)

Table 4.7: Average turnaround times current situation and multihub scenario 1

Only one inland terminal has a significant reduction in turnaround time in this multihub scenario. Inland shuttles visit the hub on the left river bank as well as the hub on the right river bank and have to pass through a lock system in the port area to reach one of the hubs. So inland barges still incur a waiting time at the locks and have to wait and moor at the right hub as well as at the left hub. Waiting times at both hubs could be reduced by providing more quay length, resulting in a reduction in turnaround times of inland barges. Due to the splitting up in two hubs, the hub operations for servicing inland barges is organized less efficiently. In total more quay length is required to reach the same level of service as in a single hub scenario. When comparing the multihub scenario with the current situation no waiting times are

Port area	**Current**		**Multihub 1**	
Waiting time	*Avg*	*Stdev*	*Avg*	*Stdev*
Right river bank	0.0629	(0.0306)	0.0000	(0.0000)
Left river bank	0.0557	(0.0115)	0.0000	(0.0000)
Hub right	/	/	0.1764	(0.0286)
Hub left	/	/	0.1847	(0.0498)
Capacity utilization	*Avg*	*Stdev*	*Avg*	*Stdev*
Quay right river bank	0.1666	(0.0017)	0.1547	(0.0019)
Quay left river bank	0.1741	(0.0017)	0.1770	(0.0020)
Quay hub right	/	/	0.1830	(0.0038)
Quay hub left	/	/	0.2132	(0.0020)
Max waiting time				
Right river bank	7.6128		0.0000	
Left river bank	4.3095		0.0000	
Hub right	/		7.4321	
Hub left	/		5.5669	
Max capacity utilization				
Quay right river bank	0.9834		0.5797	
Quay left river bank	0.9850		0.5985	
Quay hub right	/		0.9875	
Quay hub left	/		0.9833	

Table 4.8: Performance measures in the port area: current situation and multihub scenario 1

measured at the sea terminals anymore. In the first multihub scenario 38% of the quay capacity comes available at the sea terminals on the left river bank and 40% on the right river bank. This larger capacity gain is due to the local consolidation in the multihub scenario. Furthermore, the hubs could be organized at large call size terminals, where also small container batches for nearby terminals are handled. By doing so, not all containers require an extra handling in the port area.

	Confidence interval multihub 1 - current
Avg turnaround time	
Willebroek - Antw	-0.7930 ; -0.0998
Avg waiting time	
Left river bank	-0.0818 ; -0.0297
Avg capacity utilization	
Quay right river bank	-0.0160 ; -0.0080

Table 4.9: Confidence intervals comparing the current situation with multihub scenario 1

4.3.4 Multihub scenario 2

In the second multihub scenario also two hubs are provided, one in the cluster of sea terminals on the right river bank and the other in the cluster of sea terminals on the left river bank. However, inland barges only visit a single hub for which they do not have to pass through a lock system in the port area. As a result inland barges avoid waiting times at locks and only have to queue at a single hub, resulting in a larger reduction of turnaround times. The collection/distribution network offers a similar service schedule as in the previous multihub scenario, but now it is not organized locally. Each hub organizes two shuttle services per day in the collection/distribution network, visiting sea terminals in its own cluster but also in the cluster on the other river bank. A quay length of 500 metres is installed at the right hub and 200 metres at the left hub. Again vessels of size 96 TEU or 196 TEU are applied in the redistribution network. Average turnaround times of all inland terminals in the current situation and the second multihub scenario are shown in table 4.10. Table 4.11 and A.4 summarize performances measures in the port area. Paired-t confidence intervals demonstrating a significant difference between the current situation and the second multihub scenario are given in table 4.12.

Turnaround time	**Current**		**Multihub 2**	
	Avg	*Stdev*	*Avg*	*Stdev*
Deurne - Antw	15.20	(0.47)	9.16	(0.14)
Deurne - Antw/Rdam	22.08	(0.89)	22.73	(0.51)
Meerhout - Antw	29.24	(0.47)	25.64	(0.39)
Meerhout - Antw/Rdam/Adam	41.70	(0.38)	38.84	(0.59)
Genk - Antw	38.97	(0.62)	35.85	(0.67)
Genk - Antw/Rdam	49.89	(0.87)	47.28	(0.29)
Luik - Antw	46.46	(0.34)	41.90	(0.23)
Gent - Antw	20.62	(0.49)	14.73	(0.20)
Wielsbeke - Antw	38.62	(0.42)	28.77	(0.24)
Avelgem - Antw	41.19	(0.88)	35.30	(0.51)
Avelgem - Antw/Rdam	62.69	(0.48)	62.79	(0.31)
Willebroek - Antw	14.79	(0.17)	11.45	(0.07)
Willebroek - Antw/Rdam	35.59	(0.39)	35.81	(0.25)
Grimbergen - Antw	20.93	(0.21)	16.55	(0.08)
Brussel - Antw	21.91	(0.34)	19.03	(0.17)
Brussel - Antw/Rdam	40.94	(0.29)	41.30	(0.38)
Herent - Antw	21.91	(0.19)	18.75	(0.08)

Table 4.10: Average turnaround times current situation and multihub scenario 2

In this adjusted multihub scenario turnaround times of all inland terminals are significantly reduced. This reduction is explained by the fact that inland vessels only call at one hub and do not pass through any lock system in the port area. Waiting times are on average 0.1352 hours or 8.1 minutes at the right hub and 0.0572 hours or 3.4 minutes at the left hub. Maximum waiting times at the hubs can be reduced by arranging time windows with inland vessels. In the collection/distribution network shuttle services are immediately handled at the sea terminals, assuming an equal available quay length as in the current situation. Capacity gains at sea terminals on the right river bank are less in the second multihub scenario than in the first multihub scenario. In the cluster of sea terminals on the right river bank 11% of the current quay length for handling inland barges becomes available, on the left river bank this amounts to 38%. Less bundling of containers is realized in the collection/distribution

Port area	Current		Multihub 2	
Waiting time	*Avg*	*Stdev*	*Avg*	*Stdev*
Right river bank	0.0629	(0.0306)	0.0000	(0.0000)
Left river bank	0.0557	(0.0115)	0.0000	(0.0000)
Hub right	/	/	0.1352	(0.0372)
Hub left	/	/	0.0572	(0.0088)
Capacity utilization	*Avg*	*Stdev*	*Avg*	*Stdev*
Quay right river bank	0.1666	(0.0017)	0.1583	(0.0015)
Quay left river bank	0.1741	(0.0017)	0.1691	(0.0018)
Quay hub right	/	/	0.2050	(0.0026)
Quay hub left	/	/	0.1579	(0.0011)
Max waiting time				
Right river bank	7.6128		0.0000	
Left river bank	4.3095		0.0000	
Hub right	/		8.1493	
Hub left	/		2.7953	
Max capacity utilization				
Quay right river bank	0.9834		0.8696	
Quay left river bank	0.9850		0.5985	
Quay hub right	/		0.9660	
Quay hub left	/		0.9100	

Table 4.11: Performance measures in the port area: current situation and multihub scenario 2

network due to the splitting of the hub into two locations and not organizing the redistribution of containers locally. This multihub scenario also offers the possibility of organizing the hubs at a large call-size terminal and thus avoiding the extra handlings for a large part of all containers. This final hub scenario doesn't influence the waiting times at locks in the port area.

	Confidence interval multihub 2 - current
Avg turnaround time	
Deurne - Antw	-7.1630; -4.9129
Meerhout - Antw	-4.9773 ; -2.2225
Meerhout - Antw/Rdam/Adam	-3.7859 ; -1.9275
Genk - Antw	-4.5038 ; -1.7326
Genk - Antw/Rdam	-4.5122 ; -0.6957
Luik - Antw	-5.7121 ; -3.4074
Gent - Antw	-7.1644 ; -4.6099
Wielsbeke - Antw	-10.8017 ; -8.9000
Avelgem - Antw	-8.3063 ; -3.4596
Willebroek - Antw	-3.7752 ; -2.9091
Grimbergen - Antw	-4.8781 ; -3.8866
Brussel - Antw	-3.8709 ; -1.8893
Herent - Antw	-3.5707 ; -2.7537
Avg waiting time	
Left river bank	-0.0818 ; -0.0297
Avg capacity utilization	
Quay right river bank	-0.0125 ; -0.0043

Table 4.12: Confidence intervals comparing the current situation with multihub scenario 2

4.4 Discussion of simulation results

This section elaborates on the sensitivity of simulation results to assumptions made and further comments on the results. The same assumptions are made throughout the analyses of all four hub scenarios. Firstly, hub capacity is determined so that inland vessels incur an average waiting time of less than twenty minutes. Tables A.1 to A.4 in appendix report detailed information on the maximum waiting times in the current situation and the four hub scenarios. Simulation results show a relatively large variety in maximum waiting times. The first multihub scenario leads to higher maximum waiting times for handling inland barges in the port area than the other three hub scenarios. Increasing available quay length in a hub scenario will reduce waiting times of inland barges, but decrease the capacity utilization. Maximum waiting times are thus dependent on the assumptions made with respect to available service capacity. The results also indicate that negotiating time windows between hubs and inland barges is very meaningful. A second assumption relates to the service schedules in the collection/distribution network. The number and type of barges in the collection/distribution network are based on the prerequisite that inland containers have to be delivered to sea terminals within 24 hours. Tightening this constraint allows less consolidation in the collection/distribution network, which impacts on the efficiency of sea terminals. However, these assumptions are the result of discussions with multiple stakeholders. Thirdly, sailing schedules of inland terminals are assumed to remain unchanged in the hub scenarios. Inland terminals may agree time windows with the intermodal barge hub to ensure a quick handling. This type of synchronization will improve the waiting time at the hub and thus decrease turnaround times of inland barges. This would benefit all hub scenarios, but it may not compensate for the waiting time incurred when sailing through the locks. Therefore, conclusions on the comparison of the four hub scenarios would remain the same. Time windows may also be agreed at sea terminals in the collection/distribution network. This will allow a better berth planning at sea terminals for handling the shuttle services of the intermodal barge hub. Furthermore, hinterland operations and collection/distribution operations in the port area should be matched, to avoid large fluctuations in time of transhipment volumes at hubs and at sea terminals. Finally, the reference scenario in the analysis is the provisional current situation in the port of Antwerp. Future infrastructural changes, for example on the left river bank in the port area, may impact on simulation results. Additional hub scenarios may be defined and analysed by the same methodology.

Hub scenarios are analysed to support decisions on the strategic level concerning the consolidation of inland barge freight flows in the port area. After selecting a certain consolidation strategy, future research will be necessary to determine the detailed implementation of such a strategy. Practical decisions still need to be made on the exact location within the cluster of sea terminals, the most desirable terminal layout, handling equipment and operating routines. Konings (2007) notes that hubs may be organised at sea terminals for which inland vessels have large call sizes. By doing so, extra handling of many containers is not necessary. The author argues that if the extra handling of containers is avoided, the competitiveness of splitting barge services into a collection and distribution service in the port area and a trunk haul service in the hinterland is substantially improved. Another implementation issue is who will carry the additional costs of the hub operations. Simulation results show that benefits may be gained for sea terminal operators as well as inland terminal operators. Selecting a consolidation strategy which offers a win-win situation for all parties is important to create a commitment from all stakeholders. The port authority obviously plays an important role in facilitating and enabling consolidation strategies in the port area as well as in the hinterland. Bundling of freight in the hinterland is often also suggested as a solution for waiting times of inland vessels in the port area. A synchronization amongst inland barge services could reduce the number of inland vessels and increase call sizes in the port area. Theys et al. (2008) study the allocation of benefits in setting up cooperation between inland terminals by making use of game theory. Cooperation between inland terminals offers the opportunity to attain economies of scale. However, freight may only be bundled between terminals along the same river axis, whereas in the port area inland freight flows originating from a much wider area are bundled. Recent research interest in the relationship between port and hinterland operations indicates that a single solution for reducing waiting times of inland barges at sea terminals may not suffice. A combination of bundling measures in the port area and in the hinterland may be necessary to improve the intermodal transport chain.

4.5 Conclusions and future research

Bundling of freight flows is regularly put forward to solve the problem of waiting times for inland barges in the port area of Antwerp. Bundling may take place in the hinterland network or in the port area. In this chapter bundling in the port area is analysed, based on a network concept proposed by Konings (2007). Bundling in the hinterland is further elaborated in the next chapter. Four alternative scenarios for constructing a bundling network in the port area are examined with respect to the operational characteristics of the network. The discrete event simulation model SIMBA is applied to analyse the impact on waiting times and capacity utilization at potential hubs and at sea terminals and on turnaround times of inland vessels. The four alternative scenarios differ in terms of the number of hubs, their location or the organization of the collection/distribution network in the port area. The introduction of an intermodal barge hub in the port area may lead to two major benefits. The turnaround time of inland shuttle services can be reduced because of a reduced waiting time in the port area. Secondly, sea terminals may operate more efficiently because vessels with consolidated load operate in the collection/distribution network in the port area.

The following conclusions concerning the reduction in turnaround time of inland shuttle services are drawn. A reduction in turnaround time may be due to a reduced waiting at sea terminals or to less time lost by avoiding lock passages in the port area. The importance of avoiding lock passages has become apparent in this analysis. In the first two scenarios a single hub is provided in the cluster of sea terminals on the left or right river bank. These scenarios only offer a reduction in turnaround time for those inland shuttle services that do not have to pass through a lock system in the port area. In the first multihub scenario a hub is installed in both clusters of sea terminals. As a result, inland barges have to queue at both hubs and often have to pass through a lock system. This scenario offers few opportunities for reducing turnaround times of inland vessels. The second multihub scenario takes the specific structure of the port area in Antwerp into account. Inland barges only visit a single hub for which they do not have to pass through a lock system. The collection/distribution network is organized jointly for the two hubs. By doing so, the turnaround time of all inland shuttle services may be reduced significantly. The second multihub scenario is therefore the most interesting scenario for all inland terminals. The waiting time of inland barges in the port area also depends on the handling capacity at the dedicated intermodal hubs. The same service level is assumed at the hubs in all four scenarios. By increasing available quay length or by negotiating time windows, the handling time of inland barges at the hubs may be reduced and thus turnaround times may be further improved. No influence is observed on waiting times at locks in the port area in any hub scenario. Inland container vessels only constitute a very small share of total lock passages.

In all four hub scenarios barges in the collection/distribution network do not have to wait at the sea terminals, assuming an equal available quay length as in the current situation. The reduced capacity utilization at peak hours is also an indicator for potential efficiency improvements at sea terminals. In the first multihub scenario the collection/distribution network in the port area is organised locally. Simulation results show the largest reductions in maximum capacity utilization in this first multihub scenario. Vessels in the collection/distribution network only carry containers for local sea terminals. Simulation of the second multihub scenario leads to the same efficiency improvement in the cluster of sea terminals on the left river bank, but a smaller efficiency improvement on the right river bank. A better coordination between the hubs may lead to a greater reduction of maximum capacity utilization. Both single hub scenarios offer a substantial efficiency improvement at the sea terminals. In all scenarios it is assumed that all containers in the collection/distribution network are transported by barge. In reality some containers may be carried by truck to a nearby sea terminal and time windows may be fixed at sea terminals for vessels in the collection/distribution network. For these reasons, the simulation results represent a lower limit for efficiency improvements in the port area.

In the future inland terminals may adjust their schedules to the new hub strategy in the port area. Time windows could also be agreed between the hub terminal and the inland shuttle services. Hub terminals may be organized at large call size sea terminals. By doing so not all containers need to be handled twice. After selecting a certain consolidation strategy, future research will be necessary to determine the detailed implementation of such a strategy. A consolidation strategy which offers a win-win situation for all parties will be important to obtain a commitment from all stakeholders in the implementation phase. In this chapter a methodology is proposed to analyse the consequences of various hub scenarios for sea terminal operators and inland terminal operators. The simulation methodology may be applied to other hub scenarios or to hinterland networks of other ports. In future research the probability may be calculated of incurring a certain waiting time before handling in the port area. The next chapter investigates the bundling of freight flows in the hinterland. The service network in the hinterland is modelled from the perspective of a network operator to estimate potential benefits of cooperation between inland terminals. Results of bundling in the hinterland may be compared and combined with bundling in the port area. A combination of bundling measures in the port area and in the hinterland may be necessary to improve the intermodal transport chain.

Chapter 5

Service network design in intermodal barge transport

5.1 Introduction

Consolidation of freight flows is often suggested to improve the efficiency of intermodal operations. Inland terminals may cooperate with the objective to create denser freight flows and achieve economies of scale. In this way, the attractiveness of intermodal barge transport could be improved. In this chapter cooperation between intermodal barge terminals in a hinterland network is analysed from a network design perspective, as presented in figure 5.1. The hinterland network is studied as a whole to see whether or not inland terminals in the network should cooperate. Cooperation between inland terminals leads to bundling of freight flows in the hinterland of major ports. Van der Horst and De Langen (2008) emphasize the need for coordination in hinterland container transport chains.

Cooperation of inland terminals along the same waterway may be classified as a corridor network in the generic framework of transport network design by Woxenius (2007). An alternative term in literature for this type of bundling is 'line bundling'. Woxenius (2007) defines a corridor network as a design based on using a high-density flow along an artery and short capillary services to nodes off the corridor. Freight transport along inland waterways are a typical application of the corridor design due to geographical reasons. Notteboom (2007) describes the development of corridor networks along the Rhine. As depicted in the framework in figure 4.2 by Konings (2003), network design determines vessel size and circulation time in barge transport.

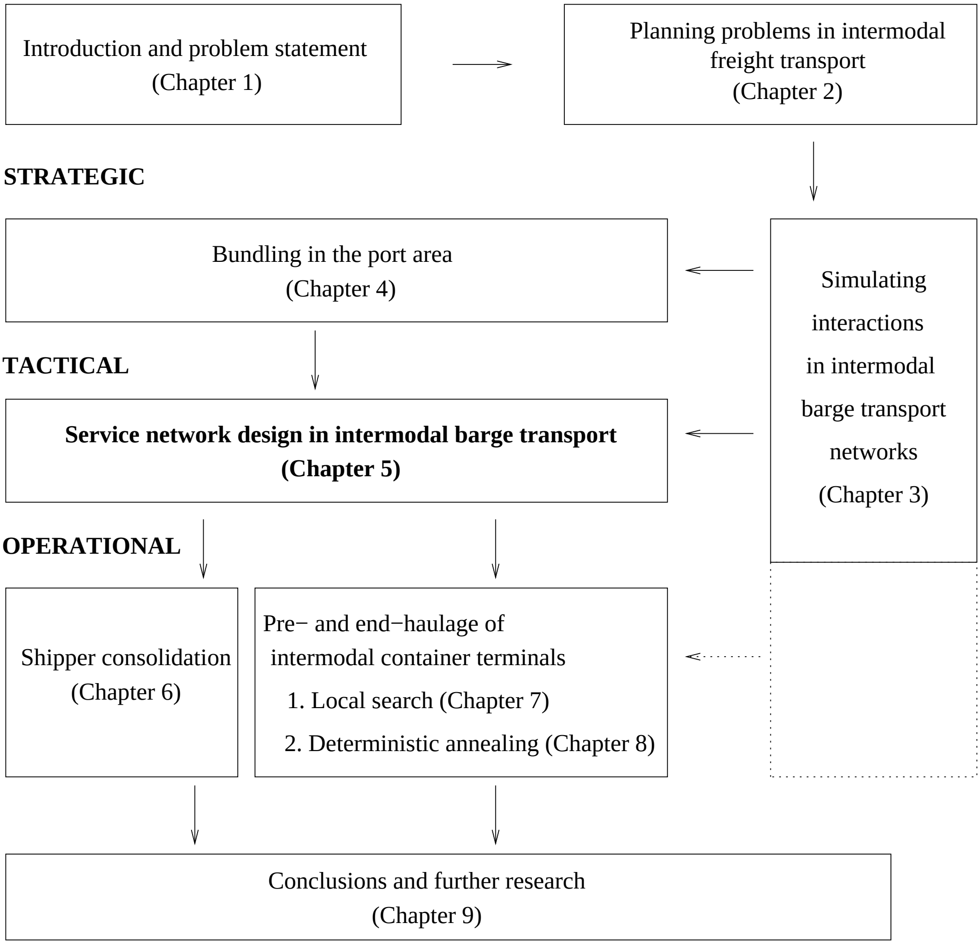

Figure 5.1: Outline of the thesis - Chapter 5

A corridor network design requires stops at intermediate terminals to be relatively short in order to keep a reasonable circulation time for all terminals along the corridor. When determining vessel size, slack capacity needs to be reserved for terminals along the corridor. In a corridor network no additional transhipment is required, contrary to a trunk collection/distribution network with an inland terminal serving as a hub in the hinterland.

In this chapter the design of the service network in intermodal barge transport is studied. The network of inland barge terminals is modelled to demonstrate potential cooperations in a corridor network. Cooperation scenarios are investigated leading to economies of scale, given the assumption that the number of departures per week offered to current customers at least remains the same. An alternative advantage of cooperation may be the increase in frequency of service, which could attract additional customers. However, the number of customers attracted and potential benefits gained are difficult to assess. Winston (1985) distinguishes between economies of scale, scope and density. An effort to structure related terminology is made by Kreutzberger (2007). Economies of scale imply that costs increase less than proportionally with vehicle capacity. Economies of scope relate to the service mix offered. A diversification of services may contribute to a higher volume and thus a higher capacity utilization. Economies of density involve the savings that result from moving a larger amount of traffic over a fixed network. Economies of density are sometimes defined as the short term equivalent for economies of scale. The term 'economies of scale' will be further used in this thesis to indicate the cost advantage of using a larger vessel through a bundling of freight flows of multiple intermodal barge terminals.

The allocation of benefits is an important aspect in setting up cooperation between inland terminals. Theys et al. (2008) study this issue by making use of game theory. The service network design methodology presented in this chapter allows to demonstrate opportunities for cooperation in the inland navigation network. The division of costs between terminals is merely mentioned in this chapter as an indication that benefit schemes are key to making cooperation between inland terminals a success, but studying their impact is not the aim of this chapter.

In section 5.2 service network design is discussed and a generic model is presented. This model is adapted to incorporate characteristics of intermodal barge networks in section 5.3. In section 5.4 the methodology is illustrated by means of a fictitious example. Next, consolidation strategies are calculated along three river axes in the hinterland of the port of Antwerp in section 5.5. Cooperation scenarios selected in section 5.5 are introduced in the SIMBA model (presented in chapter 3) in section 5.6 to evaluate the impact on turnaround times and on performance measures in the port area. Bundling in the hinterland is compared with the results of bundling in the port area (chapter 4). Finally, conclusions are drawn in section 5.7.

5.2 Service network design

Consolidation in freight transport concerns decisions at the tactical planning level. According to Crainic and Laporte (1997) service network design involves the selection of routes on which services are offered and the determination of characteristics of each service, particularly their frequency. The authors describe service network design in intermodal transportation as a major case at the tactical decision level. Formulations are classified into two main groups: network simulation and optimization models. Simulation models show a high level of detail, but may require prohibitive data input and running times. Network optimization models are less detailed but enable a fast generation, evaluation and selection of integrated, network wide operating strategies. Magnanti and Wong (1984) suggest that integer programming could be used to generate potential investment strategies that could then be tested by simulation analysis. The authors present a general overview of network design problems and show that many combinatorial problems that arise in transportation planning are specializations and variations of a generic design model.

State-of-the-art reviews on service network design in freight transportation are given by Crainic (2000) and Wieberneit (2008). Service network design arises in transportation systems where service cannot be tailored for each customer individually and a single vehicle carries freight of different customers with possibly different origins and destinations. For each origin-destination pair a route needs to be specified. A decision may be made about the type of consolidation network, general operating rules for each terminal in the network and work allocation among terminals. Empty balancing and crew and motive power scheduling may also be included in the design of the service network.

5.2.1 Generic model

The path-based multicommodity capacitated network design formulation (PMCND) of Crainic (2000) is presented next, as this general formulation will be adapted in section 5.3 to model a service network in intermodal barge transport. The problem is defined on a graph $G = (N, A)$ with N the set of nodes and A the set of links in the network. P is the set of products to be transported. In intermodal barge transport each origin-destination pair may represent a flow of a product. A path-based formulation permits to define a set of possible paths for each origin-destination pair in advance. The decision variables in the model are:
$y_{ij} = 1$ if link(i, j) is open
h_l^p = flow of commodity p on path l
The following notation is used:
P = set of products (origin-destination pairs)
L = set of all paths in the network
L^p = set of paths for product p
f_{ij} = fixed cost of opening link (i, j)

w^p = total demand of product p
k_l^p= transportation cost of product p on path l
c_{ij}^p = transportation cost per unit of product p on link (i, j)
δ_{ij}^{lp} = 1 if link (i, j) belongs to path $l \in L^p$ for product p
u_{ij} = capacity of link (i, j)

$$Min \sum_{(i,j)\in A} f_{ij}y_{ij} + \sum_{p\in P}\sum_{l\in L} k_l^p h_l^p$$

subject to

$$\sum_{l\in L^p} h_l^p = w^p \qquad \forall p \in P \tag{5.1}$$

$$\sum_{p\in P}\sum_{l\in L^p} h_l^p \delta_{ij}^{lp} \leq u_{ij}y_{ij} \qquad \forall (i,j) \in A \tag{5.2}$$

$$y_{ij} \in Y = \{0,1\} \qquad \forall (i,j) \in A \tag{5.3}$$

$$h_l^p \geq 0 \qquad \forall p \in P, \forall l \in L^p. \tag{5.4}$$

The objective function minimizes total costs of transporting p products through the network. The decision variable y_{ij} may be restricted to $Y = \{0, 1\}$ or may take on a positive integer number $(Y = N_+^A)$. A fixed cost f_{ij} is incurred for each unit of capacity or service level offered. The transportation cost of product p on path l is calculated as:

$$k_l^p = \sum_{(i,j)\in A} c_{ij}^p \delta_{ij}^{lp}.$$

Constraints (5.1) ensure that the demand for all products is met. The second group of constraints represents capacity restrictions on links in the network. The total flow on a link cannot exceed its capacity and must be zero when the link is not chosen in the network ($y_{ij} = 0$). Constraints (5.3) and (5.4) define the formulation as a mixed-integer programming problem.

5.2.2 Applications in intermodal transport

In the overview of planning problems in intermodal freight transport presented in chapter 2, the design of the intermodal service network and in particular the determination of an optimal consolidation strategy is identified as a research field requiring more attention. Relatively few scientific publications may be found on this topic. A first intermodal formulation is given by Crainic and Rousseau (1986). The authors propose a solution algorithm based on decomposition and column generation techniques. Kim (1997) presents a general description of a large scale transportation service network design and applies the model in the express package delivery industry. An application of service network design in intermodal rail transport can be found in Newman and Yano (2000a). The authors compare a variety of decentralized planning approaches with a centralized approach for scheduling trains in an intermodal network. Their decentralized scheduling approaches lead to near-optimal solutions within significantly less computational time than the centralized approach. Racunica and Wynter (2005) formulate a frequency service network design model to determine the optimal location of intermodal hubs in a hub-and-spoke network with (semi-) dedicated freight rail lines. A concave cost function is applied in order to capture cost reductions obtained by consolidation at hub nodes. The resulting model is a non-linear, mixed-integer program. The concave increasing cost function is approximated by a piecewise linear function as to obtain a linear program. This linear program is solved by two variable-reduction heuristics, which solve a sequence of relaxed subproblems. The solution method is tested on a case study of the Alpine freight network. Groothedde et al. (2005) discuss the design of an inland intermodal network for transporting palletized fast moving consumer goods. A case study is performed in which a solution is found by means of an improvement heuristic. A hub location and network design model for a general intermodal transportation network is presented by Yoon and Current (2008). Andersen et al. (2009b) formulate a service network design model to study the impact of an increased level of synchronization in intermodal rail transport on the rail efficiency and interoperability across borders.

5.3 Model formulation for intermodal barge transport

The generic model presented in the previous section is adapted to continental intermodal barge transport. A service network design model is constructed for the network of inland terminals and sea terminals. Terminals are represented by nodes in the network. A distinction is made between a set of inland nodes N^I and a set of port nodes N^P. Links may provide a connection between the two sets of nodes or connect terminals within a set of nodes. The set of links between inland terminals and the port area is indicated with A^B. Links connecting two inland terminals belong to the set A^I and links connecting two port terminals are assigned to the set A^P.

$$N^I \cup N^P = N$$
$$N^I \cap N^P = \varnothing$$
$$A^B \cup A^I \cup A^P = A$$
$$A^B \cap A^I = \varnothing, A^I \cap A^P = \varnothing, A^B \cap A^P = \varnothing$$

Links connecting inland nodes symbolize cooperation between these two inland terminals. Cooperation costs are modelled as a fixed cost for setting up a cooperation scheme between two terminals. Links between port nodes represent the time lost at lock systems in the port area. A fixed cost is charged for each vessel passing through the link. A product is defined for each origin-destination pair. Products representing freight which originates at an inland terminal and is destined for a sea terminal belong to the set P^O (outgoing). Products coming into the country from a sea terminal to an inland terminal are joined in the set P^I (incoming). For each product a set of possible paths L^P is defined.

$$P^O \cup P^I = P$$
$$P^O \cap P^I = \varnothing$$

A main characteristic of intermodal barge transport is the sailing of barges in roundtrips. Roundtrips are introduced in the generic model based on the cycle-path formulation for service network design problems with asset management as proposed by Andersen et al. (2009a). The set of cycles K represents possible roundtrips of barges in the physical network. Decision variables in the new model formulation are:
h_l^p = flow of commodity p on path l
$g^k = 1$ if roundtrip $k \in K$ is selected
e_{ij}^k = freight imbalance on link (i, j) in roundtrip k
For each product or origin-destination pair possible paths are defined. Multiple paths make up cycles. Cycles are defined by the following parameters:
$a_{ij}^k = 1$ if link (i, j) is part of roundtrip k
$b_k^{lp} = 1$ if path l for commodity p is part of roundtrip k
Cost parameters are defined as follows:
f^k = base cost of operating roundtrip k
ϕ_{ij} = concave cost function on link $(i, j) \in A^B$ depending on the volume passing through the link. All other notation is maintained as in the previous section, leading

to the non-linear integer programming formulation:

$$Min \sum_{k \in K} f^k g^k + \sum_{k \in K} \sum_{(i,j) \in A^B} \phi_{ij} [\sum_{p \in P} \sum_{l \in L} h_l^p \delta_{ij}^{lp} b_k^{lp} + e_{ij}^k] \cdot a_{ij}^k$$

subject to

$$\sum_{l \in L^p} h_l^p = w^p \qquad \forall p \in P \tag{5.5}$$

$$\sum_{p \in P} \sum_{l \in L^p} h_l^p \delta_{ij}^{lp} \leq u_{ij} \sum_{k \in K} a_{ij}^k g^k \qquad \forall (i,j) \in A^B \tag{5.6}$$

$$\sum_{k \in K} a_{ij}^k g^k \leq 1 \qquad \forall (i,j) \in A^B \tag{5.7}$$

$$(\sum_{p \in P} \sum_{l \in L^p} h_l^p \delta_{ij}^{lp} b_k^{lp} + e_{ij}^k) a_{ij}^k a_{jm}^k = (\sum_{p \in P} \sum_{l \in L^p} h_l^p \delta_{jm}^{lp} b_k^{lp} + e_{jm}^k) a_{ij}^k a_{jm}^k$$

$$\forall i, m \in N, j \in N^P, i \neq j, j \neq m \tag{5.8}$$

$$g^k \in \{0, 1\} \qquad \forall k \in K \tag{5.9}$$

$$e_{ij}^k \text{ positive integer} \qquad \forall (i,j) \in A^B \cup A^P, k \in K \tag{5.10}$$

$$h_l^p \text{ positive integer} \qquad \forall p \in P, \forall l \in L^p \tag{5.11}$$

The first component of the objective function represents the base cost of operating selected roundtrips k. The base cost includes the cost of hiring a vessel to perform the roundtrip, a waiting cost in the port area along links connecting two port nodes and a cooperation cost along links connecting two inland nodes. The cooperation cost represents the overhead of setting up a corridor network. The waiting cost is incurred when barges have to pass through a lock system in the port area. In the second component a concave variable cost function is used on the links in set A^B to model economies of scale achieved by bundling freight flows in the hinterland network. This concave cost function thus represents the benefit of cooperation. Constraints (5.5) and (5.6) are similar to the generic model. The set of constraints (5.7) assure that links between inland nodes and port nodes may only belong to a single selected roundtrip k. Decision variables e_{ij}^k in the fourth group of constraints measure the imbalance between inbound and outbound freight flows. This imbalance needs to be taken into account in the concave variable cost function of the links between inland nodes and port nodes. The cycle design variables g^k are restricted to binary values. Since the aim is to model the transportation of containers, flow variables h_l^p and e_{ij}^k are defined to take on a positive integer number.

5.4 Illustrative example

5.4.1 Description

The service network design formulation derived in the previous section is applied to a small-scale network for further clarification. The network is presented in figure 5.2.

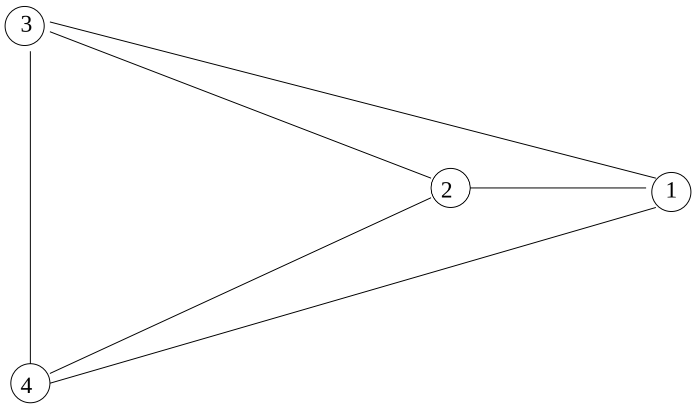

Figure 5.2: Example of small-scale network to illustrate methodology

Nodes 1 and 2 are two inland terminals in the hinterland of a seaport, which is made up of two clusters of sea terminals represented by nodes 3 and 4. The inland terminals are situated along the same river axis and could potentially cooperate to bundle their freight flows. The two clusters of terminals in the port area are separated by a lock system and barges incur a waiting time when passing through the locks. Links between inland nodes and port nodes A^B represent direct connections. Links $(1,2)$ and $(2,1)$ symbolize cooperation between the two inland terminals. Links $(3,4)$ and $(4,3)$ account for the time spent in the port area. Each inland terminal exports containers to and imports containers from both clusters of sea terminals. Table 5.1 gives an overview of the set of products P which have to pass through the network. Products are defined by an origin node, destination node and daily demand w^p, expressed in Twenty feet Equivalent Units (TEU).

Product	Origin	Destination	Demand w^p
1	1	3	82
2	1	4	41
3	2	3	185
4	2	4	53
5	3	1	60
6	4	1	25
7	3	2	90
8	4	2	67

Table 5.1: Set of products

The PMCND-formulation requires that for each product p a set of possible paths L^P is specified. Table 5.2 summarizes all possible paths for each product. Paths for outgoing products P^O are given in the first two columns. Paths for incoming products P^I are mentioned in the last two columns. Some paths may already be eliminated from the summary due to the physical characteristics of the network. Both inland terminals lie along the same river axis and terminal two is closest to the port area. It is illogical to sail back from terminal two to terminal one for outgoing products or to sail from terminal one to terminal two for incoming products. The last two paths of products three, four, seven and eight are thus redundant.

Base costs f^k of all possible roundtrips k are given in Table 5.3. Cost information has been obtained from contacts with inland barge terminals. The cost of chartering the smallest vessel on a daily basis is allocated to the links between inland nodes and port nodes. This cost amounts to 1000 euro one way starting from terminal two and 1200 euro one way starting from terminal one. A base cost of 400 euro is assigned to links connecting port nodes for taking into account waiting time in the port area. A cooperation cost of 400 euro is incurred each time a vessel stops at an intermediate terminal, thus for each link connecting inland nodes.

Product P^O	Paths L^P	Product P^I	Paths L^P
1	1-3	5	3-1
	1-2-3		3-2-1
	1-4-3		3-4-1
	1-2-4-3		3-4-2-1
2	1-4	6	4-1
	1-2-4		4-2-1
	1-3-4		4-3-1
	1-2-3-4		4-3-2-1
3	2-3	7	3-2
	2-4-3		3-4-2
	2-1-3		3-1-2
	2-1-4-3		3-4-1-2
4	2-4	8	4-2
	2-3-4		4-3-2
	2-1-4		4-1-2
	2-1-3-4		4-3-1-2

Table 5.2: Set of possible paths for each product

Variable costs on links A^B connecting the port area with the hinterland follow a discrete cost function:

$$\phi_{ij}(x) = \begin{cases} 0 & x \leq 60 \\ 500 & 60 < x \leq 90 \\ 800 & 90 < x \leq 100 \\ 1100 & 100 < x \leq 200 \\ 2000 & x > 200 \end{cases}$$

These transportation costs stand for the additional cost of chartering a larger vessel. The vessel size x is expressed in TEU. The nonlinear function captures economies of scale obtained by bundling freight flows. A larger vessel size results in lower costs per container when a volume of at least 100 TEU is reached. Vessel size is expressed

roundtrip k	base cost f^k
1-3-1	2400
1-4-1	2400
2-3-2	2000
2-4-2	2000
1-3-4-1	2800
2-3-4-2	2400
1-2-3-2-1	3200
1-2-3-1	2800
1-2-3-4-1	3200
1-3-4-2-1	3200
1-2-3-4-2-1	3600
1-2-4-2-1	3200
1-2-4-1	2800

Table 5.3: Base cost of roundtrips

in the model formulation as the sum of freight flows and freight imbalance on a link $(i,j) \in A^B$:

$$\sum_{p \in P} \sum_{l \in L} h_l^p \delta_{ij}^{lp} b_k^{lp} + e_{ij}^k$$

The capacity of all network connections is assumed to be unrestricted. A value of 603 TEU is given to the parameters u_{ij}, which equals the total demand for all products. The time frame of the analysis is a single day. It is assumed that a vessel can make a roundtrip within this time window.

5.4.2 Comparison of alternative line bundling scenarios

Total costs of three alternative service network design scenarios are calculated and compared. The problem size of line bundling in intermodal barge transport is restricted by the number of terminals involved. Therefore, the number of possible scenarios is limited and may thus be enumerated. In the first scenario both inland terminals combine their freight in a single roundtrip through the port area. This leads to the network configuration in figure 5.3. The numbers next to the selected links state the total freight passing through the network link.

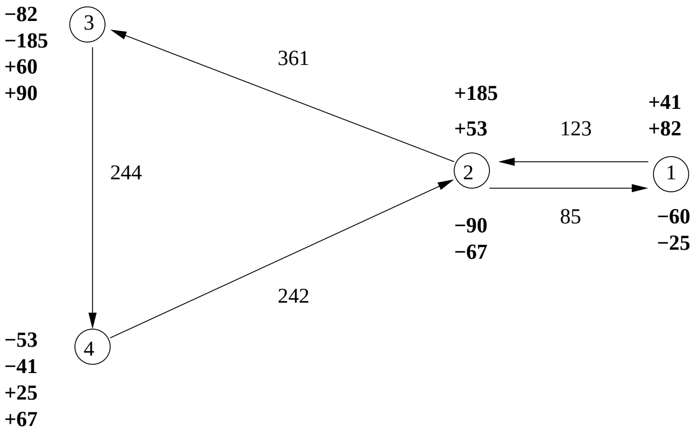

Figure 5.3: Cooperation with a single roundtrip

Total costs of cooperation with a single roundtrip are presented in table 5.4. In this scenario the two inland terminals fully cooperate with each other along the roundtrip $1-2-3-4-2-1$, leading to large freight flows on a limited number of network links. A large vessel is chartered to bundle freight from both inland terminals to both port terminals. Costs are assigned to the inland terminals proportionally to their freight flows. Variable costs on the links between inland terminals and port terminals are deducted from the discrete cost function.

Base cost f^k	
1-2-3-4-2-1	3600
Transportation cost ϕ_{ij}	
2-3	2000
4-2	2000
Total costs	**7600**
Terminal 1	2622
Terminal 2	4978

Table 5.4: Costs of cooperation scenario with a single roundtrip

In the second service network design scenario the two inland terminals cooperate but try to avoid waiting times in the port area. Two separate roundtrips are organized, $1-2-3-2-1$ and $1-2-4-2-1$, each visiting a single cluster in the port area. The selected network connections and freight flows are depicted in figure 5.4.

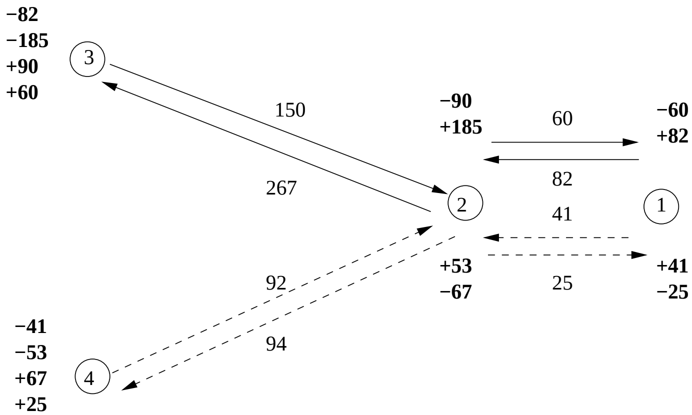

Figure 5.4: Cooperation with two roundtrips

Table 5.5 summarizes related costs. In the roundtrip $1-2-3-2-1$ a vessel with a capacity of more than 200 TEU is required to sail from the hinterland to the port area, whereas a capacity between 100 and 200 TEU satisfies the transport demand in the other direction. Due to this freight imbalance available vessel capacity is not fully utilized when sailing from the port to the hinterland. A transportation cost ϕ_{ij} of 2000 euro is incurred on link 3-2 instead of 1100 euro, which is the transportation cost of a vessel with a capacity of 100 to 200 TEU. Total costs are significantly higher than in the previous scenario because two separate vessels are chartered and less economies of scale can be reached. The waiting cost in the port area does not justify the additional cost of organizing two separate roundtrips to the port terminals.

Both cooperation scenarios are compared with the situation in which both inland terminals operate independently. Each terminal organizes its own roundtrip to the port area, $1-3-4-1$ and $2-3-4-2$. Figure 5.5 shows the relevant network connections.

An overview of base costs and variable network costs is given in table 5.6. Links $1-2$ and $2-1$ are not selected and no cooperation costs are charged. The inland terminals each carry the cost of their own roundtrip. Total costs of this service network design scenario are approximately equal to the cooperation scenario with two roundtrips, but significantly higher than the case of cooperation in a single roundtrip.

Base cost f^k	
1-2-3-2-1	3200
1-2-4-2-1	3200
Transportation cost ϕ_{ij}	
2-3	2000
3-2	2000
2-4	800
4-2	800
Total costs	**12000**
Terminal 1	4139
Terminal 2	7861

Table 5.5: Costs of cooperation with two roundtrips

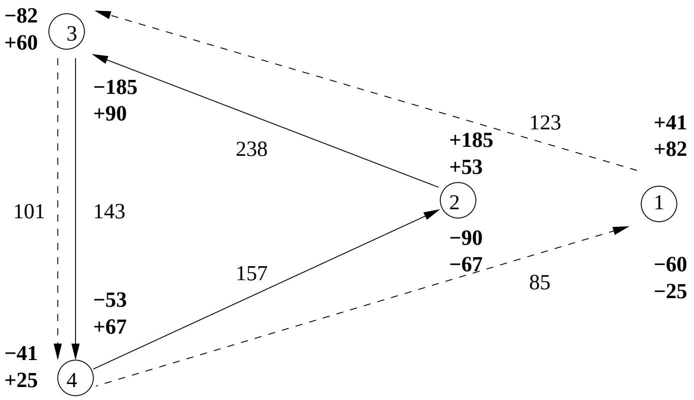

Figure 5.5: Independent roundtrips

In this fictious example full cooperation in a single roundtrip as in the first scenario is most beneficial when studying the network as a whole. When comparing the cost of the inland terminals, cooperation in a single roundtrip appears to be beneficial for both inland terminals. However, a comparison of scenario one and three shows that inland terminal one achieves most benefits from this type of cooperation. Inland terminal two already has more freight on its own to reach a certain degree of economies of scale.

Base cost f^k	
1-3-4-1	2800
2-3-4-2	2400
Transportation cost ϕ_{ij}	
1-3	1100
4-1	1100
2-3	2000
4-2	2000
Total costs	**11400**
Terminal 1	5000
Terminal 2	6400

Table 5.6: Costs of independent roundtrips

5.5 Scenario analysis in hinterland of Antwerp

In this section the service network design methodology for intermodal barge transport is applied to identify opportunities for cooperation between Belgian inland barge terminals in the hinterland network of the port of Antwerp. The result of this section is an insight in promising cooperation scenarios between inland barge terminals along each of the three main waterway axes. These cooperation schemes are introduced in the SIMBA model in the next section and compared with the results of bundling in the port area, as presented in chapter 4. In order to analyse potentials for cooperation, the assumption is made that each terminal maintains the same service level towards its customers as in the current situation. This implies that the same number of departures needs to be offered. Therefore, cooperation scenarios are analysed per departure day. The analysis of bundling in the hinterland is based on the same data collection as described in chapter 3.

5.5.1 Albert Canal

Four inland terminals are situated along the Albert Canal, each offering departures to sea terminals on the right and left river bank in the port of Antwerp. Figure 5.6 depicts the hinterland network along the Albert Canal. Cooperation scenarios are discussed in detail for departures on Tuesday, which is the first weekday all terminals offer a departure to the port of Antwerp. Results for other departure days are based on similar scenario analyses. Average volumes demanded on Tuesday (expressed in TEU) between each origin and destination are summarized in table 5.7. On this day of the week the terminal of Meerhout bundles its own freight to the left river bank.

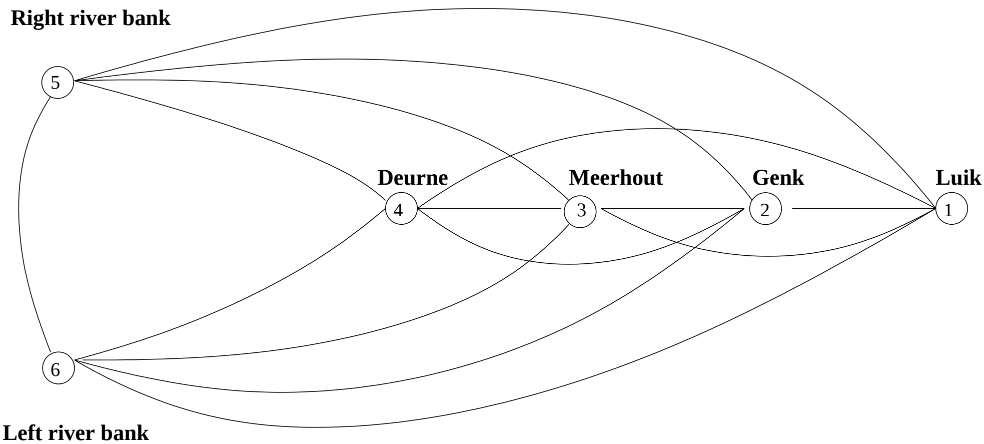

Figure 5.6: Hinterland network along Albert Canal

A similar cost approach is applied as described in section 5.4. Base costs f^k of possible roundtrips k consist of the cost of chartering the smallest vessel on a daily basis, cooperation costs in the hinterland and a waiting cost at lock systems in the port area. The cost of chartering the smallest vessel varies per terminal, as given in table 5.8. A waiting cost of 400 euro is associated with links connecting port nodes and a cooperation cost of 400 euro is charged for each stop at an intermediate terminal. The same discrete cost function as in section 5.4 describes variable costs on links connecting the port area with the hinterland. For connections between the terminal at Deurne and the port area this discrete cost function is divided by two. Due to its very near location to the port area, vessels can make a roundtrip in half a day.

Three cooperation scenarios are identified along the Albert Canal on Tuesday. The first scenario in figure 5.7 represents the current situation in which terminals operate independently. The numbers next to the arrows represent the flow (expressed in TEU) on each link in the network. In the second scenario the terminals of Luik, Genk and Deurne jointly operate two roundtrips. In the first joint roundtrip freight is bundled for the right river bank. The second roundtrip collects freight to and from the left river bank. The terminal of Meerhout operates its own roundtrip to the left river

Product	Origin	Destination	Demand w^p
1	1	5	23
2	5	1	23
3	1	6	23
4	6	1	23
5	2	5	0
6	5	2	0
7	2	6	62
8	6	2	46
9	3	5	0
10	5	3	0
11	3	6	215
12	6	3	169
13	4	5	46
14	5	4	54
15	4	6	54
16	6	4	46

Table 5.7: Set of products - Albert Canal on Tuesday

Terminal	Cost
Deurne	500
Meerhout	1000
Genk	1200
Luik	1400

Table 5.8: Base cost for chartering smallest vessel one-way - Albert Canal

bank. This is depicted in figure 5.8. The third scenario implies cooperation between Luik, Genk and Deurne in a single roundtrip serving both clusters of sea terminals, as shown in figure 5.9. These three inland terminals represent smaller freight flows

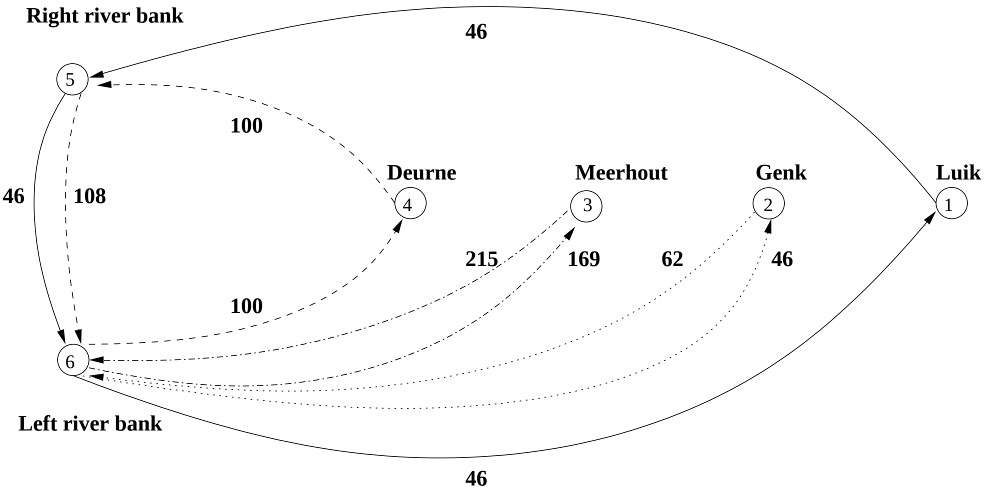

Figure 5.7: Albert Canal: Cooperation scenario 1 on Tuesday

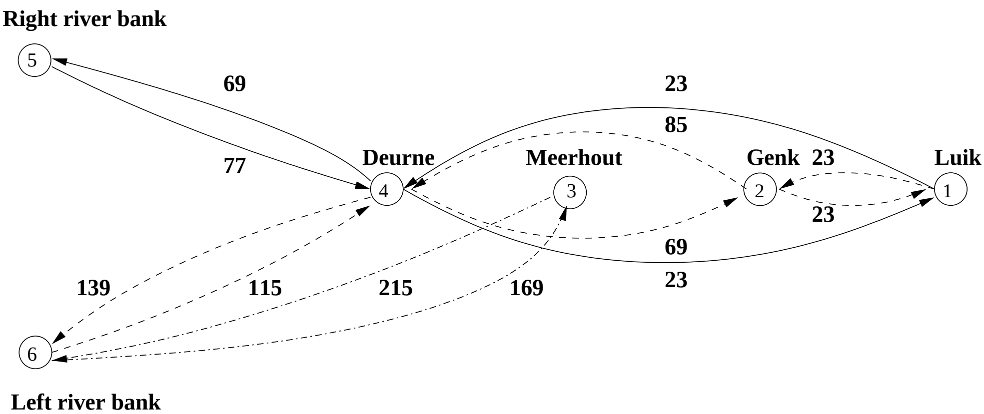

Figure 5.8: Albert Canal: Cooperation scenario 2 on Tuesday

and may benefit from cooperation. The terminal of Meerhout has enough volume to reach economies of scale on its own and thus may benefit less from cooperating with other terminals with the objective to charter a larger vessel. On the other hand, cooperation with other terminals would enable the terminal of Meerhout to further increase its frequency of service.

Table 5.9 compares the costs of these cooperation scenarios. For each scenario roundtrips and associated base costs f^k are given. Next, variable costs ϕ_{ij} are deducted from the flow on links between port nodes and inland nodes. The lowest total cost is achieved with the third scenario, although the difference with the current sce-

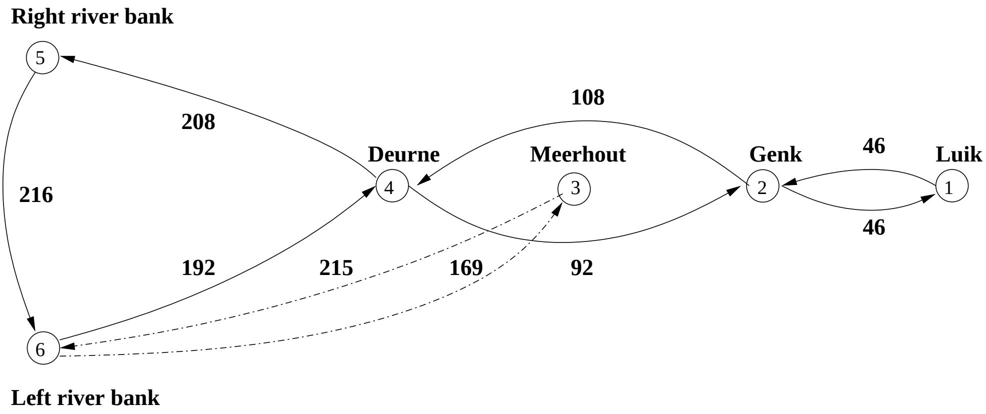

Figure 5.9: Albert Canal: Cooperation scenario 3 on Tuesday

nario of no cooperation is not large. Total costs of each roundtrip are distributed amongst the terminals involved according to their freight flows as an indication of potential benefits of cooperation. A comparison of scenario 3 with scenario 1 reveals that cooperation is most beneficial for terminal 1 in Genk and terminal 2 in Luik, which are both situated on a longer distance from the port area. Terminal 4 in Deurne does not benefit from this cooperation due to its lower transportation cost as it is situated nearby the port area. The cost analysis is based on a cooperation cost of 400 euro each time a barge moors at an intermediate terminal. A lower cooperation cost is in favour of the second and third scenario.

The same methodology is applied for each day of the week, leading to the selected cooperation scenarios in table 5.10. The table mentions the roundtrips performed per day in order to minimize total costs of the network as a whole. Terminals 1 and 2 in Luik and Genk cooperate on each weekday. These terminals are closely located to each other but have a relatively long sailing time to the port of Antwerp. Their freight volumes are smaller due to the daily frequency of service. An opportunity exists to bundle their flow and reach economies of scale, while still maintaining the same service schedule. Terminal 3 in Meerhout attracts enough volume to achieve economies of scale by bundling its own freight. Roundtrips are organized to either the right river bank or the left river bank. Terminal 4 in Deurne may cooperate with terminals 1 and 2 (Tuesday and Wednesday) or with terminal 3 (Thursday). However, as stated in the scenario analysis of Tuesday, this terminal has less financial incentives to cooperate due to its nearby location to the port area.

Scenario 1		**Scenario 2**		**Scenario 3**	
Base cost f^k					
1-5-6-1	3200	1-4-5-4-1	3600	1-2-4-5-6-4-2-1	4800
2-6-2	2400	1-2-4-6-4-2-1	4400	3-6-3	2000
3-6-3	2000	3-6-3	2000		
4-5-6-4	1400				
Transportation cost ϕ_{ij}					
1-5	0	4-5	500	4-5	2000
6-1	0	5-4	500	6-4	2000
2-6	500	4-6	1100	3-6	2000
6-2	500	6-4	1100	6-3	2000
3-6	2000	3-6	2000		
6-3	2000	6-3	2000		
4-5	550				
6-4	550				
Total costs	**15100**		**17200**		**14800**
Terminal 1	3200		2645		2024
Terminal 2	3400		2806		2376
Terminal 3	6000		6000		6000
Terminal 4	2500		5749		4400

Table 5.9: Cost comparison of cooperation scenarios along Albert Canal on Tuesday

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1-2-5-6-2-1	1-2-4-5-6-4-2-1	1-2-4-5-6-4-2-1	1-2-5-6-2-1	1-2-5-6-2-1	2-3-5-6-3-2
3-5-6-3	3-6-3	3-5-3	3-4-5-6-4-3	3-5-3	3-6-3
3-5-3				3-6-3	

Table 5.10: Selected cooperation scenarios along Albert Canal

5.5.2 Brussels-Scheldt Sea Canal

Three inland terminals offer regular departures along the Brussels-Scheldt Sea Canal, as shown in figure 5.10. The terminal at Herent is left out of the analysis since it is situated along the Canal Leuven-Dijle, which is only navigable for vessels up to 600 tons. Each terminal offers a daily service to the port of Antwerp, resulting in relatively small individual freight volumes. Table 5.11 presents average volumes transported from the three inland terminals to both clusters of sea terminals in the port of Antwerp on Monday in TEU. Table 5.12 mentions the cost of chartering the smallest vessel departing from each terminal. A waiting cost of 400 euro is assumed along links connecting port nodes and a cooperation cost of 400 euro is incurred when selecting links between inland nodes. Variable costs on links connecting the port area with the hinterland are represented by the same discrete cost function along all three waterway axes in the hinterland of the port of Antwerp.

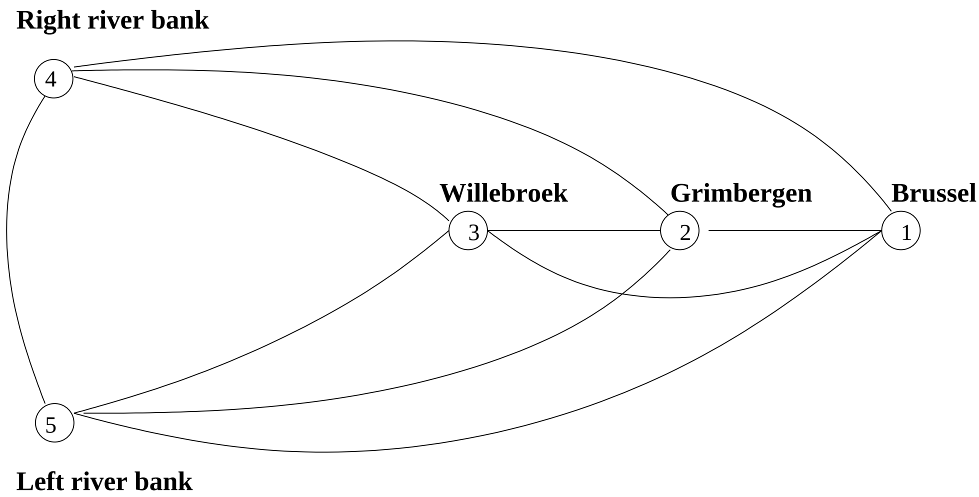

Figure 5.10: Hinterland network along Brussels-Scheldt Sea Canal

Three cooperation scenarios are investigated for departures on Monday. In the first scenario each terminal organizes its own shuttle service, as depicted in figure 5.11. The second scenario consists of two separate roundtrips in which the three terminals cooperate, but bundle freight with the same origin or destination in the port area. The first roundtrip sails to and from sea terminals on the right river bank, the second roundtrips serves sea terminals on the left river bank. This situation is shown in figure 5.12.

Product	Origin	Destination	Demand w^p
1	1	4	15
2	4	1	15
3	1	5	15
4	5	1	15
5	2	4	11
6	4	2	11
7	2	5	15
8	5	2	15
9	3	4	49
10	4	3	49
11	3	5	40
12	5	3	40

Table 5.11: Set of products - Brussels-Scheldt Sea Canal on Monday

Terminal	Cost
Willebroek	750
Grimbergen	1000
Brussel	1000

Table 5.12: Base cost for chartering smallest vessel one-way - Brussels-Scheldt Sea Canal

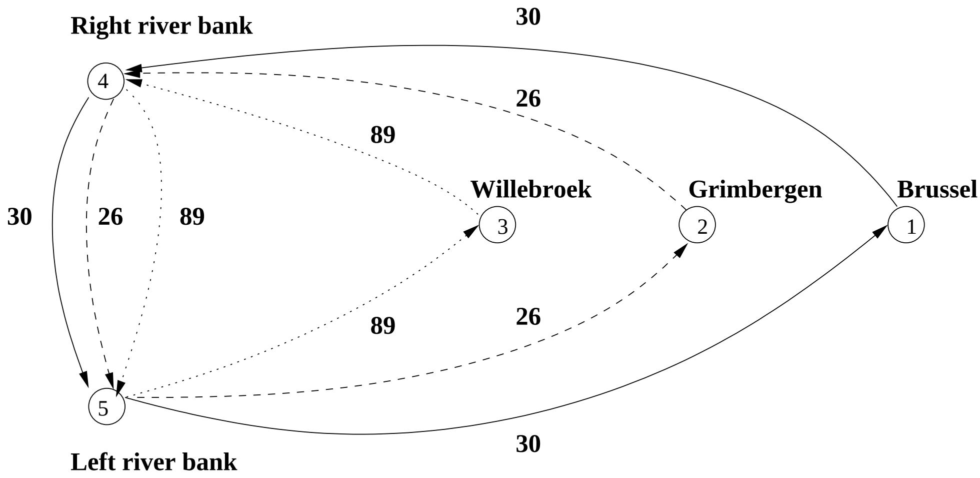

Figure 5.11: Brussels-Scheldt Sea Canal: Cooperation scenario 1 on Monday

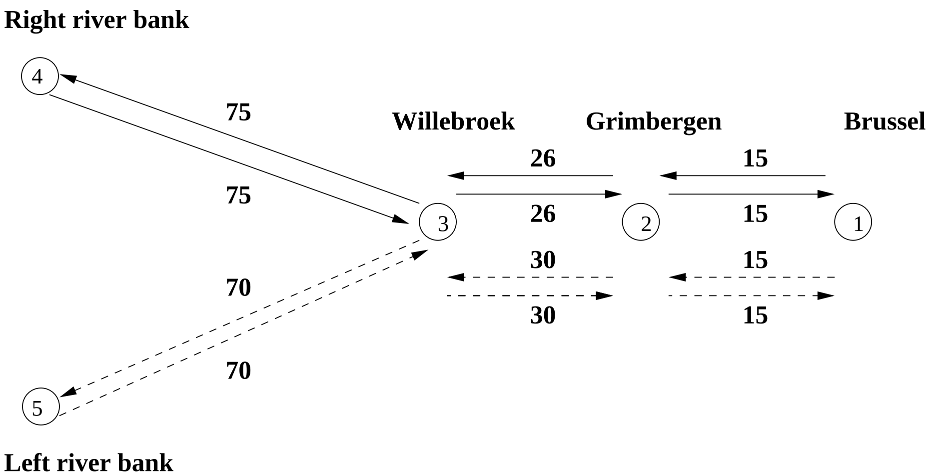

Figure 5.12: Brussels-Scheldt Sea Canal: Cooperation scenario 2 on Monday

The final scenario represents full cooperation in a single roundtrip sailing to the right and left river bank (figure 5.13).

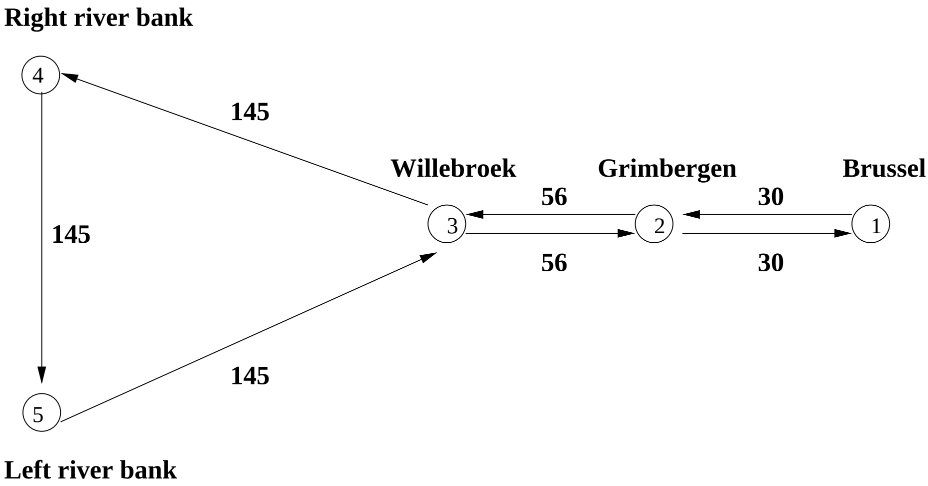

Figure 5.13: Brussels-Scheldt Sea Canal: Cooperation scenario 3 on Monday

A cost comparison of these three cooperation scenarios is presented in table 5.13. Total costs are minimized in the third scenario, implying full cooperation in a single roundtrip. Terminals 1 and 2 in Brussel and Grimbergen carry high costs in the current scenario due to their small volumes and daily schedules. By bundling their freight with terminal 3 at Willebroek in a single roundtrip only one vessel needs to be chartered instead of three. The inland terminal at Willebroek gathers more volume on its own and thus has less tendency to cooperate than the other two terminals. In the second cooperation scenario the gain of avoiding waiting costs at lock systems in the port area does not outweigh the additional cost of chartering an extra vessel. Similar analyses on other weekdays lead to the conclusion that full cooperation between the three terminals in a single roundtrip is always the most beneficial scenario along the Brussels-Scheldt Sea Canal when optimizing the complete waterway network.

5.5.3 Upper Scheldt and river Leie

Three inland terminals are located in the Western part of the Belgian hinterland of the port of Antwerp. The network structure is depicted in figure 5.14. The terminals at Wielsbeke and Avelgem are very near to each other but along a different waterway axis. Each may organize a corridor network with the terminal at Gent. The terminal at Gent could also function as an inland hub, but this would require extra handling of

Scenario 1		Scenario 2		Scenario 3	
Base cost f^k					
1-4-5-1	2400	1-2-3-4-3-2-1	3600	1-2-3-4-5-3-2-1	4000
2-4-5-2	2400	1-2-3-5-3-2-1	3600		
3-4-5-3	1900				
Transportation cost ϕ_{ij}					
1-4	0	3-4	500	3-4	1100
5-1	0	4-3	500	5-3	1100
2-4	0	3-5	500		
5-2	0	5-3	500		
3-4	500				
5-3	500				
Total costs	**7700**		**9200**		**6200**
Terminal 1	2400		1906		1283
Terminal 2	2400		1660		1112
Terminal 3	2900		5634		3806

Table 5.13: Cost comparison of cooperation scenarios along Brussels-Scheldt Sea Canal on Monday

containers between barges. In contrast, line bundling only requires containers to be added onto the vessel and thus no extra handling. An overview of average transport demand on Wednesday in TEU between the three terminals and the port of Antwerp is given in table 5.14. Costs of chartering the smallest vessel are summarized in table 5.15. All other costs are assumed to be the same as in the analyses of the Albert Canal and the Brussels-Scheldt Sea Canal.

Three cooperation scenarios are identified in the hinterland network on Wednesday. In the first scenario each terminal offers its own roundtrip to customers. Figure 5.15 shows the resulting roundtrips and freight flows. In the second scenario Wielsbeke and Gent organize a joint roundtrip, while Avelgem maintains its own shuttle service. This situation is depicted in figure 5.16.

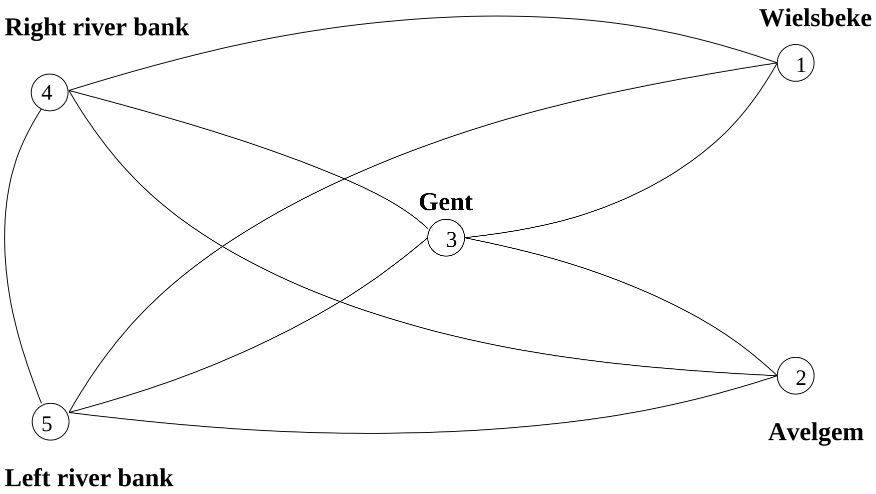

Figure 5.14: Hinterland network along Upper Scheldt and river Leie

Product	Origin	Destination	Demand w^p
1	1	4	0
2	4	1	0
3	1	5	43
4	5	1	43
5	2	4	6
6	4	2	8
7	2	5	8
8	5	2	6
9	3	4	23
10	4	3	23
11	3	5	46
12	5	3	46

Table 5.14: Set of products - Upper Scheldt and river Leie on Wednesay

Terminal	Cost
Gent	1000
Wielsbeke	1200
Avelgem	1400

Table 5.15: Base cost for chartering smallest vessel one-way - Upper Scheldt and river Leie

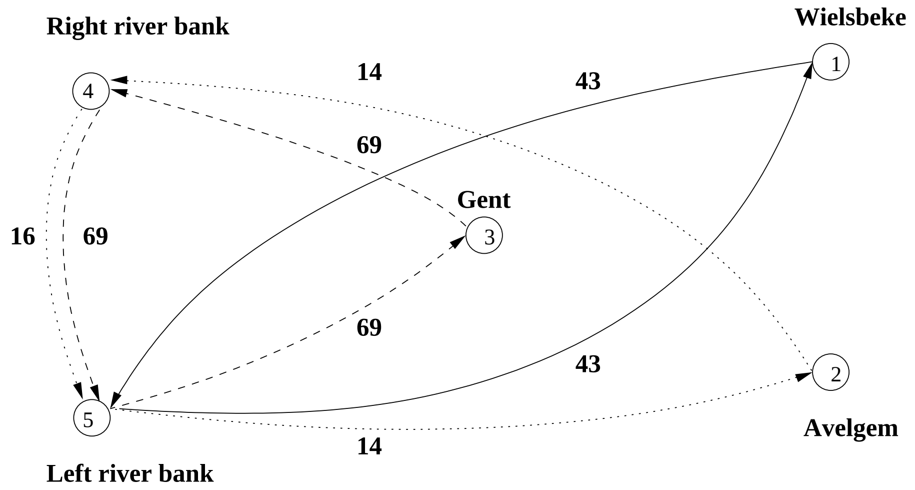

Figure 5.15: Upper Scheldt and river Leie: Cooperation scenario 1 on Wednesday

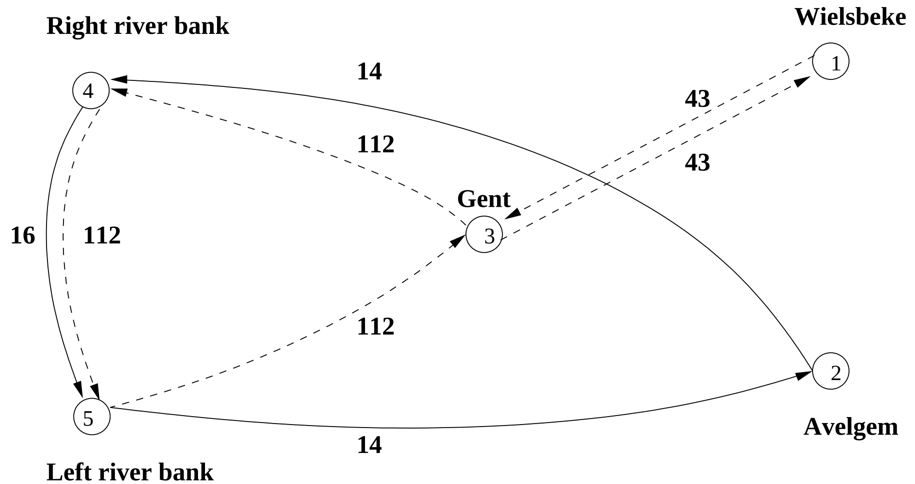

Figure 5.16: Upper Scheldt and river Leie: Cooperation scenario 2 on Wednesday

Avelgem and Gent set up a corridor network in the third cooperation scenario, while Wielsbeke organizes its own shuttle service (figure 5.17).

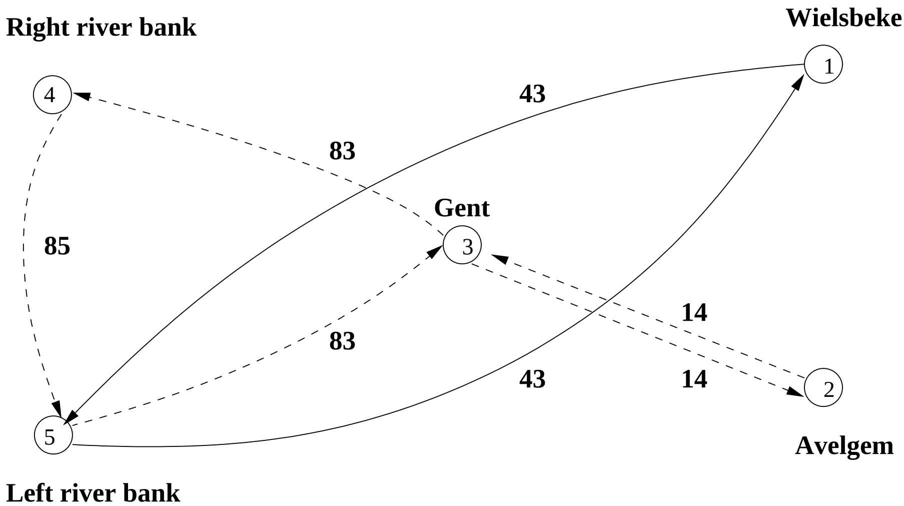

Figure 5.17: Upper Scheldt and river Leie: Cooperation scenario 3 on Wednesday

The three cooperation scenarios on Wednesday are compared in table 5.16. Scenarios two and three require the same number of roundtrips. The third scenario is the most interesting from a network perspective. The terminal of Wielsbeke only has to visit sea terminals on the left river bank. Waiting costs in the port area are less in this scenario compared to the second scenario. The cost comparison depends on the assumptions made about the discrete cost function representing economies of scale, coordination costs and waiting costs. However, the methodology allows to analyse line bundling given any changes in cost structure. In scenarios two and three cooperation between two terminals still does not lead to bundling large volumes of freight. Opportunities to achieve economies of scale related to the port of Antwerp are not large in this region of the hinterland. In both scenarios total costs after cooperation are less than or equal to the current operations. Departures are also organised on Monday and Friday. Terminal three in Gent does not ship any containers to the port of Antwerp on these days, so no line bundling opportunities exist. Resulting roundtrips are presented in table 5.17.

Scenario 1		Scenario 2		Scenario 3	
Base cost f^k					
1-5-1	2400	1-3-4-5-3-1	3600	2-3-4-5-3-2	4000
2-4-5-2	3200	2-4-5-2	3200	1-5-1	2400
3-4-5-3	2400				
Transportation cost ϕ_{ij}					
1-5	0	3-4	1100	3-4	500
5-1	0	5-3	1100	5-3	500
2-4	0	2-4	0	1-5	0
5-2	0	5-2	0	5-1	0
3-4	500				
5-3	500				
Total costs	**9000**		**9000**		**7400**
Terminal 1	2400		2227		2400
Terminal 2	3200		3200		843
Terminal 3	3400		3573		4157

Table 5.16: Cost comparison of cooperation scenarios along Upper Scheldt and river Leie on Wednesday

Monday	Wednesday	Friday
1-4-1	2-3-4-5-3-2	1-4-5-1
2-4-5-2	1-5-1	2-4-5-2

Table 5.17: Selected cooperation scenarios along Upper Scheldt and river Leie

5.6 Comparison between bundling in the hinterland and bundling in the port area

The selected cooperation schemes from section 5.5 are modelled in a new simulation scenario for the SIMBA model. In this line bundling scenario, inland barges stop at intermediate terminals to consolidate freight in the Belgian hinterland of the port of Antwerp. The same approach as in chapter 4 is applied to compare results with the current situation. Table 5.18 reports on the turnaround times in the current scenario and cooperation scenario.

Turnaround time	**Current**		**Cooperation**	
	Avg	*Stdev*	*Avg*	*Stdev*
Deurne - Antw	15.20	(0.47)	33.07	(0.33)
Deurne - Antw/Rdam	22.08	(0.89)	22.01	(0.15)
Meerhout - Antw	29.24	(0.47)	35.06	(0.54)
Meerhout - Antw/Rdam/Adam	41.70	(0.38)	42.44	(0.48)
Genk - Antw	38.97	(0.62)	53.36	(0.30)
Genk - Antw/Rdam	49.89	(0.87)	50.26	(0.71)
Luik - Antw	46.46	(0.34)	59.68	(0.40)
Gent - Antw	20.62	(0.49)	33.39	(0.56)
Wielsbeke - Antw	38.62	(0.42)	40.22	(0.37)
Avelgem - Antw	41.19	(0.88)	40.93	(1.16)
Avelgem - Antw/Rdam	62.69	(0.48)	62.52	(0.17)
Willebroek - Antw	14.79	(0.17)	23.06	(0.16)
Willebroek - Antw/Rdam	35.59	(0.39)	35.37	(0.22)
Grimbergen - Antw	20.93	(0.21)	32.59	(0.28)
Brussel - Antw	21.91	(0.34)	33.59	(0.28)
Brussel - Antw/Rdam	40.94	(0.29)	40.69	(0.40)
Herent - Antw	21.91	(0.19)	21.85	(0.20)

Table 5.18: Average turnaround times current situation and bundling in hinterland

Performance measures in the port area are given in table 5.19. The average and maximum waiting time before handling, expressed in hours, are measured at the sea terminals on the right and left river bank. Secondly, the table mentions the average and maximum utilization of quays on the right and left river bank. Table A.5 in appendix reports on the maximum waiting times of inland barges for handling in the port area in each individual simulation run.

Port area	**Current**		**Cooperation**	
Waiting time	*Avg*	*Stdev*	*Avg*	*Stdev*
Right river bank	0.0629	(0.0306)	0.0159	(0.0117)
Left river bank	0.0557	(0.0115)	0.0255	(0.0166)
Capacity utilization	*Avg*	*Stdev*	*Avg*	*Stdev*
Quay right river bank	0.1666	(0.0017)	0.1852	(0.0019)
Quay left river bank	0.1741	(0.0017)	0.1997	(0.0021)
Max waiting time				
Right river bank	7.6128		2.2597	
Left river bank	4.3095		5.1275	
Max capacity utilization				
Quay right river bank	0.9834		0.9834	
Quay left river bank	0.9850		0.9850	

Table 5.19: Performance measures in the port area: current situation and line bundling in hinterland

In table 5.20 paired-t confidence intervals are constructed to compare the results. An overview is given of the 95% confidence intervals which report a significant difference between the current situation and the cooperation scenario. Table 5.20 shows a significant increase in the turnaround time of a number of terminals. Terminals engaging in a cooperation scheme have to take a longer turnaround time into account. First, cooperation between inland terminals implies extra stops along the route. The extra stops have to be anticipated in the departure time of barges. The more terminals involved in a corridor network, the more stops are required in a corridor network. A solution may be to organize an inland collection/distribution network in which a single terminal serves as an inland hub. Secondly, terminals which already consolidate

	Confidence interval cooperation - current
Avg turnaround time	
Gosselin Deurne - Apen	16.4559 ; 19.2889
WCT Meerhout - Apen	4.7759 ; 6.8694
Haven van Genk - Apen	12.7657 ; 16.0009
Renory Luik - Apen	12.0016 ; 14.4421
IPG Gent - Apen	11.8596 ; 13.6975
RTW Wielsbeke - Apen	0.1273 ; 3.0662
TCT Willebroek - Apen	7.9164 ; 8.6251
Cargovil Grimbergen - Apen	10.8132 ; 12.5038
BTI Brussel - Apen	10.9138 ; 12.4568
Avg number waiting	
Left river bank	-0.0185 ; -0.0023
Avg capacity utilization	
Quay right river bank	0.0129 ; 0.0242
Quay left river bank	0.0207 ; 0.0306

Table 5.20: Confidence intervals comparing the current situation with line bundling in hinterland

freight to a single cluster of sea terminals see their turnaround time increase when both clusters of sea terminals are served in the cooperation scenario. Table 5.19 and 5.20 show only small or no improvements in performance measures in the port area. When looking at the individual simulation runs, maximum waiting times in table A.5 are in general lower compared to the current situation and the four hub scenarios presented in chapter 4. Capacity utilization at peak moments is still high, suggesting that cooperation along river axes in the hinterland offers less efficiency gains at the sea terminals compared with the bundling scenarios in the port area. Freight of a limited number of inland terminals is bundled, while remaining the same service level offered to customers. More opportunities to attain economies of scale may exist when reducing the number of sailings per week, given current transport volumes. From these results it can be concluded that a main motivation for setting up a corridor network in the hinterland is to attain economies of scale for inland terminals or to increase their frequency of service. No major impact is recorded on average waiting times of inland barges in the port area, but an improvement in maximum waiting times at peak moments may be observed.

5.7 Conclusions

In this chapter service network design in intermodal barge transport is studied. Service network design of intermodal transport by rail has often been investigated because of its monopolistic nature. On the contrary, intermodal transport by barge is organized by individual decision makers. A new methodology is set up to study the service network of intermodal barge transport as a whole in order to demonstrate potential benefits of cooperation between inland terminals in a corridor network.

The methodology is applied to the hinterland network of inland barge terminals in Belgium. Line bundling strategies are identified along the three major river axes. Cooperation is most interesting from a cost perspective for terminals with smaller volumes situated at a further distance from the port area. The new methodology allows to estimate the impact of policy measures to stimulate cooperation between inland terminals. Whether or not cooperation is interesting from a network perspective is sensitive to the cost of setting up and organizing a cooperative service network. The selected cooperation scenarios are simulated with the SIMBA model. This allows to compare the results of bundling in the hinterland with bundling in the port area at a dedicated intermodal barge hub. Terminals involved in a corridor network have to take a longer turnaround time into account as in the current situation. The impact on turnaround times is larger as more terminals are involved. In the cooperation scenario less efficiency gains are recorded at sea terminals as in the hub scenarios in the port area. At a hub in the port area freight is bundled of all terminals in the hinterland network, whereas in a hinterland cooperation network freight is only bundled of two to three terminals. Given current transport volumes, more bundling opportunities may be created in the hinterland by reducing the number of departures or setting up a trunk collection/distribution network. Reducing the number of departures may however lead to less service offered to customers. Cooperation between inland terminals offers an opportunity to attain economies of scale and to reduce maximum waiting times of inland barges at sea terminals.

A methodology is proposed for modelling cooperation between inland terminals along the same waterway in a corridor network. The proposed methodology may be applied to hinterland networks of other ports or to other cost data. Future research may set up an alternative service network design formulation for trunk collection/distribution networks and make the comparison with corridor networks.

Chapter 6

Shipper consolidation

6.1 Introduction

In this chapter an introductory case study is described in which clustering of freight activities is discussed at the operational level, as presented in figure 6.1. The cost of freight transport may be decreased by raising the fill rate of loading units. Shippers attain scale economies and a better utilization of transport equipment through consolidation of freight inside a loading unit. This may reduce costs of pre- and end-haulage by road and increase the attractiveness of intermodal freight transport for further continental distribution. Coloading of freight reduces the amount of trucks on the road. Societal gains are achieved by decreasing the amount of air pollution, transport noise, accidents and congestion. According to Van der Horst and De Langen (2008), coordination in hinterland transport chains is required to make hinterland transport chains efficient and effective. The authors identify coordination problems and evaluate mechanisms to enhance coordination in hinterland freight transport. Ergun et al. (2007) study shipper consolidation in the context of collaborative logistics in the trucking industry. Their goal is to identify sets of lanes of multiple shippers that can be submitted to a carrier as a bundle rather than individually, in the hope that this results in more favorable rates. The authors focus on the simplest variant, which is static and involves only full truckloads. The problem is formulated as a lane covering problem and heuristic solutions are proposed. Consolidation of freight is often proposed to reduce truck traffic in urban areas. Kawamura and Lu (2007) compare logistics costs with and without delivery consolidation in urban centers, under different sets of conditions that include population density, area size and truck weight regulation. Factory gate pricing (FGP) is an alternative approach to transport consolidation, as proposed by le Blanc et al. (2006). Under FGP, products are no longer delivered at the retailer distribution center, but collected by the retailer at the factory gates of the suppliers. The authors study asymmetric distribution networks in which supplier sites greatly outnumber retailer distribution centers. A case study is performed of a Dutch retail chain of slow moving dry grocery goods. This setting differs from the type of distribution network studied in this chapter.

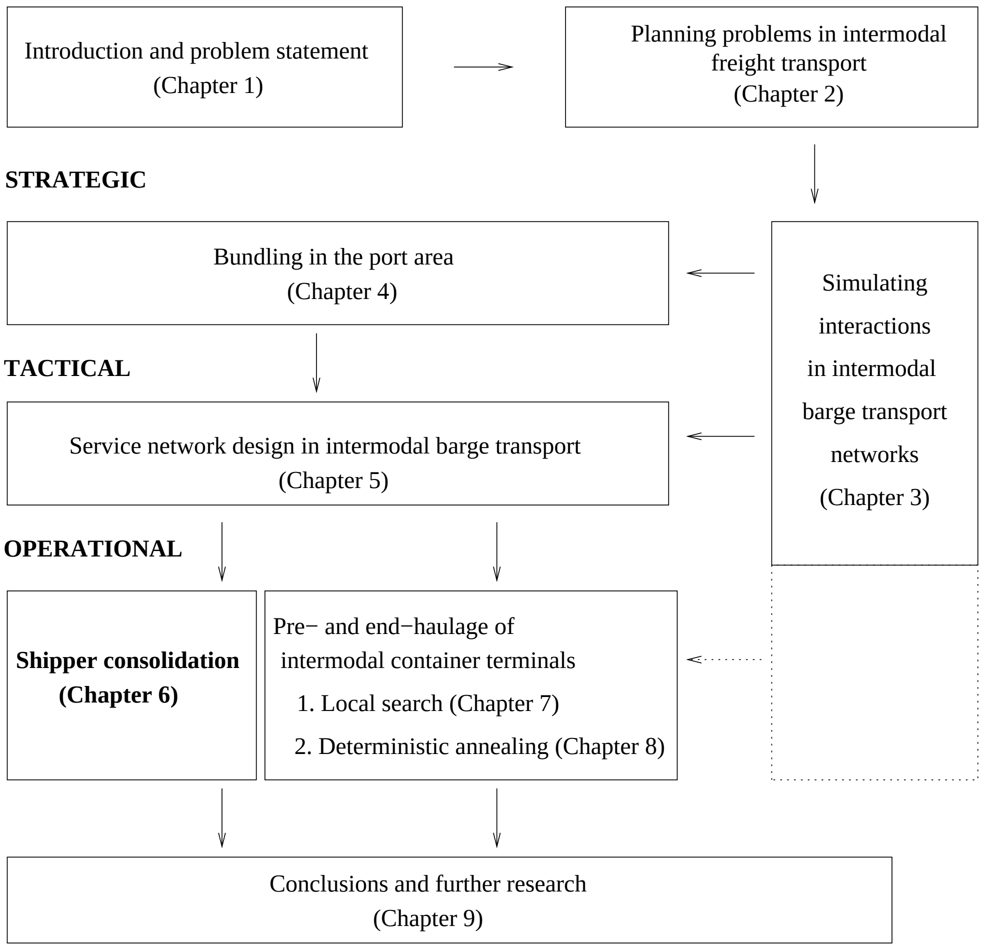

Figure 6.1: Outline of the thesis - Chapter 6

In this chapter a large real-life case study is presented to quantify possible benefits of consolidation between shippers. A consolidation scenario is defined and calculated to evaluate the performance of the distribution network on a number of output measures. Opportunities of consolidating freight from three different distribution centres are identified. Long haul truck transport distances are considered for the continental distribution of freight in Europe. First, a description of current and future operations is given in section 6.2. In the consolidation scenario, freight flows are bundled through a crossdock which is situated at or nearby an intermodal terminal. The next section 6.3 elaborates on the methodology. A simulation model is set up of the current scenario and consolidation scenario. Freight is consolidated based on a number of predefined rules. The simulation model is used as an aid to handle the large amount of data. A data set of ten weeks describing all load orders is available. The data set used in the case study analysis is presented in section 6.4. In sections 6.5 and 6.6 assumptions underlying the simulation model and consolidation strategy are summarized. Finally, in sections 6.7 and 6.8 results of current and future operations are compared and discussed.

6.2 System description

Shipper consolidation is investigated in a real life case study. Three shippers operate each a distribution centre (DC) in the neighbourhood of an intermodal terminal in Western Europe. The intermodal terminal is situated in the hinterland of a major port, offering rail, barge and road connections to the port area. Inbound flows arrive at the DCs through the intermodal terminal. The DCs are responsible for further continental distribution of goods. In this chapter the consolidation of these outbound flows is analysed. Outbound flows are mainly transported by truck. To a limited degree freight is carried by rail or short sea shipping. Warehousing operations are centralized at the three DCs, implying lower warehousing costs, but higher transport costs. Each DC is specialized in a certain product category and uses a separate planning system. In the current situation each DC operates independently. A DC has its own warehouse and shipping department and plans the loading of its own trailers and containers. Figure 6.2 depicts the current scenario. Load orders arrive from the warehouse at the shipping department and need to be handled at one of the available gates. Load orders consist of boxes in various sizes, which may be palletized or not. In the shipping department the boxes or pallets are loaded into trailers or containers. The arrival of load orders from the warehouse serves as an input for the simulation model of the shipping department. The arrival time depends on the warehouse planning and operations and is assumed to be given. DC 1 has 16 gates available, DC 2 and DC 3 each have 17 gates available.

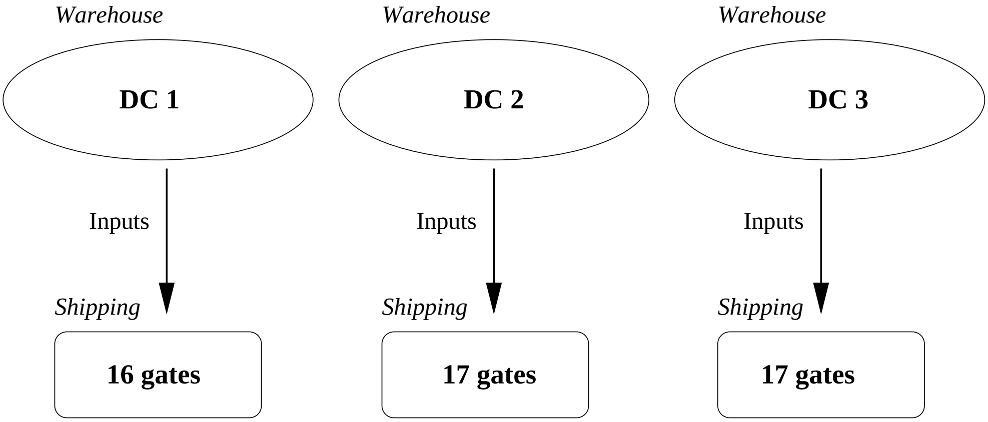

Figure 6.2: Current scenario without shipper consolidation

Figure 6.3 represents the future scenario in which load orders from the three DC's are consolidated through a crossdock at or nearby an intermodal terminal. The objective of the case study analysis is to quantify potential benefits of consolidating freight from the three DC's to joint hub destinations. No assumptions are made on the operational implementation of the crossdock. In the future scenario the crossdock is a fictitious location where the three flows of the warehouses arrive jointly, so that load orders with the same destination may be grouped in a single loading unit.

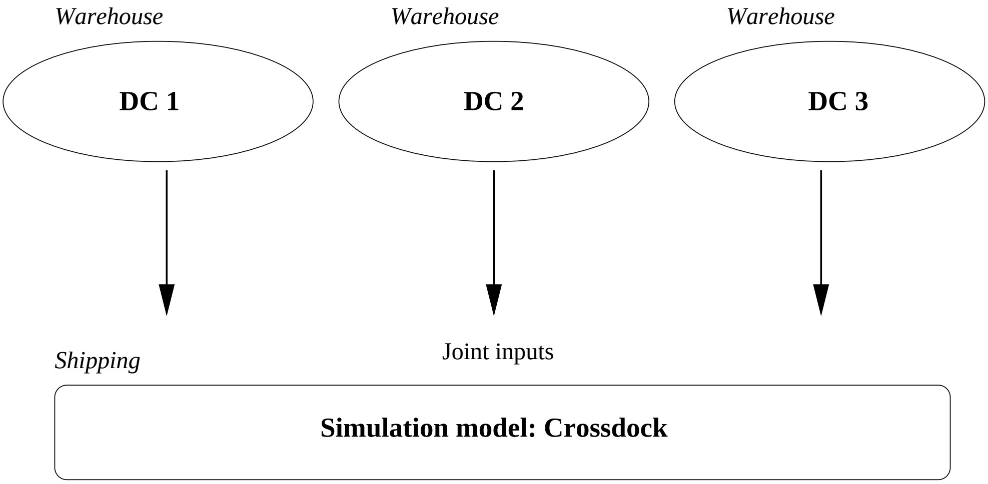

Figure 6.3: Consolidation scenario

6.3 Methodology

In this case study a discrete event simulation model is set up to calculate performance measures in the current and consolidation scenario. In the consolidation scenario the simulation model recombines load orders of various DCs in a single loading unit, based on a number of predefined rules. Results of the consolidation scenario are compared with the outputs of simulating the current situation. The simulation model is used to handle the data set described in section 6.4.1. In a discrete event system, one or more phenomena of interest change value or state at discrete points in time. These points in time are moments at which an event occurs. An event is defined as an instantaneous occurrence that may change the state of the system. The simulation model is constructed in Arena, a simulation software based on queuing theory. Figure 6.4 represents a general queuing system. Customers arrive from an external input source and queue for handling by a service mechanism. The service mechanism consists of a number of resources which provide the service. Customers leave the system after being served.

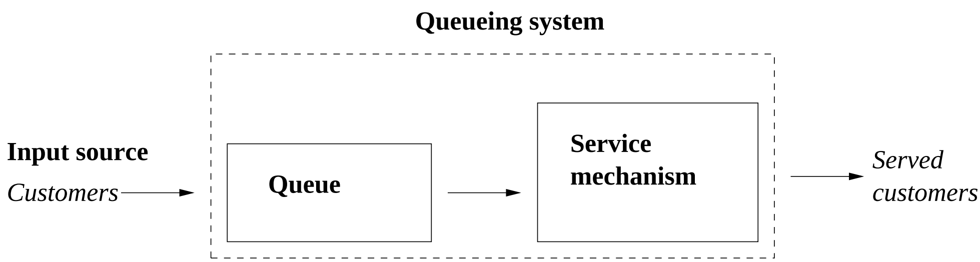

Figure 6.4: General queuing model

The customers or entities in our discrete event simulation model are load orders arriving from the warehouse into the shipping department of each DC, as depicted in figure 6.5. The warehouse planning and operations are an external source of load orders and thus not incorporated in the simulation model. In the simulation model the load orders queue for handling at the gates. The service delivered by the resources or gates is the loading of boxes or pallets onto loading units, which may be containers or trailers. Examples of state variables in this discrete event system are the status of the gates (idle or busy), the number of load orders waiting in a queue for handling at a gate or the time of arrival of a load order in a queue for handling at a gate. Events are the arrival of a load order in the shipping department or the completion of service of a load order at a gate.

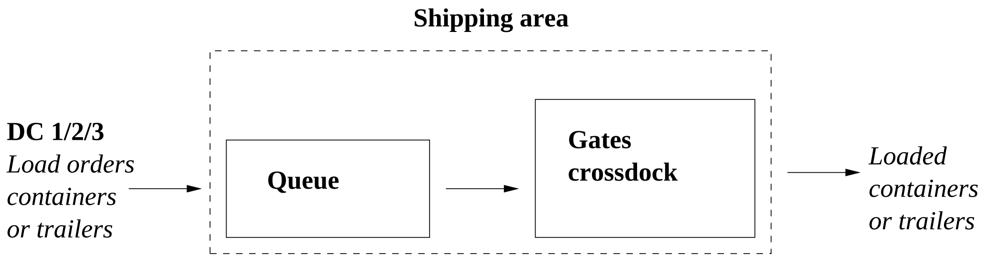

Figure 6.5: Queuing model shipping department

In the simulation model of the current situation three separate queueing systems for each DC are constructed. The assignment of load orders to loading units is taken from the given planning in the available data set described in the next section. Containers or trailers leave the site when the last load order is put onto the loading unit at a gate in the shipping department. Between the first and last load order assigned, a loading unit is waiting at a gate or at the parking area close to the gates. In the simulation model of the future scenario the load orders of the three DC's arrive as a joint input process for a single service system representing the shipping area of the fictitious crossdock.

6.4 Data requirements

The simulation model requires data on the arrival process of load orders in the shipping department and on the service process of load orders at the gates. Real data input is used for the arrival process, as described in section 6.4.1. The service process is modelled with a probability distribution and parameters are deducted from practice in section 6.4.2 .

6.4.1 Arrival process

A data set of load orders in the three DC's for a period of 10 weeks is used to estimate performance measures in the current and future scenario. Table 6.1 summarizes the attributes of load orders which are analysed in the case study. In the second column an instance of a load order is described. Base time units in the simulation model are hours. The first attribute 'shipping time' represents the moment at which the load order arrives in the shipping department. The simulation starts at time zero, so the instance in table 6.1 arrives after simulating 42.96 hours. In the data set only the arrival times of the first and last carton are given. A random moment based on a uniform distribution between this minimum and maximum arrival time in shipping is assigned to each load order. In the data set of the current situation, each load order is destined for a certain loading unit, represented by an identification number.

Attribute	**Instance**
Shipping time	42.96
Loading unit	3666
Nb of cartons	58
Cubage	4.21
Weight	395.7
Palletized or not	0
Nb of pallets	0
WOW or ph	1
Export	1
DC	2
Consolidator block	22
Direct drop	0
Cut off time	273.0

Table 6.1: Attributes of load orders

The next five attributes (number of cartons, cubage, weight, palletized or not and number of pallets) are necessary to determine the fill rate of containers or trailers and to consolidate load orders in the consolidation scenario. The instance described in table 6.1 is destined for loading unit 3666 in the current situation, consists of 58 cartons and accounts for 4.21 m^3 or 395.7 kg. The fill rate is calculated as the percentage of available volume filled. Due to the type of products, weight is not a limiting factor. However, weight could be taken into account when consolidating load with other parties. The next attribute marks whether the load order follows from either one of two special systems for warehouse operations in the distribution centres under investigation. The abbreviation 'WOW' refers to Warehouse on Wheels. In this system load orders are loaded and stocked on site for a short time period with the objective to balance the warehouse operations. 'Ph' stands for 'pack and hold', which is a similar system but load orders are stocked internally at the shipping department of DC 1. This attribute is taken into account when calculating the performance measures in section 6.7. Load orders for certain export destinations are not consolidated in the crossdock scenario, due to administrative restrictions on the generation of pack lists. The instance in table 6.1 is part of the Warehouse on Wheels system and cannot be consolidated due to its export destination. The attribute 'DC' indicates from which distribution centre a load order is originating. The attribute 'consolidator block' identifies the carrier and hub for which the load order is destined. 34 possible consolidator blocks or destinations are identified. The instance originates from DC 2 and is destined for consolidator block 22. Direct drops are loading units which are delivered directly to the end customer. Therefore these loading units are not consolidated in the crossdock scenario. This attribute takes on a value of 0 or 1, indicating whether or not the load order belongs to the system of direct drops. The final attribute 'cut off time' refers to the moment at which the container or trailer must leave the site to arrive on time at destination. The loading unit containing the loading order of table 6.1 must leave the site at the latest at a simulation time of 273 hours. Load orders can only be consolidated if their cut off times match.

Figure 6.6 represents the structure of the arrival process of load orders coming from the warehouses. Loading units may contain load orders for a single or a limited number of carrier hubs (destinations). Due to the warehouse planning and operations load orders for a certain carrier hub are part of multiple planning runs in multiple planning schedules. Each planning schedule is divided in multiple planning runs. Consequently, a certain time lag may pass between the first and last load order for a particular loading unit.

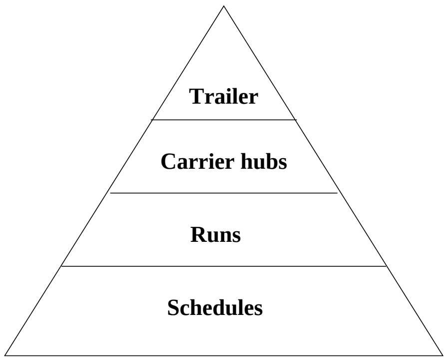

Figure 6.6: Structure of the arrival process of load orders

6.4.2 Service process

The service process represents the loading of cartons or pallets onto loading units at the gates. The number of available resources or gates is limited to 16 in DC 1 and 17 in both DC 2 and DC 3. Each load order requires that a number of cartons or a number of pallets is loaded onto a container or trailer. A probability distribution is applied to model the time necessary to load a single carton or pallet onto a loading unit. To this end a triangular distribution is chosen (Law 2007). Fig 6.7 depicts the triangular distribution for the loading of pallets. The triangular distribution is identified by three parameters: mode, minimum and maximum value. A triangular distribution gives the highest probability of occurrence to the mode and the probability decreases in the direction of the minimum and maximum value. The triangular distribution offers the advantage that only a fixed range of values is allowed and parameters are simply to determine. For the service time of pallets a mode of 5 minutes is experienced in practice. The minimum and maximum value are assumed to deviate 20 %, leading to a minimum of 4 minutes and a maximum time to load a pallet of 6 minutes. When goods are not palletized, a service time per carton is applied. A service time of 0.45 minutes per carton is mostly observed, leading to a minimum value of 0.36 minutes and a maximum value of 0.54 minutes.

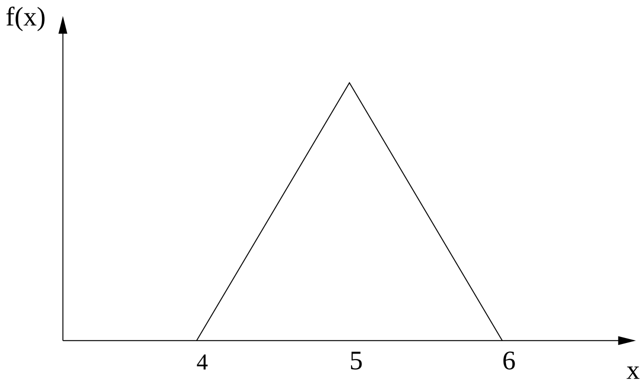

Figure 6.7: Triangular distribution

6.5 Assumptions

This section summarizes the assumptions made in calculating the performance measures of the current and future situation. Performance measures are calculated by the simulation model over a period of ten weeks. In the current situation the assignment of load orders to loading units is assumed to be given. The arrival time of load orders in the shipping department of each DC is randomly chosen between the minimum and maximum in shipping date and time. The minimum and maximum in shipping date and time are the times at which the first and last carton of a single load order arrives in the shipping department. Real data input is used for the arrival times of load orders. Service times are modelled with a triangular distribution, as described in the previous section. Table 6.2 presents the relevant outputs measured in the simulation model. The throughput time is the total time that a loading unit spends on site, including loading time and standing time. Standing time is the time period in which a loading unit is waiting at the gate or on the parking area. Load orders in the 'Warehouse On Wheels' or 'pack and hold' system are not taken into account when calculating the throughput times and standing times. These load orders are meant to wait and thus would give a misleading impression of the real throughput time and standing time. Weekends are excluded from the time performance measures, as the three DCs normally do not operate during this time. The capacity utilization of the gates is expressed as the percentage of time that the gates are in use for loading a carton or pallet onto a container or trailer. In this definition a gate is not in use when a loading unit is waiting but nothing is being loaded. An overview is also given of the amount of time per day that more than 90 % of the available gates are in use. The fill rate is expressed as the percentage of the maximum volume of a loading unit filled. The fill rate is measured for each DC and for palletized and non-palletized loading units separately. Load orders in the 'Warehouse On Wheels' and 'pack and hold' systems are included in the calculation of fill rates. A final output to compare the current and consolidation scenario is the number of loading units necessary for delivering all goods to their destination.

6.6 Consolidation through crossdock

In the crossdock scenario load orders from the three DC's destined for the same consolidator block are bundled. Consolidator blocks represent joint hub destinations. Figure 6.8 depicts the restrictions imposed on the possibility to bundle freight. First, load orders for certain export destinations are not sent through the crossdock. Pack lists for these export destinations have to be generated in advance and cannot be changed. Secondly, direct drops are treated in the shipping department of the three warehouses separately and not in the crossdock. These load orders are sent directly

Throughput time	Average
	Maximum
Standing time	Average
	Maximum
Capacity utilization gates	% time in use (avg and max)
	% time utilization > 90%
Fill rate	% of volume
	Per distribution centre
	Palletized or not
Number of loading units	

Table 6.2: Outputs measured in the case study analysis

to customer sites and therefore cannot be bundled with other load orders. Since the crossdock scenario does not yet exist, an assumption has to be made about the number of gates available in this future situation. The case study results presented in the next section are based on 30 gates in the crossdock and 5 gates remaining in the three separate DC's to handle load orders related to certain export destinations and direct drops.

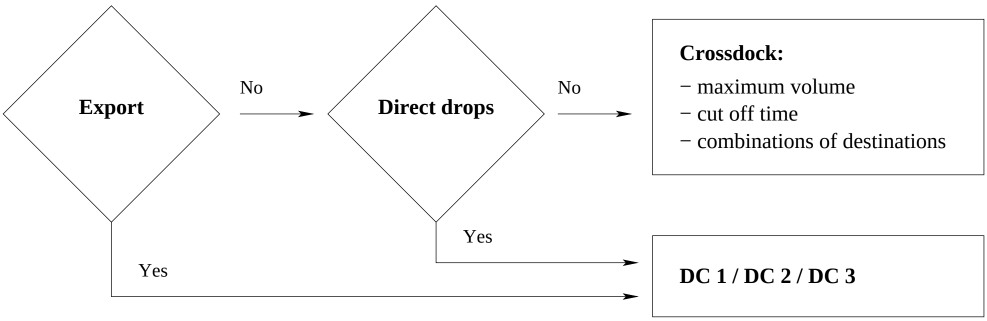

Figure 6.8: Consolidation restrictions

A volume of 2 m^3 per pallet is assumed when combining palletized and not palletized load orders. In the new crossdock loading units are filled to their maximum volume of 60 m^3. The cut off time of load orders is taken into account. Load orders are added to a loading unit when their cut off time matches the cut off time of load orders already assigned to the loading unit. Over the observed data period 34 consolidator blocks or destinations are served. A number of consolidator blocks may be combined in a single loading unit, as given in table 6.3. For example, destinations 10 and 11 may be combined in the same trailer or container.

10 / 11
13 / 14 / 15
16 / 23 / 24
17 / 18 / 19 / 20 / 21 / 34
1 / 26

Table 6.3: Combination of consolidator blocks

6.7 Case study results

In this section performance measures listed in table 6.2 are reported for the current scenario and consolidation scenario.

6.7.1 Throughput time and standing time of loading units

The throughput time of loading units is defined as the time between first and last order loaded onto the loading unit. When a loading unit is immediately loaded and so does not have to wait, this equals the sum of service times of its load orders at the gate. The standing time of loading units is described as the time during which loading units are waiting at the gate or on the parking area. The standing time thus equals the throughput time of a loading unit minus the total service time of all load orders assigned to the loading unit. When no goods are loaded onto the loading unit, it may be standing at the gate or on the parking area when all gates are necessary for loading other loading units. The average and maximum throughput time of loading units are presented in the upper part of figures 6.9a and 6.9b for the current and consolidation scenario. The lower part of these figures reports on the average and maximum standing times for the current and future situation. In the consolidation scenario the throughput time for the separate DC's refers to the loading units for certain export destinations and direct drops, which are excluded from consolidation as stated in the previous section.

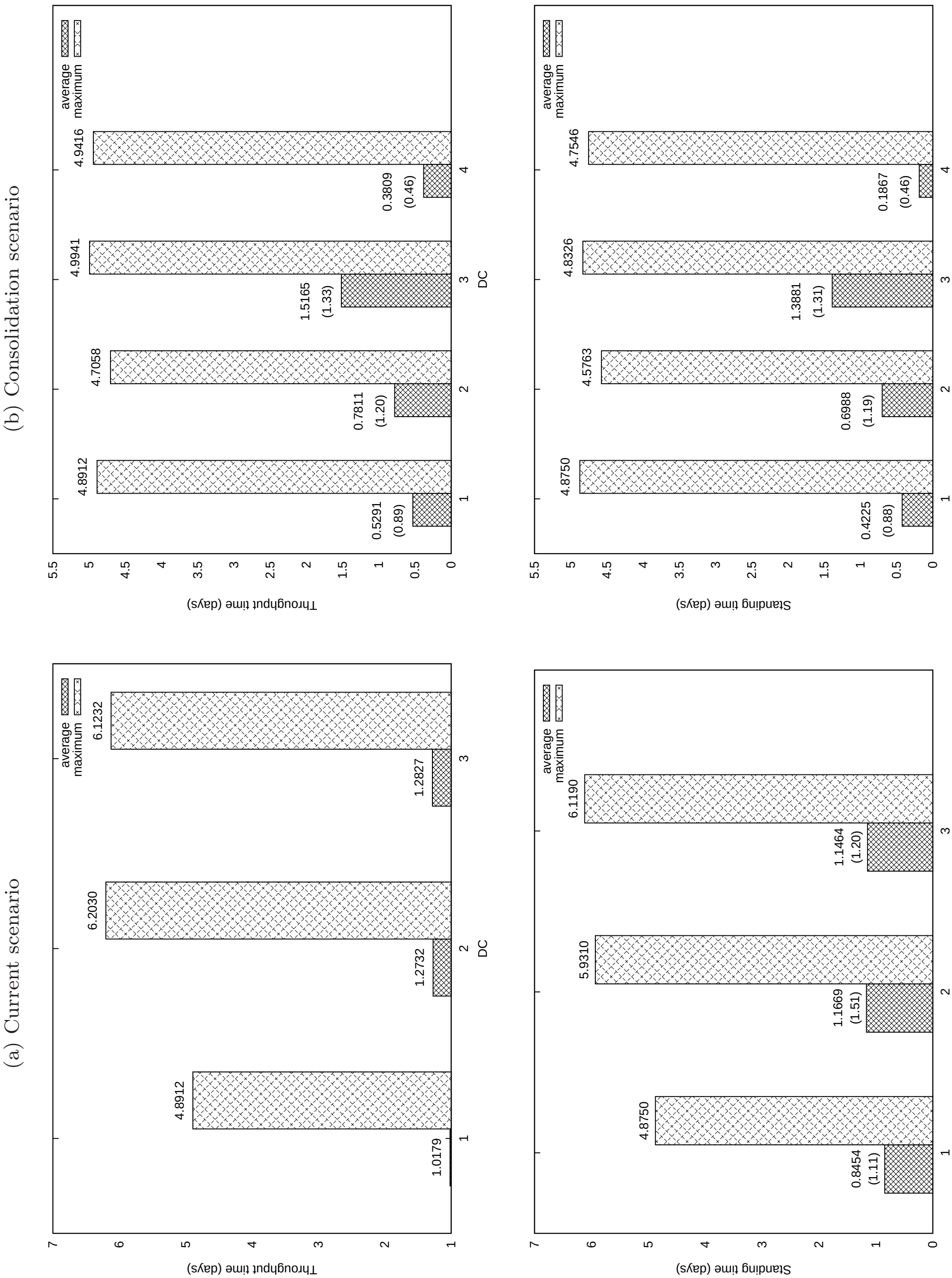

Figure 6.9: Throughput time and standing time of loading units

Results are expressed in days and weekends are not included. Loading units in the 'Warehouse On Wheels' and 'Pack and hold' system are also excluded from the throughput time, as explained in section 6.5. Figure 6.10 shows a histogram of throughput times of loading units in the current situation in order to determine possible outliers in the data set. The horizontal axis represents the throughput time expressed in number of days. The vertical axis gives the number of loading units with this throughput time in the current situation. Based on this graph outliers are defined as loading units with a throughput time of at least seven days. This results in the identification of nine outliers. These loading units are exceptions over the time frame of the data set and should not be taken into account in the case study analysis.

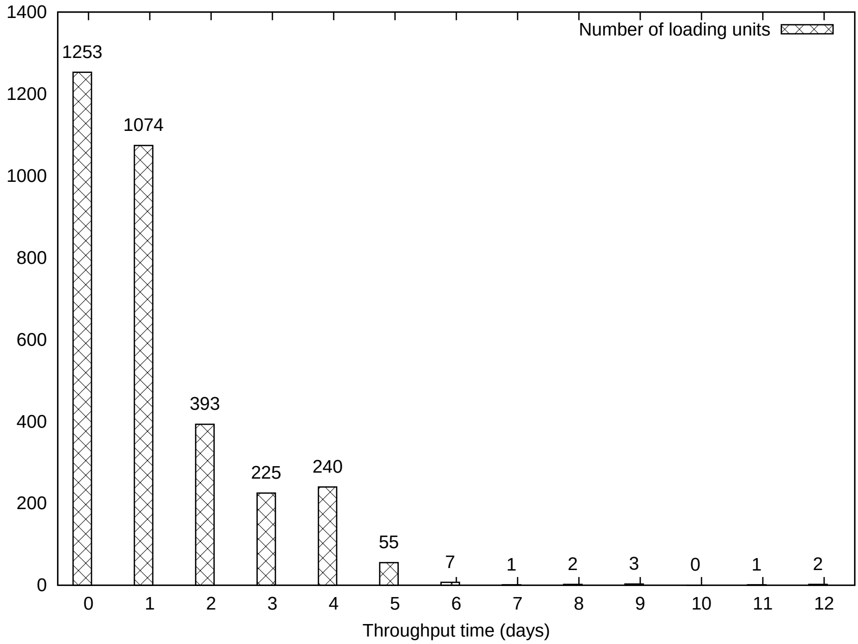

Figure 6.10: Histogram of throughput times in current scenario

A comparison of figure 6.9a and figure 6.9b shows a reduction in maximum throughput time of loading units of one day when consolidating freight and assuming the warehouse operations as given. The average throughput time over the time period of the data set also reduces from at least one day in the current scenario to 0.38 day or 9.14 hours in the consolidation scenario. The same reduction can be found in the figures on standing time of loading units. The loading of containers or trailers only takes up a very limited amount of time. Loading units spend most part of their time waiting on site. In figure 6.9b the standard deviation of throughput time is mentioned between brackets. Throughput times depend on the warehouse planning and operations. Considerable time may pass between the arrival in shipping of the first and last load order destined for the same loading unit. Time lags also occur between the arrival of the first and last carton of a single load order. However, through consolidation a reduction in throughput time of loading units may already be realized.

6.7.2 Capacity utilization of gates

An insight is gained in the utilization of available gates in each DC. The capacity utilization is the proportion of time that the gates are in use. This only includes the time during which a container or trailer is being loaded, not the time while a loading unit is just standing at the gate. The upper part of figures 6.11a and 6.11b report the average and maximum capacity utilization in the current scenario and consolidation scenario. The data period of ten weeks includes nights and weekends, which are retained in the performance measures on capacity utilization. Weekends and nights account for respectively 28 % and 23.8 % of total time.

Results of the current scenario show that the 17 available gates in DC 2 are at most used for 82 %. In DC 1 and DC 3 available gates are fully occupied during peak periods but on average only 19% of the available capacity in DC 3 and 18% of the available capacity in DC 1 are loading a container or trailer. Capacity is still available during daily non-peak periods or during night and weekend shifts. Capacity utilization in the consolidation scenario depends on the assumptions made on the number of gates. The crossdock disposes of 30 gates and 5 gates in each DC are available for handling certain export load orders and direct drops. The assumed capacity level is sufficient to deliver the same service level as in the current situation. Capacity gains could also be realized through a shift to non peak periods. In the lower part of figures 6.11a and 6.11b, three categories of capacity utilization are defined. The figures report on the percentage of time utilization equals zero, lies between zero and 90% and is greater than 90% in the current and consolidation scenario. These figures give a deeper insight in the amount of time the available gates are intensively used. Zero utilization may include weekends and nights. In the time period of the data set a limited night shift was operated in DC 1 and DC 3. Calculated results show that in the current and future situation during only a very limited proportion of time capacity utilization is higher than 90%. In the current scenario gates in the DC 3 display the highest utilization, while most capacity is still available in DC 2. In the future crossdock 30 gates are sufficient and are almost never fully occupied.

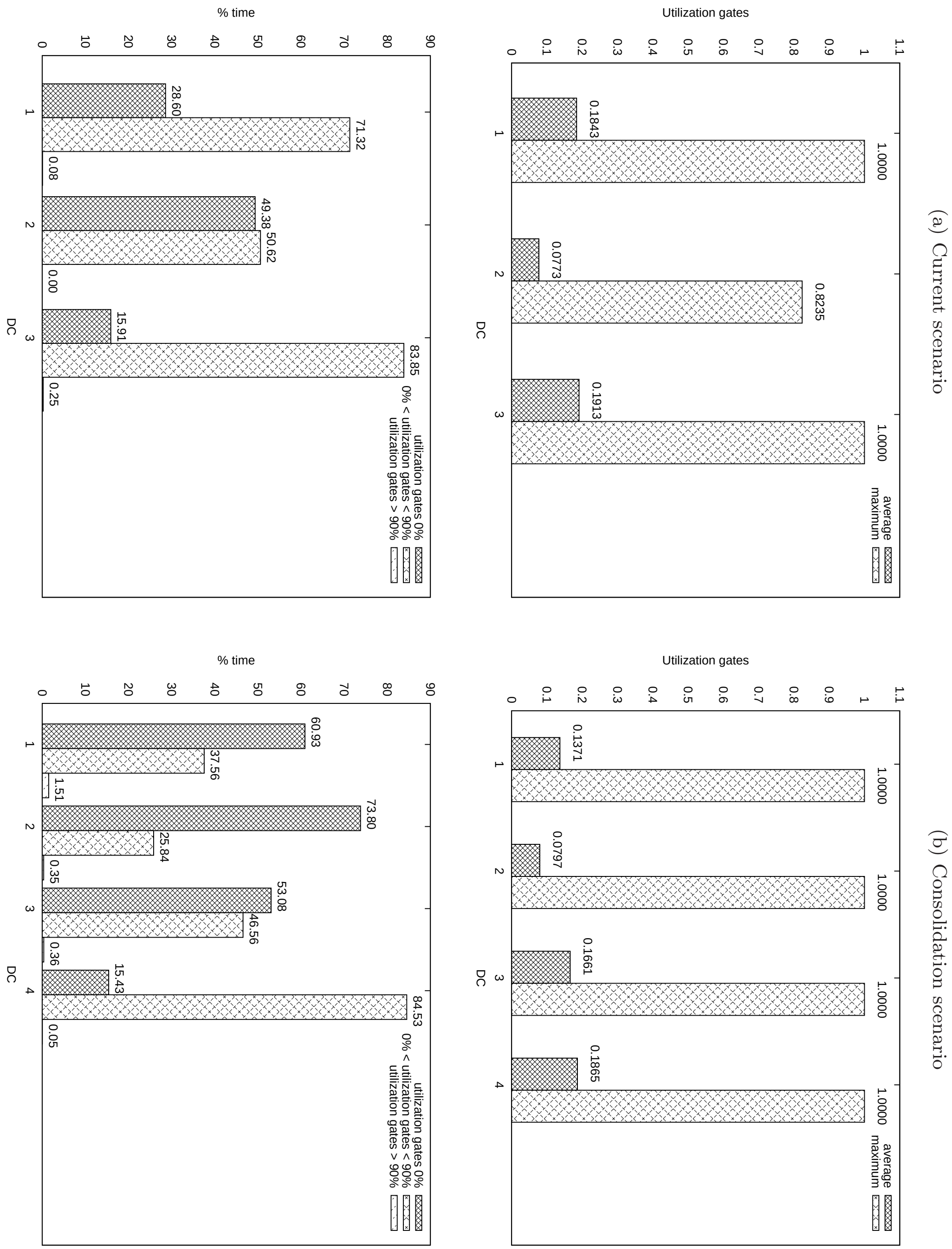

Figure 6.11: Performance measures related to capacity utilization of gates

6.7.3 Fill rate of loading units

Considering the type of goods, the fill rate is calculated based on volume. The maximum volume for loading units is set equal to 60 m^3. Load orders related to 'Warehouse On Wheels' and 'pack and hold' are included in the calculation of this performance measure. In figure 6.12a the average fill rates in the three DC's are given for the current scenario. A further distinction is made between palletized and non palletized goods. In the current situation coloading between the three DC's already occasionally exists on an ad hoc basis. Figure 6.12a shows the results without taking these loading units with coloading into account. Firstly, a difference in fill rate is noted between palletized and non palletized goods in all three DC's. Secondly, fill rates in DC 2 are lower than in the other two DC's, offering opportunities for bundling freight. Figure 6.12b illustrates the same performance measures for the consolidation scenario. The average fill rate in the crossdock increases to 74%. In particular an increase in fill rate of palletized goods is observed. The separate DC's in figure 6.12b represent loading units for certain export destinations or direct drops.

A further comparison between the current scenario and consolidation scenario is presented in figure 6.12c. The fill rates averaged over all load orders in the three DC's are calculated for three situations. First, the average fill rate over the observed period is given for the current situation excluding the ad hoc coloading of load orders between DC's. Secondly, the ad hoc coloading is taken into account to see the impact on the fill rate in the current situation. These two variations of the current situation are compared with the average fill rate in the consolidation scenario. The fill rate is subdivided for palletized and non palletized goods. Figure 6.12c demonstrates that the ad hoc coloading operations already increase the average fill rate with 3.38%. When consolidating load orders in a crossdock, the fill rate further improves with 4.76%. A large increase in fill rate is noted in palletized goods, from 45.69% to 59.67%, since palletized and non palletized load orders are combined in the consolidation scenario. Results presented are based on the assumption that the current warehouse planning and operations are given. A further improvement in fill rates could be obtained by taking consolidation opportunities in the warehouse planning and operations into account.

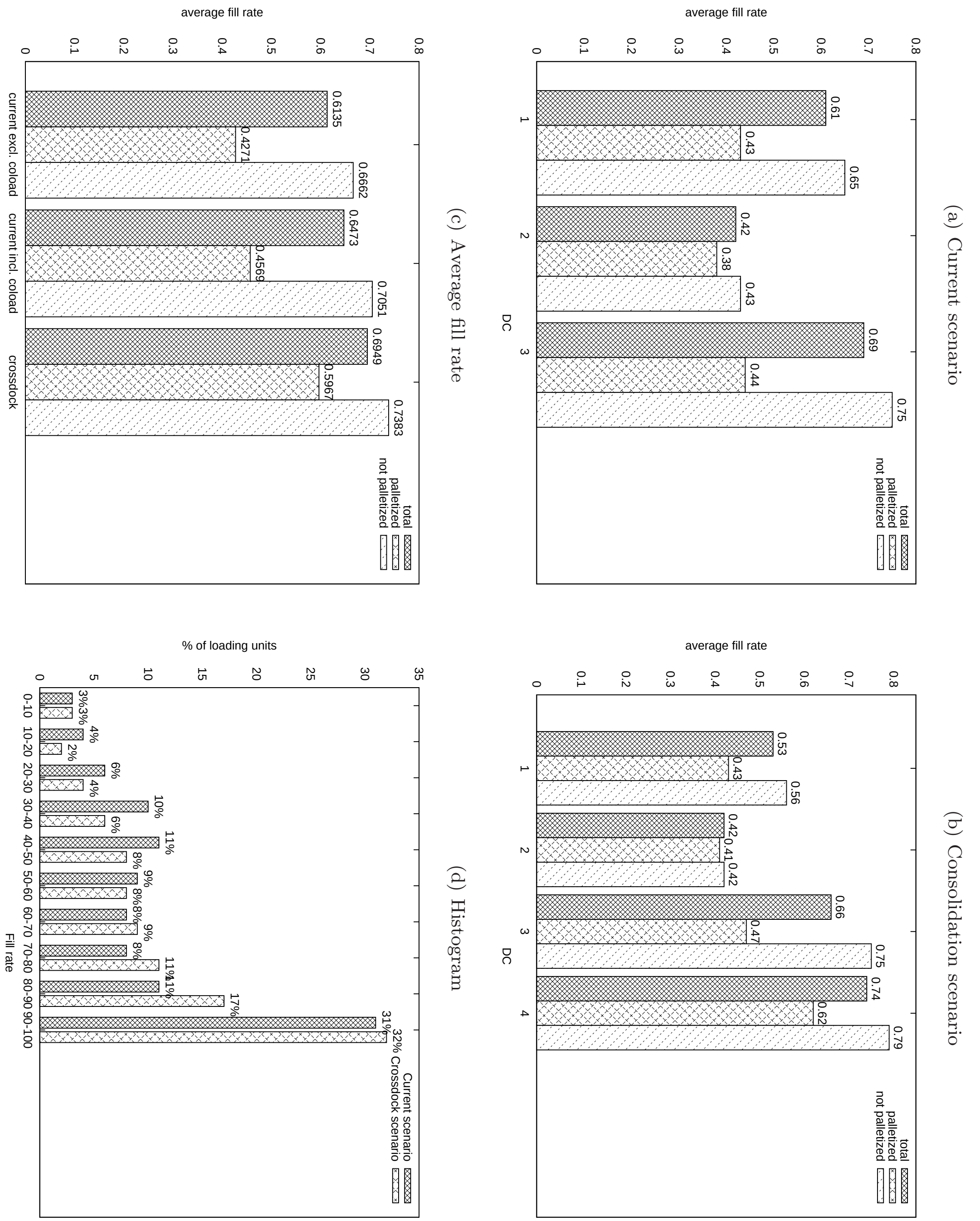

Figure 6.12: Performance measures related to fill rate

A histogram of fill rates is constructed in figure 6.12d to gain a deeper insight in the change between the current and consolidation scenario. On the horizontal axis ten categories of fill rates are shown. The vertical axis represents the proportion of containers or trailers that have a fill rate in this category. For example, in the current situation 10% of all loading units have a fill rate between 30% and 40%, whereas in the consolidation scenario only 6% of all loading units have a fill rate in this category. From figure 6.12d can be deducted that 34% of all loading units are less than 50% filled in the current scenario. This proportion decreases to 23% of all loading units that are less than 50% filled in the consolidation scenario over the time period of the data set.

6.7.4 Number of loading units

A final performance measure to evaluate the opportunities of consolidation between the three DC's is the number of loading units necessary for each (combination of) consolidator block(s). Table 6.4 lists in the second and third column the number of loading units deployed to service each destination. The fourth and fifth column give the number and percentage of loading units reduced. The table is sorted in decreasing order of share in total amount reduced, as stated in the last column. For example, the largest reduction in number of loading units is realized by combining load orders for destinations 17/18/19/20/21/34, which may be combined (see table 6.3) since they are all served by the same carrier. Some destinations demonstrate a small increase in the number of loading units due to the fact that in the given data set combinations of consolidator blocks were occasionally made which may not be combined in a standard way and thus are not combined in the consolidation scenario. In the crossdock scenario 2759 loading units are needed instead of 2966 loading units in the current scenario. Clustering freight thus leads to a total reduction of 207 loading units over a period of ten weeks.

A further understanding of the consolidation opportunities in the crossdock scenario is generated in table 6.5. For each destination the second column gives the number of loading units that go through the crossdock, thus excluding direct drops and certain export destinations. The third column mentions the number of loading units that contain load orders originating from at least two DC's. The last column expresses the percentage of all loading units that contain coload of at least two DC's. Table 6.5 is sorted in decreasing order of the percentage of loading units containing coload.

Consolidator block	**Current**	**Crossdock**	**Number reduced**	**% reduced**	**% total reduced**
17 / 18 / 19 / 20 / 21 / 34	798	742	56	7%	27%
10 / 11	183	149	34	19 %	16 %
16 / 23 / 24	144	117	27	19 %	13 %
25	121	96	25	21 %	12 %
5	92	69	23	25 %	11 %
27	135	118	17	13 %	8 %
30	219	208	11	5 %	5 %
6	117	108	9	8 %	4 %
32	99	91	8	8 %	4 %
28	52	44	8	15 %	4 %
33	50	46	4	8 %	2 %
9	241	238	3	1 %	1 %
8	60	59	1	2 %	0 %
13 / 14 / 15	69	68	1	1 %	0 %
2	54	54	0	0 %	0 %
3	32	32	0	0 %	0 %
31	7	7	0	0 %	0 %
4	21	22	-1	-5 %	0 %
7	33	34	-1	-3 %	0 %
22	97	98	-1	-1 %	0 %
1 / 26	294	300	-6	-2 %	-3 %
29	48	59	-11	-23 %	-5 %
Total	2966	2759	207		100%

Table 6.4: Comparison of number of loading units in current and consolidation scenario

Consolidator block	**Total nb loading units**	**Total nb coload**	**% coload**
25	86	83	97 %
10 / 11	148	137	93%
17 / 18 / 19 / 20 / 21 / 34	472	434	92%
16 / 23 / 24	100	90	90%
29	29	26	90%
27	117	104	89%
5	67	59	88%
28	40	35	88%
30	206	178	86%
1 / 26	273	224	82%
4	22	18	82%
13 / 14 / 15	53	42	79%
6	42	33	79%
7	34	25	74%
9	237	167	70%
22	8	3	38%
8	2	0	0%
33	1	0	0%
2	0	0	0%
3	0	0	0%
31	0	0	0%
32	0	0	0%

Table 6.5: Percentage of loading units with coloading in consolidation scenario

6.8 Conclusions

This chapter investigates clustering of freight at the operational decision level. The fill rate of loading units may be improved by consolidating freight of shippers inside a loading unit. A higher fill rate implies a better utilization of transport equipment. This may on the one hand reduce the costs of pre- and end-haulage by road or on the other hand increase the attractiveness of intermodal freight transport for further continental distribution. Potential benefits of shipper consolidation are quantified for a real life case study, consisting of three distribution centres. The following conclusions can be drawn from the case study results. First, the organization of a crossdock to consolidate freight of multiple shippers may lead to a reduction in average and maximum standing time of loading units over the observed time period. The standing time depends on the warehouse planning and operations. Considerable time may pass between the arrival in shipping of the first and last load order destined for the same loading unit. Time lags also occur between the arrival of the first and last carton of a single load order. However, through consolidation a reduction in throughput time and standing time of loading units may already be realized. Second, case study results show that the available gates are used at full capacity during only a limited period per day. Capacity gains can be realized through a shift to non peak periods. In the current scenario gates in DC 3 display the highest utilization, while most capacity is still available in DC 2. The assumptions made in the crossdock scenario about the number of available gates suffice to deliver the same service level in shipping, although in total fewer gates are required than in the current situation. The third performance measure to evaluate the consolidation scenario is the fill rate of loading units. The consolidation scenario leads to an increase of 4.76% in the average fill rate over all load orders in all three DC's. Fill rates in DC 2 are lower than in the other two DC's, offering opportunities for bundling freight. The percentage of loading units filled less than half reduces to 23% in the consolidation scenario instead of 34% in the current scenario. The crossdock also offers the opportunity to increase the fill rate of loading units containing pallets. Finally, the consolidation scenario leads to a reduction in number of loading units necessary over the observed period. Results show the opportunities of bundling freight without a change in planning. In both scenarios the warehouse planning and operations are assumed to be given. Further improvements in performance measures would be possible with the introduction of smart planning rules aimed at taking maximum advantage of consolidation opportunities. The case study results demonstrate that shipper consolidation is an interesting concept for further research. Relationships between customer demand, warehouse planning and shipping operations also need to be explored. Finally, consolidation of freight and the organisation of a crossdock imply managerial changes. A revision of business models may be necessary.

Chapter 7

Pre- and end-haulage at intermodal container terminals: a local search approach

7.1 Introduction

This chapter[1] discusses the pre- and end-haulage by road of containers handled by an inland intermodal barge terminal. Pre- and end-haulage by road represents an operational planning problem in intermodal transport, as indicated in figure 7.1. Road transport constitutes a relatively large share of intermodal transport costs. This is mainly due to empty vehicle movements. Morlok and Spasovic (1994) argue that a central planning could lead to considerable cost reductions in the pre- and end-haulage of intermodal containers. The attractiveness of intermodal transport may thus be increased by organizing the road segment in the intermodal transport chain more efficiently. To this end, a local search heuristic is presented in this chapter.

Pre- and end-haulage of intermodal barge terminals involves the pickup or delivery of containers by road at customer locations. Few research has been conducted on intermodal drayage operations. In this chapter the drayage of containers in the service area of an intermodal terminal is modelled as a Full Truckload Pickup and De-

[1] This chapter is based on Caris and Janssens (2009).

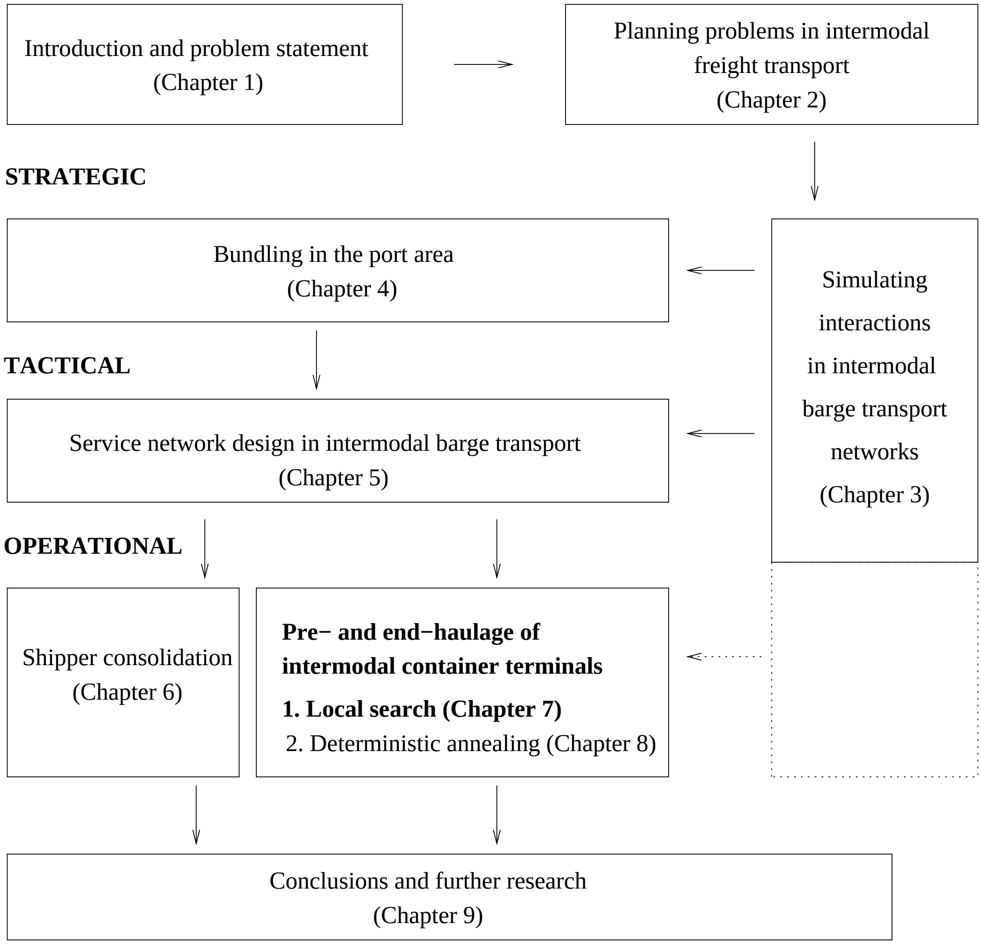

Figure 7.1: Outline of the thesis - Chapter 7

livery Problem with Time Windows (FTPDPTW). Savelsbergh and Sol (1995) review the general Pickup and Delivery Problem (PDP). The Pickup and Delivery Problem (PDP) is an extension to the classical Vehicle Routing Problem (VRP) where customers may both receive and send goods. A fleet of vehicles is required to pickup and/or deliver goods at customer locations. As depicted in figure 7.2, a delivery activity to a consignee starts from the intermodal terminal with a full container and a pickup activity returns a container to the intermodal terminal for shipment by barge. In the Full Truckload Pickup and Delivery Problem (FTPDPD) a vehicle carries a single load. In the operational planning problem under investigation, a full truckload is assumed to be a single container. Hard time windows are imposed at customer locations. A time window represents the time interval in which the service at a customer must start. When a time window is hard, late services are not allowed. The vehicle must arrive before the latest possible service time at each customer location. Time constraints may also be related to vehicles. In reality vehicles are not available all the time. In this case a time window refers to the time interval in which the vehicle is available.

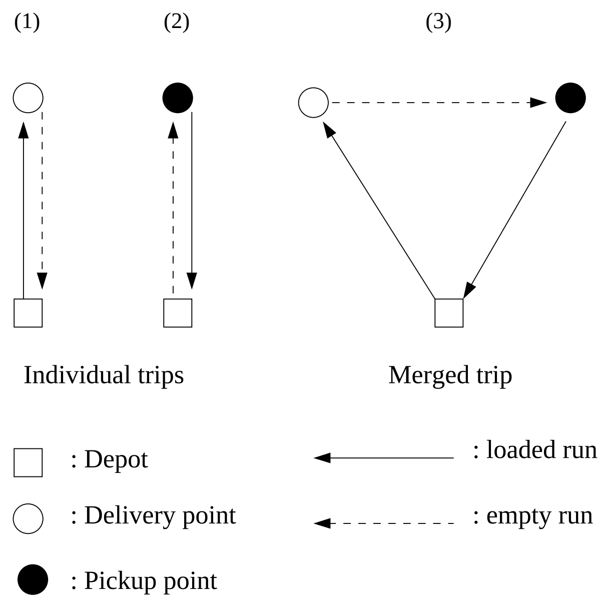

Figure 7.2: Merging trips

The organization of this chapter is as follows. Section 7.2 provides an overview of related problems in literature. The problem formulation is given in section 7.3. A lower bound on the optimal solution is presented in section 7.4. In section 7.5 a two-phase insertion heuristic is proposed. Section 7.6 discusses an improvement heuristic based on three local search operators. A small numerical example is given in section 7.7 to demonstrate the mechanism of the construction and improvement heuristics. A numerical example of realistic problem size is discussed in section 7.8. Numerical experiments are conducted in section 7.9 to test the effectiveness of the algorithms on eight problem classes, which differ with respect to three problem characteristics. Five problem instances are generated in each problem class, leading to 40 problem instances on which the heuristic procedure is tested. Finally, the impact of different values for a specific parameter in the construction heuristic is analysed.

7.2 Related literature

Desrochers et al. (1990) developed an elaborate classification scheme for vehicle routing problems in order to bring some uniformity in literature on the subject. Their classification language uses four fields to describe a particular occurrence of the VRP. The first field describes characteristics and constraints that are relevant to addresses (i.e. customers and depots). The second field specifies characteristics relevant to vehicles. In the third field all problem characteristics that cannot be identified with addresses or vehicles are described. Finally, the fourth field defines one or more objective functions. A PDP is an extension to VRP in the sense that it bears a number of typical characteristics relevant to addresses. For example, the first field of the classification scheme specifies the location of the demand. The default value refers to customers situated on nodes of a network. The authors use the value 'TASK' (task routing) to indicate the case in which each customer corresponds to an origin-destination pair. The load is picked up at an origin address and delivered to a destination address. When the assumption is made that all goods either originate from or end up at a depot, as in intermodal drayage operations studied in this chapter, a PDP is characterized in another way. The first field in the classification scheme indicates whether or not all demands are of the same type. For this kind of PDP, demands can be either pickup requests or delivery requests. Consequently, this problem is classified as a VRP with 'mixed deliveries and collections'. In the third field of the classification scheme, several service strategies are specified. The authors describe a strategy for the case of node routing with mixed deliveries and collections, i.e. delivering first to empty the vehicle and then collecting loads on the way back to the depot.

Another classification of PDP is given by Nagy and Salhi (2005). The authors describe three types of models: delivery-first pickup-second PDP, mixed pickups and deliveries and simultaneous pickups and deliveries. In the first model type a vehicle can pick up goods only after its complete load has been delivered. The underlying assumption is that it may be difficult to re-arrange delivery and pickup goods on the vehicle. The second model allows pickups and deliveries in any sequence on a vehicle route. In these two models customers are divided into linehauls (customers receiving goods) and backhauls (customers sending goods). When the assumption is made that all goods have to either originate from or end up at a depot, the first two models are jointly referred to as the vehicle routing problem with backhauling. In the final model customers may simultaneously receive and send goods.

A recent overview of state-of-the-art research on pickup and delivery problems between customers and a depot is presented by Parragh et al. (2008). Only less-than-truckload problems are covered by the authors. Less-than-truckload PDP may also be formulated for planning problems where goods need to be transported between pickup and delivery locations. Dumas et al. (1991) present an exact solution for this class of PDP based on column generation. Heuristic solutions can be found in Nanry and Barnes (2000), Landrieu et al. (2001), Lu and Dessouky (2006) and Bent and Van Hentenryck (2006).

The pre- and end-haulage of intermodal barge terminals studied in this chapter involves the transportation of full truckloads. Gronalt et al. (2003) study the problem of transporting full truckloads between distribution centres. In their Pickup and Delivery Problem with Time Windows (PDPTW) goods are transported between customer locations, as opposed to our problem definition where all containers either originate or return to the terminal. A full truckload PDPTW is also considered by Currie and Salhi (2003, 2004). The problem studied in these papers also differs from our setting with respect to the definition of customer requests. Goods have to be picked up at works of a construction company and delivered to customers. The literature study of planning problems in intermodal freight transport presented in chapter 2 mentions only three papers dealing with the operational planning of a drayage operator. Wang and Regan (2002) propose a hybrid approach to solve a PDP containing one or more intermodal facilities. Only pickup time windows are considered and the number of vehicles is fixed. The authors apply time window discretization in combination with a branch and bound method. Francis et al. (2007) model intermodal drayage operations as a multi-resource routing problem (MRRP) in which two resources (tractors and trailers) perform tasks to transport loaded and empty equipment. The authors introduce the concept of flexible tasks for which the origin or destination is not defined. A randomized solution method, called the Greedy Randomized Procedure, is proposed to solve the resulting problem. The closest related article to our research is written by Imai et al. (2007). The authors present a heuristic based on Lagrangian relaxation for the drayage problem of intermodal container terminals. In the pre- and end-haulage of intermodal containers substantial cost and time savings may be realized by merging pickup and delivery customers in a single trip, as presented in figure 7.2. Imai et al. (2007) combine customers' sites into pairs in a first stage and assign trucks to these merged trips in a second stage. In this chapter, this idea is extended with the introduction of time windows at customer locations and at the depot.

7.3 Problem definition

The FTPDPTW can be formulated in terms of a Vehicle Routing Problem with full container load. Assuming a homogeneous container type and size, the problem is to find an assignment of delivery and pickup customer pairs to a fleet of vehicles, in order to minimize the total cost of serving all customers, which includes fixed vehicle costs and travelling costs. In accordance with Dumas et al. (1991), a fixed vehicle cost is introduced to minimize the fleet size. Each vehicle used incurs a fixed cost, which may vary with the vehicle. Fixed costs include depreciation of own vehicles or leasing costs if the vehicle is hired, insurance payments and fixed costs for hiring an extra truck driver. Travelling costs are proportional to the total time necessary to serve all customers, which implies travelling time and truck waiting time at customer sites. A description of objective functions found in pickup and delivery problems is presented by Savelsbergh and Sol (1995). The two most common objective functions are the minimization of route length and the minimization of route duration. The first objective minimizes the total distance travelled, whereas the second minimizes the total time needed to execute the routes, including travel times, waiting times, loading and unloading times and break times. Alternative objectives are the minimization of client inconvenience, measured for example as the difference between the desired pickup or delivery time and the actual pickup or delivery time, or the maximization of profit. The latter is used when a transportation request may be rejected. In this chapter the minimization of route duration is chosen due to the existence of time windows. Route duration is translated into travelling costs, to add to fixed vehicle costs.

All orders are assumed to be known in advance, so the problem is studied in a static environment. An intermodal terminal is open during a pre-specified daily time window. All trucks k have to return to the terminal before the end of their depot window $(0, T_k)$. Hard time windows at customer locations are assumed. A solution for the FTPDPTW is a set of routes assigned to a set of trucks K. The FTPDPTW is defined on a graph $G = (V_0, A)$, where V_0 represents the node set. V is the set of all customers, V^D is the set of delivery customers, V^P is the set of pick-up customers and $\{0\}$ is the singleton representing the depot.

$$V_0 = V \cup \{0\}$$
$$V = V^D \cup V^P$$
$$V^D \cap V^P = \varnothing$$

The set of links A in the exact problem formulation consists of two types of connections. Links either connect the depot with a customer location or provide a connection between two customer locations. Feasible vehicle routes correspond to paths starting at the depot 0, travelling through links connecting customer locations and returning to the depot 0. Only at the beginning and at the end of a route a link is used in the network formulation to connect a customer location with the depot. The exact problem formulation does not make an explicit distinction between pickup and delivery customers. Instead, the logic of pickup and delivery customers is incorporated in the definition of travel times d_{ij} of links between customer locations. The travel time d_{ij} of links between two customer locations depends on the type of customers served. Four combinations of customers exist: first a delivery then a pickup customer, two delivery customers consecutively, two pickup customers consecutively or first a pickup and then a delivery customer. Only when a pickup customer is served after a delivery customer a truck can drive directly from one customer location to the other. The travel time d_{ij} equals the time necessary to move directly from the delivery customer to the pickup customer, denoted as t_{ij}.

$$d_{ij} = t_{ij}$$

In the other three customer combinations, in a real-life situation, the truck first has to return to the depot before serving the second customer. In this case the travel time d_{ij} on the virtual link between both customer locations is set equal to the time necessary to go from the first customer to the depot and then from the depot to the second customer.

$$d_{ij} = t_{i0} + t_{0j}$$

By incorporating the pickup and delivery information in the distances of links, the problem can be modelled as a vehicle routing problem with time windows (VRPTW), as described by Cordeau et al. (2007). A review of formulations for the vehicle routing problem with time windows is given by Kallehauge (2008). To formulate the problem the following notation is used:

V = set of customers
V_0 = set of nodes, representing customers and terminal 0
V^D = set of delivery customers
V^P = set of pick-up customers
K = set of trucks (index k)
C_{ijk} = travelling cost of link (i, j) by truck k
FC_k = fixed cost of truck k for a single route

E_i = earliest start time of customer i
L_i = latest start time of customer i
s_i = service time of delivery i
d_{ij} = travel time on link connecting customer i with customer j
T_k = time capacity of truck k
t_{0j} = travel time from terminal 0 to customer j
t_{ij} = travel time directly from delivery i to pickup j
t_{i0} = travel time from customer i to terminal 0.

The decision variables are defined as:
x_{ijk} = 1 if customer i and customer j are served consecutively by truck k, 0 else
b_i = actual time service at customer i begins.

$$Min \sum_{i \in V_0} \sum_{\substack{j \in V_0 \\ i \neq j}} \sum_{k \in K} C_{ijk} x_{ijk} + \sum_{k \in K} (FC_k \sum_{j \in V} x_{0jk})$$

subject to

$$\sum_{j \in V_0} \sum_{k \in K} x_{ijk} = 1 \qquad \forall i \in V \tag{7.1}$$

$$\sum_{i \in V_0} x_{ijk} - \sum_{i \in V_0} x_{jik} = 0 \qquad \forall j \in V, k \in K \tag{7.2}$$

$$E_i \leq b_i \leq L_i \qquad \forall i \in V \tag{7.3}$$

$$\sum_{k \in K} x_{ijk} \cdot (b_i + s_i + d_{ij} - b_j) \leq 0 \qquad \forall i, j \in V \tag{7.4}$$

$$\sum_{k \in K} x_{0jk} \cdot d_{0j} \leq b_j \qquad \forall j \in V \tag{7.5}$$

$$x_{i0k} \cdot (b_i + s_i + d_{i0} - T_k) \leq 0 \qquad \forall i \in V, k \in K \tag{7.6}$$

$$\sum_{j \in V} x_{0jk} \leq 1 \qquad \forall k \in K \tag{7.7}$$

$$x_{ijk} \in \{0, 1\} \qquad \forall i, j \in (V_0), \; i \neq j, k \in K \tag{7.8}$$

$$b_i \geq 0 \qquad \forall i \in V \tag{7.9}$$

The objective function minimizes total costs of serving all customers. A fixed vehicle cost FC_k is incurred for each truck k used. The variable cost C_{ijk} represents the cost of serving customer j immediately after customer i, depending on the travel time and possibly waiting time. The latter occurs when a pickup customer is served directly after a delivery customer. Constraints (7.1) ensure that each customer is visited exactly once. Flow conservation is enforced by constraints (7.2). Time windows at customer locations are stated in the third set of constraints (7.3). Expressions (7.4) and (7.5) enforce the consistency of time variables b_i. Hard time windows are also imposed on the total service time of a route k by constraints (7.6). Constraints (7.7) guarantee that each vehicle is used at most once. Finally, constraints (7.8) and (7.9) define the domain of the decision variables.This formulation is nonlinear because of constraints (7.4) and (7.6). Constraints (7.4) can be linearized as follows:

$$b_i + s_i + d_{ij} - (L_i + s_i + d_{ij} - E_j) \cdot (1 - \sum_{k \in K} x_{ijk}) \leq b_j \qquad \forall i, j \in V.$$

If customers i and j are not visited in the same trip, this expression reduces to:

$$b_j - E_j \geq b_i - L_i.$$

This inequality is always satisfied since the left-hand side is positive and the right-hand side is negative. Constraints (7.6) can be linearized in a similar way:

$$b_i + s_i + d_{i0} - (1 - x_{i0k}) \cdot (L_i + s_i + d_{i0}) \leq T_k \qquad \forall i \in V, \forall k \in K.$$

7.4 Lower bound

The VRP belongs to the class of NP-hard problems. Exact models are only able to solve relatively small problems. It seems that no exact algorithm is capable of consistently solving instances in excess of 50 customers (Cordeau et al. 2002). Heuristics are used in practice to solve problems of realistic size. A lower bound is proposed to analyse the performance of the heuristics presented next. According to Cordeau et al. (2007), the LP relaxation of the VRPTW provides a weak lower bound. An alternative formulation is given in this section to be able to calculate a better lower bound for the optimal solution. In the lower bound formulation delivery customers are always indicated with index i and pickup customers with index j, whereas in the exact formulation (formulation (7.1) - (7.9)) no distinction is made between pickup and delivery customers. In the exact formulation the difference between pickup and

delivery customers is incorporated in the distances d_{ij} of the links connecting customers. The lower bound formulation explicitly makes a difference between pickup and delivery customers, which leads to a FTPDPTW formulation. Each route k consists of a number of trips executed by a single truck k within the depot time window $(0,T_k)$. A *trip* is defined as an activity consisting of a sequence of tasks. Three types of sequences are depicted in figure 7.2: (1) travel from depot to a delivery customer i, delivery service, and travel from delivery customer to depot; (2) travel from depot to a pickup customer j, pickup service, and travel from pickup customer to depot; (3) travel from depot to a delivery customer i, delivery service, travel from delivery customer to pickup j customer, pickup service, and travel from pickup customer to depot. Let a trip be represented as a pair (i,j) where i represents a delivery customer and j a pickup customer. Pickup and delivery customers can be combined or can be served separately. In the case only a delivery customer belongs to a trip, the pair is written as $(i,0)$. If only a pickup customer belongs to the trip, the pair is written as $(0,j)$. In the latter two cases either the delivery point or the pickup point is represented by the depot 0. This leads to the following alternative notation. All other symbols should be interpreted as in the exact problem formulation.
$V_0^D = V^D \cup 0$ = set of delivery points including the depot 0 (index i)
$V_0^P = V^P \cup 0$ = set of pickup points including the depot 0 (index j)
CR_{ijk} = cost of performing trip (i,j) by truck k
RS_{ij} = time necessary to serve pair (i,j)
E_i = earliest start time of delivery i
L_i = latest start time of delivery i
E_j = earliest start time of pickup j
L_j = latest start time of pickup j
t_{0i} = travel time from terminal 0 to delivery i
t_{j0} = travel time from pickup j to terminal 0
s_i = service time of delivery i
s_j = service time of pickup j

In this formulation the decision variables are:
$x_{ijk} = 1$ if delivery i and pickup j are served in one trip by truck k, else 0
$y_k = 1$ if truck k is used, else 0
b_i = actual time delivery i begins
b_j = actual time pickup j begins.

$$Min \sum_{i \in V_0^D} \sum_{\substack{j \in V_0^P \\ i+j \neq 0}} \sum_{k \in K} CR_{ijk} x_{ijk} + \sum_{k \in K} FC_k y_k$$

subject to

$$\sum_{i \in V_0^D} \sum_{k \in K} x_{ijk} = 1 \qquad \forall j \in V^P \tag{7.10}$$

$$\sum_{j \in V_0^P} \sum_{k \in K} x_{ijk} = 1 \qquad \forall i \in V^D \tag{7.11}$$

$$x_{ijk} \leq y_k \qquad \forall i \in V_0^D, j \in V_0^P, i + j \neq 0, k \in K \tag{7.12}$$

$$E_i \leq b_i \leq L_i \qquad \forall i \in V^D \tag{7.13}$$

$$E_j \leq b_j \leq L_j \qquad \forall j \in V^P \tag{7.14}$$

$$\sum_{k \in K} x_{ijk} \cdot (b_i + s_i + t_{ij} - b_j) \leq 0 \qquad \forall i \in V^D, j \in V^P \tag{7.15}$$

$$\sum_{i \in V_0^D} \sum_{j \in V_0^P} RS_{ij} \cdot x_{ijk} \leq T_k \qquad \forall k \in K \tag{7.16}$$

$$x_{ijk} \in \{0, 1\} \qquad \forall i \in V_0^D, j \in V_0^P, k \in K \tag{7.17}$$

$$y_k \in \{0, 1\} \qquad \forall k \in K \tag{7.18}$$

$$b_i, b_j \geq 0 \qquad \forall i \in V^D, j \in V^P \tag{7.19}$$

In the objective function the variable cost CR_{ijk} represents the cost of performing the complete trip (i, j) by truck k, including the costs incurred by truck k to leave and return to the depot. Equations (7.10) and (7.11) guarantee that all pickups and deliveries are visited only once. Constraints (7.12) link the x and y variables and avoid to assign customers to unused vehicles. Constraints (7.13), (7.14) and (7.15) are similar to constraints (7.3) and (7.4) in the exact formulation. Depot time windows are expressed by constraints (7.16). The time necessary to perform trip (i, j), RS_{ij}, is the sum of travel times, service times and a minimum waiting time $MINWAIT_{ij}$:

$$RS_{ij} = t_{0i} + t_{ij} + t_{j0} + s_i + s_j + MINWAIT_{ij}.$$

Due to the presence of time windows at customer locations, trucks may incur a waiting time when arriving at the pickup location. The minimum waiting time between delivery customer i and pickup customer j equals:

$$MINWAIT_{ij} = \begin{cases} 0 & \text{if } E_j \leq L_i + s_i + t_{ij} \\ E_j - (L_i + s_i + t_{ij}) & \text{else.} \end{cases}$$

In this formulation the feasibility of the routes is relaxed. If two trips share the same resource (the same vehicle), it is not ensured that the time intervals over which both trips require the resource do not overlap in time. Consequently the lower bound represents the variable costs of optimally combining delivery customers with pickup customers, but underestimates the number of vehicles necessary to perform the selected trips. A similar approach for calculating a lower bound is proposed by Currie and Salhi (2003). The authors relax either the integrality constraints or time window constraints to evaluate their heuristics. The lower bound formulation leads to fewer constraints and variables and thus the problem converges faster to an integer solution. The solution of the relaxed problem gives a lower bound to the exact formulation in section 7.3. The lower bound is obtained using LINGO 10.0 software.

7.5 Two-phase insertion heuristic

Combining the service of pickup and delivery customers may lead to cost and time reductions, as presented in figure 7.2. A heuristic procedure based on merging pickup and delivery customers in a single trip is used to construct initial solutions. An insertion heuristic is developed which consists of two phases. In a first phase pickups and deliveries are combined into pairs. These pairs of customers are inserted into routes in a second phase. The initial solutions generated by the insertion heuristic are further improved with three local search neighbourhoods defined in section 7.6. As the heuristic algorithm is founded on the principle of merging pickup and delivery customers, the notation presented in section 7.4 is used in the following sections.

7.5.1 Phase 1: Pairing pickups and deliveries

Due to the existence of hard time windows, not every pickup customer and delivery customer can be combined into a feasible pair. Feasibility of time windows is checked first:

$$E_i + s_i + t_{ij} \leq L_j \qquad \forall i \in V^D, j \in V^P.$$

A list of feasible pairs with respect to time windows is drawn up. The heuristic limits the waiting time between delivery i and pickup j to a maximum amount $MAXWAIT$.

A feasible pair of customers is discarded from the list if the minimum waiting time $MINWAIT_{ij}$ is larger than allowed. This eliminates pairs of customers that are too far away from each other in time. A large waiting time between the delivery location and pickup location most probably is cost inefficient in road haulage. The combination of a pickup customer j and delivery customer i is allowed in a single trip only if:

$$MINWAIT_{ij} \leq MAXWAIT.$$

Second, interesting combinations of customers are selected. In forming pairs of pickups and deliveries, both spatial and temporal aspects are to be taken into account. The pairs of pickup and delivery customers are ranked according to two criteria: savings in travel time and time window slack. The savings in travel time obtained from serving delivery i and pickup j together should be as large as possible. The following expression for savings in travel time should be maximized:

$$(t_{i0} + t_{0j} - t_{ij}).$$

The time window slack between customers i and j should be as small as possible, which implies a minimization of:

$$(L_j - E_i - s_i - t_{ij}).$$

Both criteria are aggregated by making use of weights. The pair of pickup and delivery customers with the lowest value for the following criterion is selected first:

$$w_1 \cdot (L_j - E_i - s_i - t_{ij}) + w_2 \cdot (t_{ij} - t_{i0} - t_{0j}). \tag{7.20}$$

The weights w_1 and w_2 reflect the importance given to each criterion and serve as parameters of the insertion heuristic. The domain of the values of the weights is free. The ratio between the weights influences the importance of each criterion. Depending on the nature of the problem, more weight should be given to the savings in waiting time or the savings in travel time. The weights in the insertion heuristic are used to construct an initial solution. Numerical examples in section 7.8 will show that good solutions are found after applying the improvement heuristic described in section 7.6, independent of the value of these weights. The process of pairing customers is repeated until no further feasible combinations exist with respect to the remaining pickup customers and delivery customers. The remaining customers are served in individual trips and form an imaginary pair with a dummy customer.

A third criterion representing the opportunity cost for not choosing the best combination for a delivery i or pickup j can also be taken into account. Gronalt et al.

(2003) argue that this regret approach leads to significant improvements in the best heuristic solution found. The opportunity cost $OC1_i$ can be defined as the difference in savings in travel time achieved by the best pair for delivery i and the currently selected pair. The pickup customer j_{best} resulting in the largest savings in travel time is searched in the list of all possible combinations for delivery customer i. Travel time from the depot 0 to this pickup customer j_{best} is denoted $t_{0j_{best}}$ and from delivery i to pickup j_{best} as $t_{ij_{best}}$. The opportunity cost for a pickup customer ($OC1_j$) is calculated in a similar way.

$$OC1_i = (t_{0j_{best}} - t_{0j_{current}}) - (t_{ij_{best}} - t_{ij_{current}}),$$

$$OC1_j = (t_{i_{best}0} - t_{i_{current}0}) - (t_{i_{best}j} - t_{i_{current}j}).$$

The selection criterion (7.20), extended with this third objective, is formulated as:

$$w_1 \cdot (L_j - E_i - s_i - t_{ij}) + w_2 \cdot (t_{ij} - t_{i0} - t_{0j}) + w_3 \cdot (OC1_i + OC1_j). \qquad (7.21)$$

A similar approach may be applied with respect to the time window slack. The opportunity cost related to the time window slack is added to this extended selection criterion. This opportunity cost $OC2_i$ (respectively $OC2_j$) is defined as the difference between the time window slack of the current combination and the smallest time window slack of delivery i (pickup j) in any combination.

$$OC2_i = (L_{j_{current}} - L_{j_{best}}) - (t_{ij_{current}} - t_{ij_{best}}),$$

$$OC2_j = (E_{i_{best}} - E_{i_{current}}) + (s_{i_{best}} - s_{i_{current}}) + (t_{i_{best}j} - t_{i_{current}j}).$$

This results in the following selection criterion:

$$w_1 \cdot (L_j - E_i - s_i - t_{ij}) + w_2 \cdot (t_{ij} - t_{i0} - t_{0j}) + w_3 \cdot (OC1_i + OC1_j) + w_4 \cdot (OC2_i + OC2_j). \qquad (7.22)$$

7.5.2 Phase 2: Route construction

In a second phase routes are constructed sequentially. Vehicles are used in increasing order of their fixed costs FC_k. Pairs of customers are eligible to be inserted into routes in increasing order of their latest start time L_{ij},

$$L_{ij} = Min\{L_i - t_{0i}; L_j - t_{ij} - s_i - t_{0i}\}.$$

A pair of customers can be inserted into an existing route k if vehicle k can start later than the time necessary to serve the customers already assigned and on condition that vehicle k is able to return to the terminal within its depot window. The total time required to serve customers assigned to a vehicle k is defined as the route service time RS_k. These conditions are mathematically expressed as:

$$RS_k \leq L_{ij} \text{ and } Max(RS_k, E_{ij}) + RS_{ij} \leq T_k.$$

The route service time RS_k is initially set to 0. In case insertion into multiple existing routes is feasible, the pair of customers is added to the existing route with the smallest waiting time between the previous pair. If no insertions into existing routes are feasible, the pair of customers is assigned to an unused vehicle to create a new route.

Finally the route service time RS_k is updated. Define the earliest starting time E_{ij} as the earliest time a vehicle can leave the depot for serving pair (i, j) without unnecessary waiting between delivery i and pickup j:

$$E_{ij} = \begin{cases} L_i - t_{0i} & \text{if } L_i \leq (E_j - t_{ij} - s_i), \\ E_j - t_{ij} - s_i - t_{0i} & \text{if } E_i \leq (E_j - t_{ij} - s_i) \leq L_i, \\ E_i - t_{0i} & \text{if } (E_j - t_{ij} - s_i) \leq E_i. \end{cases}$$

This leads to the following expression for updating the route service time RS_k after the insertion of pair (i, j):

$$RS_k = \begin{cases} RS_k + RS_{ij} & \text{if } E_{ij} < RS_k, \\ E_{ij} + RS_{ij} & \text{else.} \end{cases}$$

7.6 Improvement heuristic

In this section a local search heuristic is proposed to improve a feasible solution obtained by the construction heuristic described above. Considering the nature of the problem, three neighborhoods of the local search procedure are defined. The CROSS operator recombines pairs of customers of different routes. A second operator, COMBINE, joins two routes into one. Customers are removed from a route and inserted into another route by the INSERT operator.

7.6.1 CROSS operator

Two pairs of pickup and delivery customers, (g, h) and (i, j), are selected from two different routes. These pairs are recombined into new pairs of pickup and delivery customers, (g, j) and (i, h). This move is further denoted as the CROSS operator. The local search heuristic first lists all feasible CROSS moves. A CROSS move is feasible if the pickup customers and delivery customers can be combined into new pairs, taking into account their time windows. Second, it is checked whether the new pairs of customers can be reinserted into the routes. Either (g, j) is inserted into the first route and (i, h) into the second or the other way round. Next, the local search heuristic selects the CROSS move with the largest improvement (or smallest deterioration) I_{ghij} in route service times RS_k.

$$I_{ghij} = RS_{gh} + RS_{ij} - RS_{gj} - RS_{ih}.$$

If a resulting route only contains dummy customers, the route is removed from the solution and the number of trucks necessary is reduced by one. The improvement heuristic stops after a predefined number of iterations without reduction in total costs of serving all customers.

7.6.2 COMBINE operator

The second operator checks whether two routes served by different trucks can be combined into a single route. Whereas the CROSS operator reduces the travelling costs in the objective function, the COMBINE operator is able to reduce the number of trucks. Two routes can be combined if the last pair of the first route can be served before the latest starting time of the second route.

7.6.3 INSERT operator

The third operator removes pairs of pickup and delivery customers from their routes and reinserts them into another route. The INSERT operator attempts to eliminate routes, by inserting their customers into other routes. Pairs of customers can be inserted in the beginning of a route, between pairs of customers or at the end of a route. Similar to the COMBINE operator, this operator also impacts the number of trucks used and, by this, the fixed vehicle costs in the objective function.

These neighbourhood mechanisms form subsets of the general λ-interchange mechanism, described in Osman (1993) and Osman and Wassan (2002). The CROSS operator is an example of a 1-interchange mechanism, which involves only a single customer of each route. Due to the CROSS operator, two routes may exchange either pickup customers or delivery customers of two pairs simultaneously. The INSERT operator represents a 2-consecutive-node interchange mechanism. Two consecutive customers which constitute a pair in a single route are shifted to another route. Similarly, the COMBINE operator may be seen a n-consecutive-node interchange mechanism.

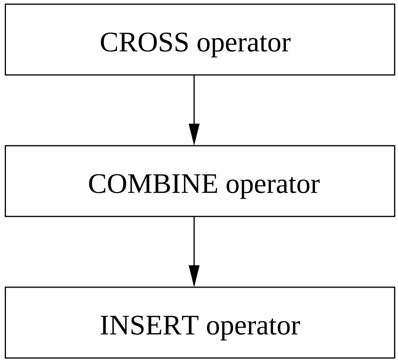

Figure 7.3: Improvement heuristic

The sequence in which the three search neighbourhoods are implemented is presented in figure 7.3. The CROSS operator is applied first to find better combinations of pickup and delivery customers. This operator improves the result of the pairing phase in the construction heuristic. Next, the COMBINE operator is used to reduce the fixed vehicle costs. Finally, the number of trucks is further reduced by the INSERT operator. The latter two search neighbourhoods affect the result of the route construction phase of the construction heuristic.

7.7 Numerical example 1

A numerical example is discussed to demonstrate the mechanism of the construction heuristic and improvement heuristic. In this example an intermodal terminal has to deliver containers to five customer sites and pick up containers at five other customer sites. The terminal is open during six hours per day. Service at customer sites takes eight minutes. The problem is studied in a deterministic environment. Travel times, waiting times and service times are therefore assumed to be constant. Table 7.1 presents the time windows imposed by pickup customers and delivery customers.

Distances, expressed in time units, from the depot 0 to customers and between customers are given in table 7.2. Table 7.3 mentions the cost CR_{ijk} of servicing each pair of customers. Fixed costs are assumed to be equal for all vehicles. Since all solutions found for this example require the same number of vehicles, fixed vehicle costs are left out of the comparison.

delivery i	E_i	L_i	**pickup** j	E_j	L_j
1	10	100	1	0	100
2	50	250	2	100	280
3	80	180	3	200	260
4	50	360	4	80	320
5	100	300	5	5	80

Table 7.1: Customer time windows

distance i j	**0**	**1**	**2**	**3**	**4**	**5**
0	0	63	48	49	12	44
1	9	57	40	41	14	40
2	47	42	5	11	48	50
3	36	45	13	16	37	43
4	18	56	32	32	18	35
5	24	82	55	53	12	26

Table 7.2: Distance matrix

cost i j	**0**	**1**	**2**	**3**	**4**	**5**
0	0.0	178.7	138.7	141.3	42.7	128.0
1	34.7	193.3	150.7	221.3	68.0	145.3
2	136.0	224.0	154.7	164.0	164.0	209.3
3	106.7	213.3	150.7	156.0	134.7	185.3
4	58.7	204.0	152.0	153.3	85.3	150.7
5	74.7	246.7	190.7	189.3	85.3	146.7

Table 7.3: Cost matrix

7.7.1 Lower bound

In order to evaluate the results of the heuristics, a lower bound on the objective function value for the optimal solution is computed. The problem is relaxed by ignoring the final group of constraints which determine the feasibility of the routes. The solution of the relaxed problem gives a lower bound to the problem including all constraints. The optimal solution for the relaxed problem formulation has a travelling cost of 758.7. The routes are shown in table 7.4. However, they are not feasible when taking constraints (7.10) to (7.13) into account.

route 1	**route 2**
2-1	1-5
3-2	
4-3	
5-4	

Table 7.4: Best routes of relaxed problem definition

7.7.2 Construction heuristic

In the pairing phase of the heuristic a maximum waiting time, $MAXWAIT$, of 30 minutes is allowed between serving a delivery customer and a pickup customer. The maximum waiting time is a parameter of the construction heuristic. Its value should be large enough to allow flexibility in the pairing phase, but small enough in comparison with the depot time window of 360 minutes. Equal weights w_1 and w_2 of five are assigned to savings in waiting time and travel time in the first selection criterion (7.14). This results in the ranked list of feasible pairs of customers given in table 7.5. Selected pairs are highlighted in bold. In this example all customers can be combined into pairs. No dummy customers are required.

In the second phase of the heuristic the selected pairs of customers are inserted into routes. Results are presented in table 7.6. Vehicle 1 returns to the depot after 313 minutes, vehicle 2 after 287 minutes. The travelling cost of this solution equals 794.7.

delivery i	**pickup** j	**selection criterion**
2	**1**	**-340**
1	**5**	**45**
1	1	50
5	**3**	**395**
3	3	435
5	2	500
2	3	530
3	**2**	**540**
2	2	635
4	3	675
4	2	780
5	4	880
3	4	920
2	4	1015
1	2	1025
4	**4**	**1160**
1	4	1405

Table 7.5: Ranked pairs of customers

route 1	**route 2**
2-1	1-5
5-3	3-2
	4-4

Table 7.6: Route construction

7.7.3 Parameter setting

The selection criterion in the first phase of the heuristic is a weighted combination of two sub-criteria. The initial solutions found by the construction heuristic depend on the values assigned to the weights in the selection criterion. A multi-start approach, assigning different values to these weights, can be applied to find the best overall solution. Solutions found for different values of the weights are presented in table 7.7. In this example, the best solution is obtained when a large weight is assigned to the savings in travel time. The corresponding routes are given in table 7.8.

weight 1	**weight 2**	**travelling costs**
0	1	776
0.092	0.908	776
0.093	0.907	**762.7**
0.188	0.812	**762.7**
0.189	0.811	801.3
0.462	0.538	801.3
0.463	0.537	794.7
1	0	794.7

Table 7.7: Parameter setting

route 1	**route 2**
2-1	1-5
4-2	3-3
	5-4

Table 7.8: Best routes found by construction heuristic

7.7.4 Opportunity costs

When the second selection criterion (7.15) is applied in the pairing phase of the construction algorithm, the same best solution with a cost of 762.7 is found. Also no further improvement in best solution is found when the opportunity costs of time window slack (7.16) are taken into account. Assigning various values to the weights in this selection criterion leads to the same best solution with a travelling cost of 762.7.

7.7.5 Improvement heuristic

The local search procedure described in section 7.6 is applied to the first solution of the construction heuristic given in table 7.6. This initial solution is obtained by giving equal weights in selection criterion (7.14) and without taking opportunity costs into account. Two CROSS moves are feasible in this solution. Table 7.9 lists the pairs of customers involved and resulting improvements. The second CROSS move is selected. Pair (i, h) is inserted into the first route and pair (g, j) in the second route. The resulting routes, presented in table 7.10, imply a travelling cost of 758.7, which is lower than the best solution found after parameter setting. From the solution of the lower bound can be deducted that at least two vehicles are required to service all customers. Therefore the COMBINE and INSERT operators are not of use in this example and fixed vehicle costs are left out of the comparison of solutions. The improvement algorithm stops after two further iterations without improvement in the objective function value.

pair (g,h)	**pair** (i,j)	I_{ghij}
5-3	3-2	-5
5-3	4-4	27

Table 7.9: CROSS moves and their improvement

It can be concluded that the improvement heuristic was able to find the optimal solution in this numerical example. A comparison of table 7.10 and table 7.4 shows that the same pairs of customers are selected, but the assignment of pairs to routes differs. Whereas the routes are not feasible in the solution of the relaxed problem, they are in the solution of the improvement heuristic.

route 1	route 2
2-1	1-5
4-3	3-2
	5-4

Table 7.10: Best routes found by improvement heuristic

7.8 Numerical example 2

A numerical example is presented to demonstrate the mechanism of the construction heuristic and improvement heuristic. In this example an intermodal terminal has to deliver containers to 100 delivery customers and 100 pickup customers. Time windows of customers are generated at random from a uniform distribution. Locations of customers are also chosen at random in a bounded area around the intermodal terminal. Service times of customers are assumed constant and equal to eight minutes. All trucks have to return to the depot after 480 minutes. Travel times, waiting times and service times are assumed to be deterministic. The terminal cooperates with a single haulier for performing the road segment of intermodal transport requests. Therefore, travelling costs and fixed vehicle costs are assumed equal for all vehicles. A fixed vehicle cost of 10 is charged per vehicle in use.

7.8.1 Lower bound

A lower bound for the heuristic solution is obtained as described in section 7.4. Results are presented in table 7.11. Only 13 trucks (N_T) are required because the constraints which ensure the feasibility of the routes are omitted. Consequently, the fixed vehicle costs (FC) are underestimated. The variable costs (VC) represent the travelling costs when delivery and pickup customers are optimally combined. This results in a lower bound of 8172.7 for the total cost (TC) of serving all customers.

7.8.2 Construction heuristic

In the construction heuristic a maximum waiting time $MAXWAIT$ between delivery customers and pickup customers of 30 minutes is allowed. The maximum waiting time is a parameter of the construction heuristic. This parameter influences the initial solution found by the construction heuristic. The maximum waiting time is constrained

$\mathbf{N_T}$	13
VC	8042.7
FC	130
TC	8172.7

Table 7.11: Lower bound on cost numerical example

to improve the quality of the starting solution for the improvement heuristic and speed up the local search process. Its value should be large enough to allow flexibility in the pairing phase, but small enough in comparison with the depot time window. A limit of 30 minutes improves the initial solution, but also creates enough flexibility for the improvement heuristic. The selection criterion in the first phase of the construction heuristic is a weighted combination of two sub-criteria. The initial solutions found by the construction heuristic depend on the values assigned to the weights in the selection criterion. A multi-start approach, assigning different values to these weights, can be applied to find the best overall solution. In table 7.12 various values are assigned to the weights in the first selection criterion (7.20). In the third column the number of trucks used in each solution is given. The fourth column mentions fixed vehicle cost. Next, the variable cost of the solution found by the construction heuristic is given. Together with the fixed vehicle cost, they sum up to the total cost of serving all customers. The solution with the lowest total cost is marked in bold. Table 7.12 shows that the construction heuristic finds better solutions as relatively more weight is given to savings in travel time.

$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{N_T}$	**FC**	**VC**	**TC**
5	0	44	440	11967	12407
0	5	**23**	230	8215	**8445**
5	5	42	420	10361	10781
1	9	32	320	8884	9204
9	1	46	460	11639	12099

Table 7.12: Construction heuristic - selection criterion 1

7.8.3 Opportunity costs

In table 7.13 the opportunity cost of savings in travel time are taken into account in the pairing phase of the construction heuristic.

w_1	w_2	w_3	w_4	N_T	FC	VC	TC
5	0	5	0	40	400	9668	10068
0	5	5	0	22	220	8313	8533
5	5	5	0	37	370	9435	9805
3	3	7	0	32	320	9045	9365
3	7	3	0	34	340	9097	9437
7	3	3	0	43	430	9945	10375
0.1	9.5	9.5	0	21	210	8271	8481
1	9	9	0	28	280	8501	8781
0.15	9.5	9.5	0	**21**	210	8265	**8475**

Table 7.13: Construction heuristic - opportunity cost 1

The best objective value is found when relatively large weights are given to savings in travel time and opportunity cost of savings in travel time and a very small weight to savings in waiting time between customers. The solution with the least number of vehicles also leads to the lowest total cost. Table 7.14 presents results when the opportunity cost related to the time window slack is added to selection criterion 1. In this case, the construction heuristic leads to solutions with a relatively high total cost. The solutions also require a large number of trucks as compared with the results in table 7.13. Results of taking both types of opportunity costs into account in selection criterion 2 are given in table 7.15. In this example savings in travel time are more important than savings in waiting time between customers. Therefore, an advantage is gained from considering the opportunity cost of savings in travel time, but not from considering the opportunity cost of savings in waiting time. Good solutions are found with high values for w_2 and w_3 and low values for w_1 and w_4.

$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$	$\mathbf{N_T}$	**FC**	**VC**	**TC**
5	0	0	5	45	450	12007	12457
0	5	0	5	43	430	10907	11337
5	5	0	5	45	450	11133	11583
3	3	0	7	46	460	11284	11744
3	7	0	3	46	460	10720	11180
7	3	0	3	47	470	11196	11666

Table 7.14: Construction heuristic - opportunity cost 2

$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$	$\mathbf{N_T}$	**FC**	**VC**	**TC**
5	5	5	5	41	410	10437	10847
3	3	3	7	48	480	10985	11465
3	3	7	3	38	380	9541	9921
3	7	3	3	40	400	9769	10169
7	3	3	3	46	460	10844	11304
1	9	9	1	34	340	8803	9143
1	8.5	9	0.1	**29**	290	8613	**8903**

Table 7.15: Construction heuristic - selection criterion 2

7.8.4 Improvement heuristic

This section reports results of the application of the improvement heuristic to the solutions obtained by the two-phase insertion heuristic in the previous section. Table 7.16 gives the number of trucks, variable cost and total cost of the solution after application of the CROSS operator. For the COMBINE and INSERT operators, the number of trucks and total cost are mentioned as these operators only affect the fixed vehicle cost. In the improvement heuristic, the maximum number of iterations without improvement is set to 10. A comparison of table 7.16 with table 7.12 shows that although there is a variation in solutions found by the construction heuristic, the CROSS operator is able to reduce the variable cost to approximately the same level. The use of the COMBINE and INSERT operators reduces the required number of trucks significantly.

w_1	w_2	CROSS			COMBINE		INSERT	
		N_T	VC	TC	N_T	TC	N_T	TC
5	0	44	8191	8631	33	8521	19	8381
0	5	23	8125	8355	23	8355	20	8325
5	5	41	8139	8549	30	8439	19	8329
1	9	32	8125	8445	27	8395	19	8315
9	1	46	8127	8587	30	8427	18	8307

Table 7.16: Improvement heuristic - selection criterion 1

Table 7.17 presents results of the improvement heuristic applied to the initial solutions given in table 7.13. The lowest total cost of 8275 differs only 1.25 % from the lower bound. The lowest variable cost of 8095 is less than 0.65% from the travelling costs when delivery and pickup customers are optimally combined. The difference in total cost is mainly due to the larger number of trucks required to assure the feasibility of the routes. Table 7.18 mentions similar results when the local search method is applied to the solutions given in table 7.14. Even though the construction heuristic leads to solutions with a higher fixed vehicle cost when only the second opportunity cost is taken into account, the number of trucks is strongly reduced by the COMBINE and INSERT operators.

Finally, the improvement heuristic is applied to the solutions constructed with the second selection criterion in table 7.19. The lowest variable cost of 8079 is reached when 30 vehicles are available, offering more flexibility to combine delivery and pickup customers. The number of vehicles can be reduced to 18 by the latter two operators, leading to the best total cost found of 8259. The lowest number of vehicles in any solution found is equal to 17. The advantage of the lowest variable cost outweighs the higher fixed vehicle cost. A multistart approach using different values for the weights in the second selection criterion (7.21) might be applied. All solutions reported in tables 7.16 to 7.19 lie within 2.97% of the lower bound.

w_1	w_2	w_3	w_4	CROSS			COMBINE		INSERT	
				N_T	VC	TC	N_T	TC	N_T	TC
5	0	5	0	40	8151	8551	30	8451	18	8331
0	5	5	0	22	8148	8368	20	8348	18	8328
5	5	5	0	37	8103	8473	29	8393	19	8293
3	3	7	0	32	8236	8556	28	8516	18	8416
3	7	3	0	34	8164	8504	32	8484	19	8354
7	3	3	0	43	8165	8595	28	8445	19	8355
0.1	9.5	9.5	0	21	**8095**	8305	20	8295	**18**	**8275**
1	9	9	0	28	8120	8400	24	8360	19	8310
0.15	9.5	9.5	0	21	8100	8310	20	8300	18	8280

Table 7.17: Improvement heuristic - opportunity cost 1

w_1	w_2	w_3	w_4	CROSS			COMBINE		INSERT	
				N_T	VC	TC	N_T	TC	N_T	TC
5	0	0	5	44	8140	8580	31	8450	19	8330
0	5	0	5	42	8136	8556	29	8426	19	8326
5	5	0	5	44	8131	8571	32	8451	19	8321
3	3	0	7	43	8132	8562	31	8442	20	8332
3	7	0	3	46	8169	8629	33	8499	19	8359
7	3	0	3	47	8100	8570	30	8400	18	8280

Table 7.18: Improvement heuristic - opportunity cost 2

w_1	w_2	w_3	w_4	CROSS			COMBINE		INSERT	
				N_T	**VC**	**TC**	**N_T**	**TC**	**N_T**	**TC**
5	5	5	5	41	8085	8495	30	8385	18	8265
3	3	3	7	48	8164	8644	32	8484	21	8374
3	3	7	3	36	8116	8476	30	8416	17	8286
3	7	3	3	39	8159	8549	31	8469	18	8339
7	3	3	3	46	8136	8596	32	8456	18	8316
1	9	9	1	34	8097	8437	31	8407	21	8307
1	8.5	9	0.1	30	**8079**	8379	25	8329	18	**8259**

Table 7.19: Improvement heuristic - selection criterion 2

7.9 Numerical experiments

Traditionally heuristics have been assessed on accuracy and speed. Cordeau et al. (2002) add two other criteria to evaluate heuristics, namely simplicity and flexibility. The authors argue that all four attributes of a good heuristic are essential to ensure its adoption by practitioners. Bräysy and Gendreau (2005) confirm that flexibility is an important consideration. Robustness is also proposed as an evaluation criterion. A robust algorithm should not be overly sensitive to differences in problem characteristics and should not perform poorly on any problem instance.

Heuristics for the standard VRPTW are compared by making use of benchmark problems presented in Solomon (1987). The pre- and end-haulage of intermodal container terminals differs from these standard benchmark problems as a full truckload instead of less-than-truckload needs to be picked up or delivered at customer locations. A new experimental design is set up to test the robustness of the local search heuristic in various problem settings. A 2^3 factorial design is developed as described in Law (2007). Three factors or problem characteristics are identified: problem size (F1), dispersal of customers (F2) and width of customer time windows (F3). For each problem characteristic a low (-) and high (+) level is selected. The problem size is expressed as the number of pickup and delivery customers to be served. The number of customers is either 100 (-) or 200 (+). In practice, intermodal terminals in Belgium serve a lower number of customers. However, the experimental design is developed to test the performance of the local search heuristic. For factor F2 customer locations are selected at random with x- and y-coordinates either between zero and 25 (-) or between zero and 50 (+). Time windows at customer locations may be narrow (between 60 and 120 minutes (-)) or wide (between 90 and 240 minutes (+)). This leads to eight problem classes. In each problem class, five problem instances are generated. In all problem classes the depot time window is set equal to 480 minutes and service time at customer locations is held constant to eight minutes. Hard time windows are defined at all customer locations, leading to a time window density of 100 %. A value of 30 minutes is assigned to the parameter $MAXWAIT$. A multistart approach is applied, varying the weights in selection criterion (7.22) of the insertion heuristic. The weights are altered from zero to 100 with changes of five units. The weights always sum up to 100. The best overall solution is reported.

A single run of the heuristic procedure takes only a few seconds. Depending on the problem size, the multistart approach runs between 10 minutes and half an hour on a Intel Core Duo 2GHz computer. In general, practical examples will not exceed the problem sizes investigated in the experimental design (100 or 200 requests to pickup or deliver a container). The market scope of an intermodal terminal may vary in practice between 30 km to 150 km, depending on the characteristics of the specific intermodal transport chain. However, when a solution is required in a shorter time span, the number of moves evaluated by the local search operators could be reduced. Bräysy et al. (2008) propose to focus only on moves that involve customers that are close to each other. In order to define closeness, a distance limit is initialized in the first solution and updated during the search. The initial limit is set to the distance between the depot and the farthest customer, multiplied by a uniform number (between 0 and 1). The maximum distance that has still enabled improvement is tracked to update the distance limit at each restart involving the creation of a new initial solution.

The speed of heuristic procedures is in contrast to the solution time for finding the optimal solution for problems of realistic size. Kallehauge (2008) presents an overview of exact algorithms for the vehicle routing problem with time windows. Kallehauge et al. (2006) describe a Lagrangian branch-and-cut-and-price algorithm for the VRPTW, intended to speed-up the solution process. The algorithm was tested on 56 Solomon problems with 100 customers. This test set was enlarged by only considering the first 25 and 50 customers of each original problem, leading to a total number of 168 test problems. When restricting CPU time to one hour, 119 out of the 168 Solomon test problems were solved. The authors conclude that their acceleration strategy performs significantly better than a traditional column generation based algorithm on a large number of test problems.

An overview of results is presented in table 7.20. The problem class and level of the three problem characteristics are mentioned in the first four columns. The fifth column represents the average gap between the solution of the local search heuristic and the lower bound over the five problem instances in each problem class. The corresponding standard deviation is given in the final column.

Problem class	**F1**	**F2**	**F3**	**avg gap**	**stdev gap**
1	-	-	-	1.68%	0.0036
2	+	-	-	2.16%	0.0033
3	-	+	-	1.53%	0.0031
4	+	+	-	1.78%	0.0053
5	-	-	+	1.11%	0.0018
6	+	-	+	1.31%	0.0008
7	-	+	+	0.91%	0.0026
8	+	+	+	1.03%	0.0013

Table 7.20: Overview of results in eight problem classes

Results show that the average gap is small and does hardly vary over the problem classes. The algorithm performs well for all combinations of problem characteristics. Results show no relation between the gap and the problem size (F1). Moreover, the standard deviation of the gap between the heuristic solution and the lower bound is small, indicating that the performance of the local search heuristic does not vary over the problem instances. Results for all 40 problem instances are given in table 7.21. Variable cost, fixed cost and total cost are reported for the lower bound solution and the best heuristic solution after applying the multistart approach. In the final column the gap between both solutions is expressed as a percentage of the lower bound. The difference between the best solutions and the lower bounds is mainly due to the fixed vehicle costs. As explained in section 7.4, the lower bound does not ensure the feasibility of the routes. Less vehicles are required in the lower bound solution, leading to an underestimation of fixed vehicle costs.

Problem		lower bound			best solution			
Class	**Instance**	**VC**	**FC**	**TC**	**VC**	**FC**	**TC**	**gap**
1	1	2734	50	2784	2769	70	2839	1.98%
1	2	2601	50	2651	2629	70	2699	1.83%
1	3	2657	50	2707	2687	70	2757	1.83%
1	4	2468	40	2508	2481	70	2551	1.72%
1	5	2713	50	2763	2723	70	2793	1.06%
2	1	5197	90	5287	5248	130	5378	1.73%
2	2	4991	80	5071	5056	130	5186	2.28%
2	3	5062	80	5142	5136	140	5276	2.60%
2	4	4861	80	4941	4919	120	5039	1.98%
2	5	5215	90	5305	5303	120	5423	2.22%
3	1	4175	70	4245	4228	90	4318	1.73%
3	2	4187	70	4257	4192	110	4302	1.07%
3	3	4194	70	4264	4213	110	4323	1.38%
3	4	4162	70	4232	4208	100	4308	1.81%
3	5	4229	70	4299	4261	110	4371	1.68%
4	1	8142	130	8272	8212	170	8382	1.33%
4	2	8245	130	8375	8337	190	8527	1.82%
4	3	8063	130	8193	8211	200	8411	2.66%
4	4	7871	130	8001	7956	180	8136	1.69%
4	5	7826	130	7956	7897	170	8067	1.40%
5	1	2622	50	2672	2633	70	2703	1.16%
5	2	2573	50	2623	2589	60	2649	0.99%
5	3	2568	50	2618	2580	60	2640	0.86%
5	4	2396	40	2436	2405	60	2465	1.21%
5	5	2657	50	2707	2663	80	2743	1.31%

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Problem		**lower bound**			**best solution**			
Class	**Instance**	**VC**	**FC**	**TC**	**VC**	**FC**	**TC**	**gap**
6	1	5066	80	5146	5091	120	5211	1.26%
6	2	4895	80	4975	4929	110	5039	1.28%
6	3	4997	80	5077	5033	110	5143	1.30%
6	4	4779	80	4859	4800	120	4920	1.27%
6	5	5074	80	5154	5108	120	5228	1.44%
7	1	4166	70	4236	4175	90	4265	0,.7%
7	2	4072	70	4142	4096	90	4186	1.06%
7	3	4080	70	4150	4112	90	4202	1.26%
7	4	4047	70	4117	4055	90	4145	0.67%
7	5	4051	70	4121	4068	90	4158	0.91%
8	1	8043	130	8173	8068	170	8238	0.80%
8	2	8063	130	8193	8104	180	8284	1.11%
8	3	7851	130	7981	7877	190	8067	1.09%
8	4	7702	130	7832	7737	180	7917	1.09%
8	5	7723	130	7853	7756	180	7936	1.06%

Table 7.21: Results of 40 problem instances

Table 7.22 summarizes the weights leading to the best solution in the multistart approach for all problem instances. In problem classes 1 to 4, time windows at customer locations are narrow (between 60 and 120 minutes). For these problem classes a low value is assigned to the time window slack (w_1) and opportunity cost of time window slack (w_4) in all but one problem instance (Class 3 - instance 5). Due to the tight time windows fewer combinations of pickup and delivery customers are possible and better solutions are found when focussing on the reduction of travel time. However, all solutions found by the local search heuristic differ only slightly, as demonstrated in the previous section 7.8. Problem instances in classes 5 and 6 have a relatively low dispersal of customers and wide time windows at customer locations. For these problem classes no unambiguous conclusion may be drawn on the importance of time window slack (w_1 and w_4) or savings in travel time (w_2 and w_3). Problem classes 7 and 8 are characterized by a high dispersal of customers and wide time windows. For many instances in these two problem classes the time window slack (w_1) or opportunity cost of time window slack (w_4) receives a high weight.

Problem class	**Instance**	$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$
1	1	0	20	80	0
1	2	0	20	80	0
1	3	0	60	40	0
1	4	5	70	25	0
1	5	5	70	25	0
2	1	0	80	20	0
2	2	5	75	20	0
2	3	0	20	80	0
2	4	5	35	60	0
2	5	0	75	25	0
3	1	0	15	80	5
3	2	5	65	30	0
3	3	0	10	85	5
3	4	0	45	50	5
3	5	0	15	15	70
4	1	0	90	10	0
4	2	10	0	90	0
4	3	5	10	85	0
4	4	5	80	15	0
4	5	5	15	80	0
5	1	0	65	20	15
5	2	0	50	50	0
5	3	0	0	100	0
5	4	70	15	10	5
5	5	30	35	30	5

continued on next page

Problem class	**Instance**	$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$
6	1	0	85	15	0
6	2	90	0	5	5
6	3	10	50	10	30
6	4	35	30	5	30
6	5	0	15	35	50
7	1	0	85	15	0
7	2	60	25	0	15
7	3	20	5	20	55
7	4	45	5	5	45
7	5	10	25	35	30
8	1	60	0	5	35
8	2	35	15	20	30
8	3	10	35	5	50
8	4	35	5	0	60
8	5	0	0	40	60

Table 7.22: Weights for best solution in multistart approach

In Table 7.23 the parameter $MAXWAIT$ is altered from 15 to 60 minutes with increases of 5 minutes in the solution of the first problem presented in table 7.21. The weights are fixed at the values found in the multistart approach given in table 7.22. The last column mentions the deviation from the smallest total cost. Results show very little variation in the solution found by the algorithm, which indicates that the heuristic method is robust to changes in this parameter.

MAXWAIT	**VC**	**FC**	**TC**	**% dev**
15	2768	70	2838	0.00%
20	2764	80	2844	0.21%
25	2764	80	2844	0.21%
30	2769	70	2839	0.05%
35	2769	70	2839	0.04%
40	2764	80	2844	0.21%
45	2773	80	2853	0.53%
50	2773	80	2853	0.53%
55	2773	80	2853	0.53%
60	2768	70	2838	0.00%

Table 7.23: Variation on $MAXWAIT$ for problem class 1 - instance 1

7.10 Conclusions

A special class of pickup and delivery problems has been explored, in which vehicles carry full truckloads to and from an intermodal terminal. An insertion heuristic consisting of two phases is proposed. The two-phase construction heuristic is able to find a feasible solution in a short time span. This solution is further improved by a local search procedure based on three operators, CROSS, COMBINE and INSERT. Although there is a variation in variable cost and fixed vehicle cost after applying the construction heuristic, the improvement heuristic is able to reduce the total cost significantly and solutions of good quality are obtained. The initial solutions found by the construction heuristic depend on the values assigned to the weights in the selection criterion. A multi-start approach, assigning different values to the weights, is applied to find the best overall solution. Numerical experiments show that the algorithm is robust with respect to variations in problem characteristics. In all problem instances a small gap between the heuristic solution and the lower bound solution is found. Furthermore, the heuristic is logically constructed and offers an intuitive and fast approach to find good quality solutions for practitioners. In the next chapter a deterministic annealing algorithm is developed and compared with the results of the local search procedure discussed in this chapter.

Chapter 8

Pre- and end-haulage at intermodal container terminals: a deterministic annealing approach

8.1 Introduction

In the previous chapter, a multi-start local search heuristic is presented to generate a near-optimal solution for the pre- and end-haulage of intermodal container terminals. In this chapter[1], a deterministic annealing algorithm is proposed in a post-optimization phase to further improve the solution found by the local search heuristic (figure 8.1). The chapter is organized as follows. Section 8.2 describes the methodology of deterministic annealing and the implementation strategy in the given problem setting. In section 8.3 a numerical example demonstrates the mechanism of the metaheuristic. Next, numerical experiments are performed in section 8.4 and in section 8.5 conclusions are drawn.

[1]This chapter is based on Caris and Janssens (2010).

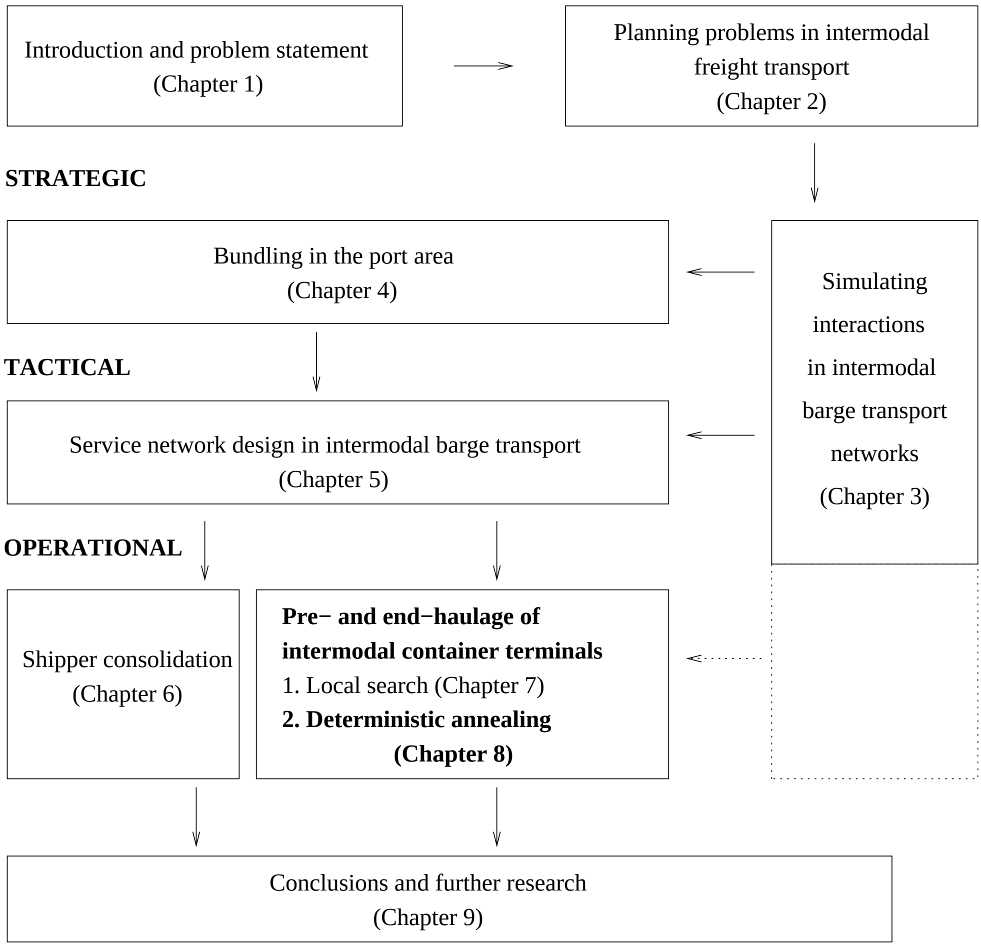

Figure 8.1: Outline of the thesis - Chapter 8

8.2 Deterministic annealing

A deterministic annealing algorithm is applied in a post-optimization phase to further improve on solutions found by the multistart local search heuristic. Deterministic annealing (DA), also referred to as 'threshold accepting', is introduced by Dueck and Scheuer (1990) as a deterministic variant of simulated annealing (SA). Simulated annealing was proposed by Kirkpatrick et al. (1983). In each step of an SA algorithm a new solution S' is generated in the neighbourhood of the current solution S. If the new solution has a better objective value, it is accepted automatically. If it is worse, it is accepted only with a certain probability. The probability of acceptance

$e^{-\Delta/T}$ depends on the change in objective value $\Delta = C(S') - C(S)$ and a parameter T, called temperature. A larger deterioration receives a smaller probability of being accepted. The temperature T is updated according to a certain annealing schedule. In the beginning of the search T is set at a level with a high probability of accepting worse solutions. Gradually, the probability of accepting deteriorations is lowered, until only improvements are accepted. A great variety of annealing schedules exist in literature. However, Dueck and Scheuer (1990) state that in most applications the success of SA is very sensitive against the choice of annealing schedule. Deterministic annealing offers a greater simplicity. The difference between SA and DA lies in the different acceptance rules. In DA a neighbouring solution with a worse objective value than the current solution is accepted if the deterioration $\Delta = C(S') - C(S)$ is less than a deterministic threshold value T. It is not necessary to compute probabilities or to make random decisions. The threshold value T is also gradually lowered until no more deteriorations are allowed.

Deterministic annealing has been applied to vehicle routing problems by a number of authors. Tarantilis et al. (2004) develop a DA algorithm for the heterogeneous fixed fleet vehicle routing problem. Their algorithm allows raising or backtracking the threshold value when no acceptances are found in the inner loop. The increased threshold value during the backtracking step is always smaller than the one before the backtracking step. Bräysy et al. (2003) apply a DA metaheuristic to the vehicle routing problem with time windows. Deterministic annealing is used in a post-optimization phase to improve results obtained by other algorithms. The authors allow to reset the threshold to its maximum value. A further extension of this DA approach is applied to the fleet size and mix vehicle routing problem with time windows by Bräysy et al. (2008). Cho and Wang (2005) present a DA algorithm for the vehicle routing problem with backhauls and time windows. An application of deterministic annealing to special instances of the traveling salesman problem may be found in Nikolakopoulos and Sarimveis (2007).

A deterministic annealing algorithm is developed for the problem formulation described in chapter 7 based on the implementation strategy of Bräysy et al. (2008). The final solution of the multistart local search heuristic serves as initial solution for the DA algorithm, presented in Algorithm 1. The following notation is used:

T = threshold value
T_{max} = maximum threshold value
ΔT = change in threshold value
i_{last} = last iteration with improvement
$n_{improve}$ = maximum number of iterations

$\bar{n}$ = predefined number of iterations without improvements
S' = new solution
S_{best} = current best solution
r = random number between 0 and 1

Algorithm 1 Deterministic annealing for FTPDPTW

```
Set best solution of multistart local search heuristic as current best solution S_best of DA
Set T = T_max and i_last = 0
for i = 1 to n_improve do
    Choose two random starting routes
    for All route pair combinations do
        Apply CROSS
        Apply COMBINE
        Apply INSERT
    end for
    if C(S') < C(S_best) then
        Set S_best = S' and i_last = i
    else
        if T ≤ 0 and i − i_last ≥ n̄ then
            Restart from S_best:
            Set S' = S_best, i_last = i and T = r · T_max
        else
            if T ≤ 0 then
                Set T = r · T_max
            else
                Set T = T − ΔT
            end if
        end if
    end if
end for
```

The three local search neighbourhoods CROSS, COMBINE and INSERT are integrated in a deterministic annealing framework. Routes are searched in a fixed order, but at the beginning of each iteration the starting point of the search is randomly chosen. Neighbouring solutions with a worse objective value are accepted when

$\Delta = C(S') - C(S)$ is less than the threshold value T. For each pair of routes at most one move for each local search operator is accepted in each iteration. In the DA algorithm a first-accept strategy is applied, whereas in the local search heuristic in the previous section the best move was chosen. The threshold value is initially set at a maximum value T_{max}. In each iteration without any improvement in objective function value T is lowered with ΔT units. The threshold value is reset to $r \cdot T_{max}$ whenever it reaches zero, with r a random number between 0 and 1. When after a predefined number of iterations $\bar{n}$ no improvements have been found and T reaches 0 again, the algorithm restarts from the current best solution S_{best} found. The process is repeated for $n_{improve}$ number of iterations.

8.3 Numerical example

A numerical example is discussed to demonstrate the mechanism of the DA algorithm. The DA procedure is applied to the first instance of problem class 1 in table 7.21. In this problem class, the intermodal terminal has to pickup or deliver containers to a hundred customer sites. Customer locations are randomly selected with x- and y-coordinates between zero and 25. Time windows at customer locations are randomly chosen between 60 and 120 minutes. In the multistart approach applied in the previous chapter, the best overall solution was obtained with the weights reported in table 8.1. A large weight is given to the opportunity costs of savings in travel time. No weight is allocated to the time window slack between customers or opportunity costs of time window slack.

$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$
0	20	80	0

Table 8.1: Weights best overall solution multistart local search heuristic

Table 8.2 summarizes the variable cost (VC) or travelling cost, fixed vehicle cost (FC) and total cost (TC) of the best overall solution after applying the insertion heuristic and the three local search neighbourhoods described in chapter 7. The insertion heuristic serves to provide an initial solution quickly. This initial solution is strongly improved by the three local search operators. The CROSS operator reduces the variable cost, whereas the two other operators are aimed to decrease the fixed vehicle cost. The final total cost differs only 1.98% from the lower bound. In the lower bound solution less vehicles are required, due to the relaxation of route feasibility with respect to the customer time windows.

	VC	**FC**	**TC**
Insertion heuristic	2903	90	2993
CROSS	2769	90	2859
COMBINE	2769	90	2859
INSERT	2769	70	2839
Lower bound	2734	50	2784

Table 8.2: Multistart local search heuristic

Deterministic annealing is applied as a post-optimizer to further reduce the total cost of this solution. In the DA algorithm the number of iterations $n_{improve}$ is fixed at 200. The algorithm is restarted from the current best solution S_{best} after 10 iterations without any improvements $\bar{n}$ with the threshold value at zero. The maximum threshold value T_{max} equals two, with a change in threshold value ΔT of 0.025. Results of three independent runs of the DA algorithm are given in table 8.3. The DA algorithm finds further reductions in travelling costs. The three runs show similar results with a gap of around 1% between the heuristic solution and the lower bound.

	Run 1	**Run 2**	**Run 3**
VC	2737	2740	2748
FC	70	70	70
TC	2807	2810	2818
Gap	0.82%	0.93%	1.22%

Table 8.3: Deterministic annealing algorithm

8.4 Numerical experiments

The DA metaheuristic is applied as a post-optimizer to the experimental design developed in section 7.9. First, a sensitivity analysis is performed to determine the parameter values for running the DA algorithm. Next, results for the 40 problem instances are given and compared with previous results of the local search heuristic. Finally, the DA algorithm is run as an independent algorithm, without first applying the local search heuristic.

8.4.1 Parameter setting

A subset of problems is selected to determine values for the parameters in the DA algorithm. A 2^{k-p} fractional factorial design is applied to identify four out of the eight problem classes (Law 2007). A 2^{3-1} fractional factorial design is constructed by choosing a certain subset of size 2^{3-1} of all 2^3 design points. In each problem class the problem instance is chosen with the largest gap between the lower bound solution and the best solution found after applying the local search heuristic in table 7.21. The largest gap with the lower bound indicates that these problem instances are more difficult to solve. Table 8.4 lists the selected problem classes and problem instance in each class. For each of the four selected problem instances three independent runs of the DA algorithm are performed in the sensitivity analysis.

Problem class	**F1**	**F2**	**F3**	**Problem instance**
1	-	-	-	1
4	+	+	-	3
6	+	-	+	5
7	-	+	+	3

Table 8.4: 2^{3-1} fractional factorial design

In literature no detailed directions are given to define T_{max}. The maximum threshold value should be set large enough to allow enough diversity in the search. However, too large values unnecessarily increase computation time. The value of T_{max} is problem specific and is usually determined on a set of test problems. Figure 8.2 presents a sensitivity analysis to determine the maximum threshold value T_{max}. The maximum threshold value is varied from zero to five with intervals of size 0.2. The change in threshold value ΔT is held constant at 0.025. For each value of T_{max} the average total cost for all four problem instances over three independent test runs is measured. The vertical axis shows the percentage deviation of the average total cost from the lowest total cost over all threshold values and test runs. A maximum threshold value of at least 1.2 is appropriate to obtain the lowest percentage deviation. Maximum threshold values less than one do not allow enough diversity in the search process. Only minor deviations are found over all threshold values, which indicates that the DA algorithm is robust for changes in maximum threshold value. A parameter value for T_{max} of 2 is applied in further analyses.

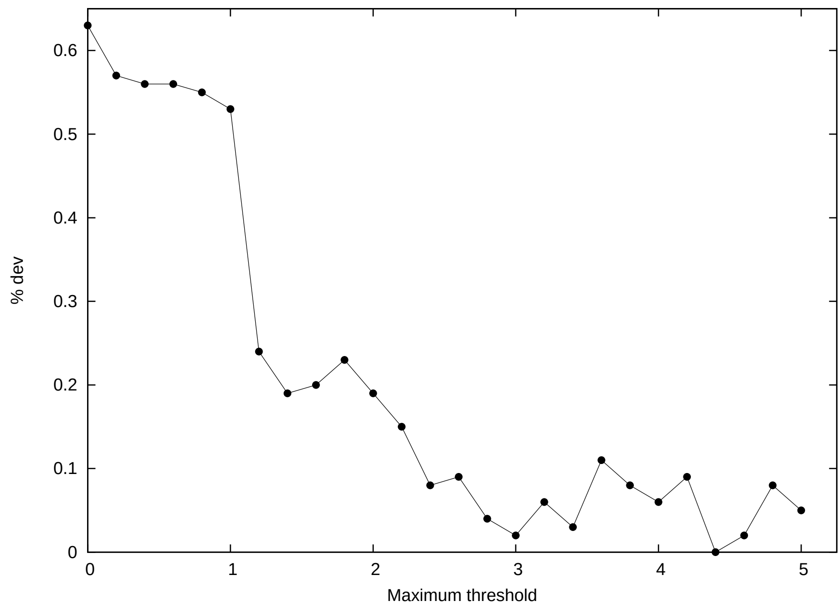

Figure 8.2: Sensitivity analysis of T_{max}

The influence of parameter ΔT on the solution quality is investigated in a similar way, as illustrated in figure 8.3. The maximum threshold value is held constant at $T_{max} = 2$ and ΔT is tested from 0.025 to 0.4 with intervals of 0.025. Only small deviations from the lowest objective function value are measured (less than 0.20%), showing the robustness of the DA algorithm for changes in ΔT. The change in threshold value ΔT is set at 0.025 in remaining analyses.

Figure 8.4 demonstrates the convergence of the algorithm over 5000 iterations for each of the four problem instances. The vertical axis represents the deviation of the objective function value from the result found after 10,000 iterations. Most improvements are found after 1000 iterations, but the algorithm is still able to further improve along the search process. The number of iterations $n_{improve}$ is fixed at 1000 for analyzing the 40 problem instances in the next subsection.

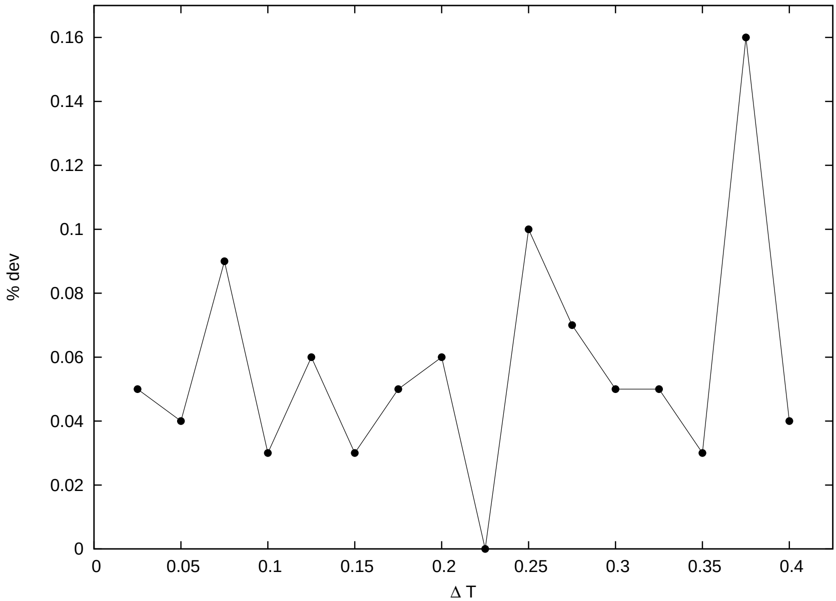

Figure 8.3: Sensitivity analysis of ΔT

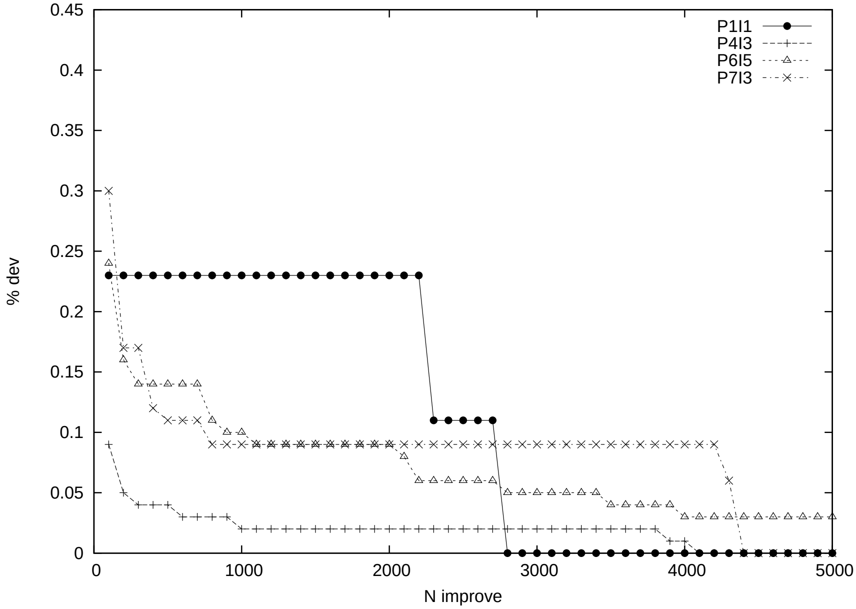

Figure 8.4: Sensitivity analysis of $n_{improve}$

Multiple initial solutions are tested for the deterministic annealing algorithm in table 8.5. Ten different initial solutions are generated by assigning the values in columns one to four to the weights in selection criterion (7.22) of the local search heuristic. For each initial solution three independent test runs are performed. The fifth column (TC) mentions the average total cost for all four problem instances over three independent test runs. The percentage deviation from the minimum value is reported in column six (% dev). The total costs differ only slightly.

w_1	w_2	w_3	w_4	TC	% dev
1	0	4	5	20600.90	0.22
1	0	8	1	20582.75	0.14
3	2	1	4	20576.25	0.10
3	3	2	2	20602.24	0.23
2	6	2	0	20611.75	0.28
0	0	6	4	20572.94	0.09
1	4	4	1	20668.48	0.55
3	1	3	3	20595.37	0.20
5	0	1	4	20594.91	0.20
3	1	4	2	20554.78	0.00

Table 8.5: Sensitivity analysis of initial solution

8.4.2 Numerical results

The DA algorithm is applied in a post-optimization phase to the 40 problem instances described in section 7.9. Table 8.6 reports the best solution over three independent runs. The gap between the lower bound solution, as described in section 7.4, and the best solution found by the DA algorithm is given in the last column. When comparing table 8.6 with table 7.21 the deterministic annealing procedure consistently finds further improvements of the best result found by the local search heuristic. Table 8.7 compares the average gap with the lower bound for each problem class after applying the local search heuristic (LS) and the deterministic annealing metaheuristic (DA). The standard deviation of the average gap shows that there are only minor deviations in results in each problem class.

Problem		lower bound			best solution DA			
Class	**Instance**	**VC**	**FC**	**TC**	**VC**	**FC**	**TC**	**gap**
1	1	2734	50	2784	2737	70	2807	0.83 %
1	2	2601	50	2651	2605	70	2675	0.92%
1	3	2657	50	2707	2668	60	2728	0.77%
1	4	2468	40	2508	2481	60	2541	1.32%
1	5	2713	50	2763	2717	60	2777	0.50%
2	1	5197	90	5287	5211	110	5321	0.64%
2	2	4991	80	5071	5016	110	5126	1.10%
2	3	5062	80	5142	5080	120	5200	1.13%
2	4	4861	80	4941	4877	110	4987	0.95%
2	5	5215	90	5305	5249	110	5359	1.03%
3	1	4175	70	4245	4207	90	4297	1.23%
3	2	4187	70	4257	4187	100	4287	0.71%
3	3	4194	70	4264	4211	100	4311	1.09%
3	4	4162	70	4232	4185	100	4285	1.27%
3	5	4229	70	4299	4260	90	4350	1.18%
4	1	8142	130	8272	8167	160	8327	0.67%
4	2	8245	130	8375	8259	170	8429	0.64%
4	3	8063	130	8193	8117	190	8307	1.40%
4	4	7871	130	8001	7904	170	8074	0.92%
4	5	7826	130	7956	7849	160	8009	0.67%
5	1	2622	50	2672	2628	60	2688	0.59%
5	2	2573	50	2623	2576	60	2636	0.48%
5	3	2568	50	2618	2571	50	2621	0.12%
5	4	2396	40	2436	2401	50	2451	0.64%
5	5	2657	50	2707	2663	60	2723	0.57%
6	1	5066	80	5146	5069	100	5169	0.45%
6	2	4895	80	4975	4908	100	5008	0.66%
6	3	4997	80	5077	5009	110	5119	0.83%

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Problem		lower bound			best solution DA			
Class	Instance	VC	FC	TC	VC	FC	TC	gap
6	4	4779	80	4859	4788	100	4888	0.61%
6	5	5074	80	5154	5083	110	5193	0.76%
7	1	4166	70	4236	4167	80	4247	0.24%
7	2	4072	70	4142	4085	80	4165	0.56%
7	3	4080	70	4150	4091	80	4171	0.51%
7	4	4047	70	4117	4053	80	4133	0.40%
7	5	4051	70	4121	4061	90	4151	0.75%
8	1	8043	130	8173	8057	160	8217	0.55%
8	2	8063	130	8193	8079	160	8239	0.56%
8	3	7851	130	7981	7869	160	8029	0.61%
8	4	7702	130	7832	7715	160	7875	0.54%
8	5	7723	130	7853	7729	160	7889	0.47%

Table 8.6: Results DA algorithm for 40 problem instances

Problem class	F1	F2	F3	avg gap LS	stdev gap LS	avg gap DA	stdev gap DA
1	-	-	-	1.68%	0.0036	0.87%	0.0030
2	+	-	-	2.16%	0.0033	0.97%	0.0019
3	-	+	-	1.53%	0.0031	1.09%	0.0023
4	+	+	-	1.78%	0.0053	0.86%	0.0032
5	-	-	+	1.11%	0.0018	0.48%	0.0021
6	+	-	+	1.31%	0.0008	0.66%	0.0014
7	-	+	+	0.91%	0.0026	0.49%	0.0019
8	+	+	+	1.03%	0.0013	0.55%	0.0005

Table 8.7: Overview of results in eight problem classes

8.4.3 Independent algorithm

In previous analyses the DA algorithm is applied as a post-optimizer after running the local search heuristic, as depicted in figure 8.5(a). In this subsection the DA metaheuristic is applied as an independent algorithm on an initial solution generated by the two-phase insertion heuristic (8.5(b)). The objective is to investigate whether the DA algorithm is able to perform equally well starting from initial solutions of relatively low quality.

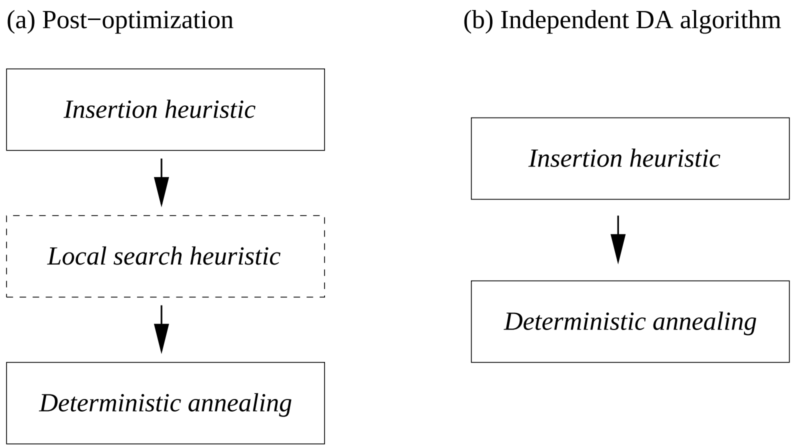

Figure 8.5: Deterministic annealing as an independent algorithm

Test instances listed in table 8.4 are used to determine the parameter settings for the independent DA algorithm. Figure 8.6 illustrates the impact of various values for the maximum threshold value T_{max}. A sensitivity analysis of ΔT is given in figure 8.7. Both graphs show great similarity with the sensitivity analysis for the DA algorithm in a post-optimization phase, as depicted in figures 8.2 and 8.3. Therefore, the same parameter values are chosen, as given in table 8.8.

Three independent runs are performed for each of the four test instances. Table 8.9 mentions the cost measures for each of the three runs. Results differ only slightly over the three runs, indicating a good robustness of the DA algorithm. Table 8.10 compares the best solution over the three independent runs of the DA algorithm with the lower bound solution. Results show that the independent DA algorithm is able to find good quality solutions,without first applying the local search heuristic.

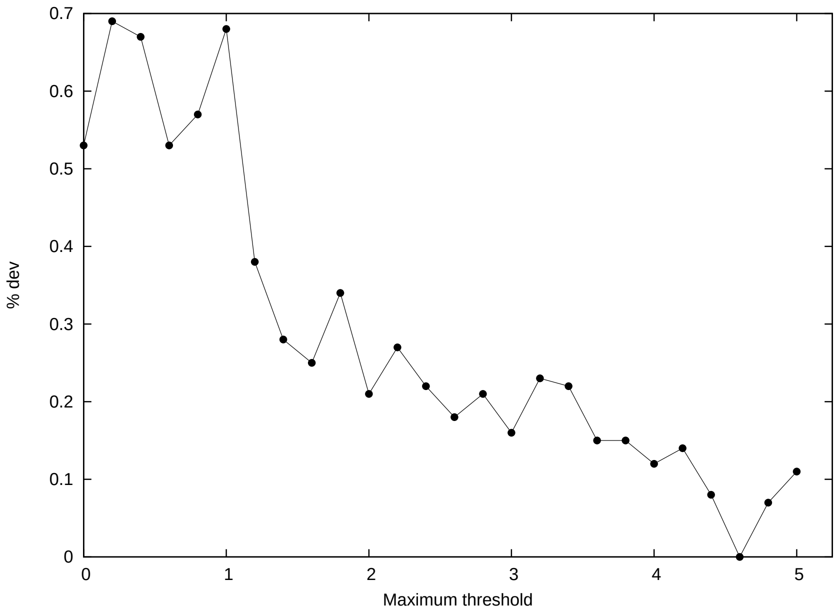

Figure 8.6: Sensitivity analysis of T_{max}

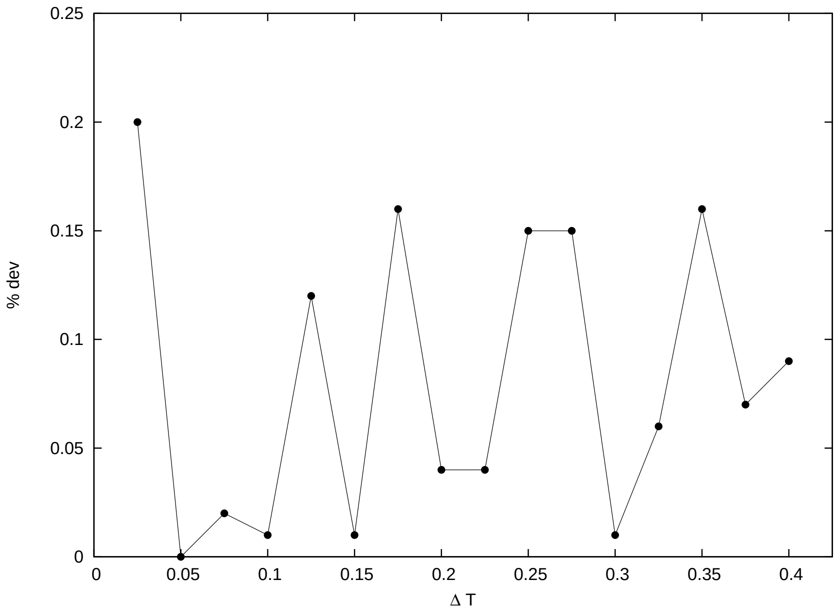

Figure 8.7: Sensitivity analysis of ΔT

Parameter	Value
T_{max}	2
ΔT	0.025
$n_{improve}$	1000
$\bar{n}$	10

Table 8.8: Parameter settings independent DA algorithm

Problem		Run 1			Run 2			Run 3		
Class	Instance	VC	FC	TC	VC	FC	TC	VC	FC	TC
1	1	2745	70	2815	2740	70	2810	2741	60	2801
4	3	8116	190	8306	8124	180	8304	8136	190	8326
6	5	5091	110	5201	5089	110	5199	5093	110	5203
7	3	4116	80	4196	4143	90	4233	4112	80	4192

Table 8.9: Results three independent runs

Problem		lower bound			best solution DA only			
Class	Instance	VC	FC	TC	VC	FC	TC	gap
1	1	2734	50	2784	2741	60	2801	0.62%
4	3	8063	130	8193	8124	180	8304	1.36%
6	5	5074	80	5154	5089	110	5199	0.89%
7	3	4080	70	4150	4112	80	4192	1.02%

Table 8.10: Gap DA algorithm with lower bound solution

A comparison between the local search heuristic, the DA algorithm as a post-optimizer and the independent DA algorithm is given in table 8.11. Deterministic annealing performs equally well as an independent algorithm starting from random initial solutions as in a post-optimization phase, after improving the quality of the initial solution by the local search heuristic. Both DA applications find solutions with a smaller deviation from the lower bound than the local search heuristic.

Problem		local search		DA post		DA only	
Class	Instance	TC	gap	TC	gap	TC	gap
1	1	2839	1.98%	2807	0.83 %	2801	0.62%
4	3	8411	2.66%	8307	1.40%	8304	1.36%
6	5	5228	1.44%	5193	0.76%	5199	0.89%
7	3	4202	1.26%	4171	0.51%	4192	1.02%

Table 8.11: Comparison on four test instances

8.5 Conclusions

In this chapter a deterministic annealing algorithm is presented in a post-optimization phase to further improve the near optimal solutions found by the local search heuristic in the previous chapter. The DA algorithm is based on the same three local search operators, CROSS, COMBINE and INSERT. A fractional factorial design is set up to test the sensitivity of the DA algorithm to changes in parameter settings. The DA algorithm is tested on the same experimental design as in chapter 7. Computational experiments confirm the robustness of the algorithm with respect to variations in problem characteristics. Finally, the DA algorithm is tested as an independent algorithm, without first applying the local search heuristic. This analysis shows that the DA algorithm generates good quality solutions independent of the quality of the initial solution.

The following extensions to the problem description in chapters 7 and 8 could be made. In reality multiple types of vehicles and containers are utilized. The local search operators could be adapted to take a variety of containers and vehicles into account. Secondly, drayage operators may be confronted with uncertain travel times, for example due to congestion. Congestion may be taken into account as stochastic travel times. Another approach to robust vehicle routing are dynamic vehicle routing problems in which not all data are known at planning time. The local search operators may be reapplied to repair the initial solution given the new information during the execution of the route. Van Woensel et al. (2007) consider time-dependent travel times due to traffic congestion. The authors apply queueing theory to model traffic congestion and conclude that total travel times can be improved significantly when explicitly taking into account congestion during optimization. Variable travel times are studied in the context of urban freight transport by Taniguchi and Shimamoto

(2004). Genetic algorithms are adopted for identifying near-optimal solutions and dynamic traffic simulation is used to update travel times. A genetic algorithm is also proposed by Haghani and Jung (2005) to solve a dynamic vehicle routing problem with time-dependent travel times. Janssens et al. (2009) present a methodology based on Time Petri nets to evaluate travel time uncertainty in vehicle routing solutions.

Chapter 9

Final conclusions and further research

The purpose of this thesis was to analyse intermodal barge transport networks with the objective of increasing their attractiveness. Two main topics are investigated. Firstly, bundling of freight is analysed at multiple decision levels. Bundling of freight in the port area (chapter 4) is compared with bundling in corridor networks in the hinterland (chapter 5). Chapter 6 presents a case study on bundling of freight inside a loading unit at the operational decision level. Secondly, the pre- and end-haulage by road is formulated as a full truckload pickup and delivery problem with time windows and solved by two heuristic algorithms (chapters 7 and 8). This final chapter summarizes main conclusions and gives directions for further research (figure 9.1).

9.1 Final conclusions

Intermodal freight transport offers interesting challenges for operations research. In this thesis a number of these research challenges have been addressed. The focus in intermodal freight transport research has been to a large extent on combinations with railways. Only few researchers consider intermodal transport by barge. This thesis studies intermodal barge transport networks due to the importance of inland navigation in Western Europe. Cooperation between actors and integration between planning problems at different decision levels is necessary. Research efforts are required to develop solution methods for intermodal planning problems.

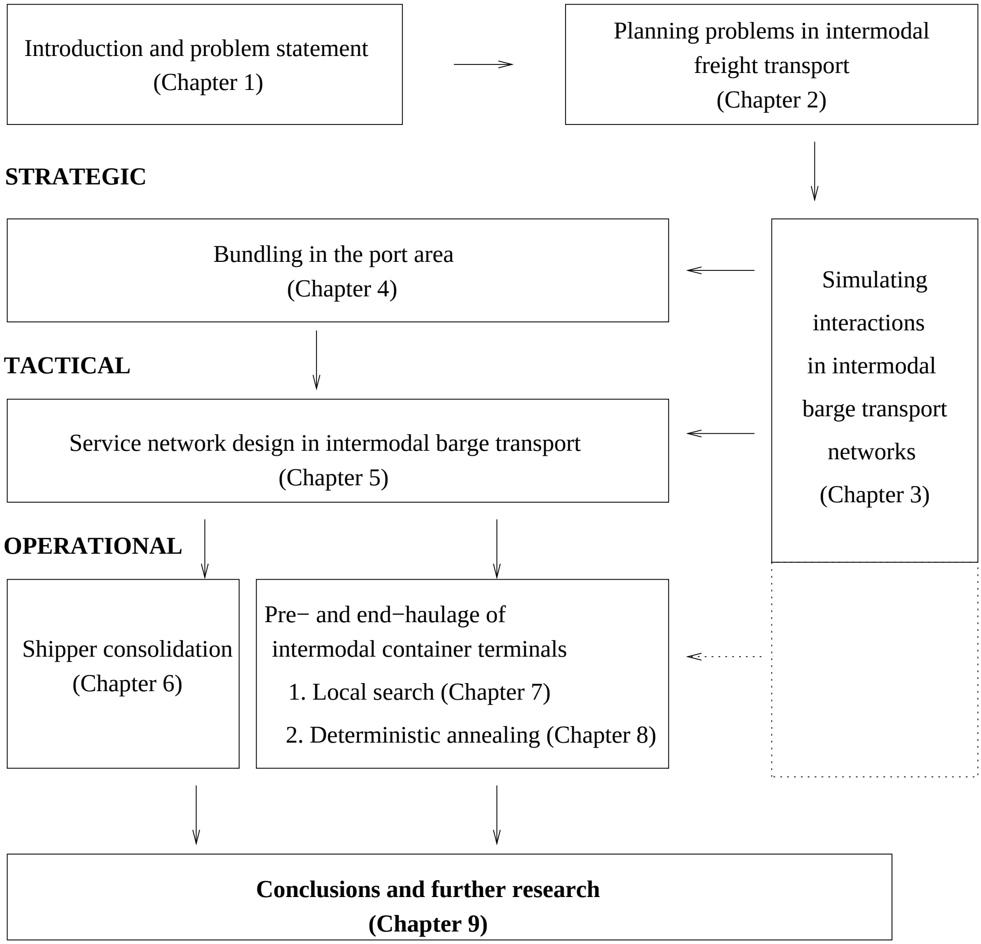

Figure 9.1: Outline of the thesis - Chapter 9

The network design of intermodal barge transport has been studied on the strategic and tactical decision level. Practitioners often suggest that more bundling should take place in intermodal barge transport. However, no consensus exists on which consolidation strategy to follow. In this thesis two consolidation strategies are compared on a number of quantitative performance measures. The Belgian hinterland network of the port of Antwerp serves as an example. Barge freight flows may be bundled in the hinterland or in the port area.

In the port area a collection/distribution network may be set up, in which inland freight flows are bundled at an intermodal barge hub. The provision of additional infrastructure is a strategic decision. Four scenarios for consolidating inland barge freight flows in the port area of Antwerp are compared by means of a discrete event Simulation model for InterModal BArge transport (SIMBA). Two key performance measures are turnaround times of inland vessels and capacity utilization at sea terminals. First, the turnaround time of inland shuttle services may be reduced because of a reduced waiting time in the port area. Second, sea terminals may operate more efficiently because vessels with consolidated load operate in the collection/distribution network in the port area. The simulation of hub scenarios in the port area reveals that turnaround times of vessels only reduce for those inland shuttle services that do not have to pass through a lock system in the port area. The turnaround time of all inland shuttle services improves significantly by taking the specific structure of the port area in Antwerp into account. The most interesting scenario from the perspective of inland barge operators is the provision of two hubs in the port area, one on each side of the three lock systems. Inland barges only visit a single hub for which they do not have to pass through a lock system. The collection/distribution network is organized jointly for the two hubs. The reduced capacity utilization at peak hours is used as an indicator for potential efficiency improvements at sea terminals. The hub scenarios assume an equal available quay length for handling inland freight flows at sea terminals as in the current situation. From the perspective of sea terminal operators, the most interesting scenario also involves the provision of two hubs, but the collection/distribution network in the port area is organized locally. By doing so, vessels in the collection/distribution network only carry containers for local sea terminals. However, a better coordination between the two hubs may improve efficiency gains at sea terminals in a joint collection/distribution network. The simulation analyses assume that all containers in the collection/distribution network are transported by barge. In reality some containers may be carried by truck to a nearby sea terminal and time windows may be fixed at sea terminals for vessels in the collection/distribution network. Inland terminals may adjust their sailing schedules to the new hub strategy or may negotiate time windows with an intermodal barge hub. Therefore, simulation results may be interpreted as a lower limit for potential reductions in turnaround times of inland vessels and efficiency improvements in the port area. A win-win situation for all parties will be necessary to obtain a commitment from all stakeholders in the implementation phase.

An alternative consolidation strategy is setting up corridor networks along hinterland waterway connections. Cooperation between inland terminals in a corridor network is formulated as a service network design problem at the tactical decision level. Corridor networks are investigated along the three major river axes in the Belgian hinterland of the port of Antwerp. Corridor networks offer interesting opportunities for terminals with smaller volumes situated at a further distance from the port area. Selected cooperation scenarios are simulated with the SIMBA model, to compare the results with bundling in the port area. Terminals involved in a corridor network have to take a longer turnaround time into account. The impact on turnaround times also appears larger as more terminals are involved. Less efficiency gains at sea terminals are reported, as freight is only bundled of two to three inland terminals, whereas bundling in the port area involves all terminals in the hinterland network. Cooperation between inland terminals offers an opportunity to attain economies of scale and to reduce maximum waiting times of inland barges at sea terminals. A combination of bundling measures in the port area and in the hinterland may be necessary to improve the intermodal transport chain.

At the operational decision level freight may be clustered inside a loading unit. Consolidation of freight of multiple shippers inside a loading unit increases the fill rate and thus the utilization of transport equipment. A higher fill rate may improve the efficiency of pre- and end-haulage by road and stimulate intermodal freight transport for further continental distribution. A real life case study is described to introduce the concept of shipper consolidation. Possible advantages are a reduction in standing time of loading units, an increase in fill rate and less loading units required over the planning horizon. Larger improvements in performance measures may be achieved when incorporating consolidation decisions in the warehouse planning and operations.

The second part of this thesis models intermodal drayage operations. Pre- and end-haulage by road involves the transportation of full truckloads to and from an intermodal terminal. A local search heuristic is proposed to find good quality solutions within a short time frame. The local search heuristic consists of an insertion heuristic and an improvement heuristic. Three local search operators are defined: CROSS, COMBINE and INSERT. Numerical experiments show that the algorithm is robust with respect to variations in problem characteristics. In all problem instances a small gap between the heuristic solution and the lower bound solution is found. Furthermore, the heuristic is logically constructed and offers an intuitive and fast approach to find good quality solutions for practitioners. Next, a deterministic annealing algorithm is applied as a post-optimizer to the near optimal solutions found by the local search heuristic. The same three local search operators are incorporated. Parameter settings are tested by means of a fractional factorial design. The DA algorithm is able to further improve solutions found by the local search algorithm. Finally, the DA algorithm is tested as an independent algorithm, without first applying the local search heuristic. This analysis shows that the DA algorithm generates good quality solutions independent of the quality of the initial solution.

9.2 Further research

As intermodal freight transport is a young research field, directions for further research can be given. First, the SIMBA model presented in this thesis is limited to barge transport. The model may be extended for further analysis to incorporate rail connections. Road transport may be added to the SIMBA model to make a comparison with intermodal freight transport. A module could be introduced to capture intermodal terminal planning and a methodology may be developed for calculating the probability of incurring a certain waiting time before handling in the port area. The SIMBA model is also suitable for analysing future growth scenarios in barge transport and simulating lockage operation rules.

Future research may introduce multiple time periods and frequencies into the service network design formulation for corridor networks. Corridor networks may offer two benefits, attaining economies of scale and increasing frequency of service. In this thesis the focus has been on the first benefit, as economies of scale can be quantified. However, it may also be interesting to investigate the effect of an increase in departures offered by inland terminals. The impact of policy measures to stimulate cooperation between inland terminals, can be estimated by applying alternative cost data in the proposed service network design formulation. An alternative service network design formulation for trunk collection/distribution networks may be developed with the objective to make a comparison with corridor networks.

Case study results demonstrate that shipper consolidation is an interesting concept for further research. An investigation may be made into how to adapt the warehouse planning to take advantage of consolidation opportunities. Relationships between customer demand, warehouse planning and shipping operations need to be explored.

Finally, a number of extensions may be made to the problem description of intermodal drayage operations. In reality multiple types of vehicles and containers are utilized. The local search operators could be adapted to take a variety of containers and vehicles into account. Secondly, drayage operators may be confronted with uncertain travel times, for example due to congestion. Congestion may be taken into account as stochastic travel times. Another approach to robust vehicle routing are dynamic vehicle routing problems in which not all data are known at planning time. The local search operators may be reapplied to repair the initial solution given the new information during the execution of the route.

Appendix A

Maximum waiting times in port area

Simulation run	**Current**		**Hub right**
	Right river bank	Left river bank	
1	3.5963	3.3326	6.2917
2	7.6128	4.0666	8.4450
3	2.7056	4.3095	7.7974
4	3.7187	3.8062	5.5155
5	3.8771	3.1175	7.2255
6	4.7428	4.1456	6.9227
7	2.8844	3.3406	7.8491
8	3.5003	1.3025	5.3793
9	3.4827	3.3136	6.8852
10	2.0875	4.1730	4.8906

Table A.1: Maximum waiting time: current situation and hub right river bank

Simulation run	**Current**		**Hub left**
	Right river bank	Left river bank	
1	3.5963	3.3326	7.9326
2	7.6128	4.0666	7.6311
3	2.7056	4.3095	4.5764
4	3.7187	3.8062	7.1295
5	3.8771	3.1175	8.3733
6	4.7428	4.1456	5.9177
7	2.8844	3.3406	6.0726
8	3.5003	1.3025	2.9095
9	3.4827	3.3136	6.6673
10	2.0875	4.1730	5.9488

Table A.2: Maximum waiting time: current situation and hub left river bank

Simulation run	**Current**		**Multihub 1**	
	Right river bank	Left river bank	Hub right	Hub left
1	3.5963	3.3326	5.2787	5.5669
2	7.6128	4.0666	5.3765	4.9224
3	2.7056	4.3095	7.4321	5.0047
4	3.7187	3.8062	6.2036	4.2929
5	3.8771	3.1175	7.2258	3.8324
6	4.7428	4.1456	5.7052	3.8210
7	2.8844	3.3406	7.0498	2.9773
8	3.5003	1.3025	5.9735	3.5994
9	3.4827	3.3136	6.0897	2.4828
10	2.0875	4.1730	6.8744	3.6920

Table A.3: Maximum waiting time: current situation and multihub scenario 1

Simulation run	**Current**		**Multihub 2**	
	Right river bank	Left river bank	Hub right	Hub left
1	3.5963	3.3326	3.1828	2.7953
2	7.6128	4.0666	2.3090	2.5227
3	2.7056	4.3095	2.4839	1.9278
4	3.7187	3.8062	2.8628	1.9431
5	3.8771	3.1175	3.5219	2.6170
6	4.7428	4.1456	3.5960	1.5383
7	2.8844	3.3406	8.1493	1.7489
8	3.5003	1.3025	4.0030	1.8928
9	3.4827	3.3136	3.4314	1.7690
10	2.0875	4.1730	6.3242	2.0451

Table A.4: Maximum waiting time: current situation and multihub scenario 2

Simulation run	**Current**		**Cooperation**	
	Right river bank	Left river bank	Right river bank	Left river bank
1	3.5963	3.3326	1.1530	1.7584
2	7.6128	4.0666	0.5742	3.4869
3	2.7056	4.3095	2.2071	1.0173
4	3.7187	3.8062	1.2059	0.5364
5	3.8771	3.1175	0.0000	1.4303
6	4.7428	4.1456	2.0557	1.1251
7	2.8844	3.3406	2.2597	5.1275
8	3.5003	1.3025	0.5355	0.4560
9	3.4827	3.3136	1.4815	1.3660
10	2.0875	4.1730	0.9027	1.5321

Table A.5: Maximum waiting time: current situation and line bundling in hinterland

Bibliography

Alessandri, A., C. Cervellera, M. Cuneo, M. Gaggero, and G. Soncin (2009). Management of logistics operations in intermodal terminals by using dynamic modelling and nonlinear programming. *Maritime Economics & Logistics 11*(1), 58–76.

Alessandri, A., S. Sacone, and S. Siri (2007). Modelling and optimal receding-horizon control of maritime container terminals. *Journal of Mathematical Modelling and Algorithms 6*, 109–133.

Alicke, K. (2002). Modeling and optimization of the intermodal terminal Mega Hub. *OR Spectrum 24*, 1–17.

Andersen, J., T. G. Crainic, and M. Christiansen (2009a). Service network design with asset management: formulations and comparative analyses. *Transportation Research Part C 17*, 197–207.

Andersen, J., T. G. Crainic, and M. Christiansen (2009b). Service network design with management and coordination of multiple fleets. *European Journal of Operational Research 193*, 377–389.

Arnold, P., D. Peeters, and I. Thomas (2004). Modelling a rail/road intermodal transportation system. *Transportation Research Part E 40*, 255–270.

Arnold, P. and I. Thomas (1999). Localisation des centres de transbordement dans un système multi-reseaux: essai de formalisation. *L'Espace Géographique 3*, 193–204.

Ballis, A. and J. Golias (2004). Towards the improvement of a combined transport chain performance. *European Journal of Operational Research 152*, 420–436.

Barnhart, C. and H. D. Ratliff (1993). Modeling intermodal routing. *Journal of business logistics 14*(1), 205–223.

Bent, R. and P. Van Hentenryck (2006). A two-stage hybrid algorithm for pickup and delivery vehicle routing problems with time windows. *Computers & Operations Research 33*, 875–893.

Boardman, B., E. Malstrom, D. Butler, and M. Cole (1997). Computer assisted routing of intermodal shipments. *Computers and Industrial Engineering 33*(1–2), 311–314.

Bontekoning, Y. M. (2006). *Hub exchange operations in intermodal hub-and-spoke networks.* Ph.D. dissertation, The Netherlands TRAIL Research School, Delft.

Bontekoning, Y. M. and E. Kreutzberger (Eds.) (1999). *Concepts of new-generation terminals and terminal nodes.* Delft: Delft University Press.

Bontekoning, Y. M., C. Macharis, and J. Trip (2004). Is a new applied transportation research field emerging? - A review of intermodal rail-truck freight transport literature. *Transportation Research Part A 38*, 1–34.

Bostel, N. and P. Dejax (1998). Models and algorithms for container allocation problems on trains in a rapid transshipment shunting yard. *Transportation Science 32*(4), 370–379.

Bräysy, O., J. Berger, M. Barkaoui, and W. Dullaert (2003). A threshold accepting metaheuristic for the vehicle routing problem with time windows. *Central European Journal of Operations Research 11*, 369–387.

Bräysy, O., W. Dullaert, G. Hasle, D. Mester, and M. Gendreau (2008). An effective multirestart deterministic annealing metaheuristic for the fleet size and mix vehicle routing problem with time windows. *Transportation Science 42*(3), 371–386.

Bräysy, O. and M. Gendreau (2005). Vehicle routing problem with time windows, part I: route construction and local search algorithms. *Transportation Science 39*(1), 104–118.

Caramia, M. and F. Guerriero (2009). A heuristic approach to long-haul freight transportation with multiple objective functions. *Omega 37*, 600–614.

Caris, A. and G. K. Janssens (2009). A local search heuristic for the pre- and end- haulage of intermodal container terminals. *Computers & Operations Research 36*(10), 2763–2772.

Caris, A. and G. K. Janssens (2010). A deterministic annealing algorithm for the pre- and end-haulage of intermodal container terminals. *InternationalJournal of Computer Aided Engineering and Technology 2*(4), 340–355.

Caris, A., G. K. Janssens, and C. Macharis (2009). Modelling complex intermodal freight flows. In M. Aziz-Alaoui and C. Bertelle (Eds.), *Understanding Complex Systems Series: From System Complexity to Emergent Properties.*, pp. 291–300. Springer Berlin / Heidelberg.

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

Caris, A., C. Macharis, and G. K. Janssens (2010). Network analysis of container barge transport in the port of Antwerp by means of simulation. *Forthcoming in Journal of Transport Geography*.

Chang, E., E. Floros, and A. Ziliaskopoulos (2007). An intermodal time-dependent minimum cost path algorithm, with an application to hazmat routing. In V. Zeimpekis, C. D. Tarantilis, G. M. Giaglis, and I. Minis (Eds.), *Dynamic Fleet Management*, Volume 38 of *Operations Research/Computer Science Interfaces Series*, Chapter 6, pp. 113–132. Springer US.

Chang, T.-S. (2008). Best routes selection in international intermodal networks. *Computers & Operations Research 35*, 2877–2891.

Chih, K., M. Bodden, M. Hornung, and A. Kornhauser (1990). Routing and inventory logistics systems (rails): a heuristic model for optimally managing intermodal double-stack trains. *Journal of Transportation Research Forum 31*(1), 50–62.

Chih, K. C. K. and C. D. van Dyke (1987). The intermodal equipment distribution model. In *Transportation Research Forum XXVII*, Number 1, pp. 97–103.

Cho, Y.-J. and S.-D. Wang (2005). A threshold accepting metaheuristic for the vehicle routing problem with backhauls and time windows. *Journal of the Eastern Asia Society for Transportation Studies 6*, 3022–3037.

Choong, S. T., M. H. Cole, and E. Kutanoglu (2002). Empty container management for intermodal transportation networks. *Transportation Research Part E 38*, 423–438.

Cordeau, J.-F., M. Gendreau, G. Laporte, J.-Y. Potvin, and F. Semet (2002). A guide to vehicle routing heuristics. *Journal of the Operational Research Society 53*, 512–522.

Cordeau, J.-F., G. Laporte, M. W. Savelsbergh, and D. Vigo (2007). Vehicle routing. In C. Barnhart and G. Laporte (Eds.), *Transportation*, Volume 14 of *Hand-*

books in operations research and management science, Chapter 6, pp. 367–428. North-Holland.

Corry, P. and E. Kozan (2006). An assignment model for dynamic load planning of intermodal trains. *Computers & Operations Research 33*, 1–17.

Corry, P. and E. Kozan (2008). Optimised loading patterns for intermodal trains. *OR Spectrum 30*, 721–750.

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

Crainic, T. G., M. Florian, J. Guélat, and H. Spiess (1990). Strategic planning of freight transportation: STAN, an interactive-graphic system. *Transportation Research Record 1283*, 97–124.

Crainic, T. G. and K. H. Kim (2007). Intermodal transportation. In C. Barnhart and G. Laporte (Eds.), *Transportation*, Volume 14 of *Handbooks in operations research and management science*, Chapter 8, pp. 467–537. North-Holland.

Crainic, T. G. and G. Laporte (1997). Planning models for freight transportation. *European Journal of Operational Research 97*, 409–438.

Crainic, T. G. and J.-M. Rousseau (1986). Multicommodity, multimode freight transportation: a general modeling and algorithmic framework for the service network design problem. *Transportation Research Part B 20*.

Currie, R. and S. Salhi (2003). Exact and heuristic methods for a full-load, multi-terminal, vehicle scheduling problem with backhauling and time windows. *Journal of the Operational Research Society 54*, 390–400.

Currie, R. and S. Salhi (2004). A tabu search heuristic for a full-load, multi-terminal, vehicle scheduling problem with backhauling and time windows. *Journal of Mathematical Modelling and Algorithms 3*, 225–243.

De Langen, P. W. and A. Chouly (2004). Hinterland access regimes in seaports. *European Journal of Transport and Infrastructure Research 4*(4), 361–380.

Desrochers, M., J. Lenstra, and M. Savelsbergh (1990). A classification scheme for vehicle routing and scheduling problems. *European Journal of Operational Research 46*(3), 322–332.

Douma, A., M. Schutten, and P. Schuur (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 17*, 133–148.

Dueck, G. and T. Scheuer (1990). Threshold accepting: a general purpose optimization algorithm appearing superior to simulated annealing. *Journal of Computational Physics 90*, 161–175.

Dumas, Y., J. Desrosiers, and F. Soumis (1991). The pickup and delivery problem with time windows. *European Journal of Operational Research 54*, 7–22.

Erera, A. L., J. C. Morales, and M. Savelsbergh (2005). Global intermodal tank container management for the chemical industry. *Transportation Research Part E 41*, 551–566.

Ergun, Ö., G. Kuyzu, and M. Savelsbergh (2007). Shipper collaboration. *Computers & Operations Research 34*, 1551–1560.

Evers, J. J. and R. De Feijter (2004). Centralized versus distributed feeder ship service: the case of the Maasvlakte harbour area of Rotterdam. *Transportation Planning and Technology 27*(5), 367–384.

Feo, T. A. and J. L. González-Velarde (1995). The intermodal trailer assignment problem. *Transportation Science 29*(4), 330–341.

Ferreira, L. and J. Sigut (1995). Modelling intermodal freight terminal operations. *Road and Transport Research Journal 4*(4), 4–16.

Fishman, G. S. (2001). *Discrete-event simulation: modeling, programming and analysis.* Springer Series in Operations Research.

Francis, P., G. Zhang, and K. Smilowitz (2007). Improved modeling and solution methods for the multi-resource routing problem. *European Journal of Operational Research 180*, 1045–1059.

Gambardella, L. M., M. Mastrolilli, A. E. Rizzoli, and M. Zaffalon (2001). An optimization methodology for intermodal terminal management. *Journal of Intelligent Manufacturing 12*, 521–534.

Gambardella, L. M., A. E. Rizzoli, and P. Funk (2002). Agent-based planning and simulation of combined rail/road transport. *Simulation 78*(5), 293–303.

Grasman, S. E. (2006). Dynamic approach to strategic and operational multimodal routing decisions. *International Journal of Logistics Systems and Management 2*(1), 96–106.

Gronalt, M., R. F. Hartl, and M. Reimann (2003). New savings based algorithms for time constrained pickup and delivery of full truckloads. *European Journal of Operational Research 151*, 520–535.

Groothedde, B., C. Ruijgrok, and L. Tavasszy (2005). Towards collaborative, intermodal hub networks. A case study in the fast moving consumer goods market. *Transportation Research Part E 41*, 567–583.

Groothedde, B. and L. A. Tavasszy (1999). Optimalisatie van terminallocaties in een multimodaal netwerk met simulated annealing. In *Proceedings van de Vervoerslogistieke Werkdagen 1999*. Connekt.

Haghani, A. and S. Jung (2005). A dynamic vehicle routing problem with time-dependent travel times. *Computers & Operations Research 32*, 2959–2986.

Huynh, N. N. (2005). *Methodologies for reducing truck turn time at marine container terminals*. Ph.D. dissertation, University of Texas, Austin.

Imai, A., E. Nishimura, and J. Current (2007). A Lagrangian relaxation-based heuristic for the vehicle routing with full container load. *European Journal of Operational Research 176*(1), 87–105.

Janic, M., A. Reggiani, and P. Nijkamp (1999). Sustainability of the European freight transport system: evaluation of innovative bundling networks. *Transportation Planning and Technology 23*, 129–156.

Janssens, G. K., A. Caris, and K. Ramaekers (2009). Time Petri nets as an evaluation tool for handling travel time uncertainty in vehicle routing solutions. *Expert Systems with Applications 36*, 5987–5991.

Jourquin, B., M. Beuthe, and C. L. Demilie (1999). Freight bundling network models: methodology and application. *Transportation Planning and Technology 23*, 157–177.

Justice, E. D. (1996). *Optimization of chassis reallocation in doublestack container transportation systems*. Ph.D. dissertation, University of Arkansas.

Kallehauge, B. (2008). Formulations and exact algorithms for the vehicle routing problem with time windows. *Computers & Operations Research 35*, 2307–2330.

Kallehauge, B., J. Larsen, and O. B. Madsen (2006). Lagrangian duality applied to the vehicle routing problem with time windows. *Computers & Operations Research 33*, 1464–1487.

Kapros, S., K. Panou, and D. A. Tsamboulas (2005). Multicriteria approach to the evaluation of intermodal freight villages. *Transportation Research Record 1906*, 56–63.

Kawamura, K. and Y. Lu (2007). Evaluation of delivery consolidation in U.S. urban areas with logistics cost analysis. *Transportation Research Record 2008*, 34–42.

Kemper, P. and M. Fischer (2000). Modelling and analysis of a freight terminal with stochastic petri nets. In *IFAC Control in Transportation Systems*, pp. 267–272. Braunschweig, Germany.

Kim, D. (1997). *Large scale transportation service network design: models, algorithms and applications.* Ph.D. dissertation, Center for Transportation Studies, Massachusetts Institute of Technology, Cambridge, MA.

Kirkpatrick, S., C. Gelatt, and M. Vecchi (1983). Optimization by simulated annealing. *Science 220*, 671–680.

Klodzinski, J. and H. M. Al-Deek (2004). Methodology for modeling a road network with high truck volumes generated by vessel freight activity from an intermodal facility. *Transportation Research Record 1873*, 35–44.

Konings, R. (2003). Network design for intermodal barge transport. *Transportation Research Record 1820*, 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*, 443–454.

Konings, R. (2009). *Intermodal barge transport: network design, nodes and competitiveness.* Ph.D. dissertation, The Netherlands TRAIL Research School, Delft.

Konings, R. and H. Priemus (2008). Terminals and the competitiveness of container barge transport. *Transportation Research Record 2062*, 39–49.

Kozan, E. (2000). Optimising container transfers at multimodal terminals. *Mathematical and Computer Modelling 31*, 235–243.

Kozan, E. (2006). Optimum capacity for intermodal container terminals. *Transportation Planning and Technology 29*(6), 471–482.

Kreutzberger, E. D. (2003). The impact of innovative technical concepts for load unit exchange on the design of intermodal freight networks. *Transportation Research Record 1820*, 1–10.

Kreutzberger, E. D. (2005). Hub and spoking in a process of changing bundling concepts of intermodal rail networks: current developments in the light of intermodal efficiency. In *Proceedings of the BIVEC-GIBET Transport Research Day 2005*, Diepenbeek, Belgium.

Kreutzberger, E. D. (2007). Transport bundeling networks and economies of scale, scope, density and network. In *Bijdragen Vervoerslogistieke Werkdagen.* Nautilus Academic books.

Kulick, B. C. and J. T. Sawyer (2001). The use of simulation to calculate the labor requirements in an intermodal rail terminal. *Proceedings of the 2001 Winter Simulation Conference*, 1038–1041.

Kuo, A., E. Miller-Hooks, K. Zhang, and H. Mahmassani (2008). Train slot cooperation in multicarrier, international rail-based intermodal freight transport. *Transportation Research Record 2043*, 31–40.

Landrieu, A., Y. Mati, and Z. Binder (2001). A tabu search heuristic for the single vehicle pickup and delivery problem with time windows. *Journal of Intelligent Manufacturing 12*, 497–508.

Law, A. M. (2007). *Simulation modeling & analysis* (Fourth ed.). McGraw Hill.

le Blanc, H., F. Cruijssen, H. Fleuren, and M. de Koster (2006). Factory gate pricing: an analysis of the Dutch retail distribution. *European Journal of Operational Research 174*, 1950–1967.

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

Limbourg, S. and B. Jourquin (2009). Optimal rail-road container terminal locations on the european network. *Transportation Research Part E 45*, 551–563.

Lin, C.-C. and S.-H. Chen (2004). The hierarchical network design problem for time-definite express common carriers. *Transportation Research Part B 38*, 271–283.

Loureiro, C. (1994). *Modeling investment options for multimodal transportation networks*. Ph.D. dissertation, University of Tennessee, USA. UMI Dissertation Service.

Lu, Q. and M. M. Dessouky (2006). A new insertion-based construction heuristic for solving the pickup and delivery problem with time windows. *European Journal of Operational Research 175*, 672–687.

Lyons, M., I. Adjali, D. Collings, and O. Jensen (2003). Complex systems models for strategic decision making. *BT Technology Journal 21*(2), 11–27.

Macharis, C. (2004). A methodology to evaluate potential locations for intermodal barge terminals: a policy decision support tool. In M. Beuthe, V. Himanen, A. Reggiani, and L. Zamparini (Eds.), *Transport Developments and Innovations in an Evolving World*, pp. 211–234. Berlin: Springer.

Macharis, C. and Y. M. Bontekoning (2004). Opportunities for OR in intermodal freight transport research: a review. *European Journal of Operational Research 153*, 400–416.

Macharis, C., J. Brans, and B. Mareschal (1998). The gdss promethee procedure. *Journal of Decision Systems 7*, 283–307.

Macharis, C., E. Pekin, A. Caris, and B. Jourquin (2008). *A decision support system for intermodal transport policy.* VUBPRESS.

Macharis, C. and A. Verbeke (1999). Een multicriteria-analyse methode voor de evaluatie van intermodale terminals. *Tijdschrift Vervoerswetenschap 4*, 323–352.

Magnanti, T. and R. Wong (1984). Network design and transportation planning: models and algorithms. *Transportation Science 18*(1), 1–40.

Marín Martínez, F., I. García Gutiérrez, A. Ortiz Oliveira, and L. M. Arreche Bedia (2004). Gantry crane operations to transfer containers between trains: a simulation study of a Spanish terminal. *Transportation Planning and Technology 27*(4), 261–284.

Meinert, T. S., A. D. Youngblood, G. D. Taylor, and H. Taha (1998). Simulation of the railway component of intermodal transportation. Working paper, Arkansas University, Fayetteville.

Meixell, M. J. and M. Norbis (2008). A review of the transportation mode choice and carrier selection literature. *The International Journal of Logistics Management 19*(2), 183–211.

Meyer, P. (1998). *Entwicklung eines Simulationsprogramms fr Umschlagterminals des Kombinierten Verkehrs.* Ph.D. dissertation, University of Hannover.

Min, H. (1991). International intermodal choices via chance-constrained goal programming. *Transportation Research Part A 25*(6), 351–362.

Morlok, E. K., J. P. Sammon, L. N. Spasovic, and L. K. Nozick (1995). Improving productivity in intermodal rail-truck transportation. In P. T. Harker (Ed.), *The Service Productivity and Quality Challenge*, pp. 407–434. Kluwer Academic Publishers.

Morlok, E. K. and L. N. Spasovic (1994). Redesigning rail-truck intermodal drayage operations for enhanced service and cost performance. *Journal of the Transportation Research Forum 34*(1), 16–31.

Nagy, G. and S. Salhi (2005). Heuristic algorithms for single and multiple depot vehicle routing problems with pickups and deliveries. *European Journal of Operational Research 162*, 126–141.

Nanry, W. P. and J. W. Barnes (2000). Solving the pickup and delivery problem with time windows using reactive tabu search. *Transportation Research Part B 34*, 107–121.

Newman, A. M. and C. A. Yano (2000a). Centralized and decentralized train scheduling for intermodal operations. *IIE Transactions 32*, 743–754.

Newman, A. M. and C. A. Yano (2000b). Scheduling direct and indirect trains and containers in an intermodal setting. *Transportation Science 34*(3), 256–270.

Nikolakopoulos, A. and H. Sarimveis (2007). A threshold accepting heuristic with intense local search for the solution of special instances of the traveling salesman problem. *European Journal of Operational Research 177*, 1911–1929.

Notteboom, T. E. (2007). Inland waterway transport of containerised cargo: from infancy to a fully-fledged transport mode. *Journal of Maritime Research 4*(2), 63–80.

Notteboom, T. E. (2008). The relationship between seaports and the intermodal hinterland in light of global supply chains: European challenges. Discussion paper 2008-10, OECD, Paris.

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

Nozick, L. K. and E. K. Morlok (1997). A model for medium-term operations planning in an intermodal rail-truck service. *Transportation Research Part A 31*(2), 91–107.

Osman, I. H. (1993). Metastrategy simulated annealing and tabu search algorithms for the vehicle routing problem. *Annals of Operations Research 41*(4), 421–451.

Osman, I. H. and N. A. Wassan (2002). A reactive tabu search meta-heuristic for the vehicle routing problem with back-hauls. *Journal of Scheduling 5*, 263–285.

Parola, F. and A. Sciomachen (2005). Intermodal container flows in a port system network: analysis of possible growths via simulation models. *International Journal of Production Economics 97*, 75–88.

Parragh, S. N., K. F. Doerner, and R. F. Hartl (2008). A survey on pickup and delivery problems, part I: transportation between customers and depot. *Journal für Betriebswirtschaft 58*, 21–51.

Pettit, S. J. and A. K. C. Beresford (2009). Port development: from gateways to logistics hubs. *Maritime Policy & Management 36*, 253–267.

Platz, T. E. (2009). *The efficient integration of inland shipping into continental intermodal transport chains: measures and decisive factors*. Ph.D. dissertation, The Netherlands TRAIL Research School, Radboud Universiteit Nijmegen.

Powell, W. B. and T. A. Carvalho (1998). Real-time optimization of containers and flatcars for intermodal operations. *Transportation Science 32*(2), 110–126.

Racunica, I. and L. Wynter (2005). Optimal location of intermodal freight hubs. *Transportation Research Part B 39*, 453–477.

Rahimi, M., A. Asef-Vaziri, and R. Harrison (2008). An inland port location-allocation model for a regional intermodal goods movement system. *Maritime Economics & Logistics 10*(4), 362–379.

Rizzoli, A. E., N. Fornara, and L. M. Gambardella (2002). A simulation tool for combined rail/road transport in intermodal terminals. *Mathematics and Computers in Simulation 59*, 57–71.

Rotter, H. (2004). New operating concepts for intermodal transport: the mega hub in Hanover/Lehrte in Germany. *Transportation Planning and Technology 27*(5), 347–365.

Rutten, B. J. C. M. (1998). The design of a terminal network for intermodal transport. *Transport Logistics 1*(4), 279–298.

Savelsbergh, M. and M. Sol (1995). The general pickup and delivery problem. *Transportation Science 29*(1), 17–29.

Solomon, M. M. (1987). Algorithms for the vehicle routing and scheduling problems with time window constraints. *Operations Research 35*(2), 254–265.

Southworth, F. and B. E. Peterson (2000). Intermodal and international freight network modeling. *Transportation Research Part C 8*, 147–166.

Spasovic, L. N. (1990). *Planning intermodal drayage network operations*. Ph.D. dissertation, University of Pennsylvania, Philadelphia.

Spasovic, L. N. and E. K. Morlok (1993). Using marginal costs to evaluate drayage rates in rail-truck intermodal service. *Transportation Research Record 1383*, 8–16.

Tan, A., R. Bowden, and Y. Zhang (2004). Virtual simulation of statewide intermodal freight traffic. *Transportation Research Record 1873*, 53–63.

Taniguchi, E. and H. Shimamoto (2004). Intelligent transportation system based dynamic vehicle routing and scheduling with variable travel times. *Transportation Research Part C 12*, 235–250.

Tarantilis, C., C. Kiranoudis, and V. Vassiliadis (2004). A threshold accepting metaheuristic for the heterogeneous fixed fleet vehicle routing problem. *European Journal of Operational Research 152*, 148–158.

Taylor, G. D., F. Broadstreet, T. S. Meinert, and J. S. Usher (2002). An analysis of intermodal ramp selection methods. *Transportation Research Part E 38*, 117–134.

Theunissen, C. and G. K. Janssens (2005). A 'less-flexibility-first' heuristic for the placement of inland vessels in a lock. *Transportation Planning and Technology 28*(6), 427–446.

Theys, C., W. Dullaert, and T. Notteboom (2008). Analyzing cooperative networks in intermodal transportation: a game-theoretic approach. In *Nectar Logistics and Freight Cluster Meeting*, Delft, the Netherlands.

Ting, C.-J. and P. Schonfeld (1996). Effects of tow sequencing on capacity and delay at a waterway lock. *Journal of Waterway, Port, Coastal and Ocean Engineering 122*(1), 16–26.

Trip, J. J. and Y. Bontekoning (2002). Integration of small freight flows in the intermodal transport system. *Journal of Transport Geography 10*, 221–229.

Tsai, J., E. Morlok, and T. Smith (1994). Optimal pricing of rail intermodal freight: models and tests. Working paper, University of Pennsylvania, Philadelphia.

Tsamboulas, D., H. Vrenken, and A. Lekka (2007). Assessment of transport policy potential for intermodal mode shift on a European scale. *Transportation Research Part A 41*(8), 715–733.

Van der Horst, M. R. and P. W. De Langen (2008). Coordination in hinterland transport chains: a major challenge for the seaport community. *Maritime Economics and Logistics 10*, 108–129.

Van Duin, R. and H. Van Ham (October 11-14, 1998). A three-stage modeling approach for the design and organization of intermodal transportation services. *Proceedings 1998 IEEE International Conference on Systems, Man and Cybernetics 4 San Diego, CA, USA*, 4051–4056.

Van Woensel, T., L. Kerbache, H. Peremans, and N. Vandaele (2007). A queueing framework for routing problems with time-dependent travel times. *Journal of Mathematical Modelling and Algorithms 6*, 151–173.

Vis, I. F. (2006). A comparative analysis of storage and retrieval equipment at a container terminal. *International Journal of Production Economics 103*, 680–693.

Vis, I. F. and R. de Koster (2003). Transshipment of containers at a container terminal: an overview. *European Journal of Operational Research 147*, 1–16.

Voges, J., H. Kesselmeier, and J. Beister (1994). Simulation and performance analysis of combined transport terminals. In *Proceedings INTERMODAL '94 Conference*, Amsterdam, the Netherlands.

Vrenken, H., C. Macharis, and P. Wolters (2005). *Intermodal transport in Europe.* Brussels: European Intermodal Association.

Walker, W. T. (1992). Network economics of scale in short haul truckload operations. *Journal of Transport Economics and Policy XXVI*(1), 3–17.

Wang, X. and A. C. Regan (2002). Local truckload pickup and delivery with hard time window constraints. *Transportation Research Part B 36*, 97–112.

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

Winston, C. (1985). Conceptual developments in the economics of transportation: an interpretive survey. *Journal of Economic Literature 23*, 57–94.

Woxenius, J. (2007). Generic framework for transport network designs: applications and treatment in intermodal freight transport literature. *Transport Reviews 27*(6), 733–749.

Yan, S., D. Bernstein, and Y. Sheffi (1995). Intermodal pricing using network flow techniques. *Transportation Research Part B 29*, 171–180.

Yoon, M.-G. and J. Current (2008). The hub location and network design problem with fixed and variable arc costs: formulation and dual-based solution heuristic. *Journal of the Operational Research Society 59*, 80–89.

Ziliaskopoulos, A. and W. Wardell (2000). An intermodal optimum path algorithm for multimodal networks with dynamic arc travel times and switching delays. *European Journal of Operational Research 125*, 486–502.

Zografos, K. G. and A. C. Regan (2004). Current challenges for intermodal freight transport and logistics in Europe and the United States. *Transportation Research Record 1873*, 70–78.

Samenvatting

De afgelopen jaren heeft intermodaal goederentransport een verhoogde aandacht gekregen omwille van congestie op het wegennet, milieuoverwegingen en aandacht voor verkeersveiligheid. Intermodaal transport wordt gedefinieerd als de combinatie van tenminste twee transportmodi in één transportketen, waarbij de goederen niet van ladingseenheid veranderen. Het hoofdtraject wordt uitgevoerd per spoor, binnenschip of maritiem schip. Het voor- en natransport via de weg wordt zo kort mogelijk gehouden. Intermodaal transport speelt een belangrijke rol in de ontsluiting van havens naar het achterland. Havens vormen een onderdeel van intermodale ketens en competitie vindt plaats tussen transportketens in plaats van tussen havens. Meer en meer aandacht wordt gelegd op continentale distributienetwerken in het achterland van havens, met als doel het verhogen van de logistieke integratie en het reduceren van de distributiekosten. Hierbij wordt de binnenvaart vaak gesuggereerd als oplossing om een goede toegang tot het achterland te verzekeren.

In deze thesis worden intermodale transportnetwerken via de binnenvaart gemodellereerd en geanalyseerd met als doelstelling hun aantrekkelijkheid te verhogen. Het onderzoek is toegespitst op twee kernaspecten in de competititiveit van intermodaal transport via de binnenvaart. Het eerste deel van de thesis bestudeert de bundeling van goederen in intermodale binnenvaartnetwerken. Het tweede deel focust op het voor- en natransport via de weg in de intermodale transportketen. Opportuniteiten voor het bundelen van goederen worden geïdentificeerd op het strategische en tactische beslissingsniveau. Het voor- en natransport via de weg wordt geanalyseerd op het operationele beslissingsniveau.

In het eerste deel van de thesis wordt een simulatiemodel ontwikkeld voor het ondersteunen van beslissingen met betrekking tot intermodaal vervoer via de binnenvaart, hierna SIMBA model genoemd. Het model wordt in de thesis gebruikt voor het analyseren van bundelingsnetwerken op strategisch en tactisch niveau. Vaak wordt gesuggereerd dat goederen meer gebundeld dienen te worden in intermodaal vervoer via de binnenvaart. Er bestaat echter geen consensus over welke consolidatiestrategie hierbij dient te worden gevolgd. In deze thesis worden twee consolidatiestrategieën vergeleken aan de hand van een aantal kwantitatieve prestatiemaatstaven. Goederenstromen kunnen gebundeld worden in het havengebied of in het achterland. Hierbij wordt het Belgische achterlandnetwerk van de haven van Antwerpen als voorbeeld gebruikt.

De eerste consolidatiestrategie bestaat uit het opzetten van een collectie/distributienetwerk in de haven, waarin goederenstromen van en naar het achterland gebundeld worden op een intermodale hub. Dit impliceert een strategische beslissing over het verschaffen van toegewijde infrastructuur voor de binnenvaart. Vier mogelijke scenarios worden vergeleken aan de hand van het SIMBA model. Twee bepalende prestatiemaatstaven hierbij zijn de omlooptijd van binnenvaartschepen en de capaciteitsbenutting bij zeeterminals. Ten eerste kan de omlooptijd van binnenvaartschepen gereduceerd worden door een verminderde wachttijd in het havengebied. Ten tweede kunnen zeeterminals efficiënter werken doordat binnenvaartschepen met geconsolideerde lading in het collectie/distributienetwerk in het havengebied varen. Het simuleren van hub scenarios toont aan dat de omlooptijd van binnenvaartschepen vooral kan gereduceerd worden door sluispassages te vermijden. Het meest interessante hubscenario vanuit het perspectief van de binnenvaart is dit aangepast aan de specifieke structuur van het havengebied in Antwerpen. Hierin worden twee hubs in het havengebied voorzien, één aan iedere kant van de drie sluizencomplexen. Binnenvaartschepen bezoeken in dit scenario enkel de hub waarvoor zij niet door een sluis dienen te varen. Het collectie/distributienetwerk in de haven wordt voor de twee hubs gezamenlijk georganiseerd. Vanuit het standpunt van de zeeterminaloperatoren bestaat het meest interessante scenario ook uit twee hubs, maar het collectie/distributienetwerk wordt lokaal georganiseerd. Hierdoor bevatten binnenvaartschepen in het collectie/distributienetwerk enkel containers voor de lokale zeeterminals. Dit wijst op het belang van een goede coördinatie tussen de twee hubs wanneer geopteerd wordt voor een gezamenlijk collectie/distributienetwerk. In de simulatieanalyses wordt verondersteld dat alle containers in het collectie/distributienetwerk per schip vervoerd worden. In realiteit kunnen sommige containers per truck naar een nabije zeeterminal vervoerd worden en kunnen tijdsvensters aan de zeeterminals afgesproken worden. Binnenvaartterminals kunnen hun afvaarten aanpassen aan de nieuwe hubstrategie en tijdsvensters met de intermodale hub afspreken. De simulatieresultaten stellen bijgevolg een ondergrens voor voor de potentiële reducties in omlooptijden van binnenvaartschepen en efficiëntieverbeteringen in het havengebied. Een winstsituatie voor alle partijen zal noodzakelijk zijn om het engagement van alle betrokkenen te krijgen in de implementatiefase.

De tweede consolidatiestrategie die onderzocht wordt, is het opzetten van corridornetwerken langs waterwegen in het achterland. Samenwerking tussen binnenvaartterminals wordt gemodelleerd als een service netwerk design probleem op een tactisch beslissingsniveau. De formulering wordt toegepast op de drie belangrijkste rivierassen in het Belgische achterland van de haven van Antwerpen. De voorgestelde methodologie maakt het mogelijk om opportuniteiten te identificeren voor het behalen van schaalvoordelen. Hieruit blijkt dat corridornetwerken interessante opportuniteiten bieden voor terminals met kleinere volumes, gelegen op een verdere afstand van de haven. Geselecteerde scenarios voor samenwerking worden vervolgens gesimuleerd met het SIMBA model om de resultaten te vergelijken met bundeling in het havengebied. Terminals die betrokken zijn in een corridornetwerk dienen rekening te houden met langere omlooptijden. De impact op omlooptijden wordt groter wanneer meer terminals deelnemen aan het corridornetwerk. De simulatieresultaten tonen bovendien dat samenwerking tussen binnenvaartterminals leidt tot een reductie in maximale wachttijden voor binnenvaartschepen in het havengebied. Minder efficiëntiewinsten worden echter geregistreerd voor de zeeterminals, aangezien enkel goederen van twee tot drie binnenvaartterminals gebundeld worden. Een intermodale hub in de haven leidt daarentegen tot bundeling van goederen voor alle binnenvaartterminals in het achterlandnetwerk. Een combinatie van bundelingsmaatregelen in het havengebied en in het achterland kan nodig zijn om de intermodale transporketen te verbeteren.

Vervolgens wordt een gevalstudie beschreven waarin lading van meerdere verzenders wordt geconsolideerd. Op het operationele beslissingsniveau kunnen goederen afkomstig van meerdere verzenders gebundeld worden in één ladingseenheid. Mogelijke voordelen zijn een reductie in de wachttijd van ladingseenheden, een stijging van de vulgraad en een daling van het aantal benodigde ladingseenheden. Een hogere vulgraad doet de efficiëntie van het voor-en natransport via de weg stijgen en kan intermodaal transport stimuleren voor een verdere continentale distributie. Deze prestatiemaatstaven kunnen nog verder verbeterd worden door het integreren van consolidatiebeslissingen met de voorraadplanning en magazijnwerking.

In het tweede deel van deze thesis wordt het voor- en natransport via de weg gemodelleerd als een rittenplanningsprobleem met ophaling en aflevering van volle ladingen en tijdsvensters bij klanten. Een lokale zoekmethode wordt voorgesteld om een goede oplossing in een korte tijdspanne te vinden. Deze lokale zoekmethode bestaat uit een invoegheuristiek en een verbeteringsheuristiek. Hiervoor worden drie lokale zoekoperatoren gedefinieerd: CROSS, COMBINE en INSERT. Numerische experimenten tonen aan dat het algoritme robuust is met betrekking tot variaties in probleemkenmerken. Slechts een kleine afwijking wordt vastgesteld tussen de heuristische oplossingen en de berekende ondergrens. Bovendien is de heuristiek logisch opgebouwd en biedt ze een intuïtieve en snelle benadering om goede oplossingen te vinden voor transportplanners. Vervolgens wordt een deterministic annealing algoritme toegepast in een post-optimalisatiefase op de oplossingen gevonden door de lokale zoekmethode. Dezelfde drie lokale operatoren worden hierbij geïmplementeerd. Tenslotte wordt het deterministic annealing algoritme getest als een apart algoritme, zonder eerst de lokale zoekmethode toe te passen. Hieruit blijkt dat het algoritme in staat is om goede oplossingen te vinden onafhankelijk van de kwaliteit van de initiële oplossing.

Publications and conference participation

Publications

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

Caris, A. and G.K. Janssens (2009). A local search heuristic for the pre- and end-haulage of intermodal container terminals. *Computers & Operations Research 36* (10), 2763-2772.

Caris, A., G.K. Janssens and C. Macharis (2009). Modelling complex intermodal freight flows. In M.A. Aziz-Alaoui and C. Bertelle (Eds.), *Understanding Complex Systems Series: From System Complexity to Emergent Properties.*, pp. 291-300. Springer Berlin / Heidelberg.

Caris, A., C. Macharis and G.K. Janssens (2010). Network analysis of container barge transport in the port of Antwerp by means of simulation. *Forthcoming in Journal of Transport Geography.*

Caris, A. and G.K. Janssens (2010). A deterministic annealing algorithm for the pre- and end-haulage of intermodal container terminals. *InternationalJournal of Computer Aided Engineering and Technology 2* (4), 340-355.

Janssens, G. K., A. Caris and K. Ramaekers (2009). Time Petri nets as an evaluation tool for handling travel time uncertainty in vehicle routing solutions. *Expert Systems with Applications 36*, 5987-5991.

Macharis, C., E. Pekin, A. Caris and B. Jourquin (2008). *A decision support system for intermodal transport policy.* VUBPRESS.

Pangilinan, J.M., G. K. Janssens and A. Caris (2008). Sensitivity analysis of a genetic algorithm for a competitive facility location problem. In K. Elleithy (eds.), *Innovations and Advanced Techniques in Systems, Computing Sciences and Software Engineering*, pp.266-271. Springer Netherlands.

Conference participation

Braekers, K., G. K. Janssens and A. Caris (2009). Review on the comparison of external costs of intermodal transport and unimodal road transport. In *BIVEC-GIBET Transport Research Day*, Brussels, Belgium, May 27th.

Braekers, K., G. K. Janssens and A. Caris (2009). Integrating empty container allocation with vehicle routing in intermodal transport. In *The International Workshop on Harbour, Maritime & Multimodal Logistics Modelling and Simulation*, Puerto de la Cruz, Spain, September 23-25, pp. 132-139.

Braekers, K., G. K. Janssens and A. Caris (2010). A deterministic annealing algorithm for the simultaneous routing of loaded and empty container movements. Forthcoming in *24th European Conference on Operational Research (EURO XXIV)*, Lisbon, Portugal, July 11-14.

Braekers, K., G. K. Janssens and A. Caris (2010). A deterministic annealing algorithm for simultaneous routing of loaded and empty containers. Forthcoming in *Proceedings of the Industrial Simulation Conference*, Budapest, Hungary, June 7-9.

Caris, A. and G. K. Janssens (2005). Selection of control variates for variance reduction in a multiresponse simulation with a small number of replications. In *Proceedings of the European Simulation and Modeling Conference*, Porto, Portugal, October 24-26, pp. 19-24.

Caris, A., G. K. Janssens and C. Macharis (2006). Modelling and optimising the inland waterway network in Belgium. In *Nectar Cluster Meeting on Freight Transport and Intermodality*, Göteborg, Sweden, March 22-23.

Caris A. (2006). Simulation and optimisation of intermodal freight transport networks including inland navigation. In *European Logistics Association Doctorate Workshop*, Grainau, Germany, June 28-30.

Caris, A., G. K. Janssens and C. Macharis (2007). A simulation approach to the analysis of intermodal freight transport networks. In *Proceedings of the European Simulation and Modelling Conference*, St. Julians, Malta, October 22-24, pp. 283-286.

Caris, A. and G. K. Janssens (2007). Pre- and end-haulage of intermodal container terminals modelled as a full truckload pickup and delivery problem with time windows, In *Proceedings of the European Conference on Modelling and Simulation*, Prague, Czech Republic, June 4-6, pp. 554-559.

Caris, A., C. Macharis and G.K. Janssens (2008). Network analysis of container barge transport in the port of Antwerp by means of simulation. In *Nectar Cluster Meeting on Freight Transport and Intermodality*, Delft, the Netherlands, March 27-28.

Caris, A. and G. K. Janssens (2008). A deterministic annealing algorithm for the pre- and end-haulage of intermodal container terminals. In *Proceedings of the European Simulation and Modelling Conference*, Le Havre, France, October 27-29, pp. 391-398.

Caris, A., G. K. Janssens and C. Macharis (2008). Service network design in intermodal barge transport. In *Vervoerslogistieke Werkdagen*, Deurne, the Netherlands, November 13-14, pp. 253-268.

Caris, A., G. K. Janssens, K. Ramaekers and C. Macharis (2009). Assessment of the impact of an additional intermodal barge terminal on a waterway network. In *Asian Simulation and Modelling Conference*, Bangkok, Thailand, January 22-23, pp. 99-105.

Caris, A., C. Macharis and G. K. Janssens (2010). Potential benefits of shipper consolidation at inland distribution centers. In *Electronic Proceedings of the 89th Annual Meeting of the Transportation Research Board*, Washington, USA, January 10-14.

Caris, A., C. Macharis and G. K. Janssens (2010). Modelling corridor networks in intermodal barge transport. Forthcoming in *World Conference on Transport Research*, Lisbon, Portugal, July 11-15.

Janssens, G. K., A. Caris and K. Ramaekers (2005). Sensitivity analysis of vehicle routing solutions to uncertainty in travel times. In *Proceedings of the BIVEC-*

GIBET Transport Research Day 2005, Diepenbeek, Belgium, November 30, pp. 483-493.

Janssens, G. K., A. Caris, K. Ramaekers and D. N. Batanov (2007). Evaluation of vehicle routing solutions by time Petri nets under condition of travel time uncertainty. In *Proceedings of the European Simulation and Modelling Conference*, St. Julians, Malta, October 22-24, pp. 163-169.

Pangilinan, J. M., G. K. Janssens and A. Caris (2005). A multi-objective evolutionary algorithm for finding efficient solutions to a competitive facility location problem. In *Proceedings of the BIVEC-GIBET Transport Research Day 2005*, Diepenbeek, Belgium, November 30, pp. 359-370.

Pekin, E., A. Caris, T. Crépin, C. Macharis, B. Jourquin and G. K. Janssens (2008). Integrated decision support tool for intermodal freight transport. In *Nectar Cluster Meeting on Freight Transport and Intermodality*, Delft, the Netherlands, March 27-28.

Van Lier, T., C. Macharis, A. Caris and H. Vrenken (2009). Internal and external co-loading of outbound flows to increase the sustainability of transport: a case study. In *Vervoerslogistieke Werkdagen*, Deurne, the Netherlands, November 12-13, pp. 193-208.

Van Lier, T., C. Macharis, A. Caris and H. Vrenken (2010). Potential for internal and external cost reduction by internally and externally co-loading outbound flows. Forthcoming in *World Conference on Transport Research*, Lisbon, Portugal, July 11-15.